Application of Industrial Heat Pumps

IEA Industrial Energy-related Systems and Technologies Annex 13
IEA Heat Pump Programme Annex 35

Final Report

Prepared by
Members of Annex 35/13

Contents

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IEA Industrial Energy-related Systems and Technologies Annex 13
IEA Heat Pump Programme Annex 35

Executive Summary

Prepared by
Members of Annex 35/13

Contents

1 Introduction

Securing a reliable, economic and sustainable energy supply as well as environmental and climate protection are important global challenges of the 21st century. Renewable energy and improving energy efficiency are the most important steps to achieve these goals of energy policy.

While impressive efficiency gains have already been achieved in the past two decades, energy use and CO_2 emissions in manufacturing industries could be reduced further, if best available technologies were to be applied worldwide.

Heat pumps have become increasingly important in the world as a technology to improve energy efficiency and reduce CO_2 emissions. In particular industrial heat pumps (IHPs) offer various opportunities to all types of manufacturing processes and operations. IHPs are using waste process heat as the heat source, deliver heat at higher temperature for use in industrial processes, heating or preheating, or for space heating and cooling in industry. They can significantly reduce fossil fuel consumption and greenhouse gas emissions in drying, washing, evaporation and distillation processes in a variety of applications. Industries that can benefit from this technology include food and beverage processing, forest products, textiles, and chemicals.

The introduction of heat pumps with operating temperature below 100 °C is in many cases considered to be easy, however, higher temperature application still require additional R&D activities for the development of high temperature heat pumps, integration of heat pumps into industrial processes and development of high temperature, environmentally sound refrigerants.

In this context, the IEA HPP-IETS Annex 35/13 "Application of industrial Heat Pumps", a joint venture of the International Energy Agency (IEA) Implementing Agreements "Industrial Energy-Related Technologies and Systems" (IETS) and "Heat Pump Programme" (HPP) has been initiated in order to actively contribute to the reduction of energy consumption and emissions of greenhouse gases by the increased implementation of heat pumps in industry

The Annex 35/13 started on 01. April 2010 and expired on 30. April 2014 with 15 participating organisations from Austria, Canada, Denmark, France, Germany (Operating Agent) Japan, The Netherlands, South Korea and Sweden

The Annex comprised an overview in the participating countries of the industrial energy situation and use, the state of the art and R&D projects in heat pumping and process technologies and its applications, as well as analysing business cases on the decision-making process in existing and new applications and in the wider application of industrial heat pumping technologies. The annex has been subdivided in the following tasks:

- Task 1: Market overview, barriers for application
- Task 2: Modeling calculation and economic models
- Task 3: Technology
- Task 4: Application and monitoring
- Task 5: Communication

2 Market overview, barriers for applications

The Task 1 Report summarized the present energy situation in general and the industrial energy use and related heat pump market subdivided into participating countries. Based upon these findings focus will be given to further work to meet the challenges for the wider application of industrial heat pumping technologies.
Although heat pumps for the industrial use became available on the markets in the participating countries in recent years, just very few carried out applications can be found. To distinguish the reasons for this situation, application barriers were also a part of the survey in Task 1:

- Lack of knowledge:

  The integration of heat pumps into industrial processes requires knowledge of the capabilities of industrial heat pumps, as well as knowledge about the process itself. Only few installers and decision makers in the industry have this combined knowledge, which enables them to integrate a heat pump in the most suitable way.

- Low awareness of heat consumption in companies:
  In most companies knowledge about heating and cooling demands of their processes is quite rare. This requires expensive and time consuming measurements to find an integration opportunity for an industrial heat pump

- Long payback periods:

  Compared to oil and gas burners, heat pumps have relatively high investment costs. At the same time companies expect very low payback periods of less than 2 or 3 years. Some companies were willing to accept payback periods up to 5 years, when it comes to investments into their energy infrastructure. To meet these expectations heat pumps need to have long running periods and good COPs to become economical feasible.

- High temperature application
  From the technical point of view one barrier can be identified regarding to the temperature limits of most commercially available heat pumping units. Many applications are limited to heat sink temperatures below 65°C the theoretical potential for the application range of IHP increases significantly by developing energy efficient heat pumps including refrigerants for heat sink temperatures up to and higher than 100°C.

3 Modelling calculations and economic models

The Task 2 Report intended to outline how the integration of IHP in processes is supported by computer software, i.e. by modeling.

In order to 'update' the Annex 21 screening program in the sense of a 'modern' development taking the original goals into account a proposal has been made that allows a consistent integration of a heat pump into a process based on pinch analysis. The basic elements of this concept are:

- Substitution of the problem table algorithm by an extended transshipment model which allows a simultaneous optimization of utilities and heat pump.
- Approximation of the heat exchanger network as in the standard pinch analysis.
- Development of an algorithm for selecting of a hot and cold stream (may be of several hot and cold streams) to which the heat pump could be connected.
- Development of a heat pump data base to be used within the simultaneous optimization. Since this optimization is nonlinear a special algorithm needs to be developed that enables convergence.

This concept of integrating a heat pump into a process is 'below' the sophisticated methods given by H.E. Becker [Methodology and Thermo-Economic Optimization For Integration of Industrial Heat Pumps, THÈSE NO 5341 (2012), ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE, Suisse, 2012]. Presently it is impossible to state whether such a development is unprecedented, relevant and needed.

The scoping analysis of existing models shows that the difference between 'pure' pinch models and sophisticated mathematical optimization models has been bridged in modern software tools. Regarding the integration of heat pumps into a process, codes like OSMOSE or CERES (amongst may be others) look promising.

Independent of any software tools, approaches and optimizations, a general heat pump data base should come more into the focus. Such a data base is needed for many purposes. Typical information to the database are not only source and sink temperature as well as size of heat pump etc. but also further details of the selected hot and cold streams to which the heat pump is selected, because this would allow to select a specific heat pump type.

The goals of Task 2 should be carefully reconsidered if a "new Task 2" team should be constituted. The State of the Art as well as industrial needs of research organizations, large companies as well as of energy consultants should be critically reviewed. We conclude that the application of general optimization methods is limited to a fairly small number of research groups and highly specialized groups within large companies. Energy consultants probably will prefer pinch analysis type models. In the whole context we consider the thesis of H.C. Becker (directed by F. Maréchal) as key reference due to the systematic methodology, based on pinch analysis and process integration techniques, to integrate heat pumps into industrial processes

4 Technology

The scope of the Task 3 Report was to identify in the industrial sector appropriate heat pumps as a technology of using waste heat effectively and for meeting future industrial and environmental requirements.

Commercially available heat pumps can supply heat only up to 100 °C. As industrial waste heat, available at low-temperatures, represents about 25 % of the total energy used by the manufacturing industry, R&D work has to be focused on high-temperature heat pumps able to recover heat at relatively low temperatures, generally between 5°C and 35°C for hot water supply, hot air supply, heating of circulating hot water and steam generation at temperatures up and higher than 100 °C.

Some development of the industrial heat pump using R-134a, R-245fa, R-717, R-744, hydro carbons, etc. has been made recently. However, except for R-744 and the flammables R-717 and HCs which are natural refrigerants with extremely low global warming potential (GWP), HFCs such as R-134a and R-245fa have high GWP values, and the use of HFCs are likely to be regulated in the viewpoint of global warming prevention in the foreseeable future. Therefore, development of alternative refrigerants with low GWP has been required.

At present, as substitutes of R-134a, R-1234yf and R-1234ze (E) are considered to be promising, and R-1234ze (Z) is attractive as a substitute of R-245fa. R-365mfc is considered to be suitable as a refrigerant of heat pump for vapor generation using waste heat, but its GWP value is high. Therefore, it seems that development of a substitute of R-365mfc should be furthered. The table below shows basic characteristics of the present and future refrigerants for IHPs.

Refrigerant	Chemical formula	GWP	Flammability	T_c °C	p_c M Pa	NBP °C
R-290	CH3CH2CH3	~20	yes	96.7	4.25	-42.1
R-601	CH3CH2CH2CH2CH3	~20	yes	196.6	3.37	36.1
R-717	NH3	0	yes	132.25	11.33	-33.33
R-744	CO2	1	none	30.98	7.3773	-78.40
R-1234yf	CF3CF=CH2	<1	weak	94.7	3.382	-29,48
R-134a	CF3CH2F	1,430	none	101.06	4.0593	-26.07
R-1234ze(E)	CFH=CHCF3	6	weak	109.37	3.636	-18.96
R-1234ze(Z)	CFH=CHCF3	<10	weak	153.7	3.97	9.76
R-245fa	CF3CH2CHF2	1,030	none	154.01	3.651	15.14
R-1233zd		6	none	165.6	3.5709	n. a.
R-1336mzz		9	none	171	n. a.	n. a.
R-365mfc	CF3CH2CF2CH3	794	weak	186,85	3.266	40.19

5 Applications and monitoring

The **Task 4 Report** focused on operating experiences and energy effects of representative industrial heat pump implementations, in particular field tests and case studies.

Industrial heat pumps are a class of active heat-recovery equipment that allows the temperature of a waste-heat stream to be increased to a higher, more useful temperature. Consequently, heat pumps can facilitate energy savings when conventional passive-heat recovery is not possible

The economics of an installation depends on how the heat pump is applied in the process. Identification of feasible installation alternatives for the heat pump is therefore of crucial importance. Consideration of fundamental criteria taking into account both heat pump and process characteristics, are useful. The initial procedure should identify a few possible installation alternatives, so the detailed project calculations can concentrate on a limited number of options.

The commercially available heat pump types each have different operating characteristics and different possible operating temperature ranges. These ranges overlap for some types. Thus, for a particular application, several possible heat pump types often exist. Technical, economic, ecological and practical process criteria determine the best suited type. For all types, the payback period is directly proportional to installation costs, so it is important to investigate possibilities for decreasing these costs for any heat pump installation.

The survey with a total of 150 projects and case studies has tried to present good examples of heat-pump technology and its application in industrial processes, field tests and commercial applications along with an analysis of operating data, when available, in accordance with the annex definition of industrial heat pumps, used for heating, ventilation, air-conditioning, hot water supply, heating, drying, dehumidification and other purposes.

6 Final Conclusions and future actions

The IEA HPP-IETS Annex 35/13 "Application of industrial Heat Pumps", a joint venture of the International Energy Agency (IEA) Implementing Agreements "Industrial Energy-Related Technologies and Systems" (IETS) and "Heat Pump Programme" (HPP) has been initiated in order to actively contribute to the reduction of energy consumption and emissions of greenhouse gases by the increased implementation of heat pumps in industry.

The Annex 35/13 started on 01. April 2010 and expired on 30. April 2014, with 15 participating organizations from Austria, Canada, Denmark, France, Germany (Operating Agent) Japan, The Netherlands, South Korea and Sweden

The programme and work has been mainly concentrated on the collection of statistical energy and environmental data and information related to industry as well as the present status of R&D and the application of heat pumps in industry. A total of 33 R&D projects and 76 applications of heat pumps in industry, in particular the use of waste process heat as the heat source, have been presented and analyzed by the participating countries.

It has been shown that in many companies and especially in SMEs, only very little and aggregated information on the actual thermal energy consumption is available and disaggregated data such as consumption of individual processes and subprocesses therefore has either to be estimated or determined by costly and time-consuming measurements, which often requires the integration of several processes at different temperature levels and with different operating time schedules. The exploitation of existing heat recovery potentials often requires the integration of several processes at different temperature levels and with different operating time schedules. Different technologies available for heat supply have to be combined in order to obtain optimum solutions.

Basis for the modeling calculation and economic models activities (Task 2) has been the update of the IHP screening program, to determine how industrial heat pumps could be used in different applications, developed and presented in "Annex 21 - Global Environmental Benefits of Industrial Heat Pumps (1992 -1996)".

The IHP screening program has been analyzed and converted from an outdated Visual Basic version to the latest Visual Basic version employing the .NET framework. This new, converted version would in principle be ready for any modifications, updates of data and models as well as for extensions. However, during the execution of Task 2 it became obvious that the authors consider this approach as a dead-end and the screening program as obsolete. Since 1997 no further work on this program has been done and the authors decline any further developments. We simply noticed that the formulation of the corresponding item in the legal text did not take this situation into account. However, parts of the screening program, for instance the database, could be easily extracted and modernized for other purposes.

Although the Annex has been prolonged by one year, mainly because of missing results from Task 2, nearly none of the deliveries could be finished as foreseen, due to the fact that most participants are not concerned directly with modeling and software aspects and a large underestimation of the wide range of software tools with their very different scopes.

Taking into account the results of the annex with detailed information on statistical data, R&D results and case studies, a possible follow-up annex should be concentrated on a consistent integration of a heat pump into a process based on pinch analysis. The basic z elements of this concept should be:

- Substitution of the problem table algorithm by an extended transshipment model which allows a simultaneous optimization of utilities and heat pump.
- Approximation of the heat exchanger network as in the standard pinch analysis.
- Development of an algorithm for selecting of a hot and cold stream, to which the heat pump could be connected.
- Development of a heat pump data base to be used within the simultaneous optimization.

Since this optimization is nonlinear a special algorithm needs to be developed that enables convergence.

Application of Industrial Heat Pumps

IEA Industrial Energy-related Systems and Technologies Annex 13
IEA Heat Pump Programme Annex 35

Basics of Industrial Heat Pumps

Final Report

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Prepared by
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IZW e.V.

Contents

1 Introduction

Securing a reliable, economic and sustainable energy supply as well as environmental and climate protection are important challenges of the 21st century. Renewable energy and improving energy efficiency are the most important steps to achieve these goals of energy policy.

About 30 % of the global energy demand [IEA, 2013] and CO_2 emissions are attributable to industry, especially the big primary materials industries such as chemicals and petrochemicals, iron and steel, cement, paper and aluminium. Understanding how this energy is used, the national and international trends and the potential for efficiency gains, are crucial.

While impressive efficiency gains have already been achieved in the past two decades, energy use and CO_2 emissions in manufacturing industries could be reduced further, if best available technologies were to be applied worldwide.

Heat pumps have become increasingly important in the world as a technology to improve energy efficiency and reduce CO_2 emissions. The heat pump markets are currently growing at a steady pace, however, in many countries focused mainly on residential heat pumps for space heating and cooling as well as domestic hot water. Heat pumps for high temperature applications and industrial use have often been neglected, as the share of energy cost has been low for companies and thus investments to improve production normally have a much higher priority than investments in energy efficiency. Increased use of energy has, to some extent, been an indication of economic growth.

Industrial heat pumps (IHPs), however, offer various opportunities to all types of manufacturing processes and operations. Increased energy efficiency is certainly the IHPs most prominent benefit, but few companies have realized the untapped potential of IHPs in solving production and environmental problems. IHPs can offer the least-cost option in getting the bottlenecks out of production process to allow greater product throughput. In fact, IHPs may be an industrial facility's best way of significantly and cost-effectively reducing combustion related emissions [Leonardo, 2007].

Industrial heat pumps are using waste process heat as the heat source, deliver heat at higher temperature for use in industrial process heating or preheating, or for space heating and cooling in industry. They can significantly reduce fossil fuel consumption and greenhouse gas emissions in drying, washing, evaporation and distillation processes in a variety of applications as well as heating and cooling of industrial and commercial buildings. Industries that can benefit from this technology include food and beverage processing, forest products, textiles, and chemicals.

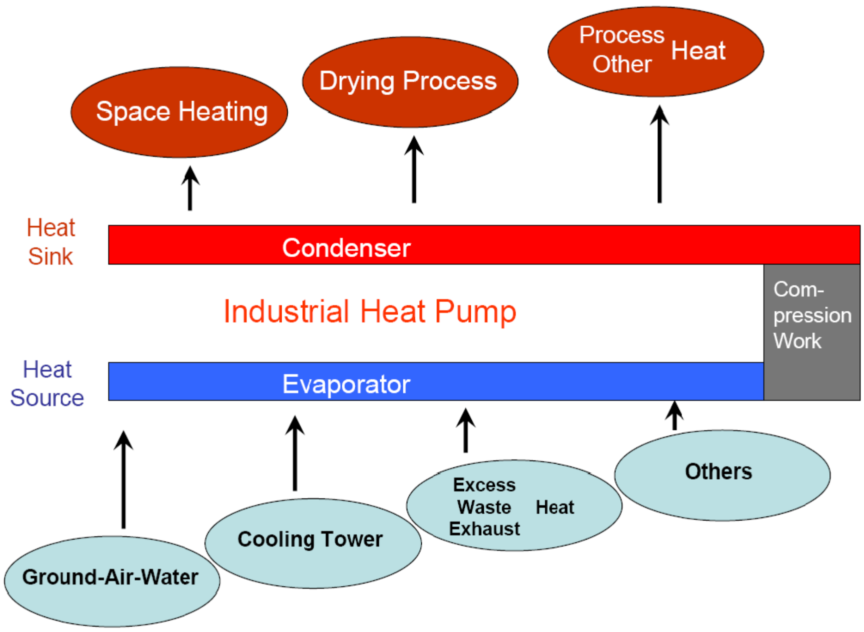

Figure 1-1: Heat sources and heat sinks in industrial heat pumps

While the residential market may be satisfied with standardized products and installations, most industrial heat pump applications need to be adapted to unique conditions. In addition a high level of expertise of heat pumps and processing is crucial.

Industrial heat pumps within this annex are defined as heat pumps in the medium and high power ranges which can be used for heat recovery and heat upgrading in industrial processes, but also for heating and cooling in industrial buildings.

Their potential for energy conservation and reduction of CO_2-emissions are enormous and at this moment not naturally a part of policy papers. The following problems and respective needs for research are related to the market introduction of IHPs:

- lack of refrigerants in the interesting temperature range
- lack of experimental and demonstration plants
- uncertainty by potential users as to HP reliability
- lack of necessary knowledge of heat pump technology and application by designers and consulting engineers.

On the other side, IHPs have the following advantages in comparison to heat pumps for space heating:

- high coefficient of performance (COP) due to low temperature lift and/or high temperature levels
- long annual operating time
- relatively low investment cost, due to large units and small distance between heat source and heat sink
- waste heat production and heat demand occur at the same time.

2 Physical principles

A heat pump is essentially a heat engine operating in reverse. Its principle is illustrated below.

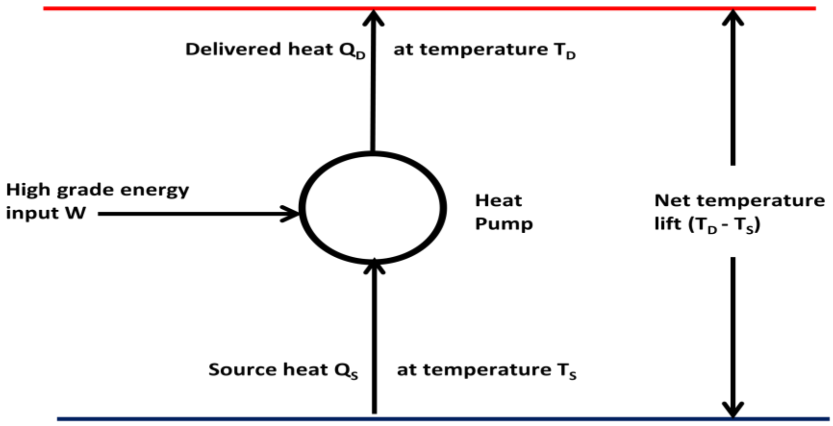

Figure 2-1: Heat pump principle

From the first law of thermodynamics, the amount of heat delivered Q_D at the higher temperature $T_D$is related to the amount of heat extracted Q_S at the low temperature T_S and the amount of high grade energy input W by the equation

$$Q_D = Q_S + W$$

Compared to heat pumps for space heating, using heat sources such as ground or water, IHPs often have the following advantages:

- high coefficient of performance due to low temperature lifts and/or high temperature levels;
- long annual operating times;
- relatively low investments cost, due to large units and small distances between heat source and heat sink;
- waste heat production and heat demand occur at the same time.

Despite these advantages, the number of heat pump installations in industry is almost negligible compared to those installed for space heating.

Note:
A coefficient of performance (COP) can be defined as

$$COP = \frac{Q_D}{W}$$

The Carnot coefficient of performance

$$COP_c = \frac{T_D}{T_D - T_S}$$

represents the upper theoretical value obtainable in a heat pump system.

In practice attainable coefficients of performance are significantly less than COP_c. Unfortunately, it is difficult to compare the COPs of different categories of IHP, which differ widely for equivalent economic performance. When comparing heat pump systems driven by different energy sources it is more appropriate to use the primary energy ratio (PER) defined as

$$PER = \frac{usefull\ heat\ delivered}{primary\ energy\ input}$$

The equation can be related to the coefficient of performance by the equation

$$PER = \eta \times COP$$

where η is the efficiency with which the primary energy input is converted into work up to the shaft of the compressor.

3 Heat pump technology

3.1 Criteria for possible heat pump applications

The first step in any possible IHP application is to identify technically feasible installation alternatives, and possibilities for their economic installation.

In simple operations, where the process in which the IHP will be used only consists of a few streams with obvious sink and source, the need for a thorough assessment is normally not necessary. In these cases, only the characteristics of the sink and source are of importance for the feasibility and selection of the IHP. The obvious parameters are:

- heat sink and source temperature;
- size (in terms of heat load) of the sink and source;
- physical parameters of the sink and source, such as phase and location

Industrial heat pumps are used in the power ranges of 50 – 150 kW and 150 to several MW.

The sink and source temperatures determine which IHP types can be used in a specific application. These types can be categorized in various ways, e.g. as mechanically- or heat-driven, compression or absorption, closed or open cycles.

3.2 Thermodynamic processes

The most important thermodynamic processes for industrial heat pumps are:

- closed compression cycle - electric driven or gas-engine driven
- mechanical (MVR) and thermal (TVR) vapour recompression
- sorption cycle
- absorption–compression cycle
- current developments, e. g. thermo acoustic, injections

and will be described in the next chapters.

3.2.1 Mechanical compression cycles

The principle of the simple closed compression cycle is shown below.

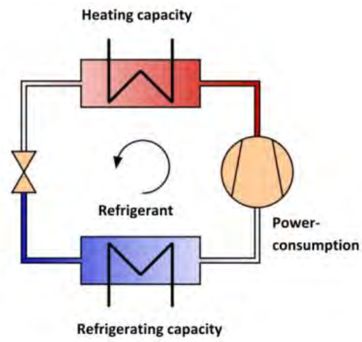

Figure 3-1: Closed compression cycle

Four different types of compressors are used in closed compression cycle heat pumps: Scroll, reciprocating, screw and turbo compressors.

Scroll compressors are used in small and medium heat pumps up to 100 kW heat output, reciprocating compressors in systems up to approximately 500 kW, screw compressors up to around 5 MW and turbo compressors in large systems above about 2 MW, as well as oil-free turbo compressors above 250 kW.

3.2.1.1 Vapour injection

In the economizer vapour injection (EVI) cycle, see figure below, a heat exchanger is used to provide additional sub-cooling to the refrigerant before it enters the evaporator. This sub-cooling process provides the increased capacity gain measured in the system. During the sub-cooling process, a certain amount of refrigerant is evaporated. This evaporated refrigerant is injected into the compressor and provides additional cooling at higher compression ratios, similar to liquid injection.

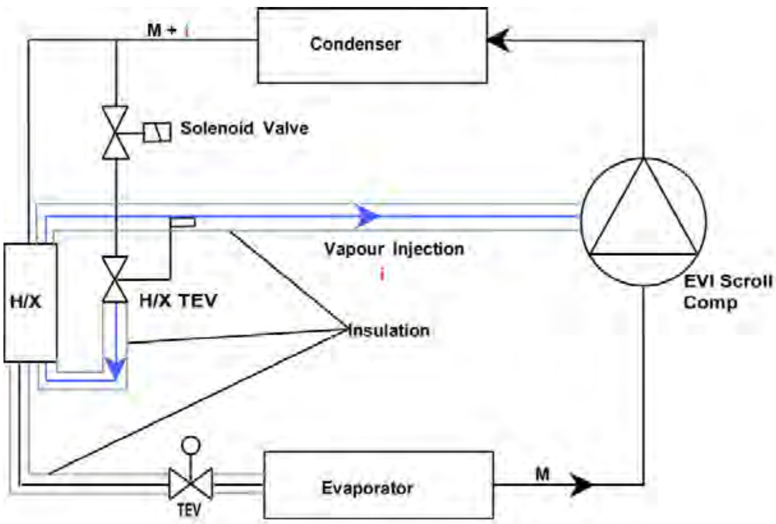

Figure 3-2: Vapour injection

3.2.2 Thermal compression cycles

3.2.2.1 Absorption heat pumps

Absorption heat pump cycles are based on the fact that the boiling point for a mixture is higher than the corresponding boiling point of a pure, volatile working fluid. Thus the working fluid must be a mixture consisting of a volatile component and a non-volatile one. The most common mixture in industrial applications is a lithium bromide solution in water ($LiBr/H_2O$) and ammonia water (NH_3/H_2O).

The fundamental absorption cycle has two possible configurations: absorption heat pump (AHP, Type I) and heat transformer (AHP, Type II), which are suitable for different purposes.

The difference between the cycles is the pressure level in the four main heat exchangers (evaporator, absorber, desorber and condenser), which influence the temperature levels of the heat flows.

The application of absorption cycles for high temperature heat recovery systems calls for the investigation of new working pairs. To qualify as a potential working pair, a mixture of two substances has to fulfil stringent requirements with respect to thermodynamic properties, corrosion and safety hazards like toxicity and inflammability.

Based on a thermodynamic analysis of an absorption heat pump cycle a systematic search for new working pairs has been required, e. g. investigation of organic compounds.

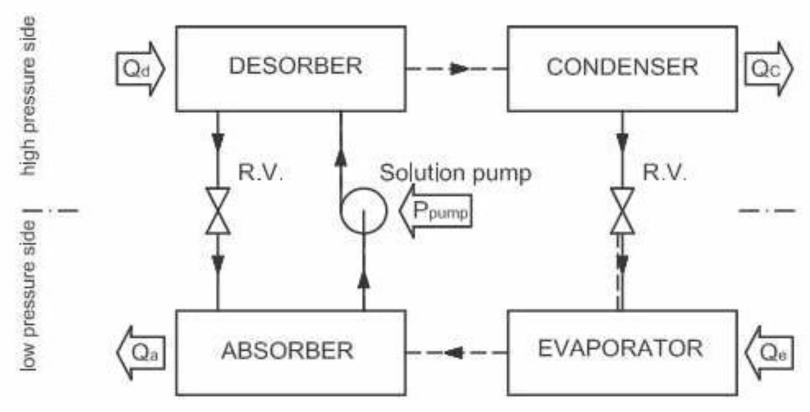

Figure 3-3: Absorption

3.2.2.2 Absorption-compression hybrid

The hybrid heat pump combines substantial parts of both absorption and compression machines - it utilizes a mixture of absorbent and refrigerant and a compressor as well. An important difference between hybrid and absorption cycle should be noticed - the absorber and desorber in the hybrid heat pump are placed in a reversed order than in the absorption machine, i.e. desorption in the hybrid cycle occurs under low temperatures and pressures and absorption under high temperatures and pressures.

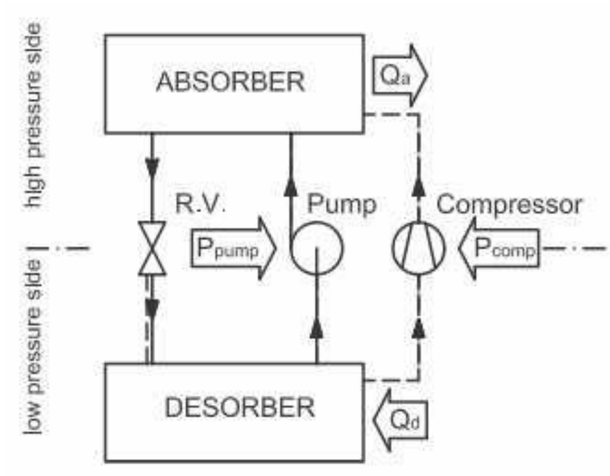

Figure 3-4: Absorption – compression hybrid

3.2.3 Mechanical vapour recompression (MVR)

Mechanical vapour recompression is the technique of increasing the pressure and thus also the temperature of waste gases, thereby allowing their heat to be re-used. The most common type of vapour compressed by MVR is steam, to which the figures below refer. There are several possible system configurations. The most common is a semi-open type in which the vapour is compressed directly (also referred to as a direct system). After compression, the vapour condenses in a heat exchanger where heat is delivered to the heat sink. This type of MVR system is very common in evaporation applications

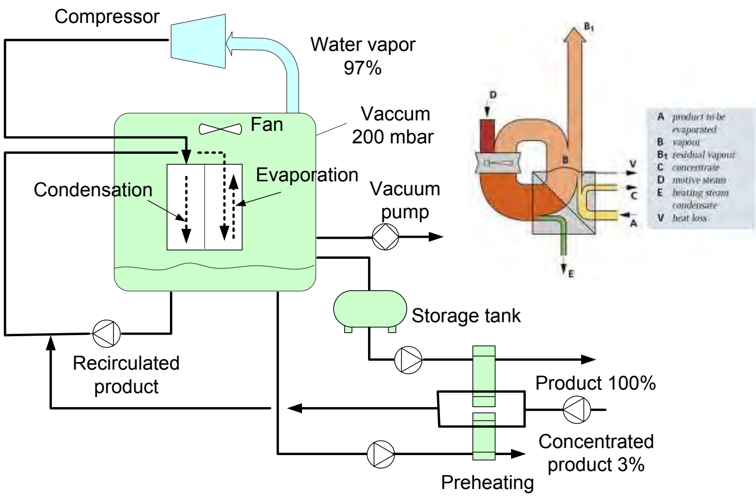

Figure 3-5: Mechanical vapor recompression [Bédard, 2002]

The other type of semi-open system lacks the condenser, but is equipped with an evaporator. This less usual configuration can be used to vaporize a process flow that is required at a higher temperature, with the aid of mechanical work and a heat source of lower temperature.

3.2.4 Thermal vapour recompression (TVR)

With the TVR type of system, heat pumping is achieved with the aid of an ejector and high pressure vapour. It is therefore often simply called an ejector. The principle is shown in the figure below. Unlike MVR system, a TVR heat pump is driven by heat, not mechanical energy. Thus, compared to an MVR system, it opens up new application areas, especially in situations where there is a large difference between fuel and electricity prices.

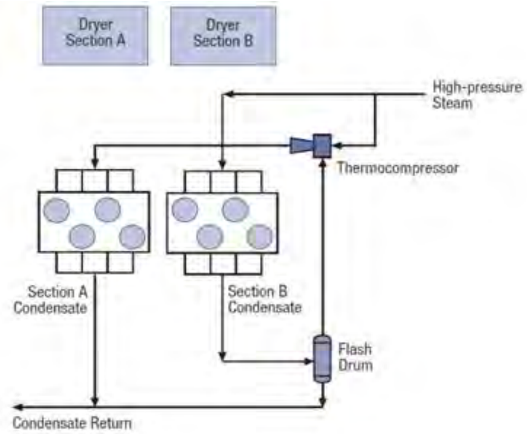

Figure 3-6: Thermal vapor recompression, Example from Japan

The TVR type is available in all industrial sizes. A common application area is evaporation units. The COP is defined as the relation between the heat of condensation of the vapour leaving the TVR and heat input with the motive vapour.

3.2.5 Thermo acoustic (TA)

The acoustic energy is subsequently being used in a TA-heat pump to upgrade waste heat to usable process heat at the required temperature. The picture below visualises the whole system. The TA-engine is located at the right side and generates acoustic power from a stream of waste heat stream at a temperature of 140 °C. The acoustic power flows through the resonator to the TA-heat pump. Waste heat of 140 °C is upgraded to 180 °C in this component. The total system can be generally applied into the existing utility system at an industrial site.

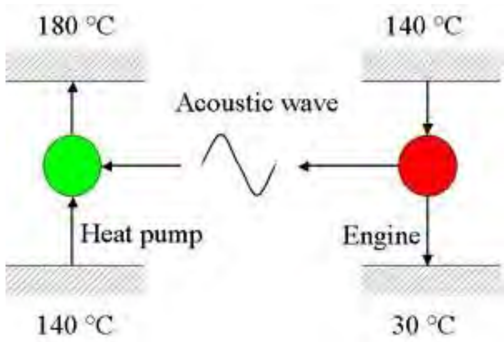

Figure 3-7: Thermo acoustic heat pump

3.3 Refrigerants suitable for high temperature heat pump

Many industrial processes have heating demands in the temperature range of 90-120 °C. At the same time, waste heat holding typically a temperature of 30-60 °C is available. Efficient heat pumping technologies are therefore attractive in order to reduce the specific energy consumption (kWh/product amount). The present, most common refrigerants, in particular HFCs are limited to heat distribution temperatures of around 80 °C. For temperature above 100 °C additional R&D is required.

Industrial heat pump using R-134a, R-245fa, R-717, R-744 and hydrocarbons (HC), etc. However, except for R-744 and the flammables R-717 and HCs, which are natural refrigerants with extremely low global warming potential (GWP.) HFCs such as R-134a and R-245fa have high GWP values, and the use of HFCs are likely to be regulated in the viewpoint of global warming prevention in the foreseeable future. Therefore, development of alternative refrigerants with low GWP has been required.

At present, as substitutes of R-134a, R-1234yf and R-1234ze (E) are considered to be promising, and R-1234ze (Z) is attractive as a substitute of R-245fa. R-365mfc is considered to be suitable as a refrigerant of heat pump for vapor generation using waste heat, but its GWP value is high. Therefore, it seems that development of a substitute of R-365mfc should be furthered. The table below shows basic characteristics of the present and future refrigerants for IHPs.

Table 3-1: Refrigerants, considered to be suitable for IHPs

Refrigerant	Chemical formula	GWP	Flammability	T_c °C	p_c M Pa	NBP °C
R-290	CH3CH2CH3	~20	yes	96.7	4.25	-42.1
R-601	CH3-CH2-CH2-CH2-CH3	~20	yes	196.6	3.37	36.1
R-717	NH3	0	yes	132.25	11.33	-33.33
R-744	CO2	1	none	30.98	7.3773	-78.40
R-1234yf	CF3CF=CH2	<1	weak	94.7	3.382	-29,48
R-134a	CF3CH2F	1,430	none	101.06	4.0593	-26.07
R-1234ze(E)	CFH=CHCF3	6	weak	109.37	3.636	-18.96
R-1234ze(Z)	CFH=CHCF3	<10	weak	153.7	3.97	9.76
R-245fa	CF3CH2CHF2	1,030	none	154.01	3.651	15.14
R-1233zd		6	none	165.6	3.5709	n. a.
R-1336mzz		9	none	171	n. a.	n. a.
R-365mfc	CF3CH2CF2CH3	794	weak	186,85	3.266	40.19

4 Energetic and economic models

As a consequence of the first law of thermodynamics all energy that is put into a process will also, in a steady state situation, leave the process. The energy leaves the process in the shape of product, waste heat and other losses.

The temperature level of the waste heat is determined by process fundamentals and process equipment design, and is thus, for an existing plant, set. However the temperature level which the waste heat appears and can be used is determined by the design of the utility systems, i.e. cooling water and air. This essential difference is often overlooked when discussing waste heat utilization.

The amount and temperature level of the waste heat can be determined by process integration methods, e.g. pinch analyses. These methods are powerful tools and give a total picture of the situation at the plant including the possibilities for internal use of the heat.

There are several competing alternatives to utilize waste heat and it is normally not obvious which is the most favorable. The heat can internally be better used for heating purposes and in new or modified process parts. Heat pumping is also an alternative which today is common practice in some branches but has a large potential to grow in others. Another option is to use the heat for heating demands outside the plant in a district heating system.

To be able to increase the awareness of possibilities and to select between the alternatives, a high level of expertise for system design, process integration and planning is crucial. Design software on process integration and design plays an important role at this stage. However, this seemingly being a complex approach needing a lot of high level expertise, simple straight forward solutions on a small scale should not be overseen.

4.1 Pinch analysis

Pinch analysis is a methodology for minimising energy consumption of chemical processes by calculating thermodynamically feasible energy targets (or minimum energy consumption) and achieving them by optimising heat recovery systems, energy supply methods and process operating conditions. It is also known as process integration, heat integration, energy integration or pinch technology [Monard, 2006].

The process data is represented as a set of energy flows, or streams, as a function of heat load (kW) against temperature (deg C). These data are combined for all the streams in the plant to give *composite curves*, one for all *hot streams* (releasing heat) and one for all *cold streams* (requiring heat). The point of closest approach between the hot and cold composite curves is the pinch temperature (pinch point or just pinch), and is where design is most constrained. Hence, by finding this point and starting design there, the energy targets can be achieved using heat pumps to recover heat between hot and cold streams. In practice, during the pinch analysis, often cross-pinch exchanges of heat are found between a stream with its temperature above the pinch and one below the pinch. Removal of those exchanges by alternative matching makes the process reach its energy target.

4.2 EINSTEIN expert system

EINSTEIN is an **E**xpert system for an **In**telligent **S**upply of **T**hermal **E**nergy in **IN**dustry [Heigl, 2014].

For optimising thermal energy supply in industry, a holistic integral approach is required that includes possibilities of demand reduction by heat recovery and process integration, and by an intelligent combination of efficient heat and cold supply technologies.

EINSTEIN is a tool-kit for fast and high quality thermal energy audits in industry, composed by an audit guide describing the methodology and by a software tool that guides the auditor through all the audit steps.

The main features of EINSTEIN are:

1. the data processing is based on standardized models for industrial processes and industrial heat supply systems;
2. Special tools allow for fast consistency checking and estimation of missing data, so that already with very few data some first predictions can be made;
3. Semi-automation: the software tool gives support to decision making for the generation of alternative heat and & cold supply proposals, carries out automatically all the necessary calculations, including dynamic simulation of the heat supply system, and creates a standard audit report
4. A basic questionnaire helps for systematic collection of the necessary information with the possibility to acquire data by distance.

The software tool includes modules for benchmarking, automatic design of heat exchanger networks, and design assistants for the heat and cold supply system.

It is a methodology that works out energy efficient solution for your production process based on renewable energy sources, e.g. heat pumps. This will lead to a significant reduction of your operating cost. The benefits of Einstein are:

- Increase in know-how for local auditors
- Reduction of energy costs and CO_2 emissions
- Improved competitiveness and saving for your company by a reduction of operating costs
- Road map for realisation of energy concepts with an economic consideration.

The present status of EINSTEIN does not include heat pumps for heat recovery and process integration. However, a new project – EINSTEIN III is presently in the stage of approval as part of the European Commission research programme EE-16-2014 "Organisational innovation to increase energy efficiency in industry", which include industrial heat pumps.

5 Research and development

Appropriate heat pump technology is important for reducing CO_2 emissions and primary energy consumption as well as increasing amount of renewable energy usage in industrial processes. The expansion of industrial applications is also important for enhancing these effects further more. In particular, development and dissemination of high-temperature heat pumps for hot water supply, heating of circulating hot water, and generation of hot air and steam are necessary. Specific problem areas are

- lack of refrigerants in the interesting temperature range
- lack of experimental and demonstration plants

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Application of Industrial Heat Pumps

IEA Industrial Energy-related Systems and Technologies Annex 13
IEA Heat Pump Programme Annex 35

Task 1:
Heat Pump Energy situation, energy use, market overview, barriers for application

Final Report

(Status: 31.05.2014)

Prepared by the
Participants of Annex 35/13

Contents

1 Summary

The world rising energy prices and environmental concern set focus on energy conservation and use of renewable energy sources.

In this context, the IEA HPP-IETS Annex 35/13 has been initiated in order to actively contribute to the reduction of energy consumption and emissions of greenhouse gases by the increased implementation of heat pumps in industry.

The heat pump markets are currently growing at a steady pace, but in many countries, however, is focused mainly on residential heat pumps for space heating and domestic hot water. While the residential market may be satisfied with standardised products and installations, most industrial heat pump applications need to be adapted to unique conditions.

The work in the Annex in task 1 starts by making an overview in the participating countries of the industrial energy situation and use, the state of the art in heat pumping and process technologies and its applications, as well as analysing business cases on the decision-making process in existing and new applications. Based upon these findings focus will be given to further work to meet the challenges in the wider application of industrial heat pumping technologies.

2 Introduction

Improving energy efficiency is the single most important first step toward achieving the three goals of energy policy: security of supply, environmental protection and economic growth.

Nearly a third of global energy demand and CO_2 emissions are attributable to industry, especially the big primary materials industries such as chemicals and petrochemicals, iron and steel, cement, paper and aluminium. Understanding how this energy is used, the national and international trends and the potential for efficiency gains, is crucial.

While impressive efficiency gains have already been achieved in the past two decades, energy use and CO_2 emissions in manufacturing industries could be reduced further, if best available technologies were to be applied worldwide.

Some of these additional reductions may not be economic in the short- and medium-term, but the sheer extent of the potential suggests that striving for significant improvements is a worthwhile and realistic effort. A systems approach is needed that transcends process or sector boundaries and that offers significant potential to save energy and cut CO_2 emissions.

Heat pumps have become increasingly important in the world as a technology to improve energy efficiency and reduce CO_2 emissions. They are presently widely used mainly on residential buildings for space heating and domestic hot water and are expected to spread to the industrial sector to be used for heat recovery and heat upgrading in industrial processes and for heating, cooling and air-conditioning in industrial buildings.

The introduction of heat pumps in food and beverage manufacturing factories and wood drying with operating temperature below 100 °C is in many cases considered to be easy, however, higher temperature application still require additional R&D activities for the development of high temperature heat pumps, integration of heat pumps into industrial processes and development of high temperature refrigerants.

In this context, the IEA HPP-IETS Annex 35/13 "Application of industrial Heat Pumps", a joint venture of the IEA Implementing Agreements "Industrial Energy-Related Technologies and Systems" (IETS) and "Heat Pump Programme" (HPP) has been initiated in order to actively contribute to the reduction of energy consumption and emissions of greenhouse gases by the increased implementation of heat pumps in industry.

The work in the Annex starts by making an overview in the participating countries of the industrial energy situation and use, the state of the art in heat pumping and process technologies and its applications, as well as analysing business cases on the decision-making process in existing and new applications. in the wider application of industrial heat pumping technologies.

The Task 1 Report summarized the present energy situation in general and the industrial energy use and related heat pump market subdivided into the annex 35/13 participating countries. Based upon these findings focus will be given to further work to meet the challenges for the wider application of industrial heat pumping technologies.

Table 2-1 gives an overview of general indicators worldwide, in OECD countries as well as European Annex participating countries.

Table 2-1: General indicator for 2008[1]

	Population (million)	GDP (billion 2000 USD)	Energy production (Mtoe)	Net Imports (Mtoe)	CO_2 emission (Mt of CO_2)
World	6 688	40 482	12 369		29 381
OECD	1 190	30 504	3 864	1 765	12 630
Annex Countries Europe	193,2	5 051	422	440,3	1 378
France	64	1 515	137	139	368
Germany	82	2 095	134	211	803
The Netherlands	16,4	449	67	34	178
Sweden	9,3	297	33	20	46
Austria	8,3	226	11	26	69
Denmark	5,5	178	27	-4,7	48

The following Figures present energy consumption, CO_2-emissions and industrial energy consumption in the 27 EU countries:

Figure 2-1 shows the final energy consumption in the EU 27 countries subdivided by energy source in 2007.

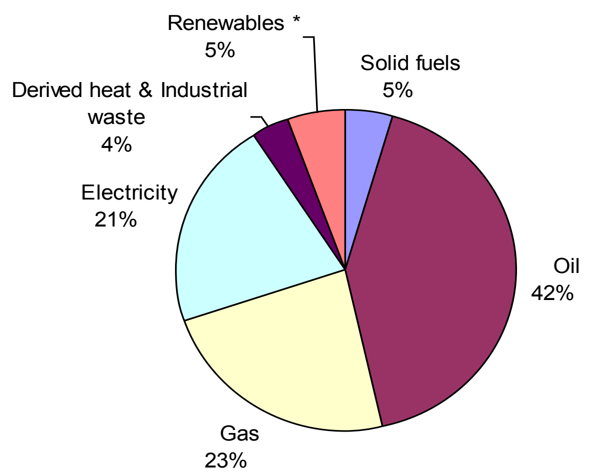


Figure 2-1: EUR27 final energy consumption by fuel 2007 (Mtoe)[2]

[1] INTERNATIONAL ENERGY AGENCY - Tracking Industrial Energy Efficiency and CO_2 Emissions – Energy Indicators 2007

[2] European Commission / ENERGY - EUROPE 2020 initiative - Energy Efficiency Plan 2011, Statistical pocketbook 2010

Figure 2-2 shows the final energy consumption in 2007 subdivided by sectors. 28 % of total energy consumption is used by the industry, number two after the transportation with 32 % and before the household with 25 %.

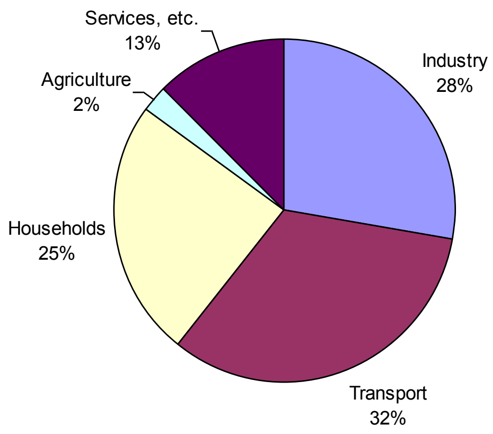


Figure 2-2: EU27 final energy consumption by sectors 2007 (Mtoe)[3]

The CO_2-emissions by sectors in the 27 EU countries are presented in Figure 2-3 with 22.3 % emitted by the industry.

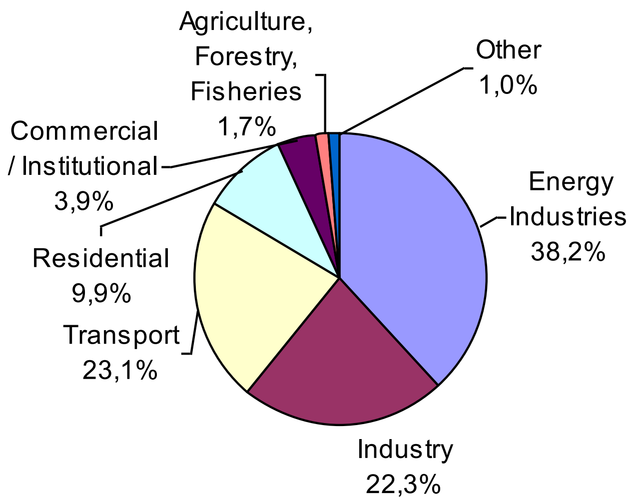


Figure 2-3: Eu27 CO_2 -emissions by sector 2007 (Mt)[3]

Figure 2-4 shows the European industrial final energy consumption by sectors in the 27 EU-countries, dominated by the Iron and Steel, Chemical, Non-mineral products and Paper and Printing industries.

[3] European Commission / ENERGY - EUROPE 2020 initiative - Energy Efficiency Plan 2011, Statistical pocketbook 2010

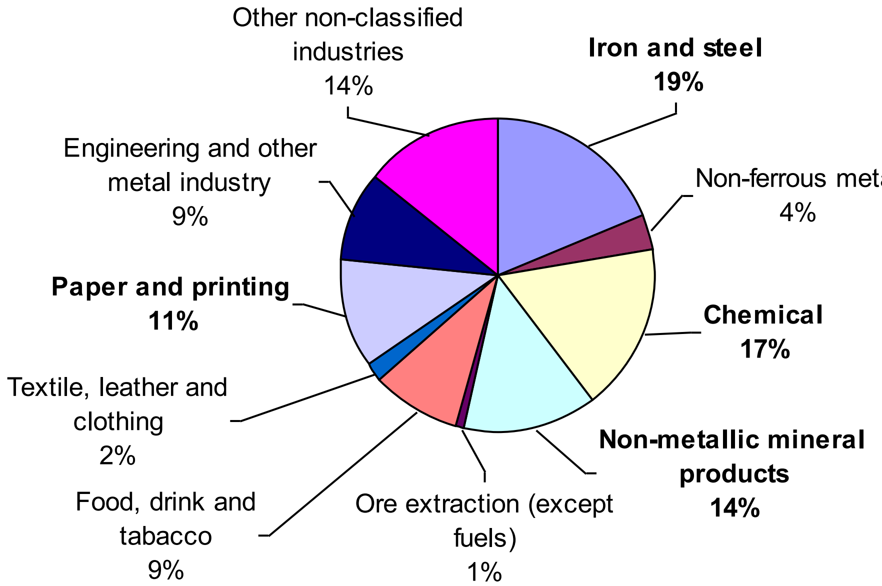
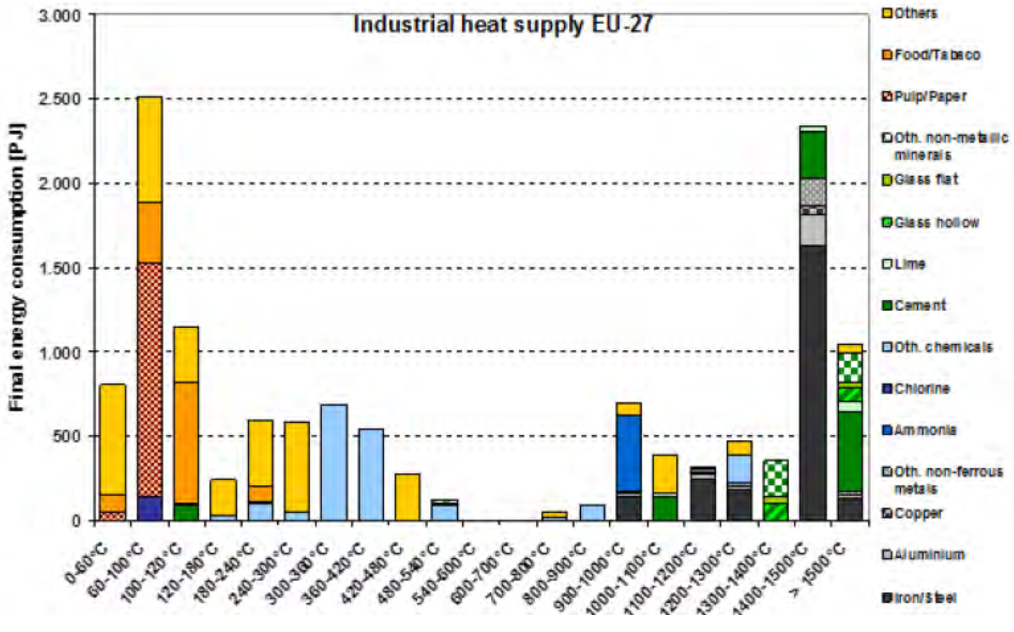


Figure 2-4: EU27 industrial final energy consumption by sectors 2008 (Mtoe)[4]



Source: SP Technical Research Institute of Sweden

Figure 2-5: EUR 27 final energy consumption by sectors as function of temperature

[4] European Commission–Eurostat -2008

3 Austria

3.1 Industrial Energy use in Austria 2009

The energy consumption in Austria has nearly doubled in the last 40 years, both in terms of combined total consumption as well as final consumption, according to Statistics Austria (2010a).

In recent years the use of renewable energy in Austria increased disproportionately due to various measures such as awareness campaigns, a variety of fundings or the creation of legal framework (Statistics Austria 2010c). A very high share of 68% of Austria's electricity supply was covered by renewable energy from hydro, wind, PV, geothermal heat and biomass. Hence, "green" electricity is in the leading position by the use of renewable energy, followed by "green" heat for district heating from biomass and geothermal energy with a share of 36%, the direct use of renewable energy from bio-heat, ambient-, geothermal- and solar-heat for heating applications with a share of 30% and biofuels[5] with a share of 7% of transport fuel. (Statistics Austria 2010c)

Despite a steady increase in the use of renewable energy sources, the bulk of Austrian energy consumption is still covered by fossil fuels such as oil and gas. This fact presents a growing problem especially as far as emissions of greenhouse gases and the security of the Austrian energy supply is concerned, as 70% of these fossil fuels have to be imported from foreign countries. Austria's dependency on foreign energy supplies amounted 64.8% in 2009 (EU average 2007 is 53.1%) and this share is steadily increasing. (Statistics Austria, 2010a)

The final energy balance split in energy carriers in Austria is shown in Table 3-1 and Figure 3-1. In 2009, 39% of the overall final energy demand in Austria (1057 PJ) was covered by oil and 17% by gas, as shown in Figure 3-1 and Table 3-1**Fehler! Verweisquelle konnte nicht gefunden werden.** (Statistic Austria, 2010b). Thus, the reduction of this high dependency on these fossil fuels should be focused in Austria. Keeping in mind the CO_2-emission and that only around 13% of the crude oil demand and 20% of the gas consumption are covered from Austrian sources, this offers a high ecological and economical potential (Statistic Austria, 2010a).

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5 biodiesel and bioethanol

Table 3-1: Austria's final energy balance per energy carriers in 2009 (Statistic Austria, 2010b)

Energy carrier	[PJ]
Oil[6]	423
Gas[7]	175
Coal[8]	22
Electricity	208
District Heat	64
Renewable[9]	166
Total	1057

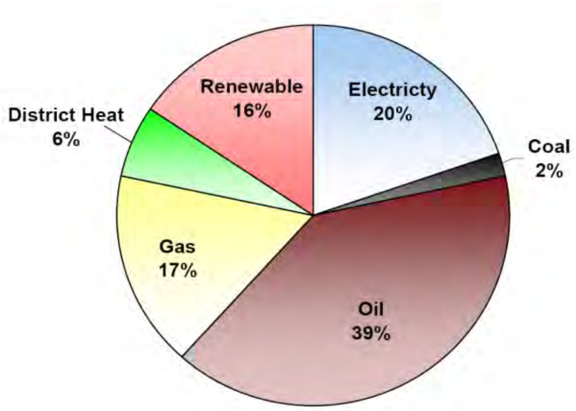

Figure 3-1: Austria's final energy balance per energy carrier in 2009 in percentage (Data based according to Statistics Austria, 2010b)

The Austria's energy demand can be classified in three main sectors:

- industry,
- transport and
- miscellaneous.

The industry sector includes the entire producing and manufacturing area in Austria. The transport sector is composed of the internal navigation, air-, rail- and road-transport as well as pipeline transport. Miscellaneous contains the aggregated domestic energy demand, including commercial and public services as well as agriculture.

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6 Oil includes: crude oil, refinery feedstock, gasoline, kerosene, fuel oil, other oil products and refinery gas (Statistics Austria, 2010b)

7 Gas includes natural gas and gasworks gases (Statistics Austria, 2010b)

8 Coal includes hard coal, lignite, BKB, peat, coke, blast furnace gas and coke oven gas (Statistics Austria, 2010b)

9 Renewable includes all energy carriers as waste, fuel-wood, bio-fuels, ambient-heat, hydro- and wind-power and PV (Statistics Austria, 2010b)

Table 3-2 represents the distribution of the final energy use across the different sectors. As shown in Figure 3-2, the final energy use in Austria is approx. uniformly distributed to the three main sectors. With a share of 29% of Austria's final energy demand, the industry offers the possibility to reduce the whole energy demand and lower the CO_2-emissions significantly.

Table 3-2: Distribution of the Austria's final energy use in 2009 across the main sectors (Statistics Austria, 2010b)

Sector	Final energy use [PJ]
Industry	308
Transport	357
Miscellaneous	392
Total	1057

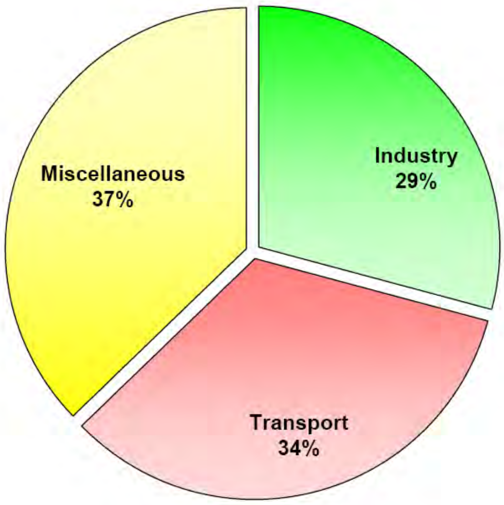

Figure 3-2: Distribution of the final energy use in Austria in 2009 across the main sectors in percentage (Data based to Statistics Austria, 2010b)

3.1.1 Energy use in the manufacturing industry

The balance of the different energy carriers in the Austrian industry is shown in Table 3-3. The most energy intensive industrial sector in Austria is the pulp, paper and print industry, followed by the non-metallic minerals processing and the iron and steel industry, as shown in Figure 3-3. Other industrial sectors with a high energy demand are found in the chemical and petrochemical industries. The Austrian manufacturing industry used about 308 PJ of final energy in 2009.

Table 3-3: Distribution of energy carriers in each industrial sector in Austria 2009 (Data according to Statistics Austria, 2010b – values for final energy consumption)

Austrian Industry Sectors	Electricity	Coal[10]	Oil[11]	Gas[12]	District Heat	Renewable[13]	Total
	[PJ]	[PJ]	[PJ]	[PJ]	[PJ]	[PJ]	[PJ]
Iron and Steel	13,2	8,2	2,2	16,3	0,2	0,6	**40,6**
Chemical and Petrochemical	13,4	0,5	0,6	14,6	2,1	6,5	**37,7**
Non-ferrous Metals	3,0	0,2	0,3	4,2	0,1	0,0	**7,7**
Nonmetallic Minerals	7,4	6,6	3,3	13,3	0,0	10,5	**41,1**
Transport Equipment	2,7	0,0	0,2	1,4	1,4	0,0	**5,7**
Machinery	11,5	0,0	1,5	7,4	1,1	0,7	**22,1**
Mining and Quarrying	2,5	0,0	0,4	1,6	0,0	0,0	**4,5**
Food Tobacco and Beverages	6,8	0,1	2,3	11,4	1,2	0,5	**22,4**
Pulp, Paper and Print	16,1	2,6	0,9	22,0	0,7	21,3	**63,7**
Wood and Wood Products	6,0	0,0	0,2	2,8	2,1	14,8	**25,8**
Construction Industry	2,5	0,0	16,0	1,7	0,5	1,9	**22,6**
Textiles and Leather	1,8	0,0	0,3	1,9	0,0	0,0	**4,1**
Miscellaneous Industries	5,4	0,0	0,4	1,8	0,5	1,5	**9,7**
Total	**92,1**	**18,2**	**28,5**	**100,6**	**9,9**	**58,4**	**307,7**

According to Figure 3-3 and Table 3-3**Fehler! Verweisquelle konnte nicht gefunden werden.**, gas and electricity are obviously very important energy carriers in the Austrian industry, due to the fact, that both are used in every industrial sector. Particularly, 22 PJ of the pulp, paper and print industry's energy demand is covered only by gas. The share of renewable energy use is very high in some industrial sectors, e.g. 57% in the wood working industry or 33.5% in the pulp paper and print industry, as shown in

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[10] Coal includes hard coal, lignite, BKB, peat, coke, blast furnace gas and coke oven gas (Statistics Austria, 2010b)

[11] Oil includes: crude oil, refinery feedstocks, gasoline, kerosene, fuel oil, other oil products and refinery gas (Statistics Austria, 2010b)

[12] Gas includes natural gas and gasworks gases (Statistics Austria, 2010b)

[13] Renewable includes all energy carriers as waste, fuel-wood, bio-fuels, ambient-heat, hydro- and wind-power and PV (Statistics Austria, 2010b)

Figure 3-3. However, there is still a need to reduce the gas demand in nearly all industrial sectors.

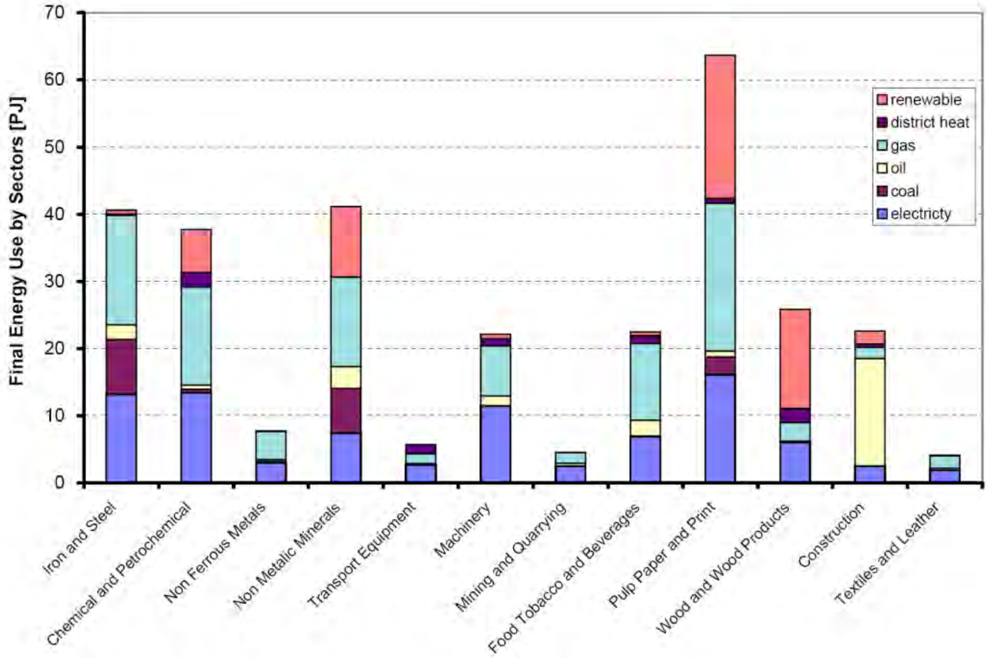

Figure 3-3: Distribution of energy carriers in each industrial sector in Austria 009 (Data according to Statistics Austria, 2010b – values for final energy consumption)

As shown in Figure 3-4, gas is still the most used energy carrier for the Austrian industry and covers 33% of the overall final energy demand, closely followed by electricity with a share of 30%. 48% of the overall final energy consumption in the industry has been covered by gas, oil and coal and only 19% by renewable energy. The problems caused by the extensive use of fossil fuels are the import- and price-dependence from foreign countries as well as CO_2-emissions, as mentioned before. In order to improve this situation, the application of industrial heat pumps offers the possibility to substitute a part of the fossil energy use by upgrading waste heat to process heat.

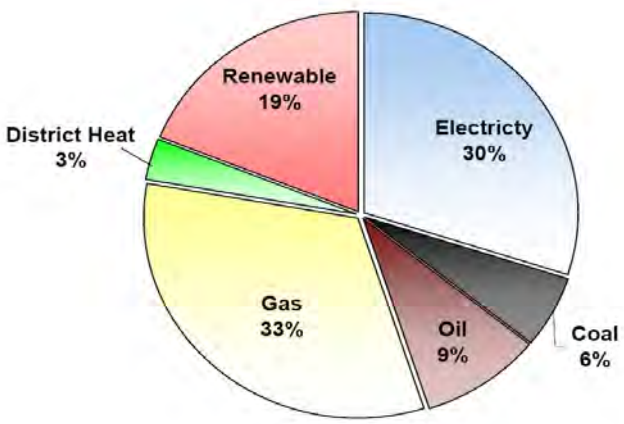

Figure 3-4: Final energy balance of the different energy carriers in Austrian Industry, 2009 in percentage (Data according to Statistics Austria, 2010b)

3.1.2 Heat demand of Austrian Industry

In order to determine the heat demand based on the overall final energy consumption of the Austrian industry, a share of 74% has been assumed for Austria for the year 2002 according to Vanonni et al. (2008). Assuming that this share has not changed from 2002 to 2009, the heat demand in the Austrian industry amounts to 228 PJ in 2009, based on the overall final energy consumption in the Austrian industry of 308 PJ according to Statistics Austria, 2010b. Even if this share would be a little bit lower, the heat demand represents the bulk of all energy functions in the Austrian industry.

3.1.3 References

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Vanonni, C., Battisti, R., Drigo, S., 2008: Potential for Solar Heat in Industrial Processes, IEA Solar Heating and Cooling Executive Committee of the International Energy Agency

3.2 Market overview

3.2.1 Austrian Industry

Austria is declared as an industrial country, even though the service sector takes the biggest share of the Austrian economic performance. The reason for this is that it is difficult to make a clear distinction between production and service in Austria. To permit an international comparison this two segments are considered together in the category "Production of goods". According to Austria 2006 (2006) it can be concluded that the industry remains the principal driver of economic activities and development in Austria. (Austria 2006, 2006)

Many small and medium-sized enterprises characterize the Austrian industry landscape. In 2006, approximately 40% of all companies of Austria had less than 10 employees, about 80% had less than 100, and only 1.4% of all companies had more than 1,000 employees. (Austria 2006, 2006)

Based on the share of industry in the gross value added, Austria has one of the world's largest industrial sectors in 2003. Following branches have traditionally accounted for the largest share of Austria's production overall: mechanical engineering and steel work, the motor vehicle trade, the chemical, electrical and electronics industries. Nevertheless, there are new fields in which Austrian companies have also performed well, as material engineering and surface coatings, IT, biotechnology and medical technology, as well as hydraulic engineering and environmental technology, in recent years. (Austria 2006, 2006).

The Austrian industry can be classified according to Federation of Austrian Industries (IV, 2010) in following sectors (Table 3-4):

Table 3-4: Sectors of the Austrian Industry [Data according to IV, 2010]

Industrial sectors in Austria
Foundry Industry
Non-ferrous Metal Manufacture
Leather production Industry
Leather processing Industry
Electro and Electronic Industry
Wood-working Industry
Chemical Industry
Automotive Engineering
Food & Drug industry
Petrol Industry
Glass Industry
Nonmetallic minerals and ceramic industry
Paper & board processing industry
Paper manufacturing industry
Apparel Industry
Textile industry
Music and Film Industry
Machinery and Metalwork Industry
Building industry
Mining
Gas- and heat supply companies

3.2.2 Process temperatures in the Austrian Industry

An estimation of the distribution of the heat demand at different temperature levels for the Austrian industry was made from the available data in Figure 3-5. For the estimation, the total final energy consumption from the table "Distribution of energy carriers in each industrial sector in Austria 2009"[14] was used with an assumption, that the share of

[14] Table 3 from the Austrian Team Report - IEA HPP-IETS Annex 13 / 35 -Application of Industrial Heat Pumps; Task 1 – Part1

the heat demand is equal for all sectors, since no detailed data were found. For the distribution of the heat demand at different temperature levels over different industrial sectors, figures from Euroheat & Power (2006) from 2003 for EU 27 plus Turkey, Croatia, Iceland, Norway and Switzerland were used. Not all industrial branches from the above mentioned table were considered, since for a number of them no figures were available. However, the industries considered account for about 80% of the total final energy consumption.

Figure 3-5 shows, that almost half (47%) of the heat energy demand in Austria is at temperatures over 400°C. About a quarter (27%) of the heat demand is at temperatures from 100°C to 400°C and a quarter (26%) at temperatures below 100°C.

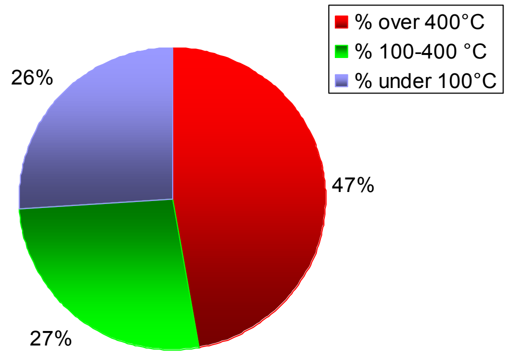

Figure 3-5: Estimation of the cumulative industrial heat demand by temperature level for selected Austrian industry branches[15] (Data according to Euroheat & Power, 2006)

The application of IHP for industrial waste heat utilization is reasonable up to 100°C or even above depending on the heat pump technology applied. This means, that the theoretical potential for the application of IHPs is about 30-40% of the overall heat demand in the industry according to the required temperature levels, including industries not considered in Figure 3-5.

In order to determine the realizable potential for the application of IHPs, it should be mentioned, that each industrial sector and each production process itself have to be regarded in detail. The operating range of thermal solar heating plants is similar to the temperature levels for the application of Industrial Heat Pumps. Various reports about the solar heating application in the industry are available in literature and have been collected to get necessary information about the process temperatures of the most significant processes in each industrial sector, which are listed in Table 3-5. As one can see in Table 3-5, there exist several different processes in the Austrian industry, which are theoretically suitable to cover their head demand by the application of IHPs.

[15] The following industry branches were not considered compared to the table 3 from the Austrian Team Report - IEA HPP-IETS Annex 13 / 35 -Application of Industrial Heat Pumps; Task 1 – Part1 “Distribution of energy carriers in each industrial sector in Austria 2009”: Wood and wood products, construction industry, textiles and leather and miscellaneous.

Table 3-5: Industry sectors and processes including appropriate temperature levels for heating applications (Data according to Brunner et al., 2007, Slawitsch et al., 2007, Weiss, 2005 and Solarwärme, 2011)

Sector	Example for temperature levels of thermal processes
Food	• Preheating of substances (20-60°C), • Pasteurizing/Sterilization (70-120°C) • Boiling (100-240°C) • Distillation (40-100°C) • Drying (40-250°C) • Vaporizing (40-170°C) • Washing(30-60°C) • Substance concentration (60-70°C) • Baking (160-260°C) • Cleaning the facility (30-70°C) • Space heating of the production hall (20°C) • Cooling (-18-20°C)
Metal	• Galvanic (20-100°C) • Washing (30-60°C) • Drying (60-90°C) • Cleaning the facility (30-70°C) • Space heating of the production hall (20°C)
Paper and board	• Preheating of substances (40-80°C) • Boiling (160°C) • Drying (110-240°C) • Cleaning the facility (30-70°C) • Space heating of the production hall (20°C)
Textile	• Coloring (40-130°C) • Laundering (40-100°C) • Bleaching (60-100°C) • Cleaning the facility (30-70°C) • Space heating of the production hall (20°C)
Chemistry	• Preheating of substances (~60°C) • Boiling (95-105°C) • Distillation (110-300°C) • Thermoforming (130-160°C) • Substance concentration (125-130°C) • Cleaning the facility (30-70°C) • Space heating of the production hall (20°C) • Cooling (5-15°C)
Wood	• Drying (50-80°C) • Squeezing (120-180°C) • Staining (50-80°C)

Table 3-6 contains the results of a review about the required temperature levels for cooling demand in the Austrian industry in the different sectors. Particularly the sectors food and chemistry require bride temperature ranges for their cooling demand, down to -50°C. A high cooling demand signifies a theoretically high potential for waste heat utilization according to the temporary simultaneity with the heat demand.

Table 3-6: Required temperature levels for the cooling demand in Austrian Industry sectors (Data according to ETA ENERGIEBERATUNG, 2008)

Sector	Temperature levels for cooling applications
Food	-50 – 6°C
Plastics	6°C
Metal	6°C
Chemistry	-50 – 6°C
Brewery	-10°c
Dairy	-10 – 0°C
Store	-30 – 6°C

3.2.3 Overview of the Austrian industrial heat pump market

In order to give an overview of the Austrian industrial heat pump[16] market a simple online-search was performed. In the course of the online-search only a few reports of IHP applications were located, which are mostly referenced by Austrian heat pump manufactures themselves. But up to now there are not any figures of already installed industrial heat pump plants in Austria or outsells available.
However, this online-search gives an overview of Austrian IHP suppliers. The Austrian IHP market includes open cycle heat pump technologies (MVR) as well as closed heat pump technologies (compression heat pumps and sorption heat pumps). Several Austrian heat pump manufactures produce compression heat pumps for industrial applications even in series. These heat pumps are nowadays assembled for the cooling and heating in residential buildings, industrial premises, hotels, office buildings and recreational facilities and for the utilization of industrial waste heat. These heat pumps have the capability to achieve heat sink temperatures up to 65°C and are designed for heating capacity up to 700 kW, most of them using R134a as refrigerant.
Generally, it can be concluded that, the utilisation rate of IHP applications in Austria is still low. However, the Austrian industry features a relative high theoretical potential of IHP application and according to IZW (2009) the market of industrial heat pumps is rapidly growing in Austria. Especially in the field of large plants the demand rises sharply.

[16] Industrial heat pumps within this annex are defined as heat pumps in the medium and high power ranges which can be used not only for heat recovery in industrial processes, but also for heating, cooling and air-conditioning in residential, commercial and industrial buildings. The power range for the refrigerating capacity of industrial heat pumps settles between 50 and 150 kW for medium power systems and between 150kW to several MW for high power systems. This heat can deliver heat at temperatures of 100 °C and more.

3.2.4 Energy prices

A rise of the energy prices is not limited to certain regions. It is worldwide observable and goes along with the demand of energy. The energy demand of Austria shows an increasing trend over the past decades. Together with the energy demand, the prices for the conventional energy carriers show a generally increasing trend. Table 3-7 shows the energy prices for the most common conventional energy carriers for the Austrian industry. Due to the trend of the energy prices of the conventional energy sources, it can be assumed that the usage of heat pumps gets more interesting and profitable.

Table 3-7: Energy prices (incl. VAT) for the Austrian industry from 2003 to 2009 (Data according to Austrian Energy Agency, 2010 for natural gas and Statistics Austria, 2011 for other energy carriers)

Final consumer prices for industry (incl. taxes)						
Year	**Black coal [€/MWh]**	**Natural gas * [€/MWh]**	**Heavy fuel oil [€/MWh]**	**Gas oil [€/MWh]**	**Fuel oil [€/MWh]**	**Electricity [€/MWh]**
2003	9,25	20,94	19,87	28,31	58,05	--
2004	16,45	20,52	21,40	32,17	61,11	92,52
2005	17,16	22,11	28,49	39,05	66,20	81,90
2006	17,24	29,53	33,41	44,99	72,31	87,00
2007	17,69	30,87	34,67	47,31	73,33	98,00
2008	20,36	--	45,98	43,66	78,42	105,43
2009	20,89	--	35,14	31,06	60,98	--

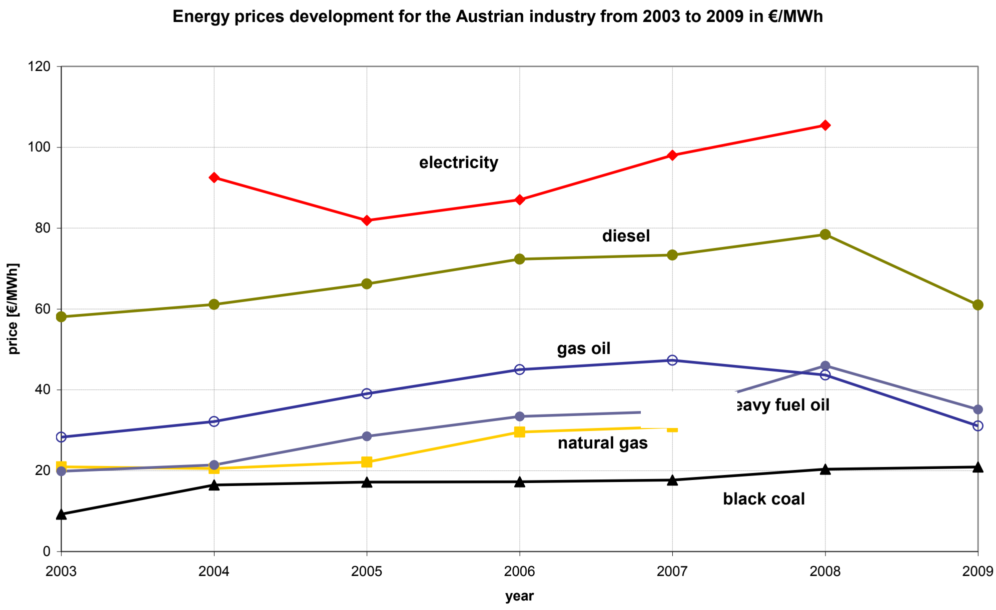

Figure 3-6: Development of energy prices (incl. VAT) for the Austrian industry from 2003 to 2009 (Data according to Austrian Energy Agency, 2010 for natural gas and Statistics Austria, 2011 for other energy carriers)

It can be seen from Figure 3-6 that, due to the global economic crisis, all energy prices, except for black coal, decreased after 2008. For 2003 and 2009 there is no data available for the electricity price. The prices of natural gas for commercial usage for 2008 and 2009 are also missing in the used sources. The prices shown are not inflation-adjusted.

3.2.5 Legal documents

This chapter gives an overview of standards as well as funding guidelines in Austria concerning the application of IHPs.

National and European Standards
The following standards are relevant in Austria for an application of an industrial heat pump plant:

- **OENORM EN 378-1** (2008-06-01) "Refrigerating systems and heat pumps - Safety and environmental requirements - Part 1: Basic requirements, definitions, classification and selection criteria"
- **OENORM EN 378-2** (2008-06-01) "Refrigerating systems and heat pumps - Safety and environmental requirements - Part 2: Design, construction, testing, marking and documentation"
- **OENORM EN 378-3** (2008-06-01) "Refrigerating systems and heat pumps - Safety and environmental requirements - Part 3: Installation site and personal protection"
- **OENORM EN 378-4** (2008-06-01) "Refrigerating systems and heat pumps - Safety and environmental requirements - Part 4: Operation, maintenance, repair and recovery"
- **OENORM EN 12263** (1999-01-01) "Refrigerating systems and heat pumps - Safety switching devices for limiting the pressure - Requirements and tests"
- **OENORM EN 12284** (2004-01-01) "Refrigerating systems and heat pumps - Valves - Requirements, testing and marking"
- **OENORM EN 12309-1** (1999-10-01) "Gas-fired absorption and adsorption air-conditioning and/or heat pump appliances with a net heat input not exceeding 70 kW - Part 1: Safety"
- **OENORM EN 12309-2** (2000-04-01) "Gas-fired absorption and adsorption air-conditioning and/or heat pump appliances with a net heat input not exceeding 70 kW - Part 2: Rational use of energy"
- **OENORM EN 13313** (2002-06-01) "Refrigerating systems and heat pumps - Competence of personnel"
- **OENORM EN 14276-1** (2006-11-01) "Pressure equipment for refrigerating systems and heat pumps - Part 1: Vessels - General requirements"
- **OENORM EN 14276-2** (2007-08-01) "Pressure equipment for refrigerating systems and heat pumps - Part 2: Piping - General requirements"
- **OENORM EN 14511-1** (2004-08-01) "Air conditioners, liquid chilling packages and heat pumps with electrically driven compressors - Heating mode - Part 1: Terms, definitions and designations"
- **OENORM EN 15316-4-2** (2005-12-01) "Heating systems in buildings - Method for calculation of system energy requirements and system efficiencies - Part 4-2: Space heating generation systems, heat pump systems"
- **OENORM EN 15450** (2008-01-01) "Heating systems in buildings - Design of heat pump heating systems"
- **OENORM EN 15834** (2008-09-01) "Refrigerating systems and heat pumps - Qualification of tightness of components and joints"
- **OENORM H6021** (2003) **"**Ventilation equipment – Keeping of cleanness and hygiene"
- **OENORM H6020-2** (2007) "Ventilation equipment in clinics and hospitals – operation, maintenance, technical and hygienic control"

- **OENORM H6021** (2003) “Ventilation equipment – Keeping of cleanness and hygiene“
- **OENORM H6020-2** (2007) “Ventilation equipment in clinics and hospitals – operation, maintenance, technical and hygienic control“
- **OENORM B5019** (2007) “Hygienic design, operation, maintenance, reconstruction and supervision of drinking water equipment”

3.2.6 Funding of industrial heat pumps in Austria

National grants for the installation of an IHP can significantly reduce the payback period and consequently take an influence on the decision to invest. The Kommunalkredit Public Consulting (KPC) banking institution manages the national grant system in Austria. According to KPC (2011a) several guidelines cover the grant regulations for IHP applications:

- Heat pumps < 400kW$_{th}$ (KPC, 2011b)
  Specifications: water/brine or water/water heat pump: COP>4
  air/water heat pump: COP>3,5
  Grant ratio: max. 30% of environmentally relevant investment costs

- Heat pumps > 400kW$_{th}$ (KPC, 2011c)
  Specifications: water/brine or water/water heat pump: COP>4
  air/water heat pump: COP>3,5
  Grant ratio: max. 15% of environmentally relevant investment costs

- Efficient energy use – process-oriented measures (KPC, 2011d):
  Specifications: industrial waste heat utilisation
  Grant ratio: max. 30% of environmentally relevant investment costs

Furthermore it is possible to apply for additional regional grants according to the different federal systems in Austria.

3.3 Barriers for applications

At present no detailed information about market barriers of IHPs in Austria are found. In the course of this Annex more detailed information’s about the barriers will be ascertained form the Austrian industry. Therefore, a questionnaire was set up in order to gather and evaluate stake holder opinions, which shall be included within the final Annex report. However, from a preliminary evaluation following barriers possibly play a major role in the Austrian IHP market:

- Despite the national grant regulations for industrial heat pump applications, the economical point of view seems to be one of the most deciding barriers, which can hind the full market success in Austria. Austrian industrial companies claim for very short payback periods. It is estimated that the payback periods should be less than three years.
- Additionally, so far the confidence in the Austria’s industrial companies in the IHP-technology is not given regarding to the less experience and knowledge. So it seems to be necessary to promote the IHP-technology to the Austria’s industrial compa-

nies, e.g. by referencing to best practise cases. Because up to now only a limited number of installations is available, it seems to be necessary to refer to foreign demonstration and good practise cases at the beginning.

- From the technical point of view one barrier can be identified regarding to the temperature limits of most commercially available heat pumping units. Many applications are limited to heat sink temperatures below 65°C but as the study of the "Process temperatures in the Austrian Industry" shows, the theoretical potential for the application range of IHP increases significantly by developing energy efficient heat pumps for heat sink temperatures up to 100°C.

To come up to their ecological potential, IHPs have to be commercial attractive on the market. The business success of IHPs depends on the profitability as well as on a flawless performance of the plants, which guarantee the confidence of the customers. The development of heat pump technologies for temperatures up to 100°C offers a greater application field. Also the dissemination of the advantages of IHP applications can promote the commercial success of IHPs.

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4 Canada

4.1 Industrial Energy use

4.1.1 Energy production in Canada

The energy industry contributes significantly to the Canadian economy, despite the global economic volatility and instable prices of fossil fuels observed since 2008. It accounts for 7% of Canada's gross domestic product and employs 2% of the Canadian labour force. In 2008, petroleum (including crude oil and natural gas liquids, upgraded and non-upgraded bitumen, and condensate) accounts for 39.4% and natural gas for 35.14% of domestic energy production, nuclear energy accounts for 6.13%, hydroelectricity for 7.49%, coal for 8.23% and wind for 0.07% (see Figure 4-1).

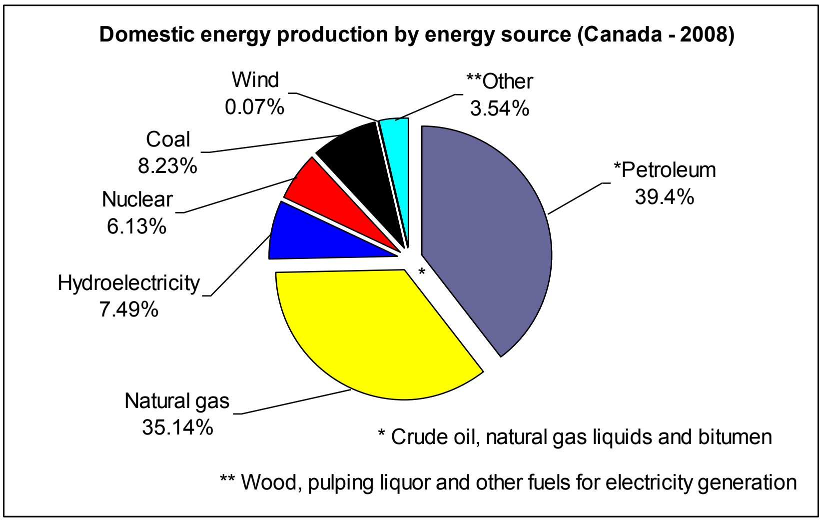

Figure 4-1: Domestic energy production by energy source – Canada 2008

4.1.2 Energy use in Canada

Canada is one of the largest consumer of energy on a per person basis in the world, consuming almost 200 GJ per capita, the equivalent of each Canadian resident using more than 5,000 litres of crude oil per year. This is approximately twice the per capita energy consumption seen in other OECD countries. 2008 total secondary energy demand (end use demand) was of approximately 11,000 PJ It is the energy used by the final consumer and represents residential (13.75%), commercial (14.04%), transportation (24.57%) and industrial (47.66%) energy demands (see Figure 4-2)

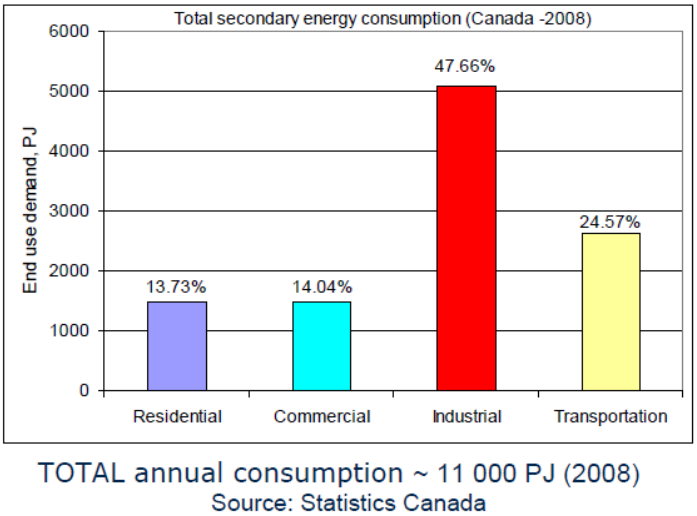

Figure 4-2: Total secondary energy consumption

4.1.3 Energy use in industry

The energy use of 14 sub-sectors of eight major Canadian manufacturing industries accounts for about 1.7 million TJ representing 65.3% of the total energy use of all Canadian manufacturing industries (2.6 million TJ). Compared to the total energy consumption, the pulp and paper sector consumes 27.6%, primary metals industries, 16% and the petroleum sector, 13.7%. Wood (3%) and food (1.2%) industries are relatively small energy consumers compared to the previous mentioned large industrial consumers (see Figure 4-3).

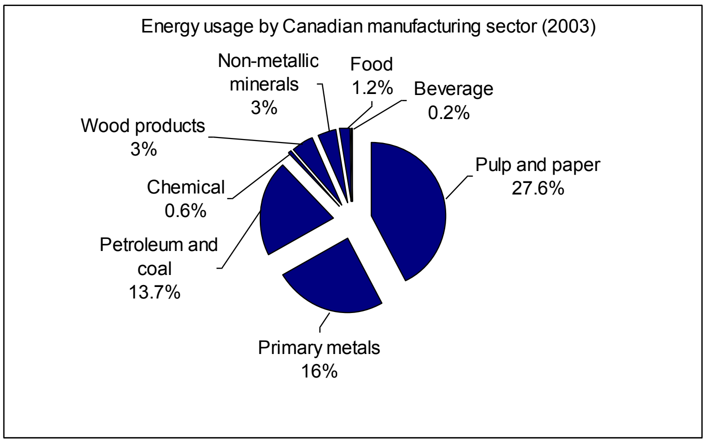

Figure 4-3: Energy use by Canadian manufacturing sectors (2003)

4.1.4 Waste heat in manufacturing industry

About 71% of the input energy is related to the environment via four classes of identifiable waste heat streams. Liquid cooling losses represent the largest class of thermal losses (553 PJ), closely followed by stack losses (524 PJ). Steam losses account for 306 PJ, and energy lost in process gases represents 290 PJ. It should be noted that “other losses” accounting for 611 PJ. However, these are normally in a form that is difficult to quantify or capture, such as radiated low-grade heat from equipment. The Figure below indicates the waste heat in 14 sub-sectors of eight major Canadian manufacturing industries:

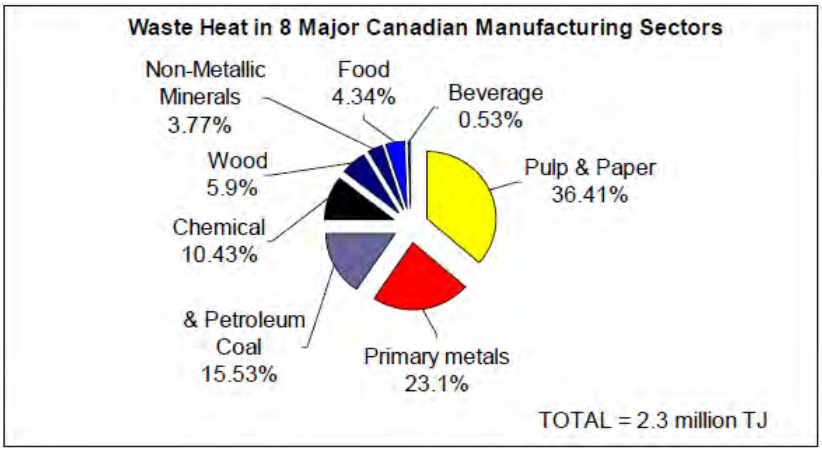

Figure 4-4: Waste Heat in 8 major Canadian Manufacturing Sectors

It shows the percentage of the total industrial waste heat that each industry sub-sector represents as a percentage of all manufacturing sector. In this Figure, not all sub-sectors of each manufacturing sector have been included. Thus, together, the selected 14 sub-sectors represent 65.3% of the manufacturing consumption, while the eight sectors account for 91.3% of the manufacturing energy usage.

More information: [1]

4.2 Market of industrial heat pumps

1994 Market Assessment

In 1994, a Canadian market assessment study [1] has investigated the industrial heat pump (IHP) potential in industries already using such heat recovery devices, as well as in processes where IHP use has been limited or non-existent. The industrial sectors already using industrial heat pumps were lumber drying, food processing (poultry, milk and cheese processing), pulp and paper production, metallurgical (iron and steel blast furnaces) and chemical production, and brewing. At that time (year end 1993), 14 chosen processes contained more than 1,900 individual plants and accounted 35% of the total Canadian industrial process heating load (**Fehler! Verweisquelle konnte nicht gefunden werden.**). About 320 (17%) of these plants used industrial heat pumps. However, more than 90% (or 295 units) were found in one industry, lumber drying. In terms of current penetration, liquor distilling showed the highest level of industrial heat pumps use. The next highest levels were found in lumber drying (27%), cheese production (6%) and poultry processing (5%).

Across the 14 processes analyzed in 1994, the cumulative market penetration of industrial heat pumps under maximum scenario was estimated to be 9% by 2010 with 225 units projected to be installed. Of the total, electric closed-cycle systems were estimated to account for 70% of the potential installations, followed by mechanical vapor recompression at 19% [1].

Projected penetration under the average scenario was estimated at over 25% for four industrial processes: chlorine/soda, newsprint, pulp and specialty paper productions

For the 14 industrial processes combined, the potential to reduce industrial process heat consumption was estimated at between 5 500 – 14 600 TJ/year by 2010. Five processes were estimated to account for some 88% of the total savings: chlorine/soda production (63%), petroleum refining (7%), iron and steel blast furnaces (7%), specialty paper production (6%) and pulp production (5%) [1].

Table 4-1: Summary of 1994 industrial heat pump application in Canada [?]

Process	Number of plants	Number of IHP
Lumber drying	1087	295
Liquor distilling	24	8
Cheese production	108	7
Poultry processing	119	6
Pulp production	39	2
Milk production	179	2
Newsprint production	42	2
Iron and steel	23	0
Sugar refining	8	0
Specialty paper	28	0
Petroleum refining	33	0
Chlorine/soda production	16	0
Textile	192	0
BTX production	9	0
TOTAL	1 907	322 (17%)

Depending on the process, the potential level of energy savings per process ranged between less than 1% to 16%, with the highest levels estimated in chlorine/soda, cheese and poultry productions, and liquor distilling.

In Canada, industrial heat pumps would be reducing natural gas-based process heating energy consumption in many processes. Therefore, while they would reduce plant- and national-level emissions of all fossil-fuel based pollutants, the primary benefit would be reduced CO_2 emissions, followed by lesser reductions in SO and NOx emissions. The greatest environmental benefits from IHP use can be in processes that rely most heavily on oil and coal process heating, as pulp and paper, iron and steel, and petroleum refining [1].

During the spring 2011, a partial market assessment study of the Canadian industrial heat pump market has been performed. In order to estimate the number of industrial heat pumps existing in four Canadian provinces at the end of 2010, a simplified questionnaire has been send to several plants in some industrial sectors shown in Table 4-2. The scope was to identify the actual state and new trends of this industrial market.

Table 4-2: Industrial sectors targeted (2011)

Example of targeted industrial sectors
Lumber drying
Milk production
Cheese production
Poultry processing
Sugar refining
Pulp production
Textile
Petroleum refining

The majority of questioned plants was in Québec (eastern Canada), Ontario (central Canada) and British Columbia (western Canada), respectively. 22 plants have been identified in Manitoba (central Canada). The number of plants having responding to the questionnaire is shown in Table 4-3 by Canadian province.

Table 4-3: Number of plants that have responded to the questionnaire (2011)

Canadian province	Number of plants
Québec	132
Ontario	94
British Columbia	91
Manitoba	22
TOTAL	**339**

The number of plants with industrial heat pumps is indicated in Table 4-4. It can be seeing that only 7.67% of questioned plants use one or more industrial heat pumps for process and/or waste heat recovery.

Table 4-4: Number of industrial heat pump installed

Number of IHPs	Number of plants	%
Any	313	92.33
1	8	2.35
2	6	1.76
3	2	0.59
4	3	0.88
5	2	0.59
6	3	0.88
7	0	0.00
8	1	0.29
9	1	0.29
TOTAL	**339**	**100**

Table 4-5 shows the number of installed heat pump by industrial process. It can be seeing that 31% of them are installed in drying processes, 27% for waste heat recovery and 8% in evaporation processes.

Table 4-5: Number of installed heat pump by industrial process

Drying		**Evaporation**		**Waste heat recovery**		**Others***		**Total**
#	**%**	**#**	**%**	**#**	**%**	**#**	**%**	
8	**31**	**2**	**8**	**7**	**27**	**9**	**35**	**26**

* Others: process thermal recovery; exhausted heat recovery

Table 4-6 indicates the number of heat pumps, primary energy used as driving energy and the year of installation. The most common new installed industrial heat pumps are based on electrical closed-vapor compression cycles used especially in drying, waste heat recovery and evaporation processes. It can be also seeing that 76.9% of the industrial heat pumps have been installed after 1994, and that 92.3% of installed heat pumps use the electricity as primary energy and only 7.7% the natural gas. That means that the number of new IHPs installed between 1994 and 2010 was of 1.25/year among the 339 plants questioned.

Table 4-6: Type and date of installed industrial heat pumps

Type*	**Number**	**Primary energy**		**Year of installation**					
-	-	Electri-city	Natural gas	-	-	-	-	-	-
W/W	6	6	0	1976	2000	2*2009	2 *n/a		
W/A	2	2	0	1997	2004				
A/A	7	6	1	1984	1992	2000	2001	2007	2009
A/W	1	1	0	1985					
Lumber drying	3	3	0	1979	1989	2000			
MVR	3	2	1	1985	2000	2001			
Other	4	4	0	2*2005	2*n/a	2010			
Total	**26**	**24**	**2**	-	-	-	-	-	-

* W/W: water-to-water; W/A: water-to air; A/A: air-to-air; A/W: air-to-water; MVR: mechanical vapor

The installed capacities of heat pumps listed in Table 4-6**Fehler! Verweisquelle konnte nicht gefunden werden.**, vary between 4 to 300 tons (14 and 1050 kW) of installed cooling capacity. The compressor nominal capacity of a mechanical vapor recompression system installed in 2001 was of 257 kW.

4.3 Barriers for applications

Despite of several benefits of industrial heat pumps, as reduced energy consumption and increased capacity of heating systems, the number of this equipment installed to date is relatively low compared to the number of existing technically and economically viable opportunities. Among other reasons can be mentioned the lack of knowledge and experience with heat pump technology. Historically, technical barriers were mainly related to the availability of reliable heat pump components and the use of heat generated. Economical barriers were related to low prices of natural gas and oil versus high electricity prices. Finally, as a legal barrier, many incentives were based on product quality and/or environmental concerns *rather* than economic.

4.4 Literature

[1] IEA HPP Annex 21: Industrial Heat Pumps - Experiences, Potential and Global Environmental Benefits, IEA Heat Pump Centre,
Report No. HPP-AN21-1, April 1995

5 Denmark

5.1 Energy use in the Denmark in 2009

In 2009 Denmark had an energy consumption of 808.9 PJ, and it has been falling since 2007. From 2008 to 2009 the consumption fell by 4.0 % from 843 PJ in 2008. The share of renewable energy is 19.7 %. The electricity production based on renewable energy is 27.4 % of which wind power contributed with 18.3 %.

Table 5-1: Energy consumption in 2009

Energy carrier	**PJ**
Oil	315.6
Natural gas	165.3
Coal	168.7
Electricity	1.2
Waste heat	15.9
Renewable	142
District heat	0.2
Total	**808.9**

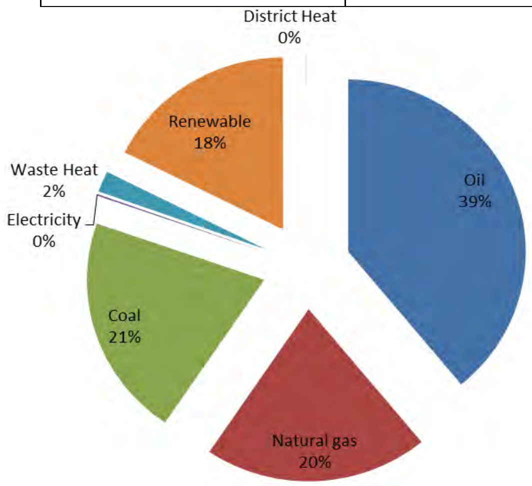

Figure 5-1: Final energy demand in Denmark in 2009 for different energy carriers [PJ]

The table depicts the net balance per energy carrier. The term ‘Electricity and District Heat’ does not refer to the electricity and district heat use but to the net result of import and export of electricity and district heat.

The following table presents the distribution of the total energy use across the different sectors. The energy use of energy companies relates to the conversion losses that occur during for example the production of electricity from natural gas or coal.

Table 5-2: -Energy use across sectors

Sector	PJ
Energy companies	146.6
Refining sector	44.9
Manufacturing industry	136.3
Transport	209.3
Residential	188.8
Commercial	83
Total	**808.9**

In this context the maufacturing industry comprises the following sectors: agriculture, forestry, gardening and fishing, the manufacturing industry and the building and construction sector.

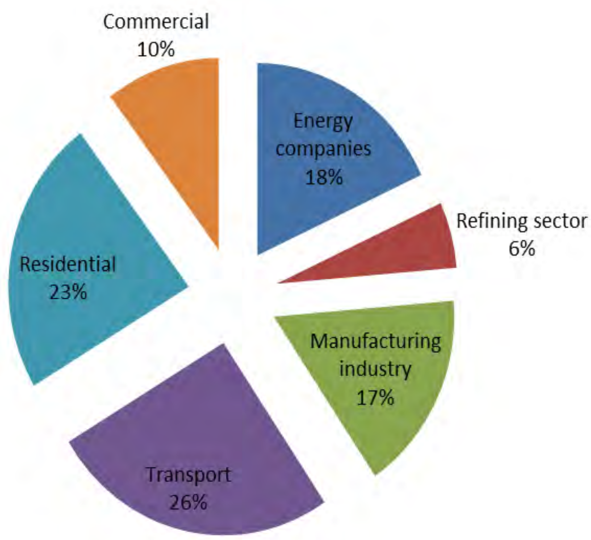

Figure 5-2: Final energy use in Denmark in 2009 for different sectors [PJ]

5.2 Energy Use in the Manufacturing Industry

The industrial energy use has been analyzed in a project from 2008 – the numbers used in this survey are from 2006. The Danish manufacturing industry used 127.2 PJ in 2006, within agriculture and fishing the consumption was 44.0 PJ, whereas the private trade and service sector used 47.6 PJ. In total, within the manufacturing industry and the trade and service sector was used 218.8 PJ.

This survey focuses on the manufacturing industry, since here is the greatest potential for large heat pumps and high temperature heat pumps.

Table 5-3: Energy use in the Danish manufacturing industry based on energy carriers in 2006 [PJ]. Wiegand og mågøe

Energy carrier	**PJ**
Oil	21.4
Natural gas	48.8
Coal, wood, straw	13.9
Electricity	35.8
Miscellaneous	7.1
Total	127.2

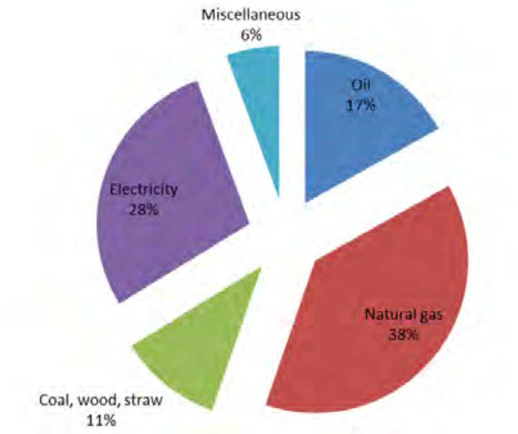

Figure 5-3: Share of industrial energy use within the different sectors

Table 5-4: Energy use in the Danish manufacturing industry based on sector and carrier

Industry sectors	**Coal**	**Rene-wable**	**Oil**	**Gas**	**Electri-city**	**District heating**	**Total**	**Share**
	[TJ]	[TJ]	[TJ]	[TJ]	[TJ]	[TJ]	[TJ]	%
Mining and quarrying	165.1	89.6	1658.0	1480.7	300.0	2.7	3696.0	**2.91**
Food, beverages and tobacco	2114.8	431.5	6997.2	12604.0	9021.0	1412.9	32581.4	**25.66**
Textile and leather	0	7.8	84.9	680.7	601.4	131.7	1506.5	**1.19**
Wood and wood products	0	2492.7	770.2	662.9	2481.0	650.0	7056.9	**5.56**
Pulp, paper and print	0	46.1	273.4	3026.5	2626.5	682.8	6655.3	**5.24**
Chemicals, medicine industry	563.8	3.4	1885.0	18016.0	5730.8	1986.8	27986.4	**22.04**
Plastic and rubber industry	0	17.463	256.0	1505.0	2551.8	154.1	4484.3	**3.53**
Metal and machinery	0	83.0	2034.4	5634.5	6782.3	1374.8	15909.0	**12.53**
Other industries	0	66.4	306.6	1044.8	2521.4	671.5	4610.6	**3.63**
Non metallic	0	0	14	1312.7	667.4	16.7	2010.9	**1.58**
Construction indus-try	10670.0	1208.1	1687.9	4323.1	2530.4	65.3	20484.8	**16.13**
Total	**13513.7**	**4446.0**	**15967.5**	**50290.7**	**35814.0**	**7149.2**	**126982.0**	**100.00**
%	**10.64**	**3.50**	**12.57**	**39.60**	**28.20**	**5.63**	**100**	

The food, beverage and tobacco industries use 25.7% of the industrial energy, whereas the medical and chemical industries use 22 %. Gas is the largest energy source in the industry and constitutes 39.6 % of the energy demand.

Table 5-5: Industrial energy use regarding sectors and application

Temperature	**Final applications**	**Fuel/FjV**	**Electricity**	**Totals**	**Share %**
		[PJ]	[PJ]	[PJ]	[%]
<70	Boiler and pipe losses	7867	0	7867	6.185575
0-120	Preheating and boiling	24592	496	25088	19.72591
40-250	Drying	15551	689	16240	12.769
40-170	Evaporation and concentration	5759	0	5759	4.528121
40-100	Destillation	3755	0	3755	2.952439
300-1000	Burning/Sintering	12444	24	12468	9.803197
300-1000	Melting/Casting	2827	2458	5285	4.15543
70	Heat up to 150 °C	345	10	355	0.279125
150<	Heat above 150 °C	1187	94	1281	1.00721
NR	Transport	605	0	605	0.475693
NR	Lightning	0	2758	2758	2.168529
NR	Pumping	0	3665	3665	2.881674
NR	Refrigeration/freezing	0	3053	3053	2.400478
NR	Fans and blowers	0	6387	6387	5.021898
NR	Compressed air and process air	0	4093	4093	3.218197
NR	Size reduction	0	1599	1599	1.257243
NR	Stirring	0	709	709	0.557464
NR	Other electrical motors	0	8545	8545	6.718665
NR	Computers and electronics	0	474	474	0.372691
NR	Other electrical users	0	345	345	0.271263
50	Space heating	16436	416	16852	13.2502
	Totals	**91367**	**35815**	**127183**	**100**

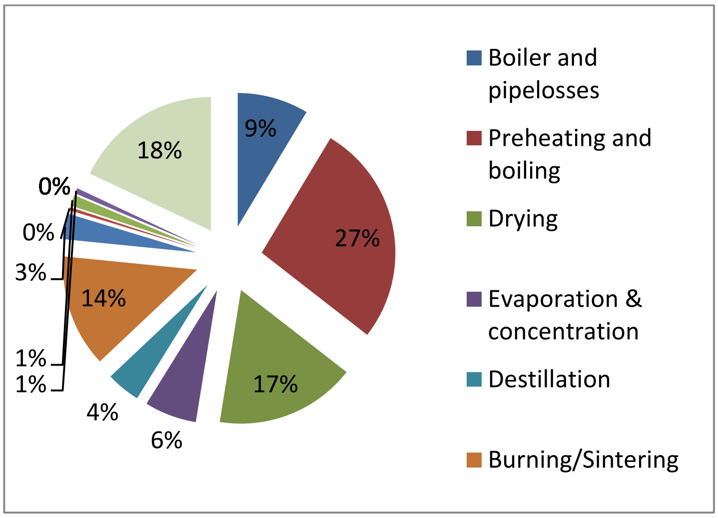

Figure 5-4: Energy use in the Danish manufacturing industry based on processes

Table 5-6: Energy use in the Danish manufacturing industry based on sectors and processes

Use	Mi-ning	Food	Tex-tile	Wood	Pulp and paper	Che-micals	Plastic and rubber	Metal	Other	Non metal-lic	Con-struc-tion	Total	Share
	[TJ]	[TJ]	[TJ]	[TJ]	[TJ]	[TJ]	[TJ]	[TJ]	[TJ]	[TJ]	[TJ]	[TJ]	%
Boiler and pipe losses	356	3136	137	751	393	1557	341	837	224	27	296	8056	6.3
Preheating and boiling	235	7011	418	168	199	14032	202	1756	97	26	1015	25159	19.8
Drying	466	5747	186	1615	2080	1190	232	1035	115	40	2920	15626	12.3
Evaporation & concen-tration	2033	4025	0	0	0	478	0	0	0	0	0	6536	5.1
Destillation	0	567	0	0	0	3188	0	0	0	0	0	3755	3.0
Burning/ sintering	165	0	0	0	0	0	0	27	0	6	11930	12128	9.5
Melting/ casting	0	0	0	0	0	11	1184	1682	349	1154	905	5285	4.2
Heat up to 150 °C	0	94	32	39	0	190	0	0	0	0	0	355	0.3
Heat above 150 °C	0	586	0	58	0	0	0	281	0	128	220	1273	1.0
Transport	96	144	3	109	51	10	30	91	33	5	33	605	0.5
Lightning	9	571	78	201	295	212	194	799	294	33	72	2758	2.2
Pumping	81	1315	41	61	320	1447	84	175	38	33	69	3665	2.9
Refrigeration / freezing	0	2016	2	0	65	623	241	55	51	0	0	3053	2.4
Fans and blowers	75	1566	84	964	409	567	291	1127	486	140	677	6387	5.0
Compressed air and process air	18	596	61	386	186	1343	222	779	276	127	98	4093	3.2
Size reduc-tion	45	290	0	47	194	53	65	2	18	7	879	1599	1.3
Stirring	0	114	0	0	54	481	42	0	0	0	19	709	0.6
Other elec-trical motors	69	2212	235	623	824	635	289	2096	809	120	631	8545	6.7
Computers and elec-tronics	0	62	1	39	215	14	33	53	58	0	0	474	0.4
Other elec-trical users	0	0	0	0	0	0	25	298	22	0	0	345	0.3
Space heat-ing	47	2540	227	1996	1371	2154	1010	4816	1741	164	712	16777	13.2
Totals	3696	32591	1506	7057	6655	28186	4484	15909	4611	2011	20477	127183	
	2.9	25.6	1.2	5.5	5.2	22.2	3.5	12.5	3.6	1.6	16.1	100.0	

5.3 Market Survey

Industrial demography:

From a conversional point of view, the foodstuff, metal and machine industries constitute the largest sectors within the Danish manufacturing industry. However, the chemical and medical industry exceeds the metal industry as regards use of energy. As for implementation of heat pumps, the foodstuff, chemical and medical industries are the most essential consumers of energy.

The extension of heat pumps is not huge in the Danish industry.

Challenges:

Profitability: The most important challenge is the rather low economic advantage by establishing heat pumps.

Focus on reutilization for heating: Furthermore, at great part of the focus has been on the reutilization of heat from the industry for the heating of rooms, and in this case the Danish energy tax system is a big challenge.

Knowledge: Lack of knowledge and experiences also constitutes a challenge in the industry.

5.4 Literature

1: Energistatestik 2009, Energistyrelsen (Danish Energy Agency), ISBN 978-87-7844-872-9

2: Kortlægning af erhvervslivets energiforbrug, November 2008, Energistyrelsen (Danish Energy Agency). Elaborated by: Dansk Energianalyse A/S; Viegand og Maagøe A/S

6 France

6.1 Energy in France[17]

2007 France used 154 Mtoe of Energy. The final energy consumption by fuel has been: 45% oil, 24% electricity, 20% gas and 7% renewable. The gross electricity generation was 570 TWh (2007): 77% nuclear, 12% renewable, 4% coal. The price of electricity for the industry has been 2008 one of the cheapest of Europe (6.15 € per 100 kWh).

The industry represented 2007 22% of the final energy consumption (33% transport, 27% household, 16% services and 2% agriculture).

The CO_2 emission of the French industry has been 2007 95.5 Mt of CO_2. The industry represented 24% of these emissions (34% transport, 17% energy industry, 14% residential).

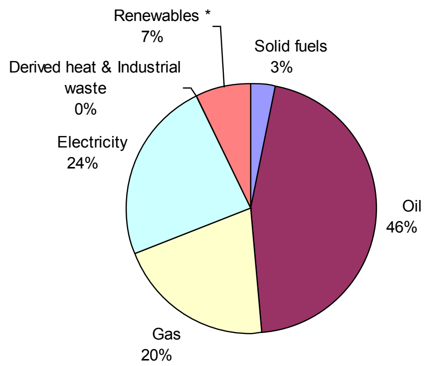

Figure 6-1: France final energy consumption by fuel 2007 (Mtoe)[18]

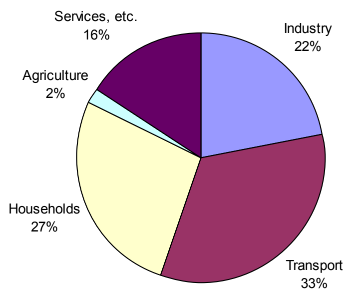

Figure 6-2: France final energy consumption by sectors 2007 (Mtoe)

[17] COMMISSARIAT GÉNÉRAL AU DÉVELOPPEMENT DURABLE - Chiffres clés de l'énergie – October 2010

[18] European Commission / ENERGY - EUROPE 2020 initiative - Energy Efficiency Plan 2011, Statistical pocketbook 2010

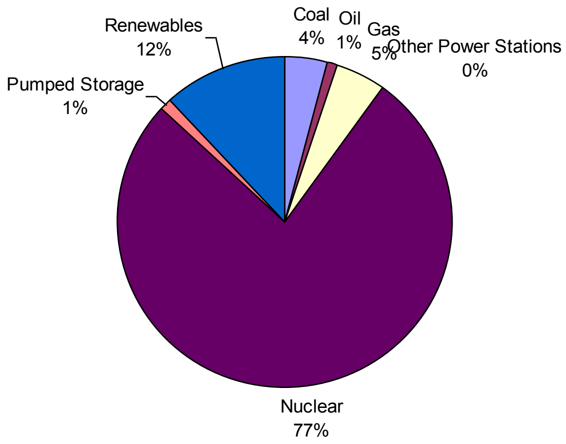

Figure 6-3: France Gross electricity generation 2007 (in TWh)

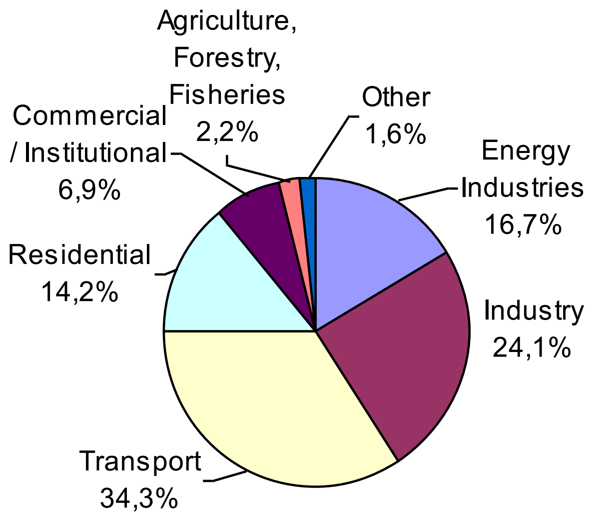

Figure 6-4: France CO_2 Emissions by sector 2007 (Mt)

6.1.1 Energy in French Industry

The industry represents 25% of the greenhouse gas emissions (24% of the total CO_2 emissions, 78% of SO_2, 44% of COV, 25% of NOx). The CO_2 emissions represent 80% of the total greenhouse gas emissions of the French industry.

The French industry represents 15% of the GDP and of the employments (3.6 for 25 millions).

The main sectors in the French industry are in 2008: 26% chemical, 17% steel, 14% Food, 13% mineral, 12% mechanical and 10% pulp and paper (two sources are presented, ADEME and EUROSTAT, the limits of the sectors are different).

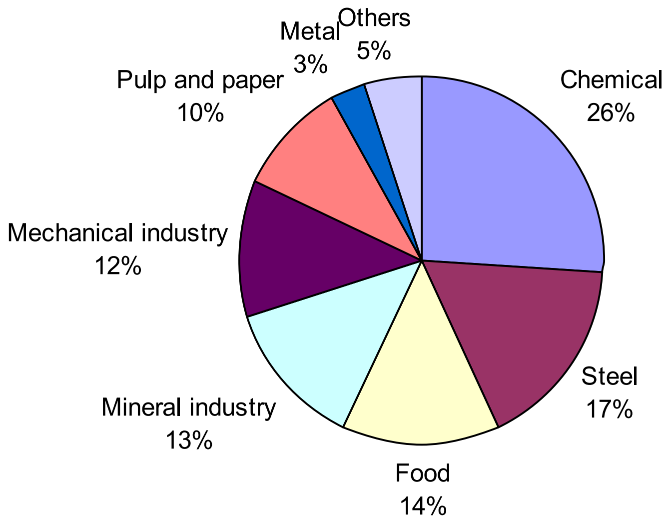

Figure 6-5: Industrial final energy consumption by sectors 2008 [19]

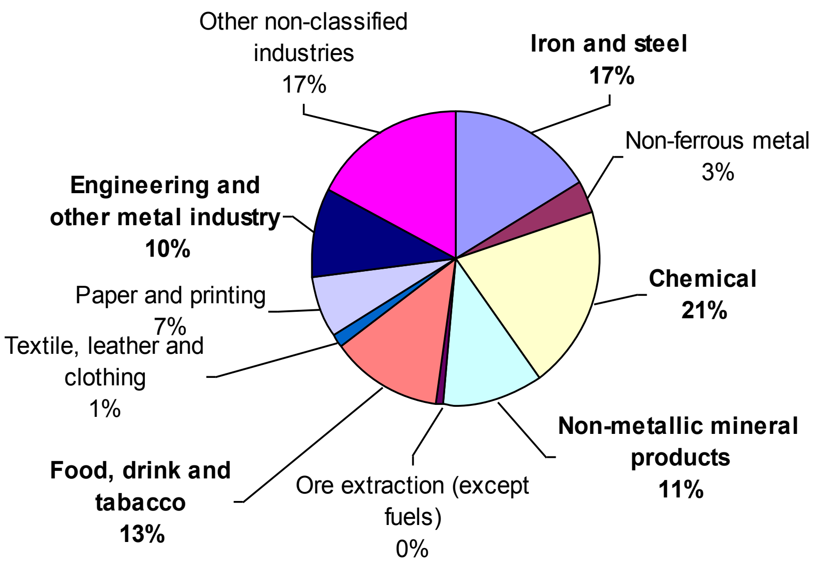

Figure 6-6: France industrial final energy consumption by sectors 2008 (Mtoe) 20

[19] Colloque Programme Energie, Vannes - France, May 29th 2009, ADEME
[20] European Commission – Eurostat - 2008

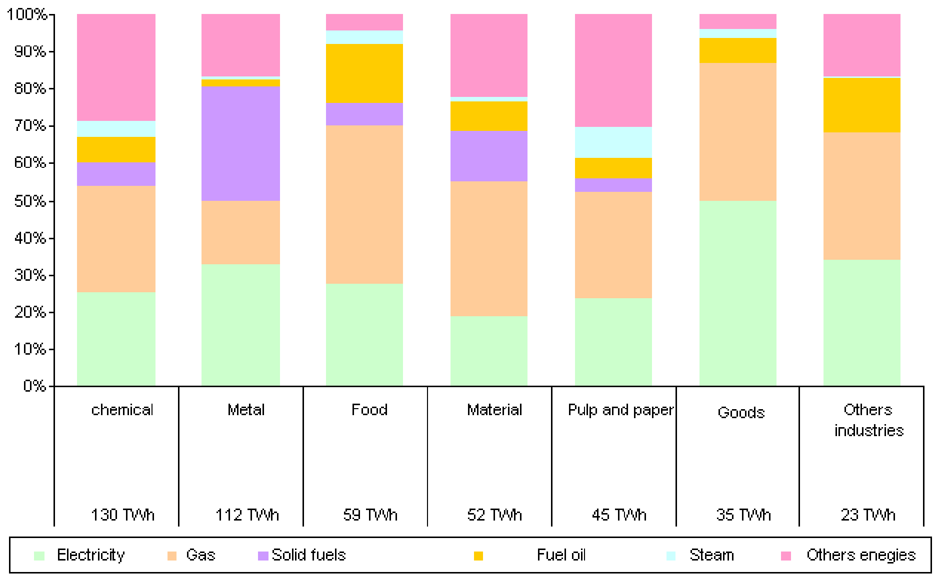

Figure 6-7: Type of energy used by industrial sectors[21]

In 2009 the energy consumption of the French industry decrease of -15.9% (-1.3% in 2008). The steel and metal industry decrease of -28.2%, the chemical industry of -10.2%, the glass industry of -15.9%, the material industry (cement, …) of -13.2% and the Pulp and paper industry of -10.1%. Only the energy consumption of food industry is stable (with +11.6% for the sugar industry).[22]

Then the electricity consumption decrease of -11% (-24% for the steel industry), the gas consumption decrease of -3.4%, fuel oil of -7.5% and coal -24% (because of the steel industry which use 70% of the coal).

The renewable energy represents 7% of the energy consumption of the industry (x2 in 10 years).

More than 70% of the energy is used to heat. In term of operation, 29% are boilers, 17% chemical reactions, 15% furnaces. The motors (motors, HVAC, Cold) represent 70% of the electrical consumption of the industry.

[21] Sources : CEREN, SESSI, AGRESTE (2010)

[22] Bilan énergétique de la France pour 2009 (Commissariat général au développement durable - Service de l'observation et des statistiques)

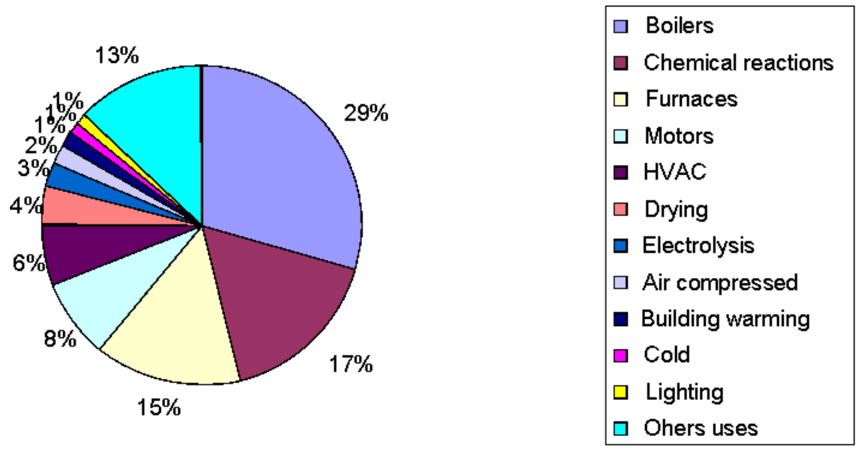

Figure 6-8: Type of uses of energy in 2007[23]

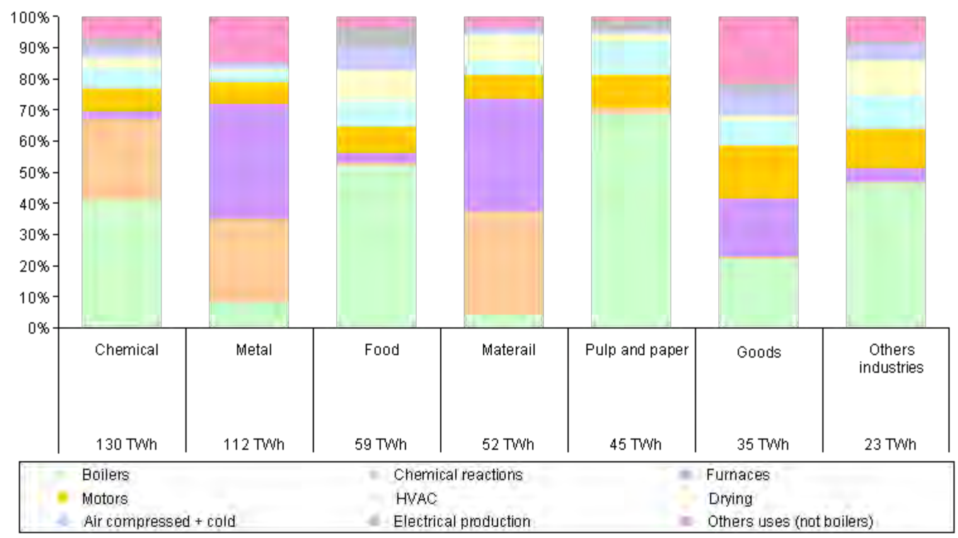

Figure 6-9: Main operations by industrial sectors[24]

6.1.2 Market assessment of industrial heat in France

This part describes the needs for heat sources and availability of cold sources.

French energy consumption analysis shows that the energy bill for the processes in the temperature range 0-200°C (all industrial sectors combined) is ten times higher than the energy bill for processes in the temperature range 0-70°C. Therefore, the development of energy efficient solutions for temperatures higher than 70°C (the limiting condensation temperature for existing industrial heat pumps), could increase potential energy savings on industrial processes by a factor of 10.

[23] Source RTE (Operator of the French electricity transmission system.)

[24] Sources : CEREN, SESSI, AGRESTE (2010)

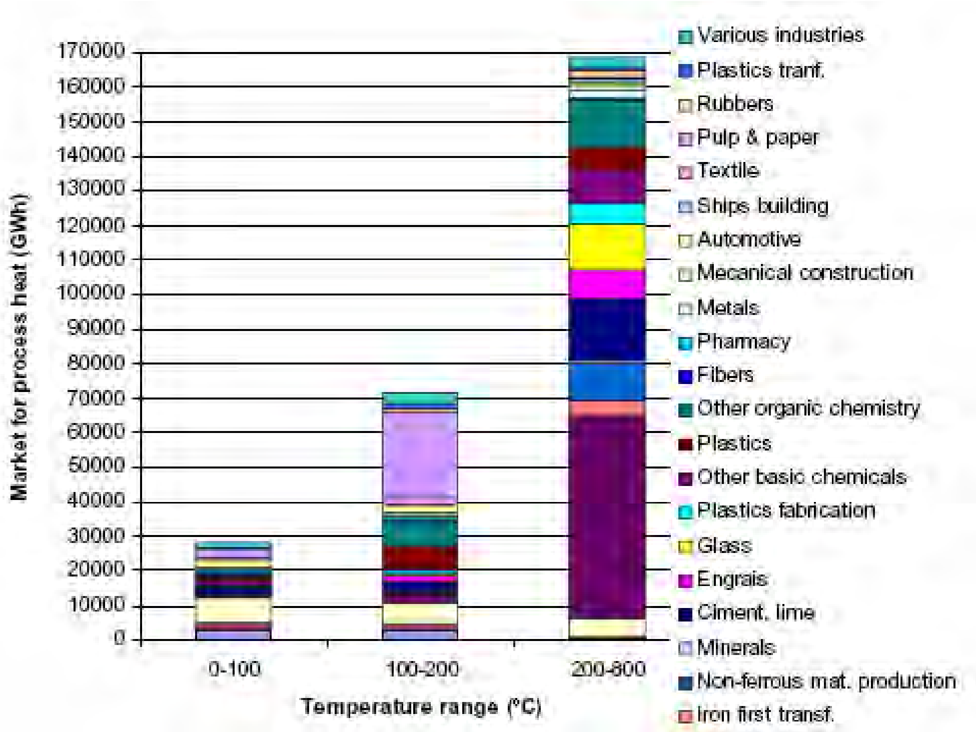

Figure 6-10: Process energy market on the 27 main industrial sectors[25]

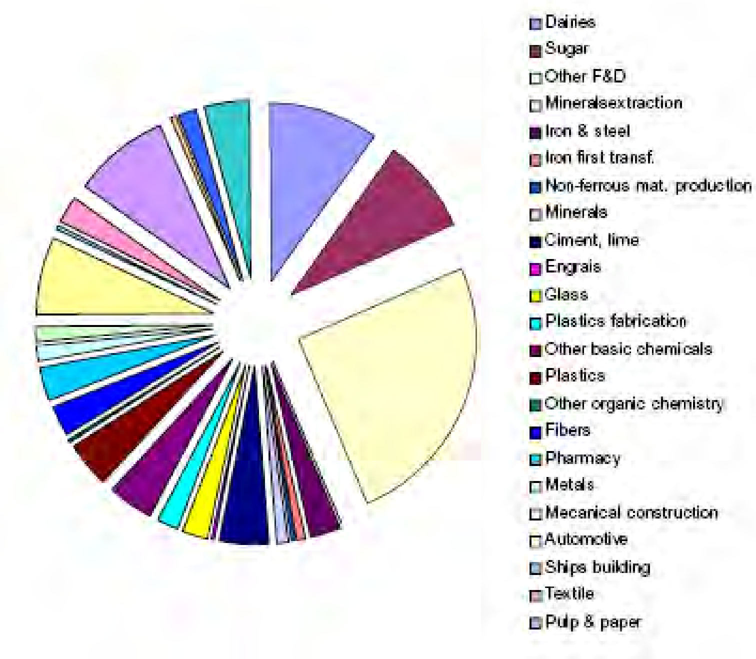

Figure 6-11: Distribution by sector of energy consumption of processes below 100°C

[25] Source : EDF-R&D (+ CEREN 2007)

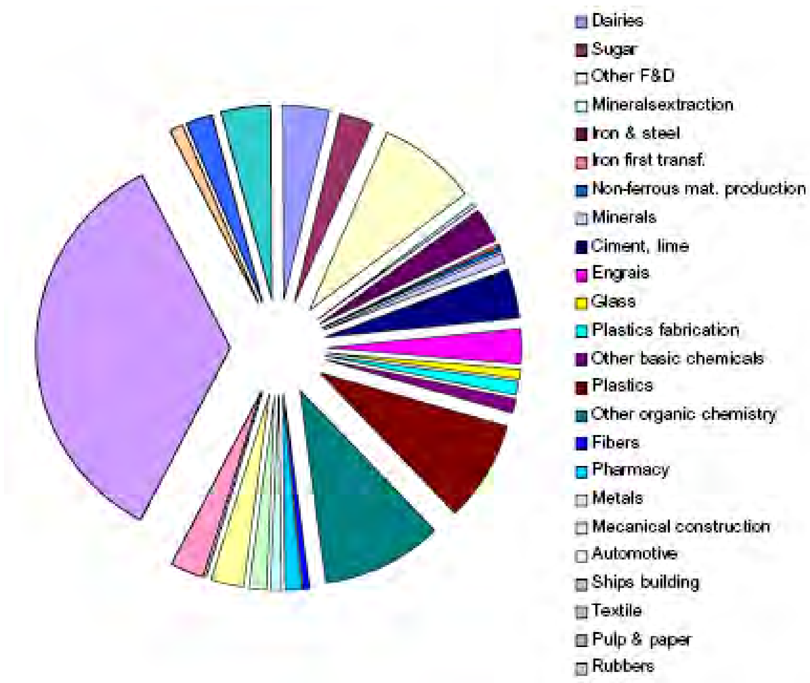

Figure 6-12: Distribution by sector of energy consumption of processes between 100°C and 200°C

By the way, the most energy consuming processes are:

- Heating of liquids and gases, very frequent between 0 and 100°C (35% of the consumption of this range) and in the food processing industry
- Drying, very frequent between 100 and 200°C (39% of the consumption in this range) and in the paper industry.

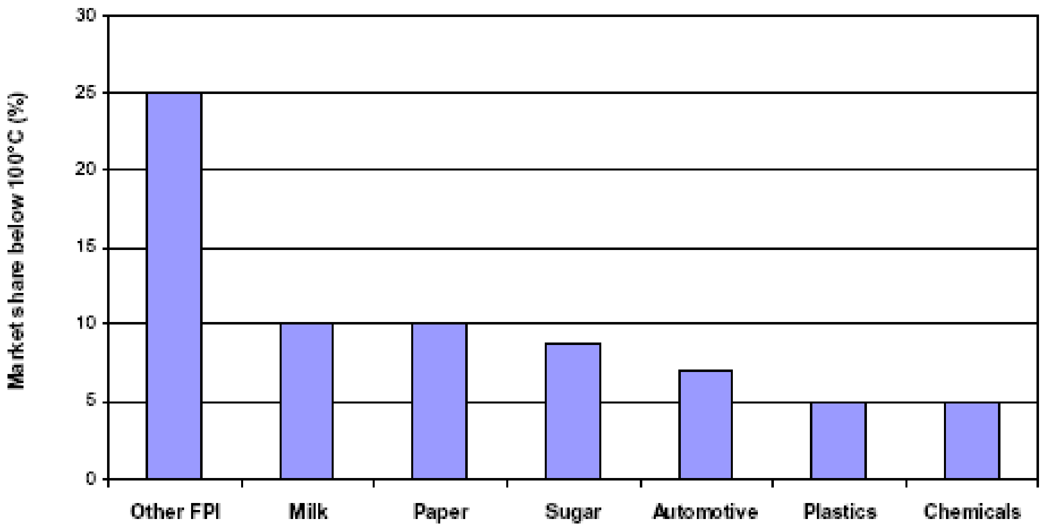

Figure 6-13: The seven sectors with the highest consumptions below 100°C

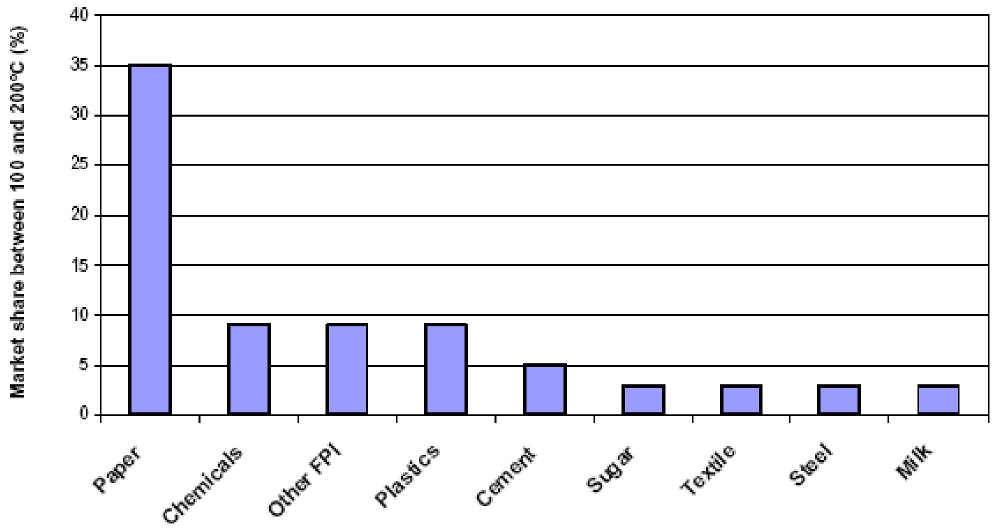

Figure 6-14: The nine main sectors for the 100°C to 200°C market

As can be seen in the figures above, in the temperature ranges 0-100°C and 100-200°C, three sectors are consuming particularly high quantities of process heat. They will be used to orientate the technological specification for a heat pump adapted to their applications:

- The food processing industry (mainly in the range 0- 100°C), including dairy and sugar;
- The basic organic chemistry industry, including manufacturing of basic plastic and elastomer materials
- The paper industry (mainly above 100°C)

These three sectors represent the respectively 64% (68%) of the total national consumption by process equipment in the temperature range 0-100°C (100-200°C).
Four other sectors consume large quantities of energy in the temperature range 100-200°C, although to a lesser extent: manufacturing of plaster, lime, cement ; automobile manufacturing ; textile industry and steelworks

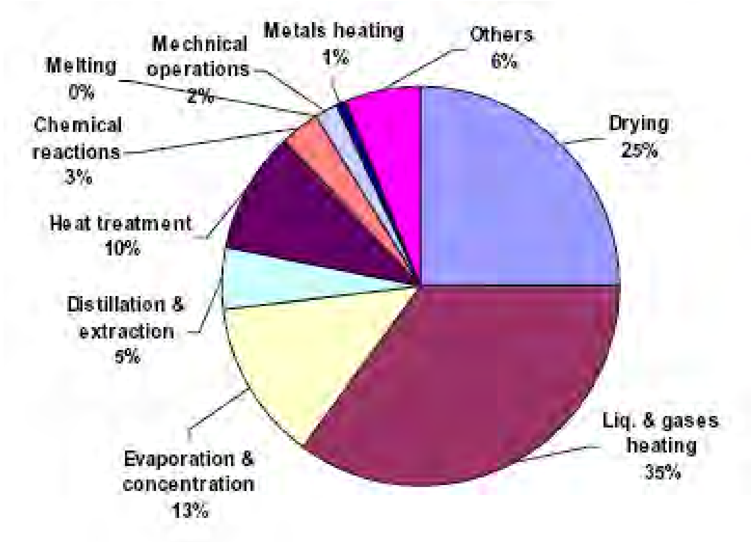

Figure 6-15: Distribution of the energy consumption on the different processes below 100°C, all sectors combined

Remarkably, each of the two temperature ranges is marked by one and possibly two major types of energy consuming operations that themselves correspond to a consumption concentration in a particular sector, despite their presence across all sectors. Thus:

- Heating of liquids accounts for 35% of energy consumption below 100°C; 47% of the energy necessary for liquid heating processes in this temperature range are consumed in the food processing industry (4.6 TWh) distributed among dairy, sugar and other food processing activities, the consumption for the dairy industry in heating of liquids being greater than consumption for all other food processing excluding sugar (see figure above).
- Drying accounts for 39% of energy consumption between 100 and 200°C; 62% of the energy necessary for drying in this temperature range is consumed in the paper sector (17 TWh), and 10% in the food processing industry (see Figure 6-16).

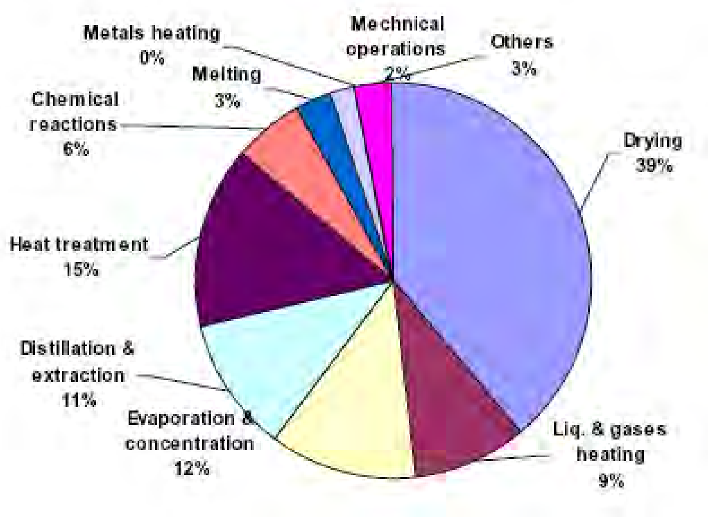

Figure 6-16: Distribution of energy consumption on the different processes between 100°C and 200°C, all sectors combined

Knowledge about consuming processes in food processing, chemicals and paper has been specified in a finer temperature range. Although the extrapolation method underestimates the number of equipment in the country and overestimates the average power per equipment, these values have validated the advantage of developing a standard heat pump for integration, substitution, make up or pre-heating for the corresponding application processes.

Key energy consuming applications for the installation of a very high temperature heat pump satisfying the two conditions (a large number of equipment and the moderate average power) are given in summary table below. Applications with a less appropriate profile composed of the number of equipment and average power, but that are still interesting due to their energy consumption have also been identified and listed in the core of this report.

It is difficult to evaluate the availability of degraded industrial heat sources that can be used by the VHT HP (Very High Temperature Heat Pump) evaporator: effluent quantities, physical and biological quality and temperatures are not well known. Nevertheless, an evaluation of the integration of a VHT HP in series on cooling units to recover heat from the cooling unit condensers, demonstrates that this solution alone could at least cover the energy consumption of the processes consuming most energy, and possibly even all process consumption, in the food processing and dairy sector.

Table 6-1: Summary of the most attractive applications of a VHT HP by temperature level

Temperature	Application	Consumption (TWh)	Number of units in France	Average unit power (MW of heat)
70 - 79°C	Dairy, pasteurisation	0.4	198	2.4
	Dairy, cleaning water	0.12	90	1.3
	Various food processing industries (FPI), heating of liquids	0.25	447	0.8
80 - 89°C	Dairy, pasteurisation	0.29	175	1.9
	Dairy, cleaning water	0.11	103	1.5
	Miscellaneous FPI, heating of liquids	0.44	438	1.6
	Miscellaneous FPI, th treatment: cooking food	0.38	521	1
	Paper, drying	0.37	276	0.8
90 - 99°C	Dairy, pasteurisation	0.27	182	1.1
	Miscellaneous FPI, heating of liquids	0.56	572	3.5
	Miscellaneous FPI, th treatment: cooking food	0.48	607	2.2
	Plastics, chemical reactions	0.02	101	1.6
100 - 119°C	Miscellaneous FPI, th treatment: cooking food	0.58	754	2.3
	Plastics, chemical reactions	0.16	80	4.5
	Other organic chemistry, chemical reactions	0.2	635	9
120 -139°C	Miscellaneous FPI, th treatment: cooking food	0.58	483	2.3
	Miscellaneous FPI, sterilisation, appertisation	0.92	678	3.8
	Plastics, chemical reactions: make up	0.13	55	16
	Other organic chemistry, heating of gases	0.75	274	3.3
140 - 159°C	Paper, make up drying	4.6	194	7.1
	Other organic chemistry, make up chemical reactions	0.83	1423	10.5
160 - 179°C	Other organic chemistry, make up chemical reactions	1.2	871	19
	Other organic chemistry, make up distillation	1.8	192	5.5

6.2 French Market overview

Looking at the industrial heat pump market in France, we can notice two main features:

- Open cycle heart pumps, MVR, are largely developed
- Closed cycle heat pumps are more and more used by industry, but the actual market is far to be fully developed.

Concerning MVR, a great number of installations has been realized in 80’s and 90’s, especially in agro-food sector. Today, most of whey concentration plants and sugar plants are equipped by MVR.

Concerning closed cycle heat pumps, the situation is different. Between the end of 80’s and the beginnings of 90’s some heat pumps were installed, especially for drying applications. EDF internal reports showed some existing machines in breweries and lumber drying. But most part of the potential market has not been penetrated by heat pumping technology. Today, rising of fossil energies price and increasing concerns related to CO2 emissions lead industry to discover again the energy efficiency potential of heat pumps. Several machines have been sold for recent years in different sectors, and particularly in dairies where, recovering energy at chiller condenser to valorize it at higher temperatures is becoming more and more usual.

Today, heat pumps can be found in different agro-food sectors (meat, dairy, oil, brewery) but also in cosmetic industries, PC processors plants and several other sectors. Anyway, their utilization is limited to hot water production or buildings heating. Market will be fully developed once heat pumps will be directly installed on the industrial process. The potential of this development is very high.

6.3 Barriers for applications

Three types of barriers hinder the full development of industrial heat pump market:

1. Profitability: payback period requested by French industrial customers is less than three years. Even if French electricity price is quite low, it’s not easy to reach such profitability. Heat pumps are profitable when COP is high and when they’re installed on a process which works all year long. For recent years, low price non conventional gas is a real barrier on heat pumps profitability.
2. Lack of knowledge: industry doesn’t know heat pumps as well as boilers. Several good references are necessary before winning customer confidence.
3. Lack of specialized engineering companies: installing a heat pump on an industrial process is not easy. Heat pump is often the heart of a more complex heat recovery system including heat exchangers, secondary hydraulic loops and storage tanks. Today in France there is no engineering company special-

ized on industrial heat pump. Several manufacturers propose heat pumps for heat recovery on chillers condensers in order to produce hot water. But societies suggesting heat pump installation directly on the industrial process are almost inexistent up to now.

The three types of barriers are strictly linked: increasing profitability means more references on industrial plants, and so a growing demand and the development of specialized engineering companies able to satisfy this demand.

7 Germany

7.1 Energy use in Germany

The primary energy consumption in Germany did not change significantly in the past twenty years. Figure 7-1 illustrates this development. The minimum in 2009 is strongly related to the financial crisis that resulted in a decrease of the German GDP by 5.1 % followed by a strong recovery in 2010 /Statistisches Bundesamt 2012/.

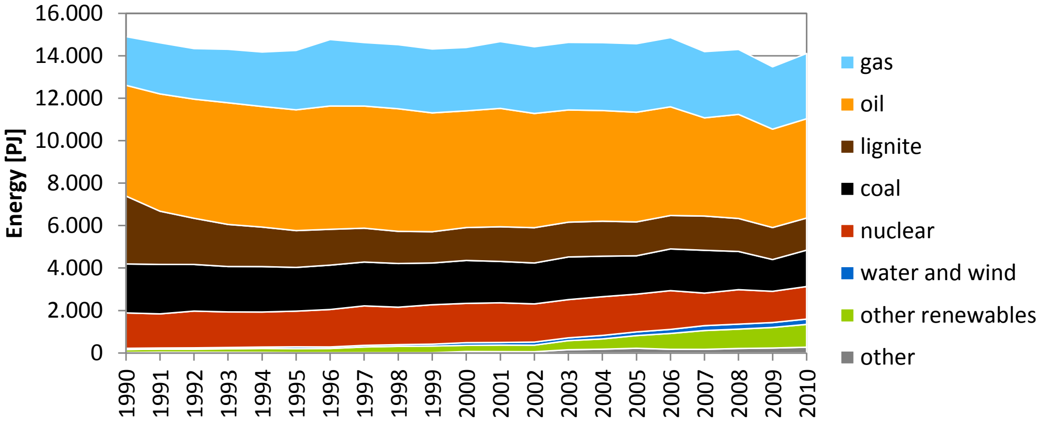

Figure 7-1: German primary energy balance per energy source /BMWi 2012/

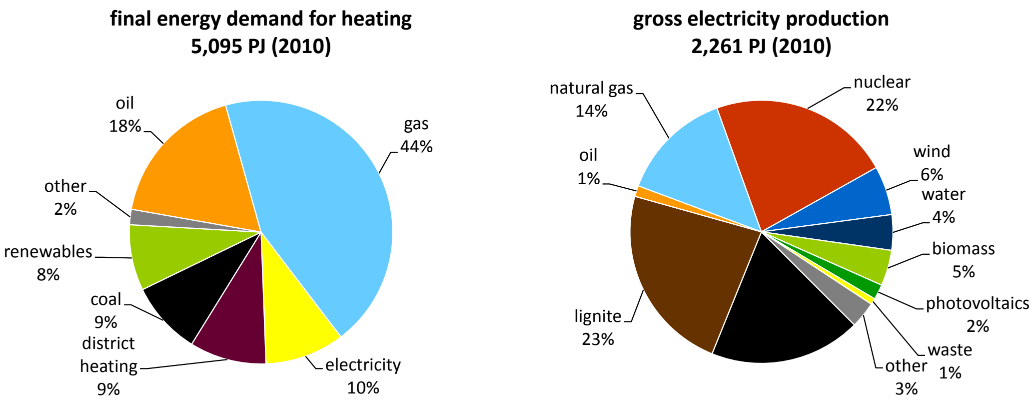

Figure 7-2: Final energy demand for heating and gross electricity by energy source in Germany /BMWi 2012/

The primary energy consumption of 14,044 PJ in 2010 was dominated by fossil energy sources. The energy mix is devided into gas (21.9 %), oil (33.3 %), lignite (10.8 %), coal (12.2 %), nuclear energy (8.8 %), water and wind energy (1.8 %), other renewables (7.6 %) and other sources (1.9 %). Figure 7-1 shows a constant increase of the renewable energy share in the last ten years.

The renewable share in final energy demand for heating has risen up to 8.1 % in 2010 but more than two thirds are covered by burning fossil fuels (Figure 7-2). In gross electricity production the share of renewable sources has risen from 7.0 % in 2000 up to

16.6 % in 2010. This led to a reduction of the specific CO_2 emissions from 623 g/kWh$_{el}$ to 562 g/kWh$_{el}$ /UBA 2012/.

The final energy demand in Germany can be classified in four main sectors:

- industry
- trade/services
- private households
- transport

In 2010 Germany had a final energy demand of 9,060 PJ. The shares of industry, transport and private household are of almost equal size around 28 %. Trade and services play a minor important role with a share of 15 %.

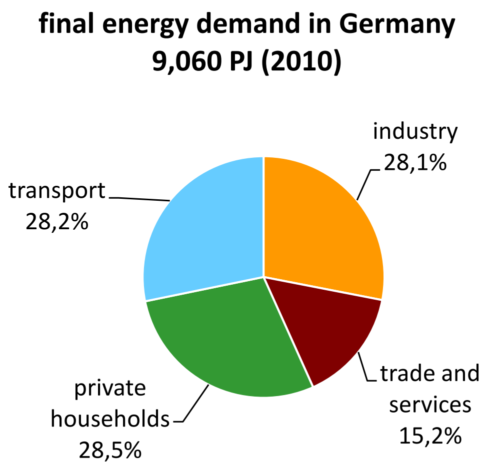

Figure 7-3: Final energy consumption in Germany by sector /BMWi 2012/

7.1.1 Final energy use in the German industry

After a decrease in the early 1990s, that was mainly caused by the collapsing industry in eastern Germany after the reunification, the final energy demand of the German industry developed constantly between 2,300 PJ and 2,600 PJ (Figure 7-4). The minimum reached in 2009 is to be seen as the effect of the financial crisis. During the last ten years the shares of renewable energies and district heat are increasing slightly, while the use of coal and oil is decreasing.

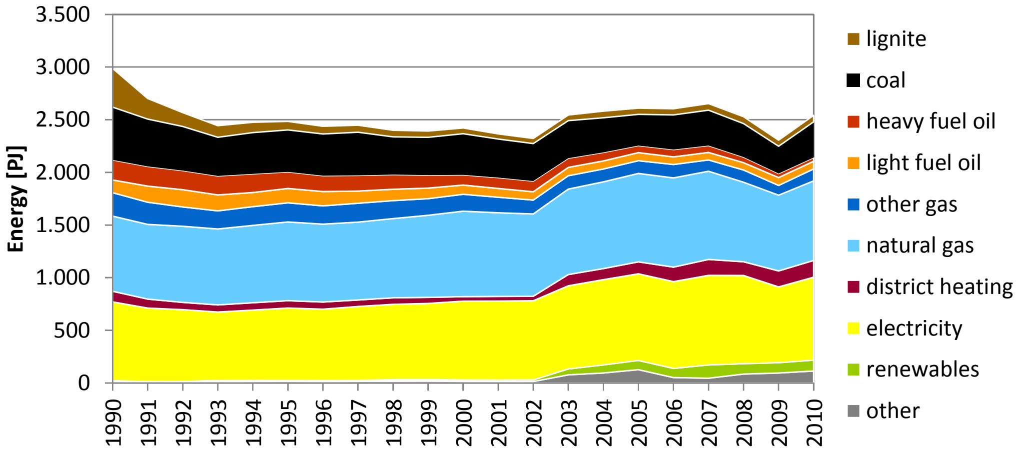

Figure 7-4: Final energy balance of the German industry from 1990 to 2010 /BMWi 2012/

In 2010 the final energy demand of the German industry has reached 2,542 PJ. The biggest share was needed in form of process heat (1,666 PJ / 65.6%), followed by mechanical energy (553 PJ / 21.7%), space heating (196 PJ / 7.7%), lighting (38 PJ / 1.5%), information and communication technology (ICT) (32 PJ / 1.3%), hot water (23 PJ / 0.9%), process cold (18 PJ / 0.7%) and climatisation (17 PJ / 0.7%). Figure 7-5 shows that heating purposes (process heat, space heating, hot water production) account for almost three quarters of the industrial final energy demand in Germany.

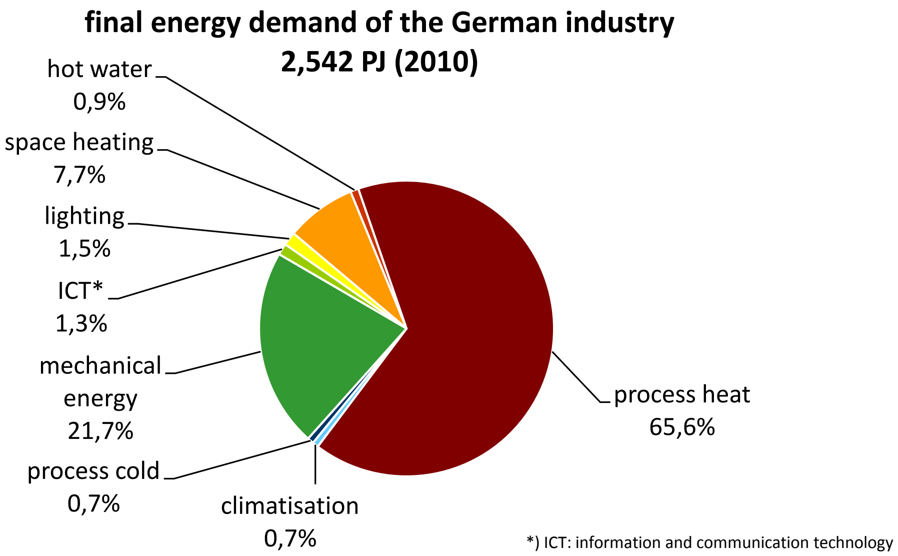

Figure 7-5: Final energy demand of the German industry in 2010 /BMWi 2012/

7.1.2 Heat demand of the German industry

The German industrial heat demand reached 1,883 PJ in 2010 (Figure 7-6). It was even more dominated by fossil fuels than the overall German heat demand (Figure 7-2). The most widely used energy source was gas (861 PJ / 45.7%) followed by coal (401 PJ /

21.3%), district heating (160 PJ / 8.5%), electricity (138 PJ / 7.3%), oil (126 PJ / 6.7%), renewables (104 PJ / 5.5%) and other sources (95 PJ / 5.0%). Although the renewable share in industrial heat production has risen slightly it is still far behind the share of renewable heat produced in private household sector (12.4 % in 2010).

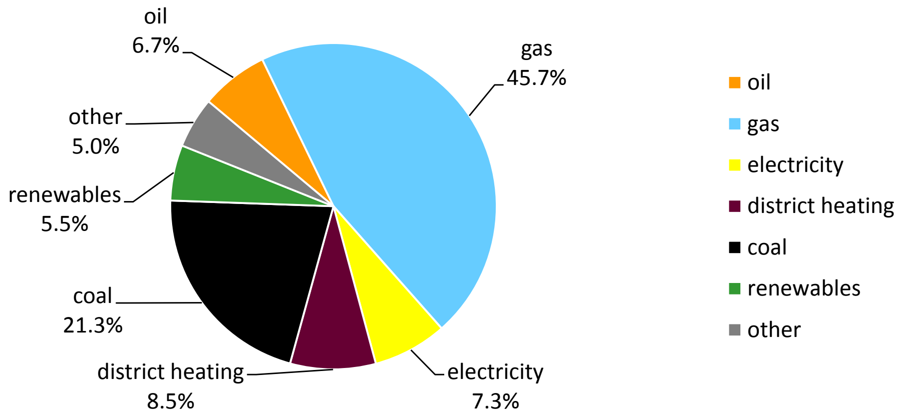

Figure 7-6: Heat demand of the German industry in 2010 by energy source /BMWi 2012/

An overview over the structure of the industrial heat demand is given in Figure 7-7. Metal production is by far the most heat consuming industrial branch followed by production of basic chemicals and food & tobacco industry. While in metal production coal is largely used for heat generation, natural gas has the biggest share in the other industrial branches.

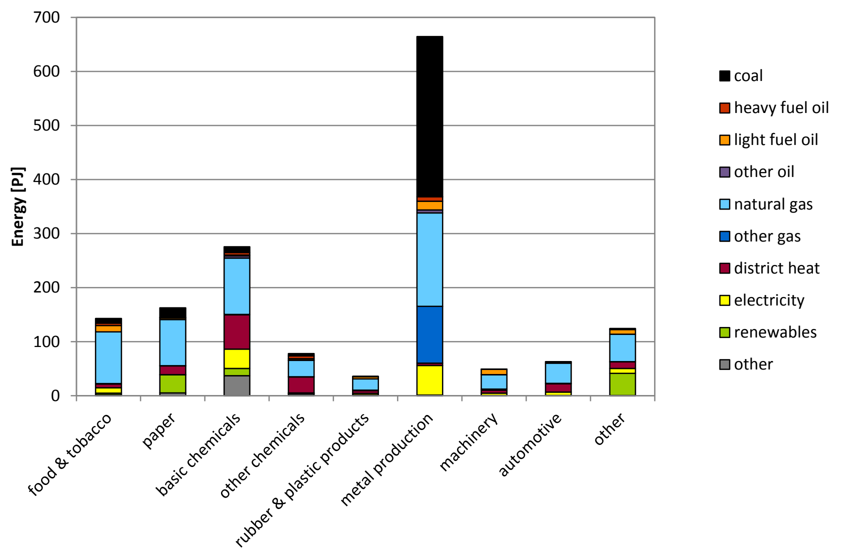

Figure 7-7: Structure of the final Energy demand for heating purposes in the German industry /AGEB 2011/

7.1.3 Industrial energy prices

As shown in Figure 7-4 the final energy demand in the German industry stayed quite constant over the last two decades. In contrast to this the energy prices for the industry have been slightly decreasing in the 1990s but started to rise in the year 2000.

Table 7-1: Development of energy prices for industry /BMWi 2012/

Final consumer prices for industry				
year	**heavy fuel oil**	**light fuel oil**	**natural gas**	**electricity**
	[ct/kWh]	[ct/kwh]	[ct/kwh]	[ct/kwh]
1991	1.04	2.07	1.47	6.91
1992	0.94	1.78	1.38	6.96
1993	0.92	1.76	1.32	7.03
1994	0.96	1.60	1.27	6.82
1995	0.97	1.52	1.27	6.74
1996	1.07	1.88	1.29	6.62
1997	1.08	1.91	1.39	6.37
1998	0.91	1.50	1.33	6.05
1999	1.07	1.96	1.27	5.34
2000	1.72	3.24	1.69	4.40
2001	1.53	2.97	2.14	4.89
2002	1.68	2.71	1.95	5.15
2003	1.70	2.81	2.16	5.79
2004	1.59	3.22	2.12	6.19
2005	2.21	4.32	2.46	6.76
2006	2.69	4.85	2.91	7.51
2007	2.62	4.77	2.77	7.95
2008	3.59	6.29	3.36	8.82
2009	2.78	4.16	3.15	10.04
2010	3.60	5.33	2.93	9.71

Table 7-1 lists the prices for the most important energy sources from 1991 to 2010. Compared to the base-year 1991 the electricity price decreased by 36.3% until 2000 and started to rise from this year on. In 2010 the average electricity price for industry was 9.71 ct/kWh, which was 40.6% higher than in 1991. The price increase for fossil fuels (heavy fuel oil, light fuel oil and natural gas) was significantly higher. In 2010 the price for natural gas was 2.93 ct/kWh (+99.7%), for light fuel oil 5.33 ct/kWh (+157.4%) and for heavy fuel oil 3.60 ct/kWh (+244.8%). In the same period of time the average cost of living in Germany increased by 42.6 %. The detailed development is shown in Figure 7-8. As energy prices are expected to further increase in the future, the market conditions for energy efficient heating technologies will further improve. For heat pumps however the electricity/gas price ratio is an important indicator for the economic feasibility. While gas prices increased faster than electricity prices in the past 10 years this ratio lead to an advantage for electrical heat pumps. This trend could be reversed in future due to the increased production of unconventional gas. This would result in an increased installation of conventional gas burners and gas driven heat pumps.

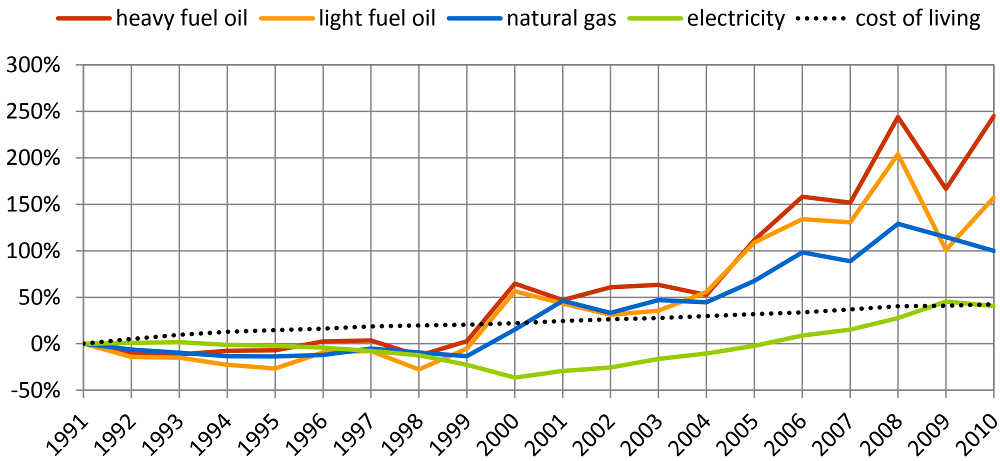

Figure 7-8: Development of energy prices for industry and general cost of living compared to the base-year 1991 /BMWi 2012/

7.2 Market overview Germany

7.2.1 German industrial sector

Although Germany is known as an industrial country with a large export of industrial products the producing sector only accounts for 24.7% (548 billion €) of the German GDP of 2,296 billion € in 2010. As shown in Figure 7-9, the service sector takes the biggest share of the German economy. Germany's export strategy and the resulting trade surplus of 128 billion € in 2010, however, are mainly driven by the producing sector.

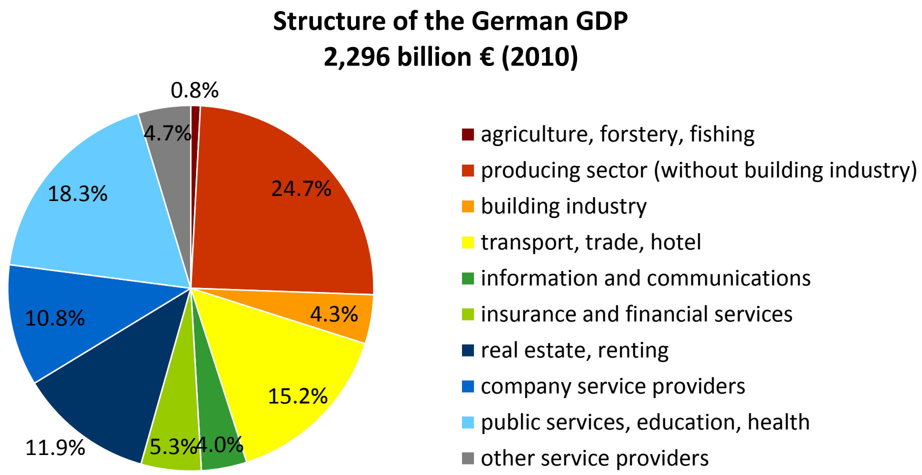

Figure 7-9: Structure of the German GDP in 2010 /Statistisches Bundesamt 2012/

The German economy is characterized by a large number of small and medium sized enterprises (SME). SMEs are defined as companies with less than 250 employees and not more than 50 million € annual turnover. All following data is taken from the year 2009, as newer statistics were not available. 99.5 % of all German enterprises fulfill the requirements of the SME definition. They account for 37.8 % of the total turnover of all German enterprises. In total SMEs employ 55.1 % of all employees in German enterprises /IfM 2011/.

7.3 Technical potential for the use of heat pumps in the German industry

The technical potential for industrial heat pumps in Germany can be derived by analyzing the heat demand of the most promising industrial sectors and the typically used processes.

Table 7-2 shows the technical potential broken down to industrial sectors and temperature levels. Data from this table is displayed in form of bar charts in Figure 7-10 Machinery, automotive, food and chemical industry show a high potential at lower temperatures up to 80 °C. These temperatures can be delivered by heat pumps using conventional refrigerants. The overall potential up to 80 °C amounts to 271.65 PJ/a, which equals 14.4 % of the industrial heat demand. When it comes to high temperature heat pumps, which operate at temperatures up to 140 °C, a great increase of the potential can be seen in food, paper and chemical industry. The technical potential for all industrial heating purposes up to 140 °C is 598.82 PJ/a. This is 31.8 % of the industrial heat demand and 23.6 % of the total final energy demand in the German industry. Figure 7-10 clearly shows a big potential for the use of high temperature heat pumps in food, chemical and paper industry. The mayor part of this potential is needed for pasteurization, sterilization, drying and thickening in the food industry, for dyeing fabrics and condensation of viscose fabrics in textile industry and for melting of polyethylene and the production of rubber in the chemical industry /Blesl et al. 2012/.

Table 7-2: Technical potential for industrial heat pumps in Germany /Blesl et al. 2012/

	hot water	space heating	PH 70 °C	additional PH 80 °C	additional PH 100 °C	additional PH 140 °C
	PJ/a	PJ/a	PJ/a	PJ/a	PJ/a	PJ/a
Food	7.72	21.19	8.28	8.11	15.26	84.64
Textiles	0.42	6.74	1.98	0.24	1.46	4.55
Wood	0.18	1.45	5.41	0.00	0.00	0.70
Paper	0.38	9.89	3.85	0.00	124.04	0.00
Printing	0.31	6.66	0.00	0.00	0.00	0.00
Chemicals	1.80	21.92	8.35	2.21	11.98	84.53
Plastic	0.49	8.85	14.86	0.00	0.00	0.00
Machinery	3.25	49.23	0.00	0.00	0.00	0.00
Automotive	2.28	29.70	7.15	0.00	0.00	0.03
Other	1.68	36.37	0.72	0.00	0.00	0.00
Sum	**18.51**	**192.00**	**50.58**	**10.56**	**152.74**	**174.44**

PH = process heat

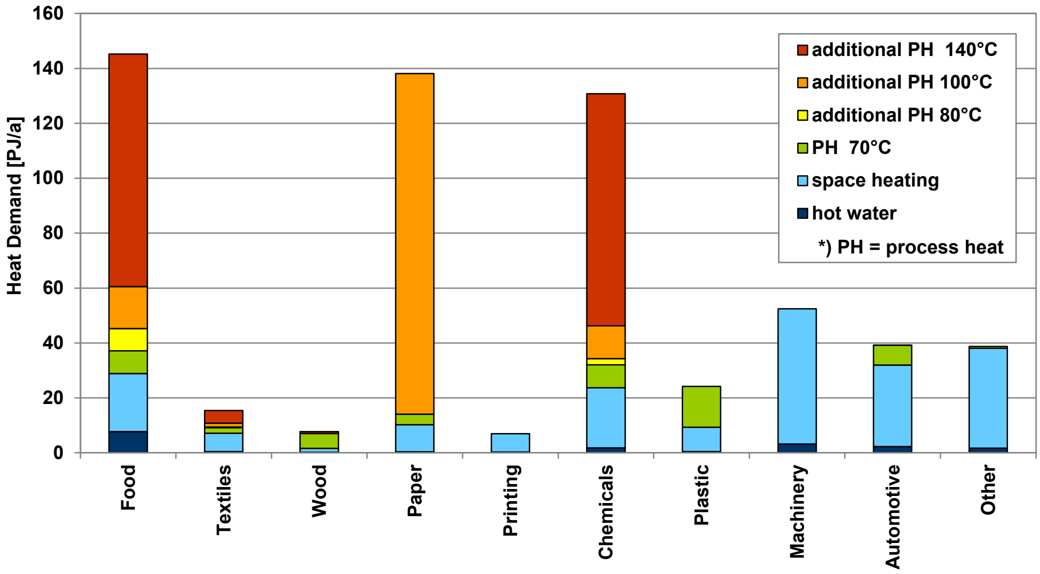

Figure 7-10: Technical potential for industrial heat pumps in Germany /Blesl et al. 2012/

7.4 German heat pump market

In Germany heat pumps are already widely used in the residential sector. Especially new buildings are often equipped with heat pumps. In 2010 612,500 heater units for residential heating were sold in Germany (Figure 7-11). Although gas fired boilers are still the most common heater type, heat pumps are increasing their market share. This lead to 51,000 sold heat pumps in 2010 and 57,000 in 2011. Half of them used ambient air as heat source.

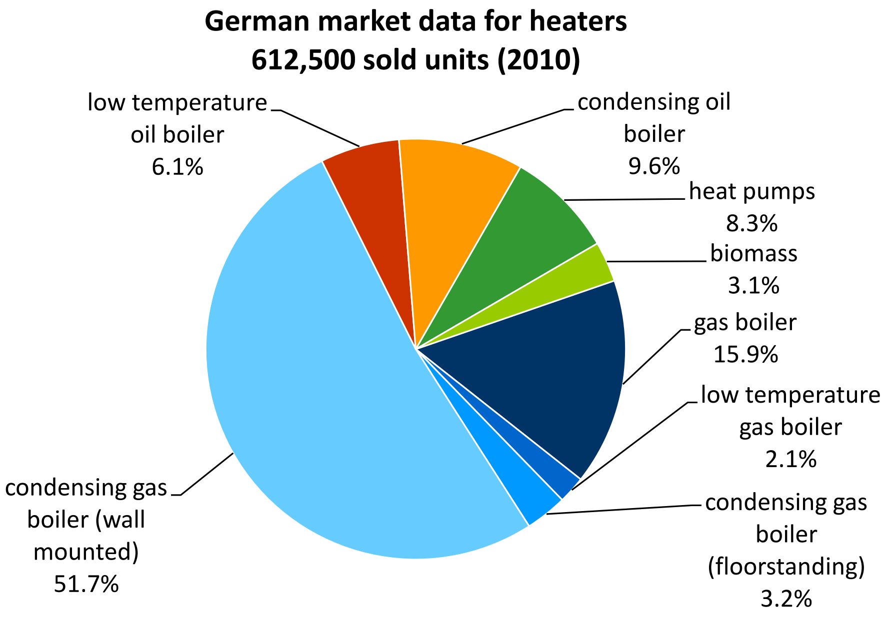

Figure 7-11: German market data for sold heater units in 2010 /BDH 2011/

Industrial heat pumps recently became available on the German market. These heat pumps not only have more power, they can also reach higher temperature levels than the models designed for the residential sector. Three different heat pump concepts using different refrigerants are available.

- Ammonia: Electrical compression heat pumps using ammonia can reach temperatures up to 90 °C.
- R245fa: Compression heat pumps using R245fa or mixtures of this refrigerant with similar properties can reach temperatures up to 100 °C.

  Current research projects aim to reach higher temperatures up to 130 °C.
- CO_2: CO2 heat pumps are especially efficient, if they are used to heat up water from a low to a high temperature level. They can reach temperatures up to 90 °C. Temperatures up to 130 °C could be available in the near future.

To distinguish the situation of heat pump planners and installers a survey has been conducted among 149 German companies. These companies were elected for the survey, if they mentioned industrial customers as well as heat pumps on their web sites. The survey was conducted in two steps. In the first step all of the 149 companies were called. Those who did not want to answer the questions on the telephone and those who could not be reached got an e-mail with information about the project and a link to a web based questionnaire. Out of 149 companies 25 filled out the questionnaire, which leads to a response rate of nearly 17 %. Figure 7-12 shows the response to the survey structured by telephone calls and e-mails.

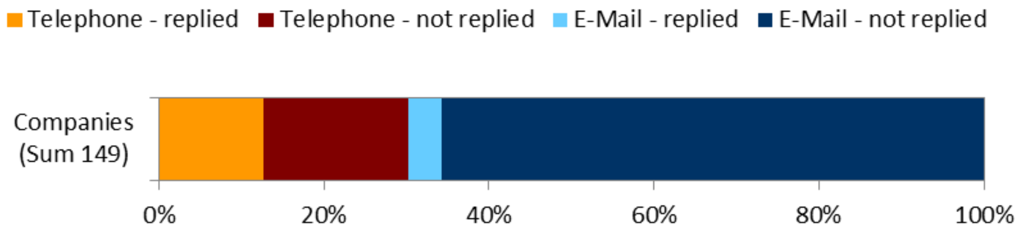

Figure 7-12: Respondents to the survey

Almost all of the respondents (96%) are experienced in planning of electrical heat pumps and 28% have experience with gas-engine heat pumps. No respondent had planned or installed a sorption heat pump.
As private households are the main application area for heat pumps most of the respondents had experience with heat pump systems for space heating (96%) and hot water production (84%). 16% had planned or installed a heat pump for process heat production. But in half of the cases the companies categorized hot water production in industrial companies as process heat.

In line with these results heat pumps are mainly applied for low temperature purposes. While 88% of the respondents had gathered experience with temperature levels of up to 55 °C, only 60 % had ever used heat pumps that could deliver up to 75°C. Only one respondent had planned ammonia heat pumps that could deliver up to 90°C.

Even though there is a large number of companies that only offer heat pump systems with small sizes of below 50 kW, 20 % of the respondents offer very large systems with more than 800 kW. Figure 7-13 shows the sizes offered by the responding companies.

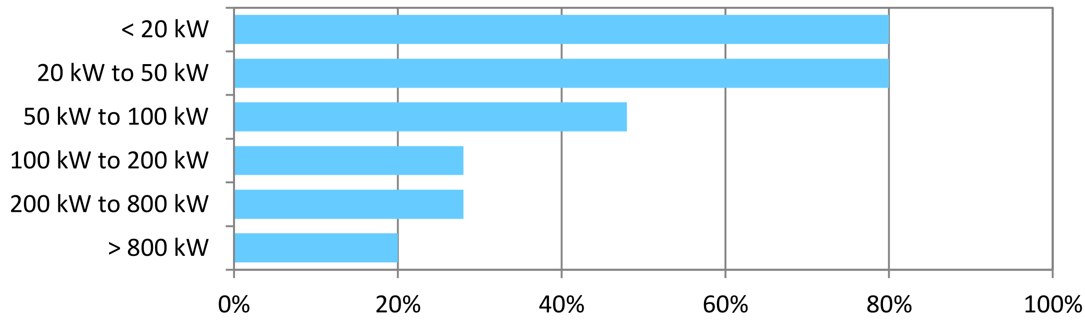

Figure 7-13: Heat pump sizes offered by the responding companies

7.5 Research and Literature

The oil price shock in the 1970s put energy research into political focus. The sudden rise of energy prices lead to a boom of energy related research. Energy research groups were founded and a large number of projects were started. Among other energy saving technologies the heat pump experienced a considerable increase of interest. Figure 7-14 shows the number of heat pump research projects that were funded by different German ministries. It also shows the amount of money invested into heat pump research from 1974 to 2011. Starting with a large number of projects in the 1970s the interest into heat pump technology peaked in the early 1980s. In 1981 funding of heat pump research reached an all-time high of 6.76 million €. With declining energy prices in the 1980s and 1990s heat pumps got out of focus. Since 2008 a growing number of heat pump research projects can be observed. Also the amount of money invested into heat pump research rose to 5.12 million € in 2011 and will continue to rise in 2012.

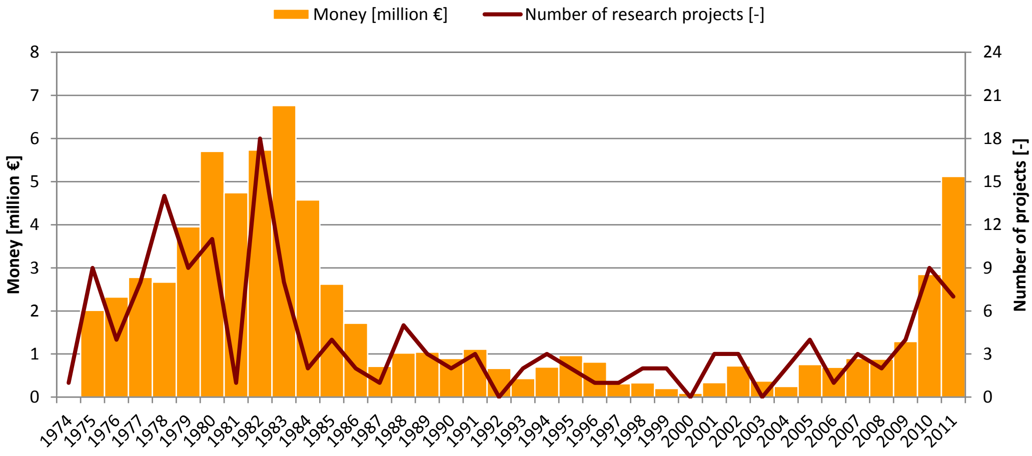

Figure 7-14: Heat pump related research projects in Germany /BMBF 2012/

To document the direct and indirect output of these research projects the amount of available literature about industrial heat pumps in German and English was analyzed. The analysis was performed by a search in the scientific search engine google scholar which can search a multitude of scientific databases. The search was performed for the terms “industrial + heat pump”, “high temperature + heat pump” and “heat pump + process heat” as well as for the German translations “Industrie + Wärmepumpe”, “Hochtemperatur + Wärmepumpe” and “Wärmepumpe + Prozesswärme”. The results of this analysis are shown in Figure 7-15 and Figure 7-16. All search terms show a rising number of publications especially since the late 1990s. In 2010 121 new publications could be found that fitted the term “Industrie Wärmepumpe”. For the English term 2350 new publications could be noted in 2010 and 2780 in 2011.

Of course the amount of available articles is overlaid with the development of the internet, but this effect should have been shrinking in the last 5 years, while a growing increase in the number of new publications can still be noted. Therefore it can be concluded that with the number of research projects also the available scientific information about heat pumps has been growing rapidly in recent years.

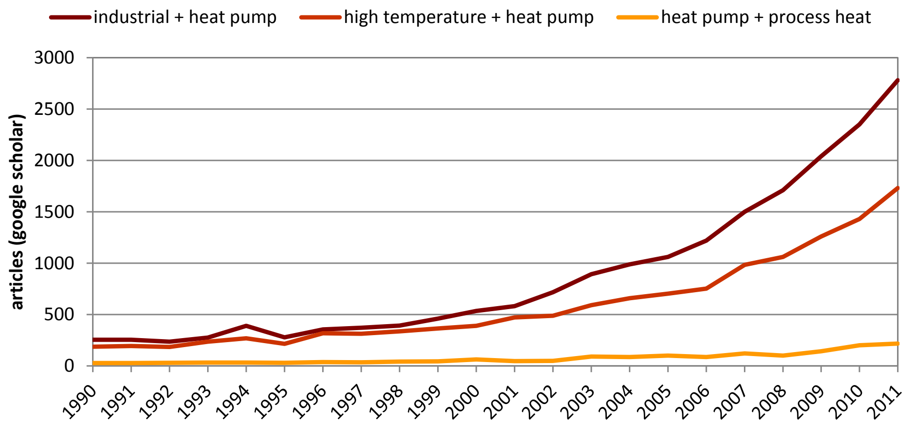

Figure 7-15: Scientific search results for industrial heat pumps (English)

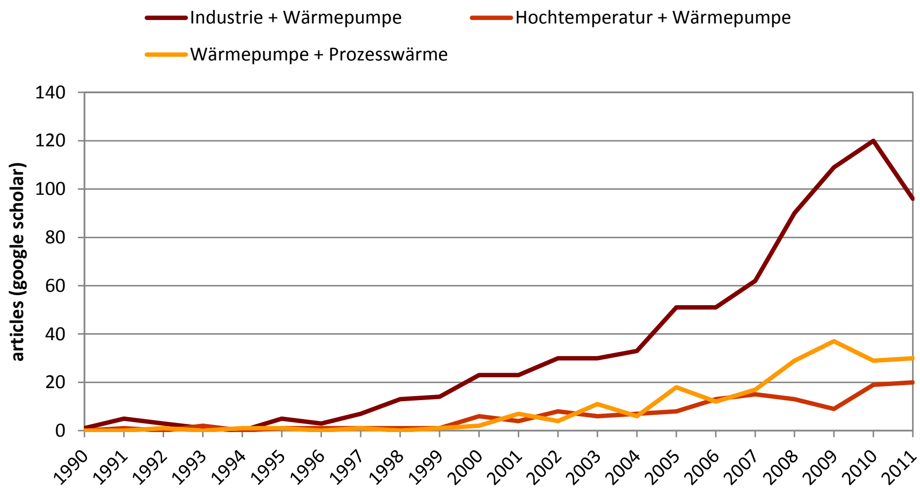

Figure 7-16: Scientific search results for industrial heat pumps (German)

7.6 Barriers for the application of heat pumps in the industry

Although heat pumps for the industrial use became available on the German market in recent years, just very few carried out applications can be found. To distinguish the reasons for this situation, application barriers were also a part of the survey mentioned in paragraph 7.4. Its results are in line with another survey from 2008 /Lambauer et al. 2008/. Four major barriers could be identified.

- Lack of knowledge:
  The integration of heat pumps into industrial processes requires knowledge of the capabilities of industrial heat pumps, as well as knowledge about the process itself. Only few installers have this combined knowledge, which enables them to integrate a heat pump in the most suitable way.
- Long payback periods:
  Compared to oil and gas burners, heat pumps have relatively high investment costs. At the same time companies expect very low payback periods of less than 2 or 3 years. Some companies were willing to accept payback periods up to 5 years, when it comes to investments into their energy infrastructure. To meet these expectations heat pumps need to have long running periods and good COPs to become economical feasible.
- Customer concerns:
  Installers named customer concerns as one of the most important barriers. They mostly prefer well proven gas or oil burner, as the heat production is a very sensible part of the factory infrastructure. As long as documented successful applications of industrial heat pumps are very rare, it will be difficult to persuade these customers to choose a heat pump.
- Low awareness of heat consumption in companies:
  In most companies knowledge about heating and cooling demands of their processes is quite rare. This requires expensive and time consuming measurements to find an integration opportunity for an industrial heat pump

Another reason for the poor diffusion of heat pumps into the industrial heating market can be found in the fact, that achievable temperatures were limited to 80 °C. As seen in Figure 7-10 just a little share of the industrial heat demand is needed at such low temperature levels.

7.7 Literature

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8 Japan

8.1 Energy use in Japan

8.1.1 Outline of Energy Situation in Japan

The primary energy consumption in Japan is 4.4% of world energy consumption. Energy supplied is highly dependent on fossil fuels such as oil, natural gas and coal. The share of fossil fuels is 84.0% of the total energy supply in 2009FY. Oil accounts for 45.8% of the primary energy supplied to Japan. Although this percentage has been declining from 77% in the peak year of 1973, the share is still the largest among all energy sources. About 96% of the energy resources supplied in Japan are imported from oversees.

Table 8-1: Primary energy supply by energy source (Japan 2009 FY)

Energy source	Primary energy [PJ]	[%]
Oil	9,866	45.8
Coal	4,452	20.7
Natural gas	3,778	17.5
Nuclear	2,465	11.4
Hydroelectricity	710	3.3
Other	280	1.3
Total	21,550	100

Other: Geothermal, Wind, Solar, Biomass, etc.

(Source: EDMC energy and economics statistics handbook, 2011)

The primary energy supplied is mainly used to produce oil products and electricity. Their shares of final energy consumption are 53.3 and 25.4 % in 2009 FY, respectively. Electricity is superior to an energy carrier. The electricity consumption has been increasing in use of heating as well as mechanical power, lighting, air conditioning and information & communication. The electrification rates are 19, 44 and 47% for industry, residential and commercial sectors, respectively.

Table 8-2: Final energy consumption by energy source (Japan 2009 FY)

Energy source	Final energy[PJ]	[%]
Oil products	7,355	53.3
Natural gas and town gas	1,351	9.8
Coal	591	4.3
Coal products	851	6.2
Electricity	3499	25.4
Other	143	1.0
Total	13,790	100

(Source: EDMC energy and economics statistics handbook, 2011)

Energy consumption in Japan can be divided into three sectors of industry, residential & commercial and transport sectors. The relative proportions of industry: commercial &

residential: transport are changed to 1.8:1.2:1 in 2009 FY from 4:1:1 at the time of the oil crises in 1970s.

Table 8-3 indicates final energy consumption by sector in 2009 FY. Although the energy demand of an industrial sector has been decreasing since 1980s, its demand is still dominant by 45.6 % of the total demand. The shares of commercial & residential and transportation sectors are 28.0 and 25.0 %, respectively.

Table 8-3: Final energy consumption by sector (Japan 2009 FY)

Sector	Final energy [PJ]	[%]
Industry	6,293	45.6
Transportation	3,451	25.0
Residential	2,161	15.7
Commercial	1,695	12.3
Non- energy	189	1.4
Total	13,790	100

(Source: EDMC energy and economics statistics handbook, 2011)

8.1.2 Energy use in the manufacturing industry

Manufacturing industry accounts for 94.3% of the industry sector. Energy consumption of manufacturing industry increased only slightly, despite the fact that its economic scale more than doubled after the first oil embargo in 1973. This is caused mainly by the improvement of energy efficiency and the structural change from the primary & secondary industry to the tertiary industry in the sector. Although four sectors of the manufacturing industry, namely iron/steel, chemical, ceramic/stone/clay and pulp/paper/processed paper continue to account for about 70% of the energy consumption of the manufacturing industry as a whole, their share is slightly declining due partly to energy saving in the industry.

Table 8-4: Energy use in the industry (Japan 2009FY)

Industry	Consumption[PJ]	[%]
[Manufacturing]	5,933	94.3
Iron & steel	1,508	(24.0)
Chemical	2,077	(33.0)
Ceramic, stone & clay	373	(5.9)
Food, beverages & tobacco	234	(3.7)
pulp, paper & processed paper	306	(4.9)
Fabricated textiles	74	(1.2)
Non-ferrous metal	131	(2.1)
Metal goods & general machine	414	(6.6)
Other	816	(13.0)
[Non-manufacturing]	360	5.7
Total	6,293	100

(Source: EDMC energy and economics statistics handbook, 2011)

Energy of the manufacturing industry is consumed for different types of use. Figure 8-1 indicates different types of use such as boiler, direct heating, cogeneration and others in the manufacturing industry. Direct heating is the largest amount of demand accounting for 56 % of the total demand. Including the amount of boiler use, both demands reach 90 % as a whole.

Iron & steel is a predominant sector to consume the direct heating energy, over 60% of the total direct heating demand. Chemical, petro-refinery and pulp/paper/processed paper sectors follow it.

As for fuel demand of the boiler, pulp/paper/processed paper and chemical sectors consume over 50% of the demand. Subsequently it is in order of steel product, oil/coal product and foodstuffs manufacturing industries.

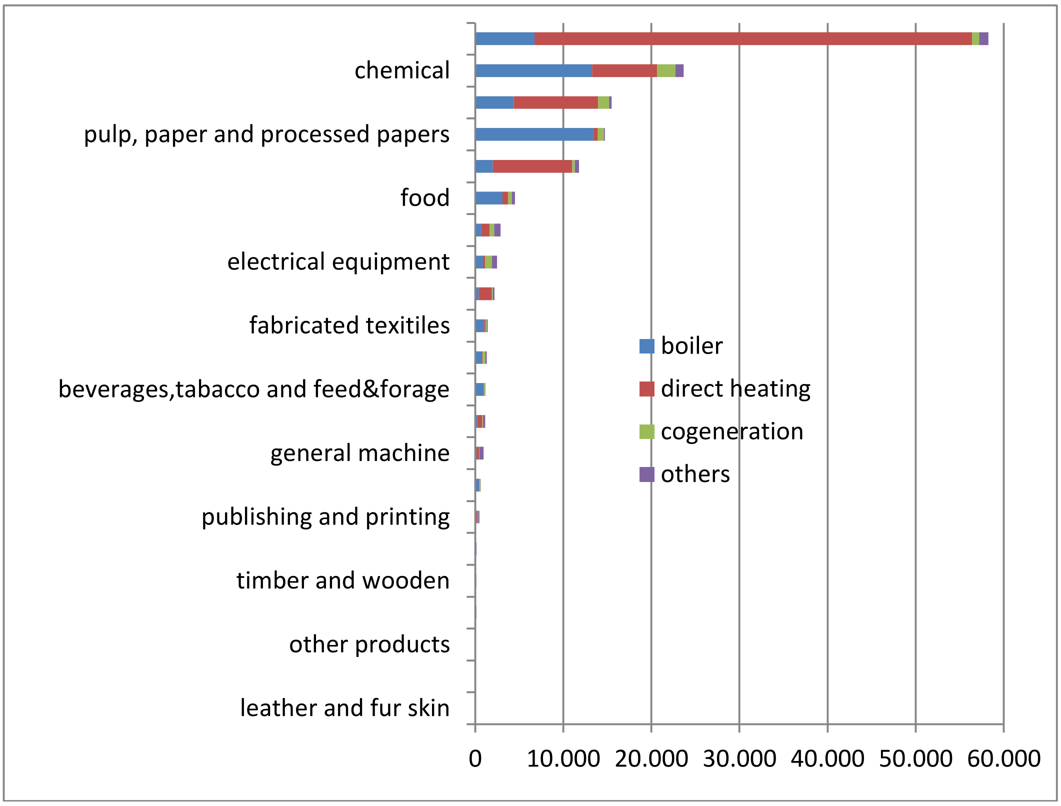

Figure 8-1: Type of energy use by sector in manufacturing industry
(million liter in oil equivalent; 2001 FY)

(Source: The structural survey of energy consumption in commerce and manufacturing, Research and Statistics Department, Ministry of Economy, Trade and Industry, 2001)

Heat produced by industrial boiler is used in various temperature ranges. Figure 8-2 shows heat demand of industrial boiler in different temperature in the manufacturing industry. Heat demands account for over 80 % in process heating over 250 °C and 17 % in the range of 150 to 200 °C, respectively. They are consumed mainly in chemical, pulp/paper/processed paper, steel and petro-refinery sectors.

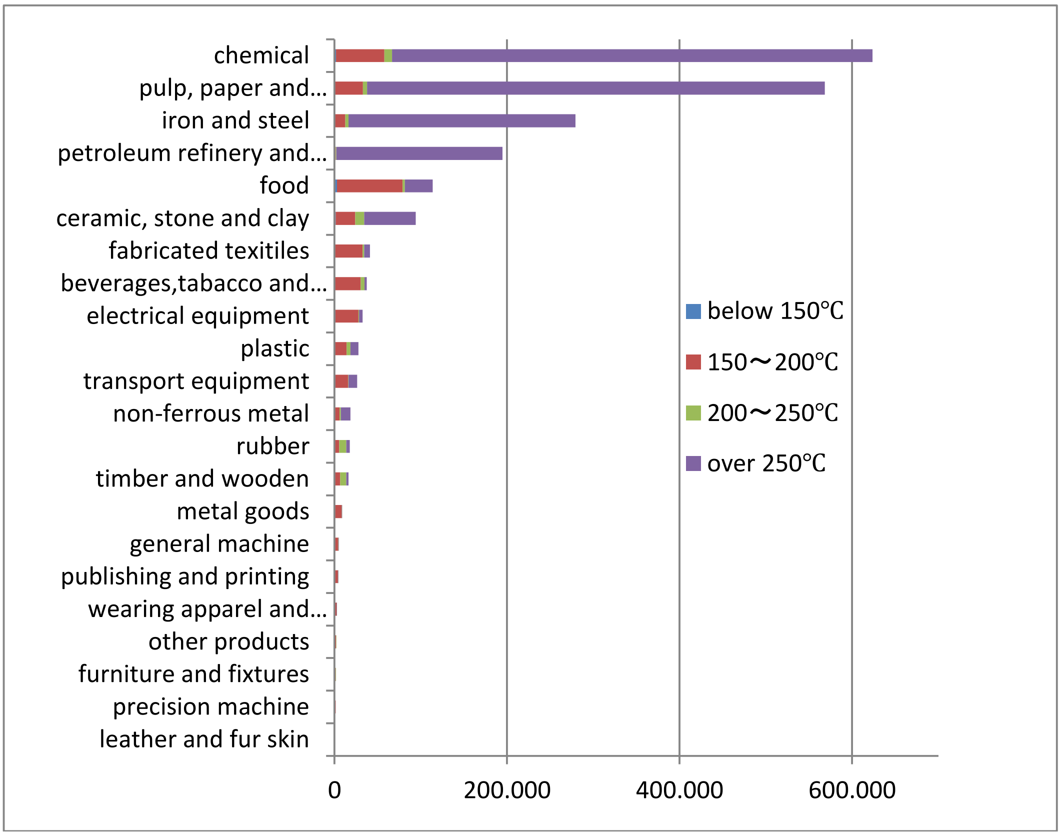

Figure 8-2: Boiler demand in different range of temperature by sector for the manufacturing industry (TJ; 2001 FY)

(Source: The structural survey of energy consumption in commerce and manufacturing, Research and Statistics Department, Ministry of Economy, Trade and Industry, 2001)

Figure 8-3 shows type of use for electricity consumption by industrial sector.

Iron & steel is a predominant sector to consume the direct heating energy, over 60% of the total direct heating demand. Chemical, petro-refinery and pulp/paper/processed paper sectors follow it.

Iron/steel, chemical, electrical equipment and pulp/paper/processed paper consume over 50% of the demand. Subsequently it is in order of steel product, oil/coal product and foodstuffs manufacturing industries.

84% of the total electricity is consumed in the power demand. Heating demand of electricity is rather small, 11% of the total electricity demand in industry. The share of electricity heating is expected to increase from the current tendency of electrification promoted by technological progress of injecting heat and industrial heat pump as well as environmental issues of preventing global warming.

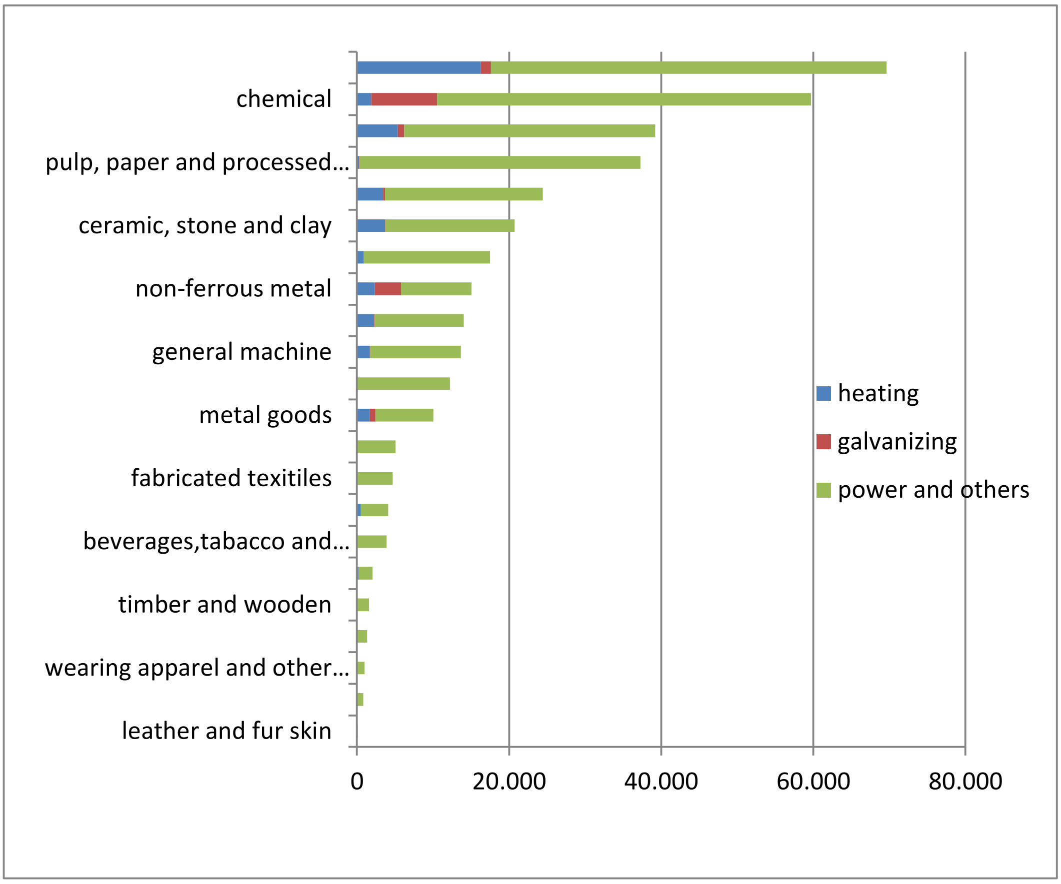

Figure 8-3: Type of electricity use by sector in the manufacturing industry (GWh; 2001 FY)

(Source: The structural survey of energy consumption in commerce and manufacturing, Research and Statistics Department, Ministry of Economy, Trade and Industry, 2001)

8.2 Japan Market overview

Heat pumps are adopted in greenhouse horticulture, hydroponic culture, plant factories and so on in Japanese prime industry. We can see improvements in quality of agricultural production, yield ratio and year-round cultivation thanks to the introduction of heat pumps. They are also used for drying process of agricultural, fishery and lumber products by cooling, dehumidification and heating function.

Cool and warm heat is used for aquaculture while a cooling seawater system is used for preservation of freshness and shipment of live fish in fishery sector. Refrigerating systems have been used for refrigerated warehouses located both at harvesting and consuming places for a long time.

Heat pumps are widely used from heating and cooling to washing in food processing plants. It is noteworthy that they have a heat-up and cool-down process repeatedly and this is the very process that heat pumps are able to show their strength and provide heat in the most effective way. We have been developing equipment that are able to produce water in suitable condition for food processing between 5 to 10 °C and around

90 °C at the same time. In addition, equipment with ability of producing around 100 °C water and steam are under development.

When it comes to air conditioners, especially air conditioners in factories, centrifugal type and high efficient heat pump chillers have been occupied much larger market share than conventional absorption chillers which use steam as heat sources. This is because technology innovation in recent years has made it possible to raise their COP. Improvements can be seen in humidifying of clean rooms and pure water heating in water production.

In machinery plants, some conventional steam-sourced systems are replaced by heat pump systems for heating in degreasing and chemical treatments. Heat pump systems with ability to heat cleaning solution and cutting liquid simultaneously have been put in practice.

Heat pumps have developed to comply with high temperatures of 120 °Celsius for coating and drying process. VRC is increasing at beer factories for molt boiling and alcohol distilling processes.

8.3 Barriers for applications

1. Higher efficiency
   Equipment with complying between 60 and 90 °C are thought to have the largest demand for industrial use and heat pump equipment are already in operation. However, heat pumps are less competitive in terms of an initial cost compared with boiler type systems. Therefore, we need to develop higher efficient equipment so that heat pumps can be competitive in terms of lifetime cost.

2. Extending adaptability for various heat sources and demands in plant
   We need to extend a temperature range of heat sources which are able to apply to daily dispatching of variable energy demand. For example, we would be able to extract refrigerated waste heat from cooling tower, high temperature heat from waste gas and heat from waste and pouring water. We need to develop an integrated technology that can extract heat from those potential heat sources by combined with heat pump systems so that we can control/adjust both the temperatures of heat source and output heat.

3. Higher temperature
   To meet requirements for higher temperatures over 100 °C, we hope to develop new technologies that produce super heated steam, pressurized water, hot air as well as new refrigerants with high condensing temperature, a new heat pump cycle and an oil-less compressor.

4. Air source heat pumps applying to old latitudes
   Although air source heat pumps are expected to be one of solutions that are available regardless of location and time, we still have room for improvements such as an application to cold latitudes and a temperature drop when defrosting.
5. Competitiveness in costs

High temperature heat pumps are more expensive than conventional air conditioning heat pumps. It is needed to reduce an initial cost by standardization, mass-production or use of simple components in accordance with temperature zones.

6. Variety of production menus
   Cool and warm heat are constantly required in relatively small scale of food processing plants. Heat sources should be spread out in those plants. We need to have production menus with small capacities for them. While many industrial sectors request the development of a high temperature heat pump which covers a wide range of temperature zones of large compressors and heat exchangers.

9 Korea

9.1 Energy consumption in Korea

9.1.1 Outline of Energy Use in Korea

The primary energy consumption of Korea is 2.3 % of world energy consumption in 2011. The total amount of the primary energy supply in Korea on 2012 is 11,669 PJ (278.7 million TOE). The total amount of energy is about 96 % of domestic energy demand is fulfilled with imported resources. Four major sources of coal, petroleum, LNG and nuclear energy occupy 96.6% of the primary energy supply in Figure 9-1.

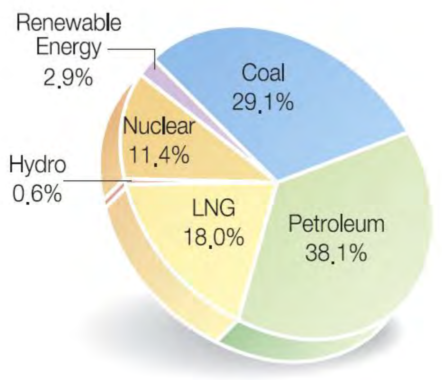

Figure 9-1: Primary energy supply by source (Korea 2012 FY)

Figure 9-2 shows the final energy consumption of Korea in 2012. Considering the fossil fuels are imported in the form of raw resources, the final energy consumption is less 25% than the primary energy, where the amount is estimated to be 8,712 PJ (208.1 million TOE). More than 60 % of coal and all the nuclear resource are converted into electric energy as a final form.

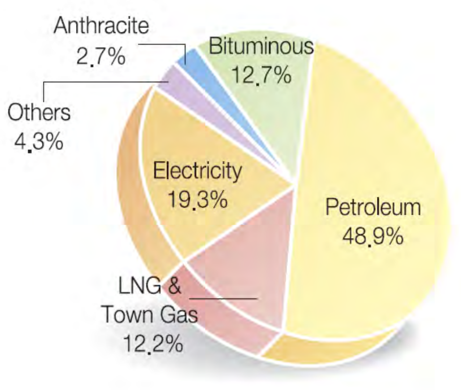

Figure 9-2: Final energy consumption (Korea 2012 FY)

Figure 9-3 shows the final energy consumption by four major sectors in Korea 2012 FY. Figure 9-4 presents annual change of energy consumption by sector. The growth of industrial sector is a major part of which portion increased from 53.7 % (1992, 2,128 PJ), 55.6 % (2002, 3,735 PJ), to 61.7 % (2012, 5,373 PJ).

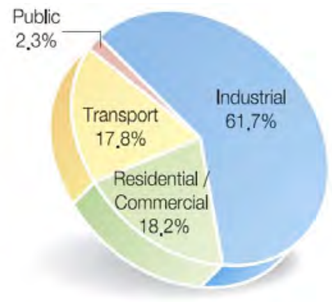

Figure 9-3: Final energy consumption by sector

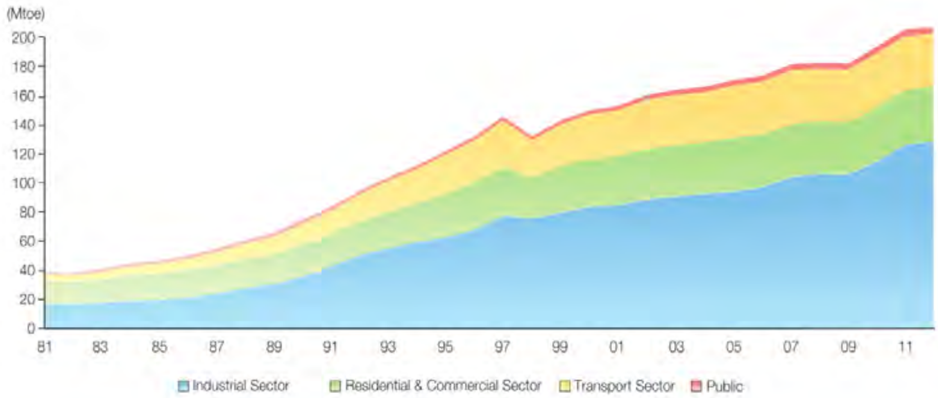

Figure 9-4: Annual history of final energy consumption by sector

(Source: 2013 Energy Info. Korea, Korea Energy Economics Institute)

Table 9-1**Fehler! Verweisquelle konnte nicht gefunden werden.** presents the distribution of the total energy use for the different sectors. The energy use of energy companies relates to the conversion losses that occur during for example the production of electricity from natural gas or coal. The refining sector is included in the manufacturing industry.

Table 9-1: Energy consumption by sector in 2012

Sector	PJ
Industry	5373
Residential & Commercial	1586
Transport	1555
Public & others	200
Total	8714

9.1.2 Energy use in the manufacturing industry

The Korean industry consists of four sectors; agricultural and fishery, mining, manufacturing, and construction. And 5,373 PJ of energy were consumed in 2012. Renewable energy of 243 PJ is included in the total industrial energy consumption, but is unclassified into subsectors. Excluding non-manufacturing sector, the amount is reduced as 87 %, 4,688 PJ. The balance of the different energy carriers in the manufacturing industry is shown in Table 9-2.

Table 9-2: Energy carriers of industrial sector in 2012

	Coal	Oil	LNG	Electric	Total(PJ)
Manufacturing	1,104	2,308	427	848	4,688
Food. Tobacco	1	7	29	35	73
Textile & Apparel	4	5	24	46	79
Wood & Wood Prod.	0	1	2	6	9
Pulp & Publications	0	4	18	36	58
Petro. Chemical	6	2,155	105	182	2,447
Non-Metallic	119	26	24	39	209
Iron & Steel	923	6	72	164	1,165
Non-Ferrous	0	2	10	0	13
Fabricated Metal	0	25	69	330	424
Other Manufact.	51	44	74	9	178
Other Energy	0	32	0	0	32
Non-manufacturing	199	193	0	49	243
Total	1,104	2,501	427	897	5,373

(Source: Yearbook of Energy Statistics (2013), Korea Energy Economics Institute)

The energy utilization by application in the manufacturing industry is shown inTable 9-3. The heat energy in the table includes both 69% of direct heating and 31% of indirect heating. Conversion loss was estimated about 514 PJ by subtracting total energy consumption out of the total energy supply.

Table 9-3: Energy consumption in manufacturing industry by functions in 2010

Function	PJ	[%]
Heat	1,312	29.1
Power	398	8.8
Feedstock	2,574	57.2
Miscellaneous	216	4.8
Total	4,501	100

Manufacturing industry in Korea is devided into 15 sectors. The type of energy utilization in each sector is as feedstock, by facilities, for transportation, and others. Table 9-4 is energy consumption by subsectors of manufacturing industry in 2010.

Table 9-4: Energy consumption by subsectors of manufacturing industry (Units in 100 ton in oil equivalent; 2010 FY)

Industrial sectors	Feed-stock	Facilities				Trans-port	Miscell.	Total
		IDH	DH	Power	Electro-chemical			
Food products	2	5,804	3,032	1,932	125	137	1,281	12,311
Beverage		1,236	488	400	15	8.2	213	2,359
Tobacco		169	26	69	2.2		8.8	276
Textile		2,966	3,624	2,237	68	94	1,024	10,014
Wearing apparel & fur articles		68	38	14	5.1	18	108	251
Leather, luggage & footwear	0.4	100	57	49	6.1	13	33	258
Wood and cork	0.1	1,774	465	269	84	45	147	2,783
Pulp & paper products	2.2	7,400	7,811	4,394	67	59	1,043	20,776
Printing and recorded media		32	213	91	1.6	10	119	467
Coke and refined petroleum	254,541	18,320	45,103	16,222	1.8	6.8	292	334,486
- Coke and Briquettes	0.6	2.3	6.8	12		1.1	5.6	29
- Refined petroleum product	254,540	18,318	45,096	16,210	1.8	5.6	286	334,457
Chemical products	186,485	39,095	40,181	22,589	3,175	119	18,601	310,244
- Basic Chemicals	148,346	23,396	24,745	14,925	2,773	28	13,058	227,270
- Fertilizer	0.7	110	174	219	32	12	79	626
- Rubber and Plastic	38,116	12,796	12,451	5,210	133	21	4,735	73,461
- Other chemical products	23	1,089	1,430	1,126	53	23	583	4,327
- Man-made fibers		1,704	1,309	1,109	186	35	146	4,487
Medical products		430	278	386	17	4.2	144	1,259
- Medicinal chemicals		56	78	57	6.2	0.7	19	216
- Medicaments		366	176	312	10	2.4	114	981
- Pharmaceutical goods		7.9	24	17	0.6	1.1	11	62
Rubber and Plastic	3.2	3,158	2,656	2,631	287	167	1,383	10,284
Non-metallic products	514	3,239	41,667	5,284	603	437	2,230	53,974
- Glass		2,027	4,834	965	479	15	215	8,535
- Ceramic ware	1.3	124	2,241	288	36	8.1	137	2,835
- Cement	507	921	33,800	3,589	53	351	1,627	40,848
- Other non-metallic	5.0	166	791	443	35	64	251	1,755
Basic metallic products	173,192	4,618	26,493	15,674	6,000	106	11,394	237,476
- Iron and steel	173,079	1,580	18,822	13,736	3,581	62	10,616	221,477
- Non-ferrous metals	87	2,947	6,601	1,128	1,818	22	436	13,038
- Cast	26	91	1,070	810	601	22	343	2,961
Fabricated metal products	10	641	4,632	3,336	818	367	1,902	11,706
Electronic manufracturing	0.1	4,462	12,324	9,606	1,923	68	2,962	31,346
Precision industry		14	216	277	17	26	240	790
Electric equipment		525	1,367	733	320	99	581	3,625
Other machinery and equip-ment	6.3	658	1,886	1,705	349	348	1,062	6,013
Motor vehicles	31	2,166	6,217	4,971	524	125	2,735	16,769
Other transport equipment	0.9	282	1,620	1,410	171	62	631	4,176
Furniture		24	226	285	13	24	149	721
Other manufacturing		162	461	357	71	14	417	1,481
Total	614,786	97,342	201,078	94,921	14,665	2,355	48,696	1,073,843

(Source: Energy consumption survey 2011, Korea Energy Economics Institute)

Since heat and power is mostly supplied by facilities, energy consumption by direct heat and indirect heat and power except by electrochemical facilities is shown in Figure 9-5.

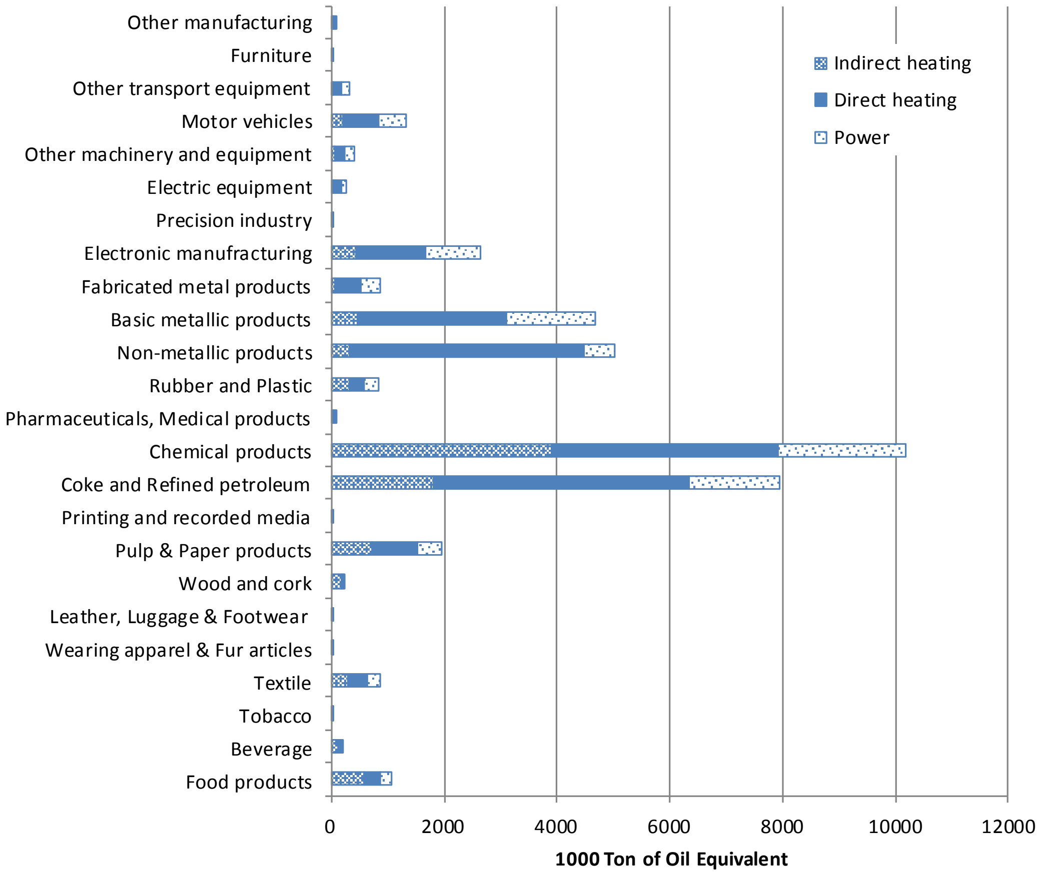

Figure 9-5: Annual history of final energy consumption by sector

9.2 Heat Pump Market of Korea

9.2.1 Market share of heat pumps

Due to its high energy-saving potential, the global heat pump market has grown rapidly in recent years. Korea strives on efforts to spread the utilization of heat pump systems, but still lags behind in market development. Table 9-5 shows the shipments of residential cooling-only air conditioners and heat pumps. As of 2010, compared to the 1.224 million cooling-only units, only 0.157 million heat pumps were sold for other applications, amounting to an 11 % market share. Various market features have contributed to the low share of heat pumps.

Table 9-5: Shipment of residential air-to-air heat pumps and cooling-only air conditioners (thousand units)

Year	Cooling only	Heat pumps
2005	1494	42
2006	1495	45
2007	1138	52
2008	1261	65
2009	1025	89
2010	1224	157

(Source: KEMCO 2011 Report)

9.2.2 Barriers for applications

From the former report on Korea market, two unique features of the Korean market are mentioned: high penetration of natural gas, and low energy prices. In 2010, the nation-wide penetration rate of natural gas in the residential sector was 72.2 %. The Seoul Special City, which is the capital and largest metropolis of Korea, had a 92.3 % penetration rate. Other major cities also have penetration rates approaching 90 %. These high numbers reflect the fact that almost every resident in the city uses natural gas, either for heating or cooling – with boilers, rather than heat pumps, taking by far the largest share.

Table 9-6 shows the retail energy prices of natural gas and electricity from IEA 2012 Key World Energy Statistics. Among the selected OECD countries, Korea has the lowest energy prices, even considering the GPD (PPP) per capita (Table 9-6). The price of electricity for domestic consumers is, for example, only 43 % of that paid by UK domestic consumers. Low energy prices make customers more sensitive to the initial cost than to the running cost. Due to Korea's preference for floor heating, boilers are typically installed in houses for domestic hot water production. Since boilers are far cheaper than water-heating heat pumps, the payback time of a heat pump is longer than in other countries. In addition, heat pumps are usually regarded as appliances, in the same way as are air conditioners. This makes it more difficult for the concept of payback to be considered by customers.

Table 9-6: The retail prices of natural gas and electricity in OECD countries

Retail prices ($)	Finland	Germany	Ireland	Korea	New Zealand	Poland	Spain	United Kingdom
Nat. gas for industry (MWh), GCV	45.19	54.37	43.91	60.21	23.76	42.57	37.72	35.51
Nat. gas for domestic consumers (MWh), GCV	62.18	92.63	80.65	64.98	102.43	72.2	89.27	64.84
Electricity for industry (MWh)	113.64	157.23	152.39	(61.94)	73.72	121.77	148.77	127.39
Electricity for domestic consumers (MWh)	213.61	351.95	259.47	88.64	212.1	198.5	295.31	204.92

(Source: IEA 2012 Key World Energy Statistics)

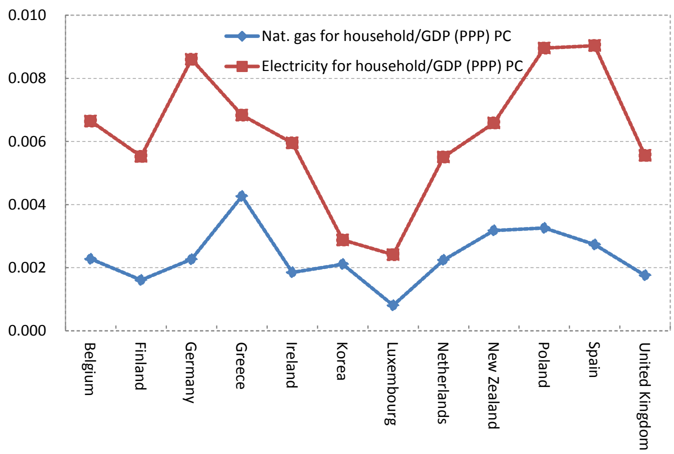

Figure 9-6: The retail prices of natural gas and electricity for domestic consumers divided by GDP (PPP) per capita

9.2.3 Potentials of heat pump applications

Despite the adverse market conditions for heat pumps, there is no doubt that they are energy-saving devices and one of the promising solutions for tackling energy problems. Although the situation is not favourable to heat pump market, some efforts to seek the possibilities to apply heat pumps to industrial applications relying on the low electricity price. Considering longer operating time of industrial heat pumps, the customers in industrial field find good economy of heat pump system.

Aside to these efforts, the Korean government supports measures to improve energy efficiency and the use of new renewable energy sources because it considers them as key players to achieve its goal of Green Growth with Low CO_2. On the government's road map to Green Energy, heat pumps were selected as one of the 15 green energy sectors to increase energy efficiency. KETEP (Korea Institute Energy Technology Evaluation and Planning) selected four heat pump systems in its Green Energy Strategy Road Map 2011, and has supported their technical development, which it hopes will create a new heat pump market in Korea.

9.3 Literature

[1] Korea Energy Economics Institute, "Energy Info. Korea", December 2013.

[2] Korea Energy Economics Institute, "Yearbook of Energy Statistics", Vol. 32, December 2013.

[3] Ministry of Knowledge Economy, "Energy Consumption Survey" – 11th Edition, 2011.

[4] M. Kim, G. Lee, B.-J. Shin, 2013, The heat pump market and its potential in Korea, IEA Heat Pump Centre Newsletter, Vol. 31, No. 4, pp. 10-12.

[5] Korea Energy Management Corporation, Annual Report 2011

[6] IEA, 2012 Key World Energy Statistics.

10 The Netherlands

Industrial processes in general need higher temperature levels. Recent developments of heat pumps focus on higher delivery temperatures of heat and a high temperature lift (difference between low (source) and high (delivery) temperature). Another trend is that industrial production processes require lower temperatures for heating. Application of heat pumps may therefore grow in the near future and contribute to further CO_2 emission reduction.

Bottle necks for this growth form the unfamiliarity with heat pumps of engineers and process designers, the complex level of integration of the installation in existing plants, the high investment costs, some experiences with unreliability in old projects, lack of references and lack of knowledge of the new higher temperature options. For successful introduction of high temperature heat pumps in industry bundling and distribution of knowledge is of importance. Process designers, engineers, consultants, contractors and end users need to be familiar with the heat pump technology, the possibilities, the advantages, good references and being aware of the do's and don'ts.

In a study by KWA commissioned by AgNL [Pennartz, 2011] the following subjects are described:

- an overview of the heat pumps options in various industrial sectors and energy consumption
- recent technological developments around industrial heat pumps after 2000
- a number of cases studies of industrial heat pumps after 2000.

10.1 Energy use in manufacturing industry

The energy balance of the Netherlands is shown in the Table 10-1 (left). The table depicts the net balance per energy carriers. Table 10-1 (right) presents the distribution of the energy use in the different sectors. The energy use of energy companies relates to the conversion losses that occur during, for example, the production of electricity from natural gas or coal. The refining sector is included in the manufacturing industry.

Table 10-1: Energy balance in the Netherlands (left)
distribution of energy use (right)

Energy Carrier	**PJ**
Oil	1221
Natural Gas	1435
Coal	328
Electricity	88
Misc	163
Total	**3235**

Sector	**PJ**
Energy Companies	431
Industry	1344
Transport	500
Residential Buildings	412
Commercial Buildings	546
Total	**3233**

The main industrial sector in the Netherlands is the chemical industry located in some concentrated areas around the Rotterdam harbor. The other main industrial sectors are food industry and the greenhouse sector. Manufacturing industry used 1344 PJ in 2006.

The energy carriers that are used by industry serve different functions (heat, power, feedstock). Table 10-2 presents the energy use by these functions for the different industrial sectors. Power relates to the energy use for driving machines or lighting. Feedstock is the so-called non-energetic energy use, where the energy carrier is used to make a product, like plastics and petrol. The conversion loss refers to the losses that occur in decentralized electricity production by industry (combined heat and power).

Table 10-2: Primary Energy use in Dutch industrial sectors

	Heat (PJ)	Power (PJ)	Feedstock (PJ)	Conversion loss (PJ)	Total (PJ)
Food & drug industry	62.8	24.8	0.2	3.7	91.5
Textile industry	3.3	1.4	0	0	4.7
Paper & board industry	24.7	13.3	0	3.7	41.7
Chemical industry	261	36	455	21	773
Refining	116	9.6	0	62.1	188
Building materials	26.8	5.2	0.1	0.1	32.2
Basic metal industry	38	12.6	73.3	13.6	138
Metal products	19.0	15.9	15.5	0	50.4
Rubber & plastic products	7.7	9.4	0	0	17.3
Other	0	0	7.6	0	7.6
Total	559	128	552	105	1344

Table 10-3: Temperature levels of heat demand

Interval	Chemical + Refining (%)	Basic metal + metal products (%)	Other (%)
< 100°C	5	15	29
100-250°C	11	0	38
250-500°C	27	5	13
500-750°C	21	0	0
750-1000°C	26	10	0
> 1000°C	10	70	20

10.2 Market overview

Potentially large energy savings are possible through the application of heat pumps in the industry. Developing and dissemination of knowledge is important for successful growth of the application of heat pumps. To stimulate the application of heat pumps it is useful to analyze heat pumps which have been placed in the past and analyze how they operate in practice. Over the past 20 years there were several feasibility studies and heat pump projects supported by the TIEB and SPIRIT programs of Novem (the predecessor of RVO) which were reported upon.

Table 10-4: Overview of older heat pump projects

Factsheet	Company old/new name	location	process	Condition
	Oriental Foods	Landgraaf	Drying of Tahoe	Company closed
	Plukon	Asten Ommel	Slaughterhouse	Feasibility only
	Solphay/Dishman	Veenendaal	MDR on Aceton	End of production
	Purac Biochem	Gorinchem	MDR on lactose	End of production in NL
	Hartman/Jardin	Enschede	Garden furniture	Feasibility only
	ITB		Plastics	Feasibility only
	Quality Pack	Kampen	Crate washing	Company closed
	Beukema/Eska Graphic Board	Hoogezand	Paper drying	Feasibility only
	Huwa Bricks factory	Spijk	Brick drying	Feasibility only
	Frico	Sint Nicolaasga	Cheese evaporative drying	Company closed
	Hoogovens/Tata steel	IJmuiden	Heat Transformer	Corrosion problems
	ARCO/Lyondell	Botlek	MDR on Distillation	no data available
NL-01	Shell	Pernis	MDR on Distillation	running
NL-02	Unichema/Croda	Gouda	MDR on Distillation	running
NL-03	Hoechst	Vlissingen	MDR on Distillation	End of production in NL
NL-04	Campina	Veghel	MDR on evaporation	running
NL-05	De Graafstroom	Bleskensgraaf	MDR on evaporation	running
NL-11	Dommelsch Brewery	Dommelen	MDR on wort	running
NL-13	GPS	Nunspeet	Heating from condensor	running
NL-15	AVEBE	Ter Apelkanaal	MVR on patatoe starch	running
NL-16	Cerestar/Cargill	Sas van Gent	MVR on	replaced by new MVR
NL-17	Fapona/Berendsen	Apeldoorn	Laundry drying	running

A study has been undertaken to look into the operation of these "older" projects looking into the experiences of the companies, if there have been any changes of the design over time, whether operating & maintenance of the installation is difficult (high level of knowledge, complexity, etc.), if promised energy savings are achieved and whether there are remarks which can be defined as lessons learned.

All companies described participated in this evaluation study. Striking is that those projects described as case and feasibility studies supported by governmental subsidies (TIEB) were never realized, despite the fact that acceptable payback periods and significant energy savings were calculated in these studies. For the other projects much has changed in the past twenty years like plant closures, moving production, no demand for the product, changes in operations, etc. As a result six of the analyzed heat pumps have been removed nothing to do with any possible malfunction of the heat pumps.

Of the eleven remaining heat pumps, ten are still in use. These are eight Mechanical Vapour Recompressors (MVR), one Thermal Vapour Recompressor (TVR) and one heat pump, which uses the heat from the condenser of the refrigeration installation for process heat. Most of these are now described in new factsheets in Task 4. Only one company was not participating with new data.

Companies with a running heat pump have generally no idea why a heat pump was chosen, given the long period since the investment decision. Most of the heat pumps still run according to their original design having relatively high operating hours (5,000-8,000 hours/year) and mostly in full load. In several cases the maintenance is outsourced for reasons of complexity, high operating hours and capacity problems in the technical department. Operating the installation is generally regarded as a relatively simple. The installations have few problems and/or malfunctions. Companies have no insight on whether the system achieves its efficiency, or whether the intended energy savings have been obtained. They have no reference, given the initial situation.

- When a steam-powered evaporation process is switched to an MVR, which is electrically powered, it must be taken into account that the ratio between heat and electricity demand shifts towards electricity. This is unfavorable for the use of gas turbines, when a company has these in use.
- A point of interest for heat pump installations which processes polluted water is that the heat exchangers require relatively high-maintenance when they have to process large quantities of polluted water.
- An additional advantage of a TVR, or a MVR is that these systems reduce the emission of odors, since all vapors are condensed.

The heat pumps generally run satisfactorily, this study provides no indications to suggest that there are major risks associated with the use of heat pumps in industrial environments.

After a long period of 'silence' there seems to be renewed interest in the market since 2010, resulting in a fast increasing number of applications. A number of new Industrial Heat Pumps have been installed resulting in a long list of projects. These projects are described in fact sheets under Task 4.

10.3 Barriers and trends

Knowledge of heat pumping technologies is an important building stone in further increasing the heat efficiency of industrial processes. But knowledge is not the final piece but it's only the beginning of a whole transition process. Companies have a lot of options for energy conservation and generation and decision space, which can lead to taking no explicit decision. The challenge is to organize competition among technology solutions that leads to more explicit decision making. Decisions on applications of heat pumps are made in competition with investments on other technologies or in other parts of the industrial process.

Until recently heat in many industrial sectors has been by-product of electricity from cogeneration and therewith heat had a low economic value. Cogeneration has been a very 'hot' technological solution in the past decades for quick gains in energy conservation. Due to the strong competition from cogeneration in industry as a heat source only a few heat pumps were installed in the past 15 years, except for vapour recompression in distillation columns. In addition compression heat pumps were not suitable for temperature levels higher than 80 °C. Nowadays there a number of developments which widens the opportunities for industrial heat pumps:

- Due to the decline of the so-called spark spread, the difference in operating costs between CHP and heat pumps are considerably narrowed. It is to be expected that a lot of CHP-installations after depreciation will not be replaced. Paper and Pulp industry being an example. In those cases, there is more attention to the internal use of process heat and thus for heat pumps.
- By using other than the traditional working fluids for refrigeration and new technologies heat pumps can lift to reach 120 °C;

- Through the use of so-called "temperature glides" the heat / electricity ratio (COP) is significantly improved.
- The introduction of chillers with an additional compression step, which are perfect for the heating of hot water or cleaning process.
- The early development of acoustic and thermochemical heat pumps and heat transformers the path towards even higher temperature ranges up to 250 °C.

These technological developments do not or barely reach industry. In addition, heat pump suppliers generally have a backlog by the negative experiences in the commercial and domestic building sector.

An important aspect also is that heat pump suppliers, knowing the possibilities of alternatives, are in most cases the last link in the supply chain, where consultants and installers often lack the knowledge in finding good economic solutions. An important issue therefore is how technology suppliers, technical personnel and management, that takes the investment decision, communicate with each other. It is the experience that management is less interested in the technical side and much more in solutions for the company. Newly developed heat pump technology has been analysed in four major business cases in chemical industry. The experience gained here leads to the conclusion that more is needed than knowledge on technology only. A ‘technology marketing’ process is needed to be able to discuss on the same level as industrial management decision making. Knowledge, skills and competence have to be developed in that process. The approach is further discussed in Task 5.

10.4 Heat pump potential

In the Netherlands heat pumps of different types can be applied in all levels of industry ranging from bulk distillation in chemical industry to the level of milk processing at the farm or growing tomatoes in greenhouses and steam production in paper and pulp. In every application, even for domestic buildings, the approach will have to be based upon the Trias Energetica in industry a systematic approach in improving the energy efficiency of industrial processes is the onion-model developed in industrial heat technology.

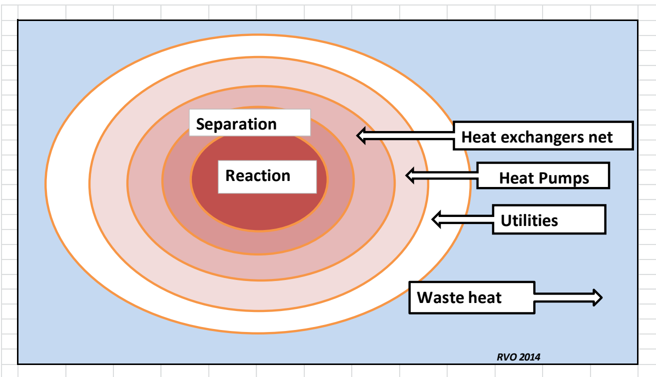

Figure 10-1: Onion model for energy efficiency improvement [Reissner, 2013]

This model will be discussed further in Task 2.

10.4.1 Chemical industry – distillation

(by D. Bruinsma and S. Spoelstra)[Bruinsma, 2011]

Distillation is the main separation technology in refineries and the chemical process industry, because of the attractive purification characteristics, the high production capacity and turndown ratio, and the straightforward design procedures. More sophisticated techniques have become state of the art to handle streams with less favorable thermodynamic properties, in particular small relative volatilities and azeotropic mixtures. The high energy demand in bulk distillation columns (1-100 MW) and the low thermodynamic efficiency (5-10%) remain the major drawbacks. A number of improvements have been developed over the years directed at reducing both operating and capital cost.

In extractive distillation (ED) a solvent or separating agent is added in order to increase the relative volatility of the components to be separated. In azeotropic extractive distillation the separating agent is used to break the azeotrope. As a consequence the reflux ratio, column diameter and reboiler duty can be reduced and/or the column height can be lower. Commercial low volatility solvents include sulfolane, triethylene glycol (TEG), NMP and NFM. The recovery cost of the solvent is an integral part of the economy of extractive distillation processes. ED is particularly effective for relative volatilities below 1.2. Industrial examples of ED processes are purification of aromatics in petro chemistry, butadiene recovery in naphtha cracking and separation of cycloparaffins from naphtha.

Instead of affecting the thermodynamics of the system also selection of the column internals is a way to increase distillation efficiency. Random and structured packings with specific surface areas from 250 up to 900 m^2/m^3 are continuously being improved with the objective to optimize stage height, pressure drop, liquid load, and turn down ratio. The main recent advancements in tray columns focus on high-capacity trays with centrifugal devices or structured packing demisters although at the cost of an increased pressure drop.

Since the 1980's dividing wall columns (DWC's) have been introduced which allow the separation of three component feeds in a single column leading to interesting reductions in both energy consumption and investment cost. Recently even more complex DWC's have been constructed to separate four component mixtures in pure products.

In contrast to improvements of the VLE or the column internals, both inside the column, a number of energy reducing measures can be considered outside the column by addressing the reboiler and condenser. These include side reboilers, dephlegmators and heat pumps. Side reboilers use waste heat at a lower temperature than the bottom reboiler and thus increase the exergetic efficiency. Dephlegmators or reflux condensers are compact heat exchangers, such as PFHE's, used to reduce energy consumption in low temperature gas separations. Heat pumps lift the temperature level of the top vapor in order to use this as the heat source for the reboiler.

Heat pumps for distillation purposes can be divided in three types: mechanically driven, heat driven and heat transformers. Mechanically driven heat pumps can be found, among others, in the following types:

- Vapor recompression heat pump (VC)

- Mechanical vapor compression heat pump - Subcritical and Trans critical (MVR)
- Thermal Vapor Recompression HP (TVR):
- Compression-resorption heat pump (CRHP)
- Absorption heat pump (AbHP) and Adsorption heat pump (AdHP)
- Thermo acoustic heat pump - linear motor driven (THP)
- Heat Integrated Distillation Column (HIDiC).

An analysis was made of distillation heat pump potential in the Netherlands, leaving out columns that do not cross the pinch and oil refinery columns. The data show that the total heat pump potential is in the order of 2.4 GW and that the average temperature lift over the column is 59 °C. These data are given in Table 10-5 (J. Cot and O.S.L. Bruinsma, Market survey, Heat pumps in bulk separation processes (2010), ECN report 7.6548.2010.0xx).

Table 10-5: Distillation in the Netherlands

Across the pinch distillation in the Netherlands

Distillation in NL	
Total $Q_{reboiler}$ (GW)	2.36
Total $Q_{condenser}$ (GW)	2.39
Average $T_{reboiler}$ (^{0}C)	128
Average $T_{condenser}$ (^{0}C)	69
Average ΔT_{column} (^{0}C)	59

Figure 10-2 represents the distribution of the reboiler duties in the Netherlands for columns with increasing temperature lift; only those columns that cross the pinch have been included.

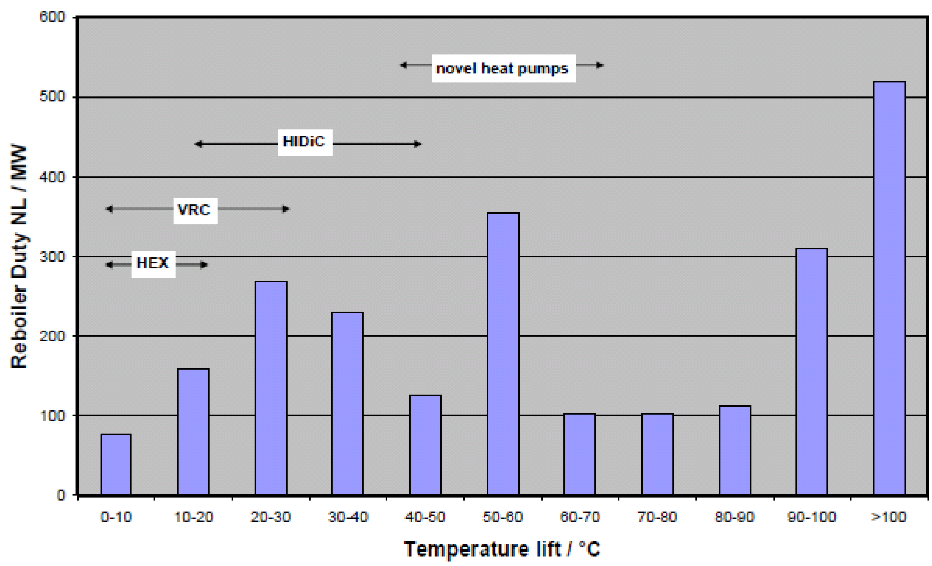

Figure 10-2: Reboiler duties for across the pinch columns in the Netherlands (2006)

In the graph four recommendation regions are identified:

- Temperature lifts below 20 °C compact heat exchangers with small ΔTHEX are crucial for the performance of the heat pump system,
- VRC's should be applied below 30 °C, which covers about 23 % of the across the pinch columns
- HIDiC's are probably interesting for temperatures in the range 15-45 °C, about 29 % of the across the pinch columns, partly overlapping with VRC but with a higher savings efficiency
- Novel heat pumps for temperature lifts of 45-70 °C, would contribute an additional 21 %.

Based on this analysis the combination of VRC, HIDiC and novel heat pumps would lead to an estimated 820 MW savings, which is almost 35 % of the reboiler duties of all across the pinch columns in the Netherlands.

10.4.2 Food industry

With an energy use of more than 62PJ in heat food industry is a large sector in Netherlands with main sub sectors: Dairy (18.0), Potatoes processing (8.7), Margarine (7.6) and Bakeries (4.8). Cooled Warehouses are a specific but important sector. Within these sectors processes like drying and cooling are the main process operations with a lot similarities in process.

Evaporators in dairy industry

The GEA handbook on Milk Powder Technology [Westergaard] states that the transforming of a liquid product into a dry powder requires means the removal of practically all water, the amount of which often exceeds the weight of the final product. During the water removal the processed product is undergoing deep changes of physical structure and appearance, starting with thin water like liquid and terminating with dry powder at the end of the process. Therefore, one single method of water removal cannot be optimal throughout the whole process, as also the product composition is different from one food product to another. In the food and dairy industry the following dehydration methods have been adopted:

- Evaporation
- Spray Drying
- Vibrating Fluid Bed Drying
- Integrated Fluid Bed Drying
- Integrated Belt Drying.

Each method should be adjusted to the properties of the processed material at each processing step. The more difficult the product, the more complex the plant.

As the development went on, the concentration was carried out in forced recirculation evaporators. In this evaporator the milk streams upwards through a number of tubes or plates. On the outside the heating medium, usually steam, is applied. The heating surface is thus increased in this system, but the evaporation surface is still limited, as the tubes and plates remain filled with product, which therefore becomes superheated in relation to the existing boiling temperature. Not until the product leaves the top of the tubes, are the vapors released and the product temperature decreases. For the separation of liquid and vapors, centrifugal separators were preferred. In order to obtain the desired degree of evaporation the product was recycled in the system. The concentration was thus controlled by the amount of concentrate discharged from the plant.

Refrigeration

An in depth study [Pennartz, 2011] has been done into the potential for heat pumps in the industrial sectors that use considerable amounts of refrigeration. Residual or waste heat available in the food sector is shown in table 1 for temperature and PJ primary energy per year. The various heat sources of the waste heat are listed in the table. Most of the waste heat is available from the condensing heat of refrigeration plants. The temperature level is between 30 °C and 40 °C. This energy source amounts to 28 PJ a year. Similarly the heat consumers have been investigated showing that 14 PJ is consumed by various processes at temperature levels between 60 °C to 110 °C. There is more residual heat available than required.

In this view, the heat demand of the food sector of 69 PJ in total can be reduced by 14 PJ by the use of high temperature add-on heat pump on refrigeration plants.

Table 10-6: Overview of available condenser heat in Dutch industry

Heat Pumps applications and potential

Sector	Total primary energy consumption (2008)	Total electrical energy consumption (2008)	Total heat (2008)	T residual heat available	Residual heat available	Delivered by:	T heat consumers	Reuse heat consumption	Consumed by:	Electricity consumption by refrigeration	Available condensing heat (T=35°C)
	PJ	PJ	PJ	°C	PJ		°C	PJ		PJprim/j	PJth/j
Sectors industry											
Cooled warehouses	2,4	2,2	0,2	35	2,8	condensers refrigeration	80/ 60	0,1	building, water	2,0	2,8
Rubber and plastic	9,6	7,4	2,2	35	1,8	cooling tower, condenser refr	80	0,1	building, rubber	0,9	1,8
Potatoes processing	8,7	2,0	6,7	30-120	4,0	eg. steam pealing, condensers refr.	70-110	1,2	pasteurizer, dryer, blancheur	1,1	1,5
Cacoa	2,3	1,1	1,2	60- 70	0,15	cocoa milling	120	0,25	preheating air for drying	0,1	0,2
Fruit and vegetables	2,9	1,4	1,5	70-120	0,8	condenser, blancheur, sterilizer	70-90	0,5	blancheur, building	0,4	0,6
Coffee production	0,9	0,5	0,4	30,0	0,1	condensers refrigeration	70	0,1	building	0,1	0,1
Margarine, Fats and Oils	7,6	0,8	6,8	35	0,3	condensers refrigeration	80	1,0	tank storage, pipe tracing	0,2	0,3
Meat procesing	4,3	2,8	1,5	30	1,8	condensers refrigeration	70	0,25	hot water cleaning	1,3	1,8
Dairy	18,0	5,0	13,0	40-60	2,5	bruden condensate from evaporators	90	1,8	spray dryer	1,8	3,2
Soft drinks	1,0	0,5	0,5	30	0,1	cooling section pasteurizers	80	0,1	pasteurizers	0,0	0,0
Beer industry	3,9	2,0	1,9	35, 100	1,2	condenser, wort boiling	70-110	0,6	pasteurizers, wort boiling, building	0,5	0,8
Bakeries	4,8	1,8	3,0	30, 200	0,3	condensers, flue gas oven, boilers	30-70	1,0	air preheating, builing, water, dough rising	0,9	1,4
Fish processing	0,8	0,6	0,2	30,0	0,5	condensers refrigeration	80	0,1	building, hot water	0,3	0,5
Biscuits, confectionary, chocolate, icecream	2,0	0,8	1,2	30, 200	0,6	condensers refr., ovens	60-100	0,5	pasteurizers, water, cookers, storage raw materials	0,4	0,6
Other food	69	40	29,0	30-70	9,0	various	70-90	6,0	various	8,0	12,8
Total Food	**138**	**69**	**69**		**26**			**14**		**18**	**28**
Chemical industry spcialized products	10,2	4,0	6,2	various			various			0,8	1,6
Oil and gas production	40,8	10,8	30,0	90		compression gas	80		building	1,9	3,9
Chemical industry bulk	300	75	225,0	various			various			3,0	5,4
Refining	140	24	116,0	various			various			3,6	6,5
Other industry	104	16	88,0	various			various			1,3	2,6
Total Other	**595**	**130**	**465**							**11**	**20**

The feasibility of high temperature add-on heat pumps depends on an analysis of:

- Residual heat, heat demand and electricity demand
- Energy monitoring of maximum and minimum capacities, average values, operating hours.
- Apply an integral approach, evaluate the competing technologies such as high efficient hot water boilers, combined heat and power (CHP) plants. A heat pump is more flexible than a CHP, since they are available in small sizes and can operate efficiently in part load.
- Investments, replacement of heating equipment.

From a sustainable point of view: refrigeration installations should not be installed, without the use of condensing heat (such as desuperheater heat, condensing heat at 30 °C, add on with high temperature heat pump >80 °C).

10.4.3 Paper and pulp

by [De Vries, 2012]
The pulp and paper sector is with 26 PJ a significant energy user in Netherlands and currently ranks fourth in the industrial sector for its energy use. This 26 PJ is primarily used as gas to power cogeneration systems conversing this into 17 PJ's of heat. This heat is then after being used as process heat dumped into the environment as heat from drying (11 PJ), losses from conversion (4 PJ and into the waste water (2 PJ). Energy costs in paper and pulp in the Netherlands are 15 - 35% of the variable costs of production.

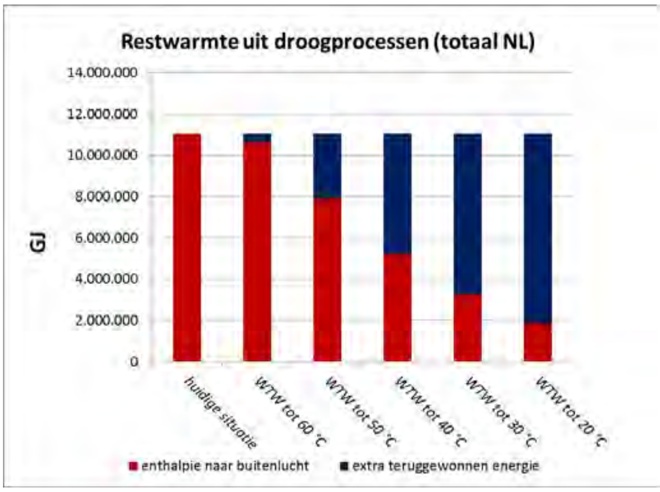

Figure 10-3: Waste heat and temperature levels in Paper and Pulp

Manufacturers have under the Multi Year Energy Agreement with the ministry of Economic Affairs constantly been working on energy efficiency for the production processes, which lead from 1990 onwards to the wide spread application of cogeneration. Several studies have been executed in the nineties of last century to find the right solution for the application of heat pumps, but due to the low costs of process heat an economical investment was not feasible. Due to the decline of the so-called spark spread, the difference in operating costs between CHP and heat pumps are considerably narrowed. It is to be expected that a lot of CHP-installations after depreciation will not be replaced. In those cases, there is more attention to the internal use of process heat and thus for heat pumps. A first R&D project has in 2013 lead to a 250kW's pilot project with a high temperature heat pump producing steam at 120 °C re-using the waste heat from the drying section. This option at this moment seems only viable for larger paper & pulp industries. According to the CEPI statistics (2012) there are in Europe some 350 paper industries of the size.

There are various possibilities to recover thermal energy from steam and waste heat in the paper drying process. These include:

- Mechanical vapor recompression and reuse of the superheated steam in the drying process;

- Use of heat pumps to recover waste heat;
- Recovering heat from the ventilation air of the drying section and using this heat for the heating of the facilities when needed.

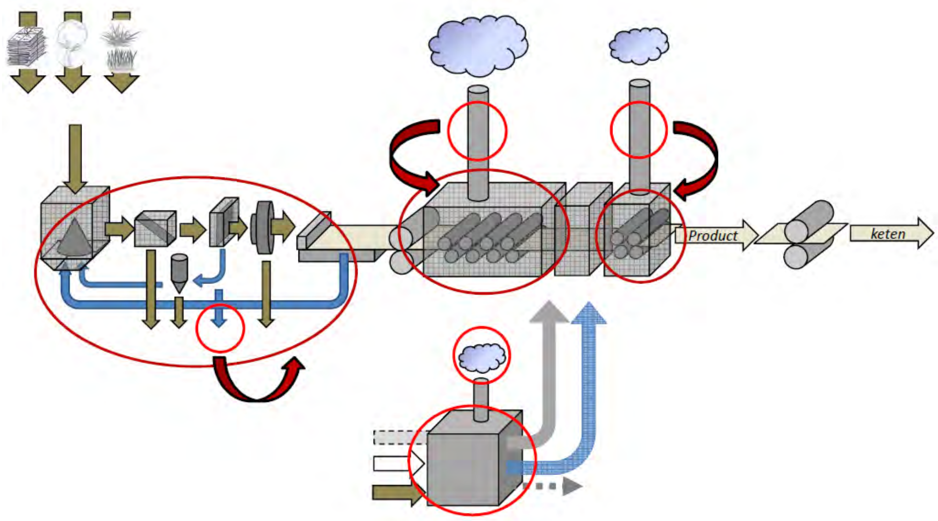

Figure 10-4: Waste heat streams that can be used (source KCPK [de Vries, 2012])

The challenge is to find the right solutions to re-use the in the process. As paper and pulp processes are rather big the best option is to re-use the heat close to where the waste heat appears.

10.4.4 Miscellaneous industrial areas

***(see www.energiezuinigebedrijventerreinen.nl*)** [Energie]

There is small success with energy conservation and the application of renewable energy at industrial areas for mixed/miscellaneous use. This is remarkable as there are many economical options for renewables and conservation. Where heat pumps in Netherlands are state of the art in commercial buildings this is not yet the case at these mixed industrial areas.

The overall energy use on existing areas with a size of 10 - 50 ha is 170 PJ which is 6% of the overall Dutch energy use. With a conservative estimate that there is potential for energy conservation of 30 – 40% this sums up to 60 PJ [6]. On the positive side is that there are good examples with new developments where renewable energy and energy conservation are basic boundary conditions to fulfill when a company considers to settle in that area. These boundary conditions are set by local governments. Of these area three examples are:

- 15 ha Kolksluis near Zijpe where heat pumps combined with a collective ATES are the main technologies
- Ecofactorij near Apeldoorn which is discussed in a factsheet under Task4
- Trompet near Heemskerk.

In the development of a new area it is of importance to develop the planning process at a very early stage and to attract companies by giving bonuses and over a long period never to depart from the goals of the planning for the area.

For existing industrial areas it is part of the renovation process which is challenging and with some small successes. Examples are given in some factsheets under Task 4.

10.4.5 Agriculture

Agriculture in Netherlands covers a large area from mushroom growth, 'bollenteelt', pig and chicken farms, dairy farming, cheese making and greenhouses. The major energy user in this segment are the greenhouses. Even for low energy growths heat pumps can give primary energy savings up to 35% [Ruiter, 2011]. In the period 2003-2013 approximately 40 growers of various crops have implemented heat pumps in their greenhouses. They comprise the following crops:

- Roses (2x)
- Tomatoes (3x);
- Orchids (Phalaenopsis) (8x);
- Freesia (2x);
- Anthurium (2x).

Recently the experience have been analyzed [Geelen, 2013] showing considerable difference with the well-established market of commercial buildings. The already installed heat pumps are 'traditional' applications. As in Paper & Pulp industry the greenhouse sector has in the past decades massively invested in cogeneration which now gets into economic problems due to negative spark spread.

By combining electric drive heat pumps with cogeneration more heat is generated and less electricity is produced for the power grid. This increases the flexibility in operational management of the energy system[26]. Heat storage as well co-producing for neighboring greenhouses and prediction of weather can lead to efficiency in management. A system is described in a factsheet.

Dairy Farmers

As an average Dairy Farms use 5,000 m^3 gas and 35,000 kWh of electricity. If all 17,500 Dairy Farms in Netherlands would adopt the ECO 200 system with heat pumps using the heat extracted from the milk storage it would give a saving up to 2PJ's. Campina Melkunie the large Dairy industry focuses strongly on these possibilities in order to get the complete chain from cow to end user of milk and cheese at a level of energy neutral. In all individual chains heat pumps are a key technology.

[26] a solution which is not possible with Paper & Pulp as these cogen systems in this sector normally are built with over capacity of heat

10.5 Manufacturers and suppliers in Netherlands

The market for industrial heat pumps is for an important part derived and developed from the market of industrial cooling and refrigeration. These manufacturers and suppliers are gradually 'discovering' the market of heating in industrial processes, but also in other markets. With their profound knowledge of thermodynamics they are developing and applying new innovative products in a fast growing market.

Compressor technology being the core of the technology with one main well established manufacturer Grasso from Den Bosch, part of GEA. The other manufacturers and suppliers in Netherlands use components from Grasso and other suppliers to create and build innovative and outstanding products. Some of the products are standardized and some of the suppliers make tailor made solutions. Many of these have applications in all different sectors ranging from industry to greenhouses, skating rings and commercial office buildings.

Figure 10-5: Grasso FX P heat pump

- **Grasso. Grenco** (www.grasso.nl), old established company and manufacturer of screw and piston compressors of different sizes. Factories in Den Bosch (NL) and Berlin (D). Under the GEA group also active in several industrial sectors with MVR compressors. The Dutch division is typically a department derived from refrigeration having developed the add-on heat pump for which they got the NVKL-Award in 2012, with an example project at Wiseman Dairies in UK.

- **IBK-Refrigeration** (www.ibkgroep.nl) from Houten, as the name suggests are specialists in refrigeration but at the same time supplying innovative heat pump concepts. IBK Refrigeration is part of the IBK-group. The first add-on heat pump was built at Unilever in Rotterdam (factsheet NL 08). Another interesting application is in ice skating rinks (factsheet NL 29). In a further development IBK is now involved in a pilot of e high temperature heat pump in paper and pulp industry, for which they got the NVKL-Award 2014.

Figure 10-6: NVKL-Trofee 2014

- **Energie Totaal Projecten** (ETP – www.etp.tv) from Dordrecht is a company delivering overall projects from engineering, design, financing, servicing and maintenance including performance guarantees for all sectors with larger systems. Their main markets are in commercial buildings and greenhouses. Based upon a chiller from international high standard they have developed a standardized high performance compact heat pump which is skid built. Heat pumps are standardized in sizes from 85kW to 3.8MW's. Several patents are pending on new breakthrough technologies. Example projects are under Greenhouses (NL-27).

Figure 10-7: ETP HWD-3800 skid

- **KODI** (www.kodi.nl) from Heerhugowaard started just like ETP as a consultancy and installer in commercial buildings and agriculture. Not happy with the products on the market KODI developed with a subsidy from Novem a high performance heat pump concept for greenhouses (see factsheet NL 27d). Standardized compression heat pumps based upon Grasso technology is now installed in several smaller industrial areas. KODI is also involved in projects like Kolksluis industrial area. On their site they give a long list of reference projects.

Figure 10-8: Typical KODI heat pump in Greenhouse

- **Reduses** (www.reduses.nl) from Nijkerk is part of a group of companies delivering all services from consultancy to installing, maintenance and monitoring. Installect, GeoComfort and Instead are the partners where Installect is responsible for installation and design, GeoComfort for the ground source (innovative concept of mono-source) and Instead for the monitoring and maintenance (innovative concept where monitoring is used as benchmarking between companies and as tool for maintenance). Reduses is manufacturer of gas engine driven heat pumps up to 250 kW's. The gas engine is from Volkswagen. Reduses have their own certified lab to do performance tests.

Figure 10-9: Reduses gas engine heat pump

- **De Kleijn Energy Consultants & Engineers** (www.industrialheatpumps.nl) is a consulting company in Druten with a focus on industrial projects and tailor made innovative solutions (factsheet NL 11). Their focus on industrial heat pumps is clear with their website and the recent visit by NEDO in 2014. For RVO Kleijn is executing a communication strategy on heat pumping technologies.

- NRG-TEQ (www.nrgteq.nl) from Rosmalen is a manufacturer of heat pumps in the range from 4 – 400 kW's. Until recently NRG-TEQ was only active in domestic and commercial buildings.

It is of importance to notice that next to these Dutch companies other large companies are active in this market where the local office often developers innovative applications with components from their 'mother'. Carrier from Hazerswoude, together with French office, is such an example. Their heat pumps are rather popular in greenhouses and commercial buildings.

10.6 Literature

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11 Sweden

11.1 Energy use in Sweden in 2011

The overall final energy use in Sweden redistributed by energy carrier is shown in Table 11-1:

Table 11-1: Final energy use by energy carrier in Sweden in 2011 [1]

Energy carrier	PJ	TWh
Oil	386	107
Natural gas	24	6.7
Coal	55	15
Biomass	275	76
Electricity	454	126
District heating	170	47
Total	**1364**	**379**

The overall final energy use in Sweden is dominated by electricity and fossil fuels standing for a share of about one third each. Biomass has an outstanding share of 20 % and district heating stands for the remaining 12 %.

11.1.1 Energy use in the manufacturing industry

Figure 11-1 presents the distribution of the total energy use across the different sectors in Sweden including the redistribution on energy carriers for the industry sector.

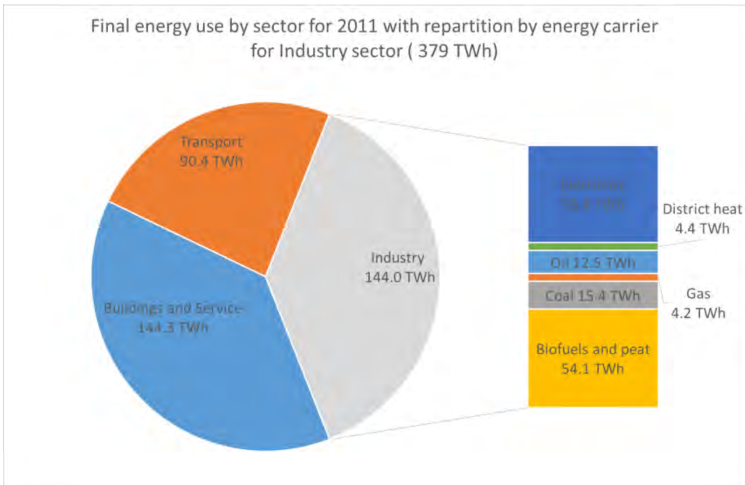

Figure 11-1: Final energy use 2011 by sector with repartition on energy carriers for the Industry sector [1].

Electricity and biofuels are the major energy carriers used in the Swedish manufacturing industry. The pulp and paper industry being one of the largest energy users mainly consumes biofuels (spent liquors to a large extent) whereas the iron and steel sector largely depend on electricity and coal (for coking processes).

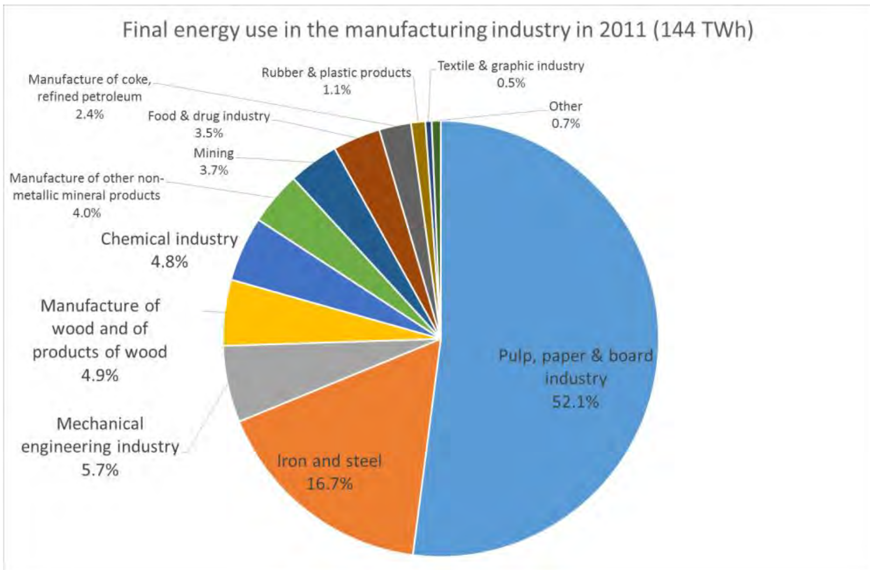

Figure 11-2: Final energy use in the different industrial sectors in 2011 (144 TWh in total) [2,3].

In Sweden the energy use in the manufacturing industry is dominated by a relative small number of sectors. The major energy user is the pulp- and paper industry standing for more than half of the total industrial energy use. The iron and steel industry is the second largest user, while the chemical, mechanical and wood manufacturing sectors are using similar amounts of energy, together standing for about 16 %. The remaining 16 % is used by the non-metallic mineral sector, food and drug sector, refinery sector and other smaller industrial sectors [1].

In Table 11-2 the energy use in the manufacturing industry is presented with fuel and electricity consumption details. Industries having a high percentage of electricity in the energy supply are less suitable for heat pump applications as there are less excess heat streams to be expected, with e.g. waste heat from electric motors being difficult to recover.

Table 11-2: Industry sector fuel and electricity use in 2011 [2,3].

Industry sector	Fuel [TWh]	Electricity [TWh]	Total [TWh]
Pulp, paper & board industry	2.1	3.3	5.4
Iron and steel	2.6	2.5	5.1
Mechanical engineering industry	0.2	0.4	0.7
Manufacture of wood and of products of wood	5.0	2.0	7.1
Chemical industry	52.5	22.6	75.1
Manufacture of other non-metallic mineral products	2.4	1.0	3.4
Mining	2.4	4.6	7.0
Food & drug industry	0.4	1.2	1.5
Manufacture of coke, refined petroleum	4.7	1.0	5.7
Rubber & plastic products	16.2	8.0	24.2
Textile & graphic industry	2.5	5.8	8.2
Other	0.4	0.6	1.0
Total	***91***	***53***	***144***

11.1.2 Market overview

A report on industrial excess heat in Sweden from 2009 presents the status of available excess heat in the different industrial sectors and the changes in excess heat delivery from 1999 to 2007. It also estimates the theoretical potentials for the different sectors. In Figure 11-3 the excess heat delivery (standard and upgraded by heat pumping) from the different industrial sectors. Due to a change in the coding system the sectors are grouped somewhat different compared to the previously presented data[27].

The amount of delivered excess heat increased by 0.8 TWh from 1999 to 2007 reaching 4.1 TWh/year. The largest supplier of excess heat is the pulp and paper sector that also increased its excess heat supply (without heat pumping) by 60 % from 1999 to 2007. Together the energy-intensive industry sectors (pulp and paper, iron and steel, petroleum refining, and chemical industry) stand for more than 90 % of all excess heat supply. Other industry sectors supply about 8% of excess heat but represent about 40% of the total number of companies supplying heat. The largest increase in heat supply of about 60% from 1999 to 2007 is seen for the wood manufacturing industry, but even the food sector increased its supply considerably (about 44%). Upgraded excess heat from low temperature heat sources by heat pumping represented about 630 GWh in 1999 but the amount delivered dropped to 265 GWh in 2007 [4].

[27] The report cited [4] uses the SNI 2002 codes while more recent data is using SNI 2007 codes.

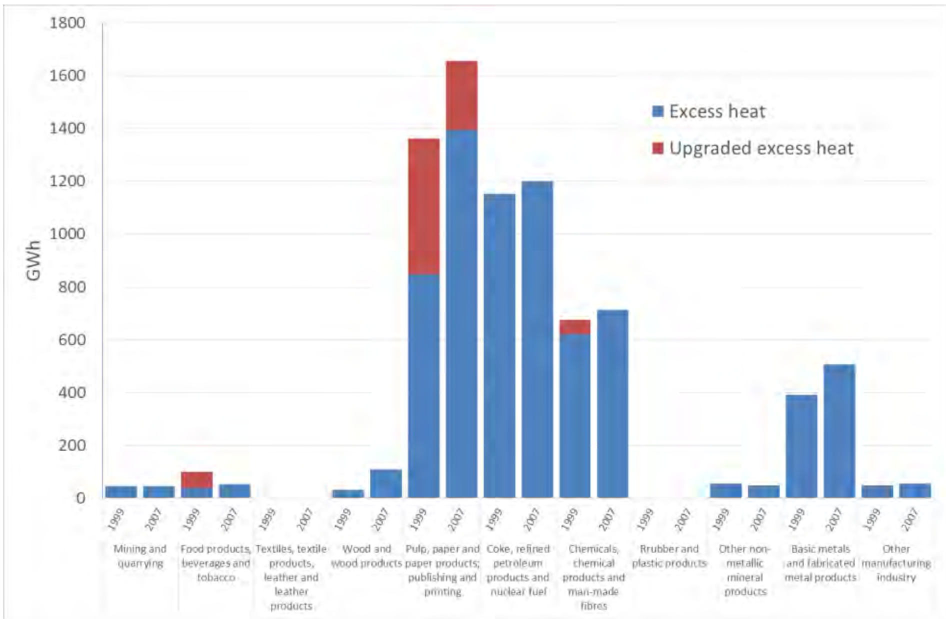

Figure 11-3. Delivered excess heat from industrial sectors in 1999 and 2007 [4].

An estimation of the potential for excess heat deliveries from the manufacturing industry sectors is presented in Table 11-3. The potential delivery estimate ranges from 6.2 to 7.9 TWh/year and is an estimated based on statistical data for the actual heat delivery as well as the industry sectors' fuel use. The calculated potential is up to 1.9 times larger than the delivered today.

The report cited here [4] discusses both the potential as well as barriers for excess heat delivery for each sector. According to the authors, a general discussion for the whole manufacturing industry sector is not possible due to varying prerequisites for the different sectors depending on their structure, location and surrounding infrastructure. A number of aspects mentioned that are relevant for industrial heat pump applications are stated in the following.

Increasing energy prices force industry to focus on energy efficiency measures and improve the profitability of heat recovery projects in general. Heat recovery from flue gases has become much more common, with biomass being used as fuel favoring the heat recovery potential due to a higher moisture content in the flue gases. The temperature level for flue gas heat recovery is rather high but even heat pump application in the lower temperature range might be considered.

Table 11-3: Excess heat delivery in 2007 and theoretical potential for manufacturing industry sectors in Sweden [4].

Industry sector	Delivered excess heat 2007 (GWh/Year)	Calculated theoretical potential of excess heat (GWh/Year)
Mining	50	250 – 300
Manufacture of food products: beverages and tobacco	61	80 – 120
Manufacture of textiles and textile products	0	0
Manufacture of wood and of products of wood	110	250 – 300
Manufacture of pulp, paper and paper products	1392	2000 – 2500
Manufacture of coke, refined petroleum products, chemicals and chemical products	1908	2500 – 3000
Manufacture of rubber and plastic products	3	10 – 20
Manufacture of other non-metallic mineral products	48	150 – 250
Manufacture of basic metals	502	900 – 1300
Other	58	100 – 140
Total	**~ 4100**	**~ 6200 - 7900**

For small scale enterprises the amount of excess heat often is rather small and heat recovery measures have not been considered yet. For district heat an increasing number of small suppliers however have a beneficial effect on the stability/reliability of the system. Considering heat pump applications, increased awareness for heat recovery have the potential to reduce the company's vulnerability with respect to changing energy prices.

11.1.3 Barriers for application

A number of barriers hindering increase excess heat delivery from the manufacturing industry are given in the cited report [4] with the ones relevant for heat pump applications are indicated here.

In particular for the small to medium size enterprises, the amount of excess heat often is considered too small or companies are not aware enough of the potential for excess heat recovery. Increasing energy prices might change this in the future.

In e.g. the wood manufacturing sector the fact that the drying equipment – representing an interesting source of heat recovery – is not running continuously is a major barrier for application. Similar problems exist in the pharmaceutical industry that is often operating batch processes with limited heat recovery potential.

The energy-intensive industry-sectors in Sweden are exposed to international competition leading to a strong strive for energy efficiency increase. Increased use of low temperature heat sources internally decreases the potential for district heat delivery but might open up for increase heat pump use. For example within the pulp and paper industry low temperature black liquor evaporation and pulp drying are applications that strive at using heat sources at lower temperature level.

11.1.4 References:

[1] Swedish Energy Agency (2013) *Energiläget 2013*, ET 2013:22, Eskilstuna, Sweden.

[2] Swedish Energy Agency (2012) *Annual Energy Balance Sheets 2010 – 2011*, EN 20 SM 1206, ISSN 1654-3688, Eskilstuna, Sweden.

[3] Swedish Energy Agency (2013) *Energy use in manufacturing industry, 2011 Final data*, EN 23 SM 1301, ISSN 1654-367X, Eskilstuna, Sweden.

[4] Cederholm, L-Å, Grönkvist, S, Saxe, M (2009) *Spillvärme från industrier och värmeåtervinning från lokaler* (Waste heat from industry and heat recovery in buildings, in Swedish), Report 2009:12, Svensk Fjärrvärme, Stockholm, Sweden.

12 Literature survey

12.1 Review of all countries

In [1] a total of 11 countries, namely France, Germany, Italy, Japan, the Netherlands, Norway, Spain, Sweden, the UK, the USA, and China, were surveyed to estimate CO_2 reduction potential by introducing current-technology heat pumps into the food and beverage fields. On the assumption that an electric drive compressor heat pump is used, applications at a boiler energy use end temperature of below 100 are selected as a heat pump applicable range.

As a result of this estimation, it has been concluded that the emission of 40 million tons of CO_2 per year can be reduced in all 11 countries by replacing applications at an end use temperature below 100 boiler energy in the food and beverage fields with heat pumps (with MVR in the beer brewing industry included). A total CO_2 reduction effect of 25 million t CO_2/year in the 10 countries other than China can be expected.

[1] Heat Pump & Thermal Storage Technology Center of Japan: Survey of Availability of Heat Pumps in the Food and Beverage Fields, March 2010

Application of Industrial Heat Pumps

IEA Industrial Energy-related Systems and Technologies Annex 13
IEA Heat Pump Programme Annex 35

Task 2:
Modeling calculation and economic models

Final Report
(20.06.2014)

Prepared by
Participants of Annex 35/13

Contents

1 Introduction

Task 2 is intended to outline how the integration of industrial heat pumps (IHP) in processes is supported by computer software, i.e. by modeling. The legal text comprises four items:

- Make SWOT analyses of available software and calculation procedures for application for different sectors.
- Analyze and update of existing models from Annex 21, where does the heat pump fit and how does it fit.
- Use the analysis of tools and findings of Task 1 to determine the gaps, needs and possibilities for new model development.
- Examine the possibilities to make software available.

During the execution of Task 2, the original legal text was slightly modified by a new activity plan:

- Database/collection of information on manufacturers of large/industrial heat pumps and their performance figures.
- Overview of software for Process Integration (PI) of industrial heat pumps.
- SWOT-analysis of integration of industrial heat pumps in industry.
- Principles for the integration of heat pumps in industry.

Unfortunately, we cannot report a complete execution of Task 2. Although the Annex 35/13 project had been prolongated by one year (mainly because of missing results from Task 2), nearly none of the deliveries could be finished as foreseen. We attribute this low interest to two facts:

- Most participants are not concerned directly with modeling and software aspects.
- The wide range of software tools with their very different scopes was largely underestimated.

Therefore, this Task 2 report expresses in some parts the Operating Agent's/ Annex Manager's view how Task 2 could be approached in a future project. The important consequence of this four years' work is to carefully reconsider the goals based on the State of the Art as well as on industrial needs if a "new Task 2" team should be constituted.

1.1 Integration of heat pumps into industrial processes: an outline of theoretical methods

Process integration (PI) methods and software tools have been compiled in numerous publications, for instance in "Process Integration Implementing Agreement within the IEA". One of its products is the comprehensive IEA Tutorial on Process Integration by T. Gundersen [1]. Software tools are discussed by the same author in Ref. [2]. Another source of general information on software tools for process integration, modeling and optimization is given by Hon Loong Lam et al. [3]. Further references are the book of L.

Puigjaner and G. Heyen (eds.) [4], the overviews given by I.E. Grossmann, J.A. Caballero and H. Yeomans [5].

Design, integration and operation of industrial processes (more generally synthesis problems) have been developed since more than 3 decades starting in the early 70's at the ETH Zürich and Leeds University by B. Linnhoff and J.R. Flower [6][1]. This work and subsequent developments are known under the key words "pinch analysis". A recent detailed overview is given by the book of I. C. Kemp "Pinch Analysis and Process Integration" and the overview of F. Maréchal [8], which we use in subsequent chapters. Generally, pinch analysis allows to determine the heat recovery potential by heat exchange in complex thermal processes, or in other words, to determine the minimum energy requirement of the process.

The general solution of synthesis problems employing all kind of optimization techniques has been developed by several researchers. Numerous contributions of I.E. Grossmann and coworkers have to be noticed. Their pioneering work dates as early as 1983 [9]. A concise overview of the mathematical programming approaches to the synthesis of chemical process systems is given by I.E. Grossmann, J.A. Caballero and H. Yeomans [5] and by the book of C. Floudas "Nonlinear and Mixed-Integer Optimization, Fundamentals and Applications", see Ref. [10].

It is important to understand the difference between these general solutions and pinch analysis: In pinch analysis optimization is restricted to a simplified heat cascade model (see below), which largely reduces the optimization problem, whereas a general solution of synthesis problems means taking all process details (process units) into account. This leads to problem sizes orders of magnitude above pinch analysis. Consequently, we will briefly discuss the two groups of models, pinch analysis and (large) optimization methods separately although these differences are more and more bridged in modern software tools.

A wealth of information is available and there is no need presenting all details. Rather, emphasis is given to the integration of heat pumps into processes. We dispense with any detailed presentation of software support for the design of the heat exchanger network (HEN), i.e. we concentrate on the integration of heat pumps into processes in the sense of a specific add-on, which programs may offer or not. Nevertheless, we are aware that the design of the HEN and the integration of a heat pump are closely related to each other.

1.1.1 Pinch analysis

Subsequently we follow the comprehensive review on pinch analysis given by F. Maréchal [8], which links pinch analysis to mathematical refined optimization methods. Pinch analysis is performed in three steps:

- the definition of hot and cold streams,

[1] This reference stands for the many publication of B. Linnhoff and his co-workers

- the calculation of the minimum energy requirement (MER), the so-called targeting step, in combination with a minimization of costs and
- the design of the heat exchanger network (HEN), the synthesis step.

Before presenting some further details, the merits of pinch analysis should be addressed:

- Pinch analysis allows a deep insight into any process. Its development was driven by detailed thermodynamic understanding of processes. Sometimes this is referred to as a holistic view. Minimum energy requirements or minimum costs are considered, as well as rules and guidelines for the design of the heat exchanger network. Nevertheless, for step three detailed knowledge and engineering judgment is required, which is augmented or supported by specific software tools.
- Pinch analysis may be considered as a mature technology and most software tools available fall into this category.

The basic idea behind the pinch analysis model is that individual hot and cold process streams are merged into fictitious hot and cold streams in order to perform a thermodynamic optimization and an optimization of costs. The thermodynamic optimization is done by the problem table algorithm, which is a specific simplification of the heat cascade model (see below). The optimization of costs is based on an approximation of the heat exchanger network (HEN). Only by these two simplifications, pinch analysis is kept rather simple. A temperature-heat load diagram can be constructed with the hot and cold composite curves (see Figure 1-1**Fehler! Verweisquelle konnte nicht gefunden werden.**). Indicated in Figure 1-1 is the pinch, which characterizes the nearest approach between hot and cold composite curves, the so-called minimum approach temperature ΔT_{min}. The pinch is defined by pinch temperature and location. The minimum approach temperature ΔT_{min} is a parameter that determines the heat transfer between hot and cold composite curves and that is used for approximately optimizing costs: A small value of ΔT_{min} means large heat exchanger areas and hence large costs, a larger value leads to smaller areas and hence to lower costs but at the expense of thermodynamic effectiveness. Further indicated in Figure 1-1 are the resulting heating and cooling duties, also called utilities.

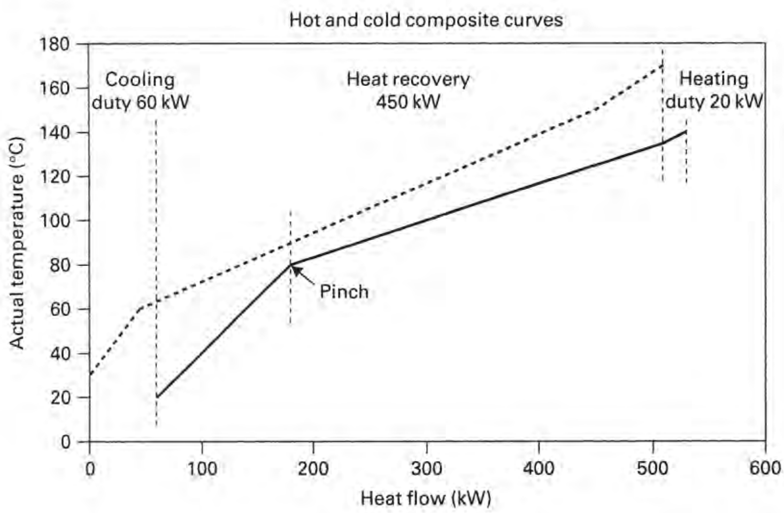

Figure 1-1: Composite curves for a four stream problem; Figure taken from Ref. [7]

In the original formulation of the pinch analysis, the integration of heat pumps is not foreseen in the targeting (optimization) step.

The design of the heat exchanger network, i.e. the synthesis step is by its nature combinatorial with a huge number of matches [8, p 184]. Pinch analysis does not follow a mathematical optimization approach, which will be discussed below, but is a sequential method mainly based on the insight gained by the thermodynamic interpretation of the pinch. More detail will be given in section 1.2.

1.1.2 Optimization Models

As early as 1983, S.A. Papoulias and I.E. Grossmann presented an optimization approach for the synthesis of total processing systems [9]. Since then, these optimization techniques were developed taking advantage of the parallel development of computer science (computers as well as numerical techniques). Significant progress has been made in optimization theory, modeling complex systems and nonlinear control with the consequence that such tools are nowadays employed routinely (I.D.L. Bogle and B.E. Ydstie, Chapter 4 of Ref. [4], p. 383). These tools are sometimes labeled **c**omputer-**a**ided **p**rocess **e**ngineering tools (CAPE). As mentioned already, a detailed overview of the present state-of the-art is given by I.E. Grossmann, J.A. Caballero and H. Yeomans [5]. Further, the book of C. Floudas [10] gives a comprehensive description of the fundamentals and the applications of nonlinear and mixed-integer optimization.

Heat pump integration has been investigated by several researchers. We mention here only the F. Maréchal group at the Ecole Polytechnique Fédérale de Lausanne (EPFL), Switzerland, which published recently several papers on this specific subject (Refs. [11], [12] and [13]). Reference [13] refers to the thesis of H.C. Becker (directed by F. Maréchal), in which a systematic methodology is presented, based on pinch analysis and process integration techniques to integrate heat pumps into industrial processes.

Generally speaking, today's comprehensive optimization methods are mature enough that heat pumps can be integrated into any process. So where is the problem? It seems that most problems origin from the fact that the integration of heat pumps is only a part of a very complex “**optimization machinery**” encountering several problems:

Mathematical problems I

The mathematical models go far beyond simple linear programming. Problems may get nonlinear and discrete (binary) variables need to be introduced, leading to programs as the mixed integer linear program (MILP) or the mixed integer nonlinear program (MINLIP). If we consider a MILP problem with m binary variables, which may take either the value 0 or 1, we have of 2^m solutions of a linear programming problem. If m is too large, combinatorial solutions are no longer feasible and specific techniques need to be applied. Nonlinear models generally suffer that convergence problems can never be excluded.

Mathematical problems II

Generally, an extremum (maximum or minimum point) can be either global (truly the highest or lowest function value) or local (the highest or lowest in a finite neighborhood). Only specific mathematical strategies, thermodynamic insight and engineering judgment can enhance the likelihood that the result of an optimization is a global minimum. This likelihood is reduced if the number of binary variables is too large for a (complete) combinatorial solution.

Problems in setting up the optimization model

In order to apply a mathematical programming techniques to design and synthesis problems, it is always necessary to postulate a superstructure of alternatives (Ref. [5, p. 5]). Or expressed in simple words: Alternatives that are not foreseen cannot be optimized. This means that the setup of superstructures is a tremendous work that needs a high degree of engineering competence, knowledge and experience. It is likely that several setups of the superstructure are needed to approach a technical solution. In addition, during the optimization it may turn out that some modification of process data (“super targeting”) could further improve the optimization. Most likely, the global optimum can only be approached by an outer iteration process covering modifications of the superstructure and of process data.

Uncertainties

The mathematics must not hide the many uncertainties involved, mainly originating from estimations and predictions of costs and the definition of the optimization target itself. The solution depends on such uncertainties. Variations of costs, the optimization target or even process data enhance the possibility that several designs fulfill the requirements, i.e. variations could turn a local minimum to a global one and vice versa, especially if several local minima are close to the global minimum.

Competence needed

It is obvious that any group performing this type of optimization needs high competence in optimization mathematics as well as thermodynamic engineering. Access to large standard optimization computer programs is mandatory, which may need some specific adaption.

We conclude that the application of general optimization methods is limited to a fairly small number of research groups and highly specialized groups within large companies. Energy consultants probably will prefer pinch analysis type models.

Integration of heat pumps

In principle, the integration of heat pumps is no particular problem. The important question in our context is whether integration of heat pumps is already a standard in process synthesis employing detailed optimization models.

We should clarify, which possibilities exist to consider various heat pump types in a superstructure. We should elaborate whether heat pump databases are in use. However, it seems that a general heat pump database is missing and its development could be a major contribution.

1.2 Integration of Heat Pumps in Industrial Processes: general principles

1.2.1 Introduction

In this section general principles for process integration of industrial heat pumps are discussed. The text is partly based on the one presented in the IEA work "Industrial Heat Pumps Experiences, Potential and Global Environmental Benefits", Annex 21, 1995 (Ref. [14]).

There are some parameters that are of major importance when integrating a heat pump into an industrial process:

- The industrial process. Each process is unique and consists, from an energy point of view, of heat sources and heat sinks. In order to process integrate the heat pump, applying for instance pinch analyze, it is necessary to have a good knowledge of these sources and sinks. The load and temperatures are then crucial but also other aspects as location and type of load are important from a practical point of view.
- The heat pump type. Heat pump types have different characteristics which will make them suitable in various situations. Operation temperature limitations will restrict heat pumps installations and also the choice between different types. Efficiency and type of drive energy are also crucial decision parameters.
- Energy costs. The cost of drive energy to the heat pump and the cost of the heat that is replaced determine the operation cost which is a large part of the annual cost.
- Capital costs. The investment costs associated with an installation of a heat pump derive from several parts. The heat pump itself (including auxiliaries) and the cost to install it is normally the largest part of the investment. However other parts may well be significant. The heat to the heat pump must be extracted and possibly a heat collecting system must be constructed. On the hot side of the heat pump also a dis-

tribution system might be necessary. Furthermore other changes and supplements often are necessary e.g. changes in the heat exchanger network (see below), drive energy supply and control system.

1.2.2 General Considerations and Principles of process integration of heat pumps

1.2.2.1 Basic pinch analysis concepts

In order to integrate a heat pump properly in an industrial process a good knowledge of the process is necessary. In this respect, pinch analysis is a very powerful tool, because the pinch temperature has an important physical meaning: It divides the heat sinks and sources into two separate parts, see Figure 1-2. In the part above the pinch, there is a net heat deficit, and heat must be added to the system by a hot utility. If a cold utility is applied above the pinch, it follows that the demand for the hot utility will increase by the same amount. Thus, valuable heat is just off-set by the amount of cooling added. On the other hand, in the part below the pinch, there is an excess of heat that must be removed from the system by a cold utility. Any heat added below the pinch must also be removed. Hence, in a well designed process, no cold utility should be used above the pinch and no hot utility below the pinch.

From these facts three fundamental rules can be stated:

- Do not cool a stream by utility above the pinch;
- Do not heat a stream by utility below the pinch;
- Do not transfer heat from a stream above the pinch to a stream below the pinch.

Pinch violations are said to exist if these rules are not fulfilled. Thus there are three types of pinch violations:

- Heat extraction from a heat sources above the pinch, i.e. a cooler above the pinch
- Heat supply to a heat sink below the pinch, i.e. a heater below the pinch
- Heat exchange between a heat source above the pinch and a heat sink below the pinch, i.e. heat exchanging across the pinch

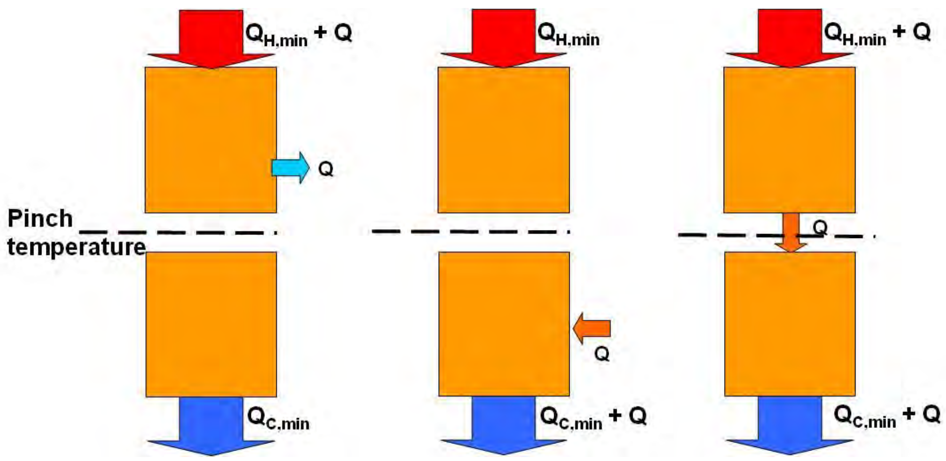

Figure 1-2: The pinch rules

1.2.2.2 *Principal consequences in a theoretical situation*

In a theoretical situation in an industrial process the minimum heating and cooling requirements are equal to the theoretical ones, i.e. there are no pinch violations. In this situation Figure 1-3 shows the consequences of the three principle alternatives of integrating a heat pump.

A heat pump should be integrated in such a way that the heat source is situated where there is an excess of heat (i.e., below the pinch), and the heat sink where there is a need for heat above the pinch. The heat pump is thus integrated across the pinch and both the hot and cold utility is reduced.

If the heat is extracted below the pinch and also delivered back below the pinch the consequence will be a larger cooling demand due to the net input of drive energy to the heat pump.

The third possibility is to extract heat above the pinch and also deliver it back above the pinch the hot utility will decrease by the drive energy to the heat pump. In this way hot utility can be replaced by drive energy which could be beneficial in a situation where the utility is limited of some reason.

In practice, technical and economic constraints of course limit the actual potential for heat pumping even if there are no pinch violations.

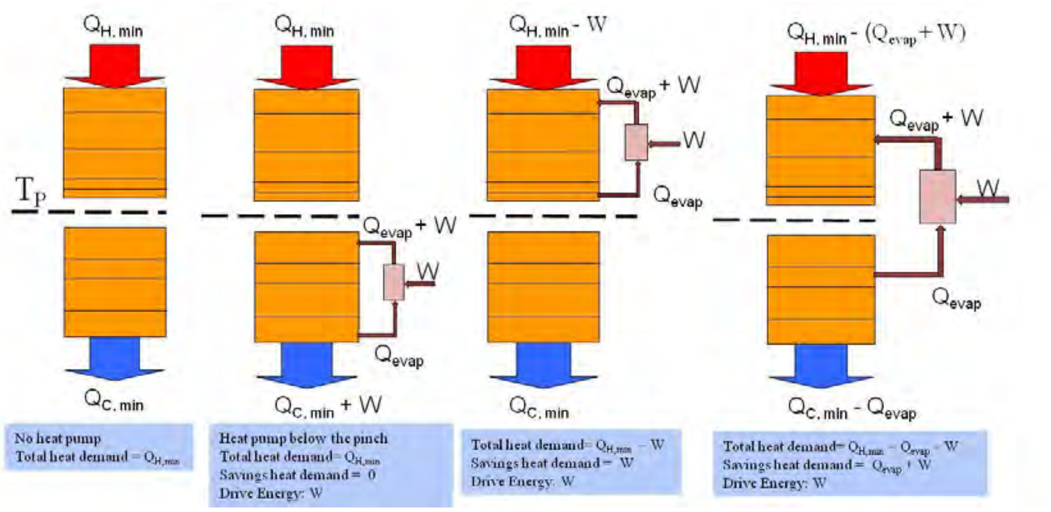

Figure 1-3: Consequences of integrating a heat pump in process without pinch violations

1.2.2.3 *Principal consequences in realistic situations*

In practice pinch violation exist in most processes due to various reasons, e.g. economic and practical. In these cases integration of a heat pump not necessarily has to be across the pinch in order to save energy. In principal a heat pump can eliminate pinch violations and thus reduce the energy used. Two main possibilities can be identified:

- A heat pump which utilizes the pinch violations cooling above and/or heat across the pinch (or part of them) and delivers the heat above the pinch will save hot utility. The amount is equal to the sum of the heat flow into the heat pump and the heat pump driving energy. The heat pump driving energy should of course be taken into account when a total energy balance is established. In Figure 1-4 the situation with a cooler above the pinch is shown.

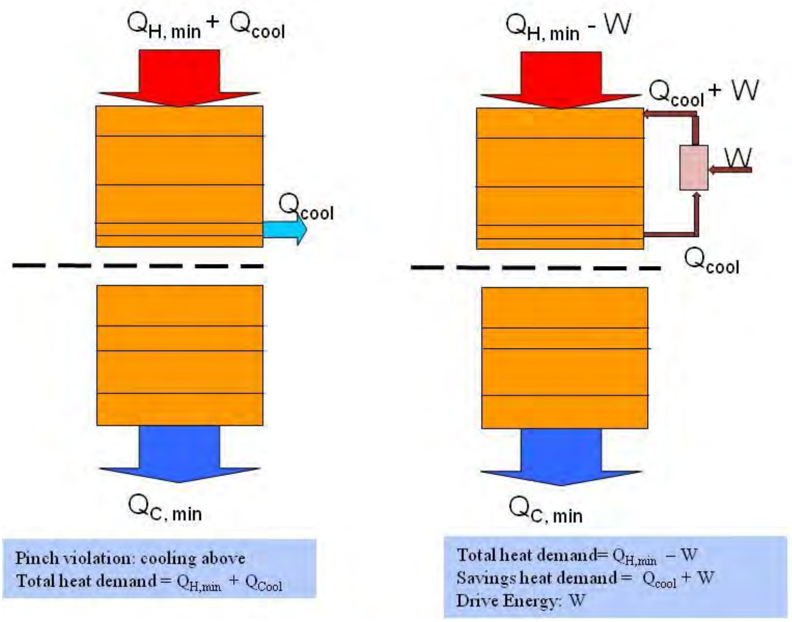

Figure 1-4: Consequences of integrating a heat pump in process in a process with a cooler above the pinch

- A heat pump, in a process with the pinch violation heating below the pinch, which extract heat and replaces this violation or part of it also saves hot utility. The amount is also in this case equal to heat flow to the heat pump and the heat pump drive energy. However in this case the drive energy needs to be cooled away. This situation is illustrated in Figure 1-5.

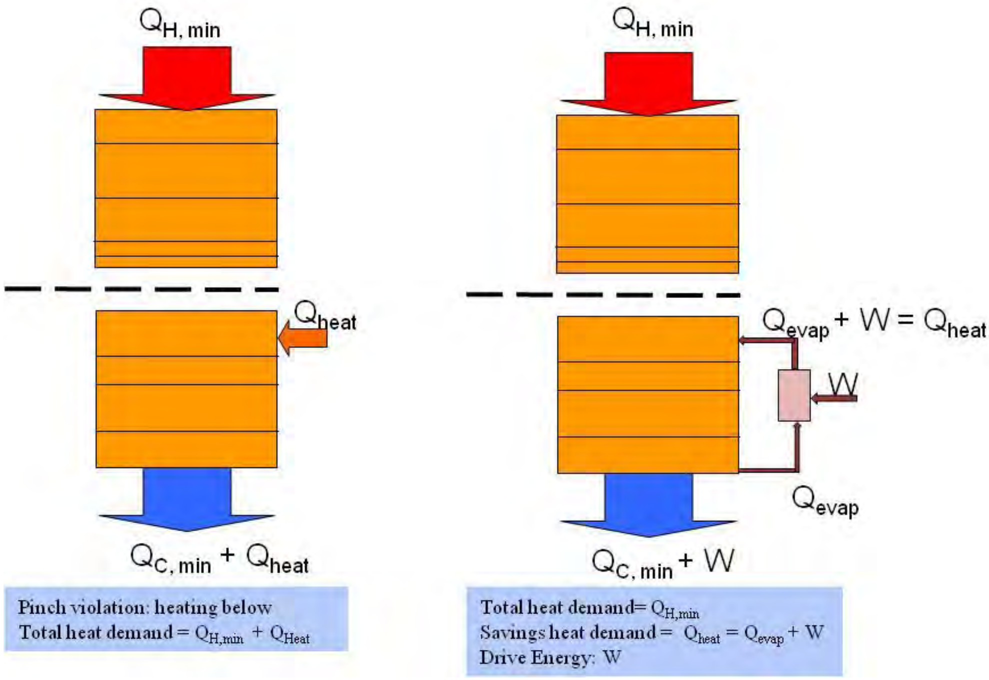

Figure 1-5: Consequences of integrating a heat pump in process in a process with a heater below the pinch

These principles show that also heat pumps not places across the pinch can save energy if pinch violations in the process exist which is the normal situation. This is in contrast to most previous published statements and opens up for more successful implementations.

1.2.2.4 Consequences on the process heat exchanger network

The consequences of integrating a heat pump into a process on the heat exchanger network can be extensive. When extracting heat to the heat pump below the pinch, the heat available for process heat exchanging might decrease. This also means that the driving force for heat exchanging decreases below the starting temperature of the heat source stream(s). This decrease in driving force means that the area needed for process heat exchanging in many cases becomes larger, and possibly that more heat exchanger units must be added. The same principals also hold for the situation above the pinch. Generally speaking, the closer in size the sink and/or source is to the theoretically maximum size at given temperature levels, the more heat exchanger network changes are necessary. The degree of these changes, however, is also dependent on the actual layout of the heat exchanger network (the location geographically and in terms of heater and cooler temperatures).

By process integrating the heat pump instead of using it from the cold utility temperature to the hot utility one, the heat pump will, in most cases, by necessity become smaller, On the other hand, this configuration may be economic as a result of the smaller temperature lift and hence higher COP.

1.3 Analysis of the Annex 21 Screening Program

1.3.1 Introduction

It has been mentioned above that the majority of software tools available for process integration fall into the pinch analysis category. Amongst these programs is the Industrial Heat Pump (IHP) screening program with the explicit objective to screen the technical and economic potential of heat pumps in various industrial processes without performing extensive and time-consuming case studies employing optimization models. The Industrial Heat Pump (IHP) screening program has been developed in the mid nineties by a group of the Chalmers Industriteknik Energiteknisk Analys (CIT-ETA) headed by T. Berntsson. Since this IHP screening program constituted a major (if not the most important) contribution to the Annex 21 Report [14, April 1995] it will be labeled subsequently as Annex 21 IHP screening program (in short screening program where not ambiguous). This model will be the starting point of our analysis of software models available.

A detailed description of the program is found in the Annex A of Ref. [14]. The intended purpose (see Ref. [14], p 41) is given as:

"The main purpose of the Annex 21 IHP screening program is to serve as a tool to allow for preliminary screening of the technical and economic potential of heat pumps in various industrial processes, based on proper integration into the process. To fulfill this purpose, a number of functions have been built into the program. These functions also make it possible to use the program as

- a database for process data
- a database for heat pump performance data
- a calculation tool to establish heat pump performance"

The pioneering idea behind the Annex 21 IHP screening program as well as its very ambitious goals and its uniqueness raised the question of today's relevance and hence lead directly to the item in the legal text of Task 2 of this Annex:

"Analyze and update of existing models from Annex 21, where does the heat pump fit and how does it fit".

Authors of the Annex 21 IHP screening program are not named explicitly. However, the presentation of the screening program within Annex 21 closely follows the publication of Wallin and Berntsson in 1994 [15], which outlines the main concept only but does not allow to fully understand the details of the screening program. Reference is made to two (at that time unpublished Papers, Refs. [16] and [17]), which were published in 1996 within the Ph. D. thesis of E. Wallin [18] as Appendices 2-5. Obviously, the original intention of the author, to publish the Appendices 2-5 in a journal has been abandoned.

Although the Annex 21 IHP screening program has been offered as an important tool for the integration of a heat pump into a process employing the pinch analysis technique, it has not been advertised or commercialized by CIT-ETA [19]. It has been made available through the IEA Heat Pump Centre (HPC) since the finalization of Annex 21 in 1997.

The Annex 21 IHP screening program has been used by several organizations but this usage is not reflected in subsequent publications. Since its finalization in 1997 the Annex 21 IHP screening program has never been modified or updated.

1.3.2 Conversion of the Annex 21 IHP screening program

During the First Annex 35/13 Meeting in 2011 [20] the update of the Annex 21 IHP screening program was discussed. The participants came to the conclusion that an update might be too lavish, expensive and time-consuming. It was agreed to check possible minor improvements and to concentrate on improved input data. Weak points were summarized by R. Nordman [21]:

- Requires detailed knowledge of both process integration and heat pump
- Outdated refrigerants' data (R12, R22, R114, HC, Steam (open type)
- Not possible to add new refrigerants (thermophysical data)
- No automatic screening possibility, user must test number of options by hand
- No transparent interaction possibility with other software (data export)
- Separate help files
- Graphical system user unfriendly
- Need new implementation which would need lots of coding although basic code is available

The new implementation suggested in the last item of the list shown above was done by the Information Center on Heat Pumps and Refrigeration (IZW): The complete Annex 21 IHP screening program (with only a few minor items missing) was converted from an outdated Visual Basic version to the latest Visual Basic version employing the .NET framework. Details of this work are documented in two internal IZW notes [22] [23].

Both versions, i.e. the original version from 1997 and the converted version from 2011 give in almost all situations identical results. Differences found in specific situations may be attributed to an error detected in the original screening program. Another reason for disagreements in specific situations could be a possible inconsistency between the source code used to build the executable of the original screening program and the source programs provided to IZW. This possible discrepancy could never be clarified. Two examples of the converted version are shown in **Figure 1-6** and **Figure 1-7**. All results (numbers) in the figures are identical with the original Annex 21 IHP screening program.

The conclusion from this conversion is obvious: The new, converted version is ready for any modifications, updates of data and models as well as for extensions. Parts of the screening program, for instance the database, could be easily extracted and modernized for other purposes.

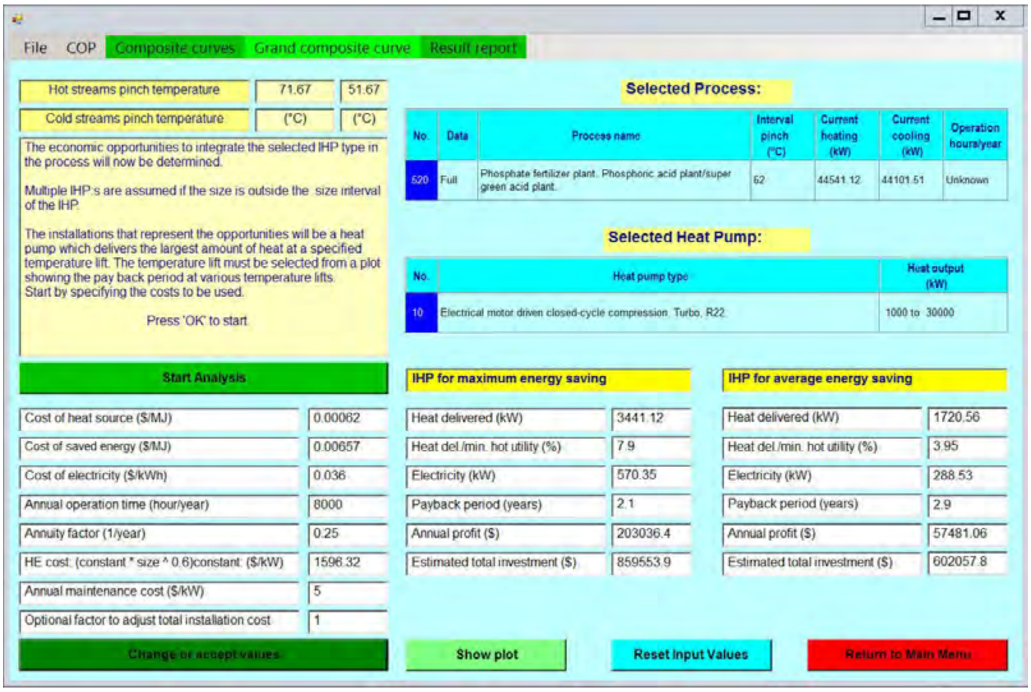

Figure 1-6: Menu item "Economic opportunities-part 1" of the revised Annex 21 IHP Screening Program (Refs. [22] and [23]); all results (numbers) are identical with the original Annex 21 IHP screening program.

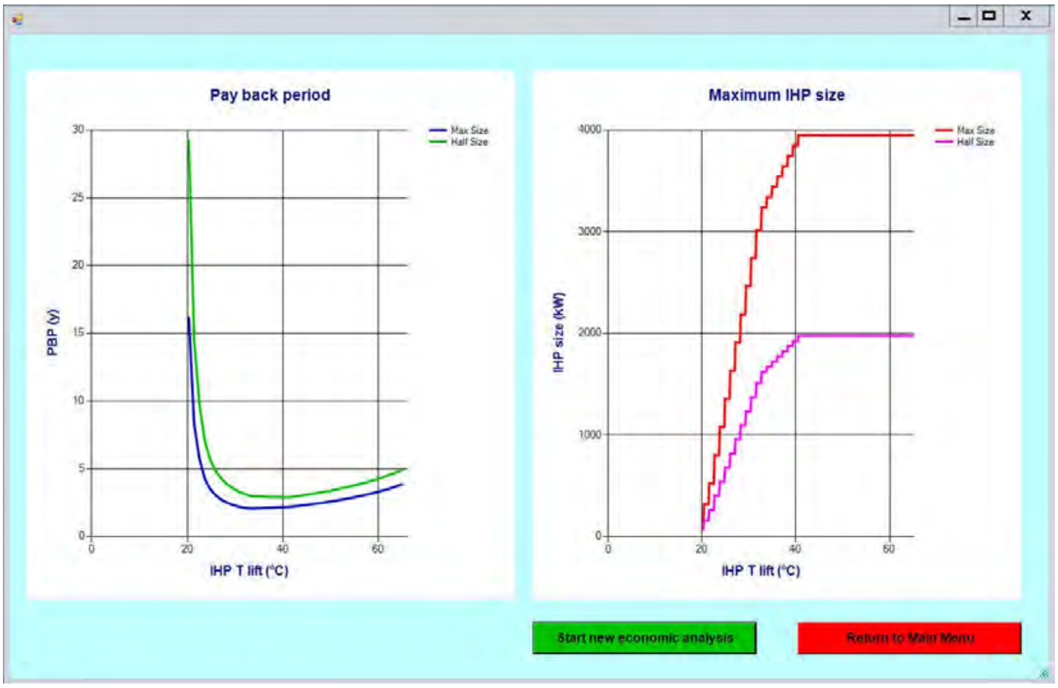

Figure 1-7: Menu item "Economic opportunities-part 2" of the revised Annex 21 IHP Screening Program (Refs. [22] and [23]); the graphs are identical with those from the original Annex 21 IHP screening program.

1.3.3 Analysis of the Annex 21 IHP screening program

Two problems make any critical analysis rather difficult, if not impossible:

- A systematic verification of the Annex 21 IHP screening program has never been published. Especially any comparison between the screening program and more sophisticated models is missing.
- The work of E. Wallin [18] gives a vast amount of details, various approximations and approaches. It is obvious that only selected models or approaches have been implemented in the screening program. Unfortunately, the information what detailed approaches have been implemented is missing. In view of the statement made above, that the screening program has not been advertised or commercialized by CIT-ETA, such a detailed description has never been intended. What is available must be considered as fair enough.

The work of Wallin is based on a very detailed thermodynamic and technical understanding of processes and heat pumps. Such a detailed understanding is also mandatory if a heat pump is to be integrated in a process employing the screening program. Its usage is a step by step optimization, guided by the experience and knowledge of the user. Besides the standard pinch analysis optimization there is no support given by further optimization methods. This approach makes the usage of the screening program rather complex and time-consuming.

It seems that the difficult usage of the screening program was one major obstacle for any updating of data and models. However, there is one compelling and convincing argument against any update of the screening program in its original form: during the execution of Task 2 it became obvious that the authors (and owners) consider this particular approach as a dead-end and the screening program as obsolete. Since 1997 no further work on this program has been done and the authors decline any further developments. We criticise that the formulation of the corresponding item in the legal text did not take this situation into account.

Nevertheless, we should not loose sight of the database for heat pump performance data, included in the screening program. Since we have worked through all details of the screening program, we know that this database is one the largest part of the screening program. It consists of rather general parts, which need only minor modifications and of input data for heat pumps which must completely be updated (for more details see below).

1.4 A modern concept for a screening program based on pinch analysis

The proposed modern concept for a screening program based on pinch analysis considers the work of F. Maréchal and S.A. Papoulias & I.G. Grossmann. Chapter 1.4.1, "*The problem table algorithm*" follows closely F. Maréchal (Ref. [8]), whereas chapter 1.4.2 "*The transshipment model of Papoulias and Grossmann*" is a short description of this model directly taken S.A. Papoulias and I.G. Grossmann [9, 709]). From these two references the concept for a new screening program based on pinch analysis has been developed. The kernel of this model has been tested through a preliminary test program (see chapter 1.4.3 “*A simple test program*”).

Although many details are incorporated in the test program it is not necessary presenting all equations. Rather emphasis is put on a more general understanding of the mathematical concept. It will be shown that the resulting equations of linear programming (linear optimization) are more or less as simple as solving a linear system of equations.

As mentioned in previous chapters, the general solution of integrating heat pumps into a problem has been discussed in all aspects and has been solved for several case studies by H.C. Becker [13]. Here we analyze an approximate solution for the simultaneous optimization of heat pump, utilities and heat exchanger network (in an approximate form) by substituting the problem table algorithm of the classical pinch analysis by a simple optimization model.

1.4.1 The problem table algorithm formulated as mathematical optimization method

The original (classical) pinch analysis is using the problem table algorithm as optimization technique, which is extremely simple but also unnecessarily limiting. The problem table algorithm stands for a specific heat balance model (heat cascade model), to obtain the minimum energy requirement. The heat cascade is represented by temperature intervals obtained by the construction of composite curves, in which energy balances are performed. The standard procedures for partitioning the entire temperature range account for thermodynamic constraints in the transfer of heat, i.e. it guarantees that the second law of thermodynamics is taken into account. Temperatures of hot streams are corrected by $-\Delta T_{min}/2$ whereas cold streams are corrected by $+\Delta T_{min}/2$. The heat cascade model of the classical pinch analysis is visualized in Figure 1-8. The vector $\boldsymbol{R}$ represents the heat cascaded from higher to lower temperatures, R_1 is the cold and R_{n+1} the hot utility, i.e. the minimum energy requirement.

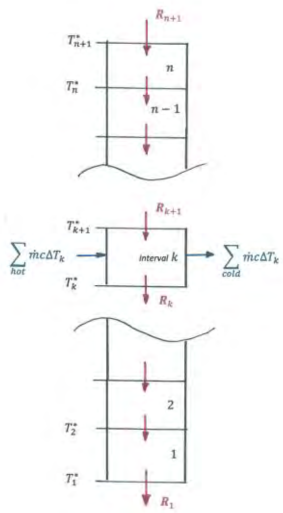

Figure 1-8: Heat cascade model underlying the classical pinch analysis; for explanations see text; corrected temperatures are labeled as T_i^*; the specific notation is given in the text.

From Figure 1-8 we see that only two utilities are considered: one hot ($\equiv R_{n+1}$) and one cold ($\equiv R_1$) utility. The reason for this restriction is quite simple: This particular form of the optimization problem to obtain the minimum energy required can be carried out by hand. However, this simplicity has its prize: Only for these restrictions the optimization problem can be solved without employing optimization methods such as linear programming (linear optimization) methods. This would already be necessary if utilities in more general configurations are to be considered. In pinch analysis these restrictions are overcome by use of the grand composite curve and performing this optimization by hand, which restricts this optimization to manageable situations only.

The mathematical form of the problem table algorithm is as follows: For the independent variables $R_1, \dots, R_{n+1}$ (the heat cascaded from higher to lower temperatures), we need to maximize the function

(1) $$z = -R_{n+1}$$

subject to primary constraints

(2) $$R_k \geq 0 \qquad k = 1, \dots, n+1$$

and simultaneously subject to the additional constraints (balance of heat)

(3) $$R_{k+1} - R_k + \sum_{hot\ streams} \dot{m}\ c_p\, \Delta\, T_K - R_k - \sum_{cold\ streams} \dot{m}\ c_p\, \Delta\, T_K = 0$$

with $\dot{m}$ = mass flow rate

c_p = specific heat at constant pressure

$\Delta T_k = T^*_{k+1} - T^*_k$

For the sake of simplicity the individual stream indices have been omitted in Eq. (3). These equations formulate a rather simple problem which can be solved by standard solvers of linear programming (linear optimization).

1.4.2 The transshipment model of Papoulias and Grossmann

A transshipment model may be considered as an extension of Equations (1)-(3) in order to consider utilities in a more flexible form. Its basis is also a heat cascade model similar to the one shown in Figure 1-8. Papoulias and Grossmann write:

"The transhipment model for the heat recovery network has the hot streams and the heating utilities as sources, the temperature intervals as the immediately nodes and the cold streams and the cold utilities as the destinations. The heat flow pattern, and thus the extended equations compared with the equations (1)-(3), is as follows:

- Heat flows into a particular interval from all hot streams and heating utilities whose temperature range includes the temperature interval.
- Heat flows out of a particular interval to the cold streams and cooling utilities whose temperature range includes the temperature interval.
- Heat flows out of a particular interval to the next lower temperature interval. This heat is the residual (excess) heat that cannot be utilized in the present interval, and consequently has to flow to a lower temperature interval.

- Heat flows into a particular temperature interval from the previous interval that is at a higher temperature. This heat is the residual (excess) heat that cannot be utilized in the higher temperature interval."

The main advantage of the transshipment model in comparison to the problem table algorithm is the significantly increased flexibility to optimize complex utility configurations with arbitrary cost structures.

The authors also show how this transshipment model could be extended to treat restricted matches, i.e. pairs of hot and cold stream that are not allowed to exchange heat. Such a case cannot be treated by the classical pinch analysis.

The statement presented at the beginning of this chapter, i.e. that a transshipment model may be considered as an extension of Equations (1)-(3) can also be reversed: The problem table algorithm is included in the transhipment model as special case. This leads immediately to the question whether the substitution of the problem table algorithm by the transhipment model as a more or less general optimization method offers advantages in a modern pinch analysis programs.

One advantage is obvious: The optimization of utilities could be done by the code if the necessary information concerning utilities (temperature, mass flow rates, costs etc.) is provided to the code by a specific "Utility Window". Of course, the user could modify this optimization of utilities of the code by using the standard approach, namely by employing the grand composite curve.

We would expect that such modifications of the classic pinch analysis approach has already be realised in one or the other pinch analysis code.

The second advantage is also obvious: by a further minor extension of the classical transhipment model (see chapter 1.4.4 "The extension of the transshipment model to integrate a heat pump"), a heat pump could be included in the process by a simultaneous optimization of utilities and heat pump. This will be discussed below.

The fundamental requirements of the substitution of the problem table algorithm by a transshipment model are applicability, numerical accuracy and reliability as well as reasonable computational times. In other words, would this substitution eventually annihilate the simplicity of pinch analysis models? We would expect that the numerical effort of the optimization is negligible, since the heat cascade model itself is a thermodynamic simplification of complicated processes.

Since the transshipment model plays a dominant role in the proposed 'modern' pinch analysis program and since all numerical aspects need to be known in principle before a major code development is started, a numerical model was written in form of a simple test program.

1.4.3 A simple test program

A simple test program has been programmed in a rather flexible form: Up to 500 temperature intervals are allowed and 'arbitrary' utilities may be considered. The optimization goal can be either minimum of energy or minimum of costs. It has to be stressed that this version of the transshipment model is a test version only, which does not include a Graphical User Interface. It has been used for various very specific situations by directly modifying the code [23].

When applied to appropriate situations (and only for such specific situations a direct comparison can be made; see Figure 1-8), the agreement between the results of the classical pinch analysis with the problem table algorithm and the transshipment model is perfect. Compared were 4 quantities for 14 very different cases taken from the process data base included in the Annex 21 IHP screening program: pinch temperature, pinch location, hot utility and cold utility (see Figure 1-9). The computational cost of both algorithms is hardly to be measured on a modern PC.

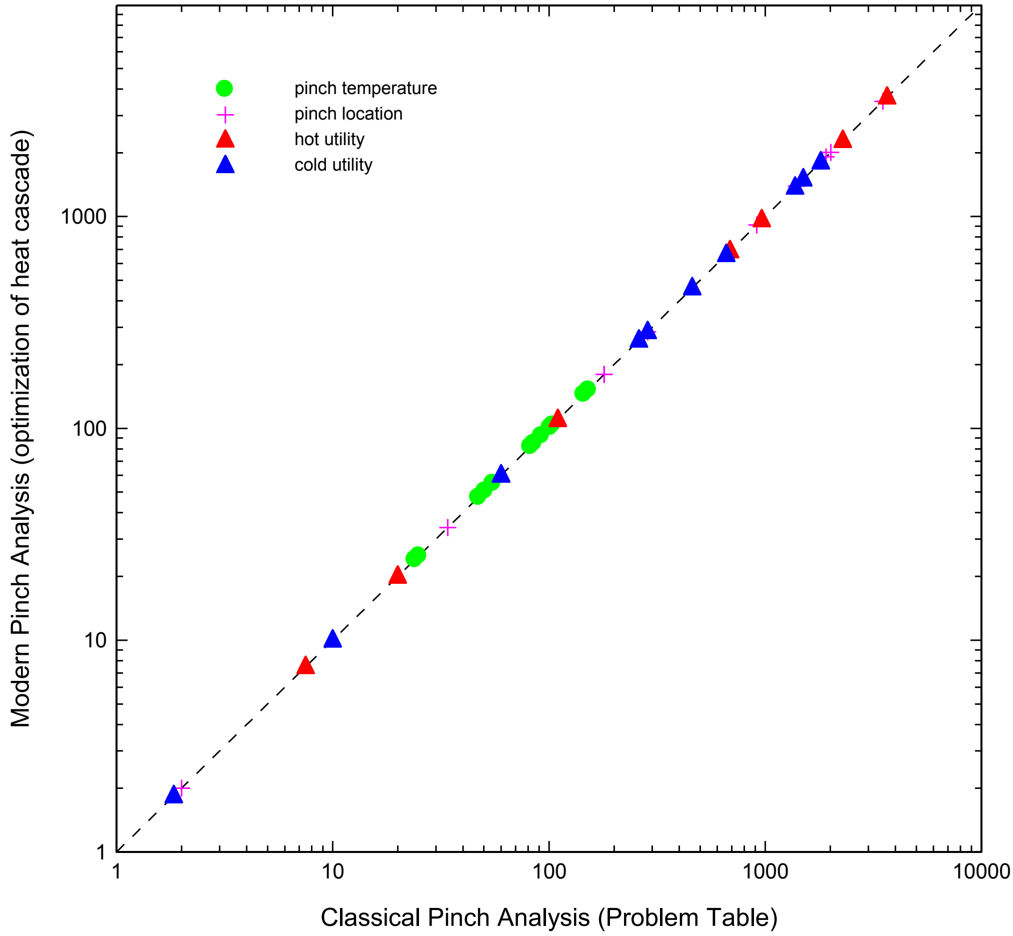

Figure 1-9: Comparison between the solution of the heat cascade model according to the classical pinch analysis based on the problem table algorithm and an optimization technique for 14 different processes; the agreement is perfect.

Our proposal that that optimization of utilities could be done by a transhipment model within a pinch analysis code if the necessary information concerning utilities (temperature, mass flow rates, costs etc.) is provided to the code by a specific "Utility Window" can be realized more or less without any restrictions.

We therefore expect that such or similar extensions of the classical pinch analysis are employed in several software tools.

The further tests confirmed applicability, numerical accuracy and reliability of the transshipment algorithm as well as short computational times. These tests included rather complicated situations of utilities and their different costs, in which we doubt that an optimization performed by hand is trivial.

Consequently there are no obstacles to further follow this approach for a modern concept for a screening program based on pinch analysis

1.4.4 The extension of the transshipment model to integrate a heat pump

The consequences of integrating a heat pump into a process on the heat exchanger network have already been discussed in chapter 1.2 “*Integration of Heat Pumps in Industrial Processes: general principles*”. In a heat pump heat is lifted from a low temperature level (heat source) to a higher temperature level (heat sink). For integrating a heat pump into a process both terms must additionally be taken into account in the transshipment model, i.e. in the heat cascade. The consequence of integrating a heat pump has not only been extensively discussed in the Annex 21 report, but also visualized in Figure 3.4 (Ref. [14], p. 31): As already discussed in chapter 1.2, the modification of hot and cold composite curves lead to a decrease of driving forces for heat exchanging below heat source temperatures and above heat sink temperatures, which implies that larger heat exchange areas are necessary.

For modeling it is important to recognize that the model gets nonlinear, i.e. not only the driving forces for heat exchange are affected but also the location of the pinch point.

1.4.5 The elements of the proposed modern concept for a screening program based on pinch analysis

Let us consider the heat balance equations in the form of the heat cascade as the first element of the proposed modern concept for a screening program based on pinch analysis.

The second element is the heat exchanger network. As long as we aim at developing a ‘modern’ screening program based on pinch analysis, we must assume that - analogous to the standard pinch analysis- the heat exchanger network is approximated by an artificial heat exchanger area A_{ex}, which depends on the minimum approach temperature ΔT_{min}. As above in the case of the heat cascade we indicate the type of mathematical dependencies only.

For a cold stream to be heated up from an initial temperature $T_{cold,in}$ to a target temperature $T_{cold,target}$ and one hot stream to be cooled down from $T_{hot,in}$ to $T_{hot,target}$, F. Maréchal gives the solution from which one can see the typical dependencies [8, p 167ff]:

$$A_{ex}(\Delta T_{min}) = \frac{\dot{m}_{hot}\, c_{p,hot}}{(1-\kappa)U_{ex}} \left[\ln\left\{ \frac{(1-\kappa)\left(T_{hot,in} - T_{cold,in}\right) + \kappa\,\Delta T_{min}}{\Delta T_{min}} \right\} \right] \quad (4)$$

with $\kappa = \frac{\dot{m}_{hot}\, c_{p,hot}}{\dot{m}_{hot}\, c_{p,cold}}$ and $\frac{1}{U_{ex}} = \frac{1}{\alpha_{cold}} + \frac{e}{\lambda} + \frac{1}{a_{hot}}$

$\dot{m}$ is the mass flow rate, c_p is the specific heat at constant pressure, U_{ex} is the overall heat transfer coefficient of the heat exchanger, α is the heat transfer coefficient, e the thickness of the tubes. Eq. (4) allows estimating the costs of the heat exchanger network and can easily be refined.

Clearly, this approach is an approximation. Unfortunately, we cannot say how good this approximation is since we are not aware of any systematic comparison between the costs estimated by pin analysis and from analyses based on detailed optimization. It is obvious that this approximation is only meaningful for those situations, in which the error of the approximation is far less than the actual potential of incorporating a heat pump.

Further elements of the model are:

- Development of a heat pump database to be used within the optimization process. Typical information to the database are not only source and sink temperature as well as size of heat pump but also further details of the selected hot and cold streams to which the heat pump is selected which allow to select a specific heat pump type. It has been mentioned in chapter 1.3.3 that the data base of the original Annex 21 IHP screening program is one the largest part of this program. It consists of rather general parts, which need only minor modifications. Most importantly, the input data for heat pumps must be updated.
- Development of an algorithm for selecting of a hot and cold stream (may be the selection of several hot and cold streams) to which the heat pump could be connected. This algorithm is not really clear in Wallin's thesis [18]. No attempt has been made to look deeper into this problem.
- The nonlinearity mentioned above requires an iteration that converges towards the solution. Generally, convergence can never be guaranteed per se, but in this case it is even worse since the nonlinearity has a rather nasty characteristic: Some of the functions are or get discontinuous. For instance the pinch point itself, or the size and price of a specific heat pump with a specific power range, where the full power range is realized by overlapping of individual heat pump models. In view of the extremely short computational costs in the range far below seconds per analysis, we have had in mind to apply a Monte Carlo technique with quasi-random sequences. This technique would have allowed obtaining results in a reasonable time. Of course there would have been the need (with the help of experts!) to replace this Monte Carlo technique by a more appropriate technique used in PI later on.

The proposal to substitute the problem table algorithm by a modified transshipment model in pinch analysis in order to integrate a heat pump into a process is supported by the approach taken by K. Holiastos and V. Manousiouthakis [25] for the optimal integration of heat pumps and engines in heat exchanger networks. Heat pumps and heat engines are considered as components of the heat exchange network. Analogous to pinch analysis, which does not deal with single heat exchangers (at least not in the targeting step), individual units (e.g. heat pumps) are not dealt with. Rather, a thermodynamic approach is considered, enabling the solution of the global optimum over all network configurations. Two subnetworks are considered, whose interaction produce the optimal network: a heat exchanger subnetwork, representing the aggregate action of heat exchangers, and a heat engine and heat pump subnetwork, representing the aggregate action of power units. The heat exchanger network is modeled by a modified equation (4) taking into account that only a fraction of the hot composite stream enthalpy will be transferred to the cold composite stream. The heat engine and heat pump network is modeled by the work available (first law) and the second law: it is necessary to ensure that the total stream enthalpy change due to aggregate heat pump/engine action in the subnetwork is zero (Ref. [25], p. 8).

1.4.6 Summary

A modern concept for a screening program based on pinch analysis can be developed by substituting the original problem table algorithm of the pinch analysis by a modified transshipment model. Numerical aspects and principal feasibility have been analyzed. However, some details of this model need to be developed:

- Development of an algorithm for selecting of a hot and cold stream (may be of several hot and cold streams) to which the heat pump could be connected.
- Development of a heat pump data base.
- Development of an iteration algorithm to cope with the specific type of nonlinearity.

In principle this analysis should be very similar to the "engineering" procedure of integrating a heat pump. However, we must be aware that the approximation of the net of heat exchangers may jeopardize the whole approach if its error is too large.

1.5 Scoping analysis of existing software tools based on pinch analysis

This chapter is called 'Scoping Analysis' since neither a detailed mathematical analysis nor any detailed analysis of functionalities, user support or user friendliness can be given within this Task 2 report. However, experiences with one of the major tools, the Einstein code, and the models used for the choice of a heat pump will be reported below.

A comprehensive State of the Art review on analytical tools based on the pinch method, is given by Y. Beucher, J.-L. Peureux and A. Vuillermoz **Fehler! Verweisquelle konnte nicht gefunden werden.**]. Methods of process energy integration with emphasis on pinch analysis are discussed and stakeholders from academic research laboratories and other non-academic players are listed. Although this compilation has been carried out over several years, it does not claim to be an exhaustive list, as numerous pinch analysis tools exist and new tools are released every year. Some of the tools presented in this report may even now be obsolete. Here, we only list the names of the programs treated in more detail in the report: STAR and SPRINT, Pinchlight, OSMOSE, Thermoptim, CERES, Pro_Pi, PinCH, Hint, Einstein, SuperTarget, AspenEnergyAnalyzer. The compilation is rather descriptive and more oriented towards giving potential users a first orientation. Although mathematical details have been omitted in the overview, the authors indicate what is to be expected from the theoretical point of view with regard to the integration of heat pumps:

OSMOSE: Developed by the group "energy integration of heating systems" headed by F. Maréchal of the Ecole Polytechnique Fédérale de Lausanne (EPFL).

Calculation models and procedures have been developed to integrate heat pumps into an industrial process. OSMOSE is an optimisation platform, rather than a tool based on the pinch method. OSMOSE uses the mathematical programming formulation of the heat cascade and aims at calculating the flows in the utility system. This approach is the only practical approach for the heat pump integration since the flows of the hot and cold streams of the heat pump are interacting with the other heat pumps and with the other utility streams like combustion gases, cogeneration and steam cycle models. It has to be highlighted that although pinch analysis gives an explanation of the principle of the heat pumping integration, the pinch analysis is mainly targeting the heat recovery and therefore can be hardly used when it comes to calculate the optimal integration of a heat pumping systems [26].

CERES: developed by the CES (Centre d'Eco-efficacité des Systèmes or Centre for Systems Eco-Efficiency) of the Ecole Nationale Supérieure des Mines de Paris (Mines Paristech). CERES enables the pinch method, but has been further enhanced with optimisation algorithms designed to select among a number of utilities (heat pumps, turbines, etc.).

Einstein: The pinch method is involved only when designing the exchanger network, and not in the choice of utilities: the tool does not really allow for determining which utilities or combinations thereof would be optimum; it only provides the possibility for testing various energy supply scenarios and to compare them based on energy, economic or environmental criteria. The module designed for heat pump integration is not easy to use, and – at least in V2.1 – had some bugs.

1.6 Conclusions

Although the Annex 35/13 project had been prolongated by one year, mainly because of missing results from Task 2, nearly none of the deliveries could be finished as foreseen. We attribute this low interest to two facts:

- Most participants are not concerned directly with modeling and software aspects.
- The wide range of software tools with their very different scopes was largely underestimated.

The Annex 21 IHP screening program has been analyzed and converted from an outdated Visual Basic version to the latest Visual Basic version employing the .NET framework. This new, converted version would in principle be ready for any modifications, updates of data and models as well as for extensions. However, during the execution of Task 2 it became obvious that the authors (and owners) consider this approach as a dead-end and the screening program as obsolete. Since 1997 no further work on this program has been done and the authors decline any further developments. We simply notice that the formulation of the corresponding item in the legal text did not take this situation into account. However, parts of the screening program, for instance the database, could be easily extracted and modernized for other purposes.

In order to 'update' the Annex 21 IHP screening program in the sense of a 'modern' development taking the original goals into account a proposal is made that allows a consistent integration of a heat pump into a process based on pinch analysis. The basic elements of this concept are:

- Substitution of the problem table algorithm by an extended transshipment model which allows a simultaneous optimization of utilities and heat pump.
- Approximation of the heat exchanger network as in the standard pinch analysis.
- Development of an algorithm for selecting of a hot and cold stream (may be of several hot and cold streams) to which the heat pump could be connected.
- Development of a heat pump data base to be used within the simultaneous optimization. Since this optimization is nonlinear a special algorithm needs to be developed that enables convergence.

This concept of integrating a heat pump into a process is 'below' the sophisticated methods given by H.E. Becker [13]. Presently it is impossible to state whether such a development is unprecedented, relevant and needed.

The scoping analysis of existing models shows that the difference between 'pure' pinch models and sophisticated mathematical optimization models has been bridged in modern software tools. Regarding the integration of heat pumps into a process, codes like OSMOSE or CERES (amongst may be others) look promising.

Independent of any software tools, approaches and optimizations, a general heat pump data base should come more into the focus. Such a data base is needed for many purposes. Typical information to the database are not only source and sink temperature as well as size of heat pump etc. but also further details of the selected hot and cold streams to which the heat pump is selected, because this would allow to select a specific heat pump type.

The goals of Task 2 should be carefully reconsidered if a "new Task 2" team should be constituted. The State of the Art as well as industrial needs of research organizations, large companies as well as of energy consultants should be critically reviewed. We conclude that the application of general optimization methods is limited to a fairly small number of research groups and highly specialized groups within large companies. Energy consultants probably will prefer pinch analysis type models. This is the main reason why we propose to develop a 'modern' screening program 'below' the sophisticated methods given by H.E. Becker [13], which may be considered as a specific add-on for standard pinch analysis codes for integration of heat pumps. Nevertheless, in the whole context we consider the thesis of H.C. Becker (directed by F. Maréchal) as key reference due to the systematic methodology, based on pinch analysis and process integration techniques, to integrate heat pumps into industrial processes.

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[23] K. Lassmann, H.-J. Laue, Information Centre on Heat Pumps and Refrigeration IZW e.V., internal reports available on request,

[24] K. Lassmann and H.-J. Laue, Upgrade of the Annex 21 IHP Screening program, IZW internal note 2 (2011), IEA HPP – IETS Annex 35 /13, Application of Industrial Heat Pumps

[25] K. Holiastos and V. Manousiouthakis, Minimum hot/cold/electric utility cost for heat exchange networks, Computers and Chemical Engineering 26 (2002) 3-16

[266] F. Maréchal, personal communication

2 Austrian Team Report - Software

Within the Task 2 of the IEA HPP-IETS Annex 35/13 different software tools regarding the integration of heat pumps in production processes and there energetic and economical savings have been analysed. Due to the lack of the availability of measurement data the tools are only described theoretically without validation.

An investigation concerning available programs for the calculation and interpretation of large heat pumps and their integration into complex systems has been carried out, focusing on software solutions that can be used by industrial companies: No time-consuming model development is necessary, technical and economic aspects might be considered, relatively simple data entry, data are easy and inexpensive to collect, etc. Since the financing of the national project does not provide costs for the purchase of software licenses, the search was limited to free software. An attempt was made to obtain demo versions of the software to analyze the applicability. From this analysis a qualitative evaluation of the available software can be carried out to prove if the tools can be used for research and as well for industry. The analysis will include, among others, the following:

- For what purposes is the software suitable?
- Which heat pump technologies can be simulated?
- How flexible is the software in terms of system design?
- Is the software suitable rather for research or for planning and calculation of real systems?

Based on the experience gained, the need for the development of new or the adaptation of existing tools and models have been evaluated. In this regard also the simulation tools EES, ASPEN Plus and CoolPack have been analysed concerning the ability for proving suitable system integrations. EES (2010), ASPEN Plus (2009) and CoolPack (2014) are tools for a theoretical analysis of different heat pump cycles by means of thermodynamics, but they are not the optimum tools for the analysis of the integration of heat pumps in complex systems, as e.g. production processes by the end users or planers concerning ecological and economical criteria.

As part of this project two software tools "TOP-Energy" (2013) & "EINSTEIN" (2013) for the analysis and optimization of energy systems including the possibility of integrating heat pumps have been traced and described in more detail.

2.1 TOP Energy

The “TOP energy” (2013) software was developed by the Department of Technical Thermodynamics - RWTH Aachen University to support the analysis and optimization of energy systems. The software consists of several modules, which are attached to a common framework. The framework provides basic functionalities, such as Open / Save Project / Export, while the modules satisfy a specific engineering task. Currently the modules eNtry for initial analysis, eSim for the simulation of Energy systems and eVariant for the comparison of different variants exist.

The TOP energy framework is a software tool, which specifies a specific application structure to carry out projects for the analysis and optimization of power engineering problems in industry. The execution of tasks is supported by implemented application modules that are controlled and monitored by the framework.

The energy oriented analyses are performed by eNtry - initial analysis and use specific questionnaires for data collection. The module checks the entered data for plausibility, calculates a number of operational energy figures and compares them with typical industry values. The results of the evaluation are presented clearly in diagrams and tables and can be exported to a report.

The optimization of energy use in the industry is determined by the simulation module eSim and the flow diagram editor, while energetic as well as economic and ecological characteristics are worked out. A comparative economic analysis for energy applications is realized with the module eValuate - variant comparison.

Two types of heat pump models are available:

- A compression heat pump is given as a component template. It is used in TOP energy as model description of a heat pump process, which is driven mechanically respectively electrically. Apart from the technical input data it is also possible to use economic data which indicate the capital- bound or the operational costs of the components. This information is used to compare the efficiency of energy system variants with the TOP Energy eValuate Module.
- The Model of an absorption chiller describes the thermal behaviour of a thermally driven heat pump. Electric auxiliary drives, for example for the solvent pump between drain and desorber are not modelled and are not included in the calculations. User input concerning capacity is required, which includes the nominal cooling capacity, power consumption (thermal) and electricity. Furthermore temperature levels can be specified for cooling, re-cooling and the thermal input. The dependencies between the temperature levels and the behaviour of the chillers are not yet implemented in this component. With an input file the characteristic of a part load behaviour for the absorption chiller can be specified, in the simplest case, there is a linear curve from 0 to 100 % of the rated power.

2.2 EINSTEIN

EINSTEIN thermal energy industry audit

EINSTEIN (Expert System for an Intelligent Supply of Thermal Energy in Industry and other large-scale applications, 2013) is a tool-kit for fast and high quality thermal energy audits in industry, composed by an audit guide describing the thermal energy audit methodology and by a software tool that guides the auditor through all the audit steps.

The free, open-source software tool EINSTEIN enables the development of strategies to reduce energy consumption and operating costs in the company. In contrast to standard measures for reducing the electrical consumption in industry such as by pumps, motors, lighting achieving good results, the optimization of the thermal energy requirements is technically quite complex (Schweiger et al., 2011). The “eye of EINSTEIN” (see takes into account heat recovery, process integration and a smart combination of economic heating and cooling supply technologies.

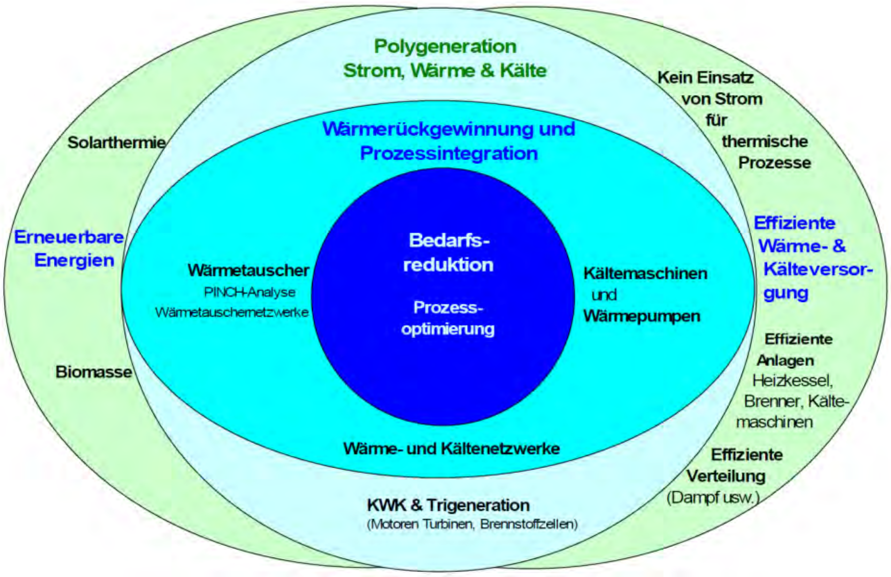

Figure 2-1: *“The eye of EINSTEIN” – holistic approach for audits of the thermal energy supply of processes (Schweiger et al., 2011)*

The software results from the Intelligent Energy Europe (IEE) project EINSTEIN with the collaboration partners: Joanneum Research (Austria), Sapienza University of Rome (Italy) and energyXperts.NET (Spain) in the framework of the IEA (International Energy Agency) - Solar Heating and Cooling and SolarPACES Programs, task 33 (Brunner et al., 2010)

EINSTEIN is a method of introducing a holistic and integrated approach to thermal energy audits for both, industrial applications as well as hospitals, office buildings and sports halls. Einstein calculates the thermal energy demand, rates savings by heat exchange using pinch analysis, points out technical alternatives for the integration of energy efficient and renewable energy systems and evaluates them. The user is guided through the entire audit process, from data collection through to the development of alternative technological solutions. The tool is aimed in particular sectors with a high proportion of low and medium temperature levels of heat, such as the food or the paper industry.

Figure 2-2: *Elements of EINSTEIN`s audit instruments (EINSTEIN, 2013)*

The software tool shows concrete results for energy and economic savings that can be achieved through a restructured or optimized heat supply system. The alternatives include all major energy- efficiency technologies (e.g. heat recovery, cogeneration, heat pumps, solar thermal and biomass).

2.3 Literature

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3 French Team Report - State of the Art Review on Analytical Tools based on the Pinch Method

3.1 Introduction

Process energy integration is intended to identify potential sources of energy recovery via heat exchange and integration of utilities in an industrial process. Historically, it has relied on the concept of Pinch Analysis.

The Pinch Method enables among other to identify potentials for the positioning of heat pumps by evaluating the operating powers and temperatures.

This review inventories tools identified as based on the Pinch Method. It does not claim to be an exhaustive list, as numerous pinch analysis tools exist and new tools are released every year. Some of the tools presented in this report may now be obsolete, since this state of the art review was carried out over several years.

3.2 Methods of process energy integration

3.2.1 Principle

The pinch analysis relies on a thermodynamic approach of the process. It involves identifying the energy flows of the process, considering only the real requirements linked to product conversion, and hence disregarding the means implemented by the industrial manufacturer to meet these needs. Once the list of streams is established, some mathematical tools can be used to identify sources of process inefficiencies and to propose corresponding upgrades.

The successive steps of the method are detailed below:

1. <u>Definition of hot flows and cold flows</u>. This involves defining the unitary process operations and quantifying their energy requirements. These requirements may be determined according to nature of the fluid (and specific heat), its temperature at input and output of the unit operation. A heat **source** (or hot flow) qualifies a fluid containing a certain amount of recoverable energy or that must be **cooled** to meet the process needs, and a heat **sink** (or cold flow) refers to a fluid that must be **heated** before being used in the process.
2. <u>Construction of composite curves</u>. Composite curves are used to establish target values of minimum energy consumption. They represent the profile of available heat sources (cold composite curve) and the profile of heating needs of the process (hot composite curve). To build these curves, the total heat availability and demand values are cumulated at various temperature intervals in the system (based on the formula $\Delta H = mC_p\Delta T$) and these enthalpy results are plotted on a diagram (T,H).
3. <u>Identification of the pinch</u>. The cold and hot composite curves are plotted on the

same diagram (in such a way that they do not overlap). The lowest vertical gap ΔTmin is identified, corresponding to the minimum allowable temperature difference between the two fluids in a heat exchanger: this is the **pinch point**. The pinch ΔTmin arises from a trade-off between the cost of an exchanger providing for heat recovery internally and the cost of utilities required to meet the heating and cooling requirements of the process.

The region above the pinch (right-hand side of the graph) requires only a heat input (Q_{hmin}) to meet the process needs, while the region below the pinch (left-hand side of the curve) only requires cooling (Q_{cmin}). Thus the process should be built in such a way as to avoid any heat transfers from a hot flow above the pinch towards a cold flow below the pinch. Otherwise, the energy consumed would need to be offset by an input from a utility (hot or cold).

4. Calculation of minimum energy requirement (MER) for the process. Once the composite curves are calibrated with the pinch point, the MER corresponds to the requirements in utilities (hot and cold) not supplied by the process itself.

3.2.2 Required data

The data necessary for a pinch analysis correspond to the characteristics of the streams needing to be heated, cooled or where there is a phase change. These data generally include:

- mass flow (kg/s)
- calorific power (kJ/(kg.°C)
- temperature of available flow and temperature that it needs to reach in the process (°C)
- latent heat for phase-changing flows (kJ/kg)

3.2.3 Results

3.2.3.1 Composite curve (CC)

Building the composite curves (Figure 3-1**Fehler! Verweisquelle konnte nicht gefunden werden.**) enables the identification of the pinch point along with a technical and economic optimisation of the potential for heat recovery via exchangers. By shifting the cold flow curve to the left or to the right, the temperature gap between the two curves (and therefore the pinch) decreases or increases respectively, which reflects that heating or cooling energy requirements decrease or increase respectively. Consequently, the energy consumption, i.e. operating costs (opex) of the facility, is proportional to the pinch. Conversely, the exchange surface area of the exchangers, i.e. capital spending costs (capex), is inversely proportional to the pinch.

Thus, depending on the selected criteria, the proposed solutions may differ.

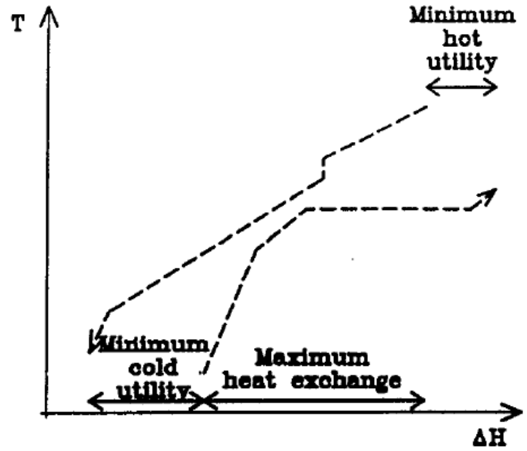


Figure 3-1: Composite curves[2]

3.2.3.2 Grand Composite Curve (GCC)

Instead of superimposing the two composite curves, it is possible to plot, for each temperature interval, the enthalpic balance, net of the interval, which provides the “grand composite curve” or GCC representing the gap between the hold and cold fluids (Figure 3-2).

The GCC is used primarily to optimise the utilities. Such optimisation is applied when several temperature levels are possible for the heating or cooling energy inputs into the process. Thus, the GCC enables an identification of opportunities for positioning heat pumps.

[2] Erik WALLIN & Thore BERNTSSON, Integration of heat pumps in industrial processes, Heat Recovery Systems & CHP, vol 14, No 3, pp. 287-296, 1994

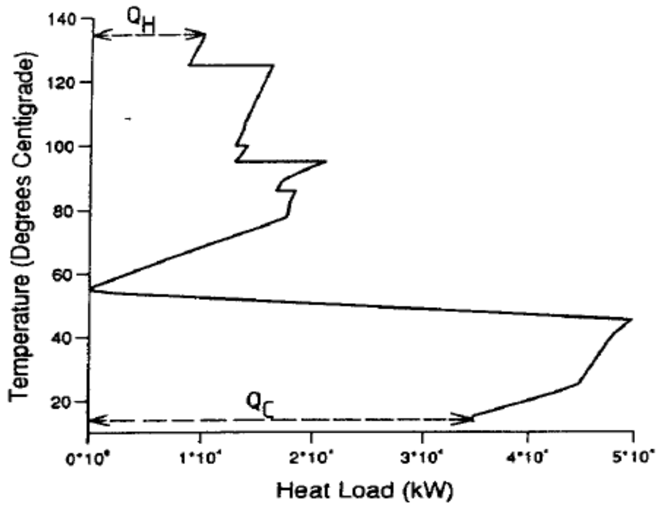


Figure 3-2: Example of Grand Composite Curve[3]

3.2.3.3 Positioning of heat pumps

Based on the pinch method, and via the data supplied by the grand composite curve, it is thus possible to optimise the positioning of utilities, and heat pumps in particular. A heat pump should be positioned through the pinch in such a way that the heat source is located below the pinch and the sink above the pinch. The presence of a pinch automatically implies the thermodynamic feasibility of a heat pump; and based on a reading of the grand composite curve, the theoretical COP of the system can be evaluated (via the condensation and evaporation temperatures). The technical and economic feasibility is however not automatic, and some tools incorporate these parameters into their calculations.

3.2.4 Benefits and drawbacks

The pinch analysis presents a number of benefits useful to enhance the energy efficiency of industrial processes.

- It provides an overall view of the industrial site under study, by optimising the recovery of often-lost energy and thus minimising energy losses in non-cooled hot flows.
- It helps adapt the utilities energy consumptions to the process requirements, unlike traditional methods which primarily address the utilities by segregating them from the manufacturing process.
- It relies on a simple graphic representation that enables the energy consumptions to be visualised and helps both the energy expert and the industrial manager to view

[3] Erik WALLIN & Thore BERNTSSON, Integration of heat pumps in industrial processes, Heat Recovery Systems & CHP, vol 14, No 3, pp. 287-296, 1994

the potential gains and the actual gains achieved in the study, thereby delivering objective analytical data.

The method however also presents a few limitations, among which the following, most frequently reported drawbacks:

- Loss of geographic information: the layout of (hot and cold) flows in the industrial site may dictate some constraints to their integration. For instance, some flows identified on the utilities side may be very remote from the production shop, which requires a very long exchanger network, thereby generating potentially non-negligible losses, or even losses higher than the energy gains identified via the pinch method. In order to remedy this problem, specific requirements (or prohibitions) should be applied when pairing some streams.
- Temporal disparity of the flow: this would be the case for instance with irregular power demands on the flows (hot and cold). This problem is frequently encountered for batch processes where energy streams are not available simultaneously and require heat storage systems to be installed. Although in some cases this difficulty may be overcome by reorganising the work schedule, this solution is however not always easy to implement for industrial managers.
- Technological difficulties linked to the process: such difficulties may be encountered in the food industry for instance where health security and bacteriological requirements are substantial. Exchanges between the various energy streams are then difficult to achieve with simple heat exchangers only.
- Lastly, the technical constraints may be compounded by economic constraints. In compliance with the IPPC (Integrated Pollution Prevention and Control) Directive, the application of process energy integration methods may prove very costly, due primarily to the substantial amount of data to be collected.

3.3 Stakeholders

A number of private companies offer off-the-shelf software programs, but research laboratories are also very actively involved in developing such tools for research purposes.

3.3.1 ACADEMIC RESEARCH LABORATORIES

3.3.1.1 University of Manchester (UK)

Presentation of research laboratory:

The University of Manchester (UMIST) and more specifically the Centre for Process Integration (CPI), is positioned as a benchmark in the field of process energy integration. Professor Bodo Linnhoff, creator of the Pinch Analysis, had developed his method within this university.

UMIST proposes several tools focussed on energy integration distributed via the Process Integration Research Consortium (PIRC). The consortium is a partnership between the University of Manchester (UMIST, School of Chemical Engineering & Analytical Science), industries (primarily from the oil industry, e.g. BP, Total, etc.) and other academic institutions.

PIRC operates on the basis of annual memberships granting access to the tools developed and to training sessions and exchange workshops.

UMIST has developed two software tools linked to the pinch method:

- SPRINT (focussed on optimising the heat exchanger network) – a detailed description is provided on page **Fehler! Textmarke nicht definiert.**.
- STAR (focussed on optimising the utilities system of complex processes, such as petrochemical) – its major functionalities are described on page **Fehler! Textmarke nicht definiert.**.

3.3.1.2 EPFL (Switzerland)

Presentation of the research laboratory:

EPFL or Ecole Polytechnique Fédérale de Lausanne is one of the prime engineering schools in Switzerland based in Lausanne. EPFL is the co-founder of the European Center Laboratories for Energy Efficiency Research (ECLEER), jointly with EDF and the Ecole des Mines de Paris engineering school.

Within EPFL, the *Laboratoire d'Energétique Industrielle* (LENI, or Laboratory of Industry Energy Engineering) headed by Professor Daniel Favrat, is an internationally recognized benchmark in the field of energy conversion systems (heat pumps, organic Rankine cycles, fuel cells) and of energy integration of heating systems; this latter research topic is headed by François Maréchal based on several methods, and the pinch method in particular, along with other environmental assessment methods such as LCA (life cycle analysis).

Following the retirement of Professor Favrat in the summer 2013, the LENI research teams have been reorganised. Activities related to energy integration are nevertheless continuing in a research group under the leadership of François Maréchal.

The LENI lab has developed three tools based on the pinch method:

- OSMOSE: presented on page 3-47 of this review.
- Pinchlight: web interface with the “basic” functionalities of OSMOSE, presented on page 3-45.
- PinchLENI: this tool was adapted and converted by the Hochschule Luzern to design the PinCH software; see presentation of the Hochschule Luzern for more details on page 8.

3.3.1.3 Mines Paristech (France)

Presentation of the research laboratory:

The Ecole Nationale Supérieure des Mines de Paris (Mines Paristech) is one of the most prestigious French engineering schools. Its CES (*Centre d’Eco-efficacité des Systèmes*) or Centre for Systems Eco-Efficiency, formerly CEP (*Centre Energétique et Procédés*), is a research laboratory dedicated to energy engineering, both on the generation and the consumption sides.

The CES has developed two tools based on the pinch method:

- CERES platform, presented on page 3-49.
- Thermoptim, presented on page 3-48.

3.3.1.4 Chalmers University of Technology (Sweden)

Presentation of research laboratory:

Chalmers University of Technology is one of the most renowned universities in Sweden.

The university has outsourced its corporate services via the engineering consulting firm CIT (or Chalmers Industriteknik) consisting of five subsidiaries, including in particular **CIT Industriell Energi with expertise in the field of industrial process energy integration.**

This subsidiary has developed and uses a tool called Pro_Pi presented on page 3-51.

3.3.1.5 Hochschule Luzern / Lucerne University of Applied Science & Arts (Switzerland)

Presentation of research laboratory:

The University of Lucerne is a recently founded Swiss university (1997). Among its faculties, the School of Engineering & Architecture is involved in developing the "PinCH" tool designed for applications of the pinch method and supported by Office Fédéral de l'Energie (OFEN).

PinCH uses the PinchLENI tool as a starting point, an open-source software for pinch analysis designed by the LENI lab at EPFL in the 1990s. PinCH has however been largely upgraded since then and is now entirely different from PinchLENI.

The PinCH tool developed by this university is presented on page 3-52.

3.3.1.6 Universidad de Valladolid (Spain)

Presentation of research laboratory:

The department of *Ingeniería Química y Tecnología del Medio Ambiente* of the University of Valladolid in Spain offers a curriculum in energy integration teaching the pinch method. However, this university does not seem to be recognized as a benchmark in the field.

The university has designed a tool called Hint, downloadable on line free of charge**Fehler! Verweisquelle konnte nicht gefunden werden.Fehler! Verweisquelle konnte nicht gefunden werden.**, presented on page 3-54.

3.3.1.7 University of Aalto (Finland)

Presentation of research laboratory:

Formally named Helsinki University of Technology (TKK), the University of Aalto is conducting research on energy integration within its Department of Energy Technology.

Their research activities focus on energy integration in paper-making sites, in particular integrated sites (simultaneous production of pulp and paper). Apart from the pinch method, they also use other methods of process analysis.

The university is developing a tool to visualise heat exchanger networks, called HeVi. The specific feature of this tool is to combine the conventional representation of flows in a Grid Diagram with a representation in Sankey diagrams.

This tool does not use the pinch method strictly speaking since it does not provide for modelling the exchanger network, but merely its graphic representation (although this representation is of great interest in itself). However, the tool version available on their web site dates back to 2008 and the web page has not been updated since then. Its development appears to have been stopped and the tool has no explicit documentation.

3.3.1.8 University of Waikato (New Zealand)

Presentation of research laboratory:

The University of Waikato in New Zealand has a dedicated laboratory called Industrial Energy Efficiency Division looking at the pinch method and the integration of discontinuous processes. The research work is carried out in close partnership with industries (dairy industry in particular) and involves both lab-scale and field-scale experimental trials.

The lab researchers publish frequent articles at the PRES conference (Conference on Process Integration, Modelling and Optimisation for Energy Saving and Pollution Reduction).

In the context of research on the pinch method, the University of Waikato has developed an in-house application of the method; this tool has however not been released outside the university and its functionalities remain unknown (only a few screenshots are available in some of their publications).

3.3.1.9 Instituto Superior Técnico (IST) of Lisbon (Portugal)

The Technical Institute of Lisbon includes a department called Integration and Optimisation of Processes with teaching and research activities on the pinch method.

The IST is involved in the development of tools such as BatchHeat, or more recently FI^2EPI on behalf of *Ferramenta Informática para Integração Energética de Processos Industriais*, developed in partnership with the Portuguese Energy Agency (ADENE). The tool exists only in a Portuguese version and we were unable to test it.

3.3.2 OTHER NON-ACADEMIC PLAYERS

3.3.2.1 AEE-Intec (Austria)

Presentation of research laboratory:

AEE – Institute for Sustainable Technologies (or AEE-Intec) is an independent Austrian research institute working in three main areas: solar heating, low-energy buildings and energy efficiency of industrial processes.

Their research focuses on energy integration of discontinuous processes (particularly in the brewery industry), size design of heat storage systems and integration of solar heating in industries.

AEE Intec develops numerous auditing tools, most of which involve the pinch method for analysis; this is the case of Einstein, a process thermal auditing tool containing a pinch method application module. Einstein is presented on page 3-54.

3.3.2.2 KBC Advanced Technology (UK)

Presentation of the company:

KBC Advanced Technology, founded in 1979, is a consulting and engineering firm dedicated to industrial processes. KBC is specialised more specifically in the oil industry but covers all energy areas (refinery, petrochemical, power generation, biofuels, etc.).

In 2002, KBC acquired Linnhoff March Ltd., an independent engineering firm created in 1983 by Professor B. Linnhoff, the founder of the pinch analysis method.

Further to the acquisition of Linnhoff March Ltd, KBC inherited the sequel tools of SuperTarget, the benchmark for applications of the pinch method that follows the Linnhoff concept to the letter. This tool is presented on page 3-57.

3.3.2.3 Aspentech (USA)

Presentation of the company:

Aspentech (abbreviated from Aspen Technology Inc.), a start-up created in 1981 at the Massachusetts Institute of Technology (MIT), has become a leader of software applications dedicated to industrial process optimisation (particularly in the chemical and petrochemical industries) and offers an extensive range of applications covering all sectors and all issues (modelling, simulation, logistics, equipment design, etc.). Their solutions address primarily the petrochemical, fine chemistry and pharmaceutical industries, but over time they tend to extend to other industrial sectors as well.

Aspentech offers an extensive range of software programs combined in the AspenONE V8 software suite, split into five categories:

- Engineering
- Petroleum Supply Chain
- Supply Chain Management
- Advanced Process Control
- Manufacturing Execution System.

The AspenEnergyAnalyzer tool (formerly known as Aspen HX-Net) fits in the first of the above software categories. This tool is presented on page 3-58.

3.3.2.4 Canmet ENERGIE (Canada)

Presentation of research laboratory:

Canmet ENERGIE is a laboratory affiliated to the Canadian Ministry of Natural Resources, specialised in technology development and research on clean energies. Its staff includes over 450 scientists, engineers and technicians.

The lab works in all fields related to energy – renewable energy sources, fossil fuels, energy consumption in buildings, etc. – in close collaboration with the industrial sphere. It includes among other a department dedicated to process energy integration.

In the field of process integration, Canmet ENERGIE has developed an **Integration** tool for applications of the pinch method as well as energy modelling and analysis of utilities (boilers, cooling units, air compressors, etc.).

3.3.2.5 ProSim (France)

<u>Presentation of the company:</u>

ProSim is a leader in the field of chemical engineering software, providing process simulation software programs and design & engineering services in the following industries: oil and gas, chemistry, pharmaceuticals, energy and other process industries.

The company was created in 1989, backed by a flowsheeting tool developed at Ensiacet in Toulouse (formerly called ENSIGC).

ProSim offers several software programs, among which ProSimPlus (for process modelling and simulation) and Simulis Thermodynamics (to calculate the properties of fluids and fluid mixes).

In 2010, this tool was limited to plotting composite curves, while ProSim's short-term goal was to develop a library of utilities models along with an algorithm for optimising exchanger networks. ProSim is currently developing a tool designed for energy integration, in partnership with Veolia under an ANR project (COOPERE). Their approach appears to be oriented to energy analysis, although they use the pinch method for basic analysis.

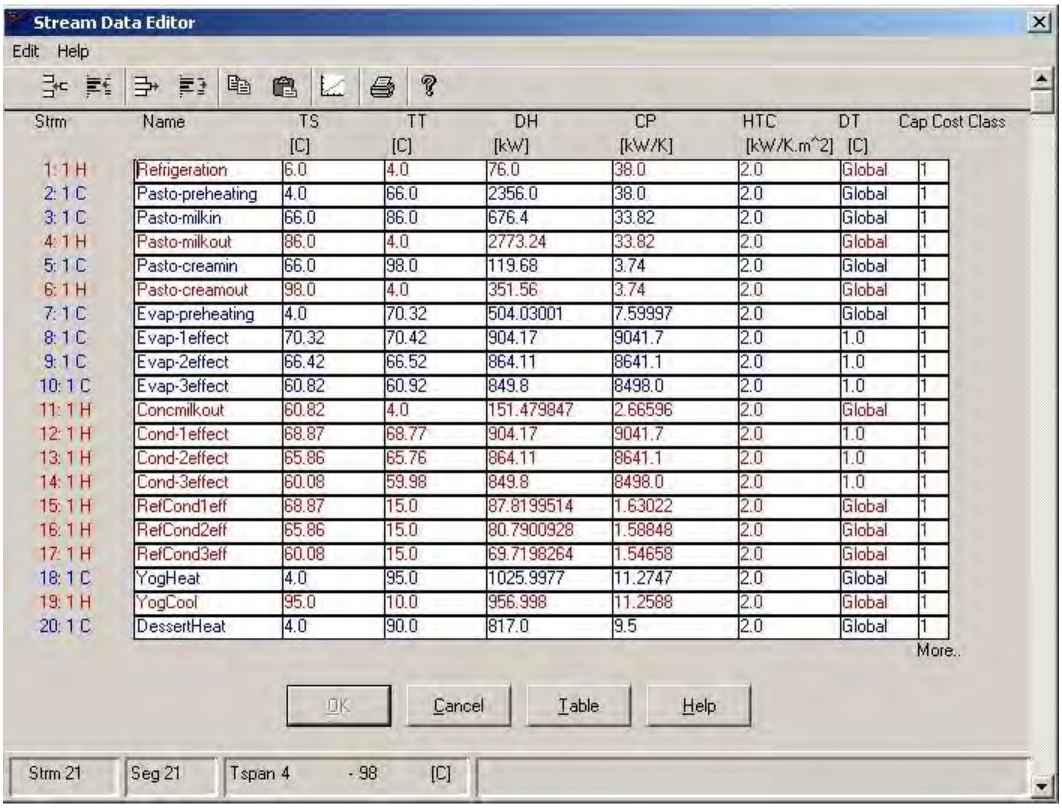
3.4 Tools

3.4.1 STAR and SPRINT

Star and Sprint are very similar and complementary tools, but used independently of each other. Figure 3-3 below shows their respective interfaces.

Figure 3-3: Comparison of interfaces in Star and Sprint

They share the basic functionalities of the pinch analysis, such as optimisation of ΔTmin, or graphic representation of composite curves and grand composite curves ("Target" menu of the interface on Figure 3-3**Fehler! Verweisquelle konnte nicht gefunden werden.**). The curves are calculated from the chart of process flows presented in Figure 3-4 below, and their data can be exported from one tool to the other.



Strm	Name	TS [C]	TT [C]	DH [kW]	CP [kW/K]	HTC [kW/K.m^2]	DT [C]	Cap Cost Class
1: 1 H	Refrigeration	6.0	4.0	76.0	38.0	2.0	Global	1
2: 1 C	Pasto-preheating	4.0	66.0	2356.0	38.0	2.0	Global	1
3: 1 C	Pasto-milkin	66.0	86.0	676.4	33.82	2.0	Global	1
4: 1 H	Pasto-milkout	86.0	4.0	2773.24	33.82	2.0	Global	1
5: 1 C	Pasto-creamin	66.0	98.0	119.68	3.74	2.0	Global	1
6: 1 H	Pasto-creamout	98.0	4.0	351.56	3.74	2.0	Global	1
7: 1 C	Evap-preheating	4.0	70.32	504.03001	7.59997	2.0	Global	1
8: 1 C	Evap-1effect	70.32	70.42	904.17	9041.7	2.0	1.0	1
9: 1 C	Evap-2effect	66.42	66.52	864.11	8641.1	2.0	1.0	1
10: 1 C	Evap-3effect	60.82	60.92	849.8	8498.0	2.0	1.0	1
11: 1 H	Concmilkout	60.82	4.0	151.479847	2.66596	2.0	Global	1
12: 1 H	Cond-1effect	68.87	68.77	904.17	9041.7	2.0	1.0	1
13: 1 H	Cond-2effect	65.86	65.76	864.11	8641.1	2.0	1.0	1
14: 1 H	Cond-3effect	60.08	59.98	849.8	8498.0	2.0	1.0	1
15: 1 H	RefCond1eff	68.87	15.0	87.8199514	1.63022	2.0	Global	1
16: 1 H	RefCond2eff	65.86	15.0	80.7900928	1.58848	2.0	Global	1
17: 1 H	RefCond3eff	60.08	15.0	69.7198264	1.54658	2.0	Global	1
18: 1 C	YogHeat	4.0	95.0	1025.9977	11.2747	2.0	Global	1
19: 1 H	YogCool	95.0	10.0	956.998	11.2588	2.0	Global	1
20: 1 C	DessertHeat	4.0	90.0	817.0	9.5	2.0	Global	1

Figure 3-4: Chart of process flows in Star and Sprint

Beyond this, their functionalities differ:

- Sprint is designed for simulating and optimising the exchanger network between the process flows or between the process and the utilities.
- Star is designed for selecting the utilities most suitable for the process (boilers, cooling units, etc.), and conducting the analysis on a site-wide scale (design of steam network and CHP systems if any).

Both tools were developed more specifically for the oil and chemical industries, and do not include the integration of heat pumps among their functionalities.

3.4.2 Pinchlight

Pinchlight is a web interface designed to carry out a pinch analysis using a remote server. This server communicates with a multifunctional optimisation platform called Osmose which applies the pinch method to the user's data.

Figure 3-5 below shows the Pinchlight interface.

Figure 3-5: Pinchlight interface

There are 5 levels of data to be entered:

1) "General" tab to enter the general data of the analysis, e.g. cost of exchangers, of commercial energy supply, climate conditions, etc.
2) "Resources" tab to enter data on commercial energy consumptions (fuels, water).
3) "Energy Distributions" tab to list the process energy demands, e.g. steam, hot water, cooling water, etc. You can for instance define the heat requirement even if the details of the consuming process are missing.
4) "Process" tab to define the hot and cold flows of the process. A database of predefined modules facilitates the definition of flows, as shown in the **Fehler! Verweisquelle konnte nicht gefunden werden.** with the example of a pasteurisation process.
5) "Utilities" tab to list the utilities existing on the site (boiler, cooling unit, compressed air...) and their performance levels. Similarly to the Process tab, predefined modules can be used to facilitate data entry (single-stage cooling cycle, CHP with combustion turbine, etc.).

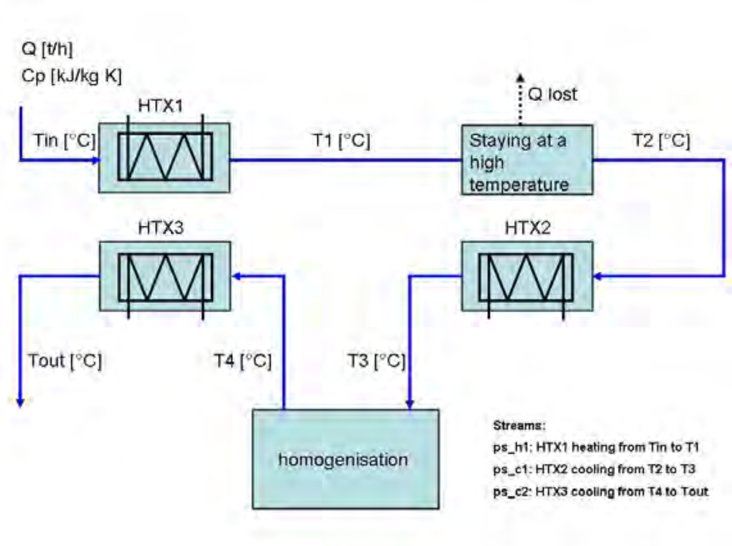


Figure 3-6: Scheme

Once the data have been entered, two major types of analysis can be carried out with Pinchlight:

- “MER” analysis (Minimum Energy Requirement) for energy integration of the process, optimisation of Tmin, and determination of the minimum energy consumption requirement. This analysis further leads to a bottom-up approach to energy consumptions on the site by comparing actual consumptions (energy bills) with consumptions calculated from the process optimisation.
- “Target” analysis to optimise the utilities and exchanger network related to the process.

Pinchlight stands apart from other tools in terms of the study of utilities: on the one hand, utilities are subject to a bottom-up analysis to inform on the actual consumption against optimum consumptions. Secondly, the optimisation of the process and of utilities is simultaneous, whereas in other tools the utilities are addressed only after the process has been optimised. Another feature of interest is the modules detailing some operations and utilities.

Conversely, Pinchlight will not allow for manual plotting of the exchanger network and the tool is not really simple to use.

3.4.3 OSMOSE

OSMOSE developed by EPFL is an optimisation platform designed for applications of the pinch method (among others, the ACV method for instance can also be applied).

Calculation models and procedures have been developed so OSMOSE can be used specifically to integrate heat pumps into an industrial process.

OSMOSE enables the positioning and sizing of heat pumps in the process to be optimised. It provides for design studies to be carried out on multi-period (or discontinuous) processes by factoring in energy storage. In addition, the tool also has functionalities for multi-target optimisation.

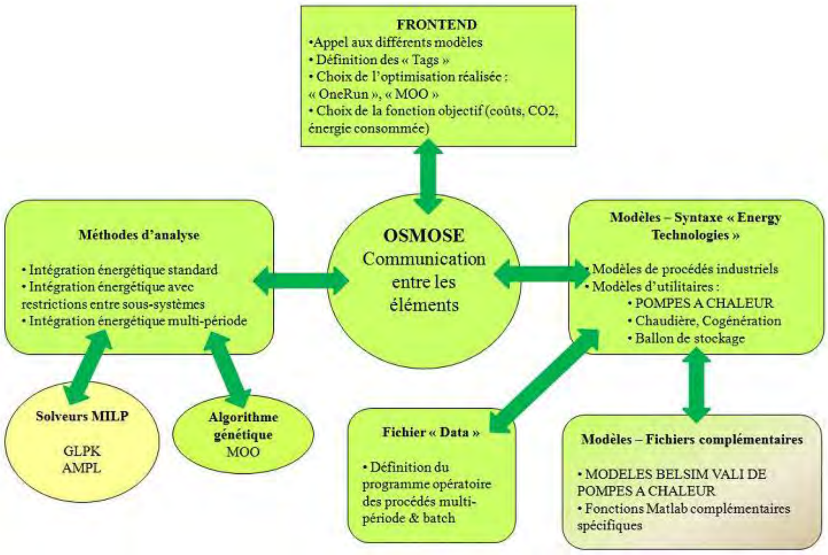


Figure 3-7: OSMOSE operating workflow

The OSMOSE platform enables discontinuous processes to be factored in and, via the multi-target optimisation function, determines the powers and temperature levels of the heat pumps to be integrated into the process. This is a highly efficient tool offering functionalities that do not exist in any other available tools.

OSMOSE however has several flaws that mitigate its qualities. Firstly, this is an optimisation platform, rather than a tool based on the pinch method; consequently, the tool is not user-friendly and learning to use it requires lengthy and complex training. In addition, it is based on many proprietary software applications (MATLAB, Belsim VALI…) whose user licensing costs are expensive.

3.4.4 Thermoptim

Thermoptim is a software package developed for the design and simulation of thermodynamic systems, in particular energy conversion processes. It consists of a diagram/flowchart editor and a simulation engine.

It provides for both an analytical and systemic approach:

- Each functional component is represented by an appropriate Thermoptim "primitive type" (vessel, process point, conversion, node, exchanger...) having its own modifiable characteristics and coupling variables.
- The full system is then modelled by assembling these primitive types via an interactive visual interface (Figure 3-8).

Once the various conversions are represented, the pinch method can be applied to the modelled system and the tool guides the user in building the exchanger network.

The primary goal of this tool is educational, hence its use is somewhat unwieldy. In addition, it is primarily suitable for energy generation systems (gas cycle turbines, Rankine cycle, etc.): while this may be overcome by building libraries of customised physical and chemical properties, it however becomes very time-consuming.

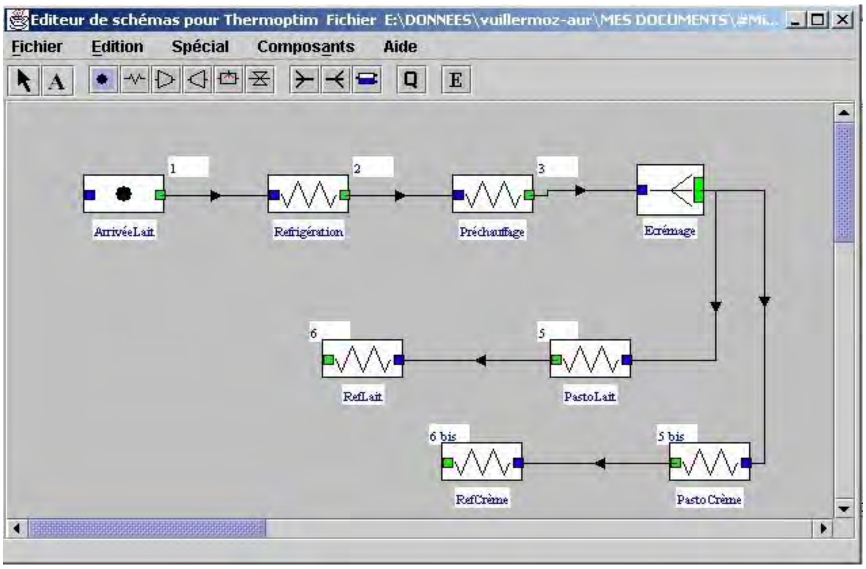


Figure 3-8: Example of modelling of a milk pasteurisation/skimming process

3.4.5 CERES

CERES is developed in the context of the ANR [French National Research Agency] project entitled "*Chemins Energétiques pour la Récupération d'Energie dans les Systèmes industriels*" involving eleven academic and industrial partners under the leadership of EDF. Its purpose is to identify strategies for the recovery and reuse of waste heat in industrial processes, and to foster the reach of innovative technologies contributing to rational energy uses.

It consists of:

- a platform designed to conduct energy integration studies,
- a library of models of industrial processes and utilities developed in Modelica language under a Dymola environment.

Note: The models library is currently developed under the Dymola environment which is a proprietary software (owned by Dassault Systems). CERES can however also operate with models developed under the free open-source OpenModelica environment.

CERES platform

The CERES platform enables **pinch method**-based studies to be carried out on energy integration. The method has been further enhanced with **optimisation algorithms** designed to select among a number of utilities (heat pumps, turbines, etc.) those that will minimise energy consumption, while factoring in the capex costs necessary to install heat exchangers, along with some environmental data.

Thus, for a given set of processes, the CERES platform allows for:

- determining the heat recovery potential and the minimum energy requirements, based on the pinch method (Figure 3-9),
- optimising the size design of utilities and exchanger network to be implemented, while minimising energy consumption and capex costs (Figure 3-10).

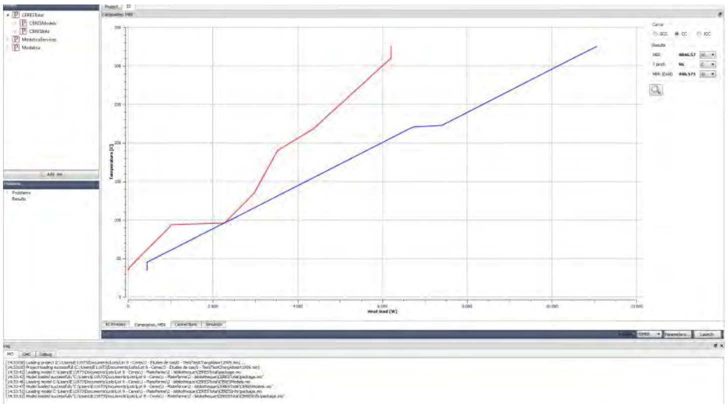


Figure 3-9: CERES platform – Composite curves and minimum energy requirement

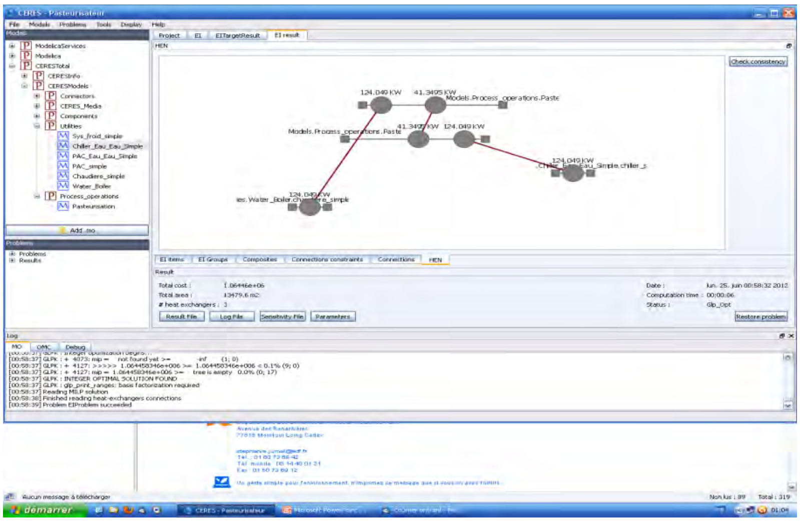


Figure 3-10: CERES platform – Optimisation and construction of utilities and exchanger network

Models library

A library of utilities and process models is currently under development in the context of the project (example shown on Figure 3-11). Table 3-1 below lists the models already developed and integrated into the platform.

Table 3-1: List of process and utilities models developed in the CERES-2 project

	Industrial processes	Utilities
Modelica models	Agri-food industry: Milk processing	Exchangers and storage Compression heat pump

	Pulp & Paper: Production of pulp and paper Metals: Cold machining	Sorption heat pump Thermoelectricity ORC

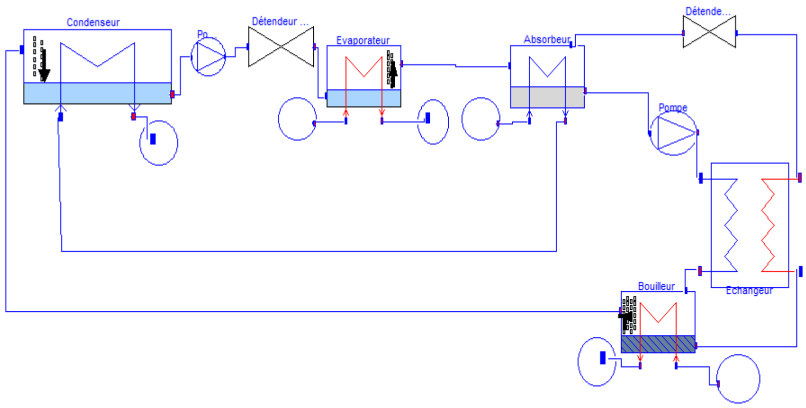


Figure 3-11: CERES library – Example of an absorption heat pump

This database of industrial processes and energy recovery and reuse technologies will be further enriched via updates and additions of new models by the users.

The CERES platform and the models library under Modelica will be available in open access once the project is completed, i.e. in mid-2014. The tool will then be free of charge with open access to everyone.

3.4.6 Pro_Pi

Pro_Pi is a tool dedicated to the pinch analysis and the construction of exchanger networks. It is formatted as a simple Excel macro (file .xls) to which are added pinch-specific functionalities (framed in red on Figure 3-12 below).

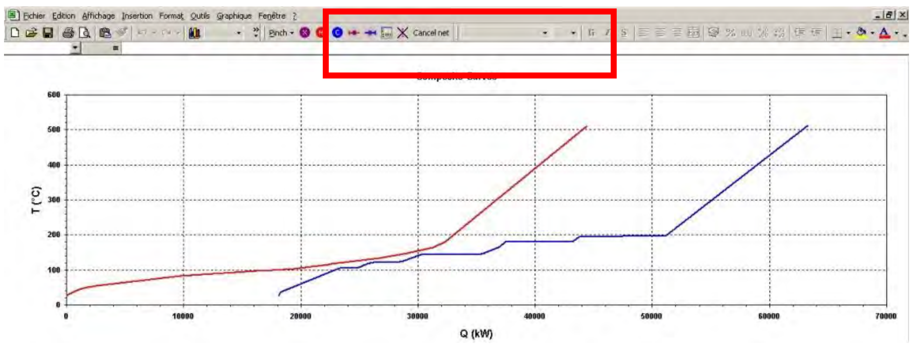


Figure 3-12: Pro_Pi interface

It also includes an interface for plotting heat exchangers.

Pro_Pi is a light-weight educational tool, usable directly under Excel. It contains the basics of pinch analysis and provides for manual plotting of an exchanger network. Modelling of utilities is rather rudimentary (quantity of heat at a given temperature), and the interface is not very user-friendly.

3.4.7 PinCH

PinCH is a tool developed by the University of Lucerne in Switzerland with support from the *Office Fédéral de l'Energie* (OFEN).

It enables the pinch method to be applied to a process or a set of processes. For each stream identified, it is possible to set the operating time frame (Figure 3-13). A Gantt diagram can thus be plotted for the process and the time parameters of the various production steps can be factored in. Based on the pinch analysis, the composite curves can then be plotted based on the Time Average Method (TAM, Figure 3-14) or based on the Time Slice Method (TSM) to account for discontinuous processes. Lastly, the tool provides the possibility for building the exchanger network for each time slice (Figure 3-15**Fehler! Verweisquelle konnte nicht gefunden werden.**).

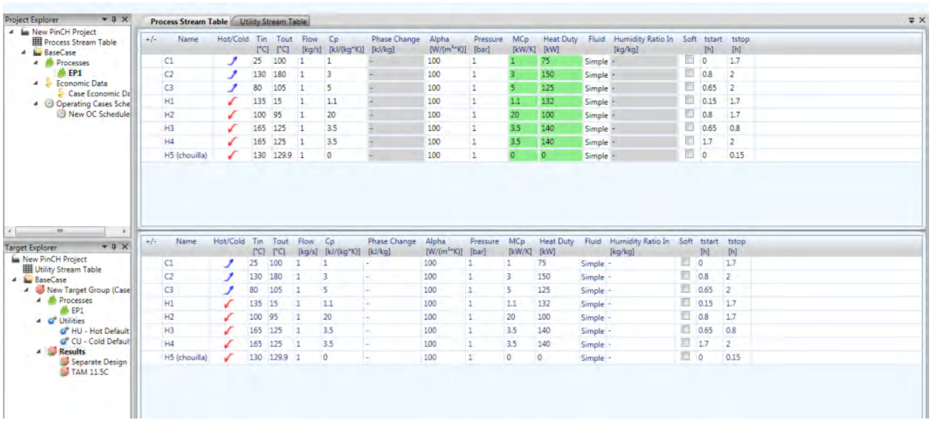


Figure 3-13: Entering flow data into PinCH

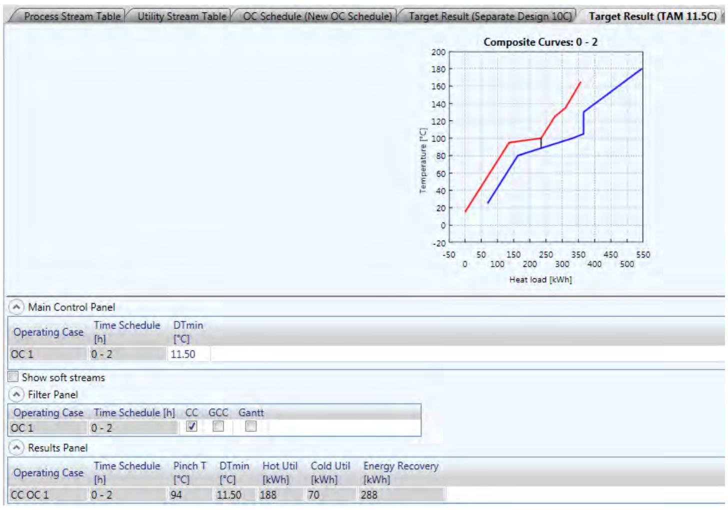


Figure 3-14: TAM analysis in PinCH

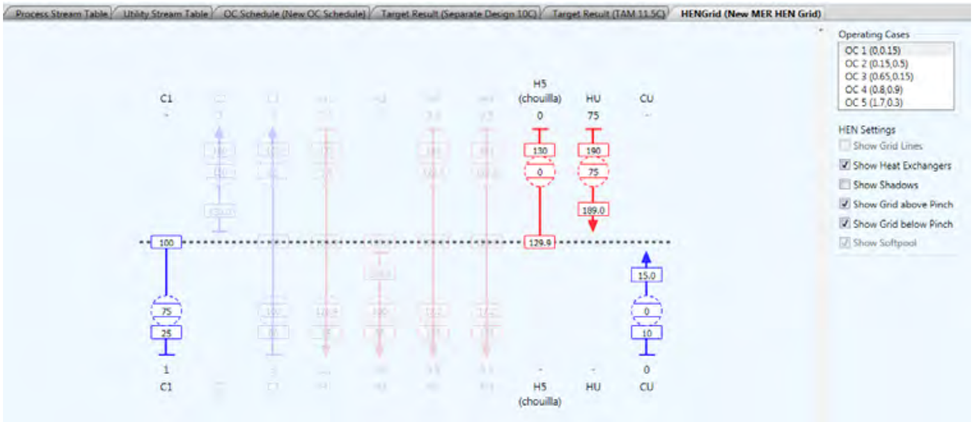


Figure 3-15: Building the exchanger network in PinCH

This software program may be ordered via a dedicated web site for a charge. The price of a single-station license is 2700 Swiss francs, i.e. EUR 2250 (in November 2012). A 10% discount is offered starting at 2 licenses and up to 25% for 5 licenses and over. It seems possible also to get lower prices if the tool is intended for research or learning purposes.

The tested version is V1.0.8.1542. This is an evaluation version where the number of flows is limited to eight. Our evaluation has however enabled us to identify the main benefits and drawbacks of this tool.

Benefits:

- Possibility for a TAM and TSM analysis.
- The exchanger cost functions can be easily parameterized.
- The license price is relatively low.
- Possibility of integrating heat pumps, MVC and motors with direct viewing on the grand composite curve.
- Parameters programmable for calculation of utilities costs.
- Where the fluid used is water, the tool automatically factors in the phase change and separates the stream accordingly.

Drawbacks:

- Non-intuitive ergonomics (subjective).
- Necessity to create a hot and cold utility meeting the MER before launching the analysis.
- In practice, it is necessary to determine a flow beyond and below the maximum and minimum temperature respectively, with enough power to meet the heat-ing or cooling requirement respectively.
- No help function (tips, default values, etc.) to position the utilities (heat pump, motor, MVC).
- No possibility of installing an ORC or a heating/cooling pump.

PinCH provides the possibility of factoring in the timing of processes, and ultimately the developers intend to integrate the multi-period function taking storage into account.

3.4.8 Hint

Hint – for Heat INTtegration – is an educational tool directed at students and dedicated to the pinch analysis and construction of exchanger networks. Figure 3-16 shows the interface. The tool was developed at the University of Valladolid in Spain.

Apart from the composite curves and grand composite curve, HINT enables the exchanger network to be plotted and modified.

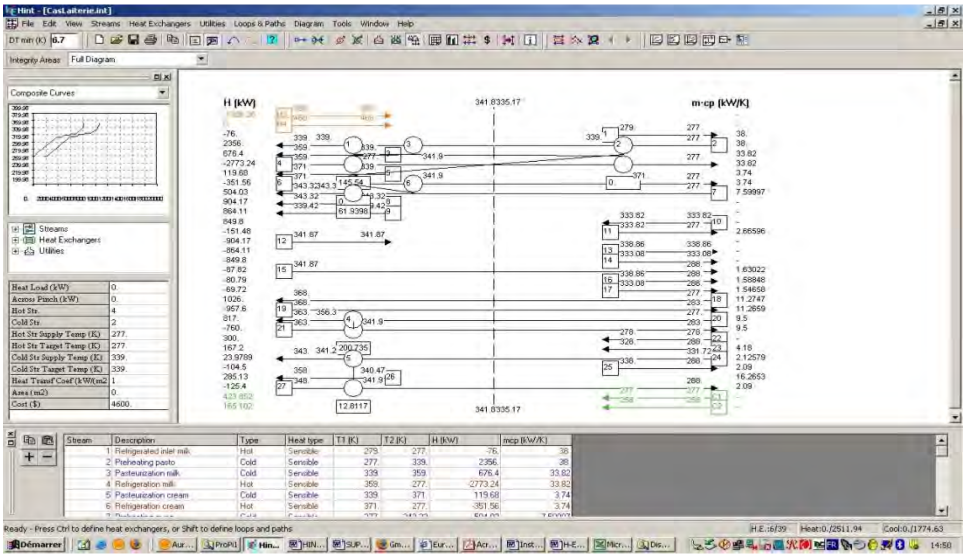


Figure 3-16: HINT interface

The HINT tool is downloadable on line free of charge. It includes the basic functionalities referring to the Linnhoff concepts, and constitutes a good resource to get familiar with the pinch method and start conducting simple studies, with a relatively easy to use interface. However, the development and related maintenance of this tool seem to have been stopped. In addition, the on-line help is very poor and a single article was published in 2008 in the journal *Education for Chemical Engineers* introducing the functionalities of the tool **Fehler! Verweisquelle konnte nicht gefunden werden.**.

3.4.9 Einstein

Einstein means "*Expert System for an Intelligent Supply of Thermal Energy in Industry and other Large-Scale Applications*".

Einstein is primarily a tool designed for thermal audits of industrial processes offering among other functionalities an application of the pinch analysis and design of exchanger networks.

The tool is the outcome of two consecutive projects funded by the program "*Intelligent Energy Europe*":

- **Einstein I** (September 2007 - August 2009)
- **Einstein II** (July 2010 - June 2012) **Fehler! Verweisquelle konnte nicht gefunden werden.**.

Einstein provides for a methodology applied to thermal audits of processes, comprising the following steps:

- Data acquisition and process modelling: all processes must be modelled according to a generic standard model (ref. Figure 3-17) including temperature rise, steady state and cooling with possible counter-flow exchange with the in-flow.
- Validation of data consistency (consistency check).
- Reduction of energy demand via process optimisation.
- Heat recovery via exchangers: this is the step that uses the pinch method (ref. Figure 3-18). Einstein plots the composite curves, the grand composite curve, and offers a choice between manual or automatic design of the exchanger network.
- Integration of new utilities and/or renewable energy sources, in particular:
    - solar heating
    - heat pumps
    - CHP
    - high-efficiency boilers

It should be noted that the pinch method is involved only when designing the exchanger network, and not in the choice of utilities: the tool does not really allow for determining which utilities or combinations thereof would be optimum; it only provides the possibility for testing various energy supply scenarios and to compare them based on energy, economic or environmental criteria (ref. Figure 3-19).

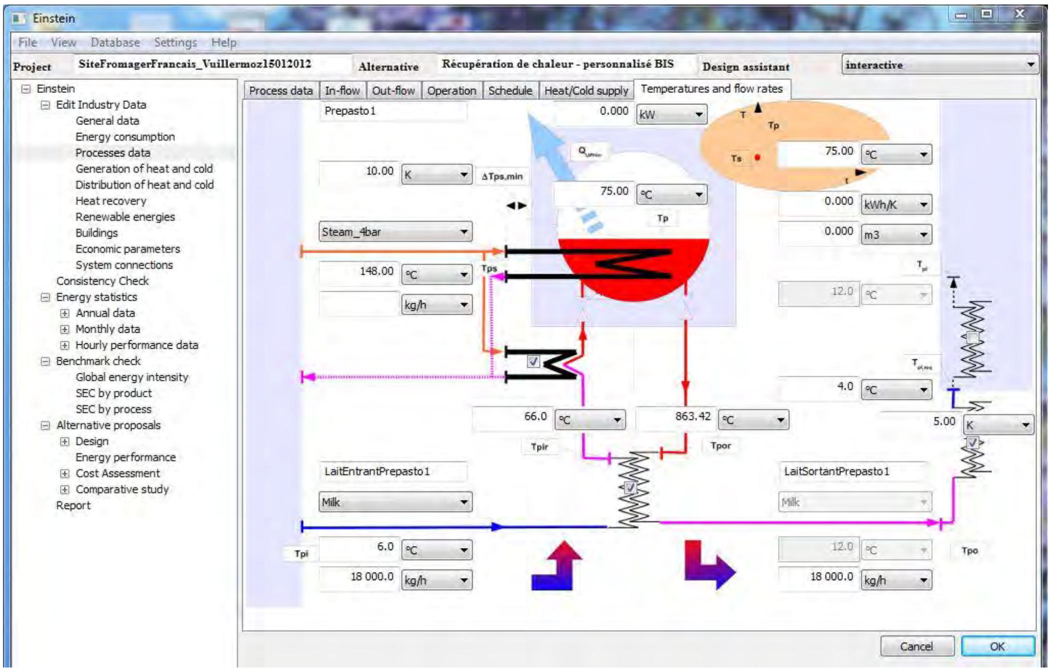


Figure 3-17: Standard model of a process

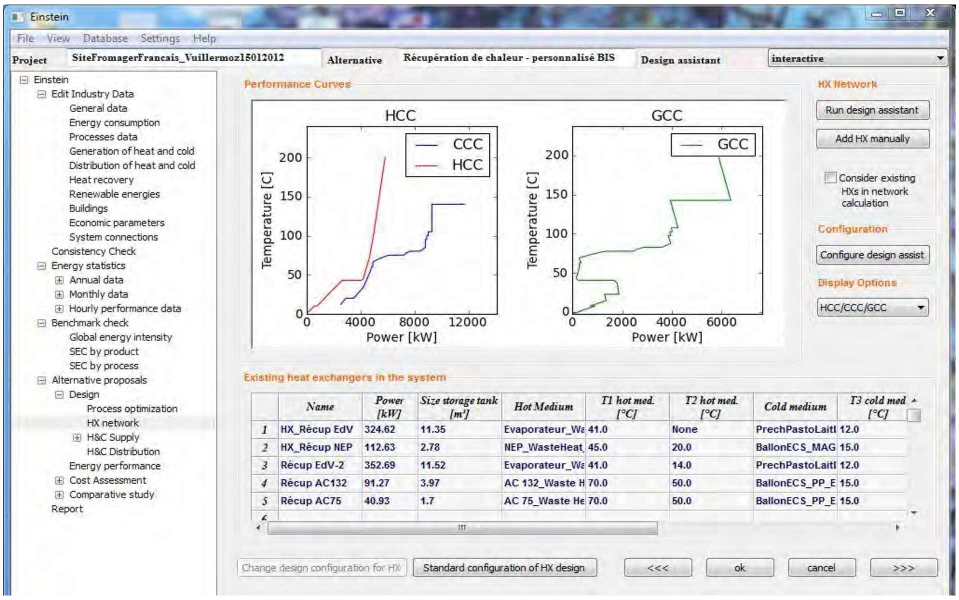
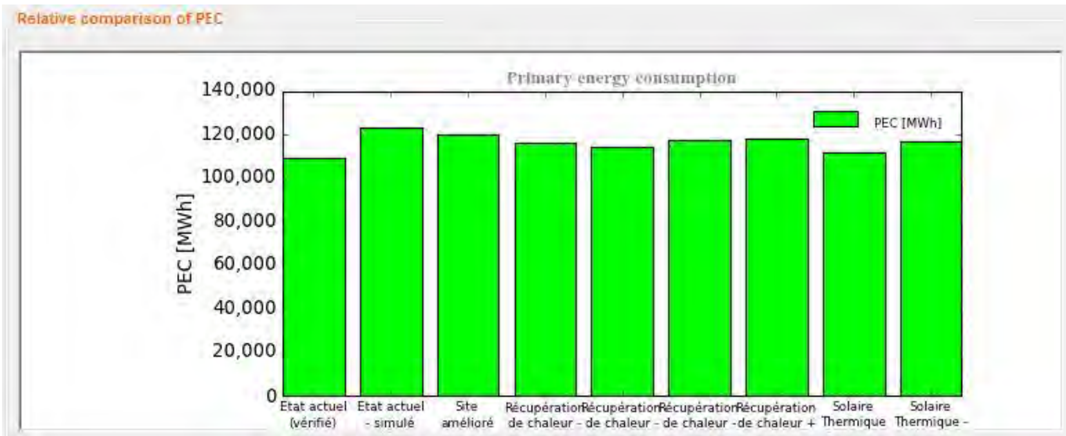


Figure 3-18: Optimisation of heat recovery via direct exchange



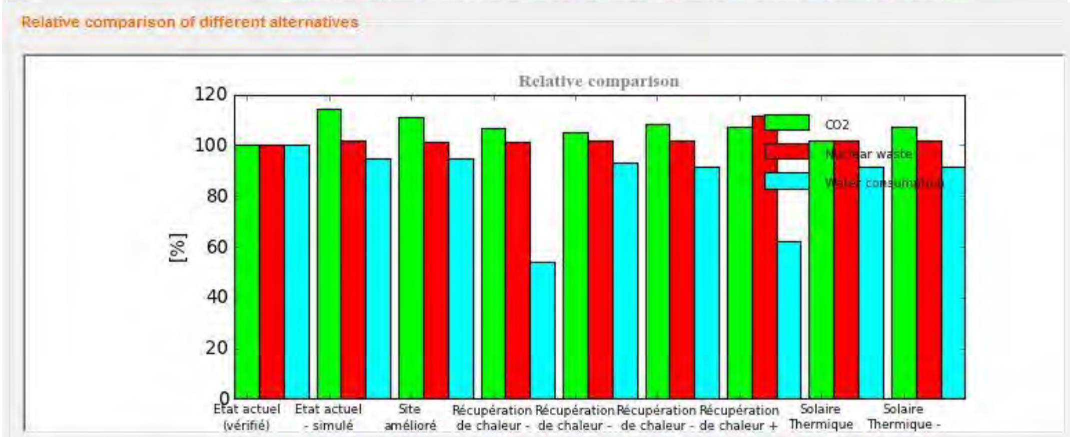


Figure 3-19: Comparison of various scenarios depending on primary energy consumption (top graph) and environmental impacts - CO_2, nuclear waste, water consumption (bottom graph)

The software is downloadable in free access on the Internet **Fehler! Verweisquelle konnte nicht gefunden werden.**. The most recent available version is the V2.2; however, we tested version 2.1.

Einstein was developed jointly by several partners, among whom the following were most closely involved:

- **Energy Experts**: a German/Spanish network of engineers and energy consultants **Fehler! Verweisquelle konnte nicht gefunden werden.**.
- **AEE Intec**: an Austrian research centre on sustainable technologies, in particular solar heating and process energy integration. AEE Intec supplied the optimisation algorithm used for automatic design of the exchanger network **Fehler! Verweisquelle konnte nicht gefunden werden.**.

Benefits:

- This is an audit tool that is not limited only to a pinch analysis and also includes other functionalities of interest, in particular the overall consistency check.
- Manual and automatic design of the exchanger network can be easily combined.
- The representation of the exchanger network in chart format is much more legible than a “grid diagram” representation.
- All economic analyses can be customized, and it is also possible to add specific pieces of equipment (e.g. heat pumps) in the database.
- It is free of charge.

Drawbacks:

- Due to its numerous functionalities, the tool is relatively complex and requires some adaptation time.
- Hot and cold flows cannot be entered directly: the standard model must necessarily be followed in order to model a process operation, which is restrictive.
- No analysis can be launched until the “consistency check” is validated, but this can be time consuming since the tool is highly sensitive and errors are relatively difficult to decipher.
- The module designed for heat pump integration is not easy to use, and – at least in V2.1 – had some bugs.
- Since European funding has now expired, this raises the issue of the viability of the tool: i.e. who will fund developments, maintenance or training?

3.4.10 SuperTarget

SuperTarget claims to be the leading tool for industrial process energy integration and exchanger network design. Its advanced data processing functionalities provide for easy application of the pinch analysis. It is split into three specific modules:

- A “Process” module to carry out a pinch analysis on a process (direct exchange is allowed between all flows).

Among other, this module provides for thermal and economic optimisation of the minimum pinch (ΔTmin) and for the design of an exchange network. Its functionalities adjust to situations of new design and facility renovation, and its “case study manager” enables easy comparisons between several scenarios. Lastly, it is fitted with a simulator to test the sensitivity of the network in response to certain changes.

- A “Column” module to apply the pinch method to the optimisation of distillation columns.
- A “Site” module for energy integration on a site (indirect exchange between several processes via the utilities network).

This latter module provides the possibility of selecting the desired process data in the Process module. Several aggregation options may be selected, depending on whether exchanges are authorized between all flows in all processes, or only via the utilities network. In addition, this module enables an exergetic analysis to study the integration of energy generation systems (cogeneration).

It was not possible to test the Supertarget tool.

SuperTarget was developed by the founder of the pinch method and is regarded as a benchmark in the field. It is however still highly oriented to the chemical and petrochemical industries, hence its functionalities are too sophisticated, particularly for designing the exchanger network. Similarly, the utilities are unsuitable, and in particular SuperTarget does not seem to offer any heat pump integration.

3.4.11 AspenEnergyAnalyzer

AspenEnergyAnalyzer belongs to the AspenONE software suite. It is designed for applications of the pinch method in accordance with the rules defined by Linnhoff.

AspenEnergyAnalyzer provides for either manual or automatic design of the exchanger network: in the latter case, up to 5 different designs are possible, indicating that the tool most likely uses a heuristic or meta-heuristic resolution mode, and does not use any linear deterministic method.

In addition, it can differentiate between a new design and a retrofit of the exchanger network, where the purpose is to optimise only the new exchangers to be added to an existing network.

This tool proved to be very similar to SuperTarget in terms of sophisticated functionalities of optimisation and modification of the exchanger network.

3.5 Conclusions

Numerous pinch analysis tools exist for energy integration of a site, based on an analysis of composite curves and grand composite curves.

However, few among these tools enable a calculation of the economic and energy benefits of installing a heat pump. The user’s expertise is therefore required. Some tools evaluate the benefit of heat pumps and recommend their positioning and number based on energy and economic criteria.

4 Dutch Team Report - Modeling in the Netherlands

Between 1992 and 1996 the IEA HPP Annex 21 generated an overview of potential industrial heat pump applications and also developed an "Industrial Heat Pump Screening Program to determine how industrial heat pumps could be used in different applications [Geelen, 2013]. The computer program should assist potential users in assessing the opportunities to integrate industrial heat pumps (IHP) into different types of industrial processes. The program has also been designed to determine the economics of heat pumps, at least on a preliminary basis. The computer program has been developed based on pinch technology concepts. It aims to identify IHP opportunities that are consistent with fully optimized plant heat exchange systems to provide the most economic IHP designs and the lowest possible plant-wide energy consumption.

The screening program contains data on more than 100 industrial processes in five main industries: food, chemicals, petroleum refining, pulp and paper, and textiles. These data can be used directly, or modified by the user as needed, to assess site-specific IHP opportunities. The computer program also contains data on more than 50 types of IHPs. Recent analyses by the Operating Agent of Annex 13/35 concluded that an update of the screening program is not advisable as since 1997 no further work has been done on the program and the software seems to be outdated. An analysis by the Operating Agent of existing software process optimization models shows that the difference between 'pure' pinch models and sophisticated mathematical optimization models has been bridged in modern software tools. Independent of any software tools, approaches and optimizations, a general heat pump data base should come more into the focus. Such a data base is needed for many purposes. Typical information to the database are not only source and sink temperature as well as size of heat pump etc. but also further details of the selected hot and cold streams to which the heat pump is selected, because this would allow to select a specific heat pump type.

Several of these specific heat pump models and databases have become available in the Netherlands during the work on the Annex. In order to integrate a heat pump properly in an industrial process a good knowledge of the process is necessary. In this respect, pinch analysis is a very powerful tool. Although broadly introduced into the market in the nineties in Netherlands, the use of models for process integration (i.e. pinch) and general process optimization is still limited to a fairly small number of research groups and highly specialized groups within large companies.

4.1 Industrial heat process optimization

Many tools are available to optimize industrial processes where depending on the situation there is no univocal answer to the question which tool is the best to use. It is important to be aware of the fact that the costs for measures for energy conservation are often more expensive when they are further from the core of the process. Still it is amazing that under the past decade of Multi-Year Agreements in Netherlands often cogeneration was installed as energy conservation measure, which in the end has to do with the fact that interfering with the core of the process is often considered as 'dangerous and risky' and with the fact that the Multi-Year Agreements within the policy of participating companies was a responsibility of the energy manager of the company, i.e. the utility manager, and not of the process manager.

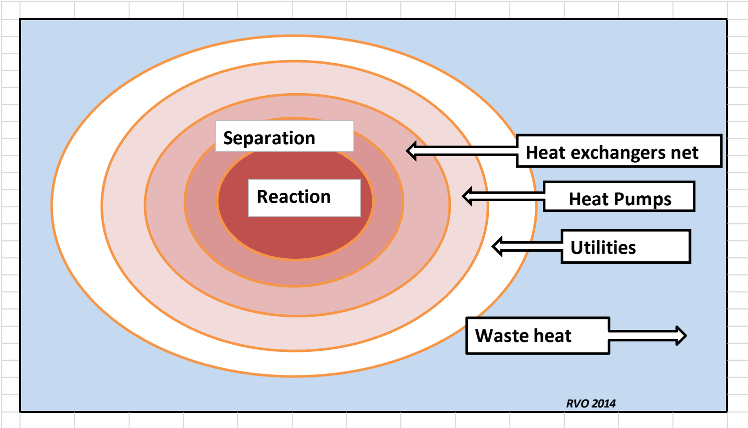


Figure 4-1: Onion model for process approach

A systematic approach in improving the energy efficiency of industrial processes is the onion-model a translation of the TRIAS-Energetica where the pre-assumption is that one should first save on energy by optimising the process and then go into thinking about the way in which the energy is exchanged within the process and then generated at the outside of the process.

The model is explained for a chemical distillation process where in the first shell the processes occurring in reactors and separators (Process) are optimized. In practice this is done by an economic optimization in which energy and other operating cost are balanced with annualized investment cost for the equipment. In distillation "Process" refers to molecular improvements such as extractive distillation as well as optimization of internals, trays and column compartments. Energy consumption can be reduced further by heat integration using heat exchangers (HEX). As heat exchangers need a driving force there is a limit to what can be achieved by heat integration. Optimization of the heat exchanger networks is done using pinch technology leading to the rule of thumb: "Do not transfer heat across the pinch temperature". In addition the "grand composite curve" (enthalpy flow rate versus temperature) provides the minimum total cooling and heating power required for the plant. Now the temperature difference at the pinch temperature, ΔTpinch, is optimized by the economy: a higher value leads to smaller investment cost in heat exchanger area but also to increased utility cost. After heat integration has been optimized, further reduction of energy consumption can be achieved in the third shell: the heat pump (HP).

Process integration, modeling and optimization problems in chemical engineering are generally complex tasks of a considerable scale and comprehensive interactions. The application of information technology (IT) and computer software tools is essential for providing fast and, as much as possible, accurate solutions with a user-friendly interface. General purpose optimization and modeling tools overviews have been available through the years. A number of computer-based systems have been developed to support process engineers in the energy and mass balance calculations. However, due to the substantial ongoing funding needed for the continuous development, only a limited number have remained on the market. They have only been secured by a substantial number of continuous sales.

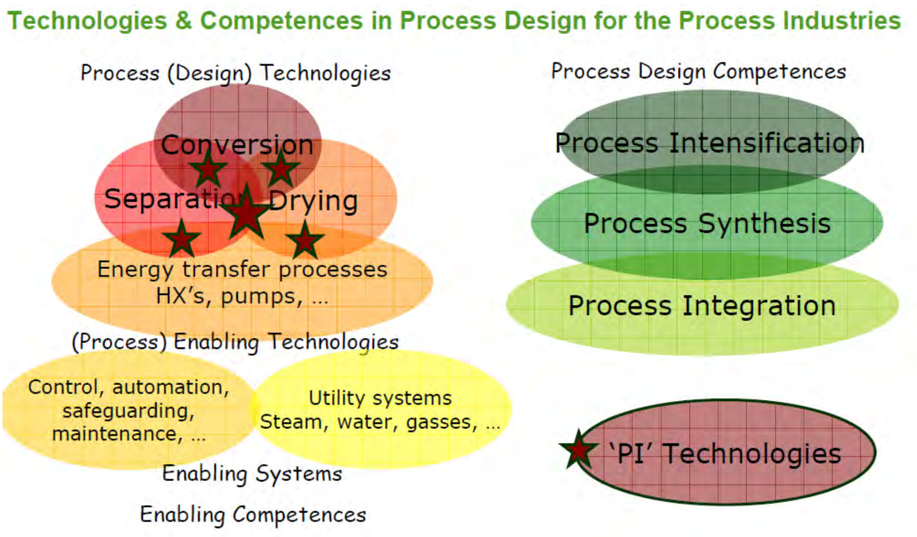


Figure 4-2: Technologies for process design in chemical industry (source TKI)

There have been a variety of efficient tools available. Each provider mainly stresses their advantages. Klemeš *et all* presented a comprehensive list of software tools that are available for the simulation of material and energy balances of chemical processing plants, which includes: (1) Aspen HYSYS (2) CHEMCAD; (3) GAMS; (4) gPROMS; (5) HEXTRAN; (6) OpenModelica; (7) PNS Solutions and S-Graph Studio; (8) PRO/II; (9) SPRINT STAR, WORK and WATER; (10) SuperTarget and (11) UniSim Design.

Computers have been changed substantially the practice of chemical engineering, allowing large advances in process modeling and simulation. The chemical engineering community has generated a rich literature about rigorous unit operation models and efficient algorithms to solve them, employing rising computational resources. Several problems, which in the past demanded a considerable occupation of engineering manpower, now can be solved by a single engineer in a fast and accurate way. Simultaneously, plant automation developments can provide a large amount of information about the process behavior in real time.

These two factors: the availability of plant data and the capacity to handle these using adequate models have opened a large field of improvements in process engineering. In a globalized world, characterized by an intensive business competition, these opportunities assume a special importance.

4.2 Available tools

By [Grift, 2011]

Tools for complex industrial processes are developed to visualize and analyze heat flows in processes to support with software the consultant in their advice on process improvements. Many of the available tools are based on graphs, diagrams and figures to easy the process of design and/or communication between experts and client.

4.2.1 Consultancy tools

Under the now long running policy of Multi-Year Agreements between industrial sectors and the Ministry of Economic Affairs, companies are benchmarked on an Energy Efficiency Index and have to make an Energy Efficiency Plan (EEP), done by an external consultant, every three years. Based upon Environmental Legislation companies, which do not participate in the program of Multi-Year Agreements, have to invest in energy efficiency measures with pay back times shorter than 5 years.

In this approach for energy conservation in industry the Netherlands Enterprise Agency (and its predecessors) have developed and used tools to facilitate the consultancy and to increase the impact by translating difficult process decisions into clearly understandable reports on management level. Some of these are:

- Energy screening
- Energy Potential Scan
- Procesintegration analyses and thermal audit (Einstein)
- Renewable energy scan

Energy analyses

An Energy Analyses which is part of the EEP consists of an energy balance, proposed measures, costs and economy and a consultancy report for decisions and an Energy Efficiency Plan for three years.

In a good Energy Analyses the heat flows and waste heat flows are mapped, not only the chimneys but also the locations in the process where the products a cooled and heated. Important to notify is the location of cooling towers and or condensers in the process. These two technologies are easily detected.

Energy Potential Scan

Energy Potential Scan is a form of participative model. Unlike traditional energy audit approach, in EPS, company and energy consultants work together to see the possibility to conserve energy. This method has been developed by Philips in Eindhoven together with Novem. There are two keys in EPS, quality and acceptance.

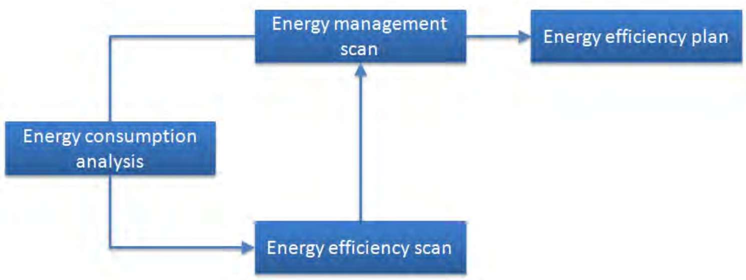


Figure 4-3: Energy Potential Scan

A key word is acceptance which created by something different from traditional energy audit where in the phase of the Energy Efficiency Scan (after the process analyses) it involves brain storming, thinking about the ideas to improve efficiency, and possible application both financially and technically. This creates commitment from management and participation of key personnel of the company.

From this very structured approach a large number of ideas are listed and discussed. The options for energy conservation a preferably developed by the company itself in an Energy Efficiency Plan.

Processintegration analyses

In a Processintegration analyses approach all heat flows for a process are mapped. For simple processes with a maximum of 20 heat flows a simple spreadsheet and pinch visualization are sufficient to develop an arrow and block diagram to engineer a heat exchanger network. For larger processes like in chemicals specialized software is needed to be able to optimize energy and economy at the same time. Based upon distances in the process between coordinates for heat, costs data and data for materials the software can propose a set of technical choices. Next to the right fit for heat exchangers the right fit for a heat pump can be calculated if the data for heat pumps are available to the program. This last boundary condition seems at this moment to be the largest problem for heat pumping technologies.

At European level it was noticed that a lot of software available for process integration analyses was not used for smaller processes as the software is often too complex or too expensive for small consultancies. Even worse is the fact that although Dutch Government thinks that process integration broadly introduced in the nineties is an accepted tool, this is not the case anymore for the larger part of industry, with exception of course for chemical industry.

In a European project a simple to use thermal audit has been developed under the name of “Einstein”. It is a freeware software tool with a report generator in Open Office.

Companies with relatively simple processes can be scanned in a few days on the potential heat integration, the internal use of waste heat, heat pumps, cogeneration and renewables like solar heat and bio-energy. The Einstein tool is still fully under development and needs as well as other software tools the right and objective information on heat pumping technologies.

Renewable Energy Scan

The Renewable Energy Scan has been developed by the Netherlands Enterprise Agency (and its predecessors) to make companies aware of the potential for applying renewable energy. This methodology is especially of interest for companies which do not have large process heat flows and can be found on many mixed industrial areas in the Netherlands.

4.2.2 Methods for Visualisation & analyse

For optimizing heat flows and to get process integration with heat exchangers and heat pumps in the first two levels of the onion the availability waste heat flows should be charted. If no data are available or if the design of the process is dated it is advised to execute when possible an extensive monitoring on the process over a certain period of time, since it is the experience (often painful) that no process runs optimally according to the design.Several methods are available for visualization of (waste) heat flows.

- Sankey diagram
- Arrows diagram
- Block diagram
- Pinch diagram
- Grassmann diagram

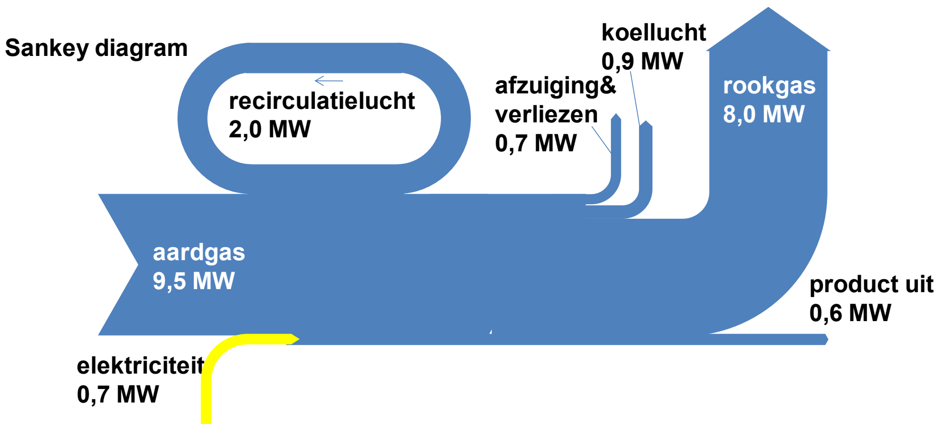


Figure 4-4: Sankeydiagram

A Sankey diagram can give insight in the energy balance on parts of the process or the complete process. The width of the arrows is a measure of the capacity of the energy flow.

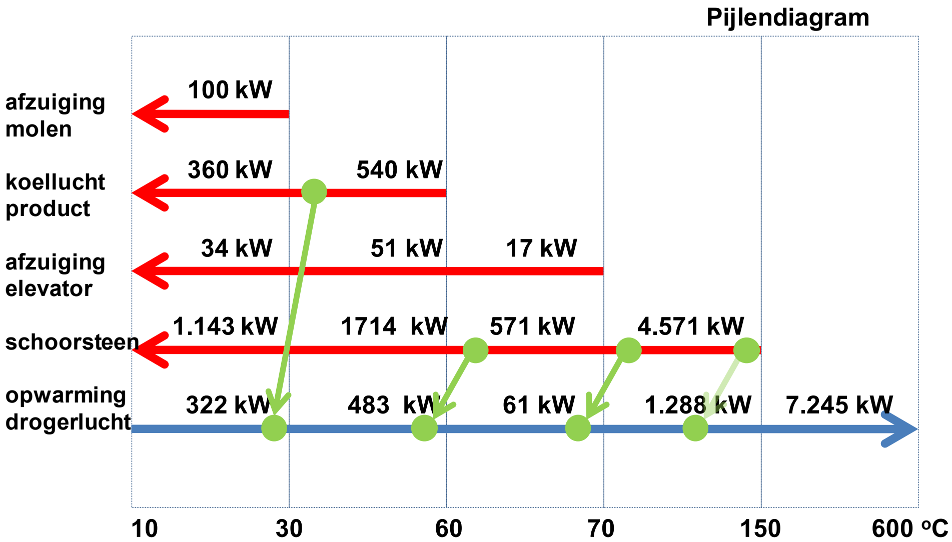


Figure 4-5: Arrows diagram

An Arrows diagram gives the heat flows at with the temperature levels. Together with the heat capacity of the flow in not too complex processes the right position for heat exchangers can be proposed. The green arrows give the potential heat exchanger between red (=hot) and cold (=blue) to be heated flows.

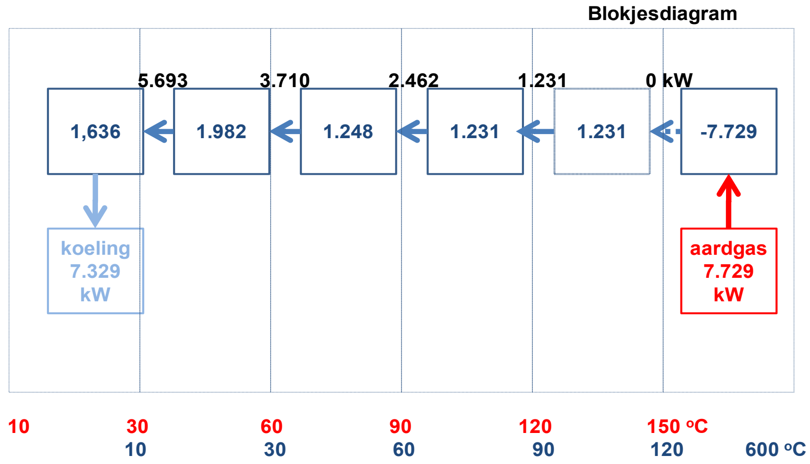


Figure 4-6: Block diagram

A block diagram is a tool to give the optimal lay out of a system of heat exchangers in a simple process. With this tool the capacity of heating and cooling can in theory be calculated. The figures in the blocks give the amount of heat residue which is available in the given temperature segment. These segments have to be placed in order to make the exchange of heat possible. The flows to be heated (blue) have to have a lower temperature than the waste heat flows (red). The block in the lowest temperature segment has to cooled by external energy. In this example only heat has to be supplied in the highest temperature segment.

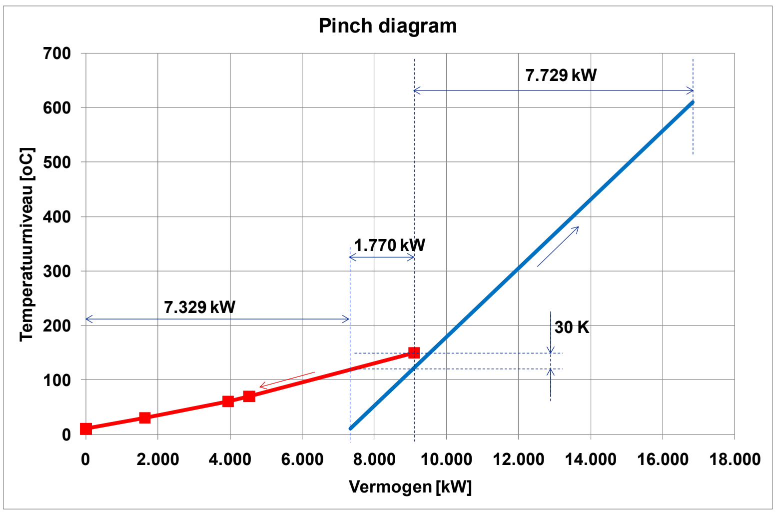


Figure 4-7: Pinch diagram

A pinch diagram gives capacities and temperatures. The process data are 'verwerkt' into a hot and cold composite curve. The hot composite curve gives all the process streams to be cooled including waste heat and the cold composite curve gives the stream to be heated. The art of engineering the process is to combine these streams in order to reduce the final heating and cooling demand of the overall process. Where the curves are closest together, i.e. the smallest temperature difference, is the so called ‘pinch’ (insnoering). A heat pump is only functional if the heat pump crosses this pinch. In the given example in the diagram a theoretical minimum heat is required of 7,729 kW’s and cooling of 7,329 kW’s, while 1,770 kW’s of waste heat can be re-used in the process.

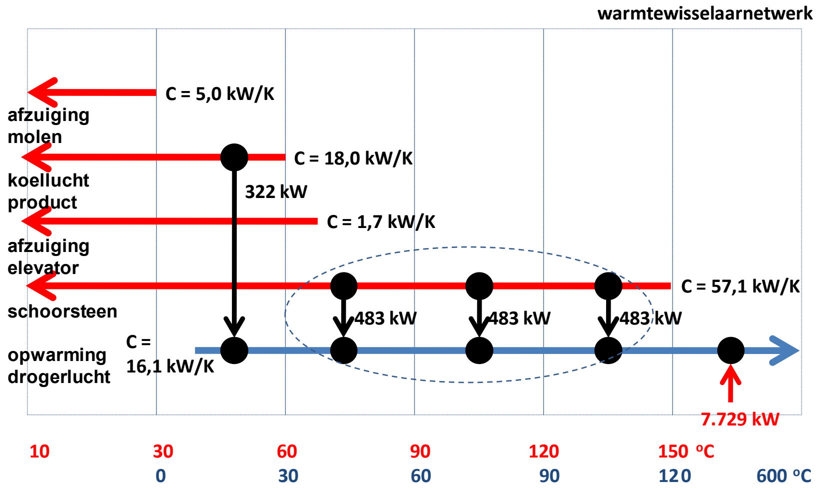


Figure 4-8: Heat exchanger Network

If the pinch temperature is known a heat exchanger plan can be engineered. For complex processes software is available to design this. For simple processes an arrows diagram can be configure the basic design of the network.

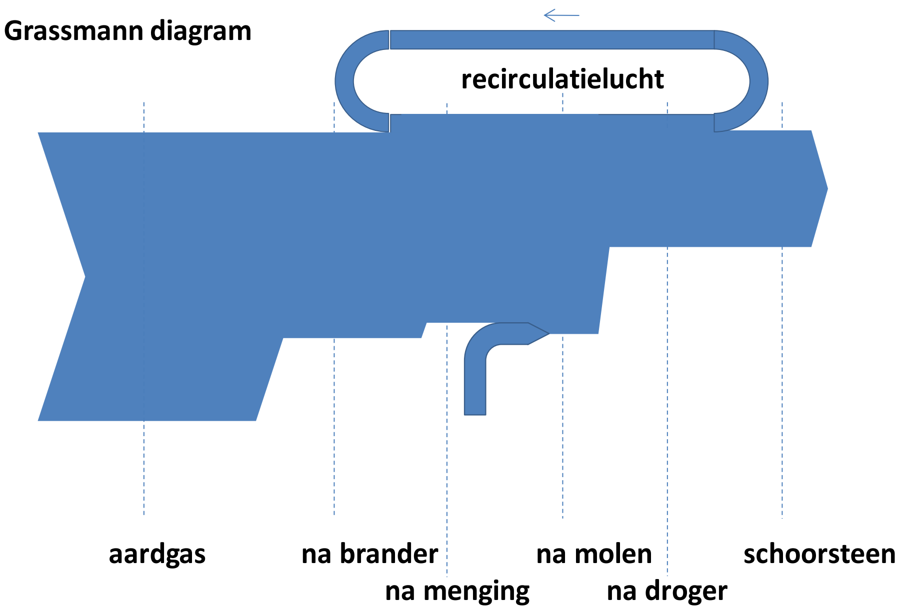


Figure 4-9: Grassman diagram

A Grassman diagram gives the exergy flows in the process. The exergy of a heat flow is a standard for the quality (temperature level) of the energy flow and a benchmark for the amount of electricity which can be generated from the flow. This is often used to analyze the optimal use of cogeneration.

4.3 Which tool fits best?

Many tools are available to optimize industrial processes where depending on the situation there is no univocal answer to the question which tool is the best to use. Several approaches for process optimisation in industry can be met with based upon the onion model as in Figure 4-1. In order of ranking:

- Process optimisation
- Process intigration
- Optimisation of Utlities
- Heat exchange with surrounding energy users

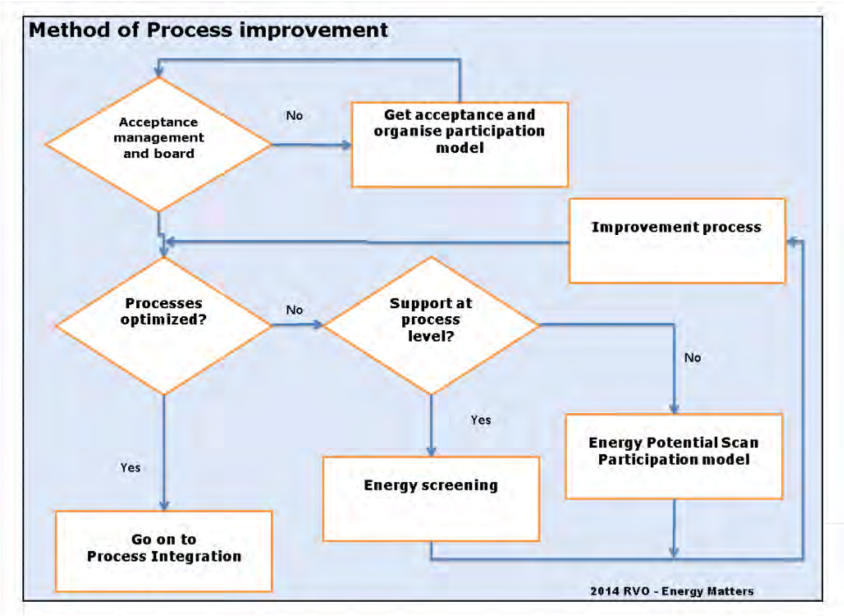


Figure 4-10: Flow diagram Improvement Process

Projects for reducing the energy use through process optimization go beyond the responsibility of the energy or utility manager alone and often have to have additional profits than only energy, like a better product or a higher yield of the production. If the project only gives reduced energy costs, the profitability is often lower than competing investments. In these kinds of projects it is of importance to create support and trust with the decision making management first, before even considering starting the project. The first phase of the project will have to focus on process mapping a improvements of the process as it is.

From the core of the original process questions can be raised as:

- Are the setpoints optimally adjusted?
- Is heat recovery already installed and optimal according to the pinch principles?
- Can temperatures be used at lower levels? Often for the easiness of installation and transport cheap steam systems are installed where only low grade heat is needed.
- Can drying processes be used by mechanical drying?
- Are heat flows mixed with degradation of heat?

Often the process (as mentioned earlier) does not run according to original design due to changes and small improvements over the years. (an interesting example is given in the factsheet on the Lips project with Doorgeest NL-18). Monitoring of the process can often already lead to large costs savings before even starting the more complex task of process integration. When it is assured that the process is optimized the task of process integration can start.

The flow diagram of the improvement process makes it clear that support and acceptance starts at management level and if the challenge can be translated to the management and board in clear and simple to understand messages the project can start. The next phase is to get participation at operational level. The Energy Potential Scan is an excellent methodology to get that result.

When the process have been basically optimized the potential for process integration can be analyzed. When not all data of the process are not already gathered in the first phase of the project, the task of data gathering must be undertaken. Monitoring of the process getting to know all mass balances, temperature levels, enthalpy levels seems to be a costly effort in time and money but will be worth every penny in the end result. The next step is to translate the data into energy-balance with costs attached (Sanky) and analyze the complexity of the process.

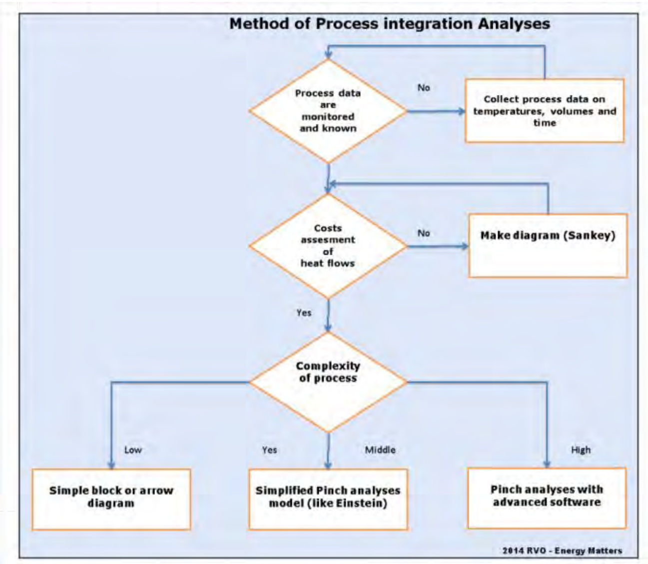


Figure 4-11: Flow diagram Integration Process

The question then raised is how many processes are suitable for process integration? In day to day practice often installers in medium sized industries are responsable for a part of the project. For cooling a refrigeration engineer is asked for. This misconception has for a long time been dominant in industry. However there are of course still a lot of smaller industrial companies can be supported with a simple block or arrow diagram. The flow diagram makes this distinction between simple and complex processes. For more complex situations Pinch software is needed to bale to calculate and design the optimal process integration. As mentioned before process integration has been broadly introduced in the nineties as tool, however it is not broadly used anymore in the larger part of industry, with exception of course for chemical industry. Therefore RVO has started togethet with the Federation of Energy Consultants (FEDEC) a series of training courses with the pinch model of 'Einstein' (see paragraph 4.4). In more complex processes a specialized consultant with advanced software steps in.

When all rational heat exchangers within the first inner circles of the process are established, the question is to optimize the utilities and to find a use for the waste heat of the process. A heat pump can be used to upgrade the waste heat over the pinch a part of the heat demand of the process. With newly developed heat pump technologies the temperature rise can be larger than originally was the case. Other possible use can be steam expansion or absorption cooling, both for the heat and cold demand of the original process. Eventually an ORC can make electricity from the waste heat if the temperature is at an acceptable level.

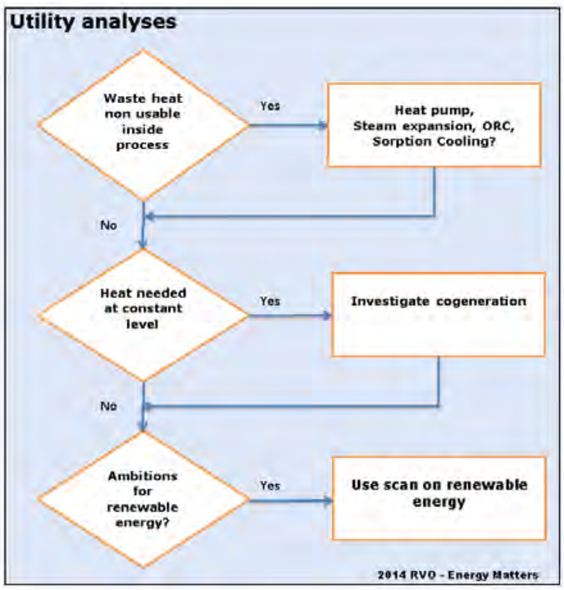


Figure 4-12: Utility Flow diagram

When there is still a constant and fair amount of heat needed for a larger part of the year cogeneration can be a serious option. However at the moment of writing the spark spread is negative, thus cogen will in almost all case be no economical option. Renewable energy options are decided on at that level where the Renewable Energy Scan as has been developed by RVO can be used. Cogeneration can also be based upon bio-energy.

When still waste heat is available a survey can be done on possible users of heat in the neighboring area where it must be closely watched that heat is not transported over too long distances with too high temperatures and transported to a heat demand with a stable demand over the year, especially in summer periods when process cooling is at its most critical. The best exergetic option for waste heat is to generate electricity with an ORC. This can be put into the grid.

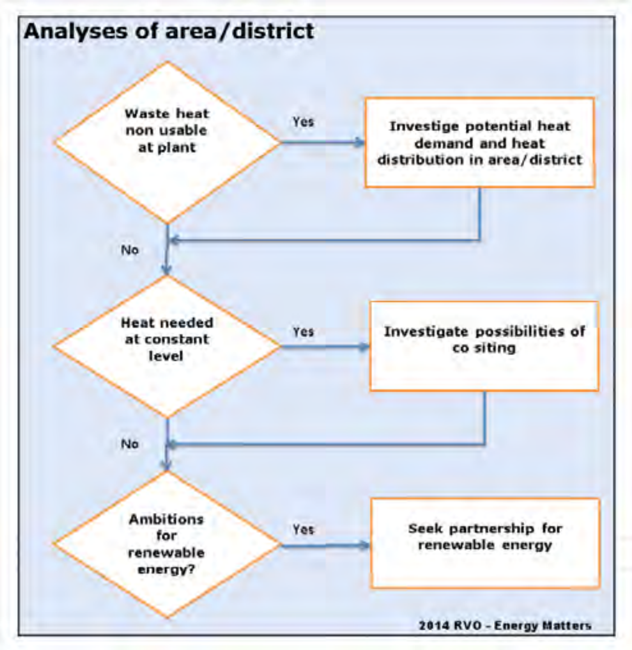


Figure 4-13: *Flow diagram for area survey*

4.4 EINSTEIN

The EINSTEIN methodology for thermal energy audit has been developed in the framework of the European (Intelligent Energy Europe - IEE).

In the follow up under EINSTEIN-II project aims to contribute to a widespread implementation of integrated energy-efficient solutions for thermal energy supply in industrial companies with a high fraction of low and medium temperature heat demand and for non-industrial users of similar demand profiles, such as hospitals, commercial centres, large office buildings, district heating and cooling networks, etc. To further optimize thermal energy supply, a holistic integral approach is required that includes the possibilities of demand reduction by heat recovery and process integration, and by an intelligent combination of existing affordable heat (and cold) supply technologies, under the given economic constraints. The follow up builds on the EINSTEIN tool kit for thermal energy auditing. This tool kit, based on an expert system software tool, guides the user through the whole procedure from auditing (preparation of visit and data acquisition), to data processing, to the elaboration, design and quantitative (energetic and economic) evaluation of alternative solutions. The tool kit, together with complementary databases, has been developed as a free and open source software project available in all the IEE project partners' languages. It uses pinch analyses as the basis is open-source software and provides the possibility for thermal energy efficiency improvements and the implementation of renewable energy within industrial processes, in different industry sectors.

The Einstein website and information (www.einstein-energy.net) claim that the methodology and Software Tool has proven in Auditing Practice (72 energy audits) that:

- The EINSTEIN methodology and tool has been successfully consolidated within the project. It has been proven that it can be applied in a great variety of different applications.
- The application of EINSTEIN compared to conventional auditing is a big help for the auditor for organizing information in a systematic and structured way and in carrying out fast feasibility analysis for a large number of possible alternative

Large Potential for Energy Efficiency An average primary energy saving potential of close to 20 %, and in some companies up to more than 60 % has been detected even under the constraint that has been applied in most audits that pay-back times should not be higher than 4 years (although this limit varied from company to company from below 2 year up to 8 years in some specific cases). If the primary energy consumption for thermal uses only is used as a reference (without electricity for lighting,

By many companies there was a positive take-up of the proposals presented (at the end of the project out of 72 companies 20 had initiated some further detail planning steps and out of them 5 already had implemented (some of) the proposed measures. The development and presentation of an attractive proposal to the company was in many other cases in-sufficient for triggering action towards a further development of detail technical issues with the objective of a real implementation of the measures.

Einstein Approach in Netherlands

In the Netherlands as in Europe it is noticable that although process integration based upon pinch analyses was broadly introduced in the nineties and should be an accepted tool, that this is not the case anymore for the larger part of industry, with exception for chemical industry. Consultants as well as energy managers within companies should therefore be trained and educated in process analyses based upon the approach described in paragraph 4.3 starting with an Energy Potential Scan and further worked out as described in the flow diagrams in Fig. 4-11.

Dependent on the complexity of the process a tool like Einstein is used or more complex tools. RVO has ordered Energy Matters after their study on which tools to use [Grift, 2011] to develop a training program together with FEDEC (Federation of Energy Consultants in Industry) based upon Einstein. The focus is to improve the availability of skilled energy auditors and energy managers and the diffusion of energy management systems and best practices. A next step will be to develop instruments to ensure availability of updated, comprehensive and usable information on energy efficiency relevant for industries. Heat pumps are one of the key technologies in this approach with models developed and described under the next paragraph.

During the process of training with Einstein bugs and small problems were discovered and are now discussed with the developers of the Einstein tool kit.

4.5 Process tools and heat pumping technology

Most of the tools discussed are focusing on heat integration and with these tools the right position and choice for a heat pump can be made. In general experienced process designers working with pinch software can easily see from the grand composite curves where heat pumps can be applied, also from the 'nose' of the curve they in general know which type of heat pump. The main problem is that it is difficult to select the right size and brand of heat pump as there is scarce information that can be directly used. A lot of information can be found on the Internet but a consultant (often highly paid) doesn't have the time available to sort out this information.

Independent of any software tools, approaches and optimizations, a general heat pump data base should come more into the focus. Such a data base is needed for many purposes. Typical information to the database are not only source and sink temperature as well as size of heat pump etc. but also further details of the selected hot and cold streams to which the heat pump is selected, because this would allow to select a specific heat pump type.

For a heat pump to be effective there are a number issues to be considered:

- The pinch temperature and the flexibility of the plant
- The thermodynamic cycle and the heat pump efficiency
- The temperature lift required
- The enthalpy balance
- The selection and constraints of heat pump equipment
- The configuration of the system
- The available utilities
- The economy or the annualized capital cost versus the utility cost

As the target group for heat pumps is a large variety of industrial sectors several heat pump selection models have been developed and are becoming available. Three of these are discussed in the next paragraphs.

4.5.1 Mastering Heat Pumps Selection for Energy Efficient Distillation[4]

By [Kiss, 2012]

An overview on application criteria for practical systems is given in [Landolina, 2012].

Distillation still remains the most popular separation technology, in spite of claiming about 40 % of the operational costs from chemical and refining plants. Distillation has a relative low thermodynamic efficiency, requiring the input of high quality energy in the reboiler to perform the separation task. At the same time, a similar amount of heat at lower temperature is rejected in the condenser. Several heat pump concepts have been proposed to upgrade that discharged energy and reduce the consumption of valuable utilities. For example, vapor compression (VC) uses work to increase the temperature of

[4] Kiss, Flores Landaetaa, Infante Ferreirac (Mastering Heat Pumps Selection for Energy Efficient Distillation)

a fluid heat transfer media in a closed loop. Mechanical or thermal vapor recompression (MVR or TVR) use the top product as working fluid in an open cycle, reducing further the investment costs. Similarly, the structure of an internally heat integrated distillation column (HIDiC) lowers the required temperature lift, reducing the compressor work. Meanwhile compression-resorption heat pumps (CRHP) use absorption processes to enhance the heat transfer, allowing higher efficiency and wider applicability range. Average energy savings when using any of the heat pump systems in distillation range from 20 to 50%.

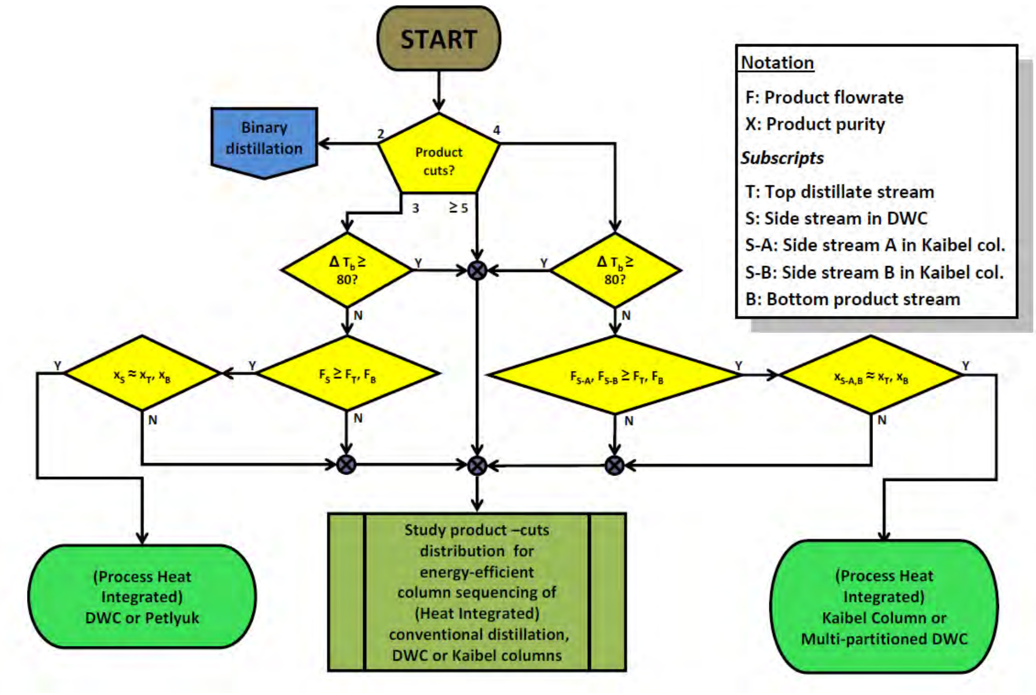


Figure 4-14: Structure

However, the energy efficient systems described in literature were evaluated for different separation tasks. Thus, their performance comparison is difficult, complicating the technology selection for other applications. To solve this problem, we developed a practical selection scheme of energy efficient distillation technologies, with a special focus on heat pumps.

Only the most promising technologies in terms of actual implementation were selected for this study: vapor compression, mechanical or thermal vapor recompression, compression-resorption and thermo-acoustic (TAHP) heat pumps, heat integrated distillation column (HIDiC), cyclic distillation (CyDist), dividing-wall column (DWC) and Kaibel distillation column. The selection criteria include the type of separation tasks, the products flow and purity specifications, the boiling point differences (ΔTb), the reboiler duty (Qreb) and its temperature level (Treb).

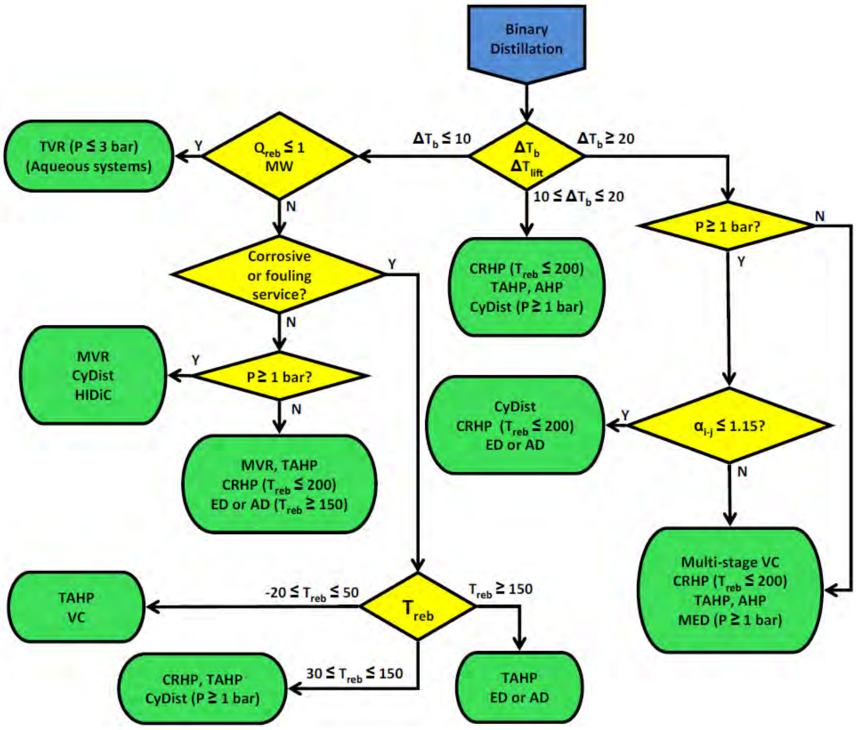


Figure 4-15:

The straight-forward selection scheme presented in this work allows the quick selection of the most suitable technology for any distillation task. Thus, the application of the proposed scheme allows considerable savings in time and resources allocated for the selection of eco-efficient separation technologies. The ultimate goal of this work is to facilitate significantly the design of energy efficient chemical processes, thus becoming a valuable tool for enhancing the sustainability of the chemical industry.

4.5.2 Heat pump models

A more general model that can be used has been developed under the Task 2 of the Annex by KWA for RVO. The challenges arose during the meetings on Annex 35 with the Dutch market consisting of consultants and institutes. The main consultants for process industries advised not to focus on process integration tools but to develop a model that could be used as an add-on to existing tools. Integrating this basic heat pump model into software models would make this model dependent on the tools. No specific new process analyses tool was deemed necessary.

The heat pump model based upon Excel would idealy be available on the Internet and could further be developed as a WIKI-approach where the market itself would fill in further details in the model and in the end applications could be hinged as factsheets to the model. This stage of development is not reached yet during the process of the Annex.

In a step by step approach the user is lead through the process filling in data from his own process.

- Find source heat with a high as possible temperature, below the pinch-temperature in the process. Determine the amount of heat available with corresponding temperature. Find out what will be the impact on the process and the existing heat integration. Determine whether it is possible to adapt the process to increase the amount and/or temperature of the source heat.
- Find process heat with a low as possible temperature but higher than the pinch-temperature. Determine the amount of process heat and temperature required.
- Determine which type of heat pump fits the process conditions that are investigated in step 1 and step 2. Heat source and heat sink temperature, power and type of process medium should be considered.
- To determine the feasibility of a heat pump, the performance of the heat pump at given process conditions should be calculated.
- When the performance of the heat pump is calculated, an indicative calculation of energy and cost savings can be performed.

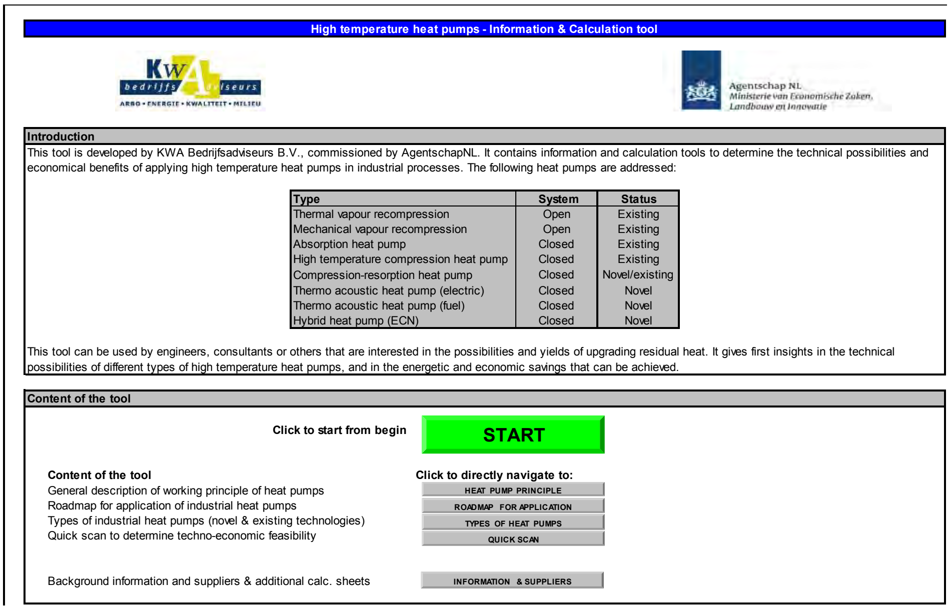


Figure 4-16: RVO - Heat pump model selection screen

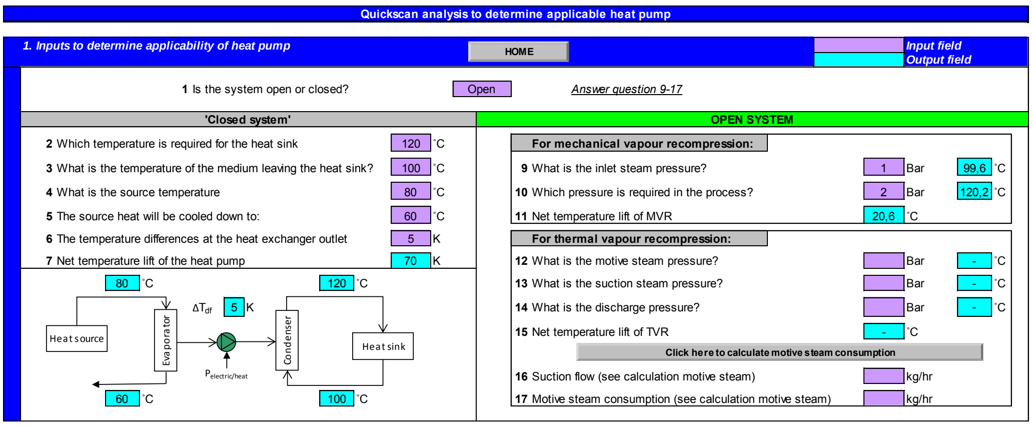


Figure 4-17: Quickscan analysis

The further development of this model will be taken up in 2014 – 2015 under a new Task 2.

4.5.3 Heat Pump Check

The Heat Pump Check is another on-line calculation tool which is developed by De Kleijn Energy Consultants & Engineers from Druten (www.industrialheatpumps.nl). The tool can help industrial companies to determine the feasibility of heat pumps for their processes. it gives a global indication of the applicability and feasibility of a heat pump. The result is a good starting point to determine if further investigation, for example by an external consultant, is useful.

SUMMARY HEAT PUMP CHECK Industrial Heat Pumps

Input

Waste heat source		**Process**	
Heat source	: Refrigeration system	Process	: Pasteuriser
Purpose installation	: Cooling+freezing	Heated flow	: Product
Refrigerant	: Other	Temperature in	: 50 °C
Condensation temperature	: 30 °C	Temperature out	: 70 °C
Cooling capacity	: 1000 kW	Heat demand	: 1000 kW
Other data			
Current heat source	: Direct gas-fired	Electricity costs	: € 0.08 / kWh
Generation efficiency	: 85%	Fuel costs	: € 0.35 / Nm3
Running hours	: 6000 hours/year	Selection heat pump	: Largest savints
Simultaneity	: 70%	Refrigerant	: Only natural

Specifications heat pump

Heat pump type	: Mechanical heat pump with natural refrigerant Ammonia (R717)
Capacity	: 1000 kW
Electric power	: 196 kW
COPh	: 5.1

196 kW

Waste heat in 30.0 °C 75 °C 70.0 °C Flow out

804 kW Evaporator Condenser 1000 kW

Waste heat out Flow in

30.0 °C 28 °C 50.0 °C

Costs and savings

Energy savings		**Financial savings**	
Reduction fuel consumption	: 562800 Nm3 per year	Fuel savings	: € 197000 per year
Extra electricity consumption	: 823200 kWh per year	Electricity costs	: € 65900 per year
		Financial savings	: € 131100 per year
Primary energy savings	: 10404 GJ per year		
Investment costs		**Payback period**	
Heat pump	: € 370000	Investment costs	: € 432100

Figure 4-18: report generated by Heat Pump Check

4.6 Literature

Geelen, 2013	Monitoring van (energetische) prestaties en knelpuntenanalyse WKO-systemen in de glastuinbouw, ir. C.P.J.M. Geelen en ir. K.J. Braber; Arnhem, December 2013
Grift, 2011	Warmtetools industrie, Jan Grift, Allan Hart (Energy Matters), april 2011, Projectnumber: 11.450
Kiss, 2012	Mastering heat pumps selection for energy efficient distillation, Kiss A. A., Flores Landaeta S. J. and Infante Ferreira C. A., (2012), Chemical Engineering Transactions, 29, 397-402
Landolina, 2012	Strategic Research Priorities for Renewable Heating & Cooling, Cross-Cutting Technology European Technology Platform on Renewable Heating and Cooling; Many authors edited by Simone Landolina – European Renewable Energy Research Centres Agency, Manuscript completed in April 2012. Brussels, © European Union, 2012

Application of Industrial Heat Pumps

IEA Industrial Energy-related Systems and Technologies Annex 13

IEA Heat Pump Programme Annex 35

Task 3:

R&D Projects

Final Report

(Status: 10.06.2014)

Prepared by the

Participants of Annex 35/13

Contents

1 Summary

In **Austria**, a small number of already existing applications of heat pumps in the Austrian industry, the relevance of this topic is growing in Austria. Beside the fact that several national manufacturers already offer industrial heat pumps, there is just a focus on high-temperature heat pumps suitable for industrial applications by the Austrian R&D heat pump community. The Austrian team identify six manufacturers deliver heat pumps with a capacity up to 1 MW and with maximum heat sink temperatures < 98 °C and describe three relevant projects.

Table 1-1: R&D-Projects in Austria

Project	System	Status	Heating Capacity	Supply Temp.	Refrigerants
Concept for waste heat upgrade for process supply	Hybrid (absorption / compression)	Prototype	25 kW	85 °C	NH_3-$LiNO_3$ and other working pairs
Utilization of industrial waste heat for refrigeration purposes	Absorption	Simulation	n. a.	100 °C	NH_3-H_2O and other working pairs
Upgrading flue gas condensation heat	Direct evaporator	Test facility for experimental analysis	n. a.	n. a.	n. a.

Canada's R&D projects have focused on recovering low-grade waste heat from relatively small- to medium-scale industrial manufacturing facilities in order to supply heat for building domestic hot water consumption and/or industrial heating purposes. The objective was to properly design, integrate and operate several types of IHPs in various energy intensive industrial processes able to provide sufficient amounts of waste heat at appropriate quality levels, flow rates and temperatures. All these projects were intended to respond to future requirements, such as a reduction of the energetic intensity of small- and medium-sized industrial processes and of environmental thermal pollution.

Table 1-2: R&D-Projects in Canada

Project	System	Status	Heating Capacity	Supply Temp.	Refrigerants
Thermally-driven ejector	Vapour compression	Laboratory test bench	9 kW (cooling)	10 °C	R-134a
Two-phase flow ejectors	Vapour compression	Laboratory test bench	n. a.	n. a.	n. a.
CO_2 ejector refrigeration	Ejector refrigeration	Feasibility study, laboratory prototype	n. a.	-5 °C	CO_2
CO_2 trans-critical HP	Compression, double stage	Simulation, Laboratory system, monitoring project	100 kW	85 °C	CO_2
Ammonia HP	Compression, single stage	Laboratory prototype	~ 48 kW	85 °C	NH_3
	Compression, double stage	Simulation	2.7 MW	90 °C	
Cascade HP	Compression, double stage	Simulation	27.2 kW	84.6 °C	R-134a, R-1234yf
Mechanical vapour compression	Mechanical vapour compression	Test in a industrial plant	n. a.	n. a.	n. a.
Low temperature drying	Compression	Laboratory-scale prototype	5.6 kW (compressor nomi-	n. a.	n. a.

			nal power input)		
High temperature drying	Compression	Industrial-scale prototype (2 units)	65 kW (compressor nominal power input)	n. a.	R-236fa

To have an overview of the potential and technical requirements of using heat pumps in industrial processes, two assessment reports have been published in 2013 for **Denmark**. The two reports are carried out with different approaches meaning that the results are not a 100 % comparable and conclusive. However both reports give good indications of the possibilities in industries. The first report considers excess heat of industries in general and the potential of utilization in different ways both internal and external. Technical and economical obstacles are taken into account. The focus of the second report is more specific on using heat pumps in different processes where heat is recovered and utilized in the same process. External utilization of industrial waste heat is not considered. The potential is assessed for processes with temperature requirements of up to 180 °C and categorized in temperature lifts of respectively 20 K, 40 K and 70 K. A requirement of 180° C and a temperature lift of 20 K means that the heat source is 160 °C whereas a lift of 70 K means that the source is 110 °C.

Both reports show that the majority of the potential require temperatures less than 100 °C, meaning that outlet temperatures is not a technical barrier in most cases. The assessments also show that there is some potential for heat pumps that only lifts 20 K, meaning that high COP values is possible while the heat capacities should in MW's. There is only a small potential for heat pumps with capacities less than 1 MW.

There have been a number of demonstration projects in the last couple of years implementing large scale heat pumps, which have primarily been trans-critical CO_2 or high pressure ammonia systems. At the moment research and development is also in the fields of water vapor systems and the ammonia/water hybrid process. Three demonstration projects are relevant for industrial purposes.

Table 1-3: R&D-Projects in Denmark

Project	System	Status	Heating Capacity	Supply Temp.	Refrigerants
Energy efficient drying with a novel turbo compressor based high temperature HP	Rotrex turbo compressor for water vapour compression	Industrial installation – timber drying	446 kW	n. a.	Steam
		Industrial installation – fish and bone meal	~2.2 MW	100 °C	Steam
Ultra high temperature hybrid HP	Hybrid (Compression / absorption)	Theoretical investigations	n. a.	180 – 250 °C	NH_3-H_2O in different mixtures
Highly efficient Thermodynamic Cycle with Isolated System Energy Charging (ISEC)	ISEC concept consists of two or more tanks. One tank is heated while the other is discharged.	Project just been initiated (duration 3 years)	n. a.	n. a.	n. a.

Since a few years, there is in **France** a renewed interest for heat pumps. Recent developments have been made to develop industrial (> 100 kW_{th}) high temperature heat pumps (> 80 °C) and very high temperature heat pumps (> 100 °C). Currently, there are only a few closed-cycle mechanical high or very high heat pumps installed in the French Industry, but interest and references are growing. The R&D activities of EDF are concentrated on three projects:

Table 1-4: R&D-Projects in France

Project	System	Status	Heating Capacity	Supply Temp.	Refrigerants
AlterECO Project	VHT HP – HFC-mixture	Experimental tests in 2011 industrial experimentation in 2014	250 kW	140 °C	ECO3™
EDF/JCI	HT-HP	Experimental tests in 2010	700 kW	100 °C	R-134a R-245fa
PACO-Project	VHT WP –water Centrifugal compressor with magnetic bearings	Experimental tests 2012/13	700 kW	140 °C	Water

It is expected to install in France at least 1,500 industrial high temperature heat pumps before 2020 in spite of various commercialization barriers:

- Lack of knowledge and experience with heat pumps
- Negative perception of heat pumps due to poorly designed models early in their use
- Volatile energy prices.

The integration of heat pump can be optimized with **thermal energy storage**, with various advantages:

- The heat pump works at its nominal point
- The thermal need can be covered with a smaller heat pump, decreasing the investment.

German heat pump manufacturers and German partners of the ANNEX 35/13 identify several projects for industrial heat pumps:

Table 1-5: R&D-Projects in Germany and from German partners

Project	System	Status	Heating Capacity	Supply Temp.	Refrigerants
NeatPump	High pressure compression	Projects in industry: chocolate factory, etc.	n. a.	Up to 90 °C	NH_3
n. a.	High pressure compression	Projects in industry: greenhouse, paper mill, etc.	Up to 14 MW	Up to 90 °C	NH_3
n. a.	Two stage compression	Installed in industry	n. a.	100 °C	R-134 / R-600a
Brewery	Single stage compression	Installed in industry	54 kW	120 °C	R-600a
Part cleaning system	Compression	Prototype installed in industry	~ 55 kW (at 50 Hz)	100 °C	R-245fa
thermeco$_2$	Trans-critical CO_2 HP	Installed in industry	Up to 1 MW	90 °C	CO_2

Research on new refrigerants for high temperature application is also done in Germany. The promising candidates are called LG6 and MF2.

Japan classifies industrial heat pumps into four general types: closed-cycle mechanical, open-cycle mechanical vapor recompression, open-cycle thermal vapor recompression, and closed-cycle absorption heat pumps.

CO_2 trans-critical cycle air-source heat pumps, capable of producing hot water of 90 °C with a heating capacity of 72.0 kW, have been commercialized in Japan and sold not only in Japan but also in South Korea, Taiwan, Indonesia and elsewhere. CO_2 trans-critical cycle water source heat pumps, capable of generating hot air of 100 °C with a heating capacity of 110 kW, have been also commercialized in Japan.

Table 1-6: R&D-Projects in Japan

Project	System	Status	Heating Capacity	Supply Temp.	Refrigerants
Dual-cycle HP water heater	Two stage compression	Commercialized	35 kW	70 °C	R-410A / R-134a
HP steam supplier (water to water)	One stage compression	Installed in industry	370 kW	120 °C	R-245fa
	Two stage compression	Installed in industry	660 kW	165 °C	R-134a / R-245fa
HP for circulating water heating	Two stage compression	Installed in industry	14 kW	90 °C	R-410A / R-134a
Waste heat recovery HP water heater	two stage centrifugal compression	Installed in industry	376 to 547 kW	90 °C	R-134a

A survey of low GWP refrigerants for high temperature heat pumps and basic analysis on their thermodynamic cycle performance is also executed in Japan, as well as the industrial application of thermal storage technologies. The latest thermal storage technologies including the ones already in practical use are explained.

More than 60 % of the total energy is consumed for the industrial application in **Korea**. A great portion of final energy in industrial field is to generate heat or provided as feedstock. So, a lot of activities have been done to improve efficiency or make advanced process in order to reduce primary energy consumption and green gas emission. The major directions of such activities are;

- Utilization of waste heat from industrial processes (reduce green gas emission and production cost) by hybridized heat source with renewables
- Production of hot water which can be directly used to the processes
- Extension of heat pump applications into advanced industrial processes formerly neglected to be a part of the processes

Under these circumstances, the application of industrial heat pump has gained much interest in these days by not only companies but also government agents.

Heat pump R&D in Korea is categorized into Energy Efficiency and Resources Program. The scope of the program is to ensure effective accomplishment of the objectives of the governments Framework Plan for the Development of Energy and Resource Technologies for the Years 2006-2015, where key parts are energy storage, heat pumps, micro

CHP, building energy, green cars, clean fuel, energy equipment, industrial process, CCS, and energy resources.

Table 1-7: R&D-Projects in Korea

Project	System	Status	Heating Capacity	Supply Temp.	Refrigerants
Hot water HP with waste heat	Hybrid Compression / Absorption	Prototype	30 kW	Over 90 °C	NH_3/H_2O
HP system with heat recovery from flue gas		Demonstration in a food factory	100 kW	60 °C	n. a.
Geothermal HP	Compression	Installed in industry	1000 RT	n.a.	R-410A
Double effect absorption HP for tow-temperature sewage waste heat recovery	Double effect absorption	Performance tests of the prototype	n.a.	70 °C	n.a.
Hybrid HP using solar heat	n. a.	Laboratory Tests	13 kW	n.a.	n.a.

R&D in the **Netherlands** on industrial process innovation is for a large part supported by the Ministry of Economic Affairs through the ISPT Innovation Program. Major players in this program are the Dutch process industry, TU-Delft and ECN. The focus on heat pumping technology as one of the key technologies is logical and has a long track record starting with basic research now reaching the pilot phase.

New developments in distillation heat pump technology are therefore aimed at novel heat pumps with a higher economic range and at new heat integrated configurations. In the Netherlands these developments are:

- Thermo Acoustic Heat Pump at ECN
- Compression Resorption Heat Pump at TU Delft
- Adsorption Heat Pump
- Heat Integrated Distillation Columns at TU Delft.

2 Introduction

One of the major programs of the IEA HPP IETS Annex "Application of industrial Heat Pumps" is to develop and advance heat pump technology to support industry to use its energy resources more efficiently. It involves using heat pumps in a role of both increasing the process efficiencies and recovering and reusing waste energy emitted in industrial manufacturing processes. It should foster research, development and prototype tests for more efficient and economical recovery of waste energy in industry, the identification of appropriate heat pump applications within the industrial sector and the subsequent development of heat pump technologies to meet the industrial requirements. In addition to system studies, high temperature heat pumps, including refrigerant and component developmental programs should be supported that would potentially result in enhanced performance and reduced costs.

The following R&D projects in the participating countries/organisations are of interest for the annex:

3 Austria

Despite a small number of already existing applications of heat pumps in the Austrian industry, the relevance of this topic is growing in Austria. Beside the fact that several national manufacturers already offer industrial heat pumps (see chapter 3.1), there is just a focus on high-temperature heat pumps suitable for industrial applications by the Austrian R&D heat pump community (see chapter 3.2)

3.1 Industrial heat pumping systems available in Austria

This chapter describes the current state of the art of available industrial heat pumps by Austrian manufacturers based on a screening of the Austrian heat pump market. According to this screening, customized as well as standardized compression heat pumps with heating capacities from 50 up to 1000 kW are offered by several Austrian heat pump manufacturers for waste heat recover and the use in commercial buildings. These heat pumps are usually designed for supplying temperature levels up to 60 °C and some of them up to 98 °C at a low heat sink temperature difference (10 K). Furthermore, absorption chillers are offered by an Austrian manufacturer, which allows the utilization of waste heat for industrial refrigeration purposes. Table 3-1 gives an exemplary overview of Austrian industrial heat pump manufacturer.

Table 3-1: Overview of Austrian industrial heat pump manufacturers (Status: Nov 2013) (without guarantee for completeness)

Manufacturer	Type	Capacity	Refrigerant	max. heat sink temp.
IDM-Energiesysteme GmbH	Compression	50 – 500 kW	R-134a	65 °C
OCHSNER Wärmepumpen GmbH	Compression	100 - 300 kW	„Öko1“	< 98 °C
HELIOTHERM Wärmepumpen GmbH	Compression	49 – 134 kW	R-134a	60 °C
FRIGOPOL Energieanlagen GmbH	Compression	Up to 1MW	R-717, R-723, R-236fa etc.	> 70 °C
COFELY Kältetechnik GmbH	Compression	100 - 700 kW	R-134a, R-717, etc.	< 80°C
PINK GmbH	Absorption	20 kW (cooling capacity)	NH_3/H_2O	Cooling applications

IDM Energy Systems GmbH offers their so called TERRA Max (see Figure 3-1), which is a compression heat pump working with two or three scroll compressors and R-407C or R-

134a as refrigerant with a capacity range from 50 to 650 kW. This heat pump type is available for heat sink temperatures below 65 °C. [IDM, 2013]

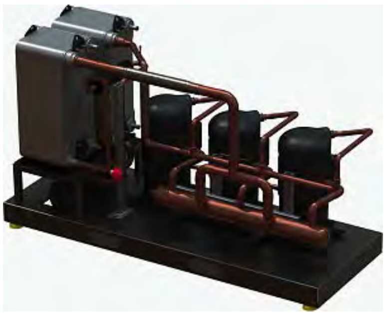


Figure 3-1: Basic construction of the Terra Max 130 [IDM, 2013]

The company **COFELY Kältetechnik GmbH** delivers compression chillers and heat pumps for households and the industry. COFELY offers the possibility to recover the waste heat from their chillers, directly or upgraded by closed or add on-HPs (R-134a, R-717 etc.). For upgrading waste heat Cofely has a standardized R134 closed compression HP with a capacity of 150 to 700 kW for heat sink temperature up to 65 °C and heat source temperature up to 35 °C for industrial application in their portfolio, using a semi hermetically reciprocating compressor or a screw compressor for a heating capacity up to 1 MW. Furthermore, Cofely also offers R-717 compression HPs for industrial application for simultaneous heating and cooling with reciprocating compressors for a heating capacity from 50 to 750 kW and screw compressors up to about 1 MW. [Cofely, 2013]

For various applications in commercial buildings or in the industry the heat pump manufacture **OCHSNER GmbH** offers a series of heat pumps with semi-hermetic compact screw compressors with a capacity from 100 to 960 kW. For heat sink temperature levels up to 65 °C Ochsner uses R-134a, R-407C or commercial refrigerants. Additionally Ochsner also offers heat pumps for industrial applications, as e.g. the “Toppump”. For high-temperature applications Ochsner offers standard industrial heat pumps, which can lift waste heat from a (external) temperature level of 40 up to 98 °C at a low temperature difference of the heat sink (5 to 10 K). As refrigerant the so called “Öko1” (by Ochsner), which is nonflammable and nontoxic, offers appropriate pressure levels at this high temperature levels. [Ochsner, 2013]

Figure 3-2: High-temperature heat pump [Ochsner, 2013]

According to the available waste heat temperature level Ochsner has two kind of this high-temperature heat pump in their portfolio, both a so called “two-stage” HP (IHWSS, see Figure 3-3) for heat source temperatures above 10°C, which is basically a cascade plant, and a “single-stage” HP (IHWS, see Figure 3-4) for heat source temperatures from 35 to 55 °C, which is designed as economizer cycle.

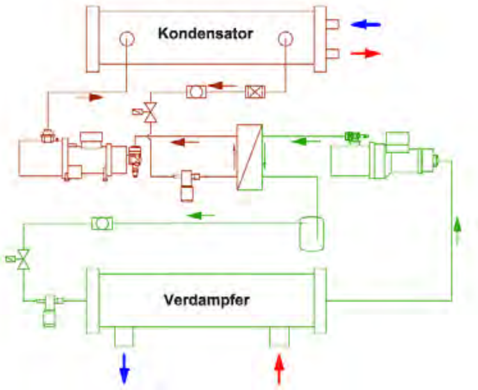


Figure 3-3: Flow scheme of the Ochsner high-temperature heat pump Type: IWHSS “two-stage” – Cascade cycle [Ochsner, 2013]

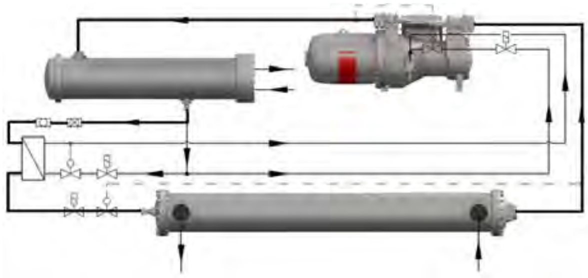


Figure 3-4: Flow scheme of the Ochsner high-temperature heat pump Type: IWHS “sinlge-stage” – economizer cycle [Ochsner, 2013]

The Austrian heat pump manufacturer **Heliotherm Wärmepumpen GmbH** offers a standardized HP (see Figure 3-5) for application in the industrial and commercial buildings for heat sink temperatures up to 60 °C and a heating capacity up to 139 kW.

Figure 3-5: Heliotherm’s heat pump for industrial application [Heliotherm, 2013]

The Austrian company **Frigopol Energieanlagen GmbH** produces compressors and customized heat pumping systems with R-717, R-723 or other refrigerants for cooling and/or heating applications with a capacity up to 1 MW with different compressor-types. For example, Frigopol (2013) has already delivered a customized plant with 1 MW capacity working with R-236fa as refrigerant for a district heating application (see Figure 3-6). Frigopol also is involved in an innovative R&D project concerning high-temperature HPs (up to 100°C) for industrial applications (see chapter 3.2.1).

Figure 3-6: R236fa high-temperature heat pump [Frigopol, 2013]

The **PINK GmbH** offers absorption chillers (see Figure 3-7) with a cooling capacity of about 20 kW, which are driven by solar thermal or industrial waste heat (> 70°C). The actual absorption chillers from Pink are single-stage plants using ammonia/water as working pair. [Pink, 2013]

Figure 3-7: PinkChiller PC 19 [Pink, 2013]

3.2 R&D projects in Austria

A screening shows that there are some R&D projects in Austria investigating different topics of heat pumping systems suitable for industrial waste heat recovery. In this chapter three relevant projects are described. One project investigated a concept for waste heat upgrade for process heat supply (see chapter 3.2.1), one the utilization of industrial waste heat for refrigeration purposes (see chapter 3.2.2) and one for upgrading flue gas condensation heat (see chapter 3.2.3) by heat pumps.

3.2.1 Hybrid (absorption/compression) heat pumping systems

The concept of an absorption/compression-heat pump system is known since the late 19th century (Osenbrück, 1895). Due to certain technical difficulties the concept coulnd't be realized commercially in large scale up to now. In general, the system is a combination of a vapor-compression cycle and an absorption solution cycle, as shown in Figure 3-8.

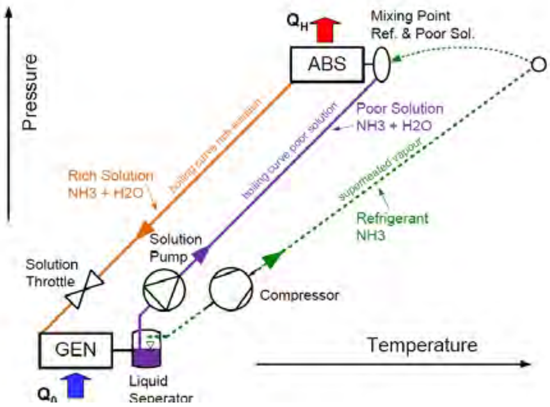


Figure 3-8: Absorption/compression- heat pump cycle in the solution field
[Moser, Zotter, Rieberer, 2011]

As shown in Figure 3-8, the refrigerant vapor from the separator at low pressure level is compressed to high pressure level by an electrically driven compressor. The high-pressure refrigerant vapor gets mixed with liquid poor solution in the Absorber (ABS) and completely absorbed by rejecting the absorption heat to the heat sink at high temperature level.

The liquid rich solution from the ABS gets expanded in a throttle to the generator (GEN) at low pressure level. Refrigerant vapor is desorbed in GEN due to heat supply from the heat source at low temperature level. The vapor is separated from the liquid poor solution in a separator afterwards. The remaining liquid poor solution at low pressure level is pumped into the ABS at high pressure level by an electrically driven solution pump, while the refrigerant vapor is compressed by the compressor.

The absorption/compression heat pump is suitable for high temperature application. Due to the use of a working pair instead of pure refrigerant, the pressure levels of absorption and desorption can be adjusted by a variation of the solution concentrations respectively changing the circulation ratio (ratio of solution mass flow to refrigerant mass flow). An absorption/compression heat pump promises several advantages in comparison to a vapor-compression heat pump:

- A high heat sink outlet temperature is possible at moderate pressure levels compared to a vapor-compression heat pump. For example temperatures above 100 °C at the heat sink can be reached with a high-pressure level below 20 bar for ammonia/water instead of a high-pressure level higher than 62 bar for pure ammonia.

- The temperature glide occurring in the generator and absorber can be varied according to the available and required external temperature glides by changing the circulation ratio. This fact offers higher coefficient of performance due to lower irreversibility in the heat exchangers (“Lorenz”-process),
- The absorption/compression heat pump is suitable for high temperature lifts, which promises a bi-generation of heat and cold.

From a technical point of view the oil-management could be an issue, if oil-lubricated compressors are used, because the working pair and the oil have to be compatible at high temperatures and arrangements for the oil return have to be considered, which are more complex than in vapor-compression heat pumps. The use of a conventional oil-lubricated compressor is limited due to high discharge temperatures and the thermal stability of the oil. At very high pressure ratios multi-stage compression has to be taken into account for higher coefficients of performance. Finally, a higher complexity of the control system results from a more complex system design.

Within the work for Annex 35 different simulation models for the “hybrid” absorption/compression-heat pump cycle have been set up for the working pair ammonia/water at the Institute of Thermal Engineering. As an example for the detailed investigation some results are shown in Figure 3-9. The coefficient of performance (COP_H, see Equation 1) and the high pressure level (p_{high}) versus the circulation ratio (f, see Equation 2) of a single stage Osenbrück-Cycle (with a solution heat exchanger, see Figure 3-10) are shown in Figure 3-9. As shown, the high-pressure level can be adjusted by the variation of the circulation ratio, which has also an influence on the COP.

$$COP_H = Q_{ABS}/(P_{Compressor} + P_{Solution\ Pump}) \qquad \text{Equation 1}$$

$$f = m_{Solution\ Pump}/\ m_{Compressor} \qquad \text{Equation 2}$$

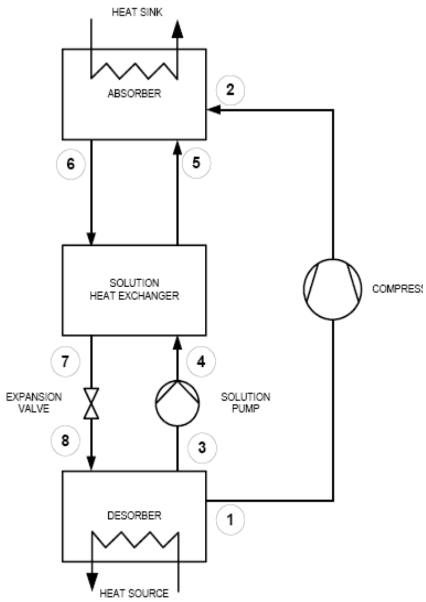


Figure 3-10: "Hybrid" heat pump cycle (Osenbrück-Cycle see Nordtvedt, 2005)

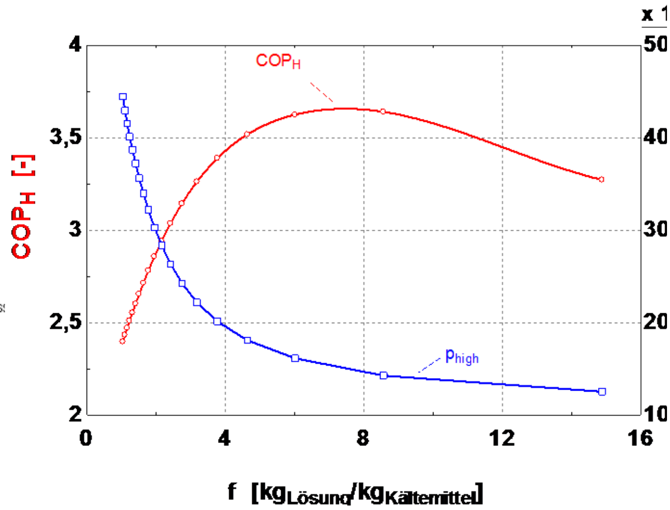


Figure 3-9: Simulation results - COP_H & p_{high} vs. f for a "hybrid"NH_3/H_2O heat pump (Osenbrück-Cycle, Figure 3-10) @ plow = 2 bar, $t_{source,ex}$ = 40°C, $t_{sink,ex}$ = 85°C [Vehovec et al., 2013]

Recently, there are increasing research activities regarding the absorption/compression-heat pumps which are commonly known as "hybrid" heat pump system (HHP). Nevertheless there are only few suppliers for commercial available HHP. For example "Hybrid Energy AS" from Norway offers customized ammonia/water-absorption/compression-heat pumps with heating capacities of several hundred kW, shown in Figure 3-11.

Figure 3-11: Pictures of two "hybrid" heat pumps by "Hybrid Energy AS"left: 300 kW, right: 650 kW heating capacity [Nordtvedt, 2009]

Within the Austrian research project "HyPump" – financially supported by the Austrian Funding Agency "FFG" (Project-Nr. 834614) – the project partners IWT (TU Graz), AIT and Frigopol (Austrian compressor and heat pump manufacturer) develop a "hybrid" heat pump for small scale application (ca. 25 kW) consisting only standardized components, for minimizing the cost. Because the major aim of this project is to develop a high-temperature heat pump for industrial waste heat recovery, which demands low payback times to achieve a high market potential.

Within the "HyPump"-project different ammonia-based working pairs are investigated and compared to each other. Ammonia/lithium nitrate (NH_3 – $LiNO_3$) has been choosen, because of the expected pure ammonia gaseous phase in order to overcome problems with the oil-lubricated compressor and the water content in the refrigerant vapor [Hannl & Rieberer, 2014].

Further to build up a prototype, different system configurations are investigated, using e.g. variation of the working pairs and design boundaries, as well as solutions for system design problems are analyzed in detail. The actual design of the test facility is shown in Figure 3-12. [Hannl & Rieberer, 2014]

Figure 3-12: Picture of the absorption-/compression heat pump prototype @ IWT [Hannl & Rieberer, 2014]

3.2.2 Absorption heat pumping systems

Absorption heat pumping systems (AHP) are often used to utilize the waste heat for industrial refrigeration purposes as well as to upgrade the temperature level of waste heat. Besides of the process itself and its components, the choice of the working mixture plays an important role in regard to efficiency and costs of an AHP-plant.

AHP are so called thermally driven heat pumps. So AHP can be driven by waste heat at temperature levels higher than 60 °C, as e.g. from oven, air compressors etc. for cooling application on one hand and on the other hand AHP, driven for example by steam with

160°C, can upgrade the temperature level of waste heat e.g. from 60 to 90°C, as e.g. to use the flue gas condensation heat for district heating purposes.

Various working mixtures have been investigated, however, just two (*NH_3/H_2O* and *$H_2O/LiBr$*) are commercially available. As industrial refrigeration application mostly requires evaporating temperatures below 0°C, the *NH_3/H_2O* AHP-process is in the focus for industrial application at the Institute of Thermal Engineering (TU Graz). Figure 3-13 shows a single-stage *NH_3/H_2O* AHP-process in the pressure/temperature diagram.

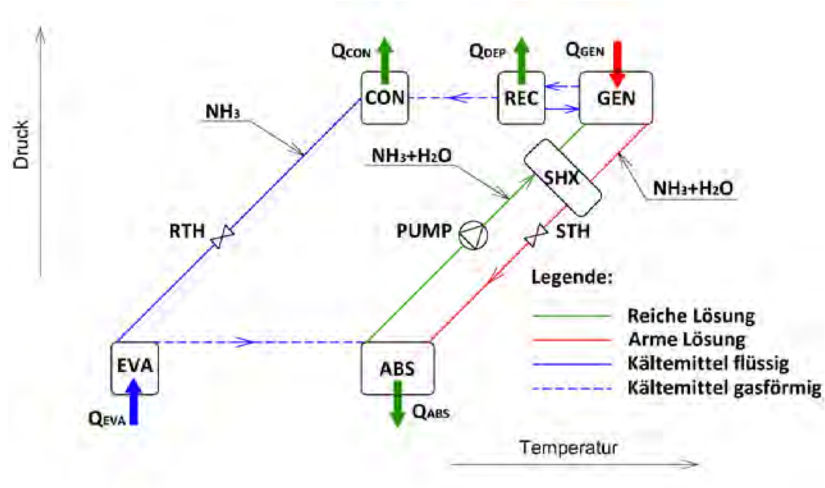


Figure 3-13: One-stage *NH_3/H_2O* AHP-process in the pressure / temperature diagram [Kotenko, 2012]

The *NH_3/H_2O* AHP process (see Figure 3-13) has been analyzed by means of thermodynamic simulation using the software program ASPEN Plus at following conditions (parameters):

- cooling water inlet/outlet temperatures of 20/25°C and 25/30°C
- cold water inlet/outlet temperatures of +2/-1°C.

The calculated values of the COP_C for cooling are shown in dependence on the hot water inlet temperature (influence the temperature of the poor solution) in Figure 3-14. Apparently, the maximum COP_C at low temperature lift (blue line) lies within the generator outlet temperature range from 80-100 °C and is about 0.69. At high temperature lift (green line) the maximum COP_C is about 0.62 and the heat at higher generator temperatures (95-100°C) is necessary. With a decrease in the waste heat temperature (down to 80-85°C), the use of the NH_3/H_2O AHP process is efficient only at low temperature lifts.

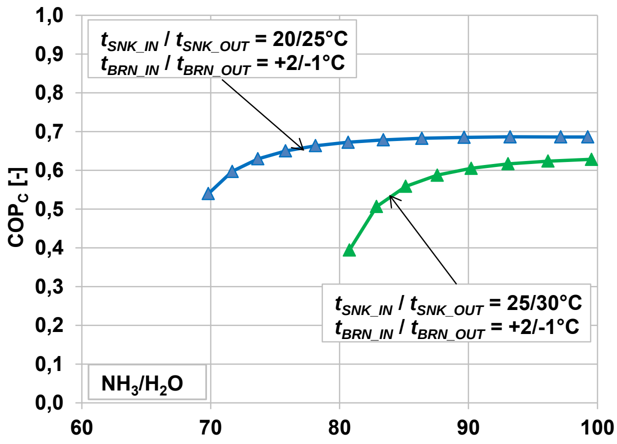


Figure 3-14: Calculated COP_C for the NH_3/H_2O AHP process at cooling water inlet/outlet temperatures of 20/25 °C and 25/30 °C and brine inlet/outlet temperatures of +2/-1 °C [Rieberer et al., 2012]

Ammonia/IL AHP process

In the last years, in order to overcome some drawbacks of the NH_3/H_2O working mixture (i.e. need of rectification) the use of ionic liquids (ILs) as absorbents has been suggested. Commonly ILs are described in the literature as substances composed entirely of ions (cations and anions) with melting points below 100 °C.

At the Institute of the Thermal Engineering (TU Graz) the NH_3/IL AHP process with two ionic liquids (*[bmim][BF$_4$]*, *[bmim][PF$_6$]*) has been analyzed and compared with the above described NH_3/H_2O AHP process.

The calculated values of the cooling COP are shown in Figure 3-15. The efficiency of the AHP process with both ILs at investigated generator temperatures is lower than that of the NH_3/H_2O AHP process. It can be seen, that there is a big decrease in the COP_C of the process with ILs at low generator temperatures. This occurs due to the low difference between NH_3-concentrations in the rich and poor solutions and, therefore, high specific solution flow rate (ratio of the flow rate of the rich solution to the flow rate of the refrigerant).

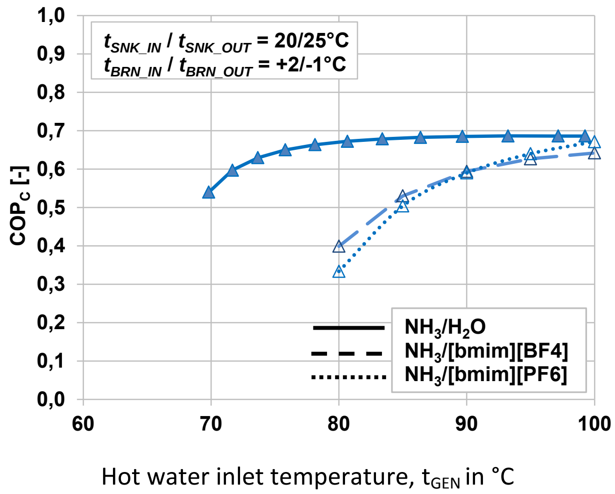


Figure 3-15: Comparison of the calculated cooling COP of the AHP processes with the working mixtures of NH_3/H_2O, NH_3/[bmim][BF_4] und NH_3/[bmim][PF_6] depending on the generator outlet temperature [Rieberer et al., 2012]

Generally, it can be concluded, that the investigated *NH_3/IL* AHP processes cannot beat the conventional *NH_3/H_2O* AHP process for the industrial refrigeration application using waste heat but could have a high potential for heating applications, as high

However, AHPs have a high potential for the utilization of waste heat, as e.g. from baking oven, air compressors etc. for industrial refrigeration purposes from an economical and an ecological point of view.

3.2.3 HPs for upgrading flue gas condensation heat

HPs, as well as AHPs and CHPs offer the possibility to use the condensation heat of the flue gas from e.g. power or co-generation plants by upgrading its temperature level, even thou the temperature level of the heat supply system is higher than the dew point temperature of the flue gas.

The aim of the current national project ICON (FFG-No.: 829964, project head: AIT, project partners: BIOS BIOENERGIESYSTEME GmbH, OCHSNER heat pumps GmbH, Scheuch GmbH) is to increase the heat output by flue gas condensation of biomass plants with heat pumping systems. Beside the heat recovery, systems for flue gas condensation in biomass plants are already known as a way for reducing the dust and plume of the exhaust systems, typically for 1 MW_{th} biomass power plants. In practice, the useful temperature level of e.g. districting heating systems are too high for flue gas condensation, as unfortunately the water dew point of the flue gas (50 to 60 °C) is often much lower than the heating return temperature. By integrating a heat pump, flue gas condensation can be made more efficient and available all-season. Therefore, this heat pump application in a biomass plant offers savings of approximately 10 to 15 % of the required fuel and related to that a significant reduction of emissions. Further, also the electrical power for flue gas de-vaporization can be reduced using a heat pump for the flue gas condensation. In conclusion, such a heat pump application in a biomass power plant offers a large ecological and economical potential. Within this Austrian project a heat pump using a direct evaporator and a refrigerant suitable for flue gas condensation is developed and investigated (see Figure 3-16Figure 3-16).

Figure 3-16: Test facility for experimental analysis of flue gas condensation @ AIT [Seichter et al., 2013]

3.3 Literature

Cofely, 2013 http://www.cofely.info/leistungen/waermepumpen/industrie/ (02.10.2013)

FRIGOPOL, 2013 *http://www.frigopol.com/en/home/* (02.10.2013)

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4 Canada

4.1 Introduction

Canadian industry requires about 48 % of the total country primary energy input. The annual energy used by eight major manufacturing industries, such as pulp and paper, primary metals and oil, accounts for about 1.7 million TJ representing 65 % of the total energy used by all Canadian industries [NEB, 2008]. But, up to 71 % of the energy input is released to the environment via waste heat streams such as stack emissions (combustion gases and hot air), steam, process gases and liquid effluents. The largest heat losses occur in the pulp and paper industry (36.4%) followed by primary metal manufacturing industries (23 %) [Stricker, 2006].

IEA-IETS Annex 13 / IEA-HPP Annex 35 [Annex 35, 2010] defines industrial heat pumps (IHP) as *medium and high thermal power units used for heat recovery and heat upgrading in industrial processes*. It also specifies that … *heat pump in medium … power ranges …can be used not only for heat recovery in industrial processes, but also for heating and air-conditioning of industrial buildings.*

Since industrial heat pumps can significantly reduce fossil fuel consumption and, thus, contribute to global energy conservation and industrial productivity improvement, as well as to reducing greenhouse gas emissions, Canada has initiated a number of R&D studies followed by some *field* demonstration projects. The scope was to indentify appropriate heat pumps applications for meeting future industry and environmental requirements.

Canada's R&D projects have been conducted in a specific national energetic context where prices of primary energies (electricity, natural gas, oil) are relatively low and where industrial companies are investing to improve production efficiency (profitability) rather than reducing their specific energy consumption.

In spite of this particular energetic environment, theoretical and experimental R&D work has been performed in order to improve the heat pump vapour compression cycles, particularly by using ejectors [Scott].

Moreover, because industrial waste heat in liquid form available at low-temperatures represents about 25 % of the total energy used by Canadian manufacturing industry, a number of R&D work has focused on high-temperature heat pumps able to recover heat at relatively low temperatures, generally between -5°C and 35 °C, and produce hot water at temperatures up to 85-90 °C [Minea, 2010]. In this area, the Canadian R&D projects have focused on using natural refrigerants such as carbon dioxide and ammonia, and more or less known thermodynamic cycles, as well as on developing national expertise and improving public and industry awareness.

4.2 Historical background

In the past, the IEA HPP Annex 9 project (High Temperature Industrial Heat Pumps - 1990) presented a status report on high-temperature industrial heat pumps, as well as a detailed description of R&D efforts going on at the time [Annex 9, 1990].

Later, the IEA HPP Annex 21 (Global Environmental Benefits of Industrial Heat Pumps - 1996) provided an overview of potential industrial heat pump applications [Annex 21, 1995], and identified the lack of operator and engineer experience as the main market barrier for industrial heat pumps. Other reasons that have contributed to a low level of industrial heat pump utilization were the relatively low cost of primary energies and a lack of knowledge on the potential benefits.

Prior to 1995, low-temperature industrial heat pumps were developed and implemented in Canada, especially in lumber drying and evaporation/distillation processes, and also in the food industry, including dairies, poultry, sugar refining, breweries, liquor production and fish processing [Annex 21, 1995].

Toward the end of 1993, 17 % of 14 chosen processes involving more than 1,900 individual plants were using industrial heat pumps, more than 90 % of which were in lumber drying. At the end of 2010, in 339 plants surveyed in Québec (Eastern Canada), Ontario and Manitoba (Central Canada) and British Columbia (Western Canada), 31 % of existing industrial heat pumps (26) were used for drying, 27 % for waste heat recovery and 8 % for evaporation processes with cooling capacities varying between 14 and 1,050 kW [Minea, 2010].

Today, in spite of their well known potential benefits (e.g. reduced energy consumption for heating, increased capacity of existing processes, and improved product quality and plant environmental performance), the number of industrial heat pumps (IHPs) installed in Canada is still relatively low compared to the number of existing technically and economically viable opportunities. Higher capital costs and low energy prices, as well as a lack of knowledge on the potential benefits and/or experience with industrial heat pump technology may explain this situation.

4.3 Canada's R&D projects

According to the definition of IHPs set forth in the Annex 35/13 legal text [Annex 35, 2010], over the last decade, Canada's R&D projects have focused on recovering low-grade waste heat from relatively small- to medium-scale industrial manufacturing facilities in order to supply heat for building domestic hot water consumption and/or industrial heating purposes. The objective was to properly design, integrate and operate several types of IHPs in various energy intensive industrial processes able to provide sufficient amounts of waste heat at appropriate quality levels, flow rates and temperatures.

During the last few years, two Canadian public research institutions, i.e. CANMET Energy Technology Centre (CETC) - Varennes [Scott] and Hydro-Québec Research Institute - Laboratoire des technologies de l'énergie (LTE) [Minea, 2010] have conducted a number of R&D projects on industrial heat pumps. All these projects were intended to respond to future requirements, such as a reduction of the energetic intensity of small- and medium-sized industrial processes and of environmental thermal pollution.

The LTE laboratory has worked on technologies aimed at extending the conventional limits of heat source and heat sink temperatures, respectively. The scope was to recover waste heat at temperatures as low as -5 °C, especially from liquid effluents, and supply heat at relatively high temperatures (i.e. up to 85 °C) (Figure 4.1). These technologies have been theoretically and experimentally studied because of their simplicity, which allows for faster industrial implementation, as well as their ability to efficiently contribute to the global reduction of energy costs and greenhouse gas emissions [Minea, 2011a; Minea, 2013]. Applications in small- to medium-sized industries, as well in large institutional buildings, such as hospitals, have been targeted because simultaneous heating and cooling processes are required in these settings. The scope was to adapt and/or improve a number of heat pump cycles for industrial heat recovery, demonstrate their energetic and environmental benefits, and prepare the industry for future demonstration and/or application projects.

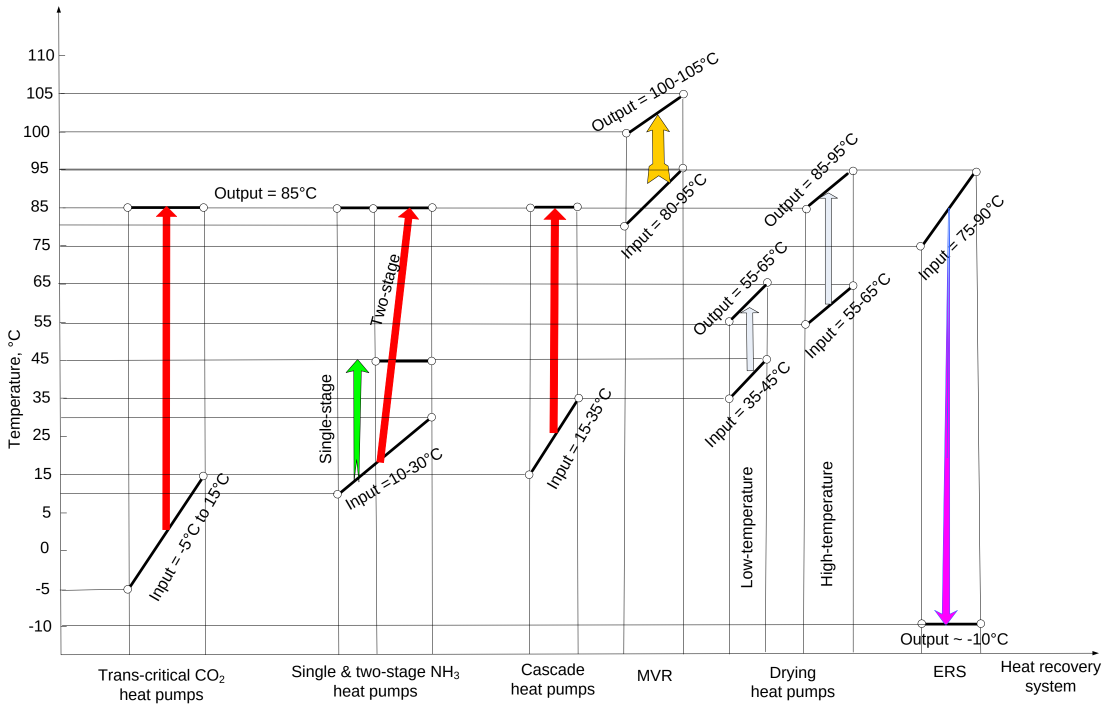


Figure 4-1: Industrial heat recovery systems studied at the LTE laboratory [Minea, 2011a; Minea, 2013]. ERS: ejector refrigeration system; Input: inlet temperature of waste heat carrier; MVR: mechanical vapour recompression; Output: output temperature of heat sink thermal carrier

On the other hand, CANMET's research laboratory focused its R&D efforts on improving the design and energy performance of ejector cooling and heat pump-ejector assisted systems [Scott]. As previously noted, primary energy prices (e.g., electricity, natural gas, oil) in Canada are today still relatively low compared with those of other industrialized countries. This reality hasn't encouraged small- and medium-sized industries to invest in heat recovery technologies such as heat pumps, even though the potential is enormous.

As a consequence, Canada's R&D projects have rather focused on future energetic and climate crises by proposing efficient and reliable technical solutions to use the enormous quantities of low-grade industrial waste heat available.

4.3.1 Thermally-driven ejector heat pumps

The use of ejectors as vapor compression devices in thermally driven heat pump systems has received increased attention over the past two decades [Scott]. Unlike mechanical vapour compression heat pumps, such systems are driven by heat instead of electricity.

Ejectors are simple devices, generally used to compress a vapour stream and produce vacuum simultaneously. They have no moving parts, are relatively easy to manufacture, represent relatively inexpensive alternatives to conventional mechanical vapour compressors, and have low maintenance costs. These features can give ejector heat pumps an advantage over other thermally driven systems with comparable COPs (e.g. absorption, adsorption). However, the ejectors require primary motive steam at a relatively high pressure, mostly 7-15 bars, and their noise level can be rather high.

In traditional industrial ejector applications, water steam is used as a moving fluid to generate vacuum and cooling effects [Ashrae, 1969]. To improve the efficiency of the simple ejector cycle, more complex cycles have been investigated [Yu, 2006], as well as the integration of ejectors in vapour compression and absorption systems. Significant efforts have also been devoted to the development of solar driven ejector refrigeration systems [Pridasawas, 2008].

More recently, new research work has shown the benefits of using other moving fluids to provide more favorable operating conditions and increase system efficiency. Several HFCs (e.g. R-245fa, R-141b, R-134a and R-142b) as well as natural refrigerants (e.g. butane, propane and CO_2) [Elbel, 2011] have been considered as alternative working fluids.

A typical ejector has one inlet to admit the motive (primary) fluid (flow) and another one to admit the gas/vapour mixture to be discharged from the evaporator (Figure 4.2a) [Scott]. At the nozzle exit area, the primary stream flows at supersonic speeds at low pressure and temperature levels. This induces the secondary flow from the evaporator to pass through a converging section, resulting in the secondary stream attaining sonic flow conditions. In the constant area section (b), the supersonic primary stream and the secondary stream mix. Friction, mixing losses and shock formation in this mixing section cause the streams to be compressed and decelerate to subsonic velocities. Further compression occurs in the diffuser, after which the mixed stream flows to the condenser (c) [Ouzzane, 2003; Scott, 2008].

Such single- or multiple-stage ejector systems are designed to convert the pressure energy of the motive fluid to velocity energy in order to carry the suction fluid, and then to recompress the mixed fluid by converting velocity energy back into pressure energy. A properly designed nozzle will economically make use of high pressure fluids to compress them from a low pressure area to a higher pressure one.

Typically, ejector efficiency involves comparing energy output to energy input. Since ejectors approximate a theoretically isentropic process, their overall efficiency is expressed as a function of entrainment efficiency. The direct entrainment of a low velocity suction fluid by a motive fluid, results in an unavoidable loss of kinetic energy owing to the impact and turbulence originally present in the motive fluid. This fraction, which is successfully transmitted to the mixture through a momentum exchange, is called the "entrainment efficiency ratio" (ω), defined as the ratio of the secondary mass flow rate to the primary mass flow rate (Figure 4.2b). For any given generator and evaporator temperatures, this parameter remains constant up to a critical exit pressure (p_c^*). Above this value, the secondary stream no longer reaches supersonic speeds, and ω decreases rapidly. When the ejector is used as a compressor in heat pump systems, the stream leaving it passes through a condenser (Figure 4.3). After the condenser, the working fluid is split in two separate flows: one returns to the evaporator while the remainder is pumped to a vapour generator in order to generate the primary motive flow.

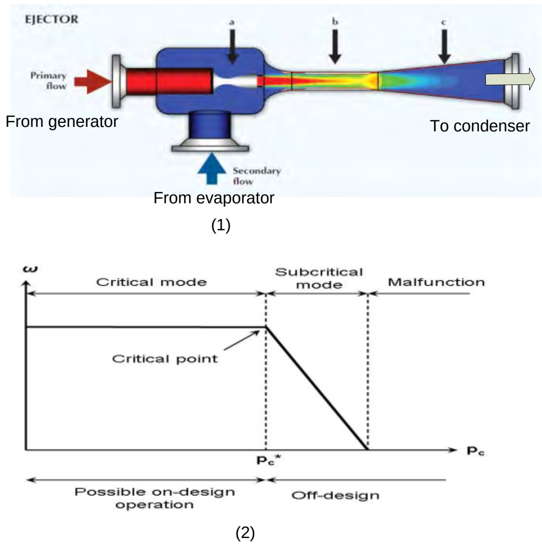


Figure 4-2: (1) Schematic representation of a single-phase, single-stage ejector; (2) typical performance curve of an ejector; p_c*- critical condenser pressure; ω- entrainment ratio [Scott]

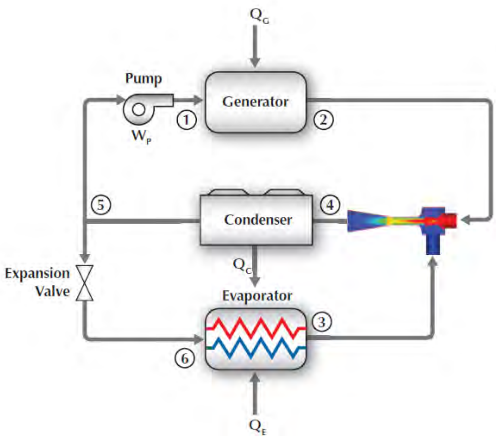


Figure 4-3: Schematic illustration of a simple ejector heat pump [Scott]

Prior to conducting experimental R&D work, the CanmetENERGY laboratory developed simulation (numerical) models of single-phase, supersonic ejectors [Ouzzane, 2003]. One-dimensional ejector models, providing a full description of the flow inside supersonic ejectors, have been developed using Computational Fluid Dynamics (CFD) methods and software [Scott, 2008].

Using the 1-D models thus developed, an ejector has been designed and built for an experimental heat pump prototype to provide cooling by using industrial waste heat and HFC-134a as a refrigerant [Scott, 2011].

The COP of thermally driven heat pumps is defined as the ratio of the useful energy produced (cooling, heating, or both) to the total energy input (thermal plus electric). The “entrainment ratio” at the critical point is representative of the highest COP attainable by the ejector heat pump, and higher entrainment ratios result in higher COPs. COPs above 0.35 have been predicted at condenser, evaporator and generator saturated temperatures of 36 °C, 15 °C and 80 °C respectively, without accounting for the motive steam boiler efficiency. The ejector heat pump COP at low temperature lifts is, therefore, of the same magnitude as for the absorption heat pump, but at much lower capital costs.

The laboratory test bench (Figure 4.4) produced up to 9 kW of cooling from the evaporator while using up to 30 kW of electricity to generate vapour as the primary moving stream. Preliminary results showed that 5 kW of cooling can be provided with a thermal COP of approximately 0.4 at condenser, evaporator and generator temperatures of 25 °C, 10 °C and 90 °C respectively [Scott].

Figure 4-4: View of CanmetENERGY’s laboratory ejector test bench [Scott]

A second R&D programme conducted at CanmetENERGY investigates two-phase flow ejectors. A first experimental test bench integrates a supersonic ejector into an existing heat pump system in order to recover the expansion valve work, otherwise lost in conventional vapour compression heat pump systems. Other test benches will be built in order to better understand the operation of two-phase flow ejectors [Aidoun, 2011].

Canmet Energy's research team estimates that thermally driven heat pumps provide interesting alternatives to conventional mechanical vapour compression systems for industrial applications. Given their high reliability and their ability to be powered by industrial waste heat, ejector-based heat recovery systems offer a significant potential for future applications in any field where industrial heat pumps are used [Scott].

4.3.2 CO_2 ejector refrigeration system

Conventional cooling systems use electrically-driven compressors. However, in many countries, during the hottest periods of the year, cooling and air-conditioning systems cause a serious electrical peak load problem. On the other hand, there is relatively abundant energy, such as various types of wasted heat, solar, geothermal and biomass energy.

The thermally driven ejector technology, also known as jet pump refrigeration or ejector refrigeration, has been used in cooling applications for many years. In their present state of development these systems have a much lower COP than vapour compression systems, but offer advantages in terms of simplicity and no moving parts, and their ability to refrigerate using industrial waste heat (or solar thermal energy) as a heat source at temperatures above 35 °C and up to 75 °C.

Since 1910, ejector refrigeration cycles have been used in air conditioning applications until the development of CFC refrigerants in the 1930's. At that time, the mechanical vapour compression cycle, much more efficient than thermally driven cycles, became predominant. However, R&D work on ejector technologies continued worldwide particularly in the chemical and process industries bringing cooling capacities up to 60 MW [Eames, 1995; Shrerif, 1998; Chunnanond, 2004; Alexis, 2005].

Other applications can be found in the food processing industry where waste heat is available and ejector refrigeration systems can be used for process cooling and transport refrigeration, as well as in tri-generation power systems where they can be used in conjunction with combined heat and power systems to provide cooling.

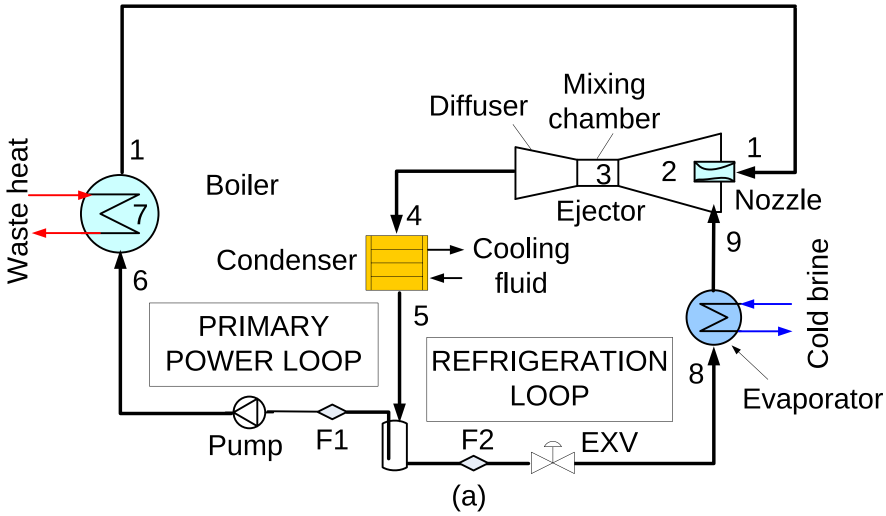
The main barriers to the widespread use of the ejector refrigeration technology include its lower COPs (± 0.3) compared to vapour compression systems and other thermally driven technologies, and the unavailability of industrial processes facilitating their application. On the other hand, the main drivers encouraging the uptake of the technology, especially in the food processing or tri-generation systems industries, are the successful demonstration of the technology benefits, the continuous increase in primary energy prices and better thermal integration in the manufacturing industry.

To increase the attractiveness of ejector refrigeration systems, R&D is still required to increase efficiency, develop alternative ejector types, such as roto-dynamic ejectors that have the potential to boost efficiency, develop ejectors that can operate with natural refrigerants other than water, such as CO_2 and hydrocarbons, to extend the range of applications below 0 °C, to enhance cycle optimisation and the integration of ejectors with conventional vapour compression and absorption systems.

A feasibility study on a CO_2 ejector refrigeration system (ERS) aimed at producing cold fluids at temperatures between 0 and approximately -5 °C by using waste heat at inlet temperatures above 35 °C has been designed and experimentally studied in Canada. A small-scale laboratory prototype using CO_2 as a working fluid was built and tested within thermal conditions simulating cold climate weathers [Minea, 2011a; Minea, 2013].

The EPS set-up (Figure 4.5) uses an ejector powered directly by thermal energy to replace the conventional mechanical compressor. The only moving part in the system is the working fluid circulation pump (see also Section 4.3.1).

The laboratory prototype consists of two loops, the power and the refrigeration loops respectively (Figure 4.5a). Within the power loop, low-grade heat is used in a boiler to evaporate a high pressure CO_2 liquid refrigerant (process 6-1) (Figure 4.6). The high pressure vapour generated, known as the primary fluid, flows through the ejector where it accelerates through the nozzle. The pressure reduction that occurs induces vapour from the evaporator, known as the secondary fluid, at state 2. The two fluids mix in the mixing chamber before entering the diffuser section where the flow decelerates and pressure recovery occurs. The mixed fluid then flows to the condenser where it is condensed, rejecting heat to the environment. A portion of the liquid exiting the condenser at state 4 is then pumped to the boiler for the completion of the power cycle. The remaining liquid is expanded through an expansion device and enters the evaporator of the refrigeration loop at state 6, as a mixture of liquid and vapour. The refrigerant evaporates in the evaporator producing a refrigeration effect, and the resulting vapour is then drawn into the ejector at state 9. The refrigerant (secondary fluid) mixes with the primary fluid in the ejector and is compressed in the diffuser section before entering the condenser at state 4. The mixed fluid condenses in the condenser, exits at state 5, and the refrigeration cycle re-starts.



(b)

Figure 4-5: Experimental set-up of the ejector refrigeration system; (a) schematic diagram; (b) view of the laboratory prototype [Minea, 2011a; Minea, 2013]

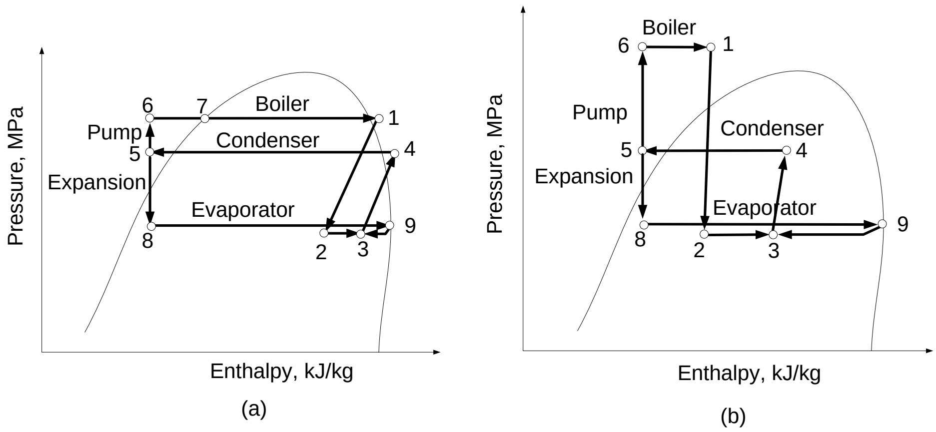


Figure 4-6: Ejector refrigeration thermodynamic cycles; (a) with a relatively low ejector inlet pressure; (b) with a much higher ejector inlet pressure [Minea, 2011a]

Table 4-1 summarizes the prototype's design parameters based on the assumption that low enough cooling fluid inlet temperatures are available in cold climates, resulting in the lowest ejector inlet pressures. This assumption leads to low ejector compression ratios (p_4 / p_3) ranging between 1.6 and 1.7.

Table 4-1: Cycle design for lowest ejector inlet pressures (see Figures 4.5 and 4.6)

State	Pressure	Temperature	Enthalpy	Flow rate
-	MPa	°C	kJ/kg	kg/s
1	6.4	25	410	0.145
4	5	15	420	0.195
5	5	15	220	0.195
6	6.4	10	220	0.145
7	6.4	12	220	0.145
8	3	-5	220	0.05
9	3	-5	435	0.05

Based on the cycle thermodynamic design at the lowest ejector inlet pressure, the boiler, evaporator and condenser design thermal capacities were 27, 11.4 and 40.7 kW respectively, with an average calculation error of 5.6% (Figure 4.6a). In this case, the system COP, defined as the ratio of the refrigeration effect to the heat input to the boiler, was 0.4, still relatively low compared to the COPs of conventional vapour compression systems, even when neglecting the energy consumption of the CO_2 liquid pump.

A 313 kW (cooling capacity) industrial-scale CO_2 ejector refrigeration machine with waste heat entering the system at 35 °C and cooling water at 20 °C has been simulated with the EES software. Using such inlet operating parameters, cold brine could be provided at 5 °C with a COP of approximately 78.4 (Figure 4.7). However, optimization work is under way by considering higher waste heat input temperatures and lower cooling fluid inlet temperatures in order to achieve much lower refrigerating temperature levels.

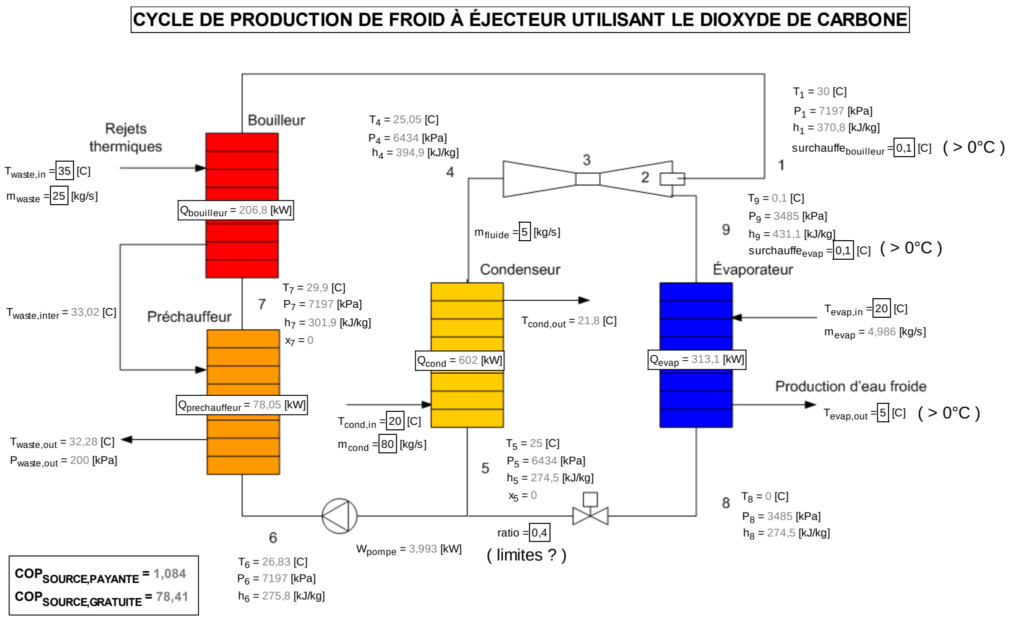


Figure 4-7: Simulation of an industrial-scale CO2 ejection refrigeration system [Richard, 2011]

4.3.3 High-temperature heat pumps

As part of the Annex 35-13 project [Annex 35, 2010], much R&D work has been done to develop/adapt and promote high-temperature heat pump applications in the Canadian small- and medium-sized manufacturing industry [8]. This section succinctly describes a number of heat recovery technologies, including high-temperature heat pumps (i.e. single- and double-stage and cascade) and mechanical vapour recompression systems, using natural (CO_2, NH_3) and low-emission (HFC-236fa, HFC-245fa, HFC-134a, HFO-1234yf) artificial refrigerants.

The principle of each technology is summarized and some of the simulation and experimental results achieved, such as operating parameters and energy performance, are provided. The data presented aim at supporting and encouraging the industry to use energy resources more efficiently by accelerating the implementation of feasible and efficient heat recovery technologies.

4.3.3.1 CO_2 trans-critical heat pumps

Industrial waste heat effluents and/or process fluids in a liquid form at temperatures between -5 °C and 25 °C are valuable heat sources for CO_2 trans-critical heat pumps in order to produce hot water (or air) at temperatures as high as 80-85 °C [Minea, 2013; Minea, 2012a].

A laboratory-scale, double-stage heat recovery system (Figure 4.8), including a pre-heating heat exchanger (as the first stage) and a 7 kW (shaft power input) CO_2 water-to-water trans-critical heat pump (as the heat recovery second stage), has been designed, built and tested [Minea, 2011; Minea, 2013; Minea, 2012a]. The pre-heating heat exchanger is required when the temperature of the industrial waste effluent (heat source) is higher than the temperature of the cold water to be heated. In this case, it recovers heat from the hotter waste heat (heat source) fluid and pre-heats the colder water (heat sink) before it enters the CO_2 heat pump. However, the pre-heating heat exchanger must be bypassed when the temperature of the waste heat source at the inlet isn't high enough to pre-heat the cold water. Consequently, the pre-heating heat exchanger is equipped with three-way motorized by-pass valves.

The heat pump refrigerating circuit contains a semi-hermetic, constant-speed CO_2 compressor, three plate heat exchangers (evaporator, gas cooler and internal heat exchanger), a low-pressure side receiver and an electronic expansion valve. A 48 kW electrical boiler supplies hot water to the evaporator simulating the industrial waste heat source. Because the scope of this study was to investigate the CO_2 trans-critical heat pump behaviour at the lowest heat source and heat sink inlet temperatures, the pre-heating heat exchanger was by-passed during all laboratory tests. After passing through or by-passing the pre-heating heat exchanger, the cold water is supplied to the once-through gas cooler at a constant flow rate, temperature and pressure. Hot water is produced at temperatures that vary with the heat source inlet temperature and flow rate. The gas cooler is connected to the hot water storage tanks by means of a closed water loop. A variable speed pump circulates the water from the bottom of the storage tanks through the gas cooler and to the top of the storage tank. In industrial field applications, energy efficiency is best under perfect hot water stratification inside the storage tanks. In a laboratory setting, as well as in the field, the hot water storage tank assembly can be easily by-passed, if required.

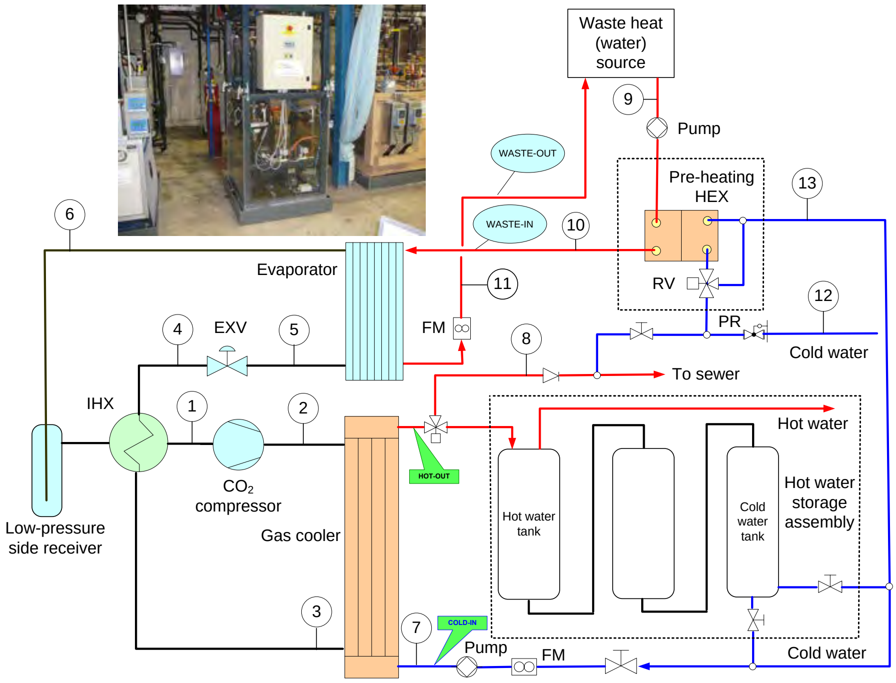


Figure 4-8: Experimental setup of the laboratory-scale, two-stage heat recovery system with a CO2 trans-critical heat pump as a second stage. EXV: expansion valve; FM: flow meter; HEX: heat exchanger; IHE: heat exchanger; PR: pressure regulator; RV: 3-way regulating valve; 1 to 13: measurement points (temperatures, pressures, flow rates) [Minea, 2011a; Minea, 2012a]

Several tests have been done under the following experimental conditions: (i) both waste heat source and heat sink fluids enter the heat pump at constant flow rates, i.e. 1 kg/s for the waste heat source water and 0.11 kg/s for the cold water; (ii) the waste heat source fluid enters the heat pump at 7 °C, 10 °C and 12 °C in the winter, and at 7 °C and 15 °C in the summer; such thermal conditions, specific for winter and summer cold weathers respectively, are considered here as "extreme"; (iii) these heat source inlet temperatures allowed for the cold water to by-pass the preheating heat exchanger; (iv) the hot water storage tank assembly is also by-passed in order to avoid water stratification issues; (v) the hot water produced is rejected to the city sewer at temperatures below 40 °C after being mixed with fresh cold water.

For higher waste heat source temperatures at the heat recovery system inlet (i.e., above 15 °C in the winter and 25 °C in the summer), the pre-heating heat exchanger can't be by-passed. It must operate in order to preheat the cold water prior to entering the heat pump evaporator. For example, if the temperature of the waste heat fluid reaches its maximum value (45 °C) at the inlet of the two-stage heat recovery system, it will be cooled down to 38 °C prior to entering the heat pump evaporator. At the same time, the temperature of the cold water will be increased, for example, from a minimum of 7 °C (in the winter) and 17 °C (in the summer) up to 38 °C before entering the heat pump gas cooler [Minea, 2012a]. Under such operating conditions, as a first stage heat recovery device, the pre-heating heat exchanger will improve the overall energy efficiency of the entire heat recovery system.

Temperatures of hot water leaving the gas cooler under "extreme" winter operating conditions are presented in Figure 4.9a. It can be seen that with cold water entering the heat pump at 7 °C, process hot water has been supplied at average temperatures of 67 °C, 69 °C and 71 °C by using waste heat water entering the heat pump evaporator at 7 °C, 10 °C and 12 °C respectively. The hot water temperatures at the gas cooler outlet increased with the waste heat source inlet temperatures as well as with the corresponding high-pressure gas cooler (compressor discharge) pressures.

The *heat pump* coefficient of performance (COP_{hp}) can be defined as the gas cooler thermal power supplied ($\dot{m}_{hot\,water}\,\bar{c}_p\,\Delta T_{gc}$, where $\dot{m}_{hot\,water}$ is the mass flow rate, $\bar{c}_p$ - the average specific heat of the heated water, and ΔT_{gc} - the hot water temperature increase within the heat pump gas cooler) divided by the compressor electrical power input. The *system* heating coefficient of performance (COP_{syst}) can be similarly defined as the gas cooler thermal power supplied by the gas cooler divided by the electrical input power of the compressor and waste water circulating pump. Figure 4.10b presents the heat pump (compressor only) and system (compressor plus the waste heat source circulating pump) coefficients of performance for the same "extreme" winter operating conditions. At constant cold water inlet temperatures, both *heat pump* and *system* heating coefficients of performance increase with the waste heat source inlet temperatures. During the winter, with cold water entering the heat pump at 7 °C and waste heat fluid entering the heat pump at 7 °C (test W-1), 10 °C (test W-2) and 12 °C (test W-3) respectively, the thermal power recovered was about 74 % of the total thermal power supplied during each of these tests (Figure 4.9b).

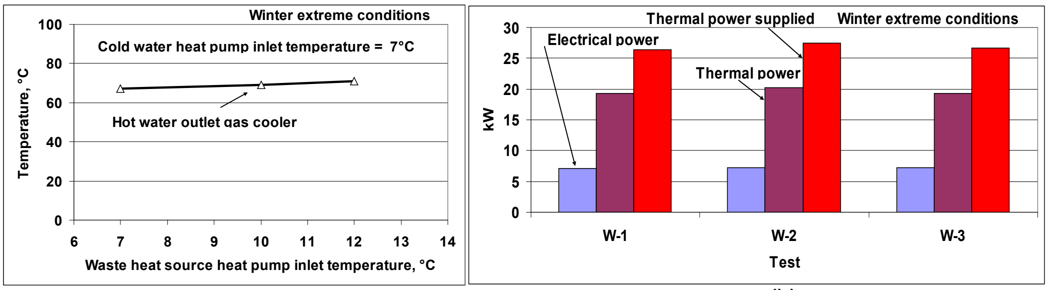


Figure 4-9: Heat pump "extreme" winter operating conditions; (a) hot water temperatures at the gas cooler outlet; (b) overall energy balance [Minea, 2013; Minea, 2012a]

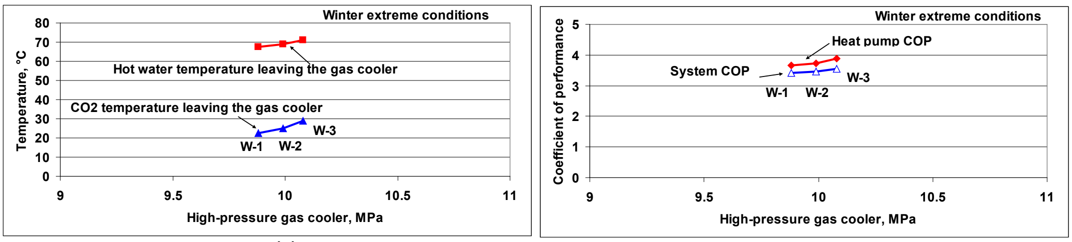
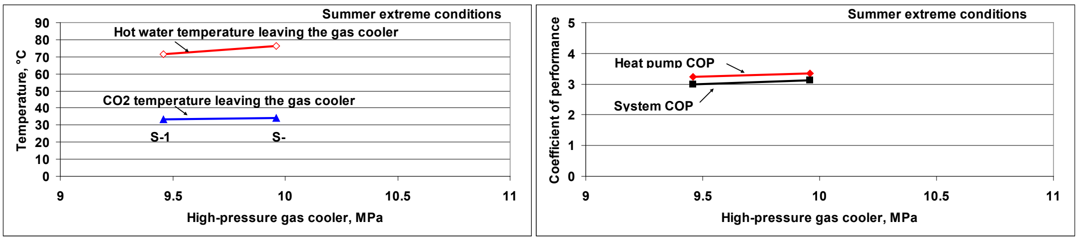


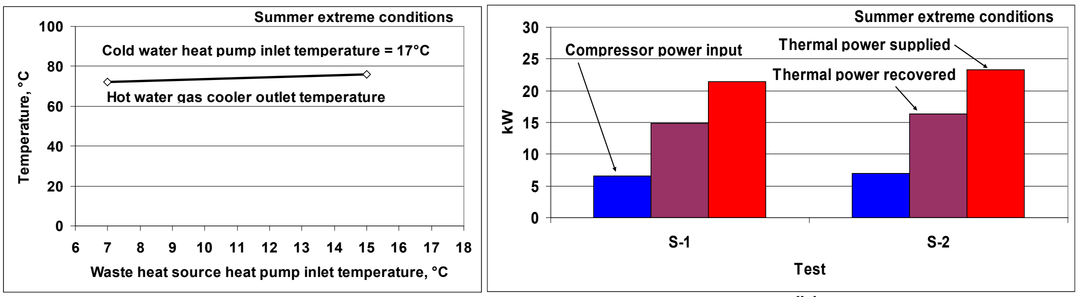
Figure 4-10: Heat pump performance in extreme winter operating conditions; (a) CO2 and hot water temperatures at the gas cooler outlet; (b) heat pump and system coefficients of performance [Minea, 2013; Minea, 2012a]

Temperatures of both CO_2 and hot water leaving the gas cooler in the *extreme* summer operating conditions (tests S-1 and S-2) are presented in Figure 4.11a. With cold water entering the heat pump at 17 °C, hot water is supplied at 72 °C and 77 °C by using waste heat water entering the heat pump evaporator at 7 °C and 15 °C respectively. Both CO_2 vapour and hot water gas cooler outlet temperatures increase with the high-pressure gas cooler (compressor discharge) pressure. Figure 4.11b presents the heat pump (compressor only) and system (compressor plus the waste heat source circulating pump) coefficients of performance for extreme summer operating conditions. Both COPs were over 3, but *system* heating COPs were about 8.2 % lower than *heat pump* COPs. Figure 4.12a shows the hot water temperatures at the gas cooler outlet in "extreme" summer operating conditions. Under these "extreme" conditions, the thermal power recovered represented about 70 % of the total thermal power supplied by the heat pump's gas cooler (Figure 4.12b). Over the experimental range of waste heat source and cold water inlet temperatures, the maximum thermal effectiveness of the internal heat exchanger was achieved in the winter (41.4 %) and the lowest, in the "extreme" summer operating conditions (17.5 %). This relatively low thermal effectiveness suggests that further design improvements and proper selection of the internal heat exchanger are required to enhance the overall heating performance of the system. The majority of experimental tests have been validated by a simulation model based on the EES software. An example of the results obtained is given in Figure 4.13.



(a) (b)

Figure 4-11: Heat pump performance in extreme summer operating conditions; (a) CO_2 and hot water temperatures at the gas cooler outlet; (b) heat pump and system coefficients of performance (COP) [Minea, 2013; Minea, 2012a]



(a) (b)

Figure 4-12: Heat pump extreme summer operating conditions; (a) hot water temperatures at the gas cooler outlet; (b) overall energy balance [Minea, 2013; Minea, 2012a]

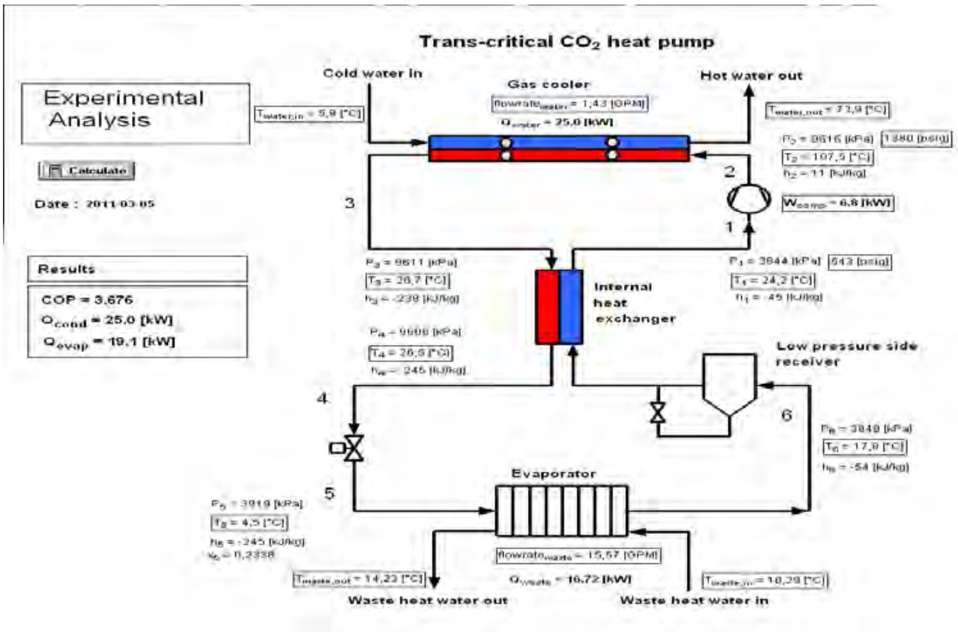


Figure 4-13: Example of trans-critical CO_2 heat pump simulation with the EES software [Richard, 2011]

Figure 4.14 schematically represents a CO_2 super-critical industrial heat pump recently implemented in a Canadian dairy plant [Minea, 2013; Marchand, 2011]. Hot water is provided at temperatures varying between 60 and 75 °C by recovering process waste heat. This IHP has been fully instrumented and an intensive monitoring project is under way. The first results are expected to be provided toward the end of 2013.

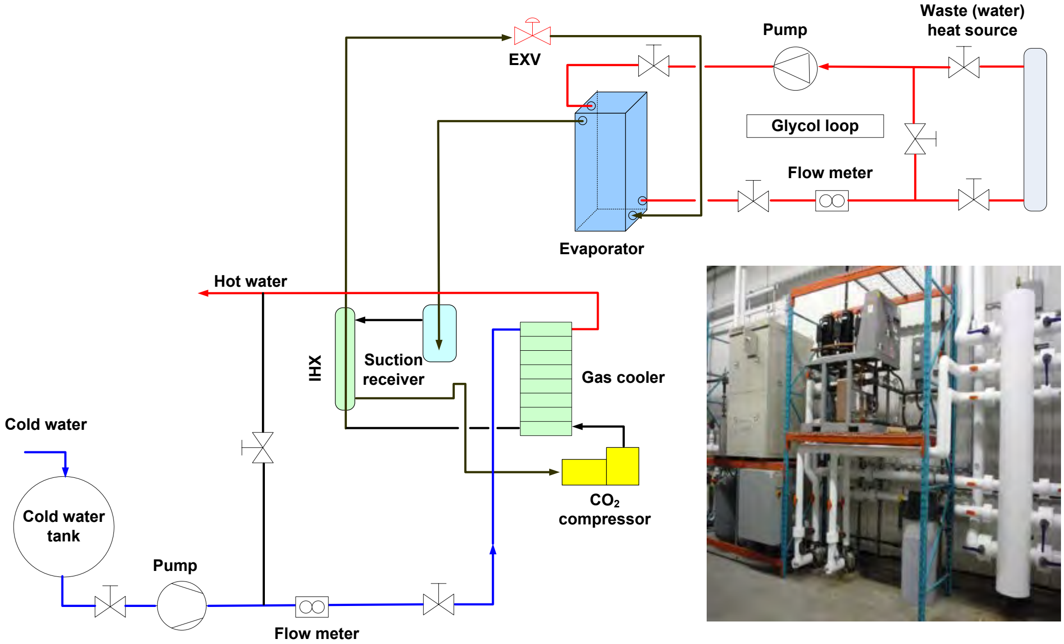


Figure 4-14: Schematic diagram of the 100 kWth CO2 trans-critical industrial heat pump implemented in a Canadian dairy plant [Minea, 2013; Marchand, 2011]

4.3.3.2 *Ammonia heat pumps*

Over the last few years, research has focused on the use of natural refrigerants to replace the synthetic ones. Among other candidates for replacement, ammonia (NH_3, R-717) is an energy efficient and cheap refrigerant with zero Ozone Depleting (ODP) and Global Warming (GWP) Potentials. In Canada, low-grade waste heat rejections at temperatures between 15 °C and 45 °C represent about 25 % of the total primary energy input of many manufacturing industries. Simultaneously, many industrial processes and domestic consumers need hot water at temperatures varying between 60 °C and 85 °C. Ammonia single- and double-stage industrial heat pumps could accomplish this task. But, even though ammonia is an appropriate refrigerant for this waste heat recovery temperature range, and in spite of its well known qualities, ammonia is still non-accepted as a natural working fluid in industrial heat pumps, especially because of its toxicity and inflammability at high concentrations in ambient air.

A single-stage 7.5 kW (compressor nominal power input) water-to-water ammonia heat pump has been designed, built and laboratory tested. The unit was installed in a mechanical room equipped with ammonia detection and discharge systems in accordance with the Canadian Refrigeration Code (Figure 4.15) [Minea, 2011a; Minea, 2013]. A 48 kW electrical boiler supplied hot water simulating the waste heat (heat source) fed into the heat pump evaporator. The condenser heat was discharged outside by an air-cooled liquid cooler.

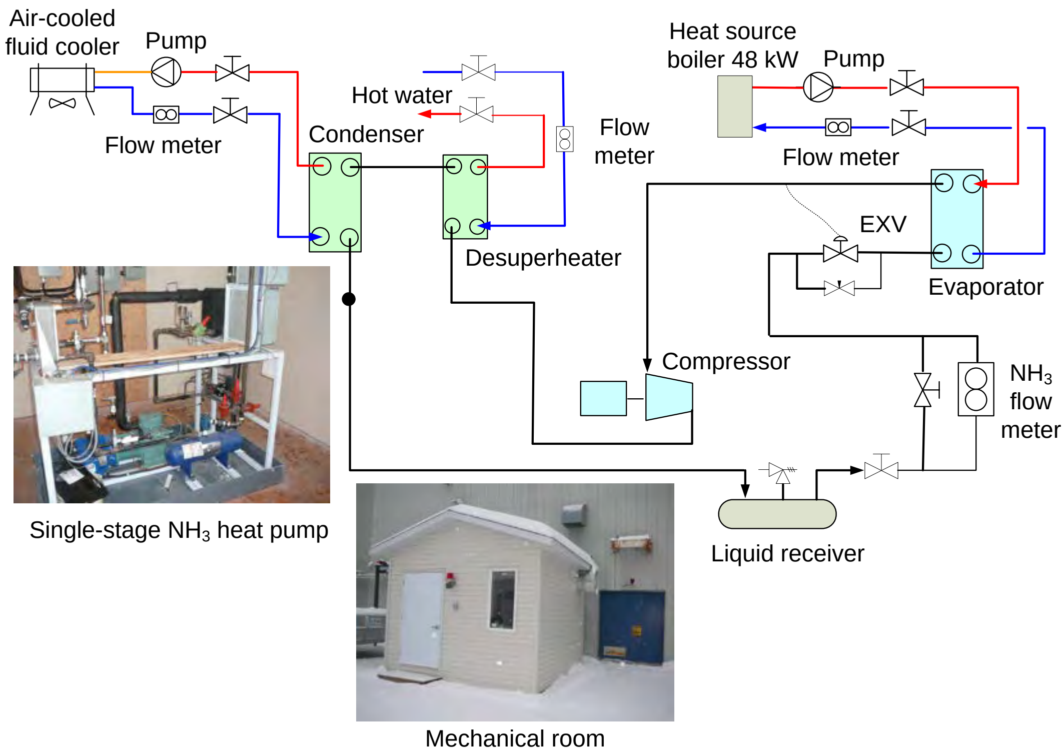


Figure 4-15: Experimental setup of the single-stage ammonia heat pump [Minea, 2011a; Minea, 2013]

The main scope of this project was to demonstrate that ammonia heat recovery heat pumps are reliable and safe in the Canadian industrial and regulatory environment, and achieve high energy performance levels. Other objectives were to encourage future R&D work, especially in the area of two-stage ammonia heat pumps, develop specific operation and maintenance skills for local technicians, promote further implementation in Canada, encourage most local manufacturers to provide ammonia heat pumps, as well as reliable detection devices, increase public confidence and promote ammonia as safe and efficient refrigerant going forward.

As can be seen in Figure 4.16a, with 1.08 kg/s of waste heat carrier fluid (water) entering the heat pump evaporator at 15 °C, the heat pump supplied 1.26 kg/s of hot water at 42 °C. At the same time, the desuperheater heated 0.19 kg/s of process/domestic hot water from 25.5 °C to 44 °C (Figure 4.16b). Based on the compressor energy consumption, the heat pump coefficient of performance was 3.84. However, it dropped to 3.46 when considering the energy consumption of the compressor and the waste heat fluid circulating pump, and to 2.85 when the energy consumption of the compressor, the waste heat fluid circulating pump (0.65 kW) and the hot water circulating pump (1.44 kW) were taken in consideration.

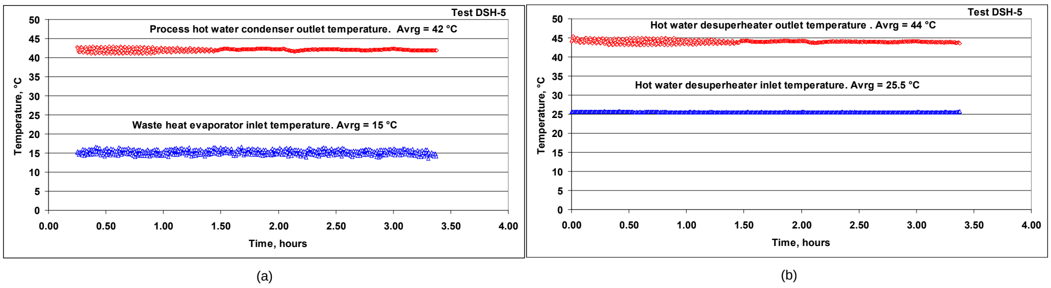


Figure 4-16: Single-stage ammonia heat pump; (a) waste heat (inlet) and process water (outlet) temperatures; (b) hot water temperatures entering and leaving the desuperheater [Minea, 2011a; Minea, 2013]

Simulation models for both single- and double-stage ammonia heat pumps have been developed using the EES software. Part of the simulation results has been experimentally validated. Figure 4.17 shows, for instance, the simulation results of a two-stage ammonia heat pump used to heat cold water from 10°C to 85 °C by desuperheating the compressor discharge ammonia vapour coming at a temperature of 90 °C from the plant's existing ammonia refrigeration system [Richard, 2011].

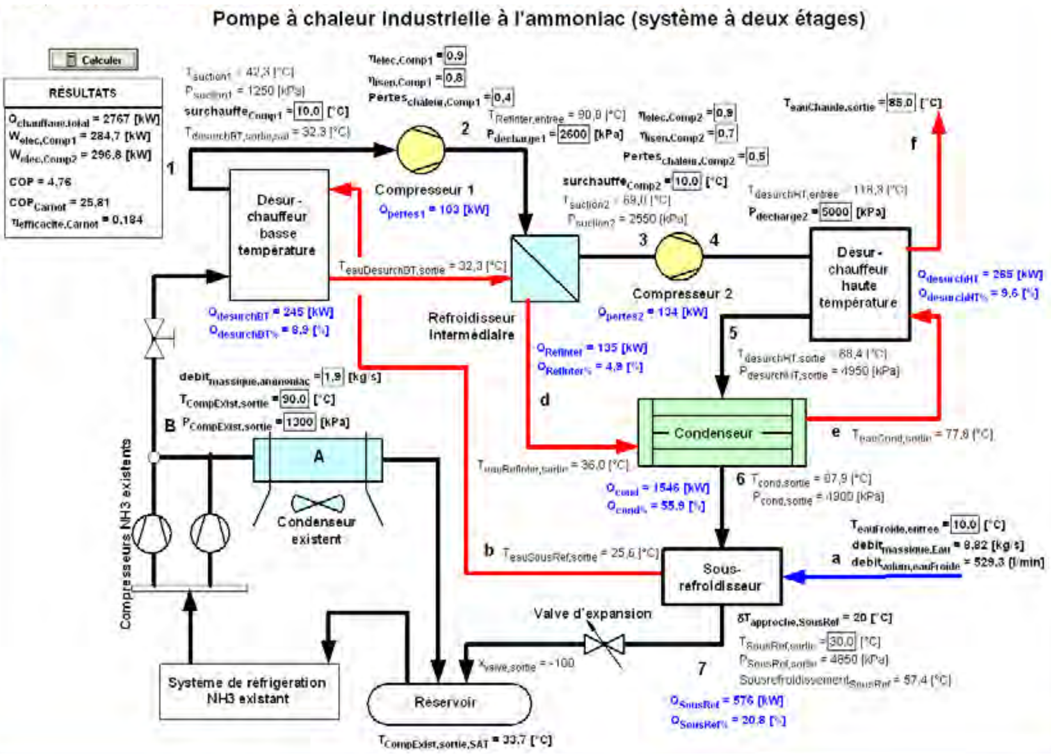


Figure 4-17: Simulation model of a double-stage ammonia heat pump [Richard, 2011]

Figure 4.18a schematically represents the diagram of a single-stage ammonia heat pump recently implemented in a new Canadian dairy plant [Gosselin, 2013]. Finally, Figure 4.18b shows an industrial double-stage ammonia heat pump implemented for recovering heat from large existing ammonia refrigeration systems [Vilter]. This implementation project is just starting and the first preliminary results are expected in December 2013.

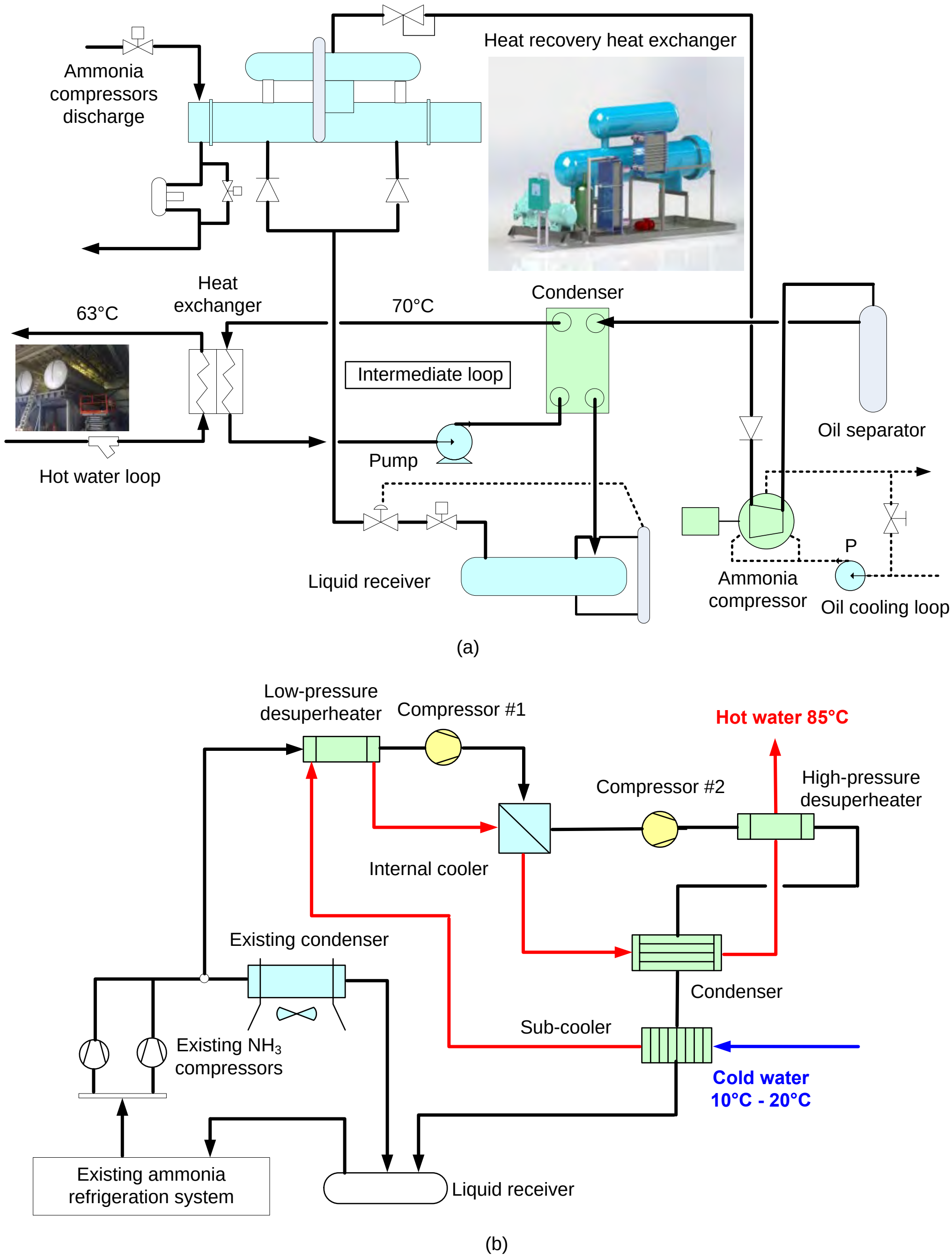


Figure 4-18: Examples of ammonia industrial heat pump applications in Canadian existing refrigeration systems; (a) single-stage application [Gosselin, 2013]; (b) double-stage application [Vilter]

4.3.3.3 Cascade heat pumps

Cascade heat pump systems have the advantage of lower pressure ratios and higher isentropic efficiencies for each stage compressor. At the same time, different combinations of working fluids can be used according to the temperature ranges of both the waste heat and heat sink sources. On the other hand, cascade heat pump systems introduce extra temperature differences in the cascade heat exchanger, greater complexity and extra control problems, and slightly reduce the overall system coefficients of performance. However, this energy performance reduction seems less critical in the context of high-temperature heat pumps recovering large quantities of *free* industrial waste heat.

Two cascade heat pump cycles have been studied in order to find the best working fluid combination, control sequences, and energy efficiency [Minea, 2011a; Minea, 2013]. The first concept (Figure 4.19) is an optimized cascade system including two closed, electrically-driven vapour compression cycles with an intermediate cascade (condenser/evaporator) heat exchanger. Compared to a standard cascade cycle, this configuration includes a liquid refrigerant pump and a vapour injection solenoid valve on the second heat pump cycle, to facilitate system start-up. At the beginning of each running cycle, the liquid pump or, alternately, the injection solenoid valve, may help remove the high-temperature refrigerant (HFC-245fa) storred inside liquid receiver #2.

The second concept (Figure 4.20) consists of two vapour compression cycles coupled by an intermediate liquid closed loop [Minea, 2011a; Minea, 2013].

Both experimental set-ups use a 48 kW electrical boiler as a waste heat source and an outdoor air-cooled liquid cooler rejecting the condensing heat via a brine (50 % water and ethylene glycol) closed-loop. They have been sized to recover waste heat (water) at temperatures varying from 10 °C to 30 °C and supply heat (process or domestic hot water) at temperatures up to 85 °C. The HFC-236fa, HFC-134a and HFO-1234yf refrigerants were successively chosen as working fluids for the first stage, and HFC-245fa, a high-temperature refrigerant, for the second stage. The main selection criteria were the thermo-physical properties and environmental impacts (ODP, GWP, etc.) of the selected refrigerants. Were selected electrically-driven reciprocating compressors of which efficiency vary between 70 % and 97 %. Because compressor capacity decreases with the evaporating temperature and the increasing pressure ratio, both compressors were equipped with automatic variable speed controllers. The electronic expansion valves were programmed to keep superheating at values varying between 5 °C and 15 °C, according to the thermal properties of each refrigerant.

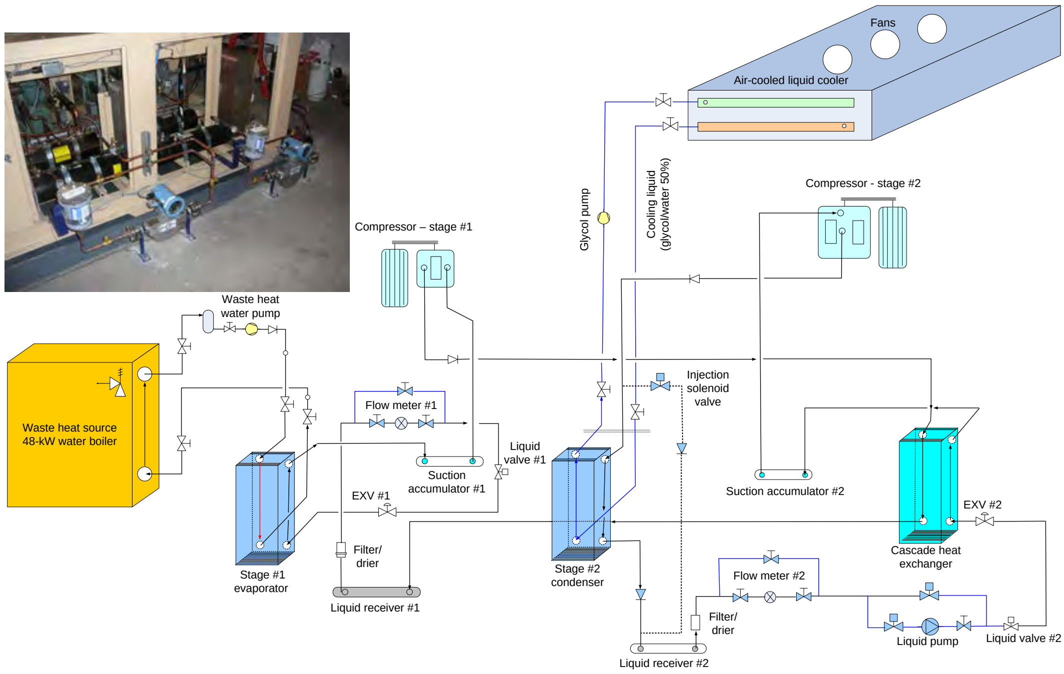


Figure 4-19: Optimized cascade heat pump prototype; EXV: expansion valve [Minea, 2011a; Minea, 2013]

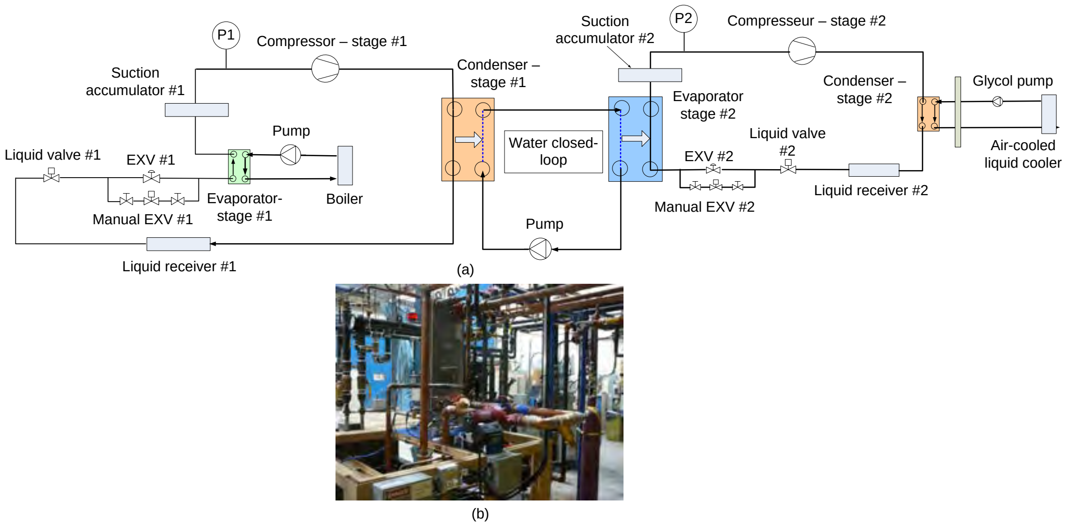


Figure 4-20: Cascade heat pump with intermediate closed-loop; (a) schematic layout; (b) view of the intermediate closed-loop; EXV: expansion valve [Minea, 2011a; Minea, 2013]

Figure 4.21 shows the simulation results for one of the laboratory experimental tests achieved with the HFO-1234yf and HFC-134a refrigerants on the first and second stage respectively. It can be seen that, by using waste heat at a 25 °C inlet temperature, hot water was provided at 84.5°C with an overall coefficient of performance of 2.08 and Carnot efficiency of only 0.34 [Richard, 2011]. However, with higher waste heat inlet temperatures, higher COPs and Carnot efficiencies were obtained.

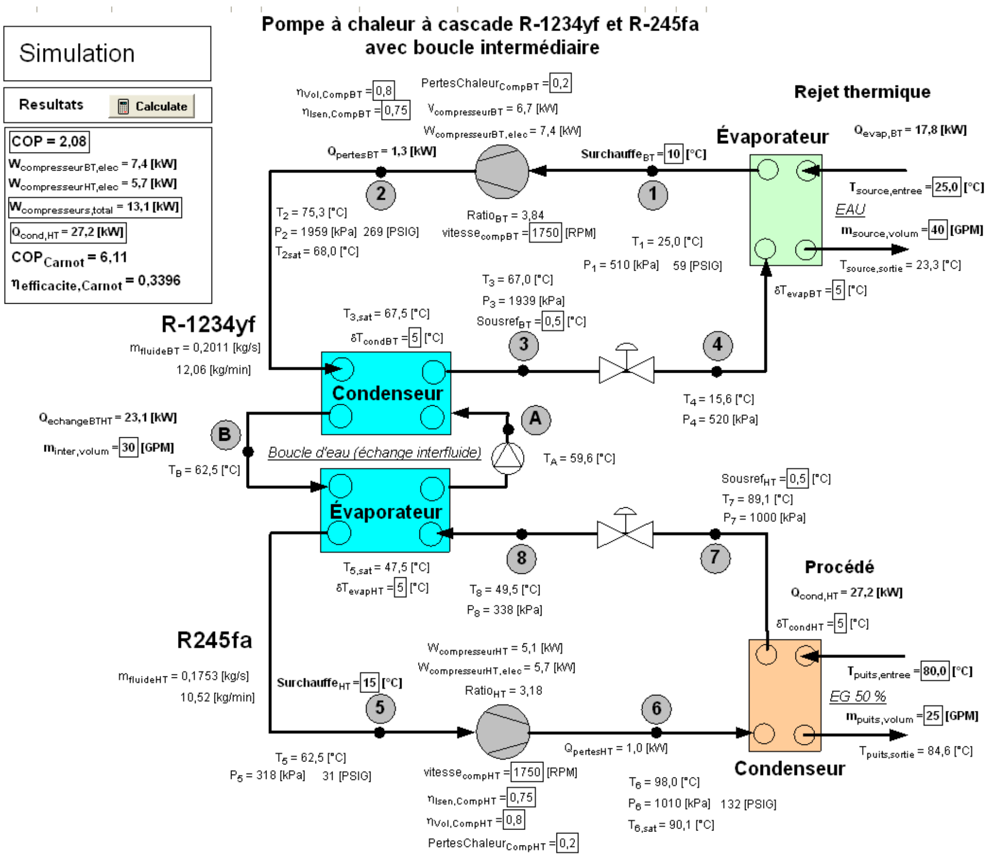


Figure 4-21: Simulation results of a cascade heat pump system with intermediate closed-loop using HFO-1234yf and HFC-134a as the first and second stage refrigerants [Richard, 2011]

For the industrial implementation of cascade heat pump systems, many practical options are available. As can be seen in Figure 4.22, the first stage in such a system may recover the waste heat rejected by an industrial ice machine in a poultry processing plant [Caddet]. The cascade heat pump is the second stage of a heat recovery system, also used to recover heat from the condensers of an existing refrigeration plant with an intermediate closed-loop. Cold water entering the system at 12 °C is heated up to 25 °C inside the pre-heating heat exchanger and then up to 63 °C with the cascade heat pump, prior to being stored inside a storage tank and/or supplied to industrial processes or other consumers.

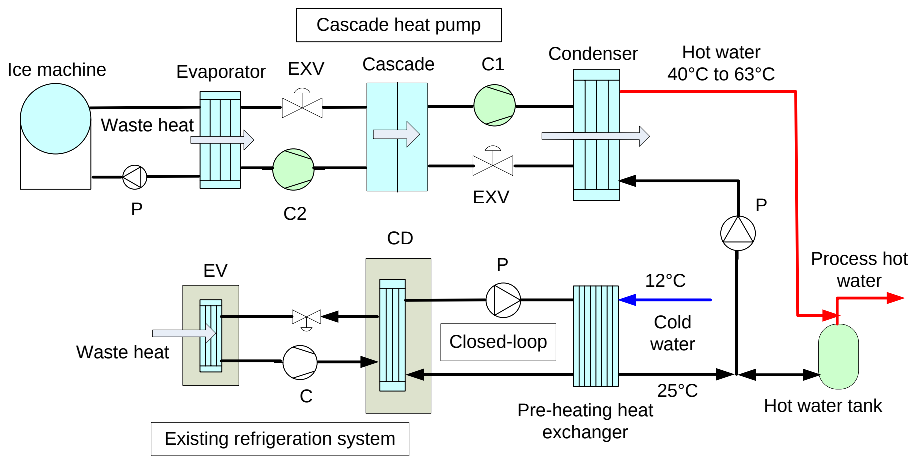


Figure 4-22: Schematic diagram of a cascade heat pump implemented in a Canadian poultry processing plant [Caddet]

4.3.3.4 Mechanical vapour recompression

In many energy intensive industrial processes, such as evaporation and distillation, low pressure steam is rejected into the atmosphere as waste heat. Among other methods, mechanical vapour recompression (MVR) semi-open thermodynamic cycles make it possible to efficiently recover this high quality (enthalpy, temperature) wasted heat. Recovering the vapour latent heat is performed by raising its pressure and temperature, and then by condensing it inside the same evaporator. To achieve this, a fast revolving, high pressure device capable of operating under vacuum (compressor or blower) is used to increase the pressure of the recovered vapour and its corresponding saturation (condensation) temperature. This way, the same vapour can used as a heating medium for the liquid or solution being concentrated by the initial evaporation or distillation process.

Selecting the compressor (centrifugal, turbo, volumetric, axial, etc.) or blower is the most important design issue. Today, centrifugal compressors are still the most common types used in MVR installations, even though the pressure ratios are restricted to approximately 2. They are usually equipped with a liquid separator in the suction line because liquid drops cause erosion, leading to lower efficiencies and possible blade failure [Annex 21, 1995].

MVR systems offer benefits such as reduced energy consumption and cooling water requirements compared to conventional steam heated evaporator systems with a similar capacity. However, higher capital costs than conventional steam heated systems, and high electrical power and voltage requirements for compressors may from an economic point of view limit the number of industrial applications. [Annex 21, 1995]

MVR systems provide very high COPs (up to 100 and even higher), being very dependent on the magnitude of the temperature lift that, generally, is - or must be - bellow 20 °C.

A mechanical vapour recompression system has been studied, improved and successfully implemented and tested in a Canadian industrial plant (Figure 4.23) [Bédard, 2002]. This MVR evaporator system is similar to a conventional steam heated, single-effect evaporator, except that the vapour released from the boiling solution is compressed by the compressor. As previously noted, the compressor raises the pressure and saturation temperature of the vapour so that it may be returned to the evaporator as a heating medium. This reduces the steam quantity required to meet the evaporative load of the overall system.

The vacuum pump maintains a pressure of about 200 mbar inside the container, which corresponds to a water boiling temperature of 60° C. The compressor (107.5 kW) increases the vapor pressure by 20 mbar and its temperature by 2 °C between the evaporating and the condensing sides. The product is continuously re-circulated from the bottom to the top of the container. Inside the heat exchanger, the compressed vapor condenses and the liquid is pumped outside. A plate heat exchanger preheats the entering product by using heat from both the condensed and concentrated product leaving the container. The compressor consumes 7.8 kWh per ton of water evaporated, while the energy required by a conventional evaporation system is of about 700 kWh per ton of water evaporated. Thus, the coefficient of performance, defined as the ratio between the thermal energy supplied divided by the electrical energy consumed, was 86. However, during system operation, about 30 kW average thermal back-up power in the form of vapor was supplied in order to keep the temperature of the product being concentrated constant. This operation increased the specific energy consumption to 9.9 kWh per ton of water evaporated and the system average COP dropped to 68. However, this last number didn't include the energy consumption of the vacuum and other circulation pumps the total electrical power of which was estimated at 60 kW) [Bédard, 2002].

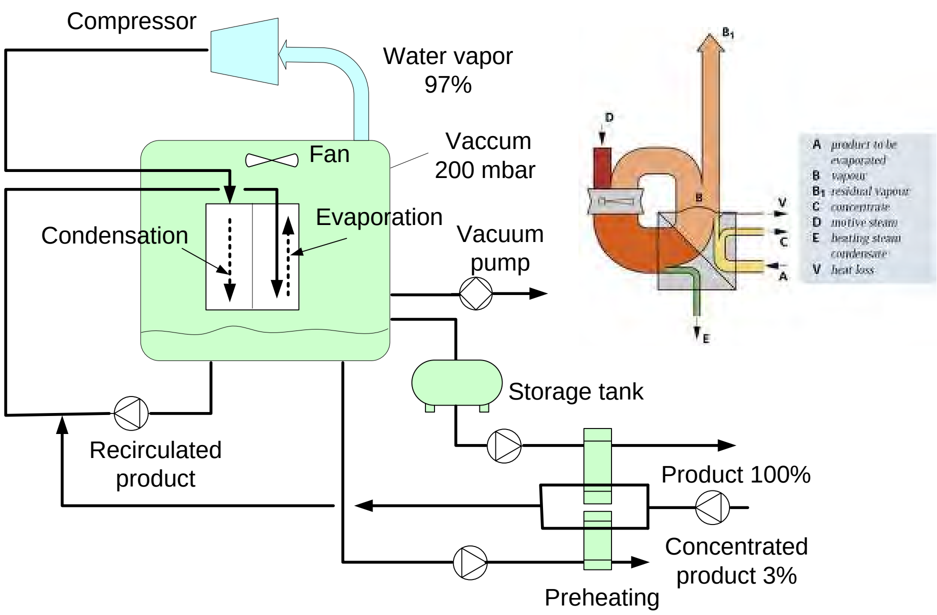


Figure 4-23: Mechanical vapour recompression system implemented in Canada [Bédard, 2002]

4.3.3.5 *Heat pump-assisted wood drying*

Wood drying is a complex, highly non-linear thermodynamic process. In Canada, most conventional hardwood and softwood drying kilns use fossil fuels (oil, propane, natural gas) or biomass (bark) as primary energy sources. However, most of them can be coupled with heat pumps for dehumidification drying purposes. In this case, practically all warm air loaded with moisture is discharged into the environment. The process consists in saving energy through re-heating and dehumidifying the process air. Warm dry air is led over the surface of the wood boards to be dried, and its very low relative humidity helps remove moisture from the wood. The water vapour picked up condenses on the externally finned heat transfer surface of the heat pump evaporator, and then is heated again by passing through the heat pump condenser. Heat is thus recovered from the dryer hot and humid air, and the recovered sensible and latent heat is used to reheat the dehumidified drying air. Other advantages include proper control of product moisture content, reduced energy consumption and relatively short pay-back periods for the industrial drying heat pumps. However, when compared with basic hot air convective dryers, drying heat pumps involve higher capital and maintenance costs, are more complex to operate and require qualified operators.

a) Low-temperature drying heat pump

A low-temperature laboratory-scale prototype consisting of a 13 m^3 forced-air dryer with variable-speed fans coupled to a 5.6 kW (compressor nominal power input) low-temperature heat pump (Figure 4.24) has been extensively studied for drying Canadian hardwood species through dehumidification [29, 30]. Hardwood, such as sugar maple and white and yellow birch, has relatively complex cell structures, and in Eastern Canada, their average green moisture content varies between 6 5% and 72 %. For these species, drying is an essential step in the manufacturing process (furniture, etc.). The dryer is equipped with steam and electrical backup heating coils. Steam is supplied at variable flow rates by a natural gas-fired steam boiler. The air flow rate over the lumber surface is maintained sufficiently high to provide a rapid air exchange and minimise dead spots. To ensure uniform heating and drying, the direction of the air flow is periodically reversed. The heat pump, including the compressor, blower, evaporator, condenser, sub-cooler, refrigeration piping and controls, is installed in a mechanical room next to the dryer. Based on the product actual moisture content, the drying schedules, as well as the heat pump hourly running times, are established prior to each drying cycle.

The heat pump compressor operating time was set in accordance with an intermittent drying schedule, as shown in Figure 4.25a [Minea, 2006; Minea, 2011b]. Both heating and dehumidification processes were controlled by the actual wet-bulb temperature of the air inside the drier. At the beginning of each drying cycle, the compressor hourly running ratio was pre-set at 100 %, and then it was continuously adjusted between 0 and 100 % in order to have the actual wet- and dry-bulb temperatures in the dryer practically equal to their setting points. Under such schedule if, for example, the compressor hourly running time was set at 60 %, it ran for 30 minutes and shut down during the next 20 minutes. After the heat pump started, the compressor running time was increased when the actual wet-bulb temperature was above the upper limit, and decreased when it was below the lower limit. Figure 4.25b shows the cumulative amount of water extracted during a typical drying cycle with yellow birch using the intermittent drying strategy shown in Figure 4.25a.

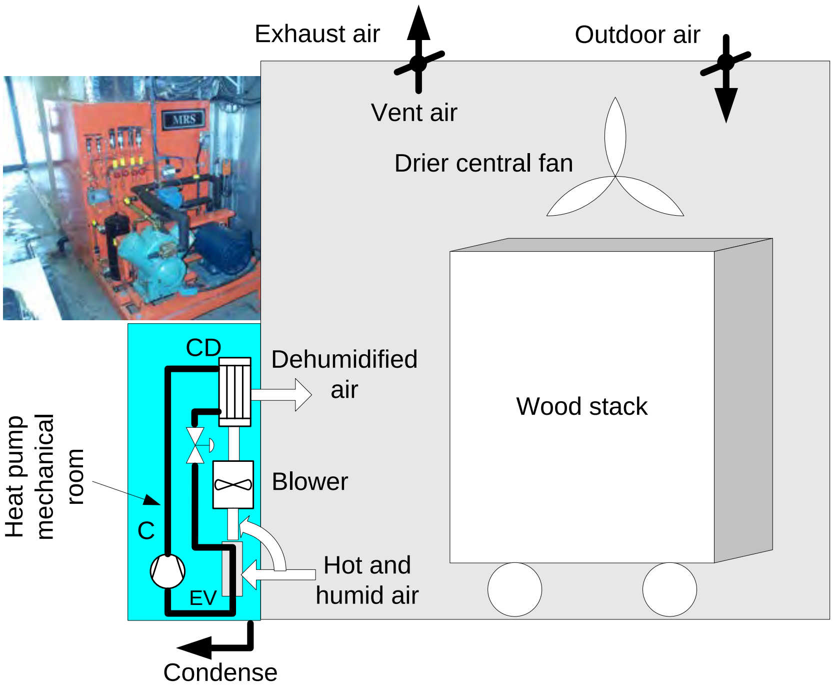


Figure 4-24: Schematic diagram of the laboratory-scale hardwood drying heat pump prototype [Minea, 2006; Minea, 2011b]; B: blower; C: compressor; CD: condenser; EXV: expansion valve; EV: evaporator; LV: liquid valve; SA: suction accumulator; SC: sub-cooler; SV: solenoid valve; VS: variable speed; A, B: air circulation direction.

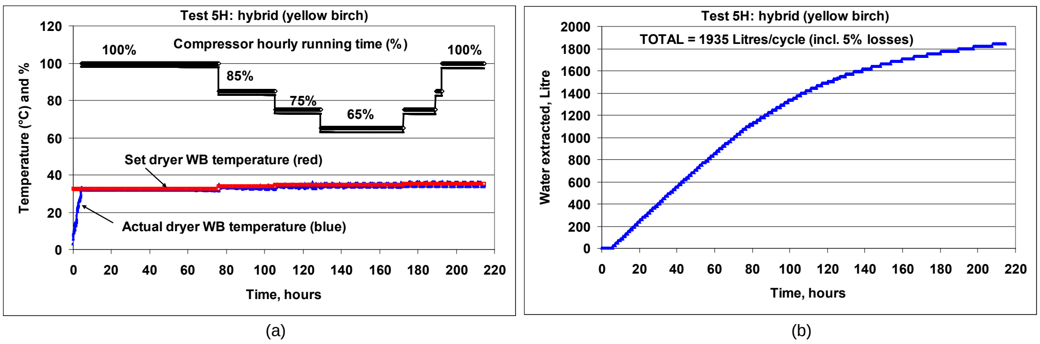


Figure 4-25: (a) Compressor hourly running profile and set value, and actual value of dryer wet-bulb (WB) temperatures; (b) cumulative amount of water extracted [Minea, 2006; Minea, 2011b]

The average dehumidification efficiency of the system, expressed in terms of the specific moisture extraction rate (SMER), which represents the ratio between the mass of water extracted and the heat pump total electrical energy consumption (compressor and blower), was 2.5 kg_{water}/kWh_{hp} above the wood fibre saturation point. On the other hand, the natural gas consumption of the same drying cycle decreased by 57.5 % as compared to the natural gas consumption of the equivalent *conventional* drying cycle. Compared to the *conventional* drying cycle using natural gas, total energy costs (electricity plus natural gas) decreased by 23 %.

b) High-temperature drying heat pump

An industrial-scale, high-temperature drying heat pump prototype, including one 354 m^3 forced-air wood dryer with steam heating coils and two high-temperature drying heat pumps (Figure 4.26) has also been studied in Canada [Minea, 2011b; Minea, 2004, Minea, 2012b]. Finished softwood lumber is produced in standard sizes, mostly for the construction industry. Softwood, such as pine, spruce and fir (coniferous species), is composed of vertical and horizontal fibre cells serving as a mechanical support and pathway for the movement of moisture. These species are generally dried at relatively high temperatures, but no higher than 115 °C, and thus high-temperature heat pumps coupled with convective dryers are required [Minea, 2011b; Minea, 2004]. An oil-fired boiler supplies steam for heating. The dryer central fans force the circulation of the in-door air. Each heat pump includes a 65 kW (nominal power input) compressor, an evaporator, a variable speed blower and electronic controls located in an adjacent me-chanical room. Both remote condensers are installed inside the drying chamber. The refrigerant (HFC-236fa) is a non-toxic and non-flammable fluid, having a relatively high critical temperature compared to the highest process temperature. Expansion valves are controlled by microprocessor-based controllers that display set points and actual proc-ess temperatures.

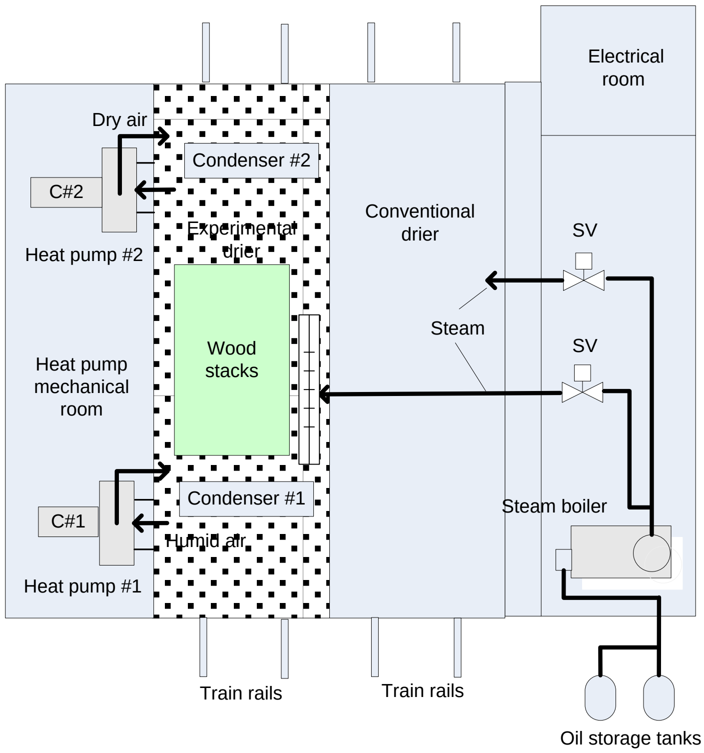


Figure 4-26: Site of the experimental industrial-scale softwood drying heat pump system [Minea, 2011b; Minea, 2004; Minea, 2012b]; C: compressor; LV: liquid valve; SA: suction accumulator; SC: sub-cooler; EXV: expansion valve; VS: variable speed; SV: solenoid valve; A, B: direction of air circulation

Based on the softwood moisture content prior to entering the drying enclosure, generally in the range of 35 % to 45 % (dry basis), optimum drying schedules were developed for each softwood species. The average coefficients of performance (COP) of both heat pumps, defined as useful thermal power output (kW) divided by electrical power input (kW), varied from 4.6 at the beginning to 3 at the end of the drying cycles. The heat pumps (compressors plus blowers) used 72 % and the dryer central fan 28% of the total energy consumption of each drying cycle. The drying time to deliver white spruce with an approximate final moisture content of 18% was about 2.5 days, while, for balsam fir, it averaged 6.3 days. Total amounts of water extracted exceeded 19,100 kg (Figure 4.27) for dried white spruce and 27,000 kg for dried balsam fir. Consequently, relatively high water extraction rates, varying between 178.8 kg_{water}/h and 313 kg_{water}/h were achieved respectively. These numbers do not include venting moisture losses (on average, 90kg_{water}/h), but account for 5% of condensed water losses. The Specific Moisture Extraction Rate (SMER) ranged from 1.46 kg_{water}/kWh (with balsam fir) to 2.52 kg_{water}/kWh (with white spruce). These values do not include the energy consumed during the pre-heating steps, nor do they include any allowance for the energy consumed by the kiln's central fan and the venting moisture losses. Finally, the energy consumed during the drying cycles with high-temperature heat pumps was between 27 % and 57 % lower than the energy consumed during the *conventional* drying cycles using oil as the sole source of energy. Also, the average reduction in specific energy costs, compared to the costs of *conventional* softwood drying cycles, was estimated at about 35 %.

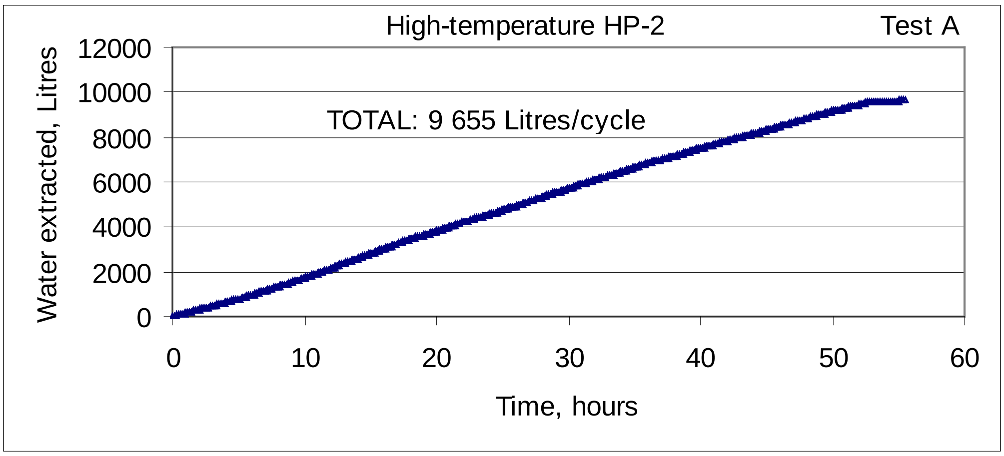


Figure 4-27: Cumulative volume of softwood water extracted by heat pump 2 only [Minea, 2011b; Minea, 2004; Minea, 2012b]

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5 Denmark

5.1 Introduction

In 2010 the Danish Commission on Climate Change Policy published a report describing the road to a Danish energy system without fossil fuels by 2050. In the political system there is consensus about the Commission's recommendations and thus, Danish energy research is to a high degree governed by these.

Figure 5-1: The Danish Commission on Climate Change Policy: "Green Energy – the Road to a Danish Energy System without Fossil Fuels. Summary of the Commission's considerations, results and recommendations", published 28 September 2010.

In the report heat pumps are attributed a significant role in the future energy supply, as a link between energy produced by electricity and utilization of excess heat. To underline the future role of heat pumps, Commission chair Katherine Richardson estimates that by 2050 between 25 % and 50 % of the district heat supply should be supplied by heat pumps. More than 60 % of the Danish households are heated by district heating.

The Refrigerant Situation

Denmark has stricter rules for use of synthetic refrigerants than most other countries. With regard to CFC and HCFC refrigerants, Denmark follows the international rules and thus, the former have been completely phased out whereas HCFCs (primarily R-22) must be phased out by 1 January 2015. As to HFC refrigerants, Denmark enforces a special rule allowing only plants with a 0.2-10 kg refrigerant filling. In practice, this means that industrial heat pumps only use natural refrigerants.

Due to this, Denmark is in a strong position worldwide particularly in relation to research, testing and experience of natural refrigerants ammonia, CO_2 and water vapour.

5.2 Ongoing R&D

In Denmark R&D on large scale heat pumps has primarily been utilized in district heating systems, with forward temperatures between 70 and 90 °C. Heat sources are typically at ambient or slightly higher temperatures and could be flue gas, surface water, thermal storages, treated sewage water etc. Technologies in focus are trans-critical CO_2, ammonia and isobutene.

Today CO_2 systems are the main choice for commercial refrigeration in Denmark and the thermodynamical properties in the trans-critical state makes CO_2 suitable in heat pumps where the medium is heated from a temperature below 40 °C up till 70-90 °C, thus making it suitable in most district heating systems.

Ammonia systems arise from industrial cooling, where the primary difference in heat pumps is higher operating pressures. Traditionally ammonia heat pumps in Denmark have been either 25 or 40 bar systems reaching a maximum temperature of 50-55 °C and 70-75 °C respectively. Today new 50 and 60 bar screw and piston compressors are being developed and demonstrated. These systems exceed 90 °C.

Isobutene is a low pressure refrigerant that can be utilized using low pressure HFC components. Isobutene systems can heat water to around 85 °C using standard low pressure components.

Heat pumps in industrial applications

Applying heat pumps in industrial processes is often much more complicated than in district heating systems. Heat production cost is what district heating is about, meaning that the fuel savings heat pumps contribute to, is of major importance causing heat pumps to be profitable. In production companies, the product is the main focus. Here energy cost is not always one of the main competitive parameters, meaning that the only benefit a heat pump provides might not be particularly important.

In industrial processes, boilers can often be difficult to convert directly to heat pumps as heat pumps are dependent on a heat source and temperature levels. In traditional systems these parameters is almost of no importance, meaning that the heat distribution systems are often build for high temperatures while heat recovery can be very difficult. This means that heat pumps in general must be built into specific processes as a heat recovery unit rather than a centralized heating system. This gets even more complex with inconsistency in timeline of heat source and demand.

Analysis of heat demands and requirements in industrial applications

To have an overview of the potential and technical requirements of using heat pumps in industrial processes, two assessment reports have been published in 2013. The two reports are carried out with different approaches meaning that the results are not a 100 % comparable and conclusive. However both reports give good indications of the possibilities in industries. The first report [Viegand, 2013] considers excess heat of industries in general and the potential of utilization in different ways both internal and external. Technical and economical obstacles are taken into account. The most important results of the first report [Viegand, 2013] are:

- ¼ of the Danish heat demand in industrial processes require a temperature of 60 °C or less
- ½ of the Danish heat demand in industrial processes require a temperature of 100 °C or less
- ½ of the Danish heat demand in industrial processes require higher temperatures than 100 °C.

The focus of the second report is more specific on using heat pumps in different processes where heat is recovered and utilized in the same process. External utilization of industrial waste heat is not considered. The potential is assessed for processes with temperature requirements of up to 180 °C and categorized in temperature lifts of respectively 20 K, 40 K and 70 K. A requirement of 180° C and a temperature lift of 20 K means that the heat source is 160° C whereas a lift of 70 K means that the source is 110 °C. The most important results of the second report [Weel, 2013] are:

- At a temperature lift of 70 K and delivering at 180 °C, around ½ of the heat demand considered can be produced by heat pumps
- At a temperature lift of 70 K and delivering at 100 °C, 75 % of the potential is possible
- At a temperature lift of 40 K around 35 % of the potential is possible. At this temperature lift it is only a small part of the potential that require higher temperatures than 100 °C
- At a temperature lift of 20 K around 25 % of the potential is possible. At this temperature lift it is only a negligible part of the potential that require higher temperatures than 100 °C
- About 90 % of the potential (regardless of temperatures) can be covered by heat pumps with a capacity of 2 MW-heat or more.

Both reports show that the majority of the potential require temperatures less than 100 °C, meaning that outlet temperatures is not a technical barrier in most cases. The assessments also show that there is some potential for heat pumps that only lifts 20 K, meaning that high COP values is possible while the heat capacities should in MW's. There is only a small potential for heat pumps with capacities less than 1 MW.

Viegand, 2013 Analysis of utilization of industrial excess heat, Viegand & Maagøe, 2013

Weel, 2013 The potential for high temperature heat pumps in industrial application, Weel & Sandvig, 2013

5.3 Demonstration

There have been a number of demonstration projects in the last couple of years implementing large scale heat pumps, which have primarily been transcritical CO_2 or high pressure ammonia systems. At the moment research and development is also in the fields of water vapor systems and the ammonia/water hybrid process.

The following three demonstration projects are relevant for industrial purposes:

“Development of Rotrex turbo compressor for water vapor compression”

The project aims to develop a new and competitive electric water vapor compressor. The compressor is based on the Danish "Rotrex" turbo compressor, which is currently used for the compression of air. The project will develop and test a prototype using water vapor at laboratory level. There has conducted preliminary tests and calculations of the compressor, using water vapor, and it has been verified that practice and theory are consistent. There are various types of compressors on the market today that can be used for the desired applications, but they are either very expensive, limited in capacity or insufficiently reliable.

Water vapor heat pumps differ from other types of heat pumps by high efficiency and low working pressure in the temperature range of 70 to 250 °C. Today systems are often custom made, which makes them very expensive and not profitable in heating applications where other alternatives are available.

The Rotrex compressor could be integrated directly into existing steam systems as a stand alone unit or in combination with traditional heat pumps, where the water vapor compressor can boost the temperature level another 20-30 °C i.e. from 90 °C to 120 °C.

Generally, the target for this technology are industrial sectors using thermal heat in the temperature range of 50 to 200 °C - and the potential is vast.

On the following pages is a paper by Weel & Sandwig, Rotrex and DTI on using the turbo compressor for drying applications:

5.3.1 Energy efficient drying with a novel turbo compressor based high temperature heat pump

Abstract

Drying is one of the most energy intensive operations for preservation of product in many industries. One way to reduce the primary energy consumption for drying is to integrate a high-temperature heat pump to recover the latent heat in the exit stream from the drying process. Rotrex, Weel & Sandvig and DTI are developing a new high-speed radial turbo-compressor designed for steam. The compressor is derived from Rotrex suit of auto mobile turbochargers. The steam-compressor is the heart in the working cycle for a heat pump suitable for integration in a drying system. The new concept is based on a modular basis where compressors can be configured in parallel and serial to match the operational specification for the actual drying system. The COP value of the drying heat pump system typically will be between 4 and 6 depending on the ac-

tual configuration. As working medium of the heat pump, steam is selected, because of its excellent thermodynamic properties at high temperatures to meet high COP values, non toxicity and zero greenhouse potential.

Introduction

Drying is one of the most energy intensive operations in industrial processes. Drying is consuming about 20 % of the total energy consumption in industrial processes worldwide. Many efforts have already been implemented to increase the drying efficiency as super heated steam drying, improved process control etc. Integration of a heat pump in a drying process does not itself improve the drying efficiency but is a way to upgrade the exhausted heat from the dryer to usable heat for the drying process. Heat pumps so far have not been suitable for industrial processes because of temperature limitation in the delivery temperature.

Furthermore, the price development for electricity and fossil fuel (gas and oil) has in the past decade been very favorable for heat pump integration in most countries.

The performance of a heat pump can be derived from the main governing equations for a simple ideal Carnot heat pump cycle. The COP value can be expressed from the temperature of the heat source T_c and heat sink T_h which represents the highest theoretical performance of a heat pump with constant source and sink temperatures.

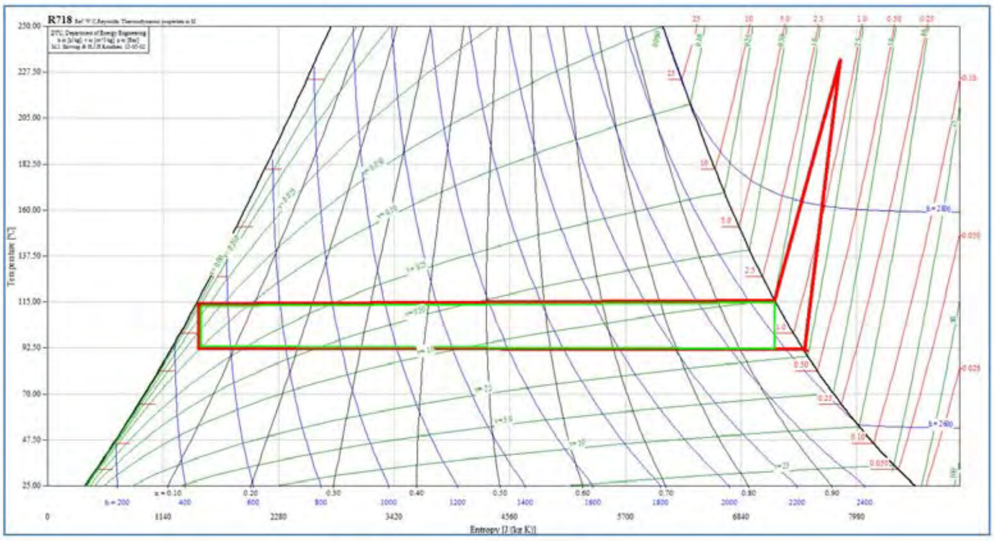


Figure 5-2: Ideal carnot cycle, Water based heat pump cycle (green) and real cycle (red) shown in TS-diagram

Typically the efficiency of a real heat pump cycle is about 0.6 - 0.75 of the theoretical values Carnot heat pump cycles when considering the actual condenser and evaporator temperatures.

$$COP_{real} = \frac{Q}{E} = 0.6 \ldots 0.75 \frac{T_h}{T_h - T_c}$$

$$COP_{Carnot} = \frac{T_h}{T_h - T_c}$$

Where E is the electricity input to drive the compressor and Q is the heat delivered by condensing the water vapour from the heat pump. The COP versus temperature lift and evaporation temperature is shown in Figure 5-3. A temperature lift of 50 K will result in a COP value about 4.5 - 5. In many drying applications and other industrial processes a temperature lift of 20 - 60 is required to transform waste heat to usable heat for the dryer design. In Figure 5-3 the relationship between achievable COP-values versus temperature lifts for a heat pump is shown. As can e seen the COP-values within 4 – 8 is achievable with a temperature lift between 30 and 70 K.

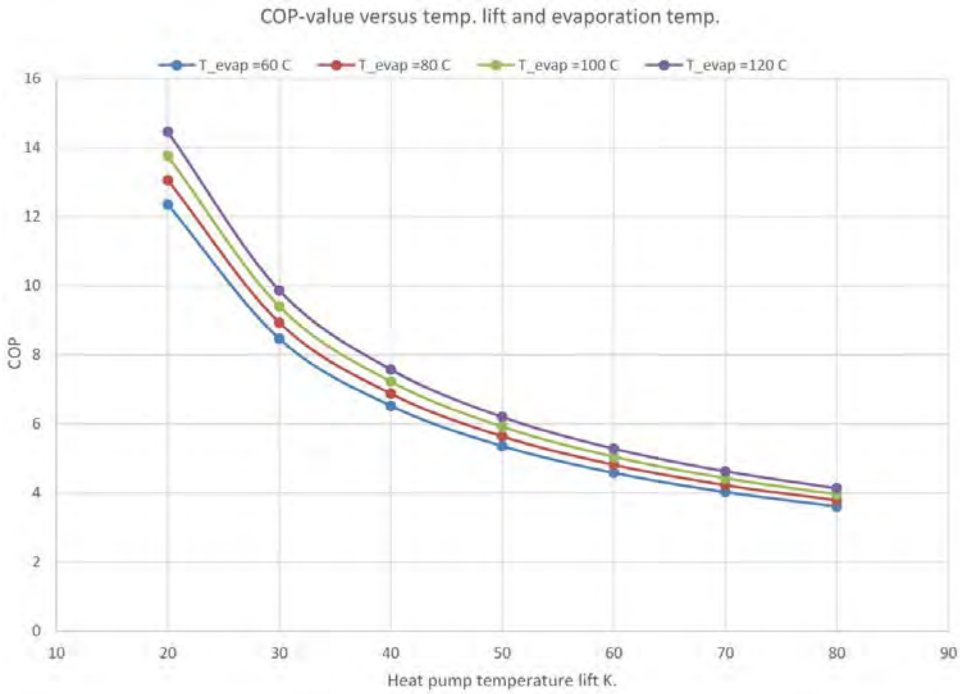


Figure 5-3: COP versus temperature lift and evaporation temperature

In many industrial applications the waste heat temperature (source temperature) is available in the range from 100 °C to 40 °C or lower and the temperature requirement for the process heating is in the range from 100 °C to 150 °C. The best heat pump to accomplish the variable source temperature and process temperature needs to have a similar temperature glide in order to minimize the exergy loss in the heat exchangers (condenser and evaporator). The Lorenz cycle heat pump introduced a temperature glide in the condenser and evaporator to reduce the exergy loss in the heat exchangers.

The COP value of the ideal Lorenz cycle is expressed by:

$$COP_{Lorenz} = \frac{T_{hm}}{T_{hm} - T_{cm}}$$

Where : *T_{hm} is the condenser temperature*

T_{cm} is the evaporator temperature

In Figure 5-4 a comparison of the ideal Carnot cycle and the Lorenz cycle in a T-Q diagram is shown. The Lorenz cycle is equivalent to an infinite Multi-stage Carnot Cycle. The Lorenz cycle can be approximated by using binary mixtures like ammonia-water or a trans-critical process (typical with CO_2 as the working fluid). In reality, in the high temperature range a multi-stage Carnot process with water as working medium in 2 - 3 stages achieves higher COP-value.

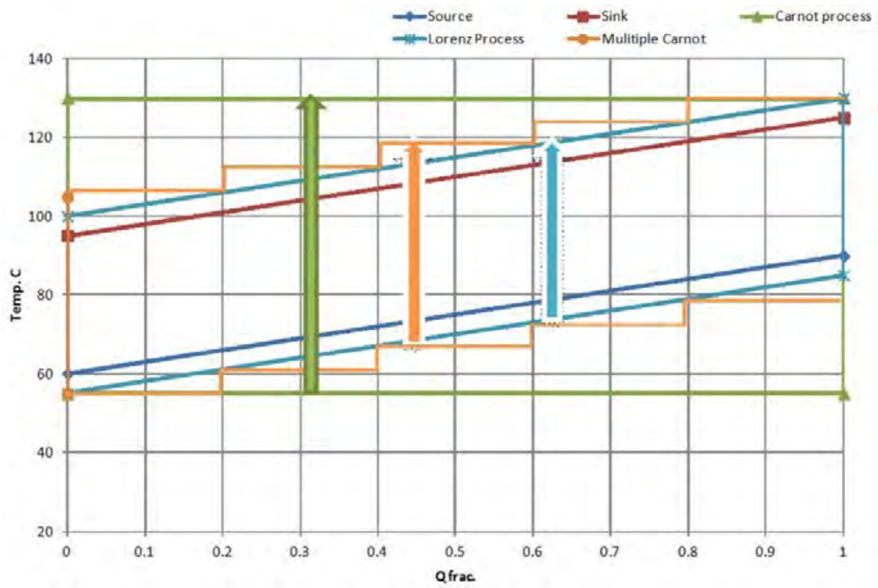


Figure 5-4: Comparison of different ideal heat pump cycles in the TQ-diagram

The main cycle and components in heat pump is shown schematic in Figure 5-18. There are only 4 key components in a heat pump: Compressor, Condenser, Expansion valve and Evaporator.

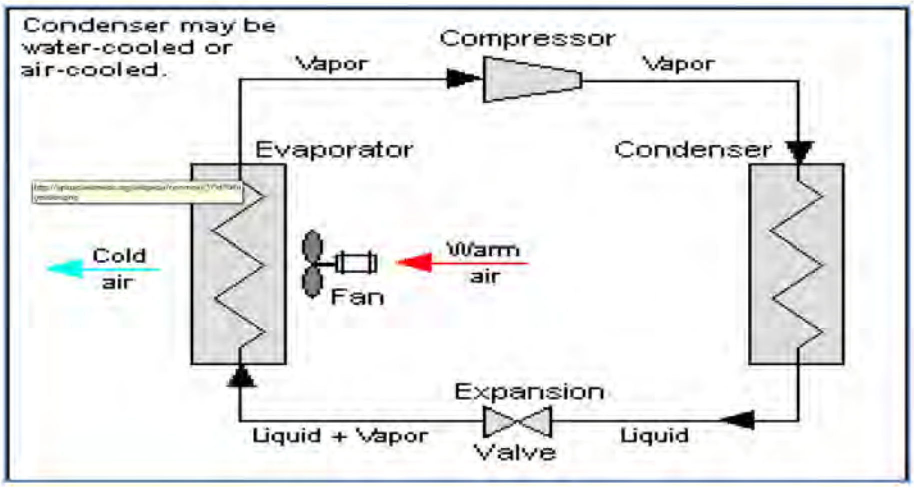


Figure 5-5: Simple schematic of the main components in the compression heat pump

In drying applications the drying temperature and the exhausted waste heat flow versus temperature will be the main governing parameters for the recoverable heat and the achievable heat pump COP value.

Existing drying systems are designed with high exergy destruction making them unsuitable for heat pump integration. New drying processes in super-heated steam have significant less exergy destruction and thereby are much more suitable for efficient heat pump integration.

A comparison of various working media for high-temperature heat pumping shows that water is the most efficient medium for condensing temperatures above 100 °C. In Figure 5-6 the COP-value for heat pumps cycles with different working fluid (water, butane, isobutane, CO_2, NH_3). For high-temperature operations it is clear that water is a superior working fluid. One drawback of water vapor is the relatively low vapor density when the evaporation temperature is below 80 °C which requires a high volumetric capacity of the heat pump compressor. Turbo compressors have very high volumetric flow rate capacity and are therefore preferable for water vapor heat pumps.

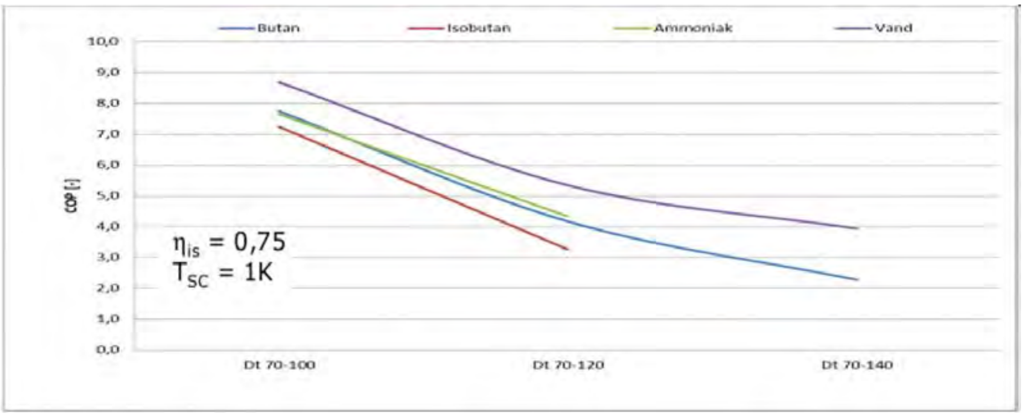


Figure 5-6: COP values of various heat pump refrigerants versus temperature lift. Evaporation temperature is 70 °C

Compressor development and test

The turbo compressor for water vapor compression is derived from Rotrex's line of automotive turbochargers. The aluminum based compressor has been replaced with a new impeller made of titanium and housing and volute are designed to meet a higher pressure ratio and high efficiency and durability. New carbon based shaft seals are implemented to prevent steam or oil leaking at the shaft, see Figure 5-7.

The compressor suction volume is about 0.28 m^3/s and the maximum pressure ratio with steam is approximately 3. A typical heat pump installation consisting of one turbo compressor unit can deliver about 450 kW heat at 130 °C when the suction pressure from the evaporator is 0.9 bar(a) (93 °C saturated steam temperature).

The Rotrex turbocharger has a unique traction geared compressor with excellent performance and approved for the automotive marked. The traction gear has a step-up ratio of 7.5 and the efficiency is 98.5 % at full load. The low-speed shaft of the traction gear is connected directly to a high speed motor (15,000 RPM) or a standard motor via a fast belt drive to assure a compressor impeller speed of up to 105,000 RPM. In Figure 5-7 and Figure 5-8 some principle drawings of the compressor assemble with traction gear, housing, impeller, volute etc. are presented.

The traction gear is lubricated by an internal oil pump which maintains a safe oil film on the traction (or friction) parts and circulates the oil through the external oil cooler.

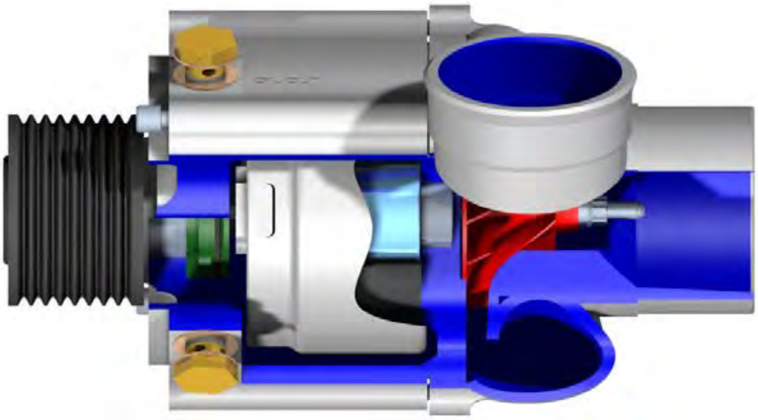


Figure 5-7: Compressor and gear

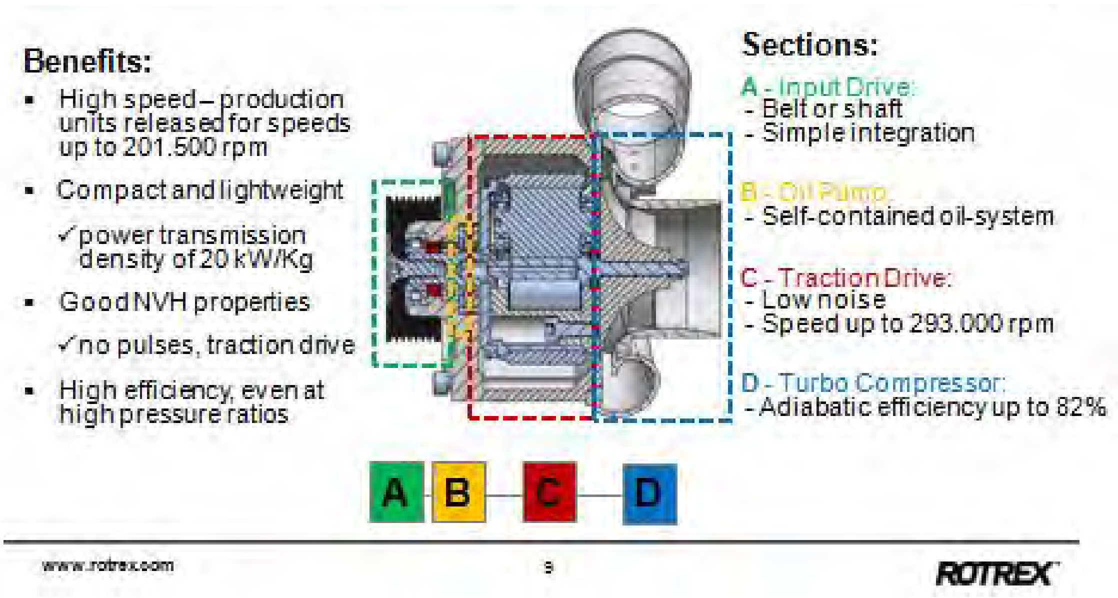


Figure 5-8: Main parts of the Rotrex compressor derived for steam compression

In Figure 5-9 the predicted performance map including the actual measured operating points are plotted during a test run on a rig installed at the production facility of Haldor

Topsøe A/S in Frederikssund. The measured performance was close to the expected performance. Pictures from the test rig are shown in Figure 5-9.

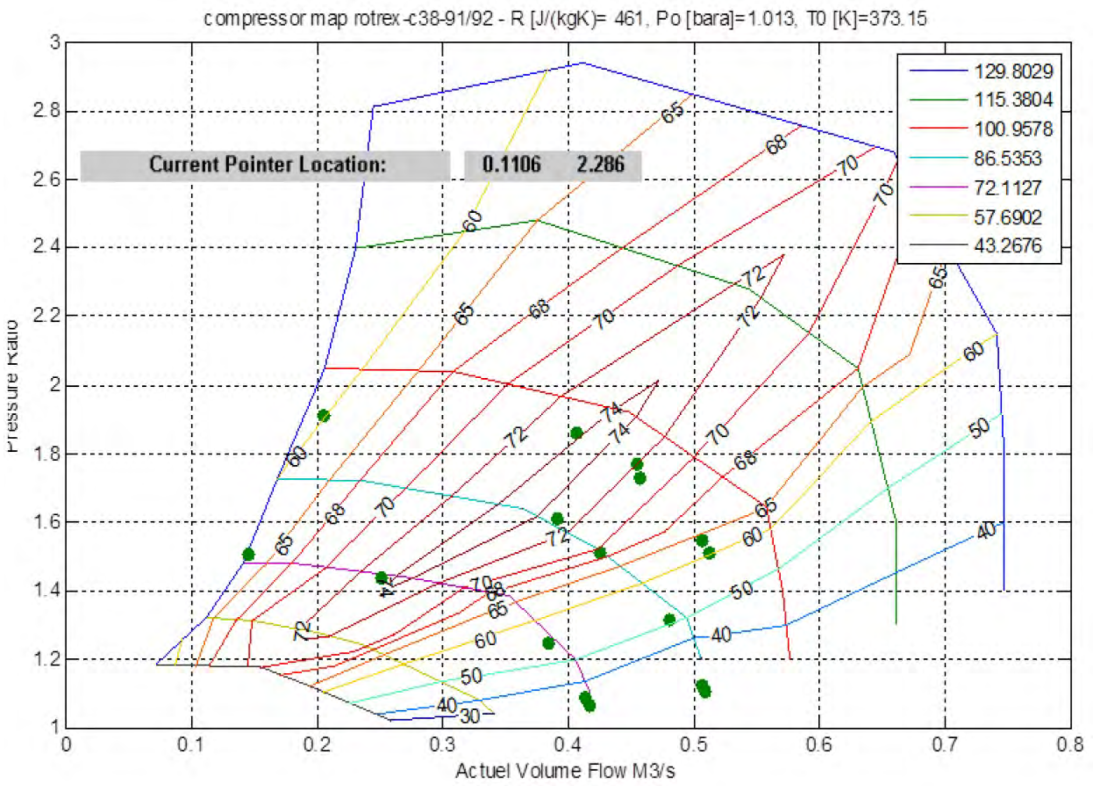


Figure 5-9: Measured operating points shown in the predicted (transformed from air to steam) compressor map

The new turbo compressor including traction gear has a very high volumetric suction capacity considering its compactness and weight of only 6 kg. For comparison a screw compressor [Mayekawa, 2002] for steam compression with a capacity of about 12,000 m^3/h has a weight of approximately 6,000 kg. The same capacity and temperature lift can be reached with 12 Rotrex turbo units arranged in a two stage (8 in 1st stage 4 in 2nd stage) parallel-serial configuration resulting in a total weight for compressors of 72 kg.

The cost of the multiunit concept of turbo compressor that can be mass produced is considerably lower than other compressor concepts with the same capacity.

Figure 5-10: Pictures from the first heat pump test at Haldor Topsøe's production facility in Frederikssund, Denmark

Heat pump applications in the drying industry

The new heat pump concept has potential for being used in many drying applications to reduce primary energy consumption. For most drying applications a temperature lift above 40 K is required for balancing cost of investment and operational cost.

The new compressor unit developed in the project (by DTI, ROTREX, and Weel & Sandvig) is designed for a pressure ratio up to 3 which is equivalent to a temperature lift about 30 K. To accomplish a higher temperature lift a two-stage configuration with compressors arranged in a serial coupling as shown in Figure 5-11 can deliver temperature lifts between 30 and 60 K.

Figure 5-11: Compressor set up in parallel combined with serial coupling to match required capacity and pressure ratio

One possible application is timber drying. Timber is dried as a batch process with a typical drying profiler versus time as shown in Figure 5-12.

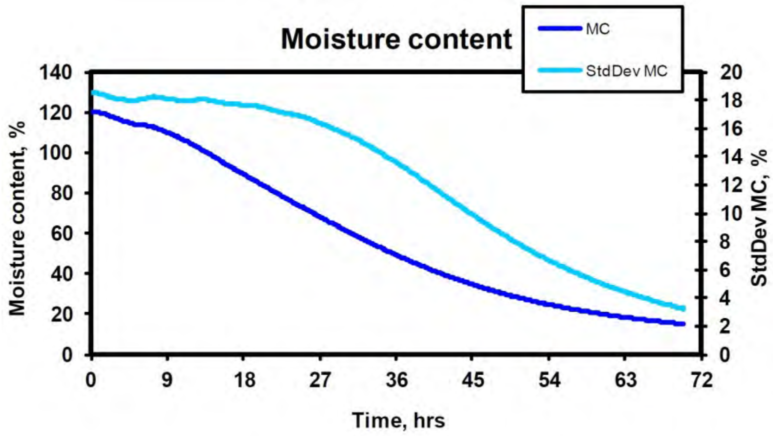


Figure 5-12: Typical drying profile for a timber drying kiln

In Figure 5-13 two options for heat pump integration in a timber drying kiln. To the left a heat pump retrofitted to a conventional “Air dryer” and (to the right) a super-heated steam kiln drying process. For the conventional kiln drying process, the heat pump circulation fan consumes about 20 kW and the compressor consumes about 84 kW when delivering 446 KW heat to the drying chamber. The total COP value is about 4. In the super-heated steam drying kiln drying concept the COP-value can reach above 7.

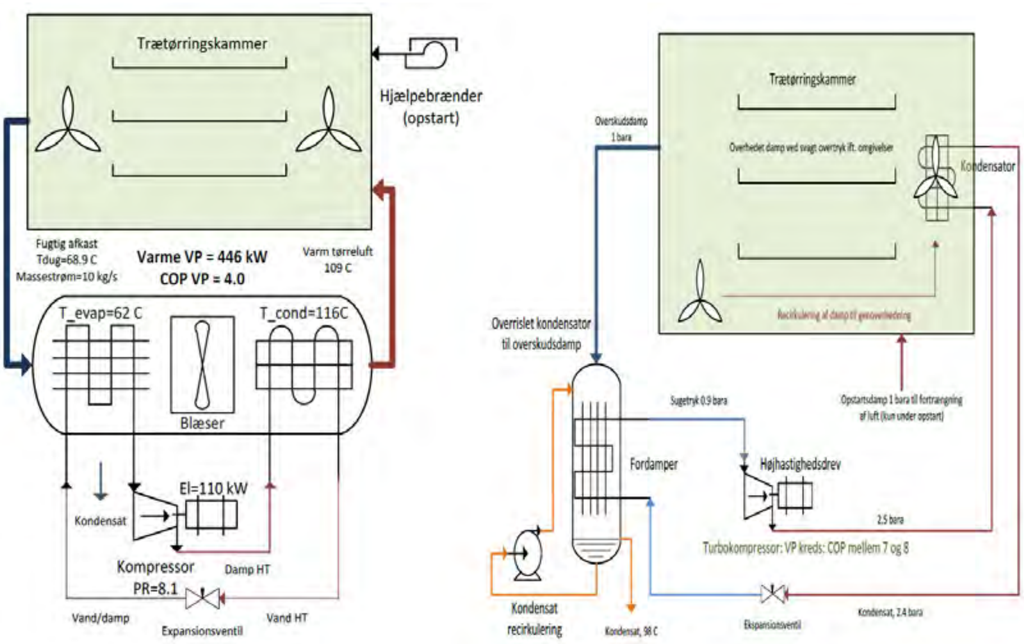


Figure 5-13: Heat pump integrated in a timber drying kiln.
Left: conventional drying and right: drying in super heated steam

Another application is a disk dryer used in fish and bone meal industry and sludge drying etc. The heat and mass balances for a heat pump integrated with a disk dryer is shown in Figure 5-14.

When integrating a heat pump with an indirect dryer it is important to reduce the amount of air in the dryer and exhaust air to a minimum in order to maintain a high dew point temperature profile at which the heat can be extracted from the exhaust stream. In addition lower air content in the exhaust implies higher heat transfer coefficient and consequently smaller heat exchanger with less pressure drop, saving power for blower.

Figure 5-15 shows the condensation temperature versus heat at 1 bara total pressure in exhaust streams from a drier evaporating 1 kg/s of water having various content of air. Almost pure water (no air content) will condense at 100 °C constant temperature. If just a small amount of air is present the condensing temperature will decline considerably. If for instance 7 % air is present, the final condensing temperature (evaporation temperature if seen from the heat pump site) will fall about 10 K and thereby requires much higher temperature lift and input of compressor power to the heat pump.

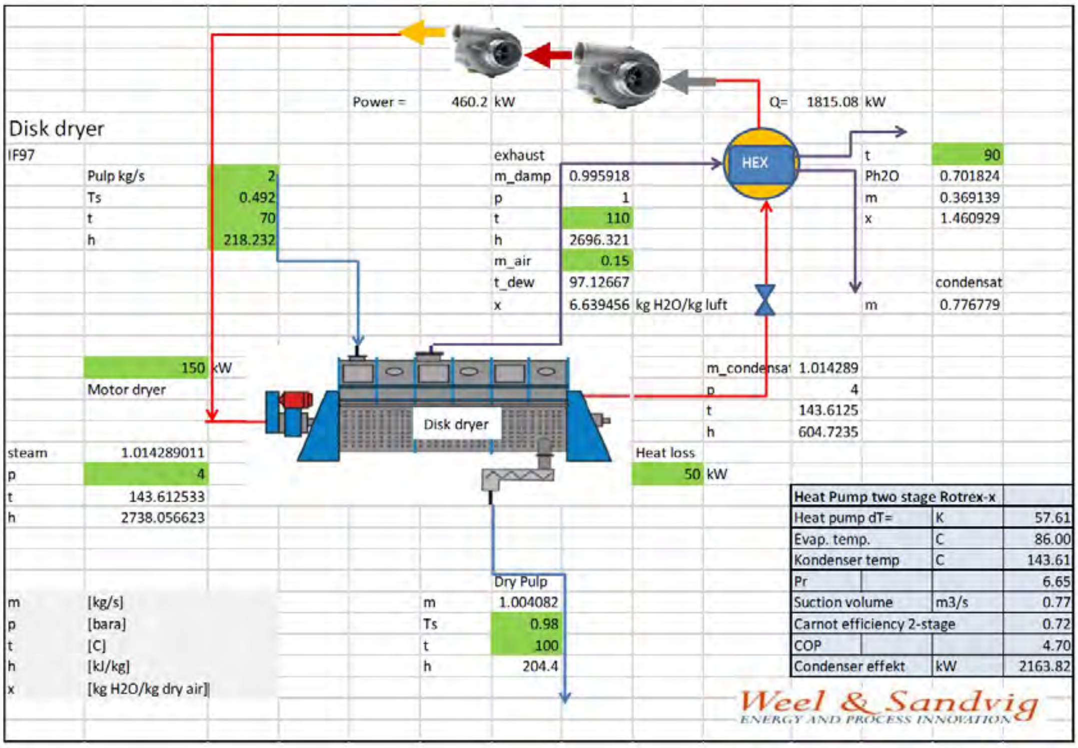


Figure 5-14: Energy and mass balance of a heat pump integrated with a typical disk dryer (fish and bone meal industry)

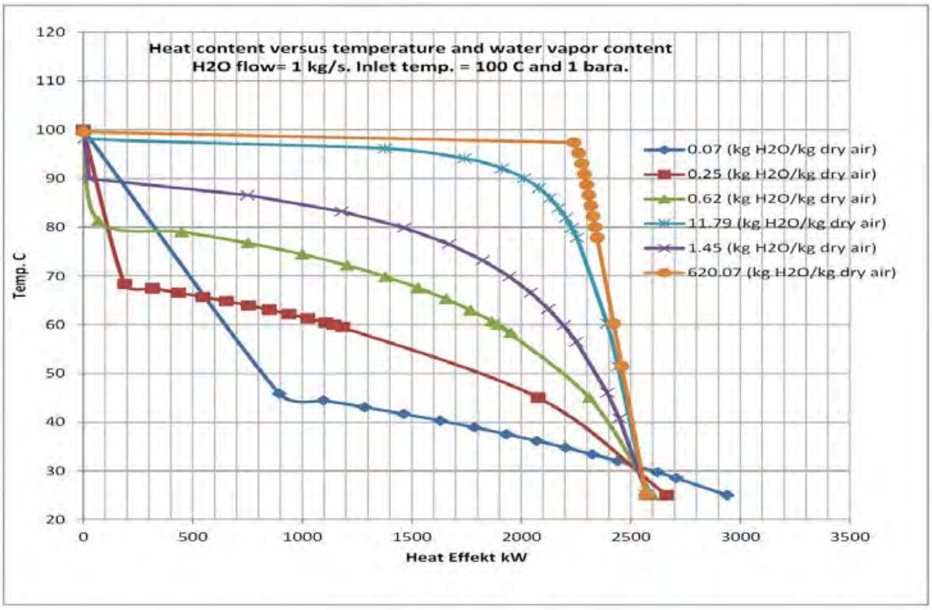


Figure 5-15: Heat content versus temperature and water vapor content

Drying of PET food in super-heated steam has been developed [Schmidt, 2012], where a heat pump has been considered, as shown in Figure 5-16.

When integrating a heat pump into a super-heated steam dryer, optimization of circulating steam flow and temperature rise and heat exchanger size has to been considered. In Figure 5-17 is shown COP values and power uptake from the steam compressor and steam circulating fan versus logarithmic mean temperature difference in steam re-heater (dTmin= 5 K). As shown there is a minimum of total power consumption.

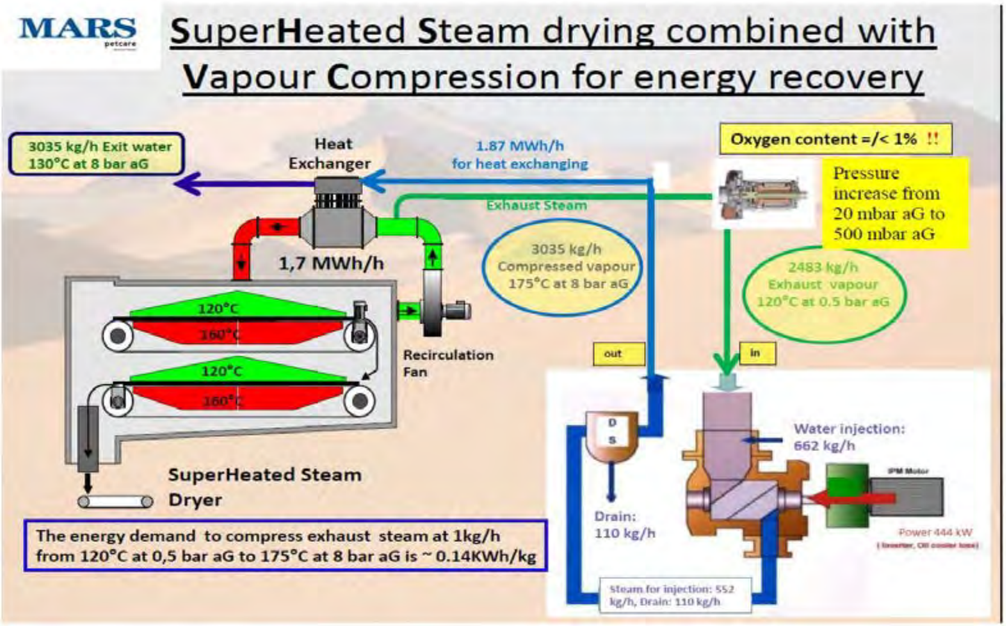


Figure 5-16: Super heated steam drying process for pet food with integrated heat pump – ref [4]

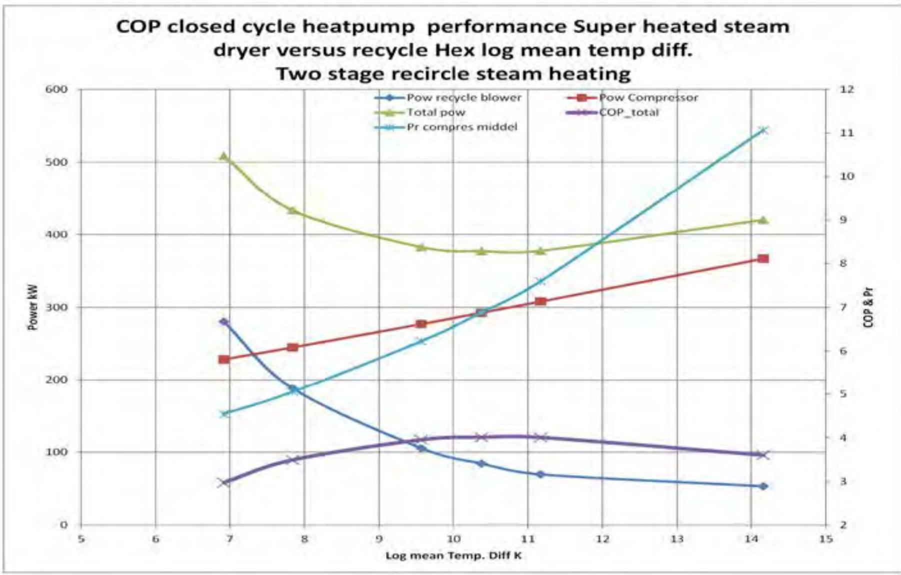


Figure 5-17: Example of optimization of a heat pump for a SHS dryer delivering 1,500 kW heat

Conclusion

We see a bright future for heat pumps in drying applications and expect this technology to provide the major energy savings and CO2 reductions in the drying industry. Analyses have shown that the new turbo-compressor based heat pump concept can be integrated into drying applications and achieve COP-values between 4 and 7.

Mayekawa, 2002 Steam Compressor for Brewery Plant Y. Endo, Mayekawa Mfg. Co. 2002.

Schmidt, 2012 SHS AS A TECHNOLOGY PLATFORM FOR SUSTAINABLE & COMPETETIV ADVANTAGE, Taastrup 02.11.2012, Siegfried Schmidt, Mars GmbH Europe.

Weel, 2012 Industrial heat pumps for high temperatures, Mogens Weel, Jens Mikkelsen, 2012.

Weel, 2013 The potential for high temperature heat pumps in industrial application, Weel & Sandvig, 2013.

5.3.2 Development of ultra high temperature hybrid heat pump for industrial processes

Industrial scale heat pumps have until recently been limited to maximum temperatures of 75-80 °C and thereby limiting the application range. During the last years new components are available and the use of high temperature heat pumps for waste heat recovery has found its way into the market. A maximal temperature of 100°C is still the limitation for these processes based on the traditional heat pump cycles and fluids. Hybrid Energy (HE), which is a partner in this project, has reinvented a heat pump process called “the hybrid process” where the absorption and compression cycles are combined. Because of this combination it is possible to reach temperatures of 110° C with standard industrial refrigeration components. This can be done with very high efficiencies. There are currently 6 hybrid plants running in the market with more than 50,000 running hours. The process has proven to be reliable and it is possible to reach the estimated values of COP. During the EUDP project “Utilization of low grade waste heat by means of high temperature heat pumps” the Danish company Innotek was introduced to HE and the hybrid process, and has signed an agreement with HE concerning cost optimization and representative for the Danish market. The interest in Denmark has grown tremendous due to this.

The aim of the project is to increase the operating limits of the hybrid process by using the new standard components that are approved to higher pressures. By using new components the maximum temperatures can be as high as 180-250 °C. This will open new markets in the food and process industry for utilizing heat pumps to recover waste energy at a lower temperature level and bring the energy back into processes at a higher temperature level. Nearly 100 % of these processes are today heated using fossil fuels.

The project will demonstrate that it is possible to develop an efficient and reliable heat pump process for high temperatures above 180-250 °C.

The project consists of three parts

1) Theoretical and practical investigation of the hybrid heat pump process for ultra-high temperatures
2) Investigation of possible implementation into the processes at the end users in the consortium and the conduction of a general market survey
3) Demonstration at one of the end users in the consortium

The project will verify that it is possible to reach temperatures in the range of 180-250 °C based on the commercial available industrial refrigeration equipment coming to the market these years. The implementation of such high capacity systems will make it possible to lower the use of primary, nearly always fossil fuels significant in processes which are nearly impossible to day. The project will investigate where an ultra-high temperature hybrid heat pump can be a profitable tool to do this. Further ultra-high temperature heat pumps (UHTHP) will make it possible to implement more renewable energy into the food and process industry.

The hybrid process

The hybrid process is a combination of the well know vapor compression cycle and the absorption cycle using the natural refrigerants water and ammonia. The two refrigerants are flowing in the hybrid process as a mixture. When mixing the two refrigerants it is possible to reach a high temperature at moderate pressures.

As shown in Figure 5-18 the maximum achievable temperature is depending on the concentration of the water/ammonia (H_2O/NH_3) solution.

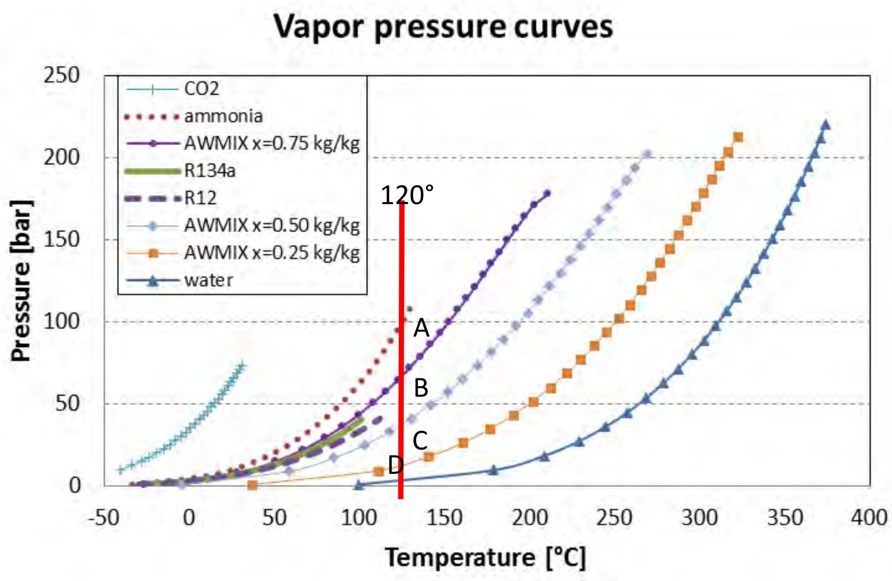


Figure 5-18: Comparison of different refrigerants the needed pressure to reach a given temperature

The figure shows the achievable temperatures for different working fluids. The red line indicates 120 °C, and it can be seen that the needed pressure in order to achieve this is highly influenced by the concentration: A: Pure NH_3 ~ 100 bar, B: 75% NH_3 ~ 65 bar, C: 50 % NH_3 ~ 35 bar and 25 % NH_3 ~ 15 bar. Using pure water the pressure is 1 bar(g).

The low operating pressure makes it possible to use standard industrial refrigeration equipment up to 110 °C, which again has a very positive impact on the competitiveness against other technologies for the same temperature level.

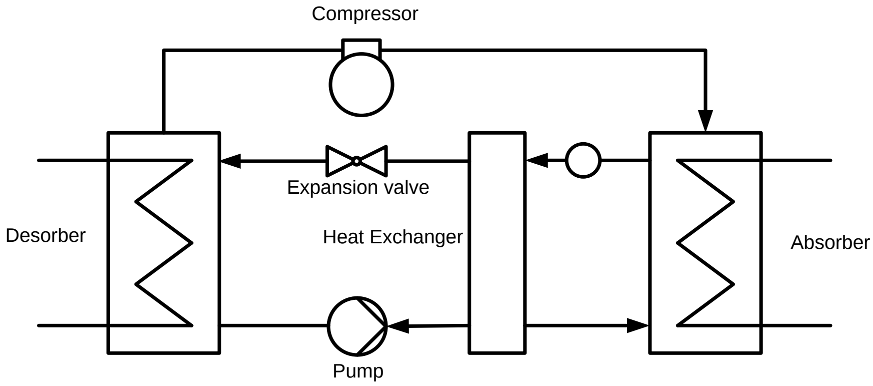


Figure 5-19: Flow diagram of hybrid process

Figure 5-19 shows a flow diagram of the hybrid process. Compared to a conventional vapor compression cycle the desorber corresponds to an evaporator and the absorber to a condenser. In the desorber heat is transferred from the heat source to the refrigerants, at low temperature (could be waste energy). In a conventional vapor compression cycle the refrigerant evaporates at a constant temperature. This is not the case for the hybrid process, where the evaporation is partial and the temperature of the refrigerants changes from the inlet to the outlet. This phenomenon is called a temperature glide.

The evaporated ammonia is compressed in a compressor to a higher temperature and pressure and the water (still liquid) from the desorber is pumped through a heat exchanger to the absorber. In the absorber the heat is rejected to a heat sink (bringing waste heat back to a process at a higher temperature). Again the heat is transferred with a temperature glide like in the desorber. In a traditional vapor compression cycle the heat in the condenser is rejected a constant temperature.

To achieve the highest COP for the process the temperature glide in the desorber and absorber should match the actual temperature profile of the heat sink and heat source. This is illustrated in Figure 5-20.

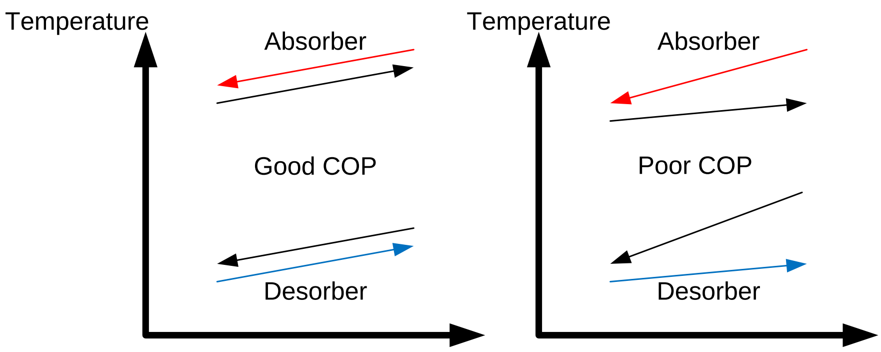


Figure 5-20: Temperature profile in absorber and desorber

5.3.3 Highly efficient Thermodynamic Cycle with Isolated System Energy Charging (ISEC)

This R&D-project has just been initiated and no experimental results are available at this time. The new concept is scheduled to be developed and demonstrated by 2016. Below is a short description of the project.

The objective is to demonstrate an improvement in the energy efficiency of heat pumps with up to 50 % by using a novel technology where heat pumps are operated with usage of storages which will reduce the average temperature level in the heat pump. The pay-back time for the investment is expected to be less than three years.

The project aims at developing and demonstrating how a high-efficiency heating unit based on the traditional thermodynamic cycle process in a heat pump can achieve an energy saving potential up to 50 % by using a newly developed “Isolated System Energy Charging” concept (ISEC). By heating one tank at a time, the condensing temperature (or evaporating temperature) of can vary according to the actual temperature of the secondary medias. This means that the condensing temperature will be only slightly higher than the medium temperature of the liquid during the heating process.

The ISEC concept consists of two or more tanks. One tank is heated while the other (which previously has been charged) is discharged. When the second tank has been discharged, the first tank is fully charged with and the system switches to discharge the first tank while the second tank is being charged. Seen from the heat source and the heat sinks perspective, the introduction of the ISEC concept does not change the conditions.

Project activities include theoretical calculation, design and construction of individual components, experimental stage and construction of actual systems during the demonstration stage.

5.4 Economy and other incentives

As mentioned elsewhere in this report, electricity is 2.5 to 3.5 times more expensive than traditional fuels for boilers, thus requiring a COP for heat pumps in this area or higher in order to be competitive in industrial applications. The initial cost of heat pumps compared to traditional heating plants is also several times higher, meaning that only heat pumps with very high COP values and many operating hours will be profitable. Because of this the most immediate applications are processes with small temperature lifts, a lot of operating hours and a steady demand meaning less complex (expensive) systems.

Although payback periods from reduced energy consumption are longer than desired in most cases, there could be other drivers. Cooperative energy policies such as reduced consumption, CO_2-foot print and so on could be met by utilizing heat pumps.

In Denmark energy consumers and providers are required to reduce energy consumption by a certain amount each year. This requirement can be met either by reducing one's own energy consumption, or by buying an excess reduction from somewhere else. E.g. three companies are each required to reduce their energy consumption by 5 MWh a year. If one of the companies finds a way to reduce energy consumption in that company by 15 MWh and the others don't reduce consumption, it is allowed for the first company to "cover" for the other two companies by splitting the excess reduction. In praxis the energy reductions (called energy savings) are traded between companies, suppliers and advisors throughout each year. The price for each MWh of "energy savings" varies depending on the buyer, availability and expectations to the market. One MWh of "energy savings" typically holds a value of between 50 and 65 Euros. For heat pumps with many operating hours (> 6,000/yr), "energy savings" will typically cover half of the investment costs meaning that this "subsidy" is essential for heat pumps in industrial applications.

"Energy savings" has no value in district heating plants as these are not part of this system. Energy consumption for residential heating is taxed and heat pumps have an advantage as tax per heat unit is considerable lower using heat pumps than other fossil fuels. This means that utilization of heat pumps in district heating systems is possible with short pay back periods as well.

6 France

6.1 Introduction

Europe is now committed on its energy policy for 2020 and further. Among other objectives, the European Union shall reduce its own CO_2 emissions and energy consumption and increase the proportion of renewable energies in its energy mix by at least 20%. Supplier obligations and white certificates were established in France in order to contribute to these energy-efficiency goals. Energy savings in the industrial sector are eligible for white certificates, as well as are the residential and commercial sectors.

Energy consumption in French industry represents 450 TWh/year. About 75% of the final energy use is for thermal purposes (furnaces, reactors, boilers, dryers etc.). The major part of that heat comes from the combustion of fossil fuels generating large CO_2 emissions. Some studies estimate that around 30% of the final energy used for thermal purposes is wasted through losses In the industrial sector, only few measures can be rewarded by white certificates in France. Most of them are obtained through boiler economizers and variable speed drives (VSD). Indeed, these two measures have high EE potential and are quite simple to implement on site. On the opposite, energy savings of more complex projects can hardly be estimated by standardized ex-ante methods and the evaluation procedure of non-standardized measures is quite slow. As a consequence, complex actions such as heat recovery on industrial processes can hardly be rewarded for the moment. However, in order to achieve energy-efficiency and CO_2 goals, actions of saving, recovering and utilizing the heat should be developed and recognized as eligible for white certificates.

The main industrial heat needs range from 60 to 140 °C and they represent about 30 TWh/year. At these temperature levels, many opportunities for heat Pump technology exist, and allow recovering low temperature heat to produce high temperature heat.

Some studies estimate that it is in theory possible to recover in flue gases between 10 % and 25% of the fuel used by thermal high temperature equipments such as boilers, furnace or dryers, which means approximately 35-85 TWh/yr for France. However, this whole potential is not entirely economically accessible. For example, some flue gases can be corrosive so that it is expensive to install a heat exchanger with a resistant material. In addition, compared to quality of products and productivity, energy savings are not a major criterion for investments in industry. EDF experienced that pure EE investments (not dedicated to the production) must generally have a payback time lower than 3 years to be accepted. Due to that strict criterion, some investments will not be “judged” as cost-effective by certain industrials so that a part of the whole potential will not be reached.

Heat pumps (HP) often require important investments. Hence, this technology will spread first and principally to sectors with the shortest payback time.

In the 80’s in France, developments of high temperature heat pump started to emerge. Due to the low price of energy and high investment, it was difficult to find a good return on investment, gas boilers were preferred. Since a few years, there is a renewed interest for heat pumps. Recent developments have been made to develop industrial (> 100 kW_{th}) high temperature heat pumps (> 80 °C) and very high temperature heat pumps (> 100 °C). Currently, there are only a few closed-cycle mechanical high or very high heat pumps installed in the French Industry, but interest and references are growing.

6.2 The French industry

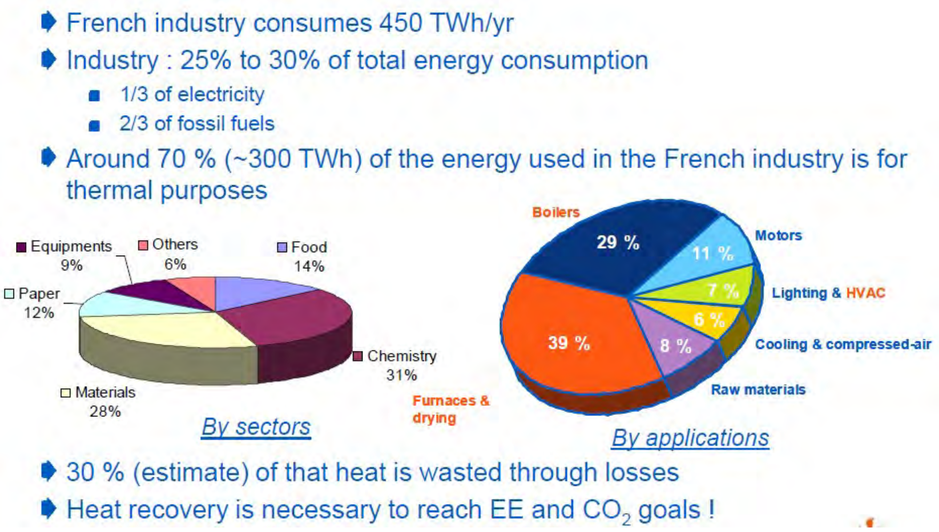


Figure 6-1: Stakes of the heat recovery in the French industry

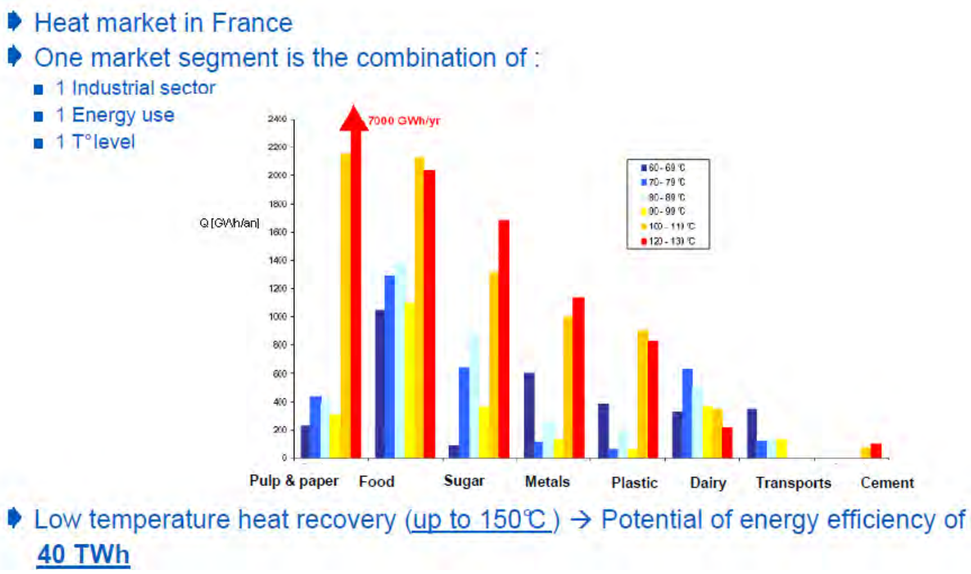
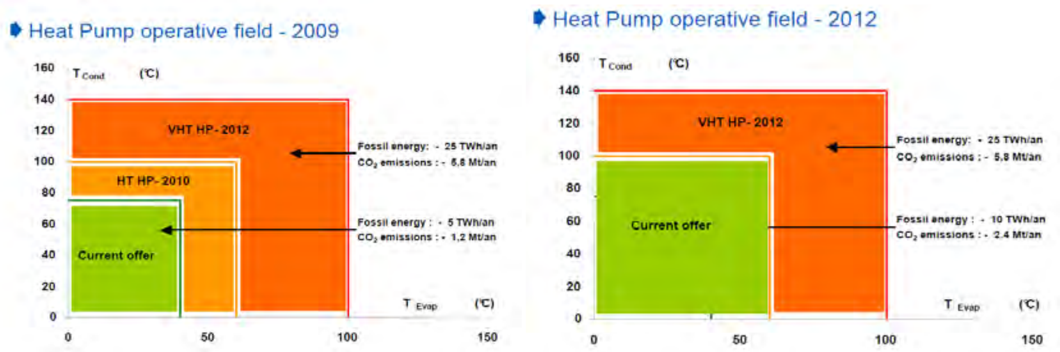


Figure 6-2: Heat market in the French industry

6.3 The temperature level

The temperature level reached by the condenser is a main parameter for heating application. Before 2009, there were no standards heat pumps able to reach a temperature above 80 °C. The identification of a huge quantity of thermal needs in the temperature range 80 – 140 °C leaded to develop systems able to heat above this temperature limit.

Figure 6-3: The evolution of the temperature level



The next figure shows the temperature levels reached by different manufacturers in 2013.

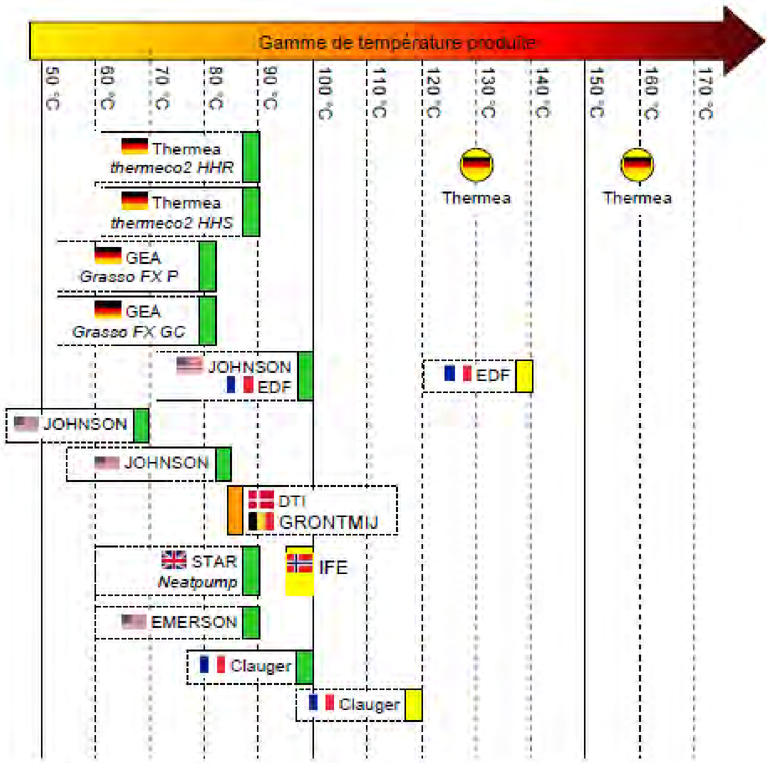


Figure 6-4: The temperature level reached by the manufacturers

The three main actors in high temperature industrial heat pumps France are: Johnson Controls (YORK), Clauger and EDF. They have a distribution and maintenance network in France.

6.4 Heat pumps in France: maturity, fluids and technology

The next chart gives details of the technology of the heat pumps developed or installed in France.

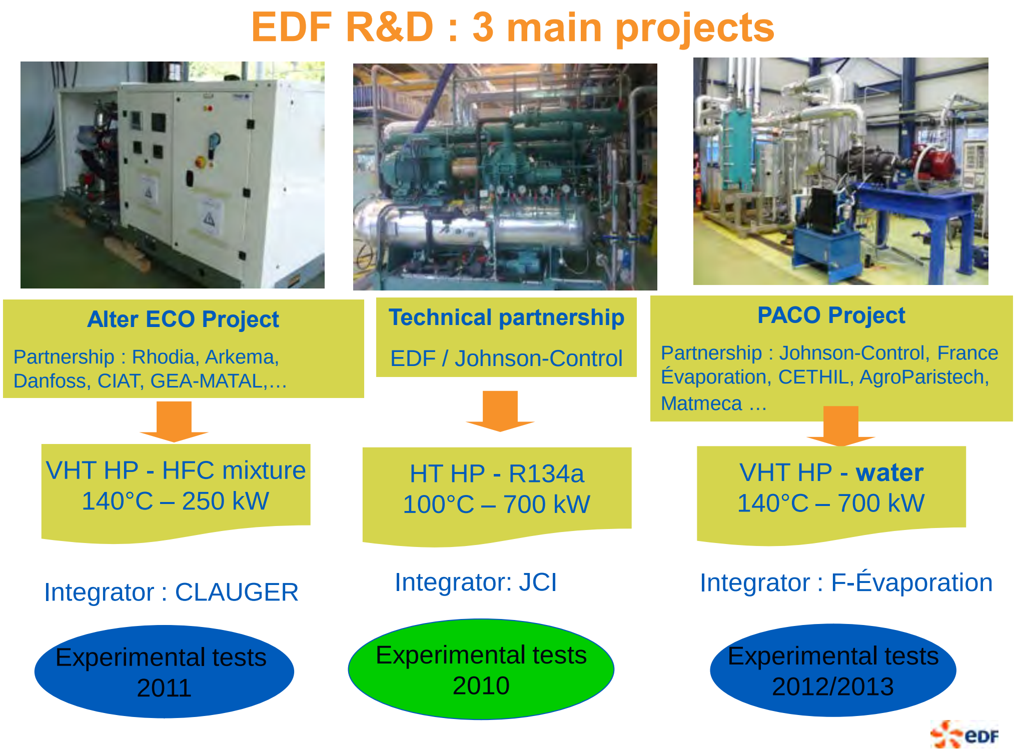
Table 6-1: Temperature, maturity and technology of industrial heat pumps in France

Temperature	Maturity	Manufacturers / Deve-loppers	Refrigerant	Compressor technologie
Up to 70 °C	Standards	Trane GEA Clauger Ciat Carrier	R134a Ammonia	Centrifugal Screw
70 - 100 °C	Commercialized	Johnson Control/EDF	R134a R245fa	Centrifugal Screw
		Clauger	Ammonia	Screw Surcompressor on chiller condenser
		GEA Refrigeration	Ammonia	Screw
100 – 120 °C	Pre commercialized	Jonhson Control / EDF	R245fa	Centrifugal
		Clauger	Ammonia	Surcompressor on chiller condenser
120 – 140 °C	Prototype	EDF – Altereco EDF – PACO	ECO3 [1] Water	Centrifugal, Scroll
140 – 165 °C	Ø	Ø	Ø	Ø

[1] ECO3 is a mixture of HFC

6.5 EDF R&D activities

EDF is working on the development of high temperature industrial heat pumps with new working fluids to reach temperature higher than 100 °C.



6.6 Current and future activities

AlterECO Project : industrial experimentation in 2014

EDF / JCI: experimental test up to 120 °C with R-245fa

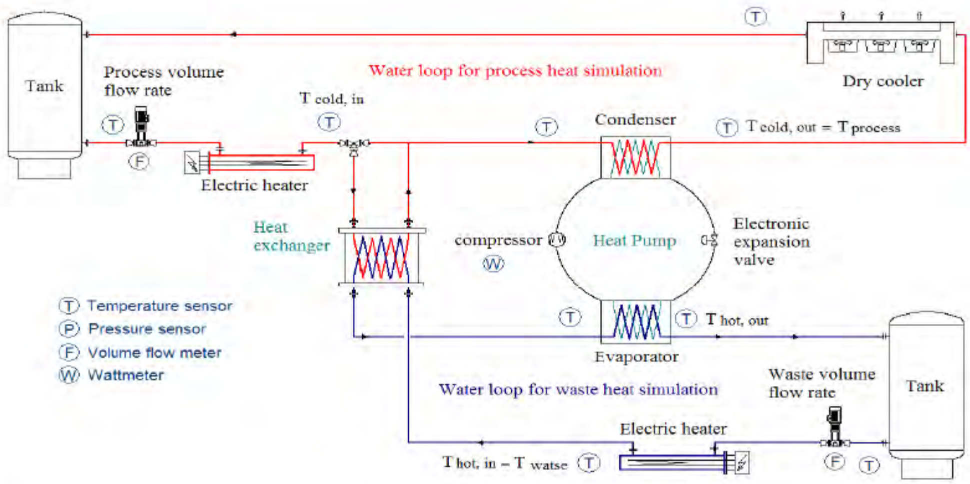
PACO Project: centrifugal compressor with magnetic bearings

6.7 Experimental test bench at EDF R&D

For machines that operate at high temperature, the EPI department of EDF R&D and Johnson Controls have developed a test bench to improve high temperature performances, made of three hydraulic loops:

- The high temperature loop (in red) allows simulating the process heat requirement. This circuit is equipped with a pump and variable capacity dry cooler. Water or pressurized water are currently used as fluid.
- The low temperature hydraulic loop (in blue) simulates the process waste heat. Water is used as fluid.

- The third loop (brown) is needed to remove heat from high temperature loop with the help of a variable capacity dry cooler. The glycolic water is usually used as fluid.



	Effluents loop		Requirements loop	
	Min	Max	Min	Max
Temperature [° C]	5	95	5	145
Flow rate [m³/h]	16	44	21	48
Storage volume [m³]	4		5	

Figure 6-5: The experimental test bench

Both high and low temperature loops include a water tank, a controlled electric heater, and a water pump with adjustable volume flow rate. Furthermore, the system includes a counter-current plate type heat exchanger for primary heat recovery before the heat pump.
Those hydraulic loops are composed with several sensors: temperature transducers PT100 (0 – 200 °C range ±0.5 K), electromagnetic flow meters (± 0.25 % in the operating range of the experimental conditions). All sensor measurements are collected at steady state conditions using a dedicated PC via convenient data acquisition software.

6.8 Technical partnership: EDF & Johnson Controls

For machines that operate at high temperature (up to 100 °C), the EPI department of EDF R&D works in partnership with Johnson Controls to improve performances of HPs (laboratory tests with fluids such as R-245fa) and promote industrial implementation.

6.8.1 Description of the heat pump

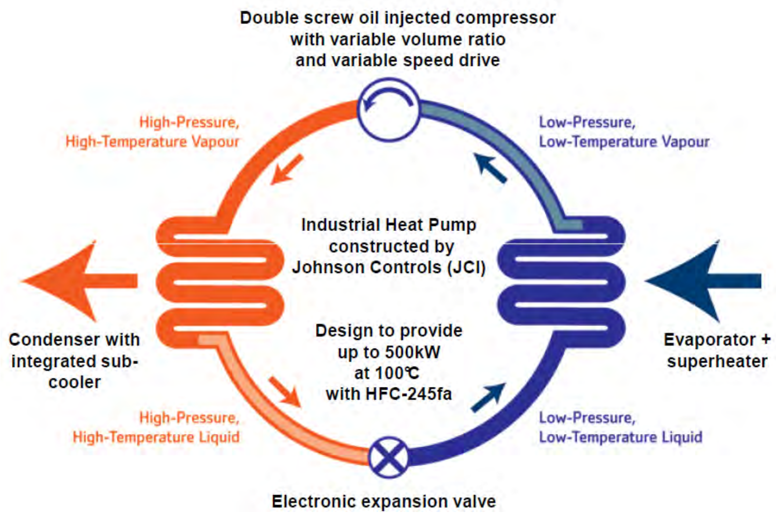


Figure 6-6: The JCI / EDF heat pump

The double screw compressor was replaced with a centrifugal compressor.

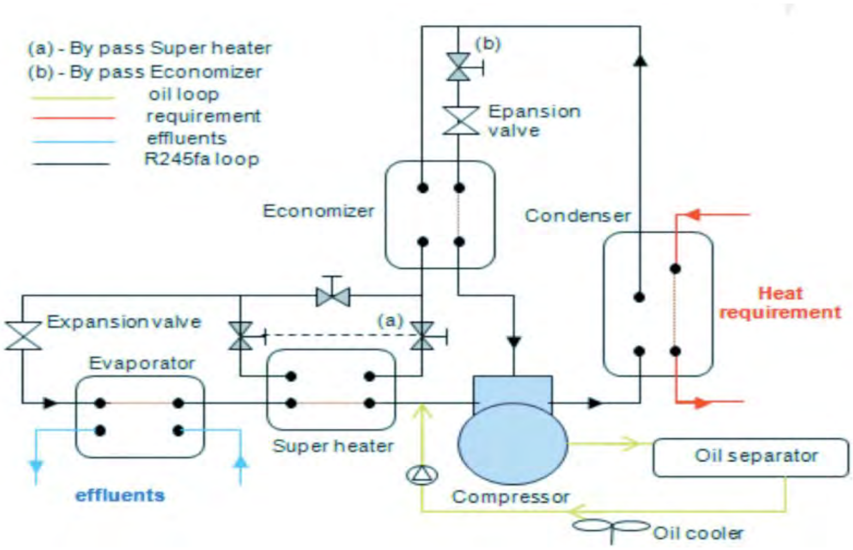


Figure 6-7: Schematic of the JCI / EDF heat pump system

Figure 6-8: Picture of the JCI/EDF heat pump

6.8.2 Results and performances

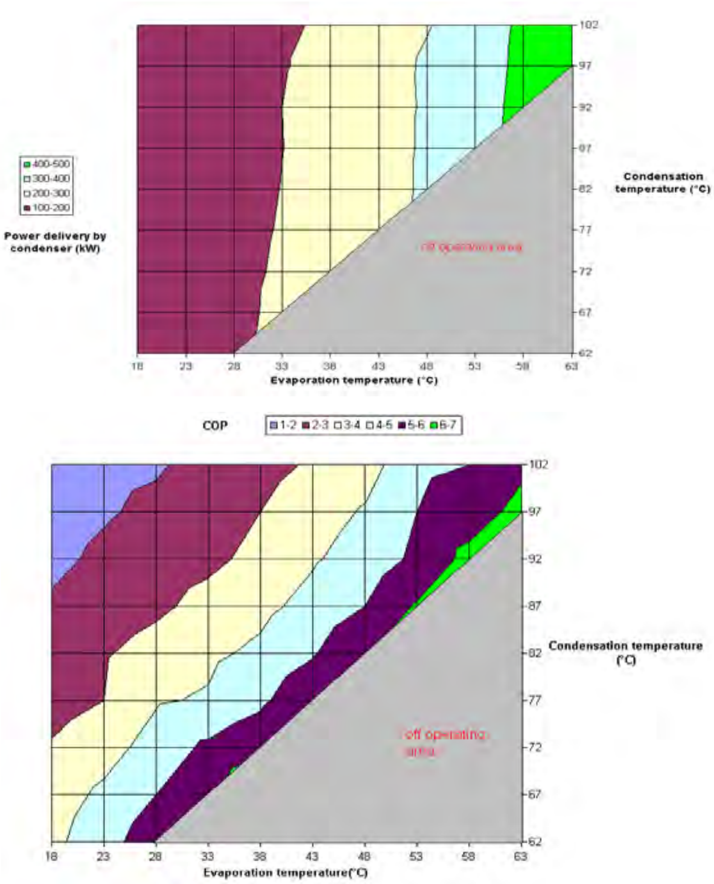


Figure 6-9: The JCI / EDF heat pump performances

6.9 Altereco project

This project includes the development and industrial testing of HPs capable of operating at 140 °C in condensation mode. The project includes a number of partners: Danfoss, Arkema, Ciat and Clauger who are studying and supplying heat exchangers, fluid, compressors, etc.
The projects leads to the publication : " Experimental results of a newly developed very high temperature industrial heat pump (140 °C) equipped with scroll compressors and working with a new blend refrigerant".
The compressor power is 75 kW. The machine performances have been characterized to demonstrate the technical feasibility. For each evaporation temperature (from 35 to 60 °C by step of 5 °C), the condensation temperature is increased by step of 5 °C from 80 up to 140 °C.
Test campaigns over 1,000 hours were carried out in industrial-like conditions to demonstrate the reliability.
The efficiency of heat recovery up to 125 °C is demonstrated. Good performances are obtained. For higher temperatures, the technological feasibility is demonstrated but some further developments have to be carried out to increase the efficiency and the economical viability: 2 stage compressors (it is designed for a given pressure ratio), expansion valve, etc.

All this demonstrates the prototype reliability and the capacity to use this newly developed machine for industrial purposes.

6.9.1 Description of the heat pump

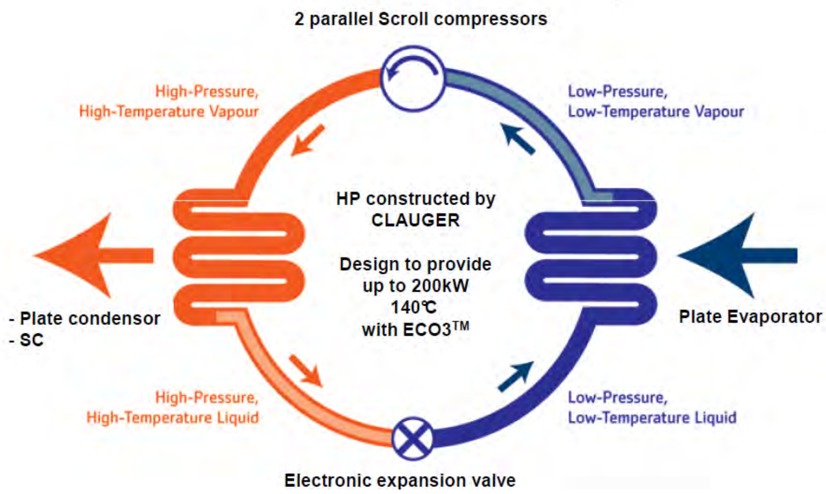


Figure 6-10: The Altereco heat pump

Figure 6-11: Picture of the Altereco heat pump

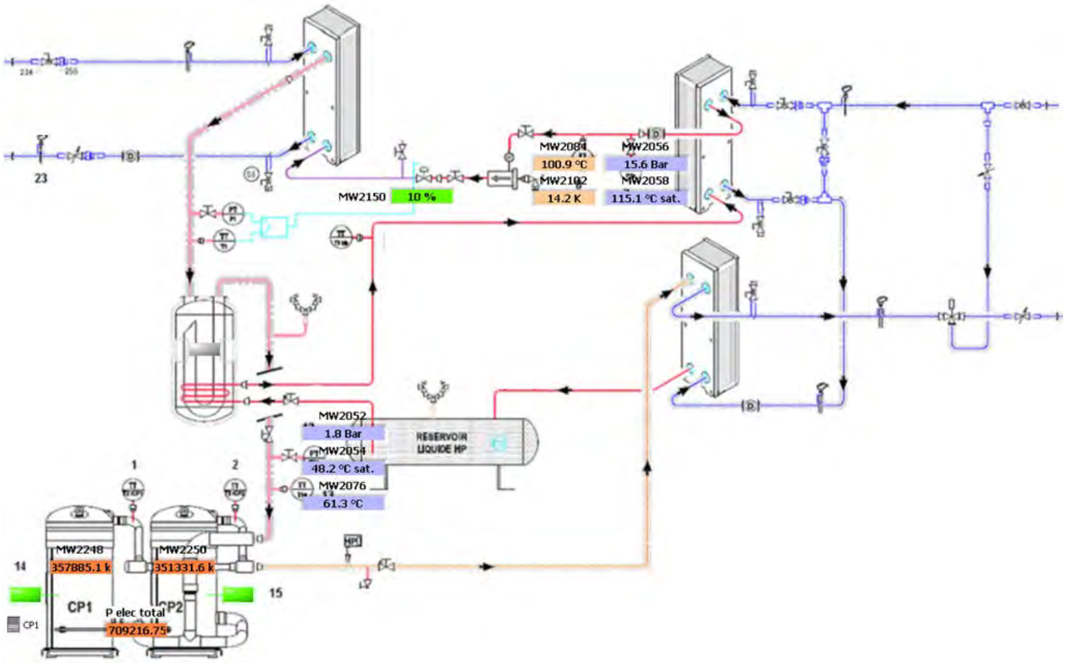


Figure 6-12: Schematic of the Altereco heat pump

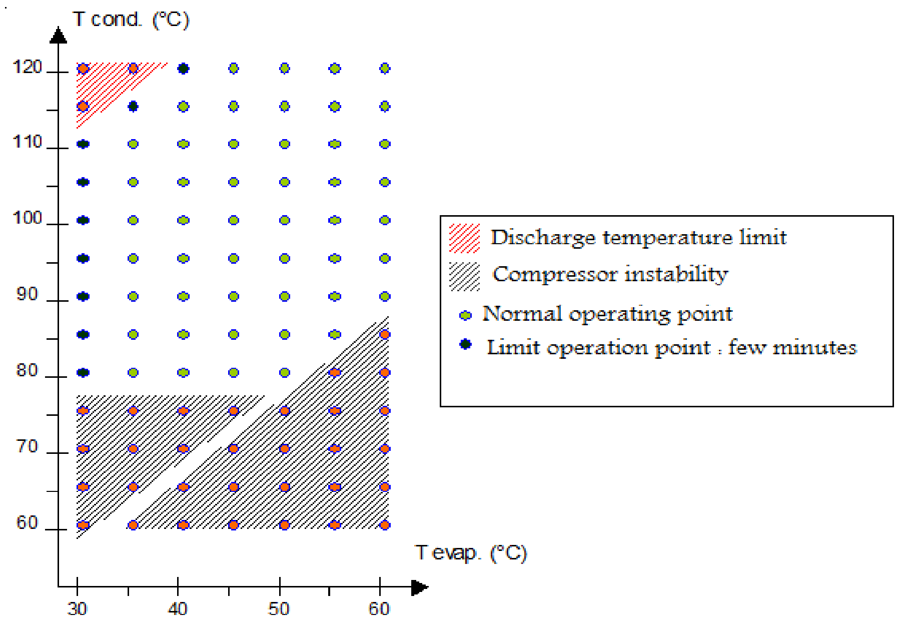
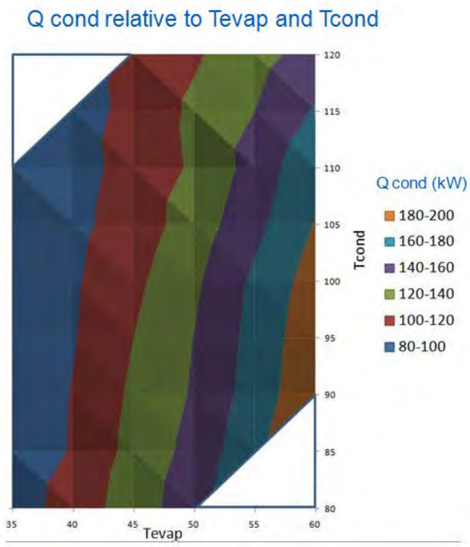
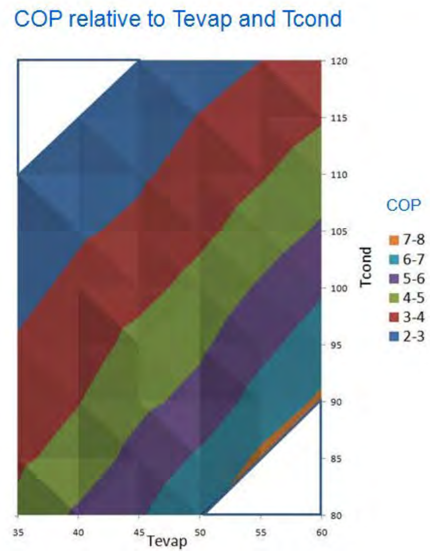


Figure 6-13: Operating points

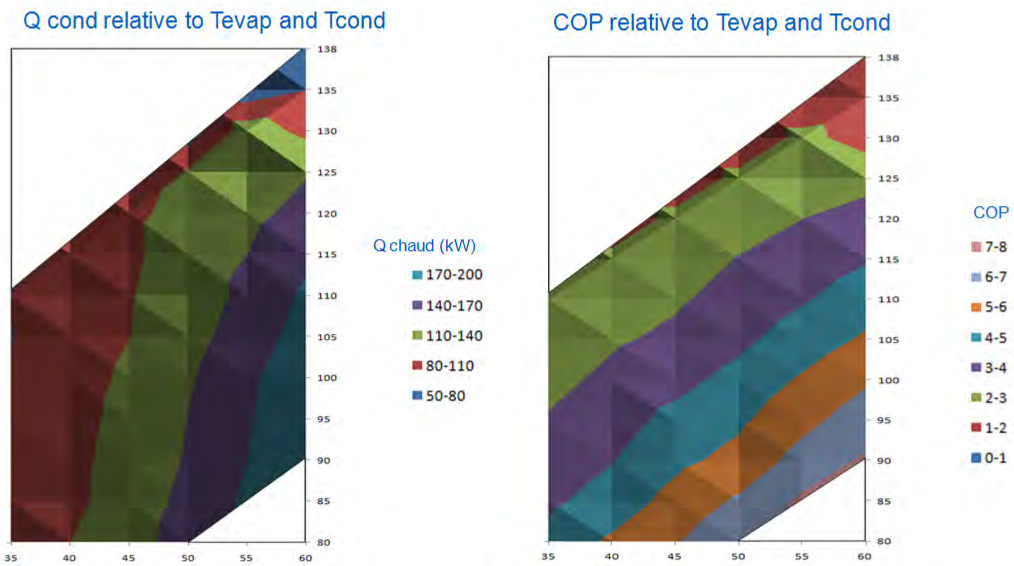
6.9.2 Results and performances

6.9.2.1 First test phase (120 °C)





6.9.2.2 *Second test phase (140 °C)*



6.10 PACO Project

Heat pump using water as refrigerant fluid is an interesting solution for waste heat recovery in industry. Water is non toxic, non ignitable and presents excellent thermodynamic properties, especially at high temperature. Indeed, like one can see on the following graph, COP of the different fluids decrease at a certain temperature (close to the critical temperature).

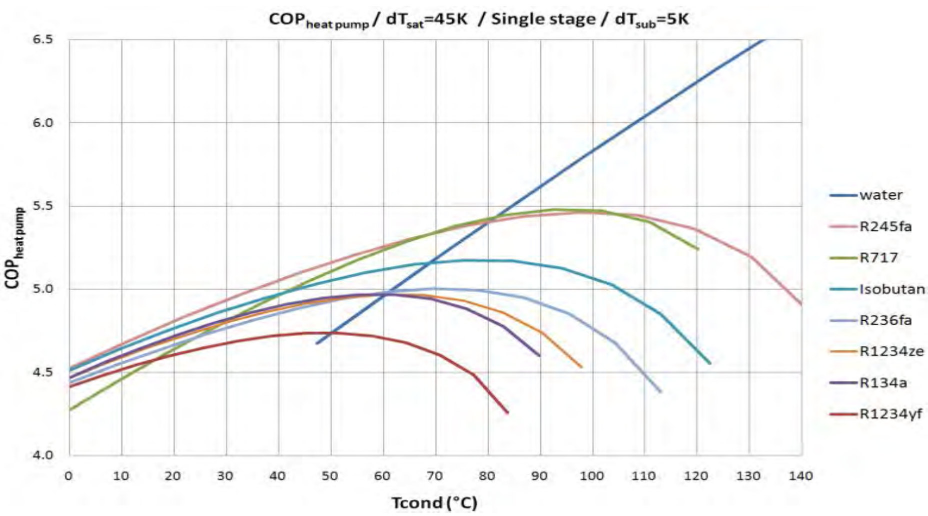


Figure 6-14: COP of different fluids vs the condensation temperature (Source: YORK)

Water HP development is complex, notably due to water vapor compression. The compression ratio of centrifugal and lobe compressors is low. It prevents gas temperature from rising more than 20 °C. For now, the only technical solution able to overcome this

drawback with moderate costs is to put two lobe compressors in series. However, theses compressors are less reliable than the others and their efficiency is low. Thus, the development of a novel water compressor is needed. Screw and centrifugal compressors on magnetic bearings seem to be the most promising technology. Discussions with the compressor manufacturers, and the numerical simulations show that the COP can be increased up to 80 % if such a compressor is integrated on a water heat pump. The price of this prototype compressor is very high, but it should decrease with the development of the market. Thus, the payoff would be guaranteed and the water heat pump would become an industrial reality.
This project, which is partly funded by the ANR, relates to the development of industrial HPs (700 kW thermal) that use water as refrigerant and are capable of operating between 100 °C and 140 °C in condensation mode. The compressors developed under this project will also be usable to apply the mechanical vapor recompression to concentration or drying applications. Johnson Controls, France Evaporation, Cethil, IMB, Agroparitech are EDF's partners for this development. The project has started in 2010. The HP prototype is under development.

Figure 6-15: Picture of the PACO project

Experimental tests have been realized up to 140 °C. At this level, technical feasibility is demonstrated but the expected performances are not reached, due to mechanical problems on the double screw compressor. A centrifugal compressor with magnetic bearings is now installed. It has been validated with air and is currently in test on the PACO heat pump with steam.

6.11 Prospects

It is expected to install in France at least 1,500 industrial high temperature heat pumps before 2020 in spite of various commercialization barriers:

- Lack of knowledge and experience with heat pumps
- Negative perception of heat pumps due to poorly designed models early in their use
- Volatile energy prices.

The population of industrial heat pumps is relatively low in all industries except lumber drying and malting. As a result, there is limited information for many industrial applications regarding proven engineering designs, actual field performance, and economics. This lack of awareness inhibits the growth of industrial heat pump installations.

There are also lingering doubts created from first generation industrial heat pumps installed in the 1970s and 1980s. Some of these early heat pump systems were improperly designed and did not perform as expected. However, a properly designed modern heat pump system will provide high reliability, often with a payback period in the range of 2 to 5 years.

Volatile energy prices are another factor that can impact the adoption of industrial heat pumps. An industrial heat pump can represent a major capital expenditure, and plant managers expect the investment to provide near term financial benefits. The financial benefits are directly tied to energy prices, and if energy prices are volatile, risk adverse decision makers may shy away from an industrial heat pump investment.

The integration of heat pump can be optimized with **thermal energy storage**, with various advantages:

- The heat pump works at its nominal point
- The thermal need can be covered with a smaller heat pump, decreasing the investment.

EDF R&D has experimental studies on this global heat recovery chain.

7 Germany

7.1 Institut für Energiewirtschaft und Rationelle Energieanwendung, Universität Stuttgart

7.1.1 Advances in the development of industrial heat pumps

7.1.1.1 Emerson Climate Technologies

In cooperation with the Scottish heat pump manufacturer Star Refrigeration Emerson Climate Technologies presented the NeatPump. The NeatPump uses ammonia as working fluid since it has a high critical temperature and a high volumetric heating capacity. Emerson developed a new single screw compressor that can achieve a discharge pressure of 61.5 bar. Ammonia heat pumps with this compressor can produce heat at flow temperatures of up to 90 °C. The illustration in Figure 7-1 shows the advances being made by this new compressor technology. The ammonia NeatPump has been applied in several projects such as district heating and the generation of process heat and cooling in a chocolate factory [Pearson 2012].

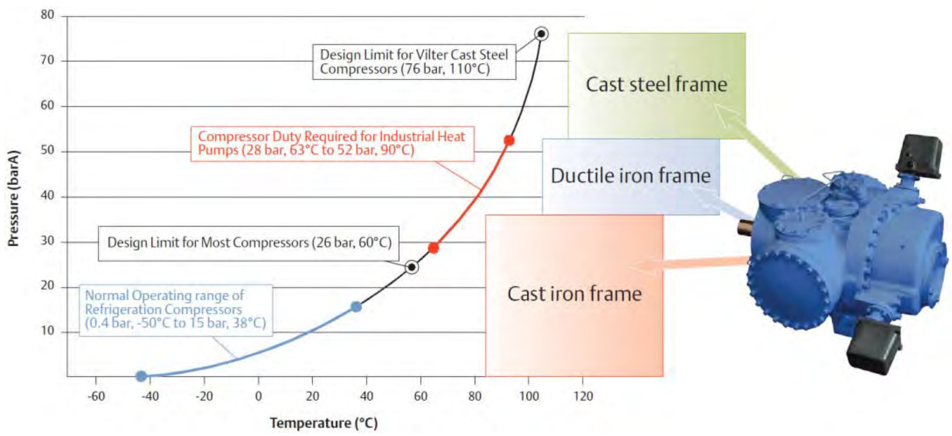


Figure 7-1: Pressure-temperature relationship and available compressor technologies [Emerson 2010]

7.1.1.2 GEA Refrigeration Technologies

GEA also developed a new compressor for high temperature ammonia heat pumps. The new double screw compressor design allows discharge pressures of up to 63 bar. This design is based on a 52 bar compressor. Compared to the standard version the new compressor was equipped with a stronger thrust bearing at the male rotor, a stronger driving shaft and other high pressure components. While the 52 bar version is limited to a maximum condensing temperature of 82 °C, the extended design can reach temperatures up to 90 °C. The compressors are available in various sizes from 165 to 2,838 kW drive power. At a source temperature of 35 °C and a sink temperature of 80 °C a heat pump using this compressor can reach a COP of 5.0 at a heating capacity of 14 MW.

Ammonia heat pumps using this technology have been applied in several projects (e.g. a greenhouse, a paper mill and a production facility for galantine) [Dietrich 2012].

7.1.1.3 Thermea Energiesysteme

Thermea is a specialized manufacturer for heat pumps using the natural refrigerant CO_2. The company two series of high temperature CO_2 heat pumps. The thermeco$_2$ HHR uses a reciprocating piston compressor. It is available in different sizes from 45 to 1,000 kW heating capacity. Due to the special properties of CO_2 the maximum heat source temperature is limited to 40 °C. On the heat sink side up to 90 °C can be achieved. The thermeco2 HHS uses a screw compressor. The heating capacity of this heat pump is 1 MW. To make use of the large temperature glide CO_2 heat pumps show in the gas heat exchanger a high temperature lift on the heat sink side is preferred. Under these ideal conditions the heat pumps can achieve COPs up to 6.9. These large size CO_2 heat pumps have been successfully applied in different operating conditions such as a district heating system with river water used as heat source /Glaser 2013/.

7.1.1.4 Huber Kältetechnik (HKT)

Huber Kältetechnik has built two high temperature heat pumps using the refrigerant isobutane (R-600a). Its high critical temperature of 135 °C and the low GDP make it an interesting refrigerant for high temperature application. However, it should not be forgotten that R-600a is highly flammable.

The first heat pump is a two stage system with R-134a in the low temperature stage and R600a in the high temperature stage. With a heat source temperature of 17 °C and a heat sink temperature of 100 °C the heat pump reaches a COP of 1.7. The heat pump is now running for more than 5,000 hours.

The second example is a single stage heat pump that is used in a brewery to heat brewing water to 120 °C. The heat sink temperature is 75 °C. With a resulting temperature lift of 45 K the heat pump achieves a COP of 3.6 at a heating capacity of 54 kW [Huber 2013].

7.1.1.5 Siemens

Siemens did a screening for existing refrigerants that can be used for high temperature applications. A promising candidate was named LG6. It is already available in large quantities. The composition of this refrigerant is considered to be confidential until the research has been finished. The known properties are a critical temperature of more than 165 °C and a GWP of 1. In addition to that the refrigerant is neither toxic nor flammable. Siemens conducted several tests in a lab scale prototype of a high temperature heat pump with a heating capacity of 12 kW. Tests were carried out with heat source temperatures of up to 110 °C and heat sink temperatures up to 150 °C. So far LG6 has shown a slightly higher COP than R-245fa. Its use, however, is limited to heat sink temperatures larger than 110 °C due to its relatively low volumetric heating capacity [Reissner et al. 2013].

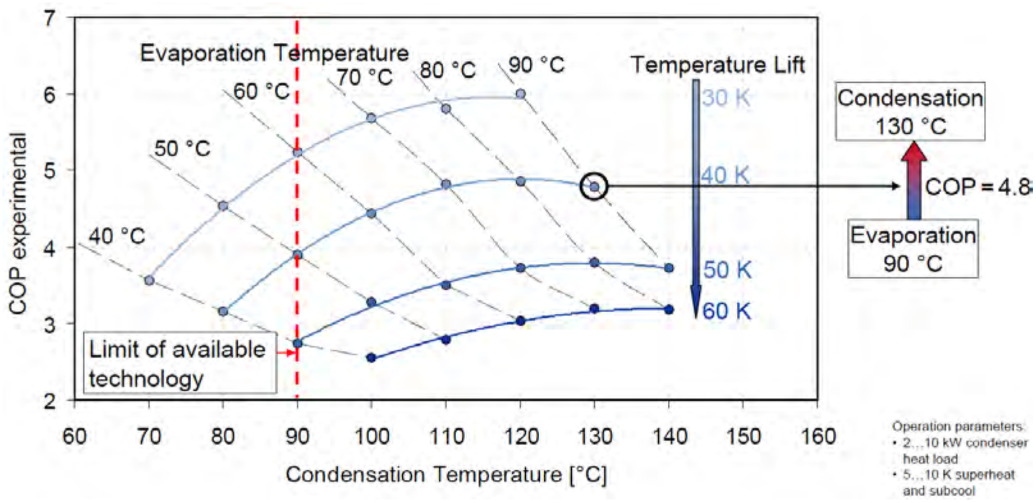


Figure 7-2: Test results for LG6 [Reissner et al. 2013]

7.1.2 Development and application of an industrial high temperature heat pump using R245fa

Within a cooperative research project the industrial plant building company Dürr Ecoclean GmbH, the heat pump manufacturer Combitherm GmbH and the institute for energy economics and the rational use of energy (IER) of the University of Stuttgart developed a high temperature heat pump, integrated it into a part cleaning system and performed an extensive testing program.

In the metal working industry many processes can be found that leave contaminations on the work piece's surface. Part cleaning systems are used to remove fats, emulsions, chips, particles and other contaminations from the work piece. Part cleaning systems can be differentiated by the degree of automation, part throughput, cleaning quality, maintenance requirements and energy consumption. However, the principle of operation is always similar. Work pieces are treated with a cleaning solution based on water or hydrocarbons. To achieve good cleaning results this solution must have a high purity. In conventional part cleaning systems contaminations accumulate in the cleaning solution. If certain purity thresholds are exceeded, the cleaning solution has to be replaced. In addition to an unavoidable down time costs for the disposal of the old cleaning solution and the purchase of the new one arise.

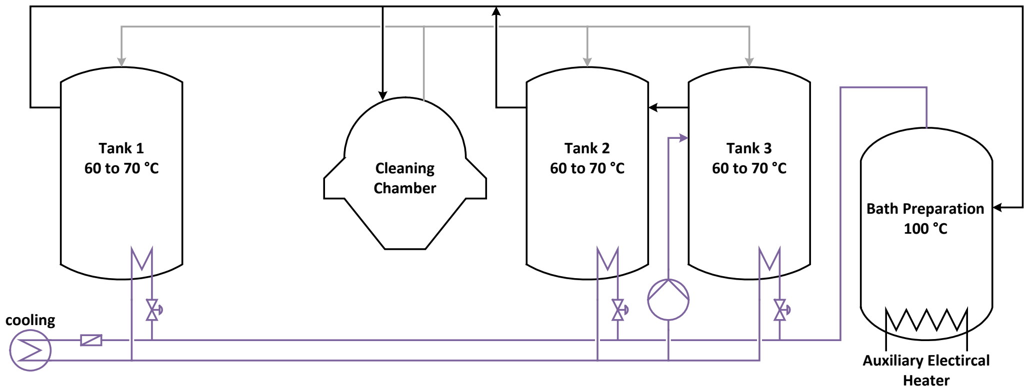


Figure 7-3: Scheme of the part cleaning system EcoCMax

Dürr Ecoclean reduced the need for regular exchanges of the cleaning solution by integrating a bath preparation unit into their part cleaning systems. Figure 7-3 shows a simplified scheme of the part cleaning system with the integrated bath preparation. In the bath preparation module heat is applied at 100 °C to evaporate the water based cleaning solution. The heat needed for this process is entirely generated by electric heaters. Contaminations that boil at higher temperatures such as oils and fats remain in the evaporator. They have to be disposed periodically. The heat content of the evaporated cleaning solution is used to heat three tanks that hold the cleaning solution at a 60 to 70 °C. In this way most of the heat can be recovered. However, if the bath preparation is operated at full load it generates more waste heat than can be recovered. In the heat controlled operation mode the bath preparation can only prepare 5 l of cleaning solution per hour. At full load up to 50 l/h can be prepared with 36 kW heat input. In this case an external cooling system needs to absorb the heat surplus. To recover this waste heat and thereby to allow the bath preparation to operate at full load without the need of external cooling a heat pump was taken into account.

Other companies took similar approaches to increase the usage time of the cleaning solution and to improve the energy efficiency of their part cleaning systems. They offer central bath preparation units that recover waste heat using mechanical vapor recompression (MVR). Those systems are of much larger size with treatment capacities of up to 1,500 l/h. The energy input for these systems is 35 Wh/l.

7.1.2.1 Development of the high temperature heat pump

In contrast to the competitive stand-alone bath preparation systems, Dürr integrated the bath preparation into the part cleaning system. Therefore operating conditions are much more volatile compared to a stand-alone bath preparation unit. Since a vapor recompression system works best at stationary operating conditions and potentially causes problems in combination with certain cleaning agents, Dürr decided to use a more flexible closed cycle compression heat pump.

To limit heat losses the condenser of the heat pump had to be integrated into the bath preparation unit. Because of the limited construction space, the heat exchanger has to be relatively small, so that a high driving temperature difference of 10 to 15 K is needed. Due to the high condensing temperature of up to 115 °C, conventional refrigerants like

R-410A or R-134a could not be used. A screening of available refrigerants resulted in the choice of R-245fa because of its advantageous properties in the required temperature range. The compressor is a reciprocating piston compressor. This compressor type offers various cooling options to control the operating temperature. To find the optimal cooling solution for the compressor, three different cooling systems were installed. All three systems can be controlled individually. This is necessary since the used compressor had originally been designed for a maximum inlet temperature of 40 °C. The operating limits are shown in Figure 7-3. The condensation temperature (t_c) is plotted on the vertical axis, while the discharge temperature (t_o) is plotted on the horizontal axis. The original design limits are marked in black. Through different tests theses limits could be extended to the dashed red line. The lubricating oil used in the compressor is considered to be stable up to 130 °C, marking the maximum operating temperature. Higher temperatures lead to coking of the oil, which damages the whole heat pump system and in particular the compressor. The compressor is powered by an electric motor. Its drive power can be adjusted by means of a frequency converter.

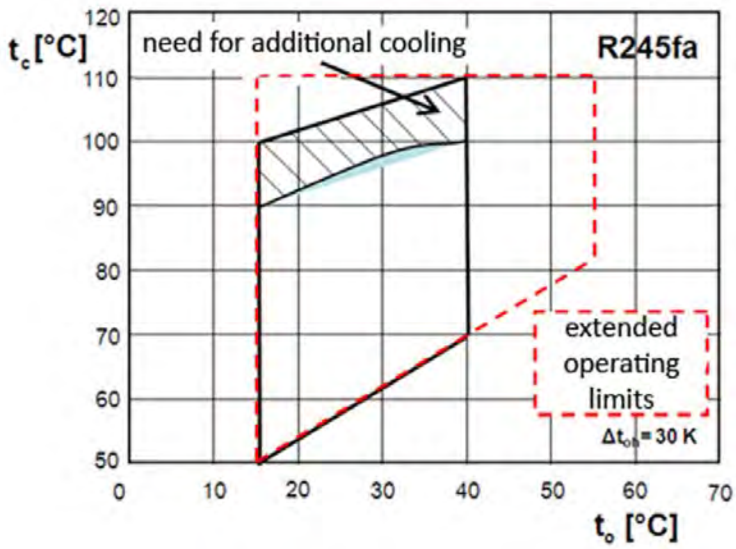


Figure 7-4: Operating limits of the reciprocating piston compressor

7.1.2.2 Integration of the high temperature heat pump

For the integration of the heat pump into the bath preparation system three variants were discussed. All three are illustrated in Figure 7-5.

- Option 1: Direct integration of the evaporator into the waste heat stream from the bath preparation unit. This option offers the highest temperatures.
- Option 2: Integration of the evaporator into tank 1. Thus the volume of the tank can be used as a buffer to create more stable operating conditions for the heat pump.
- Option 3: Integration of the evaporator into an existing filtration circuit. The external heat exchanger makes the system easier to build and to maintain. Furthermore the filtration unit in the circuit prevents particles from damaging the evaporator.

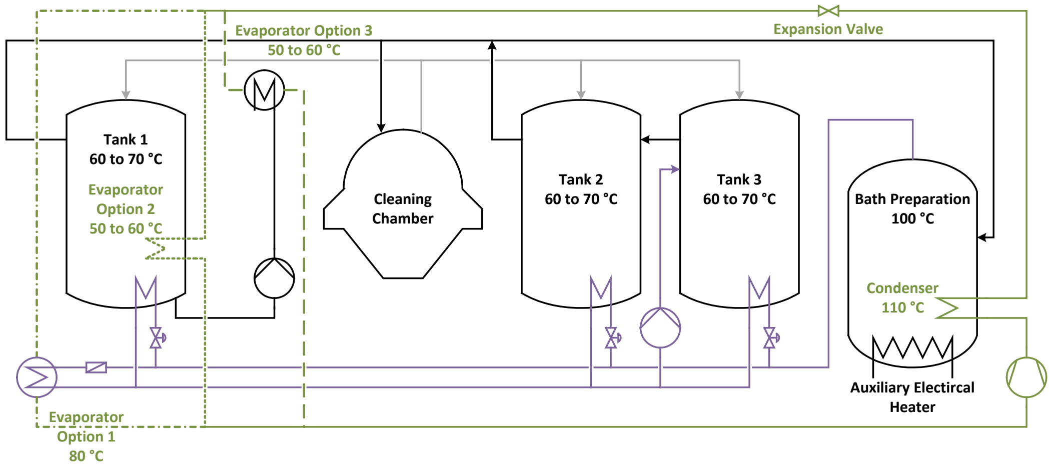


Figure 7-5: Options for the integration of the heat pump into the part cleaning system

The third option was finally implemented because it ensures the highest process reliability. In addition to that it does not require major changes in the plant design. The 36 kW electric heater remains in the bath preparation unit. Its operation, however, is now limited to the starting phase, when the water in the bath preparation unit needs to be heated up from 20 °C to 100 °C. The rest of the time the heat pump takes over the heat supply. It creates two temperature zones in tank 1 at 60 to 70 °C and in the bath preparation unit at 100 °C. In this way the cooling demand is reduced to a minimum.

7.1.2.3 Testing of the high temperature heat pump

In more than 70 series of measurement 99 values were tracked and evaluated. The system was tested in different operation modes in order to obtain a full picture of the high temperature heat pump. Since the system was tested under laboratory conditions the heat output from the cleaned parts had to be simulated by an external cooling.

The heat pumps drive power can be adjusted by means of the frequency converter. In the test runs the heat pump was run with a range of drive frequencies from 25 Hz over 50 and 60 Hz to 75 Hz. The normal operating condition would be 50 Hz.

To determine the efficiency of the high temperature heat pump its energy balance was evaluated using volume flow and temperature measurements. The measuring points are marked in Figure 7-6. The heat supply could only be measured after the bath preparation unit. Thus the heat losses of the bath preparation are included into the calculation of the coefficient of performance (COP). The COP results from the relation of heat output to electrical power consumption.

$$COP = \frac{c_p * \dot{m}_2 * \Delta T_2}{P_{el}}$$

In the test runs the heat pump reached a COP of 3.4 at a drive frequency 50 Hz. At the upper and lower end (25 Hz and 75 Hz) a COP of 3.1 was reached. In order to give information about the efficiency of the heat pump independent from the operating conditions the exergetic performance was calculated. It sets the real COP into relation to the ideal Carnot process.

$$\eta_{ex} = \frac{COP}{COP_{Carnot}} = \frac{COP}{\frac{T_{condenser}}{T_{condenser} - T_{evaporator}}}$$

The exergetic performance varies between 29.8% (25 Hz) and 32.7% (50 Hz) of the efficiency of the ideal Carnot process. Conventional heat pumps for heating purposes reach values of 40% to 50%. The results are illustrated in Figure 7-7. Regarding these results it has to be considered that the tested high temperature heat pump is only a prototype. In the final version the compressor cooling and the insulation of pipes will be improved. Furthermore it has to be kept in consideration that the calculations also include the heat losses from the bath preparation unit.

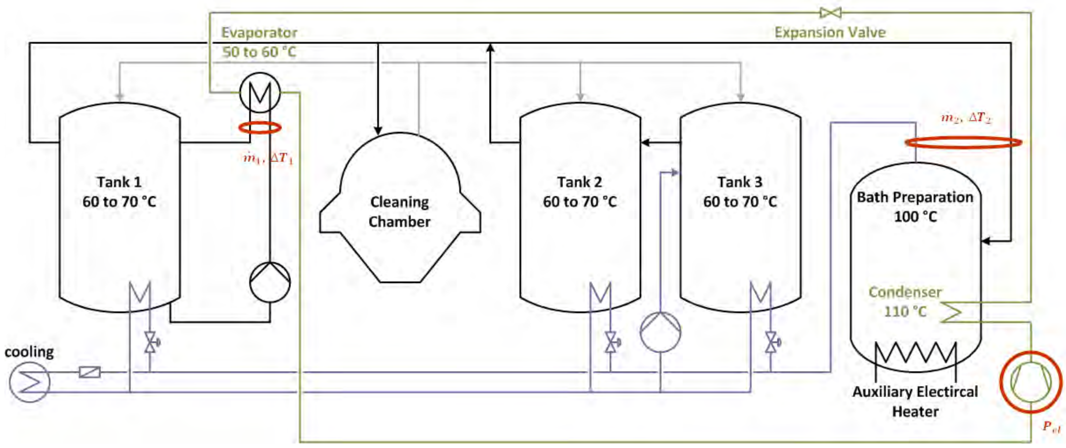


Figure 7-6: Measuring points for the calculation of the COP

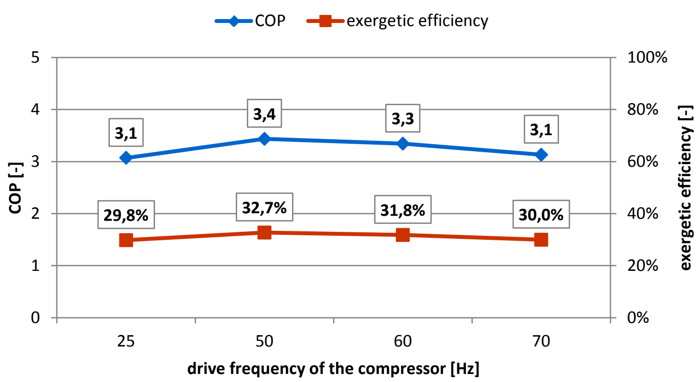


Figure 7-7: COP and exergetic efficiency of the high temperature heat pump

To determine the potential for energy efficiency measures, the thermal losses of the system were calculated. The amount of heat absorbed by the evaporator is calculated from the data of measuring point one. The sum of absorbed heat in the evaporator and drive power is the energy input flow.

$$\dot{Q}_{in} - \dot{Q}_{out} = \dot{Q}_{loss}$$

$$(c_p * \dot{m}_1 * \Delta T_1 + P_{el}) - (c_p * \dot{m}_2 * \Delta T_2) = \dot{Q}_{loss}$$

The heat output of the system is 14% to 22% (25 Hz and 75 Hz) smaller than the energy input. The missing energy is rejected in form of thermal losses. These losses occur in the compressor cooling, un-insulated pipes from tank 1 to the evaporator and in the bath preparation unit. Figure 7-8 shows the gap between energy input and heat output.

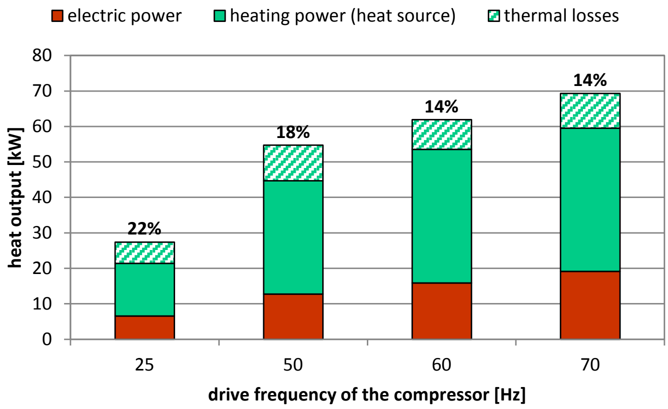


Figure 7-8: Thermal losses of the heat pump system including the bath preparation unit

If the part cleaning system is operated at maximum load, 30 kW of cooling are needed to reject the generated waste heat. After cleaning the work pieces are dried by hot air at a low pressure. To lower the air pressure in the washing chamber a vacuum pump is needed. This pump needs to be cooled with a capacity of 5.9 kW. The remaining 24 kW are the heat surplus generated by the bath preparation unit. This waste heat is now used by the high temperature heat pump to keep the bath preparation unit at 100 °C. At a drive frequency of 50 Hz the heat pump prototype only leaves 4 kW unused. Under real conditions this heat would be carried out of the system by the processed work pieces. Only in 25 Hz mode the auxiliary electrical heater would probably be needed. Figure 7-9 gives an overview of the energy flows in the part cleaning system.

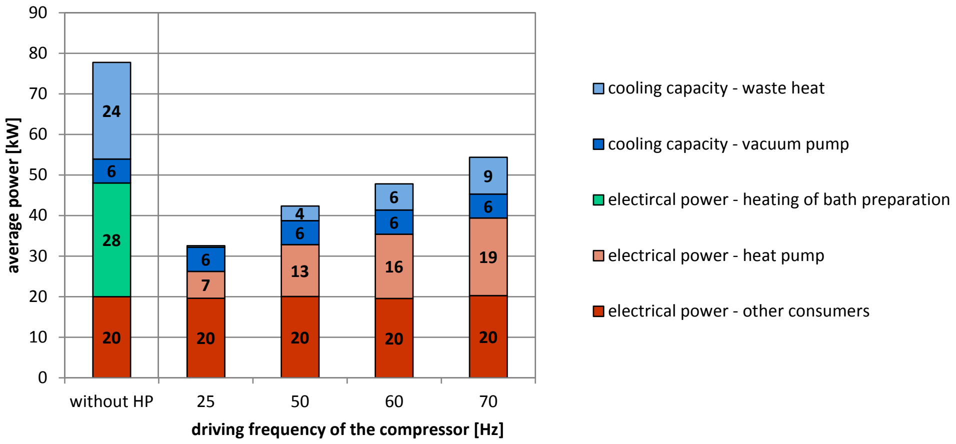


Figure 7-9: Energy balance of the part cleaning system

Beside the energy demand the bath preparation capacity is another keyfigure for the success of the heat pump system. In normal operation the part cleaning system prepares 40 l/h. With 33 l/h this value is almost reached at the lowest drive frequency at 35 Hz. At normal operation (50 Hz) 70 l of cleaning soulution are prepared per hour. The average amount of prepared cleaning solution in different operation modes is shown in Figure 7-10.

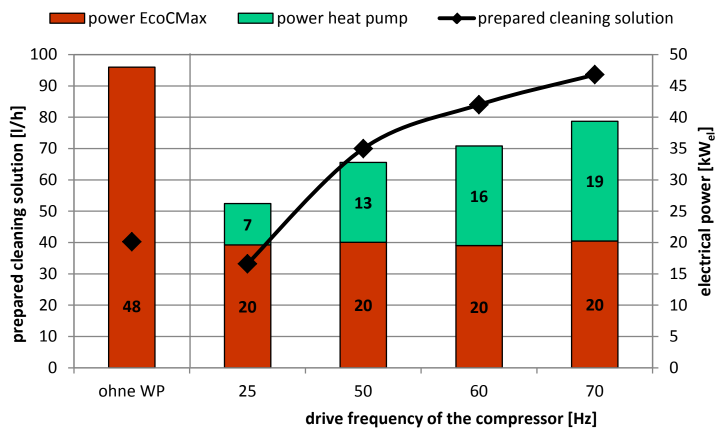


Figure 7-10: Bath preparation rate and energy consumption in different operation modes

The illustration in Figure 7-11 shows that the energy needed to prepare one liter of cleaning solution could be lowered significantly. In normal operation the heat pump system only needs 182 Wh per liter cleaning solution. The conventional system without heat recovery needs 696 Wh/l.

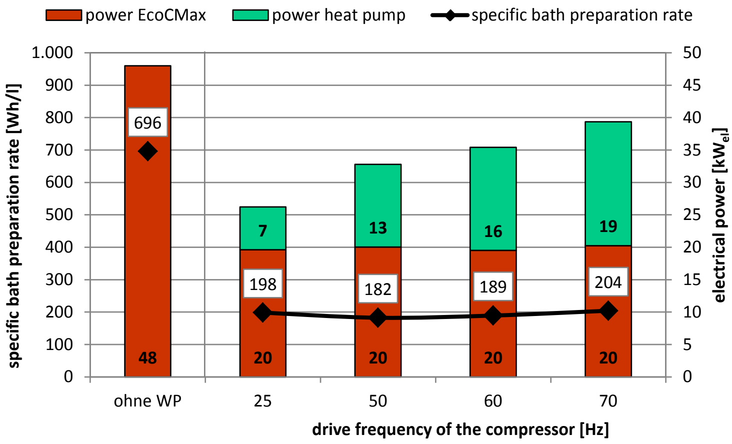


Figure 7-11: Specific bath preparation rate in different operation modes

7.1.2.4 Summary

The measurements have shown that the high temperature heat pump operates reliably. The ambitious targets in terms of energy efficiency and bath preparation rate were not only met, but exceeded. In normal operation mode at 50 Hz, the heat pump achieves a COP of 3.4. If the cooling of tank 1 is also balanced as useful cooling energy, the integrated COP is as high as 5.8. The bath preparation capacity was increased by 75%, while the energy demand was reduced by 31 %. Assuming a yearly operation time of 2,600 hours and a CO_2 emission factor of 601 g/kWh (German electricity mix) /UBA 2012/, the high temperature heat pump system saves up to 24 t CO_2 per year.

7.1.3 References

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Reissner et al. 2013	Reissner, F.; Gromoll, B.; Schäfer, J.; Danoc, V.; Karl, J.: Experimental performance evaluation of new safe and environmentally friendly working fluids for high temperature heat pumps (European Heat Pump Summit 2013). Nürnberg, 15.10.2013
UBA 2012	Entwicklung der spezifischen Kohlendoixid-Emissionen des deutschen Strommix 1990-2010 und erste Schätzungen 2011. Bundesrepublik Deutschland. 2012

7.2 thermea Energiesysteme

thermea. Energiesysteme GmbH is a German manufacturer of high temperature heat pumps using CO_2 as refrigerant (www.thermea.de).

These heat pumps are developed to support the heat pump application in the industry especially to supply process heat up to 90 °C in the capacity range up to 1,000 kW heating capacity.

The potential for such heat pumps is been identified in the present Annex by the University of Stuttgart. Thermea has contributed information coming from own marked considerations. To date thermea has installed first machines in Switzerland, Poland and Germany. Further information will be presented in Task 4 report “Case Studies”.

7.2.1 How to come up to high supply temperatures

In contrast to low-capacity heat pumps for heating flats and single-family homes, the use of heat pumps for industrial applications requires high supply temperatures. There are two ways to meet this requirement with optimal energy efficiency. They can be deduced from the function principle of the heat pump process. As is known, heat pumps are machines that elevate calorific energy from a low temperature level to a higher usable one by the consumption of electrical energy. In the most cases, a counter-clockwise running thermodynamic vapour compression process with electrical drive is used for this (Figure 7-12).

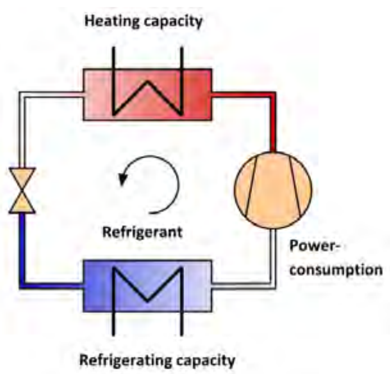

Figure 7-12: Function principle of a heat pump

At low pressure, a refrigerant absorbs heat from a heat source on a low temperature level and evaporates as a result. A compressor pumps the refrigerant vapour to a higher pressure and thus to a higher temperature at which heat is delivered to the "consumer" while the refrigerant is either isothermally liquefied or isobaric cooled. The refrigerant circuit is closed via an expansion valve.

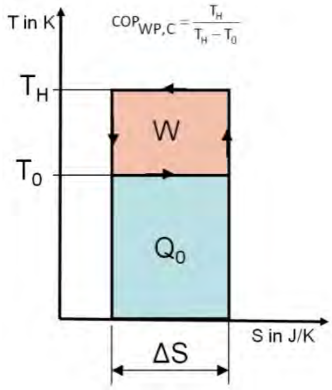

Figure 7-13: Carnot process in the T-S diagram

Figure 7-13 shows the loss-free process in the T-S chart. The $COP_{WP,C}$ (Coefficient of Performance) - which can be determined from the two temperature levels T_H und T_0 - is used for the evaluation of the energy efficiency of this process named after Carnot.

$$COP_{WP,C} = \frac{T_H}{(T_H - T_0)}$$

It can be easily seen that a high temperature level T_H can be reached with an acceptable $COP_{WP,C}$ provided the temperature T_0 is also high. This is the first method. Specific components and heat pump equipment need to be developed for the technical implementation of this high-temperature process because the operational conditions significantly differ from that in a refrigeration machine. First approaches are known from the literature. thermea is developing such a heat pump within the framework of the Annex "Industrial heat pumps" on which information will be given in due course.

A trans-critical process on the high pressure side is the second method used to reach high supply temperatures (Figure 7-14).

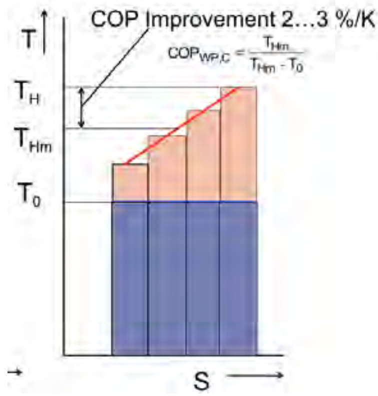

Figure 7-14: Trans-critical process on the high pressure side

The refrigerant is not liquefied on the high pressure side but the heat transfer results from cooling down of the refrigerant without phase change. Figure 3 shows that the $COP_{WP,C}$ of the modified Carnot process can be calculated from the thermodynamic mean temperature T_{Hm}. Because T_{HM} is always below T_H, this process offers energetic advantages. The lower the heat transfer medium's inlet temperature on the high pressure side the higher is this advantage. CO_2 is predestined as a refrigerant because its critical point is advantageous for this application and it also meets the thermodynamic and ecological requirements very much.

7.2.2 CO_2 as refrigerant in high temperature heat pumps

Carbon dioxide (R744, CO_2) is a known substance used in a variety of applications, e.g. in the food industries. When used as a refrigerant the typical advantages (+) are only disturbed by a few disadvantages (-):

+ Environmental compatibility (global warming potential = 1, ozone depletion potential = 0)
+ High useful temperatures
+ High volume-based (refrigeration) capacity (compact design)
+ Low compression ratio
+ Good material compatibility
+ Availability and low cost
- High pressure level (optimal high pressure up to approx. 130 bar)
- Affectation of the respiration by CO_2 requiring safety precautions

The critical point (30.98°C; 73.78 bar) allows the above mentioned trans-critical process management on the high pressure side. That is why CO_2 is well suited for an application in high temperature heat pumps.

However it has to be taken into account that only components specifically designed for CO_2 can be used due to the pressure level. It is noteable that the range of components on the market improves more and more. The unique selling point for thermea is the access to the world's first screw compressor for high-capacity CO_2 heat pumps.

Suited applications can be deduced from the knowledge that the advantage of high supply temperatures in connection with high COP values takes effect if the warm water inlet temperature in the heat pump is relatively low. Such applications include water heating, heating of outside air, pre-heating of feed water, etc. Applications with small spread such as cooking processes at a high nearly constant temperature level are unfavourable or unsuitable for CO_2 heat pumps.

7.2.3 thermea's CO_2 heat pump series thermeco$_2$

Since 2008, thermea has made great necessary research efforts based on which the heat pumps listed in Table 7-1 have been developed and launched.

Table 7-1: thermeco$_2$ series CO_2 heat pumps

Type	thermeco$_2$ HHR CO_2	thermeco$_2$ HHS CO_2
Prinzip	Reciprocating Compressor	Screw Compressor
Heating capacity	30 ... 1.000 kW	1.000 kW
max. outlet temperature heating	90°C	90°C
heat source temperatures	ca. -10 ... 40°C	ca. -10 ... 40°C

Figure 7-15 shows a greatly simplified P&I diagram for the thermeco$_2$ HHR range with reciprocating compressors. This range includes 10 basic models covering a capacity range from 30 to 1,000 kW. Figure 7-16 shows one of these models.

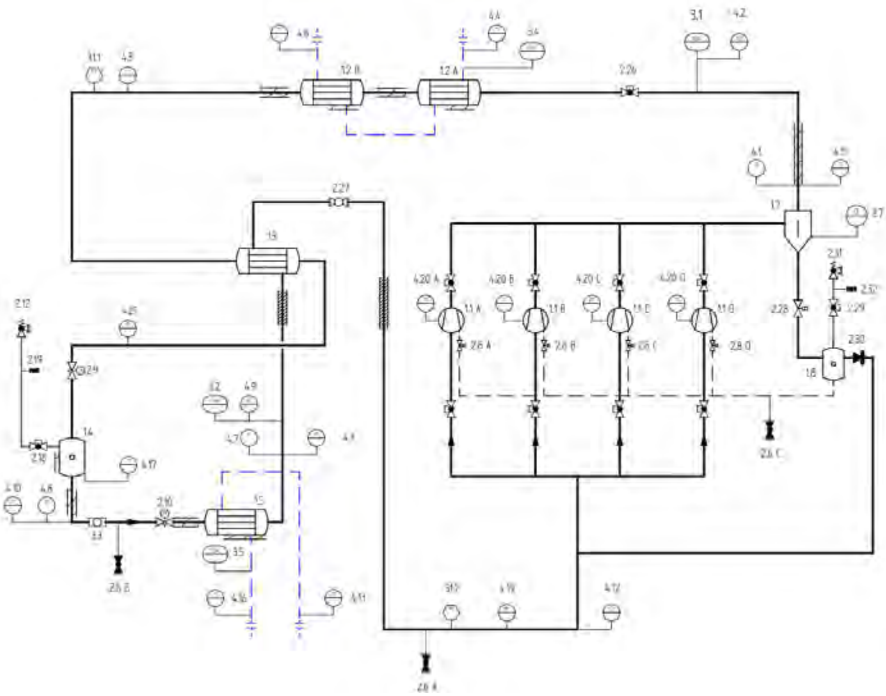

Figure 7-15: P&I diagram of the CO_2 heat pump thermeco$_2$ HHR with reciprocating compressors

Figure 7-16: One model of a CO_2 heat pump with reciprocating compressors

Usable as heat pump and for cold water/cold brine generation, the high temperature CO_2 heat pump excels by its rugged and very compact design. On a solid frame from painted sectional steel, all components are neatly arranged, completely piped internally and electrically wired to the switch cabinet. The machine is equipped with semi-hermetic reciprocating compressors and one of them can be frequency-controlled.

The trans-critical CO_2 circuit on the high pressure side is fitted with an internal heat exchanger. This heat exchanger provides a high refrigerant inlet temperature in the compressor and thus for high outlet temperatures allowing water supply temperatures up to 90 °C. This internal heat exchanger also contributes to some improvement of the COP. The refrigerant is injected to the evaporator as usual by control of the refrigerant superheating on the evaporator outlet. Additionally, a control of the high pressure is required. With the trans-critical process management, it is determined by the refrigerant amount being on the high pressure side. The refrigerant collector is installed between the high pressure control valve and the expansion valve on the medium pressure level. All heat exchangers are tube bundle apparatuses or have a coaxial design for smaller capacities.

A speed-controlled pump controls the hot water supply temperature to the adjustable set point. In the heat source circuit, also a speed-controlled pump is used to control the cold water supply temperature to a constant value.

A programmable logic controller (PLC) with convenient touch panel integrated in the switch cabinet is used for the control. Sensor and control signals can be interrogated via appropriate menu navigation. Further, the touch panel also allows the parameterisation of the heat pump (capacity, temperatures, pressures) within permissible limits. Faults or limit value violations are recorded in an alarm list.

The heat pump is equipped with all safety devices required for a safe operation as per DIN EN 378-2.

The design of the thermeco$_2$ HHS heat pump with the world's only available screw compressor type from GEA Refrigeration Germany is similar (Figure 7-17 and Figure 7-18). There is an additional oil supply for the compressor consisting of oil separator and oil cooler. To obtain the maximum COP possible, the heat from the oil cooler has to be included in the heat supply. The performance of the machine is controlled by the compressor speed the maximum of which is 6,000 rpm.

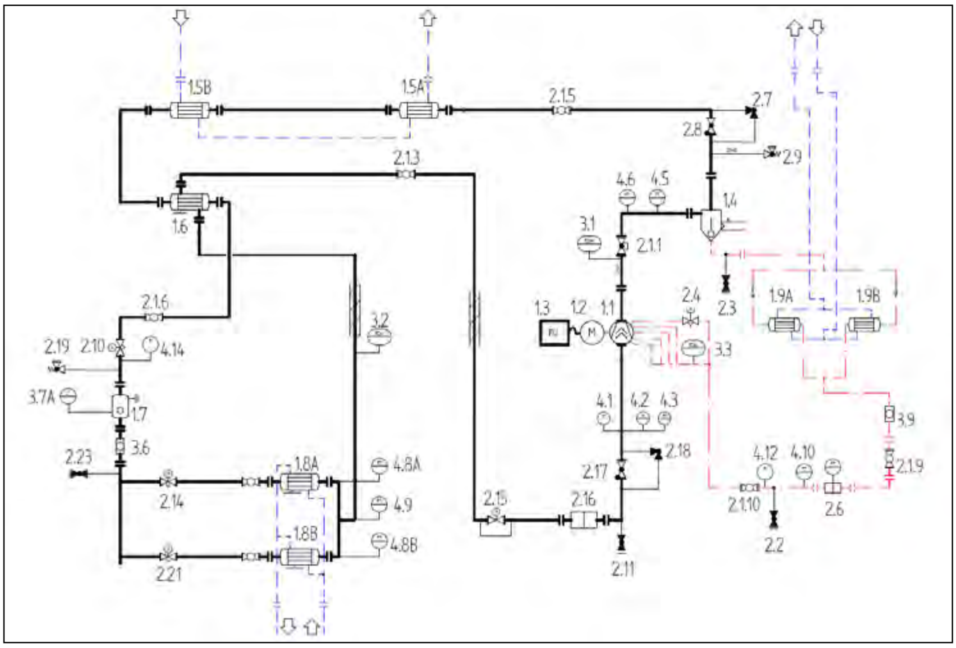

Figure 7-17: P&I diagram of the CO_2 heat pump with screw compressor

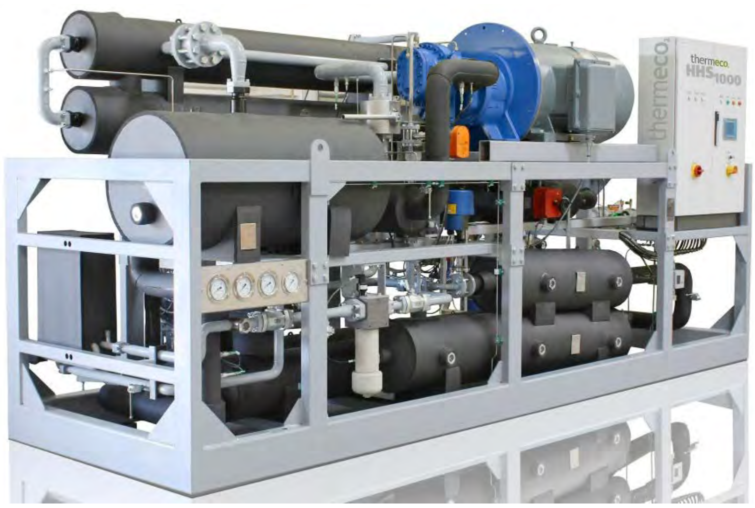

Figure 7-18: CO_2 heat pump thermeco$_2$ HHS with screw compressor

7.2.4 Summery

thermea. Energiesysteme GmbH has developed a series of high temperature heat pumps using CO_2 as refrigerant:

Type	thermeco$_2$ HHR CO_2	thermeco$_2$ HHS CO_2
Prinzip	Reciprocating Compressor	Screw Compressor
Heating capacity	30 ... 1.000 kW	1.000 kW
max. outlet temperature heating	90°C	90°C
heat source temperatures	ca. -10 ... 40°C	ca. -10 ... 40°C

Low return tempeatures from the consumer (warm side inlet) are important for high COP values and high supply temperatures. The thermodynamic middle temperatur is essencial for the COP of the transcritical process. Because of this temperature is lower than the condensing temperature of a theoretical comparable subcritical process the CO_2 heat pump reaches higher COP values. The lower the return temperature the higher this advantage.

Currently new compressors, heat exchangers and control devices are in development. This is the basis of further enhancements of the thermeco$_2$ heat pumps.

7.2.5 Literature

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HNN, 1982 Heinrich, Najork, Nestler, Wärmepumpenanwendung in Industrie, Landwirtschaft, Gesellschafts-und Wohnungsbau, Verlag Technik, Berlin,1982

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8 Japan

8.1 Overview of industrial heat pump technology in Japan

8.1.1 Introduction

Heat pump technology is important for reducing CO_2 emissions and primary energy consumption as well as increasing amount of renewable energy usage. The expansion of industrial applications is also important for enhancing these effects further more. In particular, development and dissemination of high-temperature heat pumps for hot water supply, heating of circulating hot water, and generation of hot air and steam are necessary.

8.1.2 General types of industrial heat pumps

Industrial heat pumps are classified into four general types: closed-cycle mechanical, open-cycle mechanical vapor recompression, open-cycle thermal vapor recompression, and closed-cycle absorption heat pumps. These are shown in Figure 8-1 through Figure 8-4 respectively [DOE, 2003].

Closed-cycle mechanical heat pumps, which are the most commonly deployed in variety of industrial processes, can supply cool/hot water/air by successive compression, condensation, expansion and evaporation processes in a closed refrigerant flow loop. Closed-cycle mechanical heat pumps equip with mechanical compression to upgrade the temperature of refrigerant. Their most common compression drives are electric motors.

In industrial processes accompanying steam process, open-cycle mechanical vapor recompression heat pumps are often applied to reuse low pressure waste steam by recompression with mechanical compressors. Open-cycle thermal vapor recompression heat pumps consume energy in high-pressure motive steam to increase the pressure of waste vapor. Recently, hybrid vapor recompression systems consisting of mechanical and thermal vapor recompression have been adapted to reduce the equipment cost and power consumption of mechanical vapor recompression heat pumps [Mayekawa, 2007]. These hybrid vapor recompression systems will be explained in detail in Chapter 4 of TASK 4.

Closed-cycle absorption heat pumps consist of four types of heat exchangers, namely evaporators, absorbers, generators and condensers and generally use a mixture of Lithium Bromide and water as a working fluid. There are two types of absorption heat pumps. Type1 can increase the amount of heat more than the heat source and chill at the cold end, while Type2 can increase temperature and deliver higher-temperature heat than the heat source temperature.

Steam supply is possible via mechanical heat pumps or Type 2 absorption heat pumps, which will be explained in detail in Chapter 2 of TASK 3.

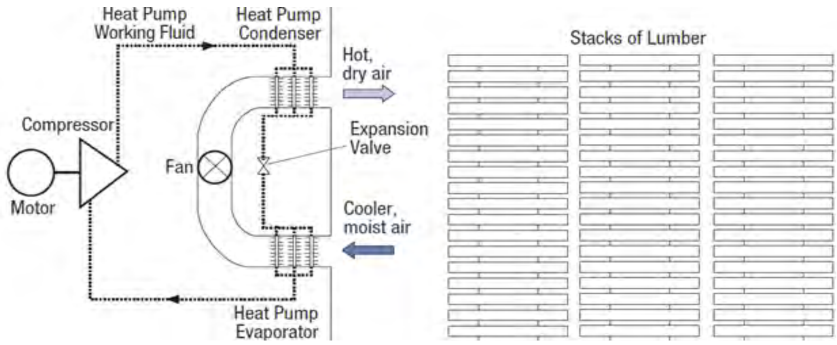

Figure 8-1: Closed-cycle mechanical heat pump [1]

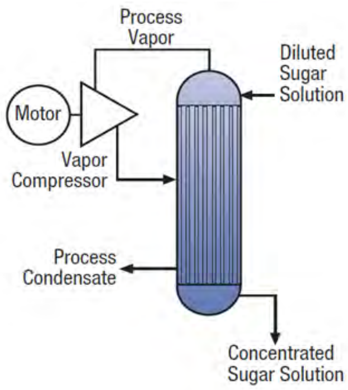

Figure 8-2: Open-cycle mechanical vapor recompression heat pump [DOE, 2003]

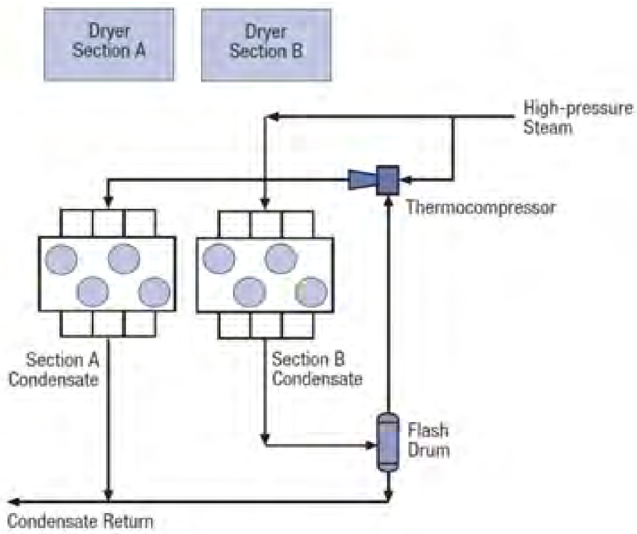

Figure 8-3: Open-cycle thermal vapor recompression heat pump [DOE, 2003]

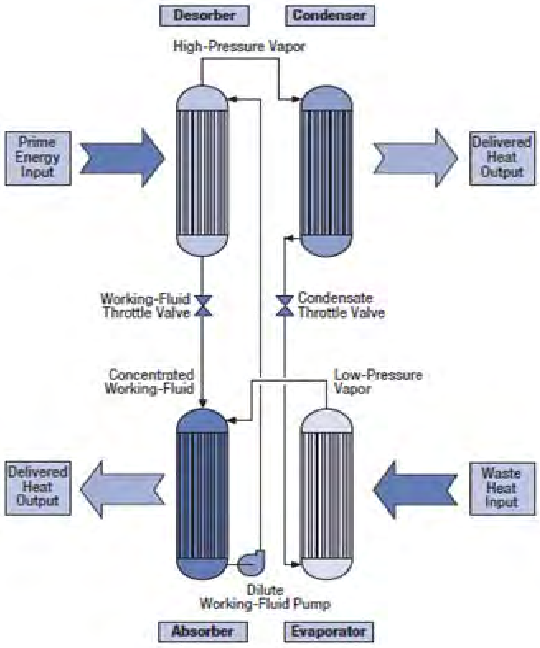

Figure 8-4: Closed-cycle absorption heat pump [DOE, 2003]

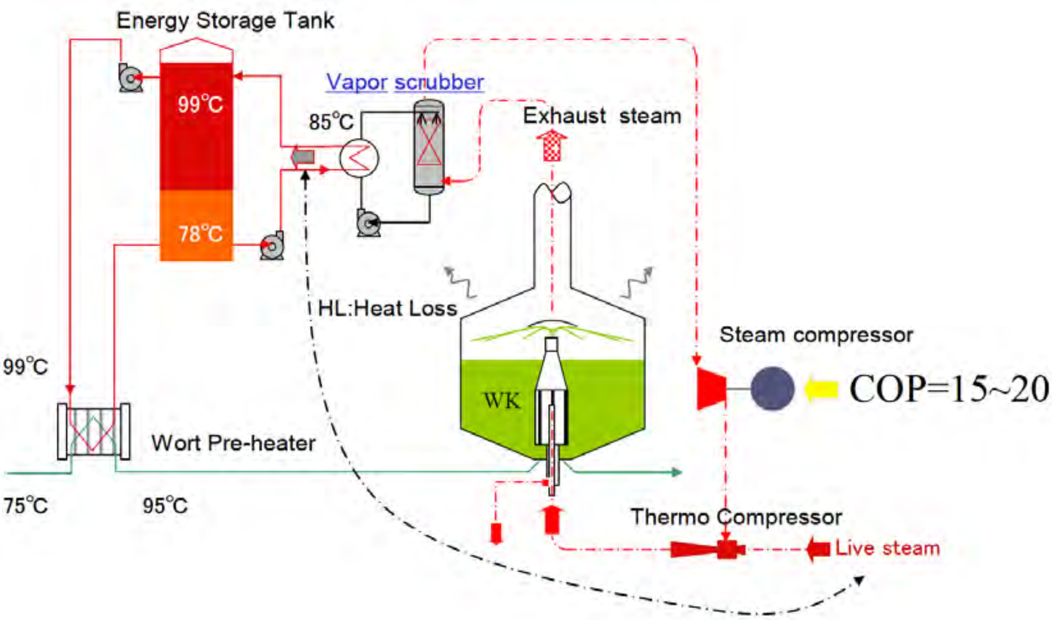

Figure 8-5: Hybrid vapor recompression System [Mayekawa, 2007]

8.1.3 Thermodynamic cycles of high-temperature heat pumps

The thermodynamic cycles of high-temperature heat pumps for hot water supply, hot air supply, heating of hot water circulation and steam generation are picked out and explained as they are most commonly deployed throughout Japan.

8.1.3.1 CO_2 transcritical cycle

CO_2 transcritical cycle air-source heat pumps, capable of producing hot water of 90 °C with a heating capacity of 72.0 kW, have been commercialized in Japan and sold not only in Japan but also in South Korea, Taiwan, Indonesia and elsewhere [Kitayama, 2011]. CO_2 transcritical cycle water source heat pumps, capable of generating hot air of 100 °C with a heating capacity of 110 kW, have been also commercialized in Japan. These heat pumps will be explained in detail in Chapter 2 of TASK 3 and Chapter 4 of TASK 4.

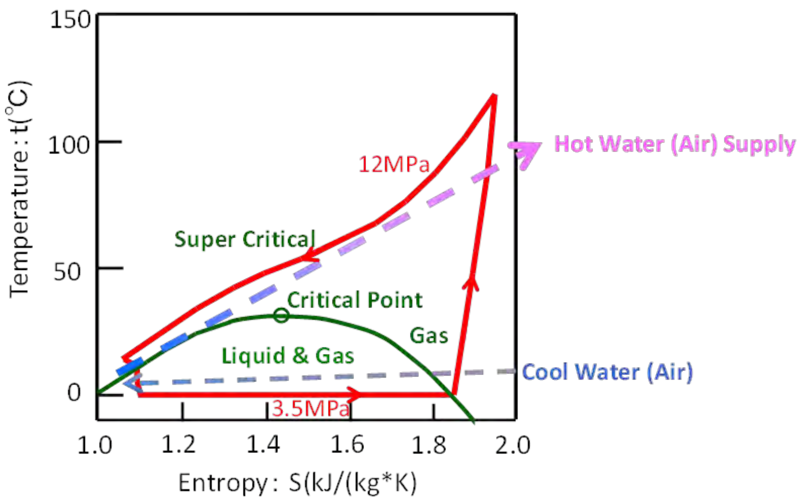

Figure 8-6: CO2 Transcritical heat pump cycle

8.1.3.2 Reverse Rankine cycle (to reheat circulating water up to between 60 and 80°C)

In many industrial processes, hot water cooled down by 5 to 10 °C in process is reheated through the heat pump cycle prior to its circulation. If a CO_2 transcritical cycle heat pump is applied to such processes, the COP generally drops. Therefore a reverse Rankine cycle, using HFC-134a refrigerant, is applied to reheat circulating hot water up to between 60 and 80 °C, which shows a high COP.

Figure 8-7 shows a reverse Rankine cycle with HFC-134a refrigerant and these applications will be explained in detail in TASK 4.

Furthermore cascade cycle heat pump will be explained in detail in Chapter 2 of TASK 3, since a cascade heat pump cycle, which consists of the HFC-134a cycle in high-temperature side and the HFC-410A cycle in low-temperature side is also efficient as the effect of cascading.

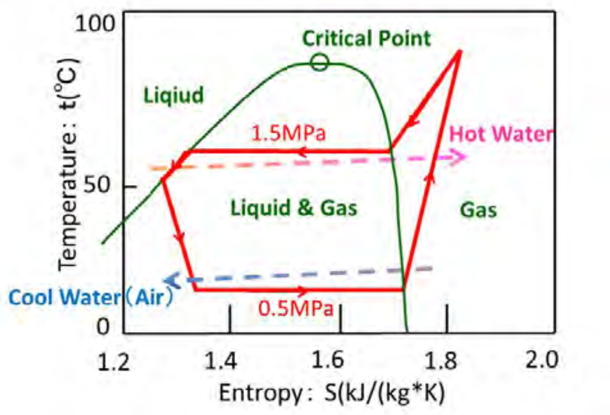

Figure 8-7: Reversed Rankine cycle (HFC-134a)

8.1.3.3 Reverse Rankine cycle (to reheat hot water up to 80 °C or over, and to generate steam of 100 °C or over)

Figure 8-8 shows a two-stage compression cycle of the refrigerant HFC-245fa. Owning to the critical temperature 150 °C or over of an HFC-245fa refrigerant, a single- or two-stage compression heat pump can be used to reheat circulating hot water to 80 °C or over and to generate steam of 100 °C or over. Heat pumps for steam generation with this compression cycle have been commercialized in Japan [4]. High pressurized hot water is generated in the heat pump unit and then evaporated in the flash tank to generate steam at a temperature of 100 to 120 °C. In order to generate steam at a temperature of 165 °C, steam is compressed by the steam compressor, and then, the pressure and temperature increase. Heat pumps for steam generation will be explained in detail in Chapter 2 of TASK 3.

It is also efficient to have the cascade cycle consist of an HFC-134a cycle for the high-temperature side and an HFC-410A cycle for the low-temperature side to reheat hot water up to 80 °C. These cascade cycle heat pumps will be explained in detail in Chapter 2 of TASK 3.

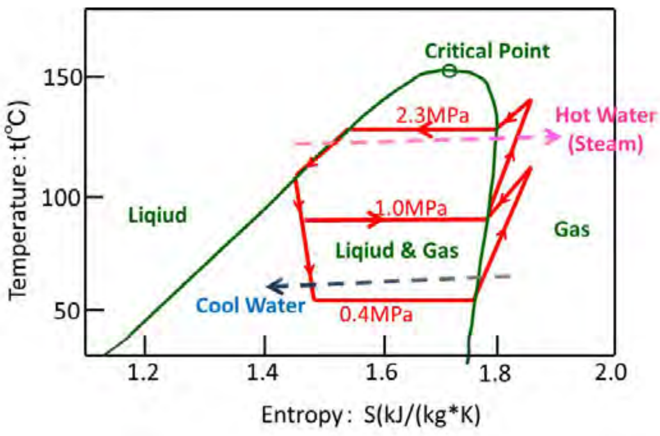

Figure 8-8: Two-stage compression reversed Rankine cycle (HFC-245fa)

8.1.4 Technologies required for industrial heat pumps

The configuration of the cycle is important to achieve a large temperature difference between the output and heat source temperatures efficiently. In addition, the technologies of compressors and refrigerants can withstand high temperatures are also important to deliver high-temperature output. These will be explained in detail in Chapter 2 of TASK 3.

Heat exchange technologies against dust and dirt are also another key issue since the industrial process fluid or industrial waste water used as a heat source for heat pumps contains dust and dirt such as oil stains, metal chips, and so forth. These will be explained in detail in TASK 4.

Refrigerants HFC-245fa and HFC-134a are suitable for generating steam or hot water of 60 °C or over. However, their downside is high GWP, indicating the necessity of low GWP refrigerants development for high-temperature heat pumps. HFO-1234ze (Z) and HFO-1234ze (E) are promising alternative materials for HFC-245fa and HFC-134a because of their compatible thermodynamic properties. Practical application for high-temperature heat pumps are expected owing to the research such as the assessing the risks related to flammability. These will be explained in detail in Chapter 3 of TASK 3.

If heat generated with heat pumps or waste heat exhausted in plants can be stored in a heat storage material, the effective use and control of the heat are enabled. Imbalance between day and night power loads is expected to improve as shown in Figure 8-9 and Figure 8-10, and waste heat is expected to be further utilized. At present, water or ice are normally used as thermal storage materials. However, thermal storage materials such as molten salt, organic material or hydrated salt can store heat over a wide temperature range from -10 to 250 °C. These thermal storage materials will be explained in detail in Chapter 4 of TASK 3.

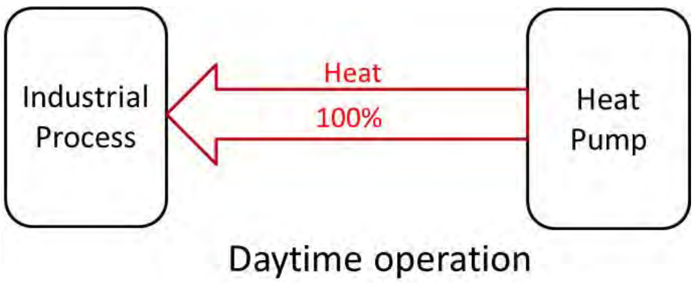

Figure 8-9: Heat pump system without thermal storage tank

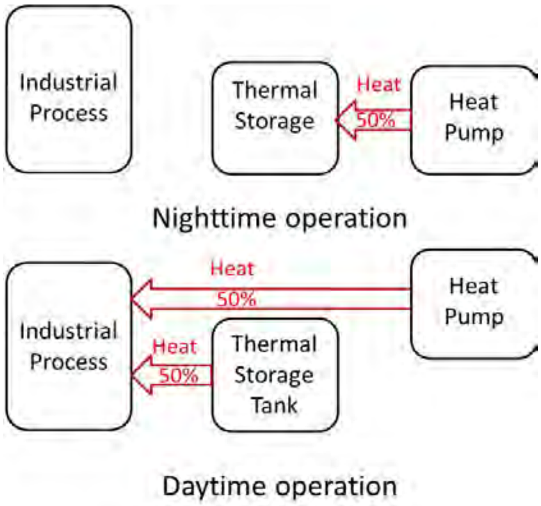

Figure 8-10: Heat pump system with thermal storage tank

8.1.5 References

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Mayekawa, 2007 Mayekawa manufacturing Co., "A case study application to ethanol distillation - the possibility of energy conservation and reduction of carbon dioxide emissions by vapor recompression (VRC) System", 'Electro-heat', No. 155, 2007 issue.

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8.2 High Temperature Heat Pump

8.2.1 DUAL-CYCLE HEAT PUMP WATER HEATER (AIR-TO-WATER)

8.2.1.1 Outline

A new industrial heat pump system was developed, which uses R-410A and R-134a in a dual cycle. This system has a coefficient of performance (COP) of 3.0 when keeping heat in the storage tank.

Since there is a strong demand to save energy and electricity in Japan, the heat pump market is expected to develop efficient thermal storage.

Adopting a dual cycle that uses two different refrigerants can greatly reduce electricity consumption to keep the heat in the storage tank. With the feature of two refrigerants in a dual cycle, this system realises stable operation under the conditions of a -20 °C outdoor temperature and a 90 °C hot water supply in cold districts. In ‘energy-saving mode', electricity consumption can be reduced to limit the use of the heating capacity in summer.

To meet the demand for saving energy and electricity, this commercial heat pump can be used for large facilities like nursing homes, hospitals, hotels, and so on.

8.2.1.2 System flow

Figure 8-11 shows the system flow. Figure 8-12 shows the P–h diagram. This system features a dual cycle. R-410A is used for the heat source unit, and R-134a is used for the cascade unit. The heat source unit is used in the normal compression cycle. The cascade unit uses the refrigerant–refrigerant heat exchanger for the evaporator and the refrigerant–water heat exchanger for the condenser.

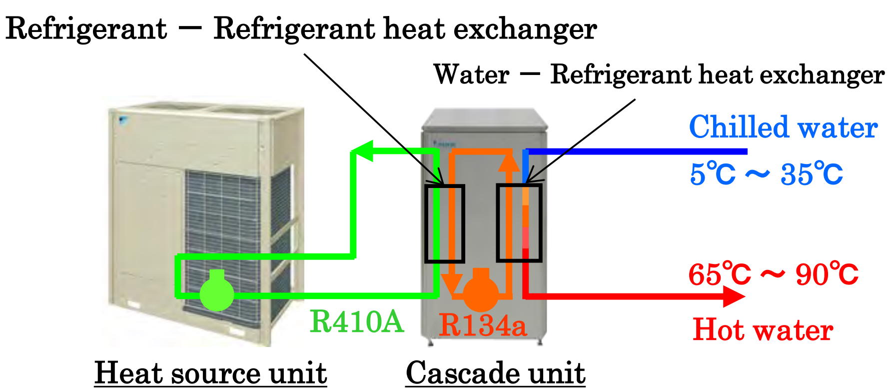


Figure 8-11: System flow

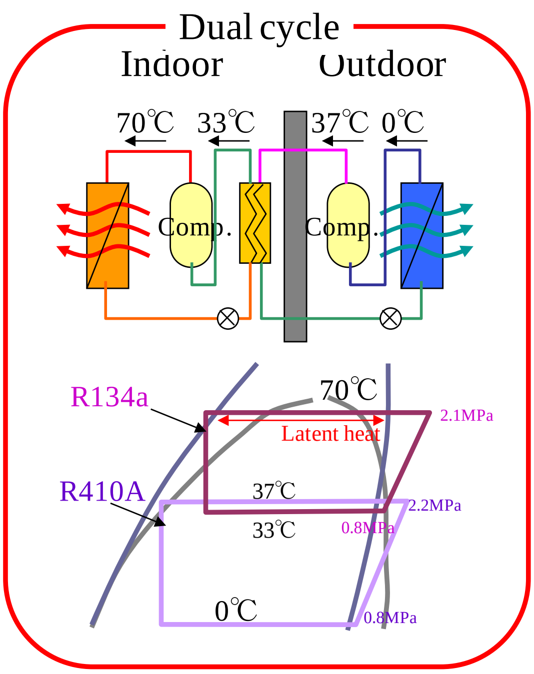


Figure 8-12: P–h diagram

8.2.1.3 System details

Figure 8-13 shows the actual developed system in practical use. Table 8-1 lists the specifications of this system. The COP hits 3.0 when reheating the hot water and keeping the hot water warm, and 4.1 when heating up the supply water, which makes it possible to reduce electricity consumption by 24%.

When the heating capacity is small in summer, electricity consumption can be reduced by changing the driving mode from normal one (maximum heating capacity of 35 kW) to energy-saving one (maximum heating capacity of 30 kW). With the demand control function, the number of operating systems can be limited, and electricity consumption can be reduced.

This system can be operated at the ambient temperature of -20 °C and the hot water supply temperature of 90 °C owing to the adaptation of a cascade cycle.

Twelve systems can be connected for a maximum hot water supply of 120 tons/day.

Since the heat source unit which absorbs the heat from the ambient air and the cascade unit which heats up the hot water have two compressors each, backup operation is still available in case one compressor is out of order.

Figure 8-13: Dual cycle heat pump water heater (Daikin: 'MEGA-Q')

Table 8-1: Specifications of dual-cycle heat pump water heater

Product name		Heat pump water heater	
Type		RLYP350B	
Configuration name		Heat source unit	Cascade unit
Ttype		RLP350B	BWLP350B
		Middle season rated	
One through	Heating capacity	35.0kW	
	COP	4.1	
	Supply water	17℃	
	Hot water	65℃	
Ambient temperature		−20℃ ～ 43℃	
Power source		3 ϕ 200V 50/60Hz	
Outward appearance		H1525mm×W1240mm×D765mm	H1525mm×W890mm×D765mm
Refrigerant		R410A	R134a

8.2.1.4 *Features of components*

As shown in Figure 8-14, a new four-surface heat exchanger was developed for the system. This system equips with the dual cycle. Generally, when a dual cycle is adopted, the system size is bigger. However, this system equips with a new heat exchanger, which reduces the volume of the heat exchanger and air flow resistance by adopting small-diameter tubes and reducing fin pitch.

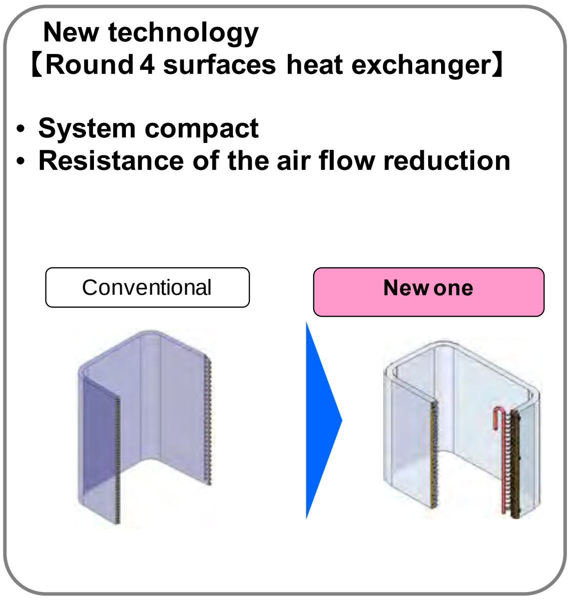


Figure 8-14: New compact heat exchanger

8.2.1.5 *Example of installation*

As shown in Figure 8-15, this system can be applied to open and closed tank flow systems. Remote monitoring is possible to prevent failure before occurring by connecting with the network system.

An automatic backup with multiple heat pump units and two compressors for each unit is adopted; thus, this system can escape shutdown with some trouble and continue a jury-rigged operation.

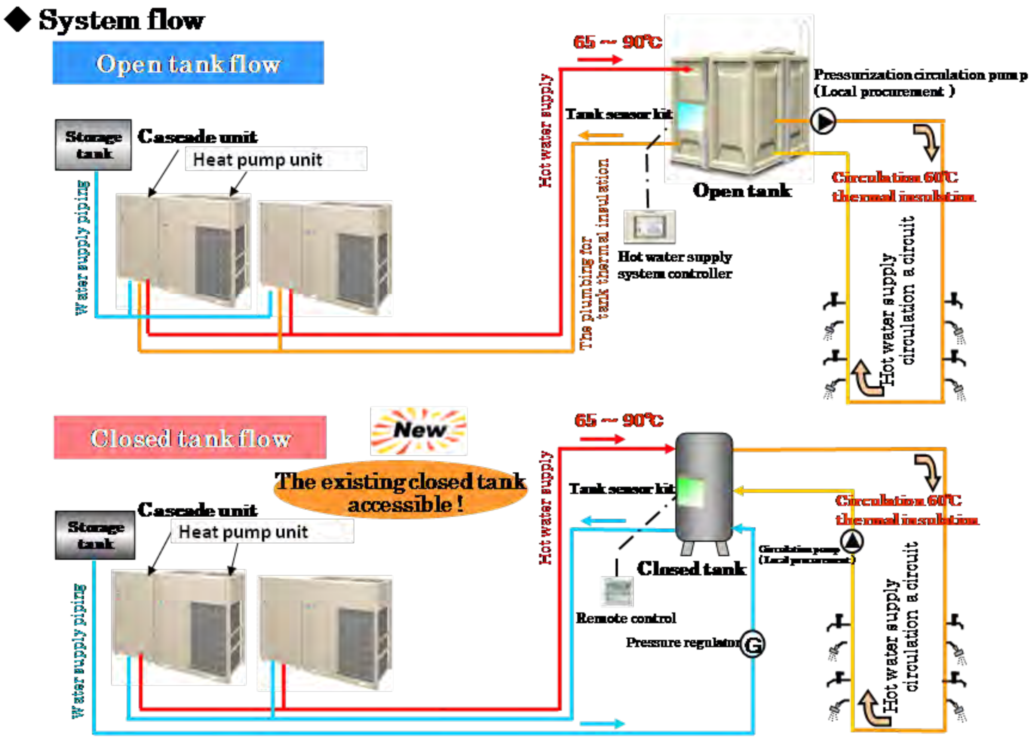


Figure 8-15: System configuration

8.2.2 CO_2HEAT PUMP AIR HEATER (WATER-TO-AIR)

8.2.2.1 Outline

Since the CO_2 refrigerant heat pump air heater adopts a transcritical cycle and uses the supercritical region of the refrigerant, this system can heat hot water to higher temperatures efficiently. Therefore, the heat pump can be replaced by the conventional systems or deployed supplementarily with the conventional systems in manufacturing processes which use combustion systems conventionally. This system has advantages over conventional industrial driers that consist of a steam boiler, heat exchanger, and dry room in terms of durability, environmental protection, maintenance, and economy.

There are many types of industrial driers: for example, a box-type air drier, a band circulation drier, a fluidized drier, and a rotational drier. A conventional drier that produces hot air uses the direct fired method but indirect heating and uses a steam boiler and an electric heater as heat sources. Other than the electric heater, these heat sources use combustion of fossil fuels.

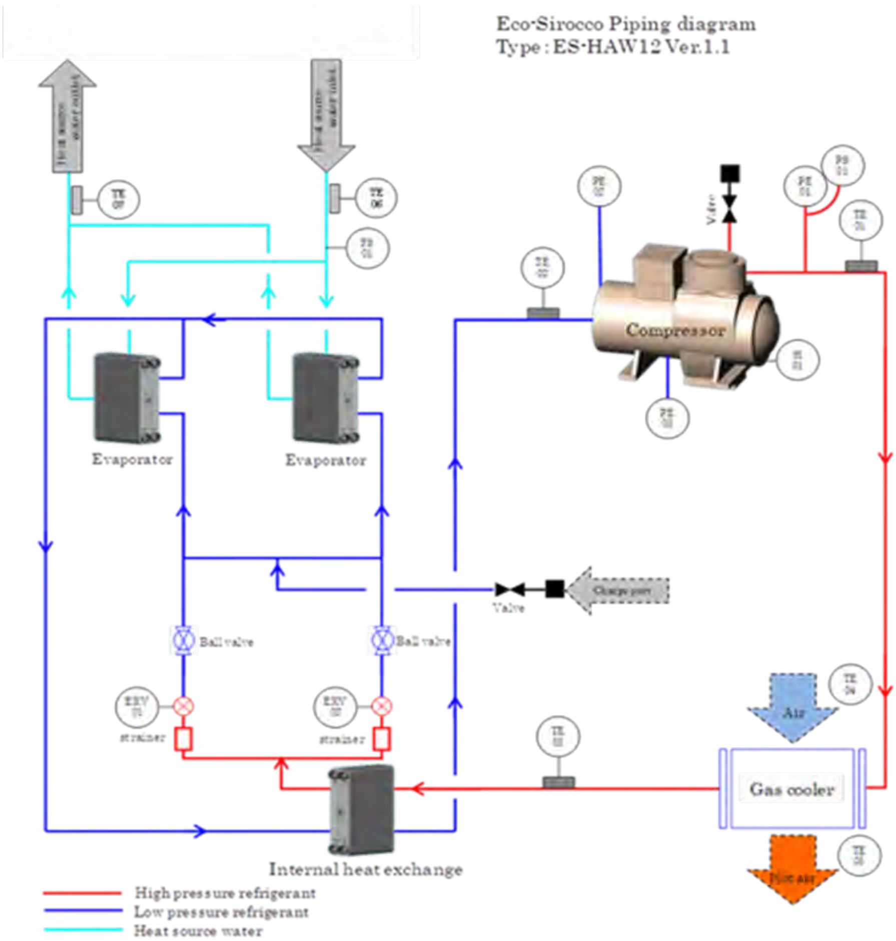
The CO_2 heat pump air heater does not use neither electricity nor direct combustion as the heat source. To widen the range of applications of the drier, it uses the supercritical region of CO_2 to efficiently heat the air to 120 °C or over.

This heat pump uses water as a heat source and can produce not only hot air but also cooling water. We can achieve further efficiency by utilising both the hot air and the cooling water simultaneously. Since the hot air is produced in the supercritical region of the CO_2 refrigerant, CO_2 emissions and energy consumption can be reduced. No NOx is produced, because this system does not take a combustion process.

8.2.2.2 System flow

Figure 8-16 shows the system flow of the CO_2 transcritical cycle. This system consists of a gas cooler, an expansion valve, a compressor, and an evaporator. Figure 8-17 shows the operating conditions of the system on the T–s diagram.

This system features the use of the supercritical region of the CO_2refrigerant. In the general compression cycle, since the two-phase region is used, the refrigerant is condensed. This is why there is a temperature limit of hot air production. However, in this system, the temperature of the refrigerant changes according to the temperature change in air to enhance the system efficiency. This kind of system for producing hot water is already commercialised under the name of Eco-Cute in Japan for residential and business uses.



Symbol	Equipment name
EXV01, EXV02	Electronic expansion valve
H01	Oil heater
PE01 ～ PE03	Pressure transmitter
TE01 ～ TE07	Resistance Temperature Detector (RTD)
FS01	Fluid sensor
PS01	Pressure switches

Figure 8-16: Flow of CO_2 heat pump air heater (Mayekawa Eco-Sirocco)

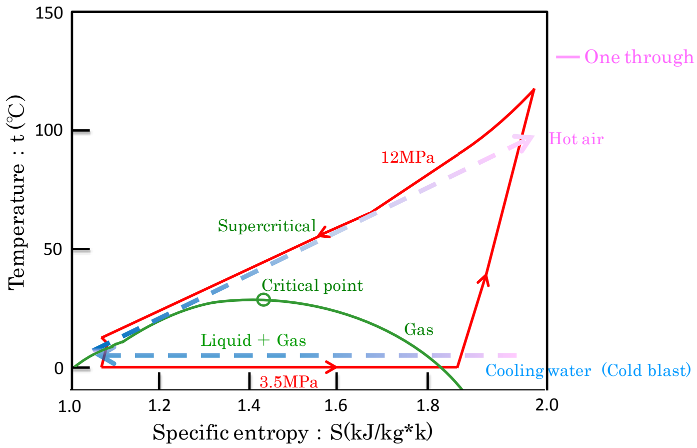


Figure 8-17: T–s diagram

8.2.2.3 System details

Figure 8-18 shows the appearance of the commercialised CO_2 heat pump air heater. Table 8-2 shows the specifications of this system: a rated heating capacity of 110 kW and a COP of 3.43. They can produce hot air up to 120 °C or over. Figure 8-19 shows the relevance between the heat source temperatures and heating capacities or COPs under the condition of ambient temperature being 20 °C.

Figure 8-18: Appearance of CO_2 heat pump air heater (Mayekawa Eco-Sirocco)

Table 8-2: Specifications of CO2 Heat Pump Air Heater
(Mayekawa Eco-Sirocco)

Performance	Heating capacity [kW]	Air temperature:	110 Inlet 20℃ (50%RH)→ Outlet 100℃
	Cooling capacity [kW]	Heat source temperature:	81 Inlet 30℃ →Outlet 25℃
	Power consumption	32	
	COPh	3.43	
	COPc	2.54	
Power source		3 φ 200V 50Hz/60Hz	
Outward appearance [mm]		W1,100×L1,600×H2,235	
Weight [kg]		1,948	
Operating temperature range	Inlet air temperature [℃]	0～50 (While driving) 0～43 (stoping)	
	Outlet air temperature [℃]	80 ～ 120	
	Air flow rate	1,500 ～ 8,000	
	Inlet heat source temperature [℃]	−5 ～ 40	
	Outlet heat source temperature [℃]	−9 ～ 35	
	Heat source flow rate [L/min]	100 ～ 330	

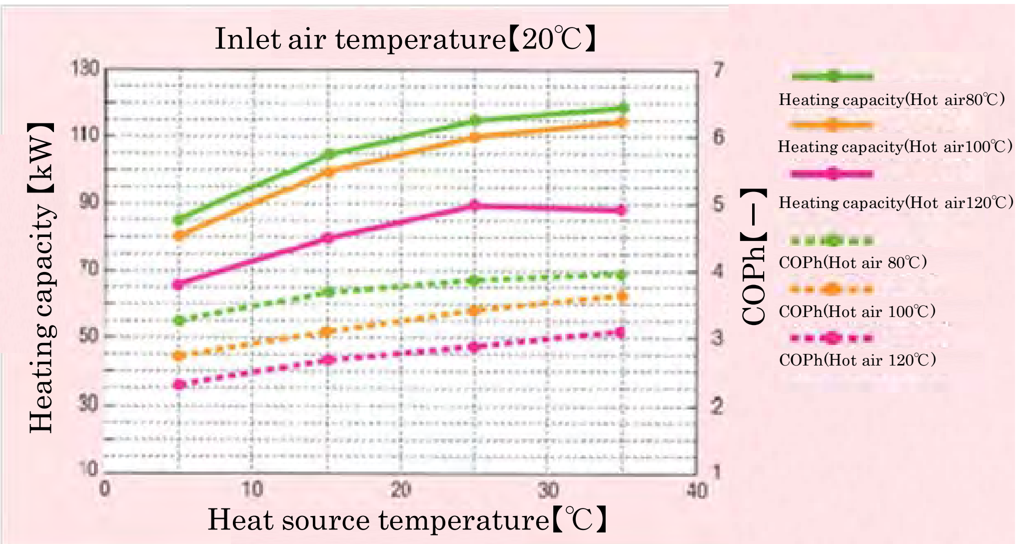


Figure 8-19: Performance Curve of CO_2 Heat Pump Air Heater (Mayekawa Eco-Sirocco)

8.2.2.4 Features of components

Figure 8-20 shows the appearance and scheme of a small CO_2 heat pump air heater produced by the Central Research Institute of Electric Power Industry. In this system, fin and tube heat exchangers are used for the air heater. In this element, air is directly heated by the supercritical CO_2 refrigerant.

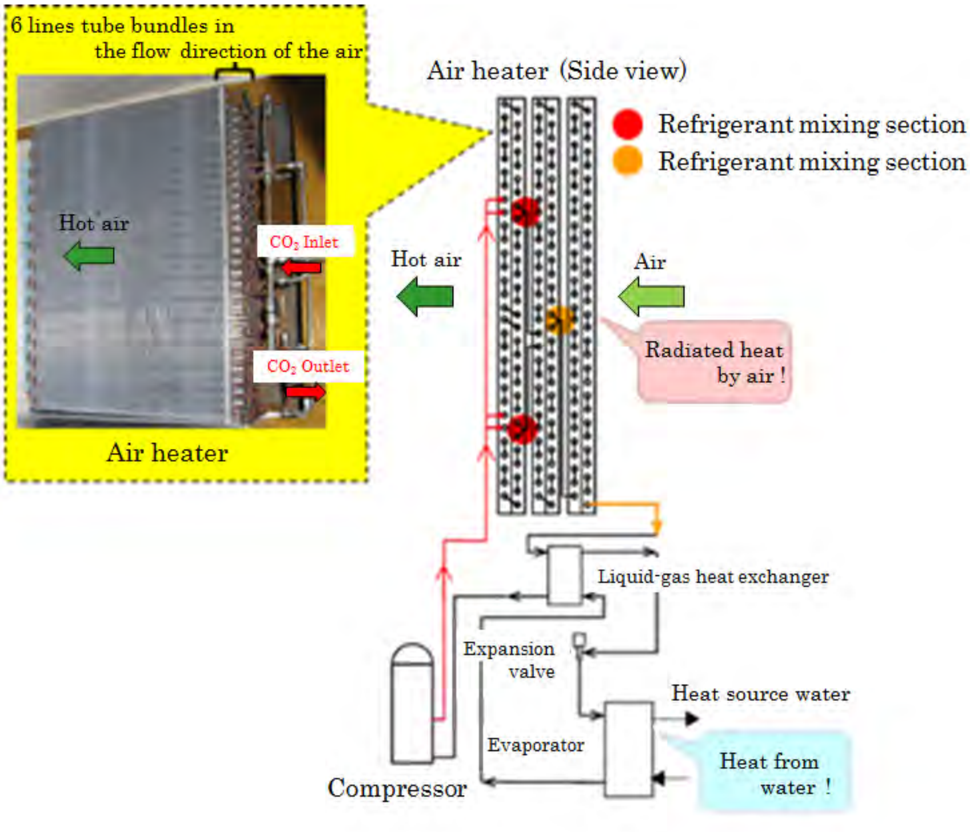
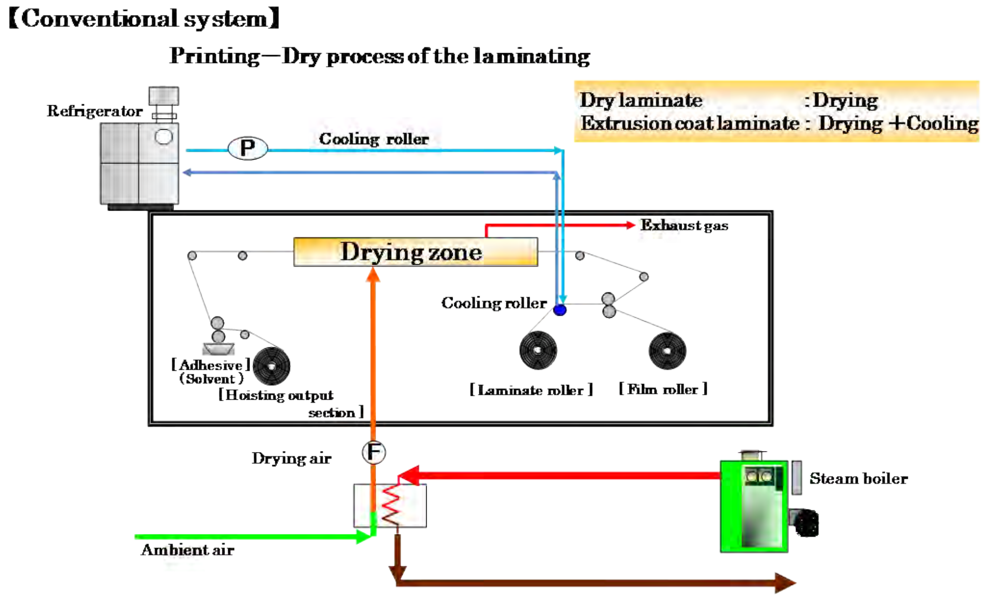


Figure 8-20: CO_2 heat pump air heater
(Central Research Institute of Electric Power Industry)

8.2.2.5 Example of installation

Figure 8-21 shows a case example installed in a laminating factory. In this factory, the CO_2 heat pump air heater is used to supply hot air for the drying process and cooling water to cool the cooling roller. With this system, the refrigerator installation is not necessary, and energy consumption for the boiler is reduced. A higher COP can be realised by simultaneous heating and cooling using one system.



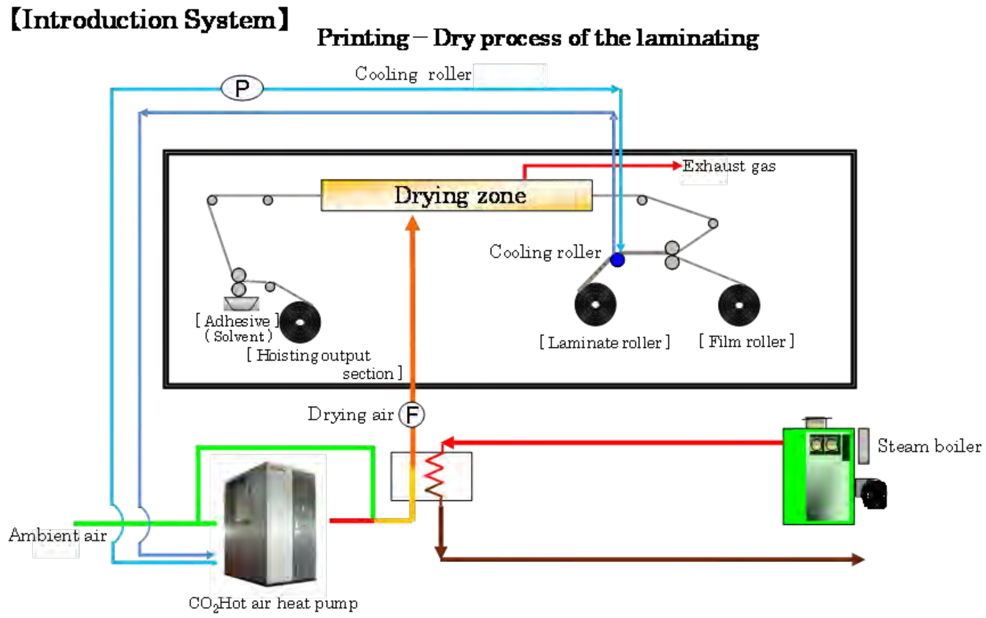


Figure 8-21: Laminating factory

Figure 8-22 shows the effect of introducing this system into the drying process. Using this system can reduce primary energy consumption by up to 46%.

Introduction effect

【The introduction effect that is anticipated by a field test】

	CO_2 emission ($t\text{-}CO_2$ / year)	Energy consumption (GJ / year)
Conventional system	147	2,900
New system	47	1,600
Reduction rate	68%	46%

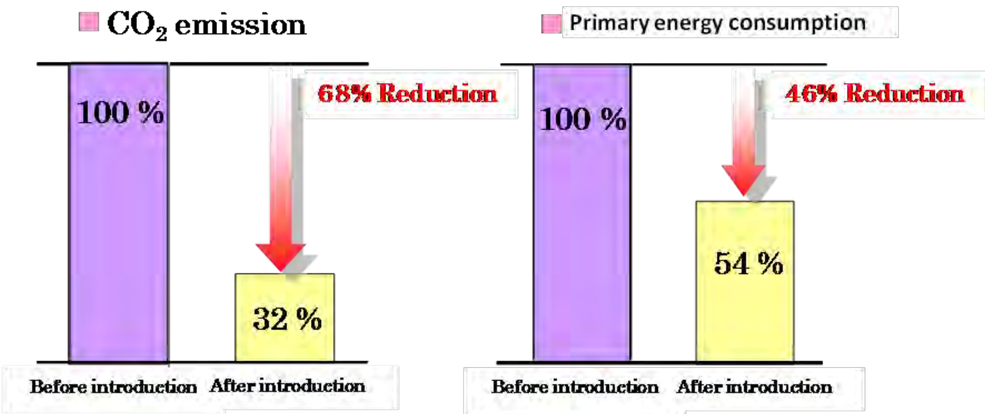


Figure 8-22: Efficiency results from adoption

8.2.3 HEAT PUMP STEAM SUPPLIER (WATER-TO-WATER)

8.2.3.1 Outline

Conventionally, a boiler is needed for 120 °C or over steam supply for processes such as sterilising, concentrating, drying, and distilling. Since there is more and more demand to save energy owing to concerns over global warming, heat pump technology, which can efficiently supply steam higher than 120 °C has a high degree of applicability.

This system realises a supply of 165 °C steam through the addition of a steam compressor and a flash tank to the vapour compression cycle.

8.2.3.2 System flow

Figure 8-23 shows the flow of this system. The flow of the heat pump to produce 120 °C steam is the same as that of the conventional heat pump. 120 °C steam is supplied from the flash tank. The refrigerant is R-245fa for SGH120, and a mixture of R-134a and R-245fa for SGH165 to achieve a good performance. For SGH165, 165 °C steam is produced by compressing 120 °C steam with a steam compressor.

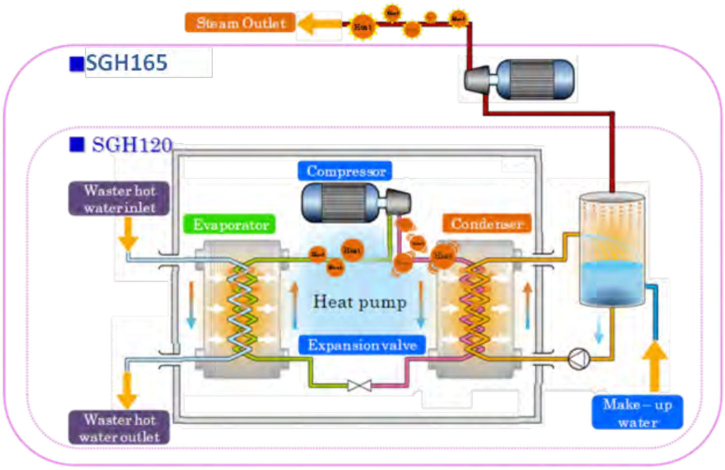


Figure 8-23: System flow (KOBELCO: SGH series)

Steam is usually produced in the central boiler room at high pressure and send to each building through a header and long piping network. Locating the heat pump steam supplier close to the process directly can reduce heat loss from the piping network.

Thus, this heat pump supplier can produce 120 °C steam for a distributed system and 165 °C steam when located close to a conventional boiler.

8.2.3.3 System details

This system is the first efficient heat pump steam supplier in the world whose steam temperature is more than 120 °C. SGH120 is a heat pump steam supplier that can produce 120 °C steam. SGH165 can produce 165 °C steam by adding a steam compressor to SGH120. Figure 8-24 shows the appearance of the commercialised systems.

In Table 8-3 their specifications are listet, which indicates SGH120 has a heating capacity of 370 kW and a COP of 3.5 and SGH 165 has a heating capacity of 660 kW and a COP of 2.5. Figure 8-25 shows COP values related to heat source temperatures.

120℃/0.1MPaG Steam supply   165℃/0.6MPaG Steam supply

Figure 8-24: Overview of system (KOBELCO: SGH series)

Table 8-3: System specifications (KOBELCO: SGH series)

Type			SGH 120	SGH 165
Capacity	Steam pressure	MPaG	0.1	0.6
	Steam temperature	℃	120	165
	Inlet heat source water temperature	℃	65	70
	Outlet heat source water temperature	℃	60	65
	Heating capacity	kW	370	660
	Steam	t/hr	0.51	0.89
	HeatingCOP	-	3.5	2.5
Heat source water temperature range		℃	25 ~ 65	35 ~ 70
Steam pressure range		MPaG	0.0 ~ 0.1	0.2 ~ 0.8
Dimensions	Width	mm	1,200	4,300
	Depth	mm	4,850	2,950
	Height	mm	2,530	2,530
Weight	While carrying	kg	4,000	6,630
	While driving	kg	4,240	6,960

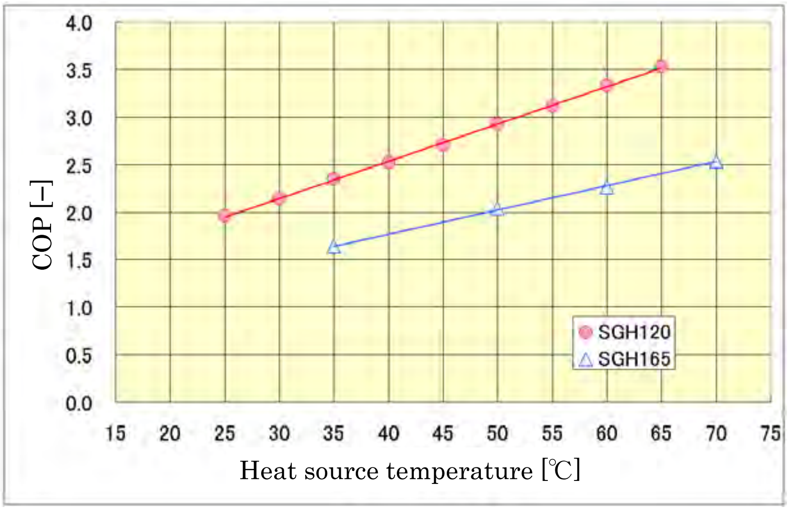


Figure 8-25: System performance (KOBELCO: SHG series)

8.2.3.4 Features of components

To comply with a compressor getting hot, a newly developed screw compressor was equipped (Figure 8-26). It is developed for high pressure and high temperature and sprays refrigerant mist into a motor for cooling down.

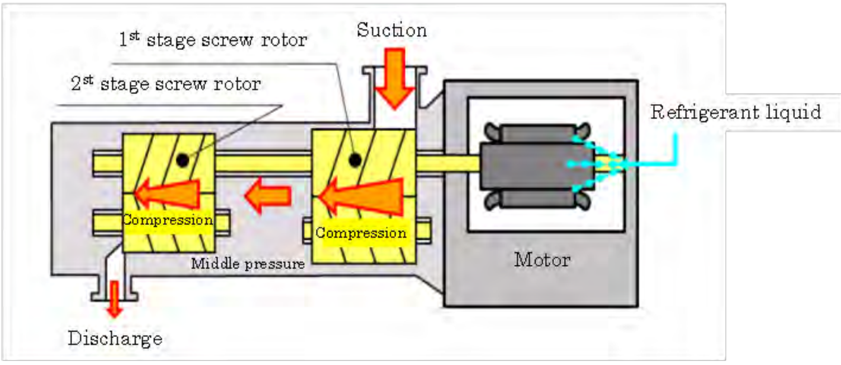


Figure 8-26: New screw compressor

8.2.3.5 Example of installation

The system was integrated in the following process (Figure 8-27). Setting the heat pump close to the process can realise a distributed heat source settlement system that uses the waste heat. With this system, piping loss can be reduced by 50 %.

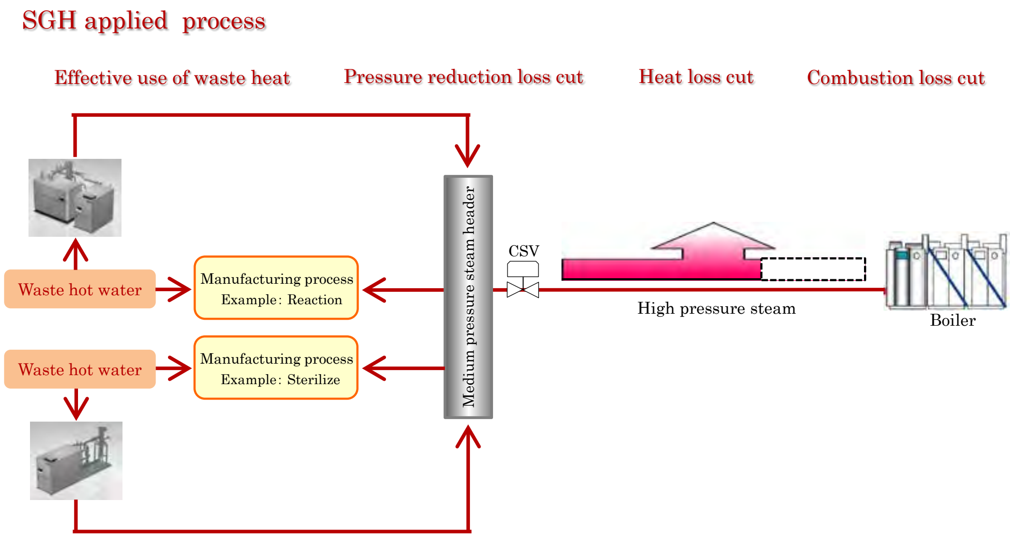


Figure 8-27: SGH-integrated process

8.2.4 HEAT PUMP FOR CIRCULATIONG WATER HEATING (AIR-TO-WATER)

8.2.4.1 Outline

Recently, heat pumps have been applied to not only air-conditioning use but also water heaters as a key technology for saving energy and reducing costs. However, the spread to the industrial market is still slow.

There are many kinds of heating processes for manufacturing, and boilers are widely used for these processes. The boiler is centralised in the power house, and steam is provided by a long piping network to the places required. This loses heat.

Many processes require hot water. Hot water that is used below 90 °C and circulated to keep the temperature of the storage tank constant has an energy demand of about 67 TJ.

Recently, industrial heat pump systems have been developed and installed. However, the market demands an efficient circulation type heat pump that is compact and easy to install. To meet this demand, a heat pump for circulation water heating has been developed for which the heat source is the air.

Generally, if a single-stage cycle is used for the air heat source heat pump, COP decreases because one compressor has to be operated with a higher pressure ratio. Particularly when hot water is circulated, the condensing pressure rises, so COP decreases with increasing hot water supply temperature.

The dual cycle was adopted to obtain 90 °C hot water outdoor the installation when hot water is circulated.

8.2.4.2 System flow

Figure 8-28 shows the system flow. This system adopts a dual cycle. Figure 8-29 shows the dual cycle on the temperature-specific enthalpy diagram. The dual cycle consists of two independent cycles and a middle heat exchanger that connects the two cycles. Since the heat absorbed in the lower temperature cycle is transferred to the higher temperature cycle, higher temperature heat can be produced even though the ambient air temperature for the lower temperature cycle is lower.

This system uses R-410A for the lower temperature cycle and R-134a for the higher temperature cycle, the latter of which is suitable for higher temperature use. In the dual cycle, since the refrigerant of each cycle is pressurised using a different compressor, different ambient air temperature limit, and different hot water temperature, the problem of a lower COP can be avoided to realise efficient operation.

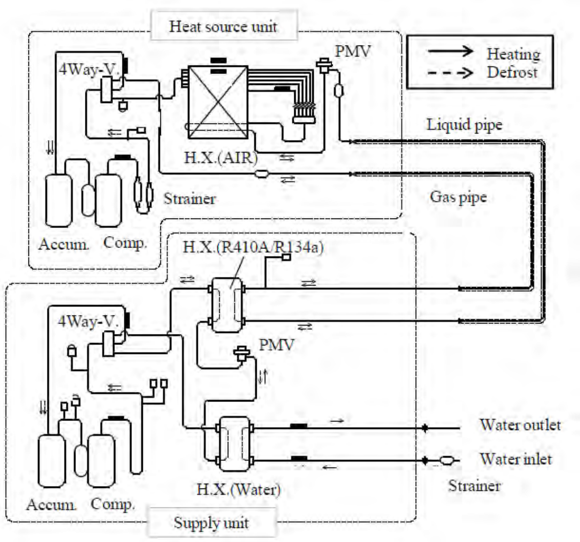


Figure 8-28: System flow

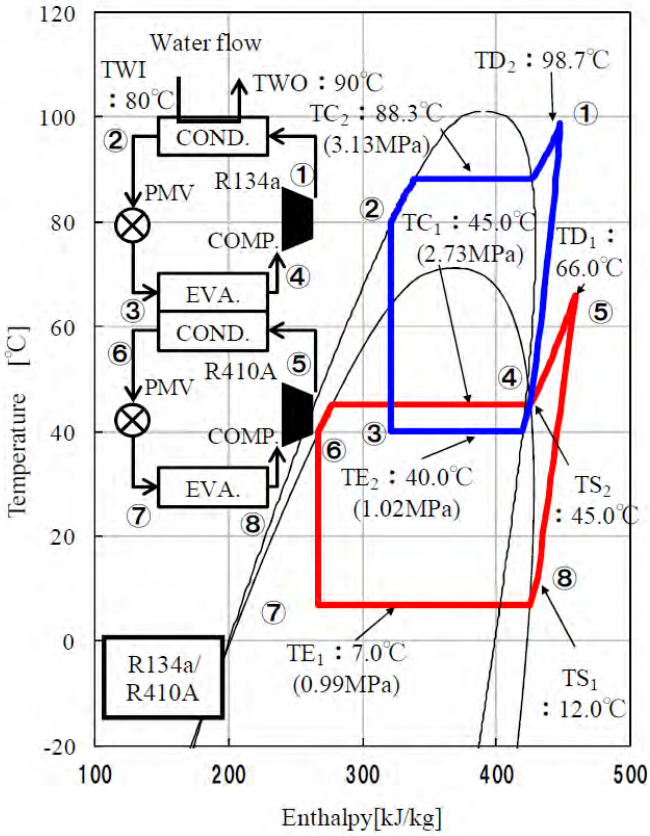


Figure 8-29: Driving conditions on specific enthalpy–temperature diagram

8.2.4.3 System details

Figure 8-30 shows the flow and overview of the system. Table 8-4 lists the specifications of this system. The system uses two units: a heat source unit that adopts the lower temperature cycle and a hot water supply unit that adopts the higher temperature cycle. Since both are connected by the refrigerant piping of R-410A, the system has many applications cases despite the variety of installation conditions.

In the heat pump unit, the refrigeration cycle and heat exchangers are optimised based on the storage type of the air-conditioning system. The heat exchangers and control method are optimised. The hot water supply unit is an indoor installation type, which is assumed to be installed near the spots where a heat-use device. This concept allows heat loss to be reduced.

This system has a dual cycle with two compressors. This increases the partial load efficiency because the load of each compressor changes depending on the ambient air temperature, hot water temperature, and heating capacity.

Figure 8-31 shows the partial load efficiency depending on the ambient air temperature. This indicates that COP can be kept higher.

As shown in Figure 8-32, the driving range of the hot water temperature was from 50 °C to 90 °C; that of the ambient air temperature was from -15 °C to 43 °C DB. A maximum of four systems can be connected in parallel.

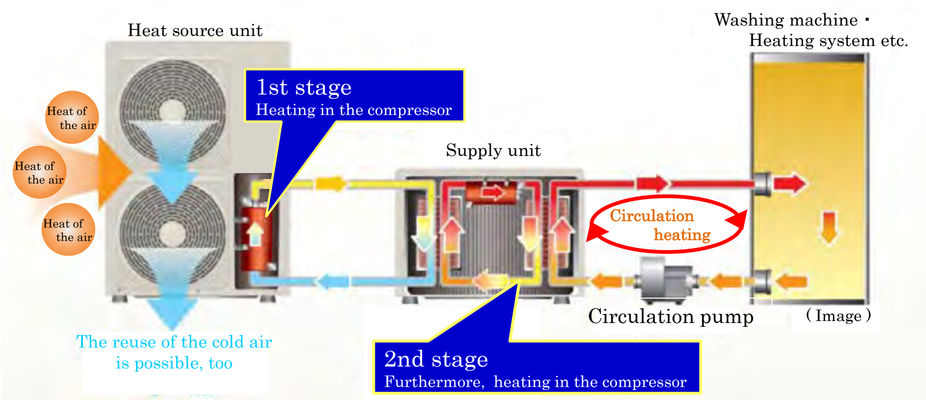


Figure 8-30: Flow and Overview of system

Table 8-4: Specifications of system

System type	HWC-H1401S	
Unit type	Heat source unit HWC-H1401H	Supply unit HWC-H1401XH
Outward appearance (width×depth×height)	900mm×320mm×1340mm	900mm×320mm×700mm
Rated power source	3 ϕ 200V (50Hz/60Hz)	
Heating capacity	14.0 kW ※1	
COP	3.5 ※2	
Hightest hot water temperature	90℃	

*1 Conditions: Normal capacity

(Conditions: Ambient temperature dry bulb 16 °C/wet bulb 12 °C, Inlet temperature 60 °C, Outlet temperature 65 °C)

*Performance changes depending on ambient temperature and inlet temperature conditions

*2 Conditions: Ambient temperature dry bulb 25 °C/Wet bulb 21 °C, Inlet temperature 60 °C, Outlet temperature 65 °C

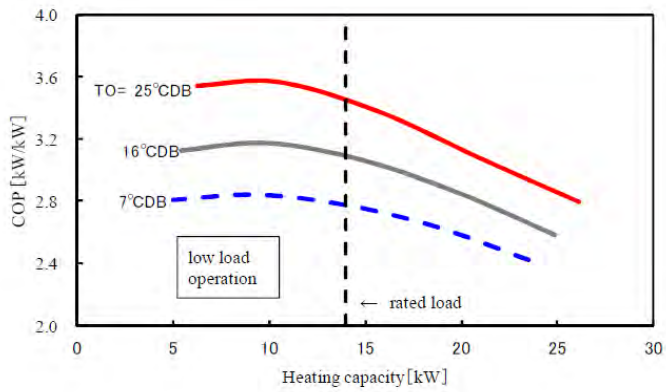


Figure 8-31: Partial load efficiency

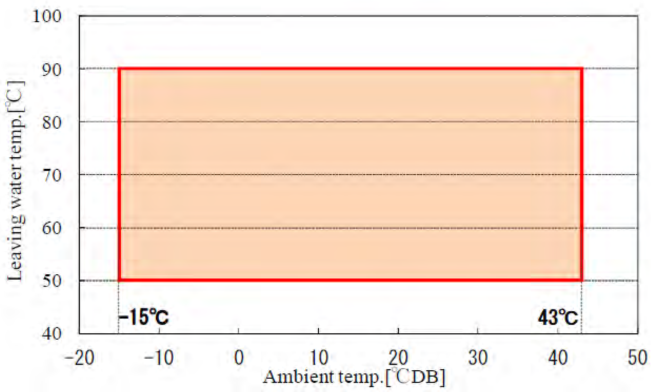


Figure 8-32: Driving range

8.2.4.4 Features of components

As shown in Figure 8-33, this system adopts two DC twin rotary compressors. The compressor for the R-134a cycle was newly developed to maintain the reliability in the higher temperature driving region than existing R-134a cycle temperature range.

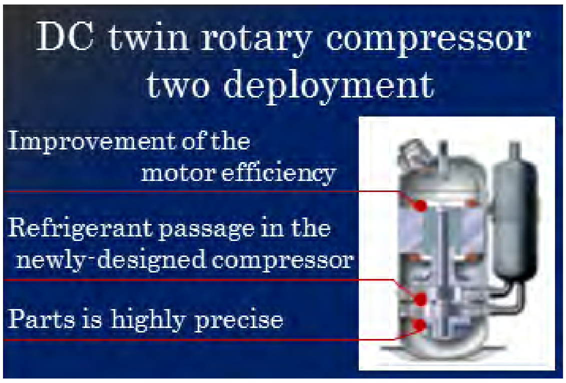


Figure 8-33: Newly developed compressor

8.2.4.5 Example of installation

Figure 8-34 shows this system being applied to washing and antirust treatment processes. This system can reduce the energy consumption by 61 % and the running cost by 65 % compared to a conventional gas boiler.

This system has several input and outputs ports for each signal assumed to be used in the factory process. As an output function, this system has non-voltage contacts that output driving and failure signals. As an input function, this system has a contact input circuit that can input the start-up, shutdown, and interlock circuit signals and an analogue input circuit that can input the auxiliary temperature, pressure, and so on as needed for industrial application.

Thus, this system has a wide range of applicability.

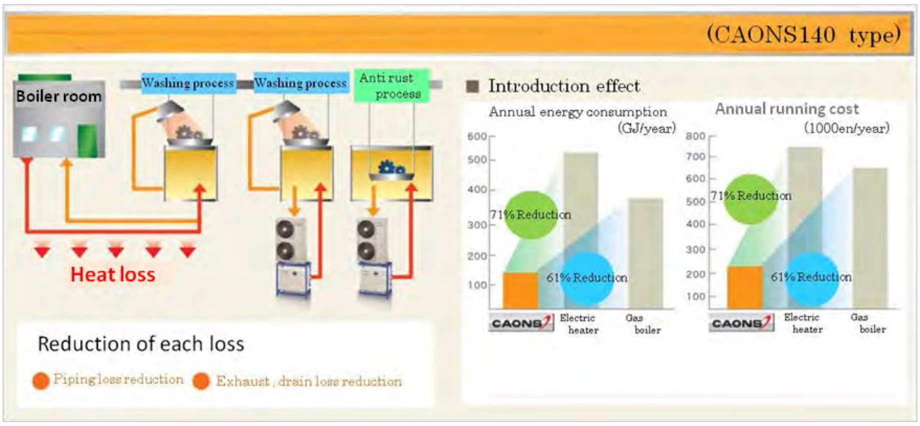


Figure 8-34: Efficiency results from adoption

8.2.5 WASTE HEAT RECOVERY HEAT PUMP WATER HEATER

8.2.5.1 Outline

A great deal of hot water is used in processes such as heating, drying, washing, and sterilizing. Most of it is produce by the boiler, which is fuelled by oil or gas. Waste heat produced in the manufacturing process is cooled down by a cooling tower.

If this waste heat can be used effectively, this will significantly contribute to saving energy and reducing CO_2 emissions. Therefore, a heat pump was applied to the hot water supply process. The waste heat recovery heat pump water heater can use waste heat with a temperature of about 10–50 °C and heat it up to 90 °C, which is supplied to processes where hot water require.

8.2.5.2 System flow

Figure 8-35 shows the system flow. This system mainly consists of an evaporator, a condenser, a compressor, an expansion valve, and an economiser. This flow is a simple single-stage cycle.

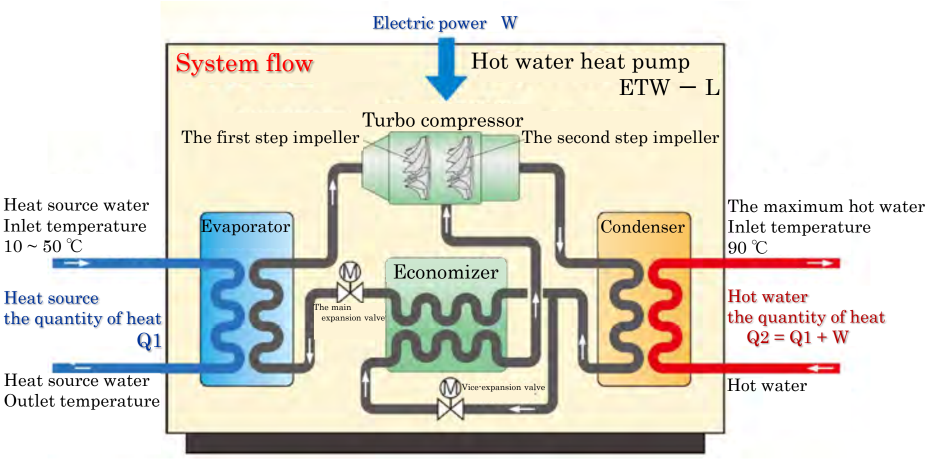


Figure 8-35: System flow

8.2.5.3 System details

Figure 8-36 shows the appearance of the system in practical use. Table 8-5 lists the specifications of this system. The heating capacity is 376–547 kW.

Figure 8-36: Appearance of system (Mitsubishi Heavy Industries: ETW-L)

Table 8-5: System specifications (Mitsubishi Heavy Industries: ETW-L)

Heat pump water heater			ETW−L		
Capacity	Heating capacity	kW	376	545	547
	Cooling capacity	kW	266	400	405
Outward appearance	Length (L)	m	1.55		
	Width (W)	m	1.2		
	Height (H)	m	2		
Weight	Basic machine mass		2500		
	Operating mass		2700		
	Oil		JOMO α68 B		
	Refrigerant		R134a		
	Holding water quantity		120		
Power source	Main power source		400V(380 ~ 440V), 50/60Hz		
	Starting current		Current value or less		
	Inverter capacity		160		
	Voltage,Frequency permission change				
Compressor	Type		MCM150L		
	Number		1		
	Electric motor output	kW	104	136	133
	Starting method		Software start with inverter		
Euaporator	Water side design pressure	Mpa(G)	1.0		
	Inlet heat source water temperature	℃	15	35	50
	Outlet heat source water temperature	℃	10	30	45
	Flow rate of heat source water	m3/h	44.3	69.3	72.9
	Nozzle diameter		100A		
	Pressure loss	kPa	18	43	48
	Drain/Air diameter		15A/15A		
Heat pump water heater			ETW−L		
Condenser	Water side design pressure	Mpa(G)	1.0		
	Inlet hot water temperature	℃	50	65	80
	Outlet hot water temperature	℃	60	75	90
	Flow rate of hot water	m^3/h	32.3	47.9	48.3
	Nozzle diameter		80A		
	Pressure loss	kPa	20	41	42
	Drain/Air diameter		15A/15A		

8.2.5.4 Features of components

This system uses a centrifugal compressor, as shown in Figure 8-37. To make the total unit compact, the sizes of the motor, gear, and compressor are reduced. This makes it easier to introduce this system to factories and plants as it improves operability and controllability.

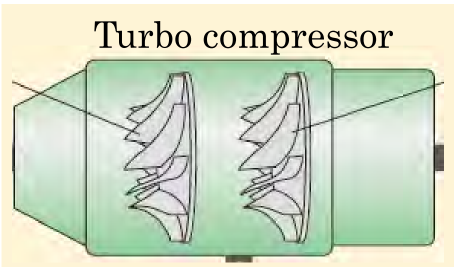


Figure 8-37: Centrifugal compressor

8.2.5.5 Example of installation

Figure 8-38 shows this heat pump applied to a pasteuriser. This pasteuriser is a system that sterilises outside bottles after beverages are filled. After the products are heated with a spray of hot water and then kept at a regulated temperature for some time, they are cooled down by a spray of chilled water. This process needs both heating and cooling. If the inlet and outlet temperatures of the hot and chilled water are the same, the heat quantities are also the same.

Conventionally, steam is used to heat up the storage tank, and the chiller cools it down. Simultaneous heating and cooling with this heat pump realises reductions of 58 % in CO_2 emissions and 32 % in running costs.

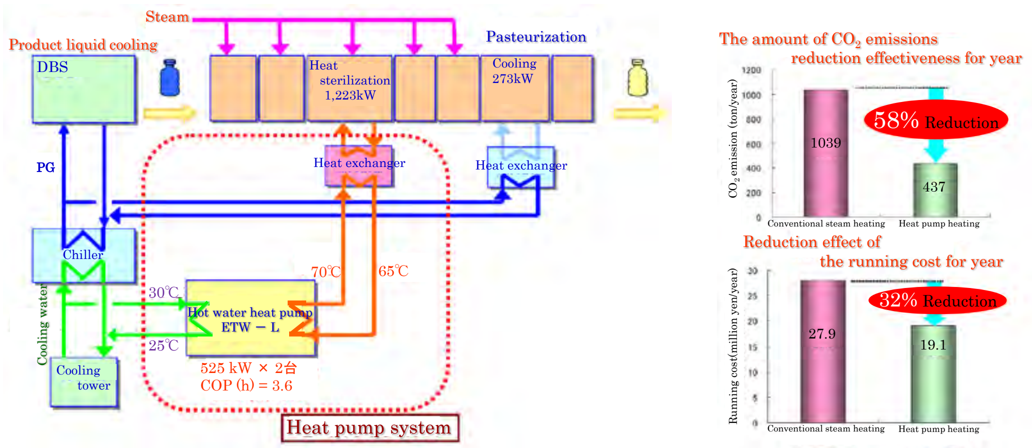


Figure 8-38: Application to pasteuriser

In food factories, humidity control is another important factor. Mechanical dehumidification, where the process air is dehumidified by chilled water from a refrigerator and then reheated, or desiccant dehumidification is normally used.

Since high-performance desiccants have been developed recently, the desiccant dehumidifier can be driven by a lower-temperature heat source supplied as hot water. For this dehumidification system, application of the heat pump water heater can save great amounts of energy. Conventionally, cooling and heating are provided separately for this dehumidification process. However, the heat pump system provides both simultaneously. This system reduces CO_2 emissions by 60 % and running costs by 50 %, as shown in Figure 8-39.

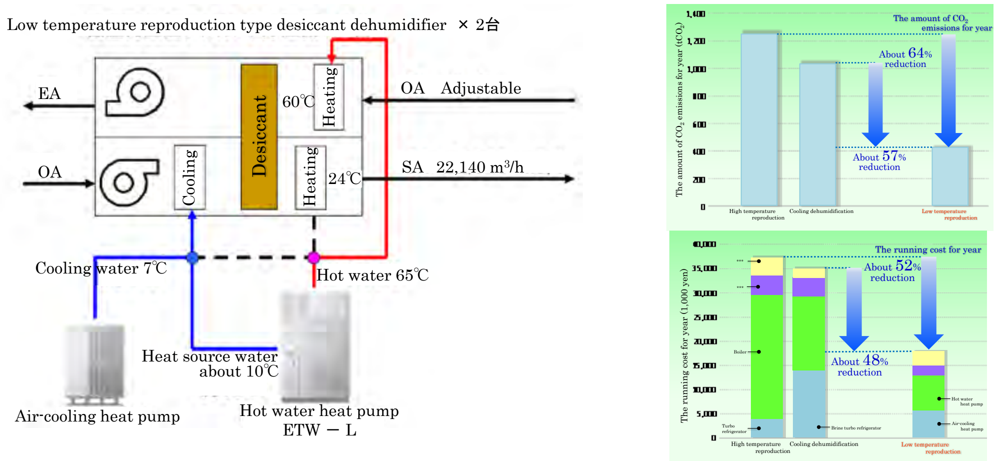


Figure 8-39: Application to desiccant dehumidifier

8.3 Survey of low GWP refrigerants for high temperature heat pumps and basic analysis on their thermodynamic cycle performance

8.3.1 Introduction

In recent years, in civilian, industry and transportation sectors, effective use of energy has been one of the most important issues in terms of greenhouse gas emission cut, the increase of energy cost, etc. Especially, in the industrial sector, introduction of heat pump technology is indispensable as a technology of using waste heat effectively.

This section examines the basic characteristics of several kinds of refrigerants, which are considered to be suitable for heat pumps to use waste heat effectively. Then, thermodynamic cycle analysis on heat pumps for hot water circulation, heat recovery and vapor generation is demonstrated.

8.3.2 Basic characteristics of refrigerants suitable for high temperature heat pump

Some development of the industrial heat pump using R-134a, R-245fa, R-744, etc. has been made recently. However, except for R-744 which is a natural refrigerant with extremely low global warming potential (GWP), HFCs such as R-134a and R-245fa have high GWP values, and the use of HFCs are likely to be regulated in the viewpoint of global warming prevention in the foreseeable future. Therefore, development of alternative refrigerants with low GWP has been required.

At present, as substitutes of R-134a, R-1234yf and R-1234ze (E) are considered to be promising, and R-1234ze (Z) is attractive as a substitute of R-245fa. R-365mfc is considered to be suitable as a refrigerant of heat pump for vapor generation using waste heat, but its GWP value is high. Therefore, it seems that development of a substitute of R-365mfc should be furthered. At first, basic characteristics of these refrigerants are compared. Table 8-6 shows basic characteristics of R-744, R-1234yf, R-134a, R-1234ze (E), R-1234ze (Z), R-245fa and R-365mfc. In this table, T_c is the critical temperature, Pc is the critical pressure, and NBP is the normal boiling point. As for the critical temperature T_c, R-744 is the lowest, and it becomes high in order of R-1234yf, R-134a, R-1234ze (E), R-1234ze (Z), R-245fa, and R-365mfc. The transcritical cycle using R-744 and the reverse Rankine cycle using R-134a are put in practical use to generate hot water of 60 to 90 °C from water of 20 to 30 °C, the reverse Rankine cycle using R-134a is developed to reheat the circulating water between heat pump and heating load utilizing waste heat effectively. The reverse Rankine cycle using R-245fa is also developed to reheat the circulating water and to generate steam from the waste heat of 50 to 60 °C. Furthermore, zeotropic refrigerant mixture of R-245fa/R-134a was put in practical use as the working fluid of the reverse Rankine cycle for generating the steam more than 120 °C. In the above-mentioned systems put in practical use, refrigerants with high GWP values are used except for R-744. Therefore, new systems using low GWP refrigerants should be developed.

Figure 8-40 shows the saturated vapor pressure curves of R-134a, R-245fa, R-1234ze(E), R-1234ze (Z) and R-365mfc. The vapor pressures become high in order of R-134a, R-1234ze (E), R-1234ze (Z), R-245fa, and R-365mfc at a same saturation temperature. The vapor pressure curve of R-1234ze (E) is shifted to the high temperature side a little as compared with R-134a. The vapor pressure curve of R-1234ze (Z) is very close to R-245fa. R-365mfc with the highest critical temperature T_c has the lowest vapor pressure among these refrigerants.

Figure 8-41 shows the relation between the latent heat and saturation temperatures of R-134a, R-245fa, R-1234ze (E), R-1234ze (Z) and R-365mfc. In a temperature region of 60 °C or less, the latent heat becomes small at the order of R1234ze (Z), R-365mfc, R-245fa, R-134a, and R-1234ze (E). At about 100 °C, the latent heat of R-245fa, R-1234ze (Z) and R-365mfc is higher than 130 kJ/kg, while that of R-134a and R-1234ze (E) decreases steeply because the critical temperatures of those refrigerants are a little higher than 100 °C.

Figure 8-42 shows the relation of volumetric refrigeration capacity and the saturation temperature. The refrigerants have the highest refrigeration capacity as follows, R-134a at 90 °C, R-1234ze (E) at 100 °C, and R-245fa and R-1234ze (Z) 140 °C respectively. The inverse Rankin cycle around 160 °C seems to be feasible using R-365mfc, while the other refrigerants are used as working fluid of the trans-critical cycle.

Table 8-6: Basic characteristics of refrigerants for high temperature heat pump applications

Refrigerant	Chemical fomula		GWP	Flamability	Tc °C	Pc MPa	NBP °C
R744	CO2	carbon dioxide	1	none	30.98	7.3773	−78.40
R1234yf	CF3CF=CH2	2,3,3,3-tetrafluoropropene	4	weak	94.7	3.382	−29.48
R134a	CF3CH2F	1,1,1,2-tetrafluoroethane	1430	none	101.06	4.0593	−26.07
R1234ze(E)	CFH=CHCF3	trans-1,3,3,3-tetrafluoropropene	6	weak	109.37	3.636	−18.96
R1234ze(Z)	CHF=CHCF3	cis-1,3,3,3-tetrafluoropropene	<10	weak	153.7	3.97	9.76
R245fa	CF3CH2CHF2	1,1,1,3,3-pentafluoropropane	1030	none	154.01	3.651	15.14
R365mfc	CF3CH2CF2CH3	1,1,1,3,3-pentafluorobutane	794	weak	186.85	3.266	40.19

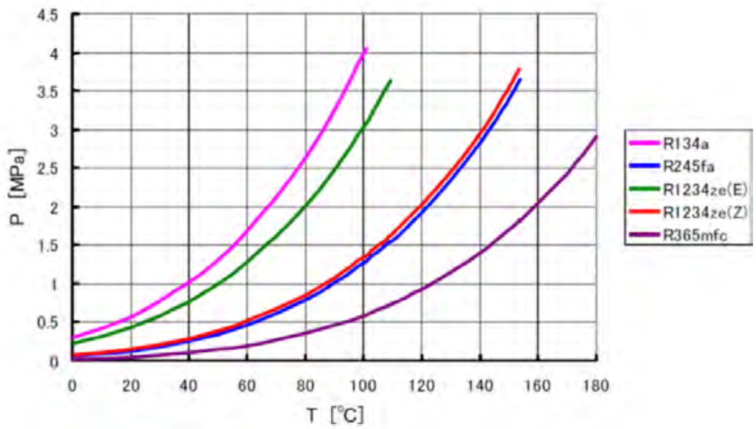


Figure 8-40: Saturated Vapor Pressure Curve

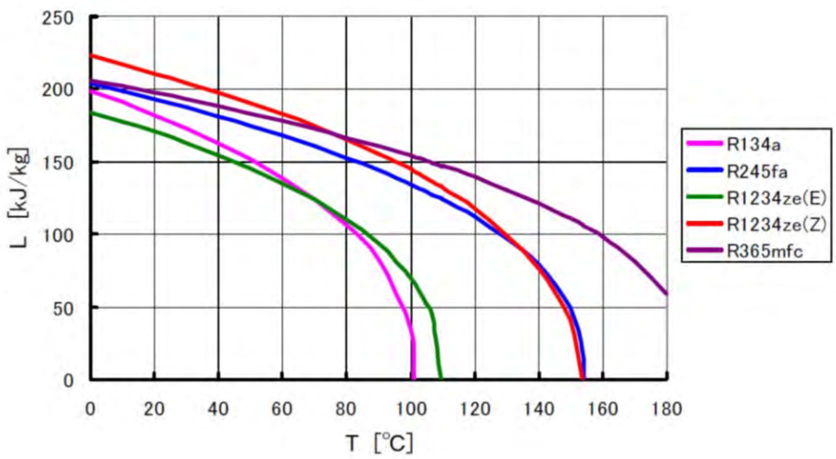


Figure 8-41: Latent heat of vaporization

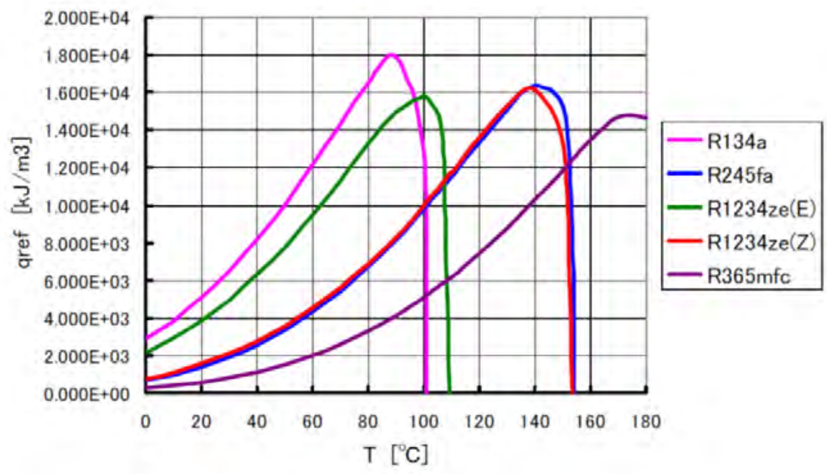


Figure 8-42: Volumetric refrigeration capacity

8.3.3 Thermodynamic analysis of cycle performance

In order to examine the possibility of introduction of heat pump as technology for effective use of waste heat, thermodynamic analysis of cycle performance is carried out under three kinds of conditions as: (case 1) reheating of circulated hot water from ambient heat source, (case 2) reheating circulated hot water from waste heat, and (case 3) steam generation using waste heat.

(Case 1) Single-stage heat pump cycle for hot water circulation

The single-stage heat pump cycle is used to reheat hot water circulating between the heat pump cycle and heating load. Thermodynamic performance of this cycle is calculated on the following condition.

- High temperature heat source

  Secondary fluid side: water returned from heating load at 60 °C is heated up to 65 °C.

  Refrigerant side: refrigerant is condensed at 67 °C and subcooled at 62 °C.
- Low temperature heat source

  Secondary fluid side: water or air at 25 °C is cooled down to 20 °C.

  Refrigerant side: refrigerant is evaporated at 18 °C and superheated up to 23 °C.
- Compressor performance

  Adiabatic efficiency: 0.92, mechanical efficiency: 0.85, electric motor: 0.9
- Refrigerants: R-134a, R-245fa, R-1234ze (E), R-1234ze (Z) and R-365mfc

The calculation results of cycle performances are shown in Table 8-7. As for any refrigerants, the values of COPs are 3.9 or more, and the primary energy efficiencies are 1.4 or more. The volumetric heating capacities of R-245fa, R-1234ze (Z) and R-365mfc are low although COPs of those refrigerants are slightly high as compared with R-134a and R-1234ze (E).

Table 8-7: Cycle performance of single-stage heat pump for hot water circulation

Refrigerant	Heating capacity kJ/kg	Volumetric heating capacity kJ/m^3	Suction–discharge pressure ratio	COP	Primary energy efficiency
R134a	152.95	3882	3.683	3.908	1.446
R245fa	170.23	1105.8	4.953	4.192	1.551
R1234ze(E)	140.48	2913.7	3.751	3.92	1.45
R1234ze(Z)	190.08	1284.9	4.47	4.246	1.571
R365mfc	172.78	451	5.732	4.207	1.557

Demand side electric power generation efficiency = 0.37

(Case 2) Single-stage heat pump cycle for thermal recovery from waste heat

The single-stage heat pump cycle is used to reheat hot water circulating between the heat pump cycle and heating load. The waste heat is used as low temperature heat source. Thermodynamic performance of this cycle is calculated on the following condition.

- High temperature heat source

  Secondary fluid side: water returned from heating load at 80 °C is heated up to 90 °C.

  Refrigerant side: refrigerant is condensed at 92 °C and subcooled at 87 °C.

- Low temperature heat source

  Secondary fluid side: water or air at 50 °C is cooled down to 40 °C.

  Refrigerant side: refrigerant is evaporated at 38 °C and superheated up to 43 °C.

- Compressor performance

  Adiabatic efficiency: 0.92, mechanical efficiency: 0.85, electric motor: 0.9

- Refrigerants: R-134a, R-245fa, R-1234ze (E), R-1234ze (Z) and R-365mfc

In Table 8-8 the calculation results of cycle performance are shown. Although the volumetric heating capacities of R-134a and R-1234ze (E) are high, the COP values and primary energy efficiencies of those refrigerants become low because their operating temperatures approach the critical temperature. Volumetric capacities of R-245fa and R-1234ze (Z) increase as compared with case (1) and the COP values of these refrigerants are comparatively high at about 3.8 or more. In the case of R-365mfc, COP is high, but volumetric heating capability is low. From a viewpoint of primary energy efficiency and volumetric heating capability, R-245fa and R-1234ze (Z) are considered to be suitable refrigerants under the present temperature condition.

Table 8-8: Cycle performance of single-stage heat pump for thermal recovery from waste heat

Refrigerant	Heating capacity kJ/kg	Volumetric heating capacity kJ/m^3	Suction–discharge pressure ratio	COP	Primary energy efficiency
R134a	111.78	5339.8	3.509	3.244	1.2
R245fa	146.89	1902.1	4.499	3.832	1.418
R1234ze(E)	109.78	4099.6	3.552	3.323	1.23
R1234ze(Z)	165.33	2131.1	4.135	3.905	1.445
R365mfc	152.84	839.8	5.15	3.89	1.439

Demand side electric power generation efficiency = 0.37

(Case 3) Single-stage heat pump cycle for thermal recovery and steam generation from waste heat

The single-stage heat pump cycle is used to generate steam from waste heat. Thermodynamic performance of this cycle is calculated on the following condition.

- High temperature heat source
  Secondary fluid side: steam at 120 °C is generated
  Refrigerant side: refrigerant is condensed at 130 °C and subcooled at 125 °C.
- Low temperature heat source
  Secondary fluid side: factory waste liquid at 100 °C is used as heat source
  Refrigerant side: refrigerant is evaporated at 90 °C and superheated up to 95 °C.
- Compressor performance
  Adiabatic efficiency: 0.92, mechanical efficiency: 0.85, electric motor: 0.9
- Refrigerants: R-245fa, R-1234ze (Z) and R-365mfc

Table 8-9 shows the calculation results of cycle performance. R-134a and R-1234ze (E) were excepted from the refrigerants for calculation, since those critical temperatures are lower than high temperature heat source temperature. COPs of R-245fa, R-1234ze (Z), and R-365mfc are 5.3 or more, and those primary energy efficiencies are also as very high as 1.9 or more. In particular, although the volumetric capability of R-365mfc is not high, its primary energy efficiency is high as 2.1.

Table 8-9: Cycle performance of single-stage heat pump for thermal recovery and steam generation from waste heat

Refrigerant	Heating capacity kJ/kg	Volumetric heating capacity kJ/m^3	Suction–discharge pressure ratio	COP	Primary energy efficiency
R245fa	109.24	5997.7	2.33	5.318	1.968
R1234ze(Z)	121.08	6279.1	2.28	5.365	1.985
R365mfc	127.84	3231	2.496	5.761	2.131

Demand side electric power generation efficiency = 0.37

8.3.4 Concluding remarks

(1) Refrigerants for high temperature heat pump

- R-1234ze (E) and R-1234yf are promising as alternative of R-134a.
- R-1234ze (Z) is promising as alternative of R-245fa.
- The alternative of R-365mfc is under research and development.

(2) Thermodynamic analysis of heat pump cycle performance

Thermodynamic analysis of cycle performance was carried out under three kinds of conditions as: (case 1) reheating of circulated hot water from ambient heat source, (case 2) reheating circulated hot water from waste heat, and (case 3) steam generation using waste heat. In the present analysis, five kinds of refrigerants R-134a, R-245fa, R-1234ze (E), R-1234ze (Z) and R-365mfc are selected as objectives of calculation. From a viewpoint of volumetric heating capacity and primary energy efficiency, it can be judged as follows.

- In case 1, R-134a is the most suitable refrigerant. However, R-1234ze (E) is the promising one because of its low GWP.
- In case 2, R-245fa and R-1234ze (Z) are suitable refrigerants.
- In case 3, R-245fa and R-1234ze (Z) are suitable refrigerants. Although the volumetric heating capacity of R-365mfc is about half lower than R-245fa and R-1234ze (Z), its primary energy efficiency is the highest.

In order to select the combination of cycle and refrigerant, which is suitable for given heat source and sink condition, thermodynamic performance analysis of pure and mixed refrigerants should be carried out not only for single stage heat pump cycle, but also for two stage and cascade heat pump cycles.

8.4 Industrial Application of Thermal Storage Technologies

Thermal storage technologies make it more convenient to transfer and use thermal energy anywhere and anytime by storing thermal energy including industrial cold energy and waste energy.

Since the Great East Japan Earthquake occurred in 2011, the power load leveling has become one of the major issues to tackle in Japan. Thermal storage technologies, which can use energy stored at night, are in particular expected to gain importance in industrial applications in the future to address this issue. This is because thermal storage technologies bring various advantages such as lower electricity prices by taking a less expensive option for night-time consumption which an electricity tariff offers, and contract amperage reduction in response to reduced installed capacity. In addition, combined systems of thermal storage technologies and heat pumps, which use renewable energy, are expected to attract attention since they can level power load, conserve energy and reduce CO_2 emission at the same time.

The latest thermal storage technologies including the ones already in practical use are explained below sorted by temperature ranges.

8.4.1 Ice slurry made from trehalose aqueous solution

Trehalose ($C_{12}H_{22}O_{11}$: Molecular weight = 342) is a relatively inexpensive natural carbohydrate that can be synthesized from starch. It is widely used as a food additive.

I. Application: Ice slurry made from trehalose aqueous solution can be utilized for cold storage of foods such as vegetables and fruit in a wide temperature range below 0 °C.

II. Characteristics: Ice slurry has a high fluidity and is excellent at absorbing heat. As shown in Figure 8-43: Freezing point of trehalose aqueous solution [Kawanami, 2011, its temperature change against concentration change is extremely small, which is very important for cold storage of food. Moreover its freezing point in the same concentration as propylene glycol (PG), an existing refrigerant for cold storage of food, is higher than that of PG. It will help raise refrigerator evaporation temperature and lead to coefficient of performance (COP) improvement.

III. Latent heat: Estimated at approximately 210 kJ/kg

IV. Combined system with heat pump, example of installation: It is used for making ice and hot water at night and cooling milk with ice during daytime.

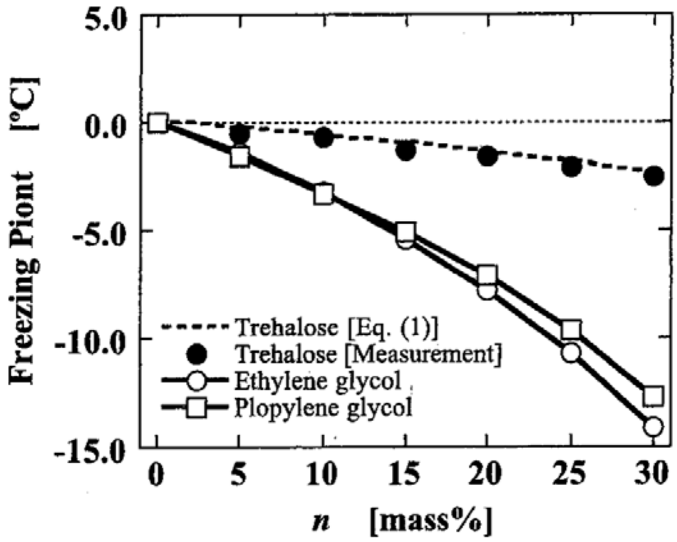


Figure 8-43: Freezing point of trehalose aqueous solution [Kawanami, 2011]

Kawanami, 2011 T. Kawanami, K. Togashi, K. Fumoto, S. Hirano, S. Hirasawa, Physical Properties and Heat Transfer Characteristics of an Environmentally Neutral Ice Slurry, Japan J. of Thermophysical Properties, Vol. 25, No. 2 (2011) p. 89-94 (in Japanese)

8.4.2 Tetra-n-butyl ammonium bromide (TBAB) hydrate slurry

i. Application: Air conditioning at a components factory (already in practical use)

ii. Characteristics: TBAB hydrate slurry changes a phase in the temperature range of air conditioning. As shown in Figure 8-44 at a concentration from 13 wt.% to 20 wt.%, its solidification temperature is from 5 °C to 8 °C, which is suitable for air-conditioning. Moreover based on the conditions of the concentration, two types of TBAB hydrate slurry can be produced. Type 1 hydrate slurry has a better function in fluidity.

iii. Latent heat: Table 8-10 shows the latent heat of Type 1 and Type 2 hydrate slurry. The difference between Type 1 and Type 2 is very small.

Table 8-10: Latent heat of TBAB hydrate crystals

	Oyama et al. [Oyama,2005]	Takao [Takao, 2002]
Type 1 (kJ/kg)	193.18	193
Type 2 (kJ/kg)	199.59	205

Oyama, 2005 H. Oyama, et al., Fluid Phase Equilibria, 234 (2005) 131-135

Takao, 2002 S. Takao, Japanese Journal of Multiphase Flow, Vol.16, No. 4 (2002) 412-414 (in Japanese)

iv. Combined system with heat pump, potential of installation: They have not been in practical use yet. However, if a heat pump can supply cold water at approximately 5 °C, it will be possible to combine the slurry with a heat pump.

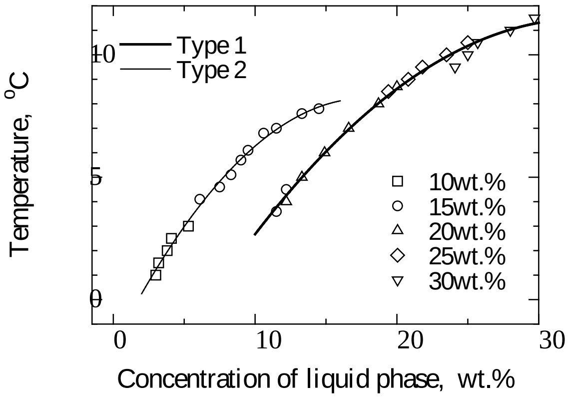
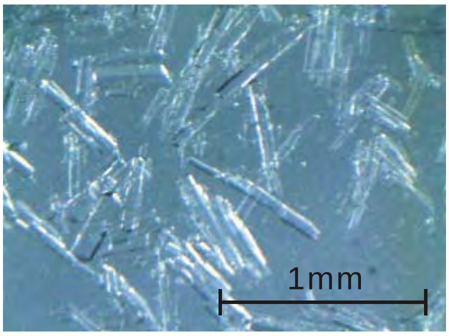
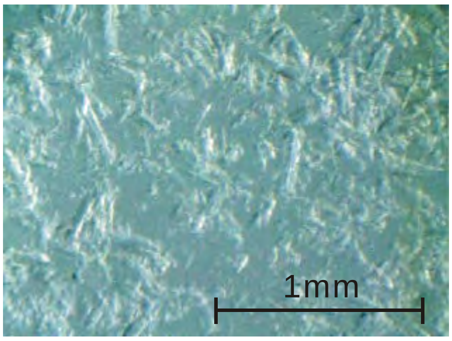


Figure 8-44: Relationship between hydrate slurry solution concentration and temperature [Kumano, 2006]

Kumano, 2006 H. Kumano, A. Saito, S. Okawa, Y. Goto, Study on Fundamental Characteristics of TBAB Hydrate Slurry, Trans. of JSME, Ser. B Vol. 72, No. 724, 2006, 3089-3095 (in Japanese)



(a) Type 1 hydrate



(b) Type 2 hydrate

Figure 8-45: Photographs of TBAB hydrate slurry [Kumano, 2012]

Kumano, 2012 H. Kumano, T. Hirata, Y. Hagiwara, F. Tamura, Effects of Storage on Flow and Heat Transfer Characteristics of Ice Slurry, Int. Journal of Refrigeration, Vol. 35, No. 1, 2012, 122-129

8.4.3 Paraffin slurry

(a) Ice slurry: produced by nanoemulsion with water as a continuous phase and tetradecane as a dispersed phase.

i. Application: Air conditioning at factories

ii. Characteristics: Paraffin slurry has fluidity and changes a phase at around 5.9 °C, which is very suitable for air conditioning. Table 8-11 shows the physical properties of tetradecane and Table 8-12 shows the nanoemulsion composition ratio. As shown in Table 8-12, two types of non-ionic surfactant (Span 80, Tween 120) are mixed for the emulsion.

iii. Latent heat: Table 8-13 shows the thermophysical properties of the nanoemulsion.

iv. Combined system with heat pump, example of installation: They have not been in practical use yet.

Table 8-11: Physical properties of tetradecane [Fumoto, 2011]

Properties	Tetradecane
Melting point (°C)	5.9
Latent heat (kJ/kg)	229.1
Specific heat (kJ/(kg・K))	1.80 (Solid), 2.14 (Liquid)
Density (kg/m^3)	810 (Solid), 770 (Liquid)
Viscosity (mPa・s)	2.47

Table 8-12: Composition ratio of nanoemulsion [Fumoto, 2011]

Tetradecane (wt%)	Surfactant (Span 80, Tween 120) (wt%)	Water (wt%)
10.0	8.0	82.0
20.0	8.0	72.0

Table 8-13: Thermophysical properties of nanoemulsion [Fumoto, 2011]

Tetradecane (wt%)	Thermal conductivity W/(m K)	Viscosity (mPa・s)
10.0	0.578 (at 28.1°C)	2.16
20.0		3.24

Fumoto, 2011 K. Fumoto, M. Kawaji, T. Kawanami, Thermophysical Property Measurements of Tetradecane Nanoemulsion Density and Thermal Conductivity, Japan J. of Thermophysical Properties, Vol. 25, No. 2 (2011) 83-88 (in Japanese)

(b) CALGRIP (trademark pending product of JSR Corporation)

i. Characteristics: CALGRIP stabilizes paraffin with a special olefin-based thermoplastic elastomer. Its latent heat storage capacity has been increased by 40 % to 100 % compared to paraffin-based latent storage material. As shown in Figure 8-46, even when it is being melted, it retains in a gel state. Various forms are available in accordance with practical application. In fact, products having melting points of 4 °C, 9 °C, 18 °C, 25 °C and 80 °C have already been developed.

ii. Combined system with heat pump, example of installation: They have not been in practical use yet.

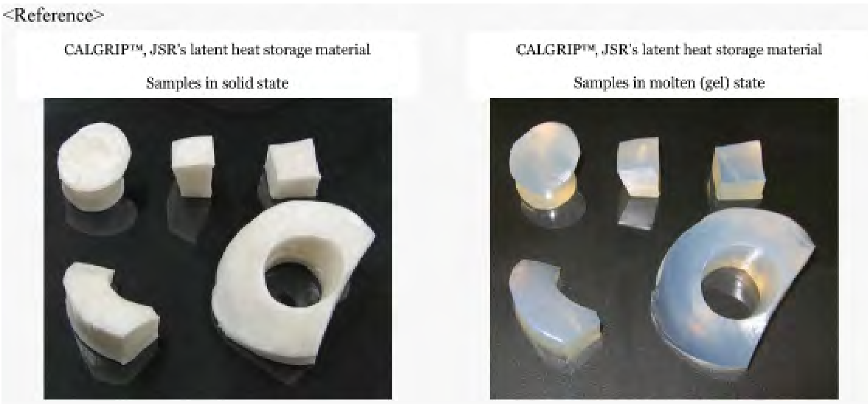


Figure 8-46: States of solidification and melting of CALGRIP [jsr]

jsr www.jsr.co.jp/news/0000086.shtml

8.4.4 Sodium acetate trihydrate: $CH_3COONa \cdot 3H_2O$

i. Application: Thermal storage for solar water heating or efficient utilization of factory waste heat of 60 °C

ii. Characteristics: Sodium acetate trihydrate changes a phase at around 60 °C and is used as a food additive.

Latent heat:

iii. Table 8-14 shows the melting point and latent heat of sodium acetate trihydrate.

iv. Combined system with heat pump, example of installation: They have not been in practical use yet.

Table 8-14: Melting point and latent heat of sodium acetate trihydrate

Melting point (°C)	58.8
Latent heat (kJ/kg)	247-255

8.4.5 Erythritol: ($HOCH_2[CH(OH)_2]_2CH_2OH$) and Mannitol: ($HOCH_2(CHOH)_4CH_2OH$)

Both are harmless polyhydric alcohol and sugar alcohol.

i. Application: Efficient use of waste heat at factories

   Erythritol and mannitol can efficiently use low-temperature waste gas below 200°C, which means most of the waste gas at factories. If the heat is not directly exchanged, durable capsules need to be developed. Latent heat: Table 8-15 shows the thermophysical properties of erythritol and mannitol.

ii. Combined system with heat pump, example of installation: They have not been in practical use yet.

Table 8-15: Thermophysical properties of erythritol and mannitol [Horibe, 2011]

Properties	Erythritol	Mannitol
Melting point (°C)	118	166.5
Latent heat (kJ/kg)	320	303.7
Thermal conductivity (W/(m K))	0.34 (at 120°C)	0.42 (at 170°C)
Density (kg/m^3)	1300 (at 137°C)	1386 (at 200°C)

Horibe, 2011 A. Horibe, J.Yu, N. Haruki, A. Kaneda, A. Machida, M. Kato, Melting Characteristics of Mixtures of Two Kinds of Latent Heat Storage Material, Japan J. of Thermophysical Properties, Vol. 25, No. 3 (2011) 136-142 (in Japanese)

8.4.6 Other thermal technologies

Figure 8-47 shows the relationship between melting point and latent heat for molten salt, organic material and hydrate, which are expected to be utilized as thermal materials. Erythritol and mannitol are also shown for reference.

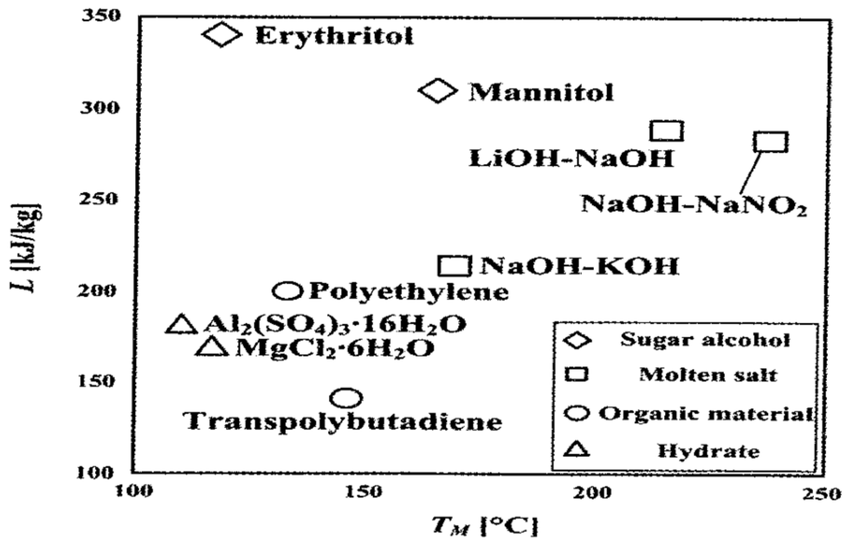


Figure 8-47: Relationship between melting point and latent heat (Horibe, 2011]

Horibe, 2011 A. Horibe, J. Yu, N. Haruki, A. Kaneda, A. Machida, M. Kato, Melting Characteristics of Mixtures of Two Kinds of Latent Heat Storage Material, Japan J. of Thermophysical Properties, Vol. 25, No. 3 (2011)

9 Korea

9.1 R&D Background of industrial heat pumps

More than 60 % of the total energy is consumed for the industrial application in Korea. A great portion of final energy in industrial field is to generate heat or provided as feedstock. So, a lot of activities have been done to improve efficiency or make advanced process in order to reduce primary energy consumption and green gas emission. The major directions of such activities are;

- Utilization of waste heat from industrial processes (reduce green gas emission and production cost) by hybridized heat source with renewables
- Production of hot water which can be directly used to the processes
- Extension of heat pump applications into advanced industrial processes formerly neglected to be a part of the processes

Under these circumstances, the application of industrial heat pump has gained much interest in these days by not only companies but also government agents.

The global heat pump market has been increased rapidly. More interest has been given to energy efficiency increase as one of the solution to urgent problems of energy cost and environmental effect. So far, the main fields of heat pump market have been heating/cooling system and hot water generation system. Therefore the researches and policies of government have been focused on these topics. It is true that the interest on industrial heat pump featuring high temperature operation range has gained relatively low interest. Furthermore, the retail energy prices of Korea have been maintained at low level. This makes the manufacturers less sensitive to the energy cost of the product. So the manufacturers pose inactive stance on the investment of energy efficiency facilities rather than productivity increase facilities.

There are well established test standards and installation guides for the heat pump for heating and cooling. And major manufacturers dominate that market with well-modularized, mass-produced products. However, the install scene for industrial heat pump has its unique requirements. So, system design and installation should be done to cover these things. It is true that industrial heat pump has weak points in standardization and mass production. This, further makes not only the manufacturers, but also installer and engineers to have much higher technical level ever before.

Despite of all of these adverse features of industrial heat pump, the confronting issues like global warming, the climate change convention, surging of energy prices, depletion of fossil fuel, and so on, have changed the working situation in industrial market, and the manufacturers have begun to consider adopting devices or facilities which are environmentally benign requiring less primary energy. Industrial heat pump has become one of the best solutions for the manufacturers.

The benefits of adopting heat pump in industrial process are

- Heat pump is one of the most optimum solutions to recycle waste heat of industrial processes
- Application of industrial heat pump can contribute to the reduction in green gas emission
- Since heat pump can use energy from air, sea water, underground water, or any other low temperature heat resources, the additional heat out of the total produced heat is classified as renewable energy

In the Korean hot water heat pump market, 50-60 °C hot water generation systems occupy most of the market share. In order to be applied to industrial process, the generation temperature should be increased up to 90 °C or above. And since heat pump systems also produce chilled water while producing hot water owing to their thermodynamic nature, process design considering both heating and cooling resources is required to maximize energy savings with heat pump. The concept of energy network has risen under this circumstance.

9.2 R&D programs of Korea

Energy R&D in Korea is supported largely by the Ministry of Trade, Industry and Energy (MOTIE). As a key operating agent, Korea Institute of Energy Technology Evaluation and Planning (KETEP) is running four major categories of Energy Efficiency and Resource Program, New and Renewable Energy Program, Power and Electricity Technology Program, Nuclear Power Program.

Heat pump R&D in Korea is categorized into Energy Efficiency and Resources Program. The scope of the program is to ensure effective accomplishment of the objectives of the governments Framework Plan for the Development of Energy and Resource Technologies for the Years 2006-2015, where key parts are energy storage, heat pumps, micro CHP, building energy, green cars, clean fuel, energy equipment, industrial process, CCS, and energy resources.

Heat pump technologies were categorized in the national roadmaps in Korea listed below.

- Environmental Energy Core Technology in National Technical Roadmap (NTRM) (2002)
- Environmental Energy Area in Innovative Technology Five-Year Master Plan (2004)
- Energy Efficient Technology of Unutilized Energy Applications in Energy Technology Ten-Year Roadmap by the Ministry of Commerce, Industry and Energy (MOCIE, a former MOTIE) (2004)
- The Seven-Runners Program for massive energy consuming equipment by MOCIE (2006)
- Korean National Green Energy Strategic Roadmap by MOTIE

1st roadmap (2009)	Solar power, Wind power, Fuel cell, IGCC, CCS, Energy storage, Electric power-IT convergence, LED, Nuclear power, Micro CHP, Green car, Superconductivity, Heat pump, Building energy
2nd roadmap (2011)	Solar power, Wind power, Fuel cell, Biofuels, CCS, High efficiency lightings, Clean fuels, Energy storage, Clean fossil fuel power, Smart grid, Nuclear power, Green car, Building energy, Heat pump, IGCC

9.3 Heat pump R&D cases

In this section, the R&D cases related with industrial heat pumps which have started or finished within the last 3 years are presented. In Korea, heat pump R&Ds are still bias to HVAC&R area, however, some researches that have potentials extended as hybrid heat source applications were introduced.

9.3.1 Development of a 30 kW grade compression/absorption heat pump producing high temperature hot water with waste heat

This application is to secure design and control technologies of compression-absorption hybrid heat pump that produces high-temperature water by using NH_3/H_2O mixture as a natural refrigerant. The goal is to develop a prototype of 30 kW class heat pump which produces hot water over 90 °C using waste heat of 50 °C from manufacturing process.

Although vapor compression cycle and absorption cycle are applied widely, there are limits for these cycles. The limitations come from various reasons like confined temperature increase, inflexible driving range, limited capacity control, degradation of heat exchange efficiency by large temperature difference between pure refrigerant and secondary fluid during condensation or evaporation, low coefficient of performance(COP) of absorption cycle, and other physical restrictions. In order to solve these weaknesses and shortcomings of current cycles, hybrid cycle that combines vapor compression and absorption cycle was proposed and a lot of researches are in progress.

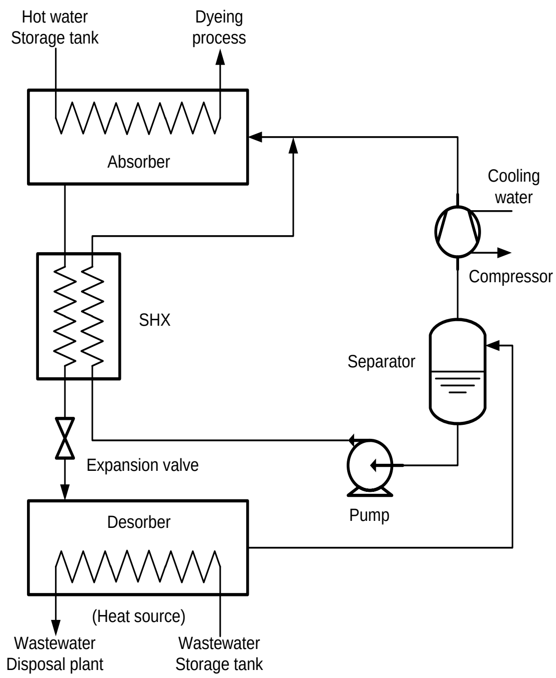


Figure 9-1: Schematic diagram of simplified compression/absorption heat pump system

A project was performed by a collaboration of a research center (Korea Institute of Energy Research: KIER) and a company (Shinsung Engineering). Through this collaboration, vapor compression/solution pumping system designed exclusively for prototype hybrid cycle including vapor-liquid rectifier design. The performance evaluation was initiated by steady-state performance simulation program, transient characteristics and control variables deduction, NH_3/H_2O concentration analysis. During the experimental evaluation, a variety of research activities for peripherals were carried out. After a long period of the optimization of each part, a prototype of 30 kW grade hybrid heat pump was produced with COP_H = 3.5 and hot water over 92 °C. This improved energy consumption efficiency 17 % compare to existing boiler when the efficiency of boiler was considered as 90 %.

Expected application area of this newly developed system is commercial facilities such as Sauna and Jjimjilbang (Korean-style dry sauna) where large capacity of heating and hot-water supply is required. This system is also applicable with connection to the facilities that generate a large amount of waste heat (ex. cogeneration plants) and can be utilized to district heating facilities in participating in a new town energy supply chain design. In an industrial complex, a large quantity of waste heat can be collected in order to utilize it as hot process water or heat source for air-conditioners for factories.

Figure 9-2: Prototype of a compression/absorption heat pump system

9.3.2 Demonstration of a high-temperature heat pump system with heat recovery from flue gases

This system effectively collects waste heat from low-temperature flue gases and utilizes this as heat source for high-temperature heat pump system that generates process hot water. The purpose of this system is to increase thermal efficiency of overall industrial boiler through exhaust gas heat recovery and heat pump.

Industrial factories and cogeneration plants produce high-temperature industrial process water by from boiler. In boiler, a large volume of flue gases under 250 °C that contain steam is discharged and thermal loss of boiler is mainly due to this exhaust gas. Therefore, many manufacturers install waste heat recovery system up to hot water of 85~90 °C and use it in preheating process to raise air temperature or boiler supply water. In case of using natural gases as a fuel, they contain few corrosives such as sulfur so manufactures can decrease the exhaust gas temperature below 60 °C under this point condensation of flue gases occurs. That means recovering more energy from latent heat of steam inside exhaust gas by lowering the temperature of exhaust gas, and water of 35~55 °C would be produced by latent heat recovery.

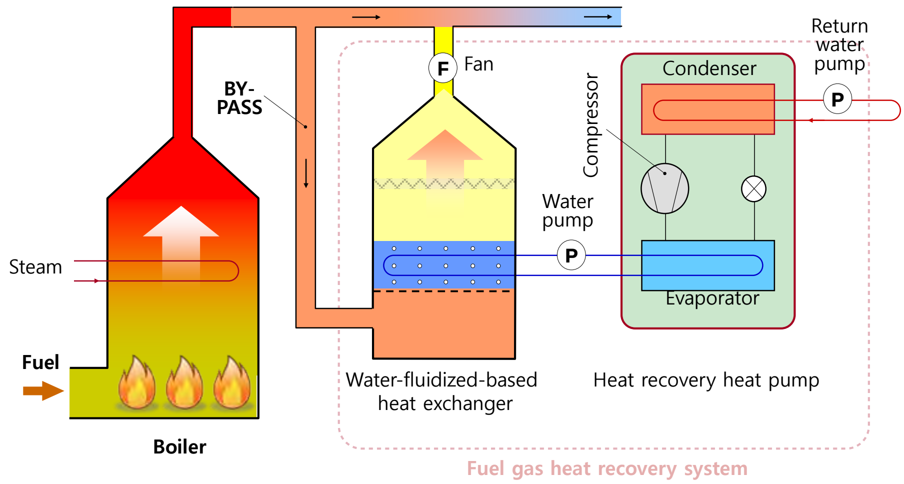


Figure 9-3: Schematic of heat pump system with flue gas heat recovery

Methane (CH_4), the main component of natural gas, generates water of 1.61 kg per cubic meter after combustion. Therefore, by collecting latent heat through condensation of all the steam inside combustion product to water, it is possible to collect additional heat of 868 kcal per cubic meter. At this point, condensing temperature of steam in exhaust gas varies from 50 °C to 60 °C depending on its excess air ratio.

In order to efficiently use recovered heat through above process, heat pump can be used. According to Korea Energy Management Corporation (KEMCO), about 40 thousands of industrial/heating boilers are installed in Korea. In addition, it is known that cogeneration plants using oil, natural gas, coal and other energy sources generate energy about 2,760 MW. However, the amount of waste heat energy inside of the exhaust gases from the plants has not been found yet.

A heat pump system with heat recovery from exhaust gas in order to utilize waste energy was installed in a food factory and its performance verification was carried out through demonstration operation. In this application, condensation heat recovery unit was installed to recover total heat of exhaust gas and its performance verification was carried out. Moreover, in connection with this heat recovery unit, a 30RT class high-temperature heat pump system was designed and produced. Demonstration operation started from winter season of 2012 and featured over 100 kW heating capacity and COP larger than 3.0. Furthermore, overall thermal efficiency of combined boiler and high-temperature heat pump system increased more than 8.2 % compare to conventional hot water boiler.

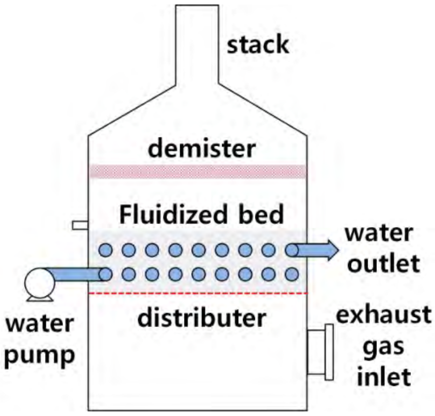


Figure 9-4: Schematic diagram of water-fluidized bed heat recovery system and its installation scene

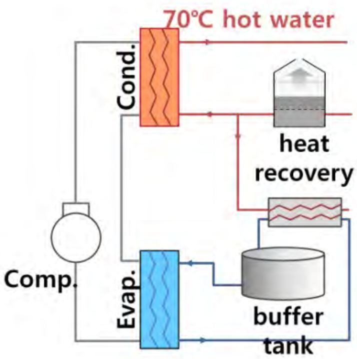


Figure 9-5: Schematic diagram of heat pump system and its installation scene

9.3.3 High-temperature heat pump for commercial drying process

Drying process is essential to various industrial fields such as chemical process, textile, paper manufacture, lumber production, electronics, wastes and other fields and it consumes a large amount of energy which takes over 7 % (6,356 thousands TOE) of industrial field energy consumption in Korea. In companies which have drying facilities use over 30% of their fuel consumption in dryer. Therefore, development of energy saving technology in this area will have great influence. The efficiency of conventional air-heating dryer is only about 30-50 %, however, the efficiency of optimally designed air-heating dryer can be raised up to 60-80 % which will remarkably contribute energy savings.

Application areas of heat pump are drying process (agricultural product, marine product, industrial product, etc.), high-temperature application field, exhaust heat recovery and other areas. Energy saving effect from heat pump complex dryer is estimated about 572 thousands TOE annually.

9.3.4 Geothermal heat pump system using R410A centrifugal compressor

Geothermal source has near constant temperature year-round which is different to the temperature of the surface of the earth or the atmosphere. Through summer season, temperature of geothermal source is usually lower than that of the atmosphere. So with coolant circulation it is possible to narrow operating temperature range of a heat pump which results in higher system efficiency (COP) compared to the conventional heat releasing method with cooling tower. Inversely, in winter season, temperature of geothermal source is usually higher than that of the atmosphere so it provides better heat source compare to air-source heat pump system which also brings enhanced efficiency.

For wide application of geothermal heat pump system in future, efficiency (COP) and capacity enhancement are necessary along with reduction in initial investment cost. So, research on enhancement of geothermal heat pump system was carried out that adopted centrifugal compressor which is easy to be scaled up and has higher efficiency compare to displacement-type compressor such as scroll or screw compressor which are applied to current geothermal heat pump. Trend for designing environment-friendly/high-efficiency refrigeration cycle with centrifugal compressor of 100 RT grade which was connected with high speed motor and oil-less bearing is actively attempted by leading companies such as Danfoss-Turbocor. In Korea, responding activity was needed for domestic market by developing centrifugal compressor technologies.

In this project, a 100 RT grade geothermal heat pump with oil-less centrifugal compressor was developed. The test run was performed at the central machinery room of KAIST in Daejeon after the installation of open and closed type geothermal system to the air-conditioning devices. By applying inverter-driven motor and gas bearing to a high speed rotor of centrifugal compressor, the developed oil-less centrifugal compressor has price competitiveness for mass production. In case of open type geothermal system, as underground water is used for heat source of heat pump, wide-Gap plate heat exchanger that strongly endures contamination was first developed and applied.

The key technologies are geothermal heat pump cycle design, high pressure aerodynamic design, high speed rotor design, oil-less bearing development, wide-Gap plate heat exchanger design, mold and product development of wide-Gap plate heat exchanger, etc. In addition, core element design technology of geothermal turbo heat pump was developed and reference on a 100 RT grade geothermal system was secured through field test. Moreover, technologies for production, operation and performance evaluation of centrifugal compression heat pump system were established. Other technologies were also secured such as oil-less gas bearing manufacture and test/evaluation, inverter-driven high speed motor design and production, heat exchange technology for fluids that have high viscosity or fouling is concerned. Heat pump system from this project showed heating COP of 4.1 and cooling COP of 6.9.

Expected benefits with heat supply system using geothermal source are environmental improvement (energy saving, reducing CO_2 emission, etc.), new and renewable energy utilization and so on. Because of those positive effects, this system is applicable to air-conditioning system for building and green house complex air-conditioning and heat supply. A 100RT grade heat pump unit with centrifugal compression technology is expected to be highly competitive where screw compressor types are currently dominant in the market. Moreover, by developing wide-gap plate heat exchanger technology, it will be simple to use underground water, high viscosity fluid or highly contaminated heat source directly.

With this improved efficiency of heat pump system, payback period become shorter so that the rapid penetration of geothermal air-conditioning system is expected. The 100RT grade high efficiency centrifugal compression technology can be applied widely such as heat pump systems and chillers that utilize other heat source and air-conditioning system for high efficiency/environment-friendly buildings.

9.3.5 Double effect absorption heat pump development for low-temperature sewage waste heat recovery

In order to obtain heat from unused low-temperature heat (sewage treatment temperature lower than 20 °C) in absorption heat pump for heating in winter season, and to make hot water up to temperature level of 70 °C, a double effect absorption heat pump system needs to be introduced which has double evaporation-absorption process. Under low temperature heat source, COP becomes low because system only utilizes half of its refrigerant capacity which takes heat from low-temperature heat source. In such a case, system can form double effect cycle that renews refrigerant by condensing it and yields COP of 1.6. The development of such technology can be applicable to wide range of temperature level for absorption heat pump cycle.

Core technologies are double evaporation-absorption cycle that raise heat rejection temperature by accepting low-temperature heat source and double effect double absorption heat pump technology to increases COP.

The developed system make it possible to utilize unused low-temperature energy by applying a heat pump with absorption cycle which was conventionally used for air cooling facility that releases low-temperature heat which is slightly hotter than the atmosphere. In addition, by a prototype demonstration of absorption cycle that was already been patented but difficult to commercialize, it was possible to utilize unused energy. The target performance was checked through the performance test of the prototype and this development of absorption cycle technology enlarges the operational temperature range of absorption heat pump cycle.

9.3.6 Development of hybrid water source heat pump using solar heat

In this project, a hybrid heat pump using solar heat was built with 4 solar collectors which were connected in the form of 2 rows by 2 columns providing 30 % of heat demand of evaporator and the number of PCM module was 220. A single heat pump system showed cooling capacity of 10.5 kW and cooling COP over 3.2 when cold supply water flow rate and temperature was 50 lpm (liter per minute) and 18 °C respectively.

Heating capacity was 13 kW and heating COP was over 3.0 when hot supply water flow rate and temperature was 40 lpm and 18 °C respectively.

At the test of PCM which is inside the solar heat storage tank, the temperature difference of evaporator was much smaller at mode 1 which uses latent heat of PCM than that of evaporator at mode 2 which doesn't. When comparing the reaching time to the temperature level of 7 °C, mode 2 take 30 minutes and mode 1 with PCM takes 200 minutes (about 3 hours) which is feasible for heat pump operation.

When operating hybrid heat pump using solar heat until 3 P.M. with high solar radiation, heating capacity over 13 kW and COP over 3.3 were achieved. The capacity and COP decreases after 3 P.M.

Henceforth, a hybrid heat pump system that utilizes solar heat as a heat source for evaporator is expected to become competitive product that can save a large amount of energy.

9.3.7 Demonstration of a geothermal heat pump system and ground heat exchangers which are installed to the substructure of buildings

The introduction of geothermal air-conditioning system in Korea was relatively late compare to the developed country but the government has invested a lot of money on this and the number of demonstration cases has been increasing. As ground heat exchangers take more than 50% of the installation cost of geothermal air-conditioning facilities, research and development is required in order to lower installation cost and improve performance. Technological problems are listed below that disturb rapid propagation of geothermal heat pump system using ground heat exchanger which is installed to the substructure of buildings

1. Lack of data for standard design of ground heat exchanger and system
2. Lack of construction methods that consider geological structure and climate condition of Korea
3. Lack of data for capacity calculation method and construction cost of ground heat exchanger
4. Lack of demonstration data to prove reliability overall system and ground heat exchanger

Therefore, performance analysis, system performance evaluation, design data and construction standard establishment and other researches are required for ground heat exchanger which is installed to the substructure of buildings.

Ground heat exchanger which is installed to the substructure of buildings can be divided into two type that are energy pile and energy slab. Energy pile can be utilized as ground heat exchanger by inserting U-tube, double U-tube, W-tube or coil-shaped pipe inside of empty space in concrete or steel pile. Energy slab can also be utilized as ground heat exchanger by installing heat exchanger horizontally to the foundation slab under the building. Installation cost of ground heat exchanger for large buildings is low because these buildings already have many piles so this method fits to Korea where a lot of skyscrapers and apartment exist.

Through this project, a 58RT grade energy pile/energy slab demonstration plant was built and data collection and performance test for demonstration plant were carried out for a year. An energy pile/energy slab design program was also developed. Construction and design standard were established for energy pile/energy slab geothermal air-conditioning system which save 9 % of construction cost compare to vertical closed type.

The developed technology is expected to be applied for buildings in downtown (installation of vertical type heat exchanger is incapable due to narrow space), buildings in reclaimed land (energy pile/energy slab), apartment complexes and buildings (reduction in installation cost of geothermal air-conditioning system).

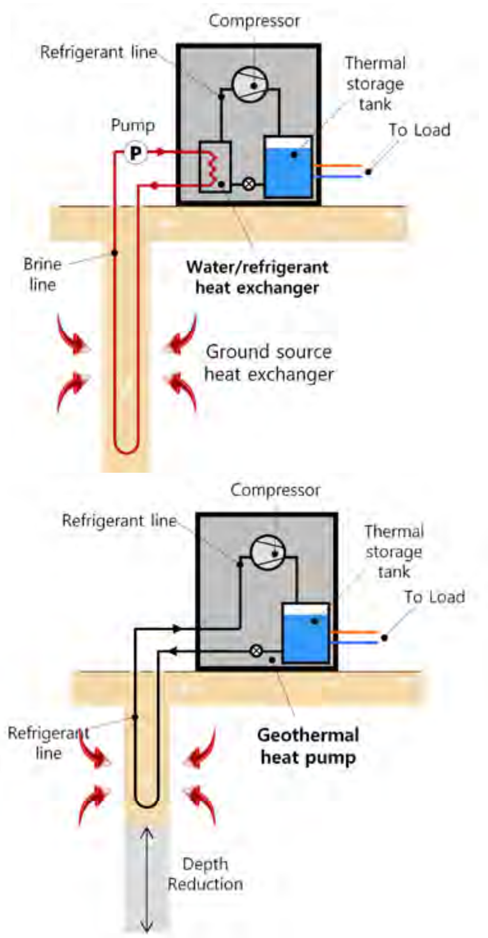
9.3.8 Technology development for vertical closed type direct exchange (DX) geothermal heat pump system

Among renewable energies, the demand for thermal energy utilization has been kept increasing. Among geothermal air-conditioning market, the installation of geothermal heat pump in building sector is popular but that of residential scale geothermal heat pump is still delayed because of the economic feasibility and construction ability. This project developed technologies for the direct exchange geothermal heat exchanger that connects underground loop with refrigerant loop which is different from conventional system that has 3 loops (refrigerant, indoor, and underground water circulation) Through this construction, refrigerant flows directly to underground where direct heat exchange occurs and this method is highly efficient because underground circulation pumps are not necessary.

Direct exchange(DX) geothermal heat pump technology does not use water/refrigerant heat exchanger but installs refrigerant circulation coil into the underground so as to gain heat directly from geothermal source and this method is expected to show excellent performance compare to conventional vertical closed type system which uses HDPE material U-tube. For the DX system, design factor, heat recovery and heat release theory were developed. In addition, researches for source technology were carried out through performance test and performance evaluation for the commercialization in Korea.

Research development details are followings. Basic specification was determined for the installation of direct exchange geothermal heat exchanger and an installation procedure for this was developed. It proceeded through two times of constructions. The performance test was done for DX underground heat exchanger which was connected to a 3RT grade geothermal heat pump system and 100 hours continuous operation was carried out. Using performance indices that were obtained from performance test, long-term driving performance was predicted. In addition, a program was developed that can analyses direct exchange geothermal heat exchanger in connection with TRNSYS which is commercial program. With the result of geothermal heat exchanger development, a guideline for construction method was made and arranged in order to make use of it.

Developed technologies can be applicable for air-conditioning system in residential and small buildings. They can also be applied to large buildings if modularized and distributed. These can be applicable to renewable heat energy propagation business in connection with 'Renewable Heat Obligation (RHO)' in Korea and to single house in connection with 'One Million Green Homes Program'. Therefore small business-oriented market is expected to form.



(a) Conventional GSHP (b) DX GSHP

Figure 9-6: Comparison of a conventional HDPE GSHP and a DX GSHP

10 The Netherlands

R&D in the Netherlands on industrial process innovation is for a large part supported by the Ministry of Economic Affairs through the ISPT Innovation Program. Major players in this program are the Dutch process industry, TU-Delft and ECN. The focus on heat pumping technology as one of the key technologies is logical and has a long track record starting with basic research now reaching the pilot phase.

More than 80% of the total energy use within the Dutch industry consists of the need of heat in the form of steam at different pressure levels and for firing furnaces. The total industrial heat use (530 PJ/year) together with exothermic heat from chemical reactions is eventually released to the ambient atmosphere through cooling water, cooling towers, flue gasses, and other heat losses. We call this heat loss ‘Industrial waste heat’. A first, most logical, solution to this waste heat problem is to reuse the heat within the same process through process integration or at the same site. In an ideal process that will be within the process unit otherwise technology will have to be applied to transform the heat coming out of the process to a common carrier. This being high pressure steam or electricity generated by a high temperature heat pump or an ORC.

European R&D and the goals set are defined by the European Technology Platform on Renewable Heating and Cooling (RHC-Platform) in their recent Strategic Research and Innovation Agenda for Renewable Heating and Cooling. Industrial heat pumps are an important part in that strategy. The report is presented to the European Commission as advice on which technology to support.

In this chapter ISPT and RCH are discussed followed by a general description of research ande development projects. Please note that for confidentiality reasons, exact details of the process and the control and design alternatives for these projects are not provided and only described in general terms.

10.1 TKI- ISPT Innovation Program

Mid 2012, ISPT founded its Topconsortium Knowlegde and Innovation for Processing (TKI-ISPT) This TKI connects the chemistry, agriculture and food, energy, and biobased economy sectors.

The TKI Processing takes care of the innovation contracts for:

Topsector energy	Energy reduction in the industry (EBI) and Biorefinery
Topsector chemistry	Process Technology
AgriFood	Sustainable Manufacturing
BioBased Economy	TKI-ISPT executes the biorefinery part for the innovation contracts of the topsectors

DSTI (Dutch Separation Technology Institute) is a partnership in which industry, universities and knowledge institutes work closely together to develop breakthrough technologies for application in different sectors of the process industry. “Together we can take bigger steps, have more impact, and share the risks”.

So far, 45 companies from the Food, Pharmaceutical, Oil and Gas, Chemical and Process Water Industries and 8 knowledge centers, have joined DSTI. The estimated budget is EUR 65 million for the next 5 years. The research program covers all aspects from (fundamental) knowledge generation to technology implementation.

The program contributes to the process industry’s sustainability objectives in terms of product value, efficiency, energy savings, and the reduction of emissions through the generation and application of new knowledge in collaborative development and demonstration programs.

TKI-ISPT has been working on translating the plans of the innovation contracts into a coherent set of activities. These activities are executed within 14 cross-sectoral clusters of which for interest for heat pumps:

- Energy Efficient Bulk Liquid Separation
- Drying and Dewatering
- Utilities & Optimal Use of Heat
- Process Intensification
- Sustainable Business Models
- Maintenance

From PPP-ISPT and the TKI Action-program 2012 several projects are running which will be finalized leading to pilot projects 2014/2015, with the focus on the application of newly developed prototype heat pumps in chemical industry and paper and pulp.

- Utilities and optimal use of heat

This cluster aims to:

- reduce (fossil) energy use for the production and use of industrial heat;
- improve competitiveness of stakeholders by reduction of energy costs;
- create new market possibilities for equipment manufacturers;
- improve the energy efficiency of industrial processes.

The estimated energy saving potential equals 100 PJ/year. The use of heat within industry is responsible for more than 80 % of the final energetic energy use. Heat is used for heating feedstock, enable reactions, and to drive separation processes. The required temperature level spans a broad range, depending on the specific process. At the same time, large quantities of waste heat are released to the ambient atmosphere that cannot be reused in an economical way.

- *Reuse of waste heat:*

The recovery and reuse of industrial waste heat is hindered by technological and economic barriers. Several possible paths can be envisioned that start from economical heat recovery of waste heat. Next, waste heat can be converted into process heat, process cold or power. Finally, heat storage and distribution can be realized.

All activities carried out within this cluster are related to:

- o Technology scouting
- o Feasibility studies
- o Research & Development
- o Dissemination.

The main bulk separation processes within chemical and refining industry are distillation, absorption/desorption, and crystallization. The thermodynamic efficiency of these processes is usually very low (<10 %). Environmental implications and increasing energy costs demand improvement of energy efficiencies. Significant reductions in energy consumption are expected by using innovative heat pump concepts for removal and supply of heat from/to a separation process. The efficiency of e.g. distillation systems can be increased by heat integration of reboiler and condenser using high lift high temperature heat pump concepts.

10.2 European Technology Platform on Renewable Heating and Cooling (RHC-Platform)

RHC-Platform has produced the present Strategic Research and Innovation Agenda for Renewable Heating and Cooling [Landolina, 2013].

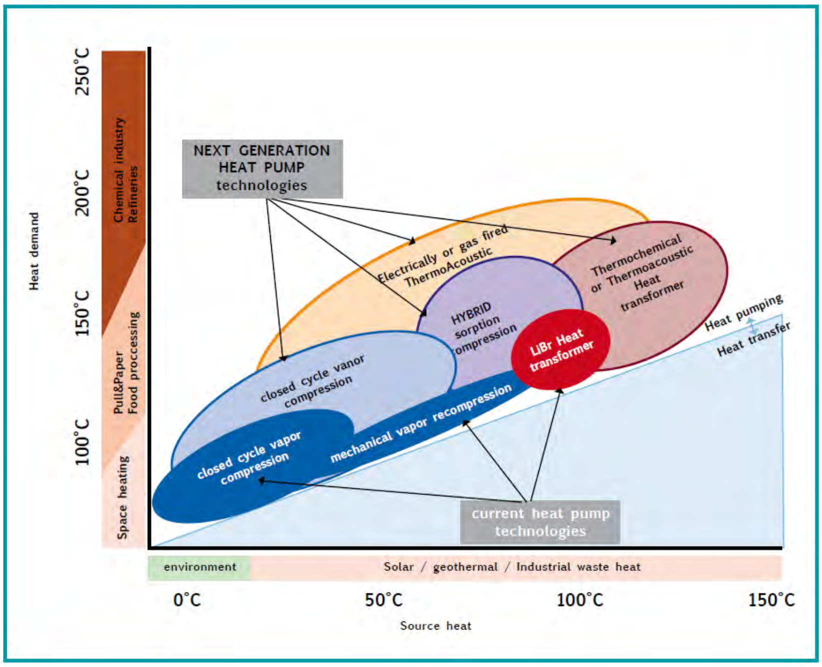


Figure 10-1: Heat pump technologies and their operating temperatures

Figure 10-1 plots the driving temperature ("source heat") against the delivered temperature ("heat demand") for various heat pump technologies. Current vapour compression systems deliver heat at a maximum temperature of ~80°C. New vapour compression systems should use low GWP synthetic refrigerants or natural refrigerants (such as butane or water) to reach temperatures of up to 150°C. Components and materials should be developed to achieve temperature lifts of up to 70 K. The use of water as the working medium allows the heat pump to be integrated into industrial heating processes. Alternative concepts such as heat transformers are interesting when a heat source of more than 90°C is available. Current systems use thermally-driven compression to upgrade waste heat from 100°C to 140°C. Reversible solid sorption reactions, such as the reaction of salts and ammonia are applicable for heat transformation at temperature levels up to 250°C. Similarly, thermoacoustic systems can accept a range of driving temperatures and output heat also in a wide temperature range. A hybrid system can be created by adding mechanical compression as driving input to a heat transformer, allowing for use of low temperature waste heat and still generating temperature lifts of up to 100 K.

A broader range of operating temperatures and higher temperature lifts are needed to increase the application potential and the energy saving potential that heat pumps offer. The end users' demands extend beyond the required temperature and cost of the system to topics such as the toxicity & flammability of the working medium and the reliability of the system. No single heat pump technology can cover this entire range of demands, meaning different heat pump technologies should be developed in parallel. The main objective is the exploration of alternative thermodynamic cycles for heat-pumping and heat transforming for different industrial applications, with the goal to increase the operating window of industrial heat pumps so that they can deliver heat at medium pressure steam levels (app. 200°C).

Not only will these improvements allow larger energy savings, but they will also unlock the benefits of economies of scale for the European heat pump industry.

The Figure above shows four types of technology that can potentially overcome the aforementioned limitations in terms of temperature range and lift. Not only these improvements will allow larger energy savings, but simultaneously it will unlock the benefits of economies of scale for the European heat pump industry. Apart from their operating temperatures, these technologies have different levels of maturity. They form a chain of new heat pump technologies in which the mechanical vapour compression systems with new working fluids are the next generation to be tested at a small scale in real applications for higher delivery temperatures. The salt-ammonia sorption and thermoacoustic heat transformers are in the development stage of laboratory prototypes, proofing the concept of the system. The hybrid sorption-compression systems and gas fired thermoacoustic heat pumps are in the stage of proofing the principle.

Conventional heat pumps provide limited temperature lift. Therefore heat pumps are required, which can operate at the temperature levels of the column and provide the desired temperature lift between condenser and reboiler. These heat pumps are presently not commercially available and therefore need to be developed. The project covers the theoretical and experimental verification of the performance of innovative heat pumps integrated in a separation process. Presently three innovative heat pumps are identified, but early on in the project an assessment is made whether additional systems should be considered. The three heat pump concepts to be covered in the program and their main technological challenges are the following:

1) Thermo acoustic heat pumps: achieve the required efficiency with a design integrated within a separation process.
2) Thermochemical heat pumps: identify the proper solid/vapor combination and ensure stability and continuous heat supply.
3) Compression-resorption heat pumps: manufacture compressors that can operate under “wet” conditions. The project is setup in two phases: Phase 1: Feasibility and heat pump selection Phase 2: Testing model heat-pump systems under reference operation conditions

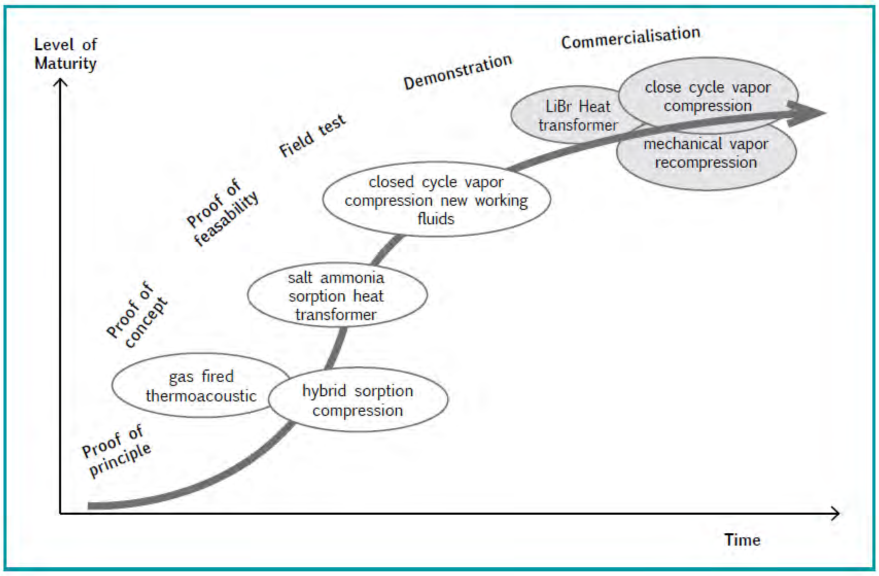


Figure 10-2: Development stages of new concepts for industrial heat pumps (source: RHC-Platform)

In their advise to the Commission the RHC Platform [EU, 2013] have proposed:

	Research and Innovation Priorities	Predominant type of activity	Impact
CCT.12	Enhanced industrial compression heat pumps	Development	By 2020
CCT.13	Process integration, optimisation and control of industrial heat pumps	Demonstration	By 2020
CCT.14	Improvements in Underground Thermal Energy Storage (UTES)	Demonstration	By 2020
CCT.15	Improvement of sorption cooling from renewable energy sources	Development	By 2025
CCT.16	New concepts for industrial heat pumps	Research	By 2030

CCT.12	Enhanced industrial compression heat pumps
Objective	Development of advanced compression refrigeration cycles based on novel working fluids for use in medium temperature industrial applications (condensation temperatures up to 150 °C and evaporation temperatures up to 100 °C). Applications of these novel heat pumps include process heat generation as well as waste heat recovery in industrial processes yielding substantial increases in energy efficiency. R&D topics to be addressed in this context comprise: • new working media (low GWP, non-inflammable) or natural refrigerants (water), • improved compressors and lubrication methods for high evaporating temperatures (up to 100°C), • heat exchangers with improved design for direct using of condensing gases (flue gas, exhaust air, drying processes, etc.).
State-of-the-art	Current vapour compression systems deliver heat at a maximum temperature of ~80 °C.
Targets	• Carnot efficiency of at least 0.35 • At least 2 demonstration projects should be realised by 2020. • Condensation temperatures up to 150°C • Temperature lift up to 60 K • Energy saving up to 30% • Cost target heat pump unit: 200 to 300 Euro/kW
Type of activity	20% Research / 60% Development / 20% Demonstration

CCT.13	Process integration, optimisation and control of industrial heat pumps
Objective	Development and demonstration of electrically and thermally driven heat pumps in individual industrial applications as well as in combination with district heating and cooling networks including thermal energy storage. R&D topics to be addressed comprise: • classification of processes (temperature levels, time-based energy demand, etc.), • process integration of industrial heat pumps (control and hydraulic design), • impact of heat pumps on existing process (dynamic behaviour), • selection of components (refrigerant, compressor, heat exchangers etc.) for the process identified,
State-of-the-art	First prototypes of compression heat pumps with evaporation temperatures of up to 40°C and condensation temperatures of up to 80°C are available but still need to be demonstrated. First prototypes of absorption heat pumps using new working pairs without crystallisation effects are available, but not demonstrated yet in real-life operating conditions.
Targets	• 5 lighthouse projects with a capacity of minimum 1 MWth implemented by 2020 • Compression heat pump: minim sCOP of 5, energy savings of at least 30% • Absorption heat pump: minimum sCOP of 1.5; energy savings of at least 50% • Cost target on system level for electrically driven heat pumps (unit plus installation): 400 to 500 Euro/kW
Type of activity	30% Development / 70% Demonstration

CCT.16	New concepts for industrial heat pumps
Objective	A broader range of operating temperatures and higher temperature lifts are needed to increase the application potential and the energy saving potential that heat pumps offer. The end users' demands extend beyond the required temperature and cost of the system to topics such as the toxicity & flammability of the working medium and the reliability of the system. No single heat pump technology can cover this entire range of demands, meaning different heat pump technologies should be developed in parallel. The main objective is the exploration of alternative thermodynamic cycles for heat-pumping and heat transforming for different industrial applications, with the goal to increase the operating window of industrial heat pumps so that they can deliver heat at medium pressure steam levels (app. 200°C). Not only will these improvements allow larger energy savings, but they will also unlock the benefits of economies of scale for the European heat pump industry.
State-of-the-art	The efficiency of any heat pump system increases as the temperature difference, or "lift", decreases between heat source and destination. Efficiently providing heat for industry at temperatures higher than 90°C with heat pumps is difficult. Industrial heat pumps (for heating purposes) currently consist of closed cycle vapour compression, open cycle mechanical vapour recompression and Lithium Bromide (LiBr) heat transformers.
Targets	• Delivery temperature up to 200°C • Temperature lift ≥ 70 K • Energy output compared to current technology ≥ 20%
Type of activity	70% Research / 30% Development

10.3 Technological developments

Before 2005, heat pumps were merely refrigeration plants where pressures are increased to deliver condensing heat at temperatures of 35°C up to 50°C. This operation range also depends on the evaporation temperature, efficiency and pressure ratio. The refrigeration compressors have a design pressure of 25 bar. This is also a limit for higher condensing temperatures. The large manufacturers of industrial refrigeration in the Netherlands, i.e. GEA-Grenco with their seat in Den Bosch and IBK from Houten, have discovered this new market of high temperature applications and already executed projects (see factsheets in chapter 4). A large application potential of industrial heat pumps is still not used because of these limited supply temperatures of about 100°C of commercially available heat pumps. If these supply temperatures could be increased, more industrial processes could be improved in their energy efficiency. The main reason for the limited temperatures has been the absence of adequate working fluids [Reissner, 2013].

10.3.1 CO_2 – Heat Pump

Beginning of 2000 the refrigeration industry is introducing CO_2 again as refrigerant and secondary refrigerant. CO_2 is a natural refrigerant without ozone depletion potential and with a low global warming potential. It is therefore a sustainable alternative for the synthetic refrigerants such as the HFC types.

Since CO_2 is a high pressure refrigerant, the refrigeration industry had to develop equipment with design pressures up to 45 bar. It is this development that has led to the construction of 50 bar industrial compressors. Using these compressors with ammonia or HFC like R134a as refrigerant, high temperature heat pumps (HT heat pumps) can be produced for industrial purposes. Condensation heat at temperatures up to 80°C can be delivered in a large variation of capacities with good efficiency.

HT heat pumps are also executed with CO_2 as refrigerant in a transcritical cycle. Larger units for water heating from 10° up to 70°C are available in a range up to 120 kW running with any heat source and can even produce cooled water (8°C). Essential is that the CO_2 at condensing pressure can be strongly cooled in order to maintain a sufficient efficiency. This is possible by a process flow that starts to heat up at e.g. 15°C. The COP of CO_2 can be higher than ammonia in case of high temperatures differences. Compressor sizes for these high pressures are however limited available.

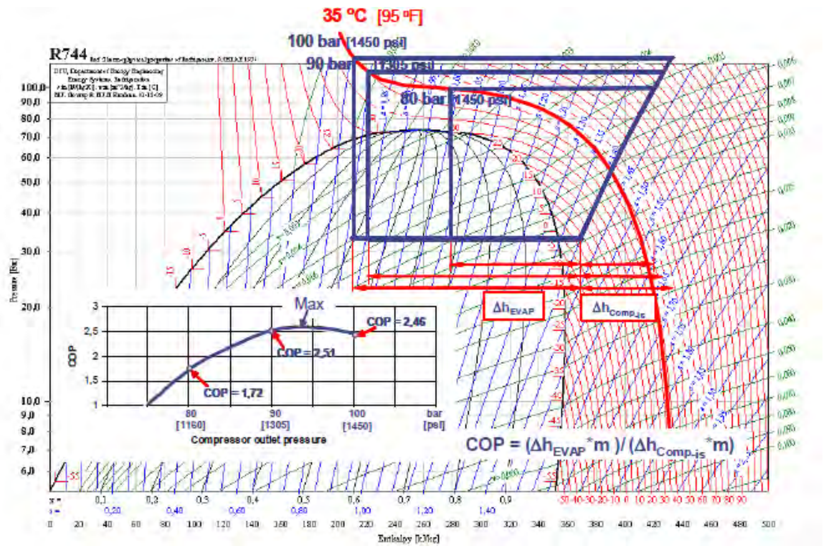


Figure 10-3: Efficiency of the CO_2 heat pump cycle, depending upon the discharge pressure [source HPC]

10.3.2 n-Butane heat pump

With the search into natural refrigerants for heat pumps the refrigerant, n-butane is regarded as a proper medium in high temperature heat pumps with condensing temperatures up to 120°C. These temperatures can be reached in standard 25 bar compressors. This type of HT heat pump is based on conventional, reliable refrigeration design with special safety attention and features for safety. Several feasibility studies have been carried out in industry and refrigeration contractors nowadays offer the HT heat pumps.

The feasibility studies show the technical and economical implications that arise when integrating the n-butane heat pump in existing installation. To integrate a heat pump it is necessary to redesign the original process and thus the equipment (heat exchangers, process layout). This should clearly be a task for manufacturers and suppliers of process equipment.

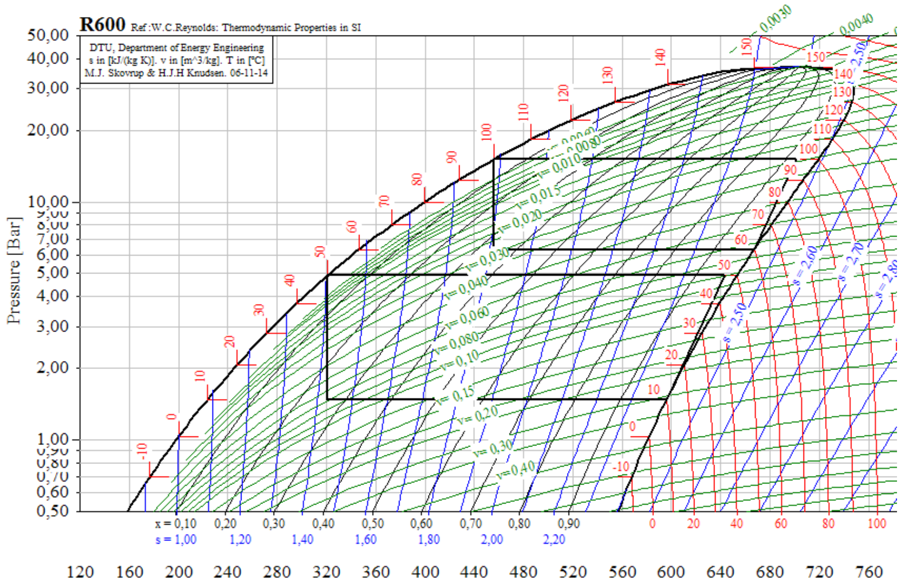


Figure 10-4: n-Butane heat pump cycle (at 60/100°C: COP=7.1 and at10/50°C: COP=6.8) (source GEA-Grenco)

As can be seen in Figure 10.4, the n-butane gas is compressed in the gas-liquid area of the n-butane Mollier (log p-h) diagram. Therefore it is necessary to preheat the suction gasses before they enter the compressor. This can be executed in heat exchangers that simultaneously heats up the suction gas and cools down the liquid after condensation. This is a regular design aspect in refrigeration installations.

10.3.3 New refrigerants

An interesting paper is presented at the 11th Heat Pump Conference in Montreal 2014 [Reissner, 2013], where it is stated that an ideal working fluid should be non-flammable, non-toxic and should have a low GWP, no ODP and a high critical temperature. Four ideal working fluids are identified: LG6, MF2, R1233zd and R1336mzz.

Table 10-1: Properties of ideal working fluids for high temperature use [Reissner, 2013]

Working fluid	T_{crit} [°C]	Flammable or toxic	ODP	GWP
R1233zd	166	no	0.0003	6
R1336mzz	171	no	0	9
LG6	>165	no	0	1
MF2	>145	no	0	<10

Important producers of these new working fluids with high condensation temperatures and low GWP are Honeywell, Siemens en Dupont. First pilots are reported of.

Interesting is the development of LG6 by Siemens showing a temperature lift of 50K with an experimental COP of 4.8.

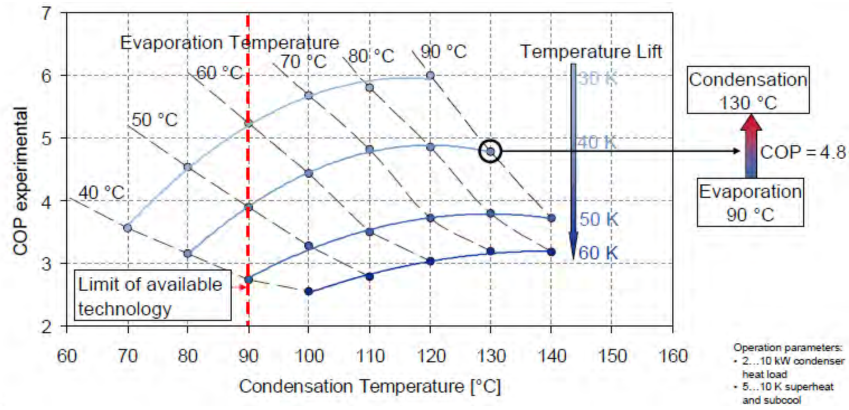


Figure 10-5: LG6 Siemens

At a presentation Dupont even claims better results with DR2.

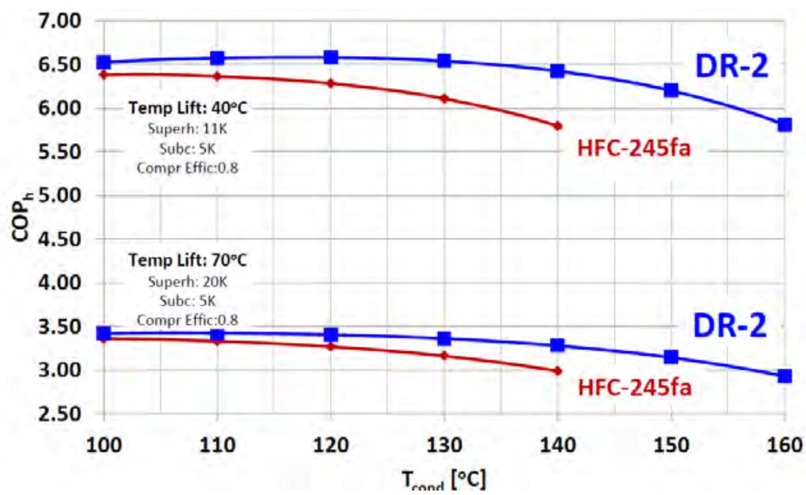


Figure 10-6: DR-2 Dupont

Solstice™ L41 from Honeywell is based upon R-32 as an alternative for R-410a and already used by several heat pump manufacturers, the largest application being by Friotherm in the district heating heat pump in Drammen (Oslo). R-1234yf will be applied by ETP in the Netherlands.

R-410A Alternatives

Refrigerant Supplier	Designation	Composition	(Mass%)	GWP	ASHRAE Class	Thermo Performance* Capacity	Efficiency
Arkema	ARM-70a	R-32/R-134a/R-1234yf	(50/10/40)	482	A2L	-15%	3%
Daikin	D2Y-60	R-32/R-1234yf	(40/60)	272	A2L	-20%	2%
DuPont	DR-5	R-32/R-1234yf	(72.5/27.5)	490	A2L	0%	1%
Honeywell	L-41a	R-32/R-1234yf/R-1234ze(E)	(73/15/12)	494	A2L	-6%	2%
Honeywell	L-41b	R-32/R-1234ze(E)	(73/27)	494	A2L	-9%	2%
Mexichem	HPR1D	R-32/R-744/R-1234ze(E)	(60/6/34)	407	A2L	-1%	0%
Daikin/National	R-32	R-32	(100)	675	A2L	8%	1%
National	R-32/R-134a	R-32/R-134a	(95/5)	713	A2L	5%	1%
National	R-32/R-152a	R-32/R-152a	(95/5)	647	A2L	3%	1%

* Relative to R-410A 4C ET / 38C CT

10.4 Running R&D Projects

An analysis was made of distillation heat pump potential in the Netherlands, leaving out columns that do not cross the pinch and oil refinery columns. The data show that the total heat pump potential is in the order of 2.4 GW and that the average temperature lift over the column is 59 °C.

Conventional heat pump cycles are driven by compressors or blowers depending on the required volumetric capacity and pressure ratio or temperature lift. The economic range for the VRC configuration driven by a compression heat pump is limited to columns with a temperature difference of about 300 °C. The heat pump which has to meet these requirements has to operate in a temperature window of 100 to 250 °C. The required temperature lift should be in the order of 50-100 °C. The heat pumps that are available nowadays are not able to fulfill both requirements.

New developments in distillation heat pump technology are therefore aimed at novel heat pumps with a higher economic range and at new heat integrated configurations. In the Netherlands these developments are:

- Thermo Acoustic Heat Pump at ECN
- Compression Resorption Heat Pump at TU Delft
- Adsorption Heat Pump
- Heat Integrated Distillation Columns at TU Delft

10.4.1 Thermo Acoustic Heat Pump

Heat transformers can be applied in cases where waste heat is available at sufficient high temperatures (> 90-100 °C). The advantage of these concepts is that they don't require additional energy to drive the system. Typical efficiencies are 25-30 %, meaning that this fraction of the waste heat can be reused in the process. Disadvantage of a heat transformer is that the other part of the waste heat still needs to be cooled to the ambient atmosphere. The general concept of a heat transformer is depicted in Figure 10.7 below.

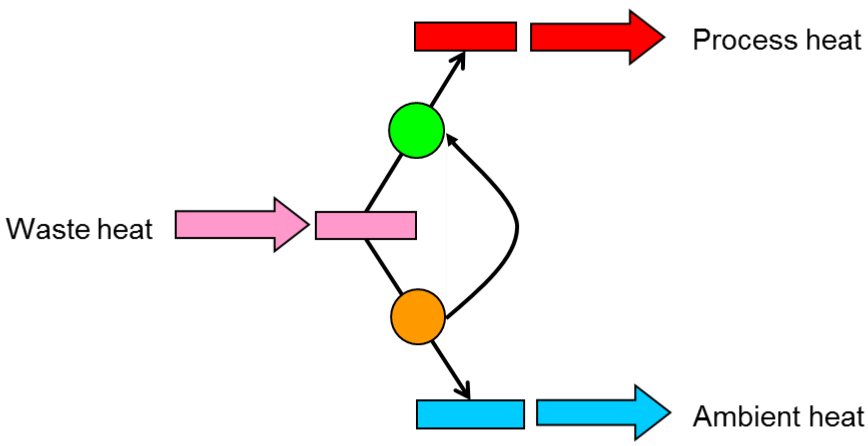


Figure 10-7: Thermodynamic concept of a heat transformer

Two technological principles are being applied at ECN to realise this heat transformer. These principles are based on thermoacoustics and thermochemistry.

Thermo Acoustic Heat Transformer

Thermoacoustic (TA) energy conversion can be used to convert heat to acoustic power (engine) and to use acoustic power to pump heat to higher temperature levels (heat pump). The systems use an environmentally friendly working medium (noble gas) in a Stirling-like cycle, and contain no moving parts. Although the dynamics and working principles of TA systems are quite complex and involve many disciplines such as acoustics, thermodynamics, fluid dynamics, heat transfer, structural mechanics, and electrical machines, the practical implementation is relatively simple. This offers great advantages with respect to the economic feasibility of this technology.

When thermal energy is converted into acoustic energy, this is referred to as a thermoacoustic (TA)-engine. In a TA-heat pump, the thermodynamic cycle is run in the reverse way and heat is pumped from a low-temperature level to a high-temperature level by the acoustic power. This principle can be used to create a heat transformer, as depicted in Figure 10.8.

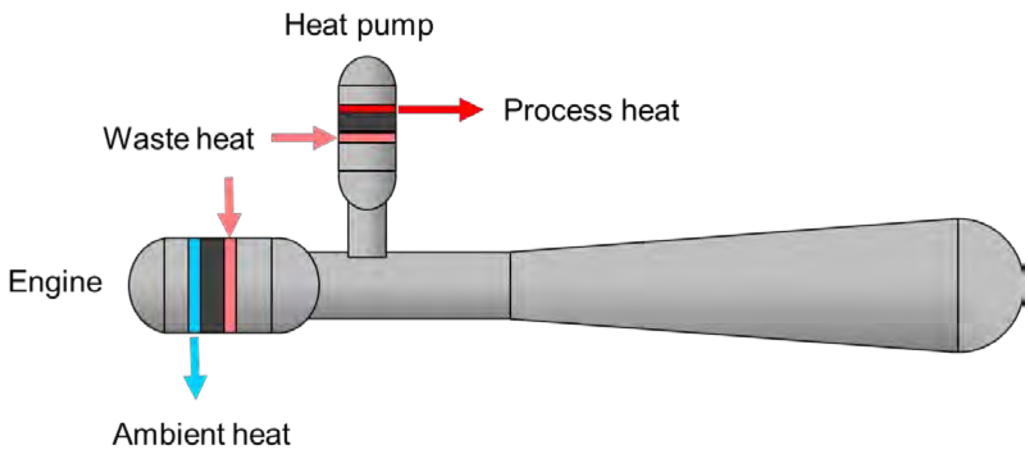


Figure 10-8: TA heat transformer

The TA-engine is located at the left side and generates acoustic power from a stream of waste heat stream at a temperature of 140 °C. The acoustic power flows through the resonator to the TA-heat pump, located on top of the resonator. Waste heat of 140 °C is upgraded to 180 °C in this component. The total system can be generally applied into the existing utility system at an industrial site. The picture below gives an experimental setup of a 10 kW system

Figure 10-9: Thermo acoustic heat transformer at ECN

Thermochemical heat transformer

Thermochemical heat pumps use the heat released/dissipated during ad/desorption of gas in solids to create a heat pump cycle. This process consists of an alternating cycle consisting of a discharge phase and a regeneration phase, in which the solids are generating heat during adsorption of the gas, respectively require heat to release the adsorbed gas from the solid.

The system operates at three temperature levels. These temperature levels are the waste heat temperature, the ambient temperature and the temperature of the upgraded heat. The system consists of two reactors, each containing a different salt. For this specific system use is made of lithium chloride as low temperature salt (LTS) and magnesium chloride as the high temperature salt (HTS). Ammonia vapour is exchanged between these two salts. Industrial waste heat is used to free the ammonia from the LTS. The ammonia flows, driven by the pressure difference between the two reactors, to the HTS and reacts with the HTS. This exothermic reaction delivers heat at high temperature. During the regeneration step the ambient temperature cools the LTS and the waste heat heats the HTS. The ammonia vapour flows back to the LTS under these conditions. The scheme below shows the implementation of such a system in an industrial process. Both the LTS and HTS reactor vessel are built in twofold in order to achieve a continuous system. A switching control system determines whether the above pair of reactor vessel are loading (regenerating) or discharging. The other vessels are running in the reverse process.

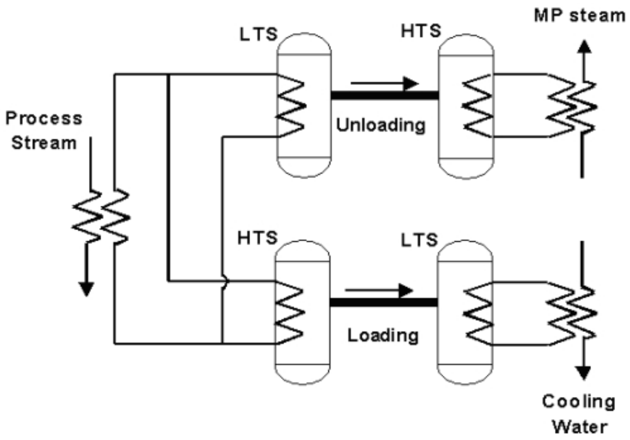


Figure 10-10: Thermochemical heat pump transformer

Figure 10-11: Thermochemical heat pump component testing

Figure 10.11 shows picture of a reactor element that is used to measure the heat uptake and release by the salt during cycling experiments. Lab-scale experiments have shown that the required operating temperature and temperature lift can be achieved. Business cases have been evaluated with industrial end-users from the chemical & refining industry which show positive economic results. Important requirement is the power density which is the main challenge.

10.4.2 Hybrid Systems

Thermochemical heat transformer

This system is an extension of a regular thermochemical heat pump. The extension consists of a compressor that adds flexibility to the system with respect to operating temperatures, and more important, enables to use of lower temperature waste heat than the system without compressor.

The final requirements for this application are:

- Driven by a compressor and waste heat in the temperature range 50 - 150°C;
- Delivering process heat in the temperature range up to 250°C, with process heat temperature at least 50°C higher than the waste heat temperature;

- System efficiency (process heat out/waste heat in) >25 %, depending on operating temperatures, (average) Electrical COP > 5;

Figure 10.12 depicts the thermodynamic concept (right side) of this hybrid concept and a picture of the setup (left) that has been used to test a compressor under batch type operating conditions.

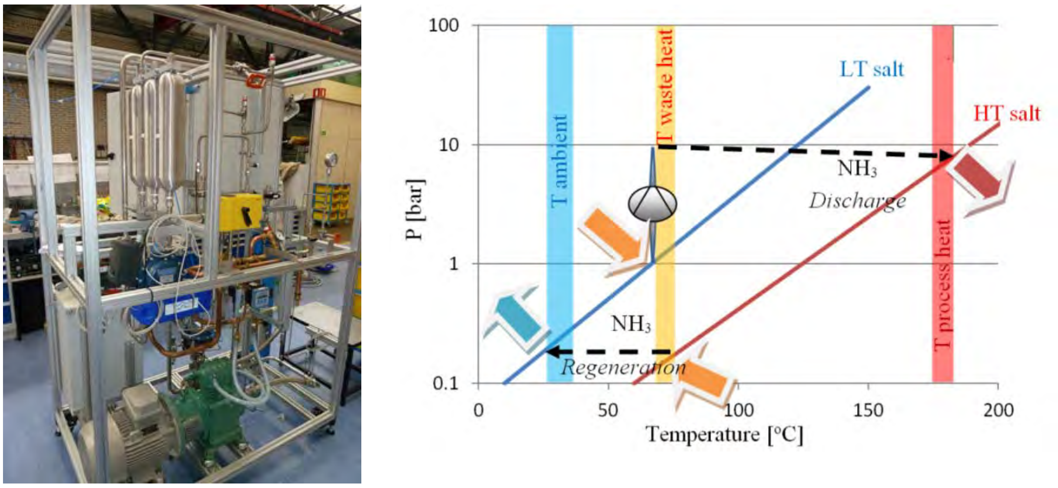


Figure 10-12: Hybrid Thermochemical-compression heat pump testing

Compression Resorption Heat Pump

Usually, heat pumps work best if the heat added or extracted at a constant temperature. However, several applications exist where the temperature of the streams will change as heat is added or extracted. The temperature difference over the glide leads to an extra exergy loss over the heat exchanger, unless the working fluid of the heat pump has the same glide. This principle is applied in the Compression Resorption (CR) heat pump. In the CR heat pump the working fluid is a zeotropic mixture, usually ammonia-water. The composition of this mixture is adjusted until the glide of the working fluid optimally matches the glide at the process stream.

The cycle can be designed to show a temperature glide in the resorber that corresponds to the temperature glide of the industrial waste flow that has to be heated. For specific operating conditions the cycle performance is significantly better than for the vapour compression cycle. The main problem of the cycle is the compressor that has to be suitable for oil-free wet compression and still show acceptable isentropic efficiencies. Hybrid Energy solves this problem by separating the liquid and vapour and compress these separately. A higher efficiency could be obtained if a compressor would be available that could compress the mixture. These compressors must be suitable for high compression ratios and for simultaneously compress vapour and increase the liquid pressure. The compressor should further be not sensible to liquid carry over.

The main goal of the developments at the Technical University of Delft is a wet compressor that is suitable for operation in compression resorption heat pumps.

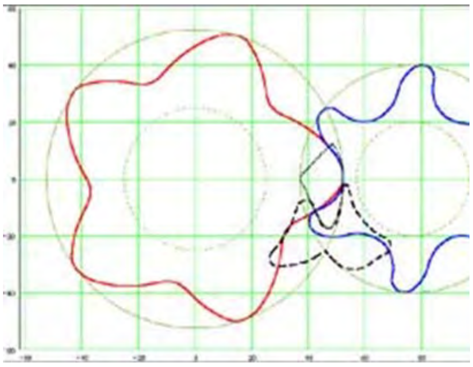


Figure 10-13: Principle of compression and prototype of compressor

In addition, large efforts have been put into the development of new multichannel re/absorbers that would be much more compact compared to conventional heat exchangers.

10.4.3 Electrically and gas fired thermoacoustic systems

The working principle of TA heat pumps has been described above. Since TA systems use a noble gas as working medium, these systems can be applied in a wide range of temperatures unlike regular compression or sorption heat pumps. Using this property of TA systems, ECN is developing two types of heat pumps, with two different drivers: mechanically and gas-fired.

A 10 kW mechanically driven system has been developed by ECN and Bronswerk Heat Transfer and is shown in Figure 10.14. This system is presently tested and subject of another paper at this conference.

Figure 10-14: *Electrically driven thermoacoustic system*

A thermoacoustic system can also be driven by high temperature heat, for example generated by a gas burner. Biggest challenge here is to transfer the heat from a gas burner to the thermoacoustic system. Figure 10.15 below shows the thermodynamic represention of this system (left) and a picture of an experimental thermoacoustic engine that is heated by hot flue gasses.

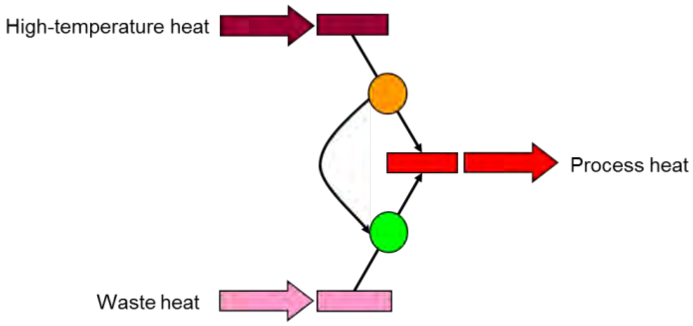


Figure 10-15: Thermodynamic scheme for gas-fired TA heat pump (left) and photo of the engine part

Both systems have virtually no limits with respect to operating temperature, other than the structural integrity limits of the pressurized resonator. In addition, large temperature lifts can be generated which means that these general concepts can be applied in a large variety of applications.

10.4.4 Minichannel heat exchangers for compression resorption heat pumps

Current separation processes within chemical and refining consume large amounts of energy. Increasing rising energy costs demand improvement of energy efficiencies. Significant reductions in energy consumption are expected by using innovative heat pump concepts for removal and supply of heat from/to a separation process. The research should lead to a fully integrated system consisting of traditional distillation and novel heat pump technology.

The amount of heat transferred will be determined by measuring mass flow, temperature and pressure at in- and outlets of a mini channel test section. From this data and the use of a fluid properties library, heat and mass transfer coefficients can be determined. Also the pressure drop can be measured.

Goals of the project are achieving high heat transfer rates and large surface area to volume ratios. This should lead to reduced investment cost and an optimized heat pump system.

Mini channel test setup 4 diameters from 0.5 to 2 mm, 5 lengths each one 6 mm tube as a reference.

Figure 10-16: Mini channel heat exchanger

10.5 Heat Integrated Distillation Columns

A large part of the work is undertaken by TU-Delft and partially published in a paper for the 10th Heat Pump Conference in Tokyo. It concerns the integration of heat pump technology in a distillation column.

In certain cases it is possible to split the process into two parts. An example is a distillation column where the rectifier and stripping section can be split from each other and exchange heat. In order to exchange heat the rectification section has to work at higher temperature and therefore higher pressure than the stripping section. This is reached by placing a compressor between the top of the stripping section and an expansion valve at the bottom of the rectification section. Possible advantage compared to compression-resorption heat pumps is the lack of one temperature driving force. The operating principle of a HIDiC is shown in Figure 10.17.

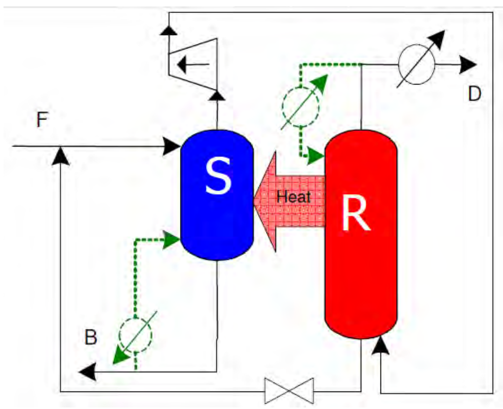


Figure 10-17: Scheme

Vapour from the top of the stripping section is compressed and directed to the rectifier. In the rectifier the vapour condenses, creating an internal reflux that is returned to the top of the stripper. The heat of condensation is used to evaporate the liquid at the stripper side. Usually the reboiler duty can be close to zero and a small external reflux is required at the top of the rectifier in order to produce the required distillate purity.

Optimization of the pressure ratio for a constant separation task is based on the balance between the compressor power cost and investment cost for compressor and HIDiC column. The HIDiC configuration can reduce the utility cost compared with the VRC with an additional 25-35% and the total annualized cost with 10-20%.

A simulation study on the existing plant was undertaken by Delft University of Technology focusing on enhancing thermodynamic efficiency of energy intensive distillation columns by internal heat integration. In the simulation study, taking propylene/propane splitter as base case, an internally heat integrated distillation column (HIDiC), offers significant potential for energy saving compared to energy requirements associated with operation of conventional and heat-pump assisted distillation columns. The rectification section of a propylene/propane splitter contains usually two times more stages than the stripping section, implying a number of heat coupling possibilities, which appears to be strongly influencing the thermal efficiency of the HIDiC. The configuration with the stripping section stages thermally interconnected with the same number of stages in the upper part of the rectification section emerged as the most efficient configuration, allowing a reduction in energy use in the range 30 to 40 % compared with a state of the art heat-pump assisted column, depending on the trade-off between the operating compression ratio and the heat transfer area requirement, the latter one being the key limiting factor.

In general, a distinctive feature of HIDiC is the fact that it combines advantages of direct vapour recompression and adiabatic operation at a significantly reduced total column height and therefore may be considered as an example of a most compact, and with respect to thermal energy conservation potential, an ultimate design of a distillation column.

10.6 Literature

Landolina, 2012	Strategic Research Priorities for Renewable Heating & Cooling, Cross-Cutting Technology European Technology Platform on Renewable Heating and Cooling; Many authors edited by Simone Landolina – European Renewable Energy Research Centres Agency, Manuscript completed in April 2012. Brussels, © European Union, 2012
EU, 2013	Strategic Research and Innovation Agenda for Renewable Heating & Cooling, European Technology Platform on Renewable Heating and Cooling, Manuscript completed in March 2013. ©European Union, 2013.
Reissner, 2013	Reissner, F., Gromoll, B., Schäfer, J., Danov, V., Karl, J., 2013a. Experimental performance evaluation of new safe and environmentally friendly working fluids for high temperature heat pumps, European Heat Pump Summit, Nürnberg, Germany

Application of Industrial Heat Pumps

IEA Industrial Energy-related Systems and Technologies Annex 13

IEA Heat Pump Programme Annex 35

Task 4:

Case studies

Final Report

(Status: 03.06.2014)

Prepared by the

Participants of Annex 35/13

Contents

Appendix:

1 Summary

The participating countries itentify several realized projects and case studies in different application in which industrial heat pumps are used.

Industrial heat pump applications are rather seldom in **Austria** up to now, several applications in various industrial sectors have been identified during the IEA HPP - IETS Annex 35/13, as e.g.:

- Mechanical vapour recompression systems (MVR), e.g. in salt mining plants or in breweries
- Upgrading waste heat by compression heat pumps (CHP), e.g. in the metalworking industry
- Absorption heat pumping systems (AHP) for industrial refrigeration purposes driven by waste heat, e.g.in the food industry or in laboratories
- Gas-fired AHP for heating application of industrial buildings, e.g. in a brewery
- AHPs and CHPs for flue gas condensation in power plants in the wood working or energy supply industry
- HP systems in laundries.

Eight examples and one feasibility studies are described in detail.

Table 1-1: Overview of realized projects / factsheets in Austria

Industry	System	Thermal Capacity	Supply temperature	Effects
Food industry -meat	Closed compression	257 kW	55 °C	Reduction CO_2 emissions 75 %
Artificial Ice rink	Add-on closed compression	413 kW	60 °C	Reduction CO_2 emissions 75 %
Electronic manufacturing	Absorption and compression	n. a	n. a	Payback period 7.9 a
Brewery	Compression	370kW	77 °C	Payback period 5.7 a
Biomass cogeneration plant	Absorption	Ca. 7.5 MW	95 °C	Reduction CO_2 emissions 6,000 t/a
Freezer Warehouse	Cascade Compression	511 kW	n. a.	Payback period 5.4 a
Automotive production	Compression	2 x 146 kW	n. a.	Payback period 13.6 a
Multifunctional office building	Compression	3 x 693 kW	60 °C	Payback period 3.4 a
Process heating	Compression	Ca. 200 kW	n. a.	Payback period < 6 a

Canada's report focuses on low- and high-temperature heat pump applications in small- and medium-sized industrial manufacturing processes, not only for heat recovery, but also for heating industrial buildings, when possible. These include food and beverage plants because they use large amounts of primary energy, mostly for heating, via gas-fired boilers to produce hot water and cooling processing operations via electrically driven mechanical refrigeration devices. Because economic performance is greatly influenced by energy consumption efficiency, food plants are seeking ways to recover and reintroduce waste heat into various industrial processes.

Table 1-2: Overview of realized projects / factsheets in Canada

Industry	System	Thermal Capacity	Supply temperature	Effects
Food industry	CO_2 trans critical	Ca. 100 kW	75 °C	n. a.
Hospital	CO_2 trans critical	Ca. 100 kW	75 °C	n. a
Food industry	Compression NH_3	N.N.	Up to 93 °C	n. a.
Fish farm	Compression NH_3	190 kW	10 – 12 °C	Payback period 1.28 a
Wood drying Low temperature	Add-on closed compression	5.6 kW	n. a.	Reduction total energy costs by 21.5 %
Wood drying High temperature	Compression	2 x 65 kW	Up to 100 °C	Reduction total energy consumption up to 50 %
Poultry processing	Mechanical vapor recompression	N.N.	63 °C	Payback period 2.7 a
Cold warehouse	Mechanical vapor recompression	2 x 22.3 kW	70 °C	n. a.
Metallurgical plant – Cooling towers	Compression Water to water	17.6 MW	70 °C	n. a

Denmark reports about four realized projects see table below.

Table 1-3: Realized projects / factsheets in Denmark

Industry	System	Thermal Capacity	Supply temperature	Effects
Drying air for milk powder	Hybrid NH_3/CO_2	1.25 MW	Up to 85 °C	Payback period 1.5 a
District heating	Compression High pressure NH_3	4.0 MW	Up to 68 °C	Payback period 2.5 a
Heating of green houses	Compression High pressure NH_3	2.0 MW	Up to 90 °C	n. a.
Washing metal items	Closed compression	25 kW	60 °C	Payback period 2.5 a

France identifies 10 projects with industrial heat pumps, eight in the food industry and two for district heating.

Table 1-4: Overview of realized projects / factsheets in France

Industry	System	Thermal Capacity	Supply temperature	Effects
Food industry (8 projects)	Closed compression with NH_3	Up to 1.2 MW	65 °C	Payback period ~ 4 a
Heating network (2 projects)	compression	Up tp 6 MW	Up to 90 °C	Payback period ~ 4 a

German partners report about 24 realized projects and case studies. Mainly (18) of them are located in Germany and represents several applications/ industrial branches.

Table 1-5: Overview of realized projects / factsheets from Germany

Industry	System	Thermal Capacity	Supply temperature	Effects
Slaughter House	CO_2 trans critical	800 kW	90 °C	Reduction CO_2 emission 510 t/a
Cafeteria	CO_2 trans critical	52.7 kW	80 °C	Reduction CO_2 emission by ~50°%
Dairy	Compression High pressure NH_3	3.45 MW	Up to 73 °C	n. a.
Chocolate manufacturing	Closed compression	2 x 600 kW	60 °C	Reduction CO_2 emission 120 t/a
District heating	Compression High pressure NH_3	13 MW	90 °C	Reduction CO_2 emission 12,700 t/a
Surface Finishing		200 kW	90 °C	Payback period ~ 4 a
Prefabricated house manufacturing	Closed compression	180 kW	90 °C	Payback period < 5.5 a
Waste treatment	Gas absorption	500 kW	82 °C	Payback period 6.7 a
Automotive	Compression	1,683 kW	75 °C	n. a.
Coating Powder Production	Compression	240 kW	45 °C	Payback period 5 a
Production of plant and herb extracts	Compression	61.5 kW	50 °C	Payback period 10 a
Electronics	Compression	90 kW	70 °C	n. a.
Glass	Compression	64 kW	40 °C	n. a.
Mechanical engineering	Compression	20 kW	60 °C	Payback period 2 a
Wires production	Compression	220 kW	55 °C	Payback period 3.2 a
Sheet metals	Gas absorption	194 kW	60 °C	Payback period 4 a
Sheet metals	Compression	274 kW	60 °C	Payback period 6 a
Screw production	Compression	584 kW	Up to 58 °C	Payback period 2 a
Electroplating	Compression	143 kW	Up to 80 °C	Payback period < 4 a
Sheet metals	Compression	260 kW	65 °C	Payback period 3 a
Malt production	Compression	3,250 kW	35 °C	n. a.
Brewery	Compression	77 kW	55 °C	Payback period 6 a
Textile	Compression	137 kW	50 °C	n. a.
Stone and earths	Compression	110 kW	60 °C	Payback period 3.2 a

Japan has many industrial heat pumps in practical use. Among the many installed cases, here they focus on heat pump technologies of simultaneous production of heating and cooling, vapor recompression, high temperature heat production and agricultural use because they are growing in sales and also expected further growth in the future. 6 cases were picked out as typical examples of above mentioned prospective industrial heat pump technologies and their details, such as backgrounds of installation, system specifications and effects from economic and energy saving points of view, are explained. In total, about 29 case studies are reported in factsheets.

Table 1-6: Overview of realized projects / factsheets in Japan

Industry	System	Thermal Capacity	Supply temperature	Effects
Cheese production	Compression		75 °C	Power reduction
Freeze-dried food product manufacturing	CO_2 trans critical	92 kW	90 °C	Reduction CO_2 emissions and energy cost by 80 % and more
Noodle production	CO_2 trans critical	56 kW	90 °C	Reduction CO_2 emissions by 31 % and energy cost by 25 %
Noodle production	CO_2 trans critical	72 kW	90 °C	Payback period 8.2 a Reduction CO_2 emission by 43%
Chicken	CO_2 trans critical	80 kW	90 °C	Reduction CO_2 emissions by 65 % and energy cost by 88 %
Lettuce growing	Compression	4 x 28 kW (cooling capacity)	24 °C	Stable production
Brewery		111.6 kW	70 °C	Reduction of water supply energy by 18 %
Whisky and material alcohol	Vapor recompression (MVR, TVR)	4.2 t/h	n. a.	Reduction of primary energy consumption by 43 %
Paper making	CO_2 trans critical	40 kW	75 °C	Reduction CO_2 emissions by 50 % and energy cost by 42 %
Styrofoam molding	CO_2 trans critical	110 kW	90 °C	Reduction CO_2 emissions by 63 % and energy cost by 48 %
Pharmaceutical production	Compression	247 kW	45 °C	Reduction CO_2 emissions by 24 % and primary energy consumption by 24 %
Circuit breaker production	Compression	2 x 55.8 kW	65 °C	Reduction CO_2 emissions by 19 % and energy cost by 11 %
Transformer case production	CO_2 trans critical	110 kW	80 – 120 °C	Reduction CO_2 emissions by 19 % and energy cost by 12 %.
Automotive	Compression	566 kW	n. a.	Payback period 3 – 4 a Reduction CO_2 emissions by 47 % and energy cost by 63 %.
Automotive	Vapor recompression	300 kg/h	n. a.	Reduction CO_2 emissions by 79 % and primary energy consumption by 77 %
Automotive – Painting process	Compression	3,755 kW	n. a.	Reduction CO_2 emissions by 48 % and energy cost by 25 %.
Automotive – Washing process	Compression	8 x 45.3 kW 6 x 22.3 kW	65 °C	Reduction CO_2 emissions by 86 % and energy cost by 89 %
Greenhouse	Compression	6 x 18 kW	20 °C	Reduction CO_2 emissions by 63 % and primary energy consumption by 49 %

In the industrial sector, as a solution for energy saving, the number of heat pump installation and operation increases in **Korea**. They identify 10 representative heat pump installation and operation cases in industrial sector:

- Reduction in usage of steam for de-ionized (DI) water heating by installing a heat pump and heat exchanger
- Energy saving through installation of waste heat recovery heat pump
- District heating with a sewage heat source heat pump
- Heat which collects waste heat from a cooling system in an Internet Data Centre server room
- Energy saving through change from thermal vapour recompression (TVR) to mechanical vapour recompression (MVR)
- Steam generation through TVR and MVR
- MVR in a sugar refinery factory
- MVR in a reaction tower
- Reuse of waste steam to the process steam by TVR.

Over the past 20 years several feasibility studies and project realizations of heat pump projects have been performed in **The Netherlands**. These are evaluated in this study. Some of them are more than 20 years running and they are still in use.

Table 1-7: Extract of realized projects / factsheets in the Netherlands

Industry	System	Thermal Capacity	Supply temperature	Effects
Chemicals – Distillation of PP-splitter	Mechanical vapor compression	5.8 MW	n. a.	Payback period 2 a
Drying of potatoes	Compression	880 kW	70 °C	Payback period 4 a
Margarine production	Add on compression	1.4 MW	65 °C	Payback period 4 a
Brewery	Thermal vapor compression	n. a.	97 °C (?)	Payback period 2 - 3 a
Slaughterhouse	High pressure compression NH_3	440 kW	65 °C	Payback period 4 - 5a
Potato starch	Mechanical vapor compression	2.7 MW	n. a.	Reduction CO_2 emissions 10,092 t
Warehouse	Compression	252 kW	20 °C	Payback period < 5 a
Greenhouse Tomatoes	Compression	3 x 1.25 MW	42 - 50 °C	Reduction CO_2 emissions by 40 – 60 %

2 Introduction

Industrial heat pumps are a class of active heat-recovery equipment that allows the temperature of a waste-heat stream to be increased to a higher, more useful temperature. Consequently, heat pumps can facilitate energy savings when conventional passive-heat recovery is not possible.

The purpose of this case studies survey is to present good examples of heat-pump technology and its application in industrial processes in accordance with the definition of industrial heat pumps in Annex 35/13, "which are used for heat recovery and for heat upgrading or cooling/ refrigeration in industrial processes or for heating and cooling in industrial buildings".

The focus is on the most common applications, with guidelines for initial identification and evaluation of the opportunities being provided and as input to the market overview of software and calculation models of Task 2.

The most common industrial application of heat pumping is dehumidification drying of lumber. In this application, warm, humid exhaust air from a lumber-drying kiln is the heat source for a closed cycle mechanical heat pump that delivers heat to the incoming air. In addition to energy benefits, the lower operating temperature of heat-pumped kilns improves product quality; the heat pump removing VOCs (volatile organic compound) from the exhaust also provides an environmental benefit.

While lumber-drying applications are numerous, the size of the units is usually small in terms of the heat delivered. For example, 50 kW heat output would be considered a large application; however, industry is developing larger systems of 1.0 – 1.5 MW. Closed-cycle applications that are not for lumber drying range from 0.3 to 6 MW heat output, and typically heat streams, such as process liquids or air.

The most common large-heat-load application is vapour compression evaporation. In this application, evaporated vapour is compressed over a small pressure range and condensed to provide the energy to drive the evaporation process. Such systems deliver 6 MW to over 30 MW at a low cost.

Evaporators and flash-steam recovery systems frequently incorporate thermo-compression systems. For example, paper dryers commonly use thermo-compressors to recover flash steam from dryer condensate.

Absorption systems are commonly used in chilling applications as alternatives to mechanical chillers, rather than in heat pump applications.

3 Austria

Although industrial heat pump applications are rather seldom in Austria up to now, several applications in various industrial sectors have been identified during the IEA HPP - IETS Annex 35/13, as e.g.:

- Mechanical vapour recompression systems (MVR), e.g. in salt mining plants or in breweries
- Upgrading waste heat by compression heat pumps (CHP), e.g in the metalworking industry
- Absorption heat pumping systems (AHP) for industrial refrigeration purposes driven by waste heat, e.g.in the food industry or in laboratories
- Gas-fired AHP for heating application of industrial buildings, e.g. in a brewery
- AHPs and CHPs for flue gas condensation in power plants in the wood working or energy supply industry
- HP systems in laundries, etc.

In this report some selected realized plants (see chapter 3.1) as well as a feasibility study (see chapter 3.2) are described.

3.1 Examples of realized plants in Austria

This chapter gives a brief overview of selected heat pump applications of different types in the Austrian industry, as data were available:

- A closed compression heat pump in a meat industry plant for heating applications (see chapter 3.1.1)
- An add-on compression heat pump for a chiller of an artificial ice rink for heating application (see chapter 3.1.2),
- A combination of an electrical chiller and an absorption heat pump in an electronic factory for cooling purposes (see chapter 3.1.3)
- A closed compression heat pump in a brewery for heating applications (see chapter 3.1.4)
- An absorption heat pump in a biomass plant for heating applications (see chapter 3.1.5)
- A cascade compression heat pump for bi-generation purposes in freezer warehouse (see chapter 3.1.6)
- A compression heat pump for waste heat recovery in an automotive supplier plant (see chapter 3.1.7)
- A ground coupled heat pump for heating and cooling of a Multifunctional Office Building (see chapter 3.1.8)

3.1.1 Compression heat pump in a meat industry plant

Company	efef Fleischwaren GmbH (REWE Austria Fleischwaren GmbH)
Location	Schweizer Straße 75, 6845 Hohenems, Austria
Process application	Sausage manufacturing plant
Type of heat pump	Compression Heat Pump
Capacity	Heating Capacity ca. 257 kW
Reduction in CO_2 emission	75% (for the delivered heat by the HP)
Manufacturer/supplier	Cofely Kältetechnik GmbH
Pay back	No data available
More information/contact	Jürgen Furtner Cofely Kältetechnik GmbH, Langegasse 19, 6923 Lauterach; Österreich - Austria Tel.: +43-5574 6705-14, Fax: +43 5574 6705-22 Juergen.Furtner@cofely.info, www.cofely.info

Description of the plant

The meat factory efef Fleischwaren GmbH (REWE Austria Fleischwaren GmbH) supplying the retail and wholesale distribution in Austria, see Figure 3-1. Currently, around 150 people are employed. The crude products obtained from the slaughterhouse processed into finished products such as fresh meat, smoked or cured meats and packaged for retail sale. [Cofely, 2013]

Figure 3-1: Pictures of efef meat factory in Hohenems [efef, 2013]

1995/96 efef has expanded their location in Hohenems focusing in low energy consumption of their plant. Therefore an electrically driven compression heat pump has been considered for the usage of the waste heat from the central electrically driven chiller as well as other chillers and from the central air compressors for heating applications, as shown in Figure 3-2. This heat pump lifts up the temperature level of the waste heat at about 30 °C to an adequate level of about 55 °C for space, process and cleaning water heating. The heat pump consists of two separate condensers, one for space and process heating and the other one for cleaning water heating. Further also an adequate storage system for the maximum daily heat demand has been considered. About 100 m³ of cleaning hot water are required each working day and about 50 % of it is covered by the waste heat utilization and the other 50 % by a gas fired steam plant. [Cofely, 2013]

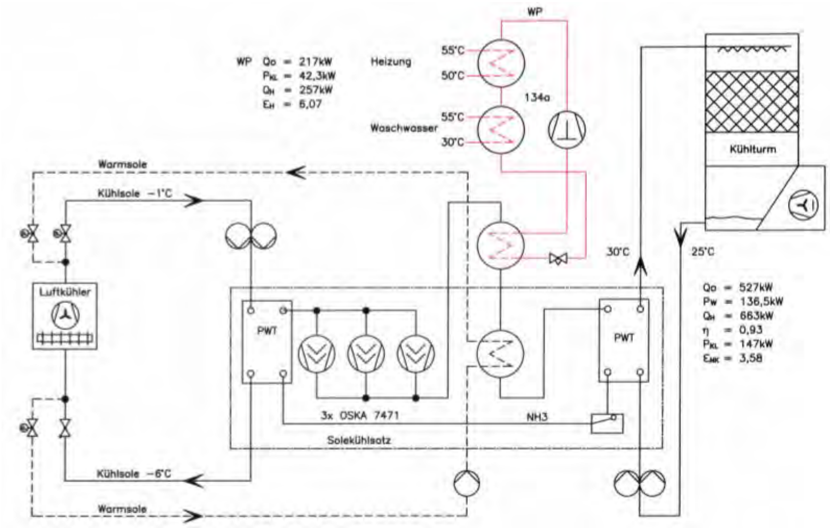


Figure 3-2: Process flow sheet of the heat pump including the waste heat sources at efef Hohenems in Austria [COFELY, 2012]

Specifications of heat pump [Cofely, 2012]

Description	Heat Pump	
Type	Single-stage R 134 a compression heat pump	
Heating capacity	Ca. 257 kW (ca. 55 °C)	
Cooling capacity	Ca. 217 kW (ca. 26 °C)	
Power consumption	Ca. 42 kW_{el}	
Heat source Description and temp	Waste heat from three air compressors and the condensation heat of one electrical chiller	Temp.: 26 °C
Heat sink Description and temp	Space heating and cleaning water	Temp.: 55 °C
Refrigerant	R-134 a	
Compressor type	Semi hermitical reciprocating compressor	
COP	Ca. 6.1	
Storage water tank	Yes	
Manufacturer of heat pump	COFELY GmbH	

Running experience, savings and economics

According to Cofely (2013) the customer is completely satisfied with the heat pump performance and operation.

3.1.2 Add On-Compression heat pump in a sports centre

Company	Eislaufbahn Gmunden www.sportzentrum.gmunden.at
Location	Fliegerschulweg 44, 4810 Gmunden– Austria
Process application	artificial ice rink
Type of heat pump	Add-on compression heat pump
Capacity	Heating capacity ca. 257 kW
Reduction in CO2 emission	75 %
Manufacturer/supplier	Cofely Kältetechnik GmbH
Pay back	No data available
More information/contact	Jürgen Furtner Cofely Kältetechnik GmbH, Langegasse 19, 6923 Lauterach; Österreich - Austria Tel.: +43-5574 6705-14, Fax: +43 5574 6705-22 Juergen.Furtner@cofely.info, www.cofely.info

Description of the plant

The sports centre of the city Gmunden in Austria also operates an artificial ice rink, as shown in Figure 3-3.

Figure 3-3: Pictures of ice rink in Gmunden [Gmunden, 2013]

As shown in Figure 3-4 waste heat from the ammonia (NH_3) chiller of the artificial ice rink can be used for heating application directly by an add on heat pump with a heating capacity of 413 kW or rejected to the ambient. The evaporating temperature level of the realized add-on heat pump is about 25 °C.

The heat sink of the add-on heat pump is a storage tank with a temperature level of about 60 °C, see Figure 3-4. The used NH_3 reciprocating compressor has a maximal electrical power consumption of 71 kW.

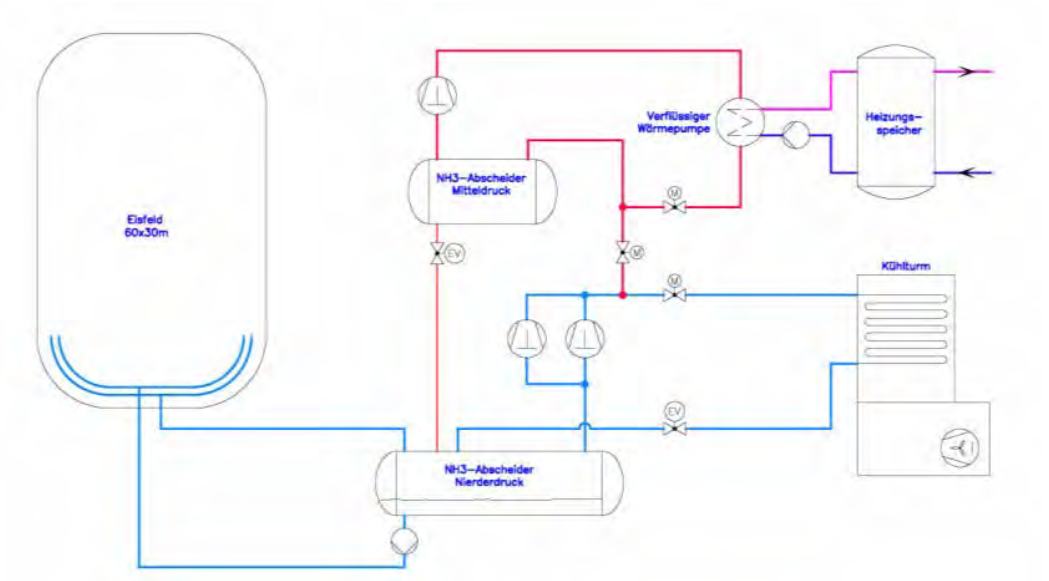


Figure 3-4: Process flow sheet of the add on heat pump of the chiller for the ice rink at Gmunden, Austria [COFELY, 2012]

Specifications of heat pump [Cofely, 2012]

Description	Add on heat Pump	
Type	Single-stage R 717 compression heat pump	
Heating capacity	Ca. 413 kW	
Evaporator capacity	Ca. 347 kW	
Power consumption	Ca. 71 kW_{el}	
Heat source Description and temp	Waste heat from an electrically driven chiller: Ammonia vapour from a middle pressure vessel	Temp.: ca. 25 °C
Heat sink Description and temp	Storage tank for space heating	Temp.: ca. 60 °C
Refrigerant	R-717	
Compressor type	Reciprocating compressor	
COP	Ca. 5.8	
Storage water tank	Yes	
Manufacturer of heat pump	COFELY GmbH	

3.1.3 Absorption and compression heat pump in an electronic factory

Project summary

Company	Seidel Elektronik www.seidel.at
Location	Frauentalerstr. 100, 8530 Deutschlandsberg– Austria
Process application	Electronic manufacturing factory
Type of heat pump	Absorption and compression Heat Pump
Running hours	No data available
Year of realization	2011
Primary energy savings (assumed)	168,627 kWh/a (40% of natural gas demand)
Manufacturer/supplier	- Frigopol - Yazaki
Pay back	7.9 a (calculated)
More information/contact	DI (FH) Karin Kölblinger sattler energie consulting GmbH Krottenseestr. 45, 4810 Gmunden, + 43 (0) 7312 / 73799 office@energie-consulting.at, www.energie-consulting.at

Description of the plant

SEIDEL Electronics is a manufacturer of custom-made solutions and an outsourcing partner for electronic and mechatronic products. Around 700 employees work in their locations in Austria, Hungary, Slovakia and Slovenia [Seidel, 2013]

At their factory in Deutschlandsberg in Austria (see Figure 3-5) with a production area of 7,200 m² approximately 350 people are employed. Also their R&D center for electronic and mechatronic assemblies manufacturing, as well as complete equipment installation and distribution are located there.

Figure 3-5: Seidel Elektronik in Deutschlandsberg (Seidel, 2013)

Initially the electrical energy consumption per year amounts about 450 MWh only for refrigeration purposes of the plant in Deutschlandsberg and about the same value of 460 MWh of natural Gas are required to cover the heating demand of this factory. In order to improve this situation besides several measures, like the electricity is only delivered by hydro power etc. a compression heat pump (see Figure 3-7) and an absorption chiller (see Figure 3-6) has been considered. The above mentioned compression heat pump is also used for process cooling in summer. The temperature level of the waste heat from the compressors amounts about 75 °C.

Figure 3-6: Absorption chiller at Seidel, Deutschlandsberb [klima:aktiv, 2011]

The waste heat from this heat pump as well as from the air compressors of the factory are used to drive the above mentioned absorption chiller for cooling purposes. For this a cold water storage tank is used.

Between summer and winter the heat pump is primarily used for heating, but surplus heat is used for driving the absorption chiller.

In winter the absorption chiller is out of operation and the required capacity for cooling processes is only delivered by the electrically driven heat pump and the waste heat is used for heating application.

Since the start-up of the operation of the heat pump and the absorption chiller the natural gas consumption is reduced by about 40 % [Seidel, 2012a] and according to Seidel [2012b] it was assumed that energy cost can be reduced by 16,000 to 18,000 € each year due to these applications. Comparable data are not available.

Seidel Electronic have a green vision, so they plan a CO_2–neutral production in Deutschlandsberg up to 2014 with further measures for a sustainable energy supply at their factory [Seidel, 2012b].

Figure 3-7: Compression heat pump at Seidel, Deutschlandsberb [klima:aktiv, 2011]

3.1.4 Compression heat pump in a brewery

Project summary

Company	Mohrenbrauerei August Huber Dr.-Waibel-Str. 2, 6850 Dornbirn, www.mohrenbrauerei.at
Location	Dornbirn – Austria
Process application	Brewery
Type of heat pump	Compression Heat Pump
Capacity	Heating Capacity ca. 370 kW
Year of realization	2012
Primary energy savings	1,426 MWh/a
Reduction in energy costs	64,067 EUR/a
Invest costs	365,000 EUR
Manufacturer/supplier	COFELY GmbH (WKÖ, 2012)
Pay back	5.7 a
More information/contact	Ralf Freitag Mohrenbrauerei August Huber Dr.-Waibel-Str. 2, 6850 Dornbirn, +43 (0) 5572 3777 leitung-produktion@mohrenbrauerei.at, www.mohrenbrauerei.at sattler energie consulting gmbh DI (FH) Martin Hinterndorfer Krottenseestr. 45, 4810 Gmunden, +43 (0) 7612 737 99 Martin.hinterndorfer@energie-consulting.at

Description of the plant

The Brewery Mohrenbrauerei is the oldest and most modern brewery in Vorarlberg, the most western province in Austria. Since 1834 the traditional company in Dornbirn is owned by the Huber family and produces approximately 218,000 hectoliters drinks per year. The product range includes beer, whiskey and lemonades. Further the Mohrenbrauerei also trades with wine, water, sodas and juices from Austrian and international manufacturers. [Klima:aktiv, 2012]

Figure 3-8: The Mohrenbrauerei in Dornbirn [klima:aktiv, 2012]

Energy efficiency and sustainability is still more than a mission for the Mohrenbrauerei. The management and the brewery's staff are involved in developing solutions and the implementation of energy efficiency measures. In recent years, optimizations in the areas of heating control, standby of PC devices and accessories and the air conditioning were already conducted. They also use alternative energy sources as electricity from solar panels. [Klima:aktiv, 2012]

Initially the brewery used gas fired steam plant with an annual natural gas consumption of 4,700 MWh/a and a boiler with an annual natural gas consumption of 900 MWh/a to cover the brewery's heating demand. [Klima:aktiv, 2012]

In order to improve this situation the Mohrenbrauerei decided to use the waste heat from their chillers with a high temperature heat pump for heating purposes instead of dissipating it to the ambient. This heat pump has a hating capacity of 370 kW and works with ammonia as refrigerant. The overall heat demand (space & process heating) is covered by this heat pump. Additionally, also water for the process water grid is heated up to 77 °C by the heat pump. [Klima:aktiv, 2012]

Figure 3-9: High temperature heat pump at Mohrenbrauerei in Dornbirn [klima:aktiv, 2012]

Figure 3-10: One of the heat storage tanks at Mohrenbrauerei in Dornbirn [klima:aktiv, 2012].

For a highly efficient use of waste heat additional heat storage tanks have been realized, one for the brew water and one for the heating grid, see Figure 3-10Figure 3-10. [Klima:aktiv, 2012)

With this application the Mohrenbrauerei saves 1,844 MWh/a of natural gas by consuming only 418 MWh/a of electrical energy for the heat pump operation, which means that the seasonal performance factor of this heat pump is quietly high [Klima:aktiv, 2012]

From an economical point of view it has to be mentioned that the payback time amounts less than 6 years. [Klima:aktiv, 2012]

Specifications of heat pump

Description	Heat Pump	
Type	Ammonia compression heat pump	
Heating capacity	370 KW	
Heat source Description and temp	Condenser waste heat from chillers	
Heat sink Description and temp	Space and brew water heating grid	Temp 77 °C
Refrigerant	Ammonia	
Storage water tank	Yes(two)	
Manufacturer of heat pump	COFELY Kältetechnik GmbH	

Running experience, savings and economics

Energy cost savings	64,067 EUR/a
Energy savings	1,426 MWh/a (18.3%)

3.1.5 Absorption heat pump for flue gas condensation in a biomass plant

Project summary

Company	Salzburg AG für Energie, Verkehr und Telekommunikation Bayerhamerstraße 16, 5020 Salzburg, Austria
Location	Salzachtalstraße 88, 5400 Hallein – Austria
Process application	Biomasse cogeneration plant
Type of heat pump	Absorption Heat Pump
Capacity	Heating Capacity ca. 7.5 MW
Running hours	Ca.7 500 $h_{operation}$/a (Ca. 6 200 $h_{FullLoad}$/a) Overall: ca. 37,000 $h_{operation}$ up to now
Year of operation	Since 09/2006
Primary energy savings	Ca. 15,849 MWh
Reduction in CO2 emission	6,000 tons/a
Manufacturer/supplier	INVEN Absorption GmbH
Pay back	According to Salzburg AG the application of the AHP is profitable
More information/contact	Dipl. Ing. (FH) Thomas Bergthaller Salzburg AG, Elisabethkai 52, 5020 Salzburg, Austria Tel. +43/662/8884-8862, Fax +43/662/8884-170-8862 thomas.bergthaller@salzburg-ag.at www.salzburg-ag.at

Description of the plant

Schweighofer Fibre GmbH in Hallein (Austria), see Figure 3-11, is a wood-working industrial company and part of the Austrian family enterprise Schweighofer Holzindustrie. Their core business is the production of high-quality cellulose and bioenergy from the raw material wood by an efficient and environmentally-friendly use. [Schweighofer, 2013]

Figure 3-11: The Production Plant of Schweigerhofer Fibre GmBH in Hallein (Schweighofer, 2013)

A biomass power plant including a steam generator supplies the in-house steam grid and covers the company's energy demand at the site. The capacity of this cogeneration plant, which is fired by 77 % of external wood and 23 % of in-house remants, amounts to about 5 MW_{el} and 30 MW_{th}. Beside the in-house power supply of Schweighofer Fibre GmbH the biomass plant also delivers electricity for about 15,000 households and heat for the local district heating grid.

The operator of this power plant in Hallein is the Salzburg AG (2013) which is a regional infrastructure provider of energy, transport and telecommunications. In 2006 an absorption heat pumping system (AHP) has been realized for the utilization of waste heat of the flue gas of the biomass power plant, shown in Figure 3-12.

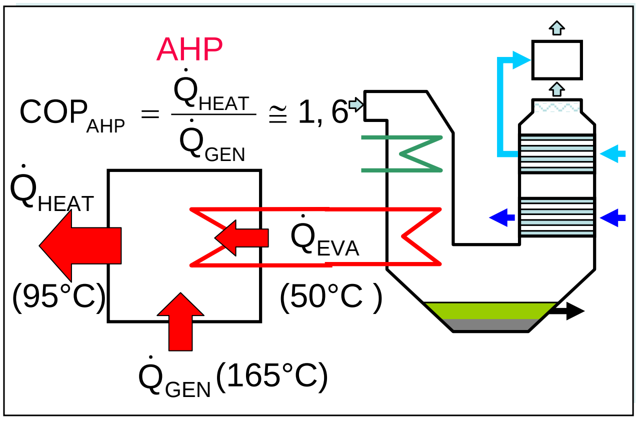


Figure 3-12: Process flow sheet of the flue gas condensation of the biomass plant in Hallein in Austria by using an absorption heat pump system (Rechberger, 2009)

The AHP offers the possibility to use the condensation heat of the flue gas by upgrading its temperature level, even thou the return flow temperature of the existing district heating grid is higher than the dew point temperature of the flue gas. At evaporating temperatures of the AHP lower than 50 °C the flue gas gets sub cooled below the dew point temperature. Hence, the temperature level of the condensation heat of the flue gas is lifted up to a useful level for the district heating. Otherwise, the condensation heat of the flue gas could not be used and would be dissipated to the ambient.

The applied AHP is a single-stage Water/LiBr absorption heat pump (Figure 3-13) with a solution heat exchanger (SHX) and a heating capacity of ca. 7.5 MW. The driving source of the AHP is steam from the biomass heating plant at ca. 165 °C. According to the existing monitoring system the AHP operates with a seasonal performance factor (SPF) of about 1.6. Due to the high efficiency and the high operating hours of the AHP this industrial heat pump application enables a significant fuel and emission reduction. Additionally to the ecological advantages this application offers an economical benefit for the operator of the plant.

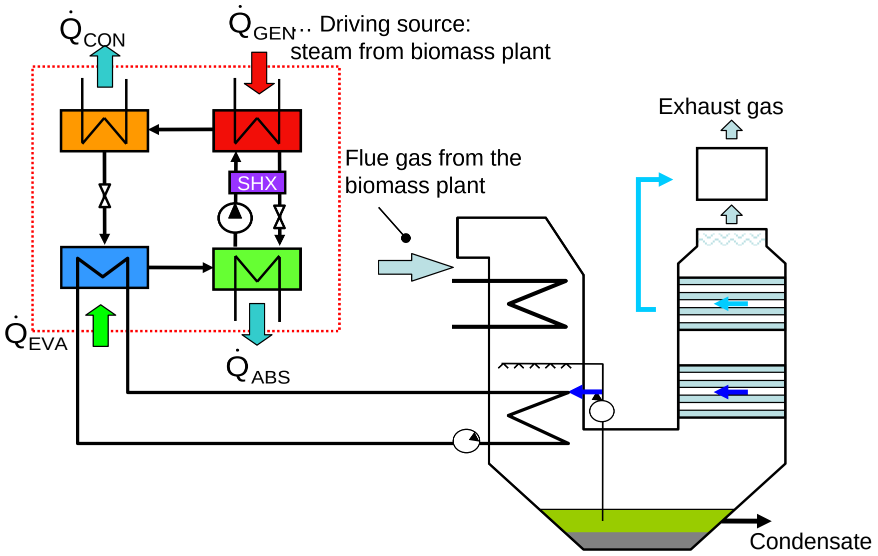


Figure 3-13: Process flow sheet of the absorption heat pump system for the flue gas condensation of the biomass plant in Hallein (Austria) (Rechberger, 2009)

Specifications of heat pump

Description	Heat Pump	
Type	Single-stage H2O/LiBr - absorption heat pump	
Heating capacity	Ca. 7.5 MW (ca. 95 °C) at fullload	
Cooling capacity	Ca. 3.0 MW (ca. 50 °C) at fullload	
Power consumption	Ca. 4.5 MW_{th} (ca. 165 °C) at fullload Ca. 20 kW_{el} at fullload	
Heat source Description and temp	Flue gas	Temp.: 50 °C
Heat source Description and temp	Steam	Temp.: 165 °C
Heat sink Description and temp	District heating	Temp.: 95 °C
Refrigerant	Water	
Solvent	LiBr	
Compressor type	Absorption process (no compressor, one solution pump)	
COP_H	Ca. 1.6	
Operation hours	In total about 37,000 h and about 7,500 h per a	
Storage water tank	None	
Manufacturer of heat pump	INVEN Absorption GmbH	

Running experience, savings and economics

Energy cost savings	- Fuel cost - Cost for fuel storage - Cost for ash removal
Energy savings	- Ca. 15,000 MWh/a
Other savings	- Higher performance - Cost saving cause no vapour discharge system is required

Challenges and prospects

Potential	- Cogeneration plants
Other Possibilities of application	- Double-stage absorption heat pump systems - Compression heat pump systems for flue gas condensation
Application of heat pump solves process problems	- No vapour discharge system required
Application of heat pump increases the value chain	- Yes

3.1.6 Refrigeration plant and heat recovery optimization in a freezer warehouse

Project summary

Company	Daily Service Tiefkühllogistik GesmbH & Co KG Gewerbestr. 6, 4481 Asten www.daily.at
Location	Asten – Austria
Process application	Freezer warehouse
Type of heat pump	Compression Heat Pump
Year of realization	2011
energy savings	371,800 kWh/a
Reduction in energy costs	39,620 EUR/a
Invest cost	215,000 EUR
Pay back	5.4 a
More information/contact	Andreas Schilde Daily Service Tiefkühllogistik GesmbH & Co KG Gewerbestr. 6, 4481 Asten, +43 (0) 7224 67391, A.schilde@daily.at, www.daily.at sattler energie consulting gmbh DI (FH) Martin Hinterndorfer Krottenseestr. 45, 4810 Gmunden, +43 (0) 7612 737 99, Martin.hinterndorfer@energie-consulting.at

Description of the plant

Daily service is a commercial and non-proprietary logistics services company, providing the Austrian Market with frozen products. Achieving economic and environmental benefits to commercial and industrial customers is an essential element of corporate strategy. Since 2005 the company has improved its energy efficiency with different measures.

Figure 3-14: Daily Service Tiefkühllogistik GesmbH & Co KG in Asten [Klima:aktiv, 2012b]

In 2007 a new freezer warehouse with an efficient Ammoniak/CO_2 plant has been built. The waste heat from this cooling system is used for heating purposes. The consumption of electrical energy in 2010 is approximately 7,340 MWh/a and the heating demand 1,030 MWh/a. The Daily Services GmbH has four different cooling areas that need to be cooled around the clock. The cooling energy for the sorting hall and for the high bay warehouse is provided on the one hand by the NH_3/CO_2 cascade chiller and on the other hand by a R-22 refrigeration system. The consumption of the refrigeration systems for the adapted areas totals at approximately 3,870 MWh of electricity per year. Both refrigeration units are equipped with heat recovery, which decouple a total of heat of about 906,072 kWh/a. This heat is used for heating purposes in the administration buildings, workshops, offices and production. Additionally for the space heating about 119,923 kWh/a are required which are reheated by a direct electric heater. The defrosting of the evaporator of the R-22 system, which will be decommissioned, also requires approximately 7,045 kWh/a heat. The evaporators of the R-22 unit are defrosted electrically.

Figure 3-15: compression heat pump at Daily Service Tiefkühllogistik GesmbH & Co KG[klima:aktiv, 2012b]

The existing R-22 machine is relieved due to the poor COPs and shifts the load to the NH_3/CO_2 cascade as it is not operated at its capacity limits. Therefore two new evaporators are installed and at the same time four of the existing evaporators of the R-22-unit are shut down. Thus, the electric defrosting and the loss of refrigerant, which was created by the leaks in the old evaporators, will be avoided. By shifting the cooling operation from the R-22-unit to the NH_3/CO_2 cascade about 244 720 kWh/a electricity can be saved.

The new evaporator tare defrosted with waste heat and therefore no additional electrical power is required. The energy saving is amounts at approximately 7,045 kWh/a. The leakage losses of the unit and of the entire R22 system are reduced due to the migration from the R22 to the NH_3/CO_2 refrigeration system. The reduction of CO_2 emissions is approximately 227,300 kg/a (R-22 = 152 kg/a).

To recover the heat from the NH_3/CO_2 cascade a condenser with a capacity of 511 kW is installed. The heat demand of about 250,963 kWh per year can now be made fully available through this recovery due to a low temperature heating system. In addition also the operation of the old heat recovery and the backup heating with the direct electric heater are saved. Therefore the electric energy demand can be reduced by about 119,923 kWh / a. All savings apply only to electrical energy, as the current heat demand is covered from the heat recovery of the chillers.

Specifications of the NH_3/CO_2 – cascade compression heat pump [mycom, 2007a and 2007]

Description	Compression Heat Pump
Type	NH_3/CO_2 – cascade compression heat pump
CO_2-Cycle	
Cooling capacity	Ca. 305 kW_{th} (ca. -38 °C) at full load
Power consumption	Ca. 73.5 kW_{el} at full load
Refrigerant	R 744
Compressor type	C6HK
Swept Volume	193 m³/h
COP_C for refrigeration	Ca. 4.15
Manufacturer of compressor	Mycom
Speed	1,450 rpm
Condensing temperature	-5 °C
Evaporating temperature	-38 °C
Suction Pressure	1.08 MPa
Discharge Pressure	3.05 MPa
NH_3-Cycle	
Evaporator capacity	Ca. 410 kW (ca. -10 °C) at full load
Power consumption	Ca. 104 kW_{el} at full load
Refrigerant	R 717
Compressor type	Single stage screw compressor 13.6eMEE
Swept Volume	622 m³/h
COP_C for refrigeration	Ca. 3.94
Manufacturer of compressor	Mycom
Speed	2,950 rpm
Condensing temperature	35 °C
Evaporating temperature	-10 °C
Suction Pressure	0.29 MPa
Discharge Pressure	1.35 MPa

3.1.7 Optimization of cooling and heating supply in an automotive factory

Project summary

Company	Magna Auteca AG Elin-Süd-Straße 14, 8160 Krottendorf / Weiz, www.magna-auteca.com
Location	Krottendorf / Weiz – Austria
Process application	Automotive production
Type of heat pump	Compression Heat Pump
Capacity	app. 2 x 146 kW
Year of realization	2012
energy savings	444 100 kWh/a
Reduction in energy costs	21 360 EUR/a
Invest coste	290.000 EUR
Pay back	Ca. 13.6 a
More information/contact	Robert Schneider Magna Auteca AG Elin-Süd-Straße 14, 8160 Krottendorf / Weiz, +43 (0) 3172 / 5100-0, office.auteca@eu.magna.com, www.magna-auteca.com sattler energie consulting gmbh DI Peter Sattler Krottenseestraße 45, 4810 Gmunden, +43 (0) 7612 / 767 99-0, office@energie-consulting.at, www.energie-consulting.at

Description of the plant

Figure 3-16: Magna Auteca AG in Krottemdorf [Klima:aktiv, 2012c]

Magna Auteca Ltd. - an operation from the Magna-International-Group is the European market leader for mirror drive components. The production is located in Weiz with approximately 280 employees. The Magna Auteca AG produces annually about 18 million electric mirror drives and about 7 million electric Beiklapp drives for the Automotive industry.

The electric energy consumption in 2011 was approximately 4,635 MWh/a and the gas consumption approximately 691 MWh/a. The cooling system consists of two equally sized chillers (one chiller as redundancy), each with a maximum cooling capacity of 146 kW. These chillers operate with an average assumed COP of 2.5 – which means that they already run inefficiently. Around 45 % of the cooling demand is covered by the cooling towers. The electricity consumption for the cooling systems including cooling towers is about 88,500 kWh per year.

Figure 3-17: Cooling tower [klima:aktiv, 2012c]

Space heating is done by a natural gas fired boiler with a thermal capacity of 812-928 kW. This boiler is only used for space heating. The annual efficiency amounts to about 92 %. The major existing ventilation system has a nominal air flow of 60,000 m³/h and consists of a rotary heat exchanger, which recovers 70% of the exhaust heat. A second ventilation unit with a nominal air flow of 6,000 m³/h is currently supplied via a heating coil from the boiler. At an inlet air temperature of 21 °C the ventilation systems requires of about 457.400 kWh heat per year.

Currently four circulation pumps for cooling distribution are installed. 2 x P1 with 7.5 kW and 2 x P2 with 5.5 kW. The second pump is installed to get the redundancy. The consumption of the circulation pumps is about 75,500 kWh of electricity per year. The pumps for the cooling tower and for the transport of cold water to the buffer currently consume approximately 57,180 kWh of electricity per year.

The existing chillers are replaced by more efficient compression chillers. Additionally a new heat exchanger for heat recovery with free cooling function and frequency-control is equipped and a heat pump is purchased. The two new chillers have a nominal COP of 3.53 which is about 30% more efficient than the average COP of 2.5 of the existing chillers. The new Buffer tank, the new piping (including insulation) and the efficient pump station reduce the cooling demand by about 3% to 340,580 kWh/a. By the use of free cooling (COP 46) the new chiller only has to provide approximately 127,870 kWh of cooling per year, and is therefore less often in operation than before.

The waste heat from the chillers is used as heat source for the heat pump. The heat output at the higher temperature level can then be used for heating the supply air in the ventilation equipment. In the larger, existing ventilation equipment (air output 60,000 m³/h with rotary heat exchanger), a new heat recovery preheater is equipped and the heat from the heat pump can be used. In the second ventilation equipment (air capacity 6,000 m³/h) also the heat recovery preheater is supplied with heat from the heat pump.

Figure 3-18: high efficient pump [klima:aktiv, 2012c]

The actual amount of heat provided by the heat pump depends on the cooling operation and the heating demand. In total, about 260,360 kWh/a heat have been generated by the heat pump. The power consumption of the heat pump is approximately 70,080 kWh/a – based on the COP for heating (= 3.7).

The existing pumps are replaced by a highly efficient pressure rising facility. The new pumps are correctly designed on the basis of carried out demand measurements and are equipped with a frequency converter control. In the course of the renovation also the circulation pumps and pumps for the cooling tower and later free cooling will be replaced by new efficient pumps.

3.1.8 Ground Coupled Heat Pump Heating and Cooling System for a Multifunctional Office Building

Project summary

Company	STRABAG AG Donau-City-Straße 9, 1220 Wien www.strabag.at
Location	Vienna– Austria
Process application	multifunctional office building
Type of heat pump	Compression Heat Pump
Capacity	3x 693 kW
Year of realization	2003
Reduction in energy costs	80,700 EUR/a
Additional costs	273,700 EUR
Pay back	3.4 a
More information/contact	Andreas Zottl AIT Austrian Institute of Technology GmbH Giefinggasse 2, 1210 Vienna, Austria andreas.zottl@ait.ac.at http://www.ait.ac.at

Description of the plant

Figure 3-19: STRABAG HOUSE [Strabag, 2013]

The STRABAG HOUSE was constructed as a multifunctional office property. The 21,000 m² area of the 50 m high building is divided in 13 floors with about 18,000 m² office area and 3,000 m² for shops and commerce. The building is heated by floor convectors and cooled through micro perforated sheet-metal cooling ceilings.

Energy supply needed for heating and cooling is effected through a ground coupled heat pump system with an installed cooling capacity of 3*693 kW. The heat pumps are linked to a closed loop heat exchanger comprising of cast-in-situ driven piles integrated into the foundation. In total 68,000 m of PE-pipes were furnished partly in the foundation of the building and partly in 250 17m long cast-in-situ driven piles; the thermal energy is exchanged in 800 circuits. The system was designed in a way that the office and retail space require no additional power supply – apart from the electric power needed for the operation of the energy supply system.

For heating purpose the heat pump can be used on the primary circuit side to extract thermal energy from the ground via the foundation structures, which is then raised to a higher temperature level (heatingmode). In many cases the building can be cooled at virtually no cost through the direct use of the temperatures available in the ground. Here the heat transfer medium which circulates through the energy supply system is used directly for cooling purpose (free cooling mode).

If the underground temperatures do not allow free cooling, the installed heat pumps are used as refrigerator units and the ground is deployed as the heat sink for the heat pump system (cooling mode). The system was designed in a way that the office and retail space require no additional power supply – apart from the electric power needed for the operation of the energy supply system. Therefore the system operation can be distinguished into the four modes: heating, heating + free cooling, cooling + free cooling and cooling.

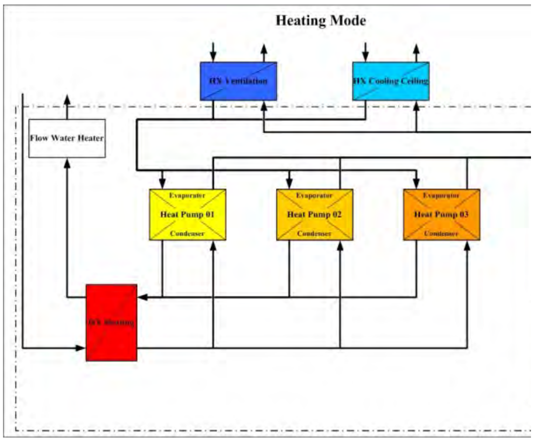


Figure 3-20: Schematic of heating mode [Presetschnik et al., 2005]

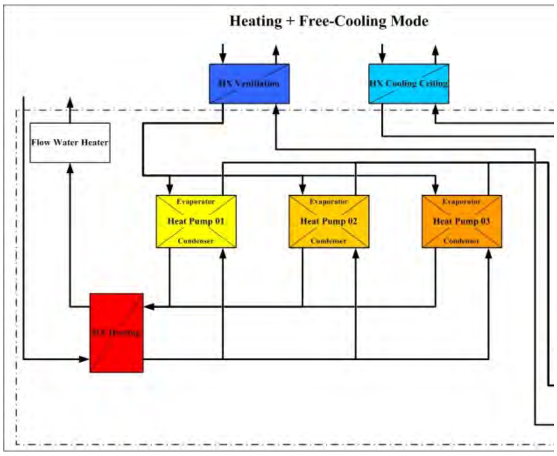


Figure 3-21: heating + free cooling mode [Presetschnik et al., 2005]

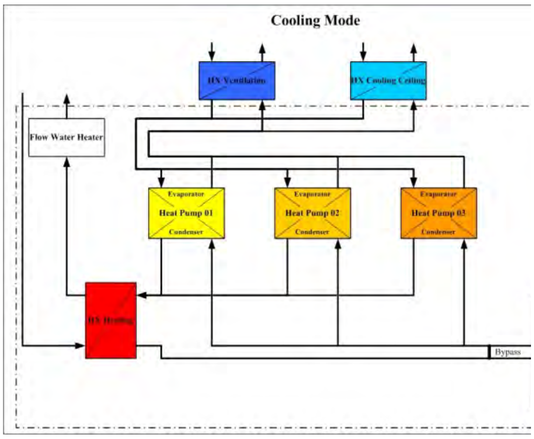


Figure 3-22: Schematic of cooling mode [Presetschnik et al., 2005]

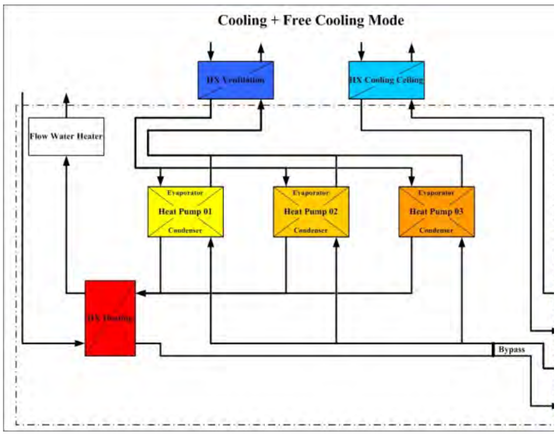


Figure 3-23: cooling + free cooling mode [Presetschnik et al., 2005]

Measurement Results

The monitoring of the energy supply system installed in the STRABAG HOUSE during the first two years of operation in the period 2003/2004 and 2004/2005 has shown that the system can accomplish the requirements with respect to the heating and cooling demand of the building. Less than one percent of the heating demand was supplied by the electric flow water heater.

Table 3-1: energy demand and SPF

	2004	2005	total	unit
Heating demand	2 700 849	2 991 357	5 692 206	kWh
Cooling demand	1 491 900	1 559 100	3 091 000	kWh
Electric energy	1 699 022	1 747 208	3 446 230	kWh
SPF	2.47	2.63	2.55	-

The results have shown a seasonal performance factor (SPF) of 2.55 for the total energy supply system in the first two years of operation. However the conditions especially during summer in a consequence of the final system adaptations have affected adversely the performance of the system. Do due adoptions of the control parameters the system shows a higher SPF in the second period of the monitoring.

The comparison of the system performance factors of the weekly evaluation shows that the system operations, depending on the average outdoor temperature for each calendar week, is a far more stable during the observation period 2004/2005.

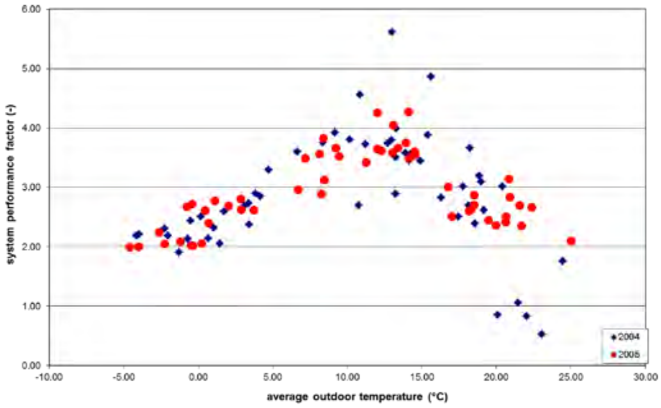


Figure 3-24: SPF comparison (Presetschnik et al., 2005)

Depending on the four different operating modes the system is operated with different efficiencies, the SPF of the total system is in a range between 2.26 and 6.55.

Table 3-2: SPF depending on operating mode

Operating mode	chiller	system
Heating	2.55	2.63
Cooling	2.58	2.26
Free-Cooling + cooling	1.81	7.81
Free-Cooling + heating	3.23	6.55

Less than two percent of the heating and cooling demand of the building was provided in the two free cooling modes. The utilisation of free cooling might be increased by the adaptation of the control set points of the energy supply system.

For future implementation of such a system it is recommended to decrease the flow temperature of the heating system to improve the performance of the energy supply system.

From an ecological point of view the installed system shows a favorable CO_2 balance compared to conventional heating and cooling systems based on natural gas, fuel oil or on the usage of district heating.

Building design criteria

application	space heating and cooling					
installed capacity	3 x 693 kW cooling capacity					
heat pump type	TRANE RTWB 222					
refrigerant	R 134a					
heat source	ground coupled system					
Details						
a) collector type	250 energy piles + 6,500 m² base plate					
b) energy pile length	17 m					
c) overall pipe length	68,000 m (800 parallel circuits)					
d) transfer medium	brine (antifreeze + water: -10°C)					
e) flow rate (m³/h)	heating	90	chilled water	cooling	144	chilled water
		90	cold water		90	cold water
heating distribution system	heating	floor convectors	cooling	cooling ceilings		
supply temperatures (°C)	heating	outlet	55	cooling	outlet	15 / 7
		inlet	45		inlet	17 / 13
auxiliary heating	2 x 250 kW direct electric water heaters					

Technical data chiller

Type	water chiller, RTWB
machine size	222
cooling capacity	693 kW
electric power	172 kW
COP	4.03
refrigerant	R-134a
refrigeration cycle	2
refrigeration charge	2 x 74 kg
compressor type	screw-type compressor
number of compressors	2
evaporator type	tube bundle heat exchanger
cold water volume evaporator	560 litre
condenser type	flooded tube bundle heat exchanger
maximum water temperature	60 °C
minimum cold water temperature	-12 °C
maximum cold water temperature	15 °C

3.2 Feasibility study of an application in Austria

This chapter describes a possible but interesting application of an industrial heat pump in an Austrian metal working plant. Initially, a monitoring of the operation of the heat pump was planned and the documentation should be part of the Austrian contribution on the HPP Annex 35. But, unfortunately the heat pump has not been realized up to now, because the decision of the industrial company for or against the heat pump application is still outstanding due to internal reasons by the company.

3.2.1 Compression heat pump for waste heat recovery of a chiller in a metal-working plant

Project summary

Company	Umdasch Schopfitting (Former: Assmann Ladenbau GmbH) Ottokar Kernstock-Gasse 16 8430 Leibnitz
Location	Ottokar Kernstock-Gasse 16 8430 Leibnitz
Process application	Process heating
Type of heat pump	Compression Heat Pump
Capacity	Heating Capacity ca. 200 kW
Running hours	NOT REALISED YET Assumed ca. 4,000 $h_{FullLoad}$/a
Year of operation	NOT REALISED YET
Reduction in CO2 emission	Assumed 60 tons/a
Manufacturer/supplier	NOT REALISED YET
Pay back	< 6 a
More information/contact	Ing. Volker Vehovec T +43 3452 700 261 volker.vehovec@umdasch-shopfitting.com

Within the national R&D project “Promise Demo IF” (FFG-No: 825537), the possible integration of an industrial heat pump (IHP) in an Austrian metalworking industrial company has been investigated, which pointed out the big economical and ecological potential of industrial heat pump applications.

For this, a feasibility study for the utilization of the waste heat from an existing chiller by an IHP has been carried out. Also the energy efficiency and cost-effectiveness of the IHP has been analyzed to determine technical, ecological and economical criteria as a basis for the decision of the industrial company for or against the IHP application.

The possible application

The main objective of this project was to find an appropriate electrically driven IHP to increase the temperature of the condenser waste heat from an existing chiller at approximately 45 °C to 80 °C, to use it for the heat supply of the galvanic baths inside the industrial plant.

So far, the chiller is used to cool the welding plants inside the industrial plant. This compression chiller works uses R-22 as refrigerant and according to the supplier of the chiller, it has a nominal cooling capacity of 152 kW (see Table 3-3).

Table 3-3: Data of the chiller according to Fa. CLIMAVENTA [6]

Capacity of the Chiller WRAR 0702/B	in	Value
Nominal cooling capacity	kW	152
Cold water temperatures	°C	7 / 12
Max. electr. power consumption (@ambient temperature of 35°C)	kW	58
Max. possible heat capacity of the low temperature waste heat recovery	kW	208
Cooling water temperatures of the low temperature waste heat recovery	°C	45 / 40

The chiller (see Figure 3-25) exists of two parallel refrigerant cycles with one common evaporator and a heat exchanger in each cycle to recover low temperature waste heat from the chiller at approximately 45 °C, which was already used for the heat supply of a low temperature galvanic bath inside the company.

An analyses - by measuring the thermal and electrical energy flows from and to the chiller as well as the temperature levels of the internal and the external cycles, see Figure 3-25Figure 3-25 - has been carried out in order to identify the temporally available capacity and temperature of the useable waste heat of the chiller.

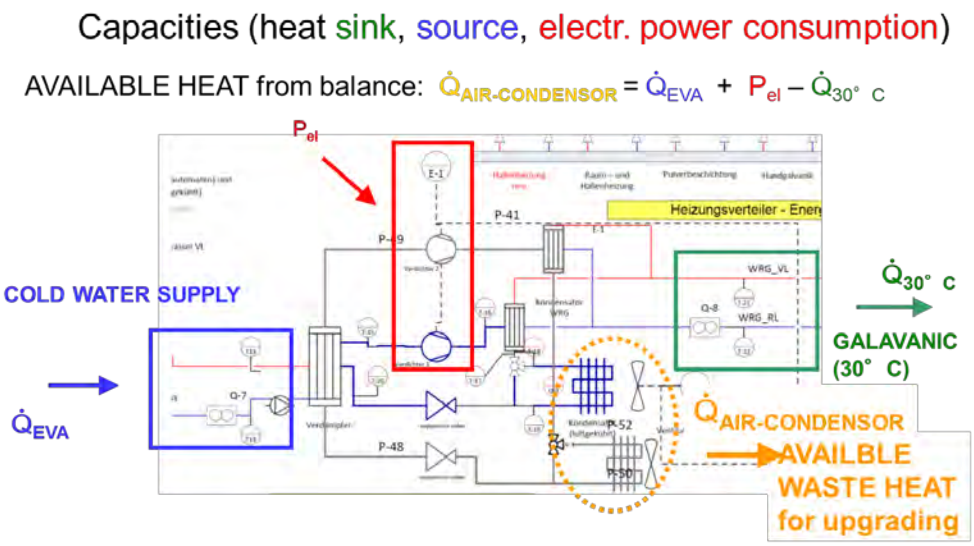


Figure 3-25: Schematic view of the existing chiller (Rieberer & Zotter, 2012)

The measurement showed that in average a waste heat capacity of ca. 70 kW at a temperature level of 40 °C is available at a usual utilization of the chiller. Reasons for this are a high part load rate of the chiller (even at full utilization of the welding plants) and that a share of the waste heat is already used to heat the low temperature galvanic bath.

Besides the availability of heat source also the "availability" of the heat sink has a major influence on the utilization of the IHP, because demand and supply have to fit together. Primarily, the IHP should be used to supply process heat to the galvanic baths. Further investigations regarding the best integration of the IHP into the existing heating grid show that the primary return of the heating system should be used as a heat sink for the IHP. The main reason for this is that the average heating demand of the primary heating cycle is much higher than the heat capacity of the IHP and due to this fact all the available waste heat can be used by the IHP for the heat supply inside the industrial plant without any additional storage.

Based on this data and the statistical records of the operating hours of the chiller the expectable full-load hours of the IHP have been extrapolated at 4.000 h per a.

Theoretical analysis

Several HP systems with different refrigerants have been investigated for this application. Major thermodynamic properties for choosing a refrigerant as the volumetric cooling capacity, the level of high and low pressure, the discharge temperature of the compressor as well as the global warming potential (GWP) of the fluid itself has been compared to each. Furthermore, also the expected efficiency have been determined by calculating the COP for the given temperature levels.

According to Table 3-3, the highest COPs have been calculated for ammonia (R717) and water (R718). Both of them are natural refrigerants (GWP = 0). However, water has a very low volumetric cooling capacity and therefore it is not appropriate for this application. When using ammonia, its toxicity and flammability have to be taken into account.

R-245fa (Pentafluorpropane) is a high-temperature refrigerant and its saturation pressure allows high condensing temperatures. However, it has low volumetric cooling capacity and there are no “standardized” heat pumps with this refrigerant available on the market so far.

R-600a (Isobutane) has very low GWP und is promising for high-temperature applications due to its thermodynamic properties. The biggest withdrawal for its usage is its high flammability.

R-134a (Tetrafluorethane) is a conventional refrigerant for condensing temperatures below 85 °C. It is not flammable and not toxicity. However, when using this refrigerant its high GWP has to be taken into account.

A hybrid heat pump (compression/absorption HP) working with the mixture ammonia-water suits at high-temperature applications due to the fact that the high-side pressure of the process can be varied by changing the ammonia concentration in the sorption cycle. However, no standardized heat pump suitable for this application is available on the market yet.

Table 3-4: Comparison of different HPs and refrigerants

Scheme	Refrigerant	COP_H	p_{SAT} (80°C)	GWP	Toxicity	Flammable
		[-]	[bar]	[kg_{CO2-eq}/kg]	[-]	[-]
Cascade	R-134a	3.8	27.5	1300	No	No
Add-on	R-134a	4.6	27.5	1300	No	No
Cascade	R-245fa	4.2	8.3	950	Low	No
Cascade	R-600a	4.0	13.8	3		Yes
Cascade	R-717	4.3	43	0	Yes	Yes
Cascade	R-718	4.4	0.5	0	No	No
Cascade	NH_3-H_2O (Hy-brid-HP)	3.8	Variable	0	Yes	yes

Manufacturer

Different manufacturers have been contacted concerning an offer for the heat pump. But only the Austrian supplier Cofely offered possibly plants for this application, a closed and an add-on heat pump. Two schemes of the heat pump integration were studied: Add-On HP and cascade HP (see Figure 3-26). As the refrigerant, R-134a was suggested.

According to Cofely their add-on HP would achieve a COP of approximately 4 and the closed compression HP approximately 3.5. The reason for this is that the available temperature level of the heat source is better utilized by the add-on HP than by a closed HP. However, the installation of the add-on HP would requires the substitution of the existing refrigerant R-22 by R-134a, which leads to a reduction of the cooling capacity of the chiller on about 30 %. Furthermore, the installation of the Add-On HP is a challenge from the technical point of view, as avoiding oil carry-over and more complex control system. Additional, also the investment costs of the add-on HP are higher than for the closed one.

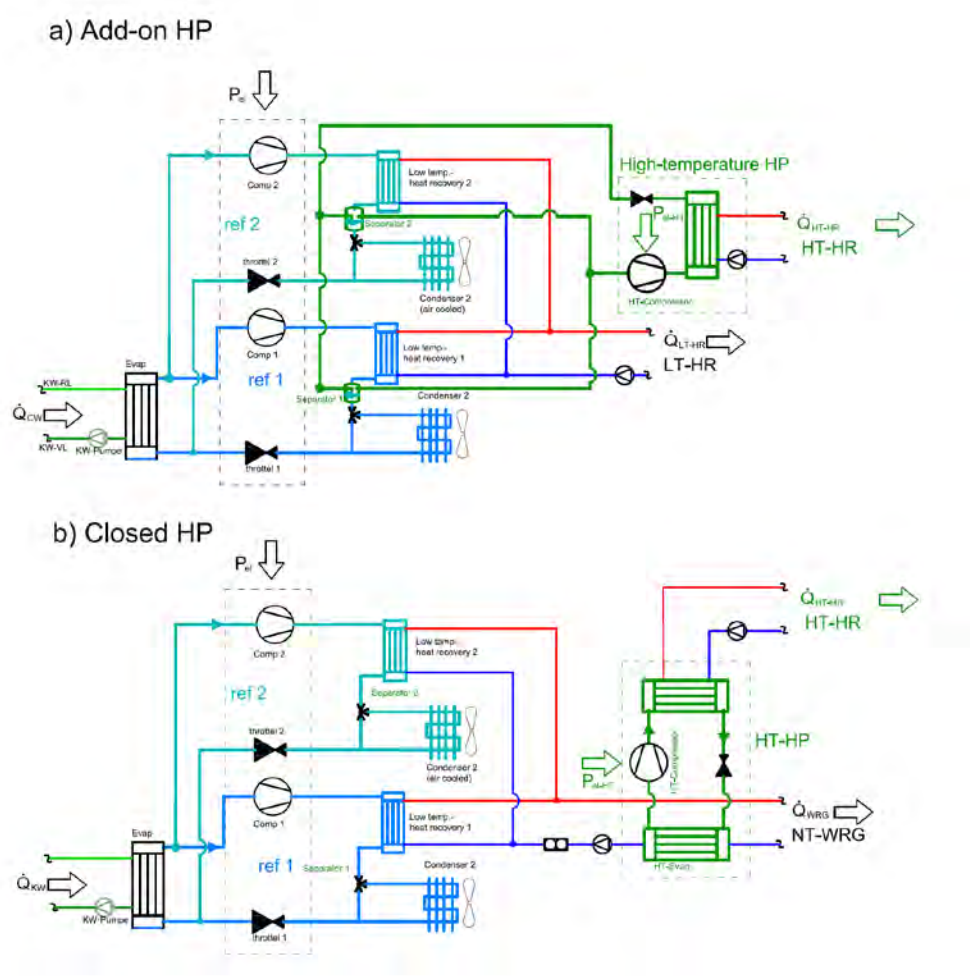


Figure 3-26: Investigated types of the heat pump (R-134a) integration: add-On HP (a) and closed HP (b)

Technical analysis

Taking these facts into account the closed R-134a HP will be preferred for the waste heat utilization. Figure 3-26(b) shows that the evaporator of the cascade HP is installed in the return pipe of the primary water circuit of the existing boiler, and not in the supply pipe, because of following reasons:

- If there is no demand on high-temperature heat, the waste heat of the R-22 chiller can be utilized by the low-temperature heat recovery system and/or rejected to the ambient by the existing air-condenser.
- The existing heat exchanger installed in the return flow of the low-temperature heat recovery system has a heating capacity of about 208 kW and is big enough to be used for both low-temperature and high temperature heat recovery.
- The R-22 chiller could be in operation without any constructional changes up to the substitution of the existing refrigerant (additional cost savings).

Economical and ecological analysis

Based on the offer of Cofely, the analysis of the cost-effectiveness of the cascade HP was carried out and it showed that the pay-back period is less than 6 years using static calculation and less than 7 years using dynamic calculation. Figure 3-27 shows the sensitivity analysis of the static pay-back period. It can be seen, that it depends strongly on the future gas and electricity prices, as well as on the SPF.

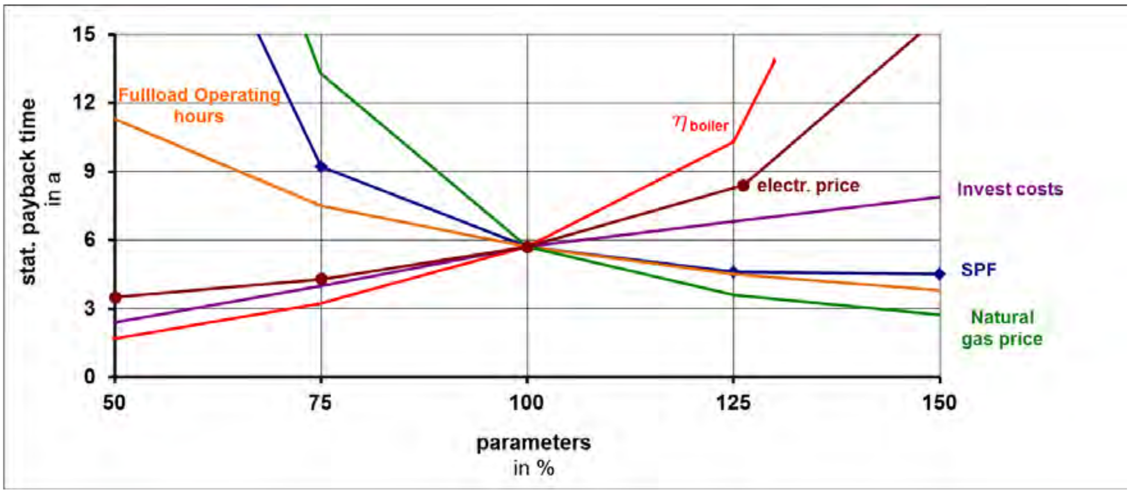


Figure 3-27: Sensitivity analysis of the pay-back period

Beside the economic benefit it has to be mentioned that this installation of the IHP allows a reduction of the CO_2-emmisions by approximately 60 tons per year compared to the existing gas boilers, which is a relative reduction of about 60 %.

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4 Canada

4.1 Introduction

Heat pumps contribute to global energy conservation and industrial productivity improvement, as well as to the reduction of greenhouse gas emissions. They are most cost effective in countries with low electrical energy prices compared to fossil fuel costs. This is not the case in Canada where industrial heat pumps have to be implemented in a context where prices of almost all primary energies (electricity, natural gas, oil) are relatively low and where *technical* (efficient use of heat generated and unreliable devices) and *legal* (lack of public or private incentives) issues are still barriers to the widespread application of IHPs. As a consequence, most Canadian companies are investing to improve production efficiency rather than reducing their specific energy consumption. However, there are promising industrial heat pump applications in Canada because large amounts of waste heat are available, especially from lumber dryers, liquid process effluents (24.2 %), process gases (12.7 % of total waste heat), refrigeration plants, cooling towers, evaporation processes, etc.

Prior to 1995, several hundred industrial heat pumps were developed and implemented in Canada, especially in the lumber drying sector, and also in the food industry, including dairies, poultry, sugar refining, breweries, liquor production and fish processing. For example, in 1993, 17 % of 14 investigated processes in more than 1900 individual plants were using industrial heat pumps based on the closed-vapour compression cycle, more than 90 % of which were used for lumber drying [Annex 9, 1990].

At the end of 2010, in 339 plants surveyed in Québec (Eastern Canada), Ontario and Manitoba (Central Canada), and British Columbia (Western Canada), 31 % of existing industrial heat pumps (26) were used for drying, 27 % for waste heat recovery, and 8% for evaporation processes with cooling capacities varying between 14 and 1050 kW. The future market penetration rate of IHPs in Canada is estimated at 5 % per year until 2030, ~ 80% of which could be closed vapour compression cycles and ~ 20 % mechanical vapour recompression systems [Minea, 2010].

Task 4 of the IEA Annex 35-13 project focuses on *operating experiences and energy effects* of representative in-country IHP implementations. According to the Annex legal text, successful case studies have to be presented along with an analysis of operating data, when available [Annex 35, 2010].

Canada’s Task 4 country report focuses on low- and high-temperature heat pump applications in small- and medium-sized industrial manufacturing processes, not only for heat recovery, but also for heating industrial buildings, when possible. These include food and beverage plants because they use large amounts of primary energy, mostly for heating, via gas-fired boilers to produce hot water and cooling processing operations via electrically driven mechanical refrigeration devices. Because economic performance is greatly influenced by energy consumption efficiency, food plants are seeking ways to recover and reintroduce waste heat into various industrial processes.

In this context, the heat pump technology could be used extensively to recover heat from relatively low-temperature sources and bring it to higher temperatures, or recover *latent heat* from hot and humid air streams. Frequently, in order to increase the overall efficiency of such systems, heat exchangers and heat pumps are used together in two or multiple stage heat recovery configurations.

4.2 CO_2 trans-critical heat pumps

4.2.1 General

Many implementation options exist for CO_2 trans-critical heat pumps, several of them being recommended by the manufacturers themselves. For example, Figure 4.1a presents the implementation principle of CO_2 industrial heat pumps for recovering heat from liquid waste effluents [Mycom], and Figure 4.1b shows a typical heat recovery example from large industrial or commercial building air-conditioning systems. Figure 4.2a shows a system used to recover heat from groundwater in order to heat water for domestic purposes and/or industrial processes. In the case of cooling systems, including ice cold storage, it is also possible to recover heat to produce process hot water (Figure 4.2b). Also, CO_2 sub- or trans-critical heat pumps could be used for recovering heat in fish farming facilities (Figure 4.3a) and in pasteurization processes (Figure 4.3b) [Mycom]. Even if the number of CO_2 heat pump industrial applications is practically unlimited, each particular application needs a careful study prior to its implementation.

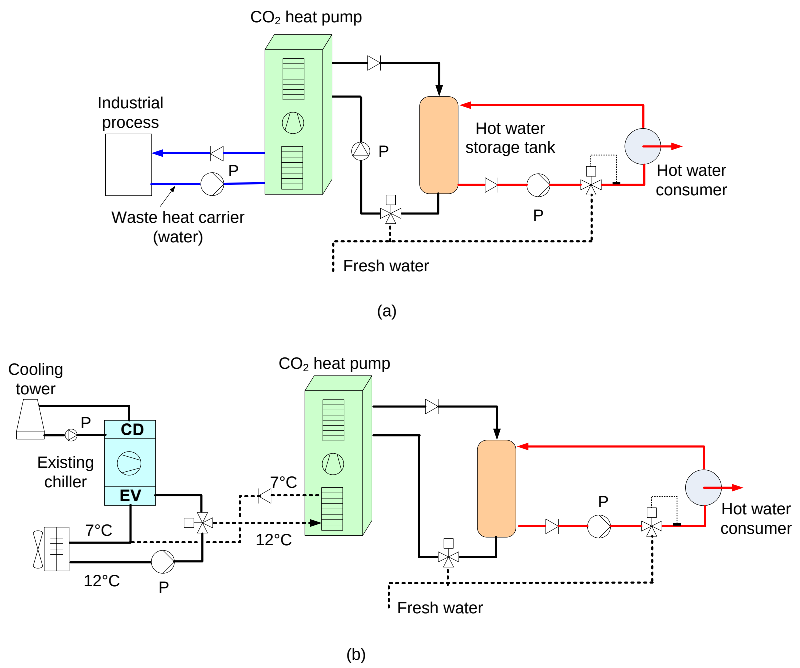


Figure 4-1: Industrial heat recovery with CO2 heat pumps; (a) from process waste heat; (b) from building air-conditioning systems [Mycom]

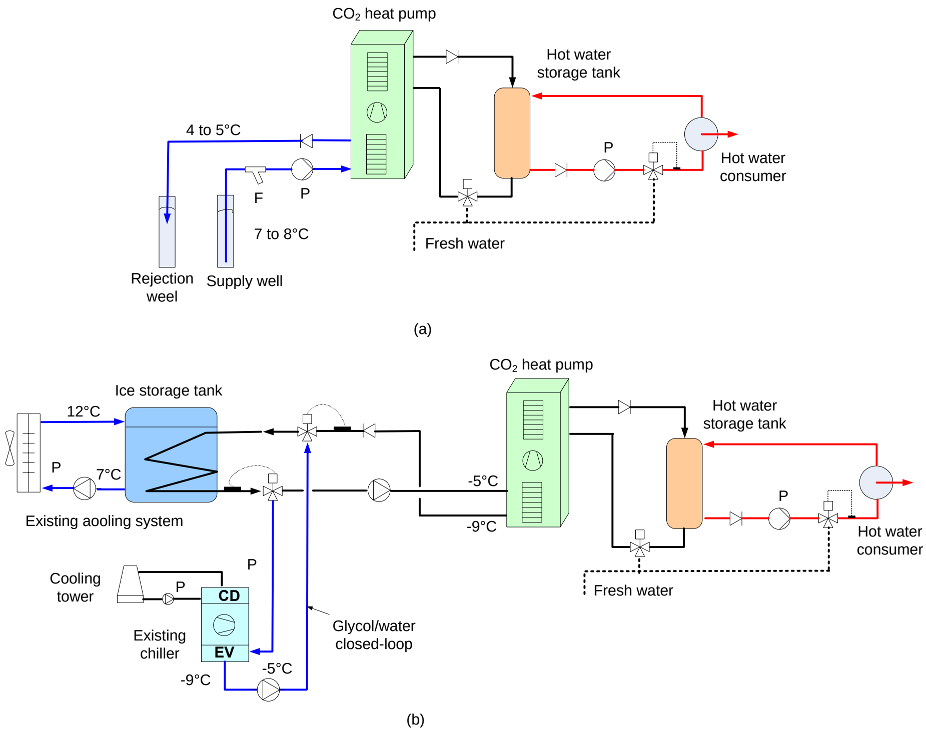


Figure 4-2: Industrial heat recovery with CO_2 heat pumps; (a) from groundwater; (b) from cold (ice) storage systems [Mycom]

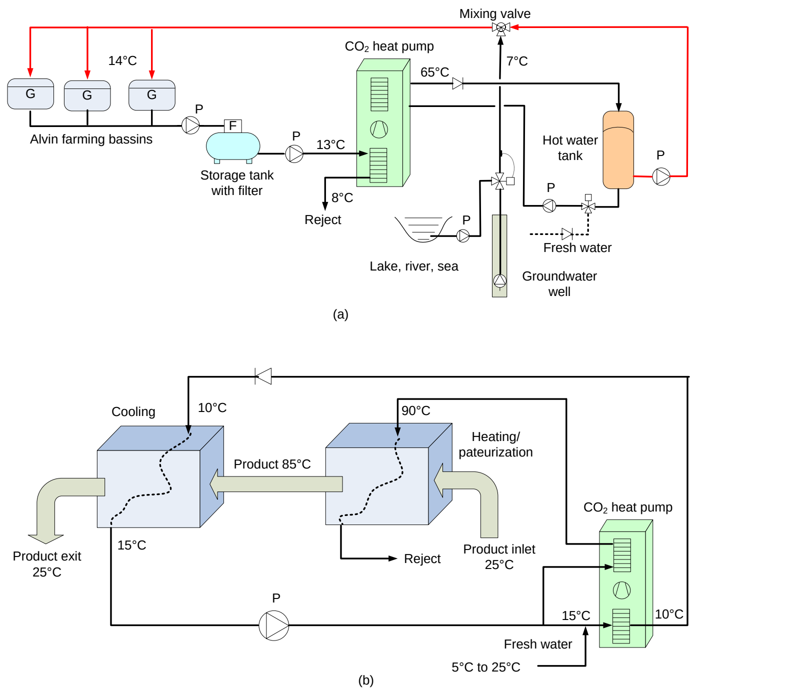


Figure 4-3:Industrial heat recovery with CO2 heat pumps; (a) in fish farming facilities; (b) in pasteurization processes [Mycom]

4.2.2 Food industry

Figure 4.4 schematically presents a CO_2 super-critical industrial heat pump recently implemented in a Canadian dairy plant [5, 6]. It is a 25 kW (compressor nominal power input) CO_2 trans-critical heat pump able to supply up to 100 kW of thermal power. The unit, adapted to the plant's actual process thermal conditions, provides hot water at temperatures varying between 60°C and 75°C by recovering heat from the plant's industrial process [Marchand, 2011], [Minea, 2013], [Lebeduin]. Because both heating and cooling thermal effects are used, the overall energy efficiency of the industrial process is further improved. The first results of the monitoring project will be available toward the end of 2013.

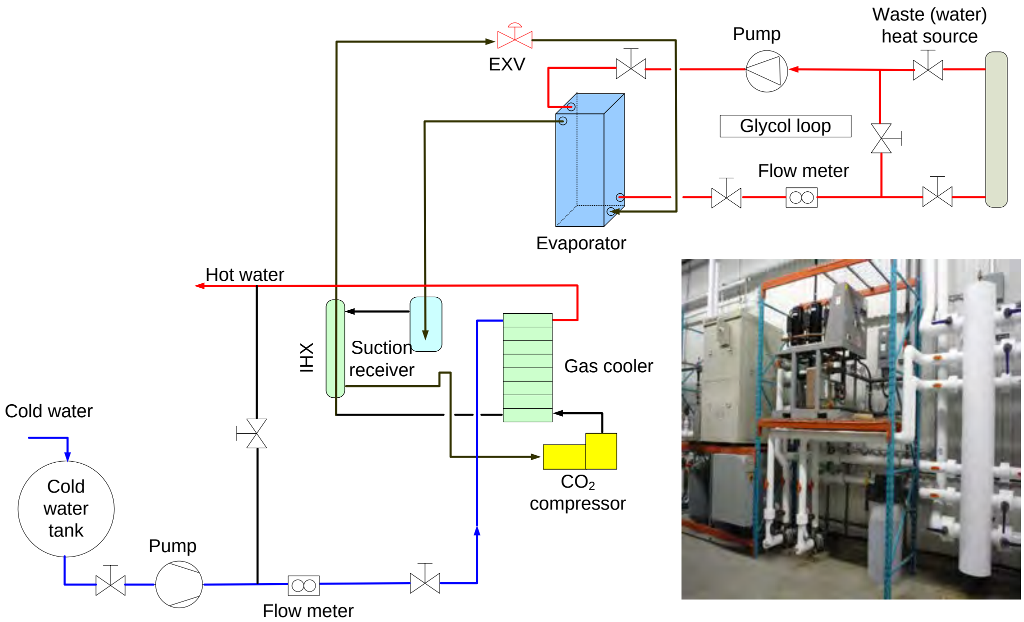


Figure 4-4: Schematic diagram of the first CO2 trans-critical industrial heat pump implemented in a Canadian dairy plant; EXV: expansion valve; IHX: internal heat exchanger [Marchand, 2011], [Minea, 2013], [Lebeduin]

A second Canadian dairy plant could integrate a similar 100 kW_{th} CO_2 trans-critical heat pump between two energetic systems, i.e. between a washing water closed-loop and a process water cooling loop (Figure 4.5) [Soteck, 2012]. The main purpose of this system is to reduce the annual consumption of fossil fuel. Process water at 12 °C (heat source) is circulated within a closed loop between the buffer tank and the heat pump evaporator. By recovering heat from this water loop, the heat pump produces cold water at 7 °C, able to cool a process fluid from 16 °C to 12 °C using a heat recovery heat exchanger. The cooling process provides additional energy savings to the heat recovery system and increases the system overall COP.

On the other hand, cold city water is heated inside the heat pump gas cooler up to 85 °C, prior to being supplied to the plant's washing loop via a storage tank. The heat pump runs only when the process closed loop is operational and, in case of trouble, the industrial processes will not be impacted because the heat recovery system is completely separated from the normal industrial process.

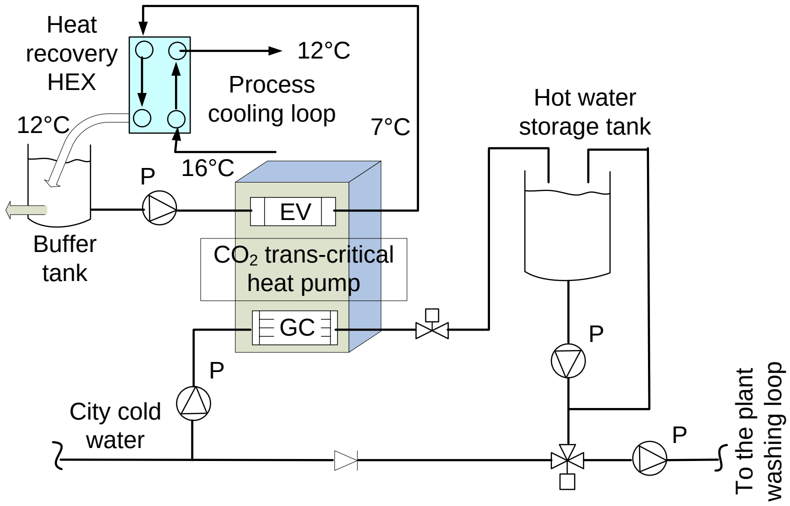


Figure 4-5: Schematic diagram of the CO2 trans-critical industrial heat pump implemented in the second Canadian dairy plant; EV: evaporator; HEX: heat exchanger; GC: gas cooler; GPM: US gallon per minute; P: pump [Minea, 2013], [Soteck, 2012]

4.2.3 Hospitals

As can be seen in Figure 4.6, CO_2 trans-critical heat pumps can also be implemented in hospitals requiring large quantities of process and domestic hot water [Minea, 2013], [Ecosystem, 2012]. In this case, the process and domestic water is heated within a double steam installation (Figure 4.6a). City cold water is heated up to 30 °C in a pre-heating heat exchanger linked to the building's mitigate water closed loop. The pre-heated water is then heated up to 65 °C in steam-to-water heat exchangers. The annual hot water consumption was estimated at about 8 million liters produced by burning 40,000 m^3 of natural gas in 80% efficient boilers [Minea, 2013], [Ecosystem, 2012]. Figure 4.6b presents the integration scheme of the 100 kW_{th} CO_2 trans-critical heat pump. Water from the existing building mitigate water closed loop (25 °C – 35 °C), being the heat pump's heat source, can be seen entering the heat pump evaporator and leaving it at temperatures between 20 °C and 30 °C. On the other hand, city cold water (at 5 °C in the winter and 12 °C in the summer) enters the heat pump gas cooler and leaves it at temperatures varying between 70 °C and 75 °C. The hot water storage capacity exceeds 5.5 m^3 while the instantaneous hot water demand is around 212 L/min, which is decidedly higher than what the CO_2 heat pump can produce. However, maximum daily hot water requirements are 34 L/min. only, and drop to 11 L/min at night. Consequently, the storage tanks can ensure continuous water consumption for more than 15 hours [Ecosystem, 2012].

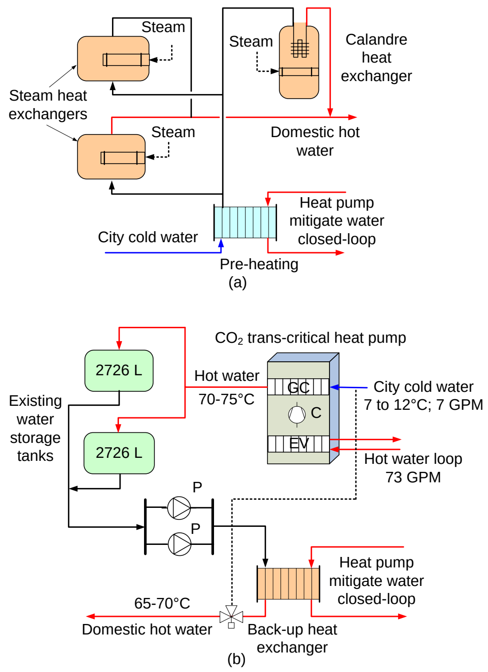


Figure 4-6: CO2 trans-critical heat pump implementation in a large Canadian hospital; (a) existing system; (b) proposed heat recovery system. EV: evaporator; GC: gas cooler; GPM: US gallon per minute [Minea, 2013], [Ecosystem, 2012]

4.3 Ammonia heat pumps

4.3.1 General

Preliminary laboratory tests [Minea, 2013] have helped validate the relevance of using single-stage ammonia heat pumps for heat recovery in industrial processes, as well as their energy performance. They have also demonstrated that, today, it is possible to correctly control the majority of safety issues (leakages, etc.). Figure 4.7a shows the integration principle of single-stage ammonia heat pumps in industrial processes, and Figure 4.7b shows this same principle in large industrial NH_3 refrigeration systems. Such units, equipped with high-pressure compressors and desuperheaters, may produce process hot water at 60 °C and 63 °C from cold water entering the system at 10 °C and 16 °C respectively [Vilter-Emerson].

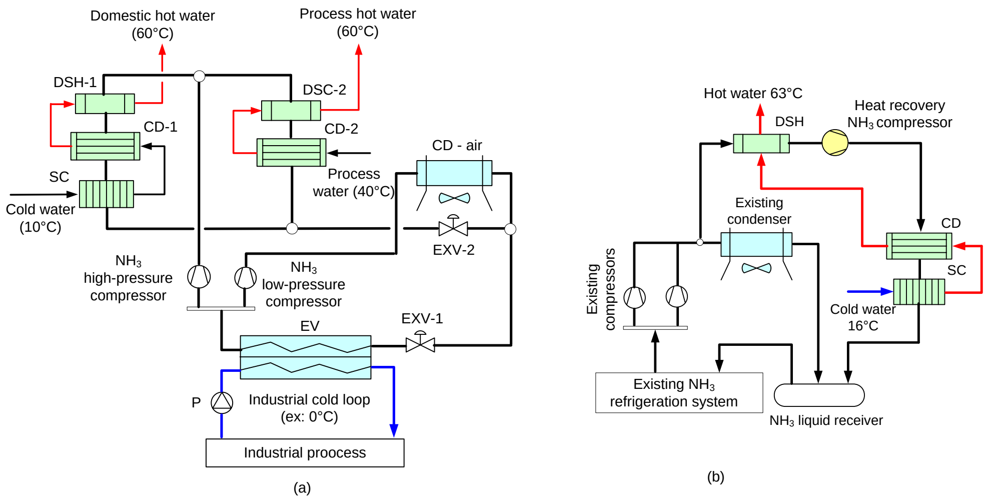


Figure 4-7: Heat recovery principle with single-stage ammonia heat pumps; (a) stand-alone system recovering heat from an industrial process; (b) integrated system recovering heat from an existing refrigeration system [Vilter-Emerson]

4.3.2 Food industry

Figure 4.8 shows the schematic diagram of a single-stage ammonia heat pump recently implemented in a new Canadian diary plant [Gosselin, 2013]. This ammonia heat pump, used for heating process water by recovering heat from the plant's ammonia refrigeration system, contains, among other standard components, a 150 kW ammonia compressor and a condenser that heats a brine (water/polypropylene – 10 %) closed loop. Heat is recovered from the superheated ammonia vapor coming from the existing ammonia compressors in a special heat exchanger and transferred to an intermediate hot water closed loop via a second heat exchanger. Since hot water isn't produced and consumed simultaneously, a large hot water storage system is provided. This heat recovery system allows the dairy plant to save up to one million equivalent kWh per year.

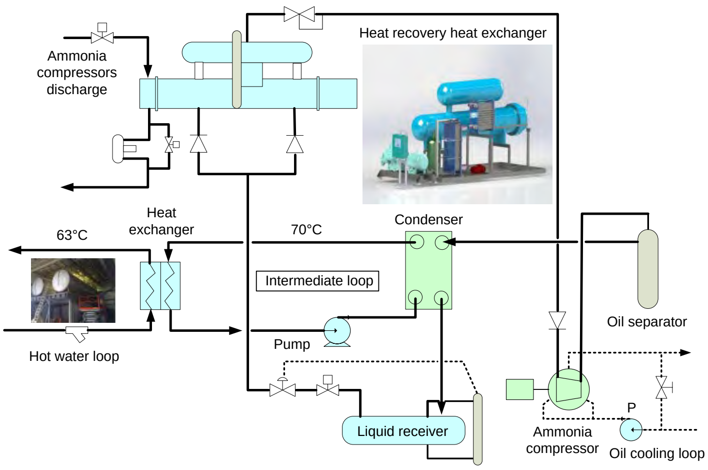


Figure 4-8: Schematic diagram of a single-stage ammonia heat pump implemented in a new Canadian diary plant [Gosselin, 2013]

The ammonia screw compressors available today on the market can work at higher pressures (≥ 45 bars) and condensing temperatures (Figure 4.9a) [Vilter-Emerson]. Consequently, two-stage ammonia heat pump cycles (Figure 4.9b) are feasible, being able to supply hot water at temperatures of up to 85 °C-90 °C by using industrial waste heat at relatively low temperatures. These two-stage ammonia heat pumps, equipped with desuperheaters, could recover heat, for example, from discharge gases in existing ammonia compressors and produce hot water at 85 °C from cold water entering the system at 10 °C to 20 °C (Figure 4.10a) or from sea, lake or river water (4 °C in the winter and 20 °C in the summer), in order to supply hot water at different levels (60 °C, 80 °C and 90 °C) to be re-used in industrial processes or for district heating (Figure 4.10b) [Vilter-Emerson]. Several feasibility studies aimed at implementing such advanced heat recovery two-stage, high-temperature ammonia systems in Canada are under way.

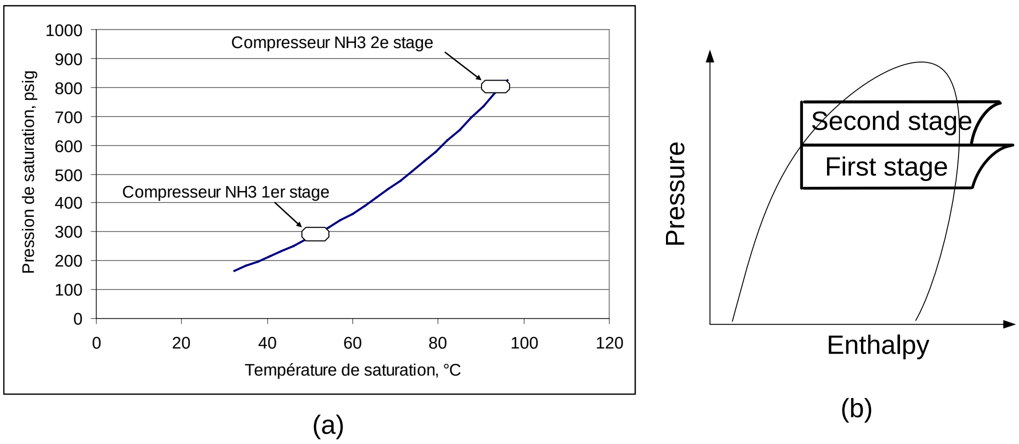


Figure 4-9: Ammonia screw compressors for industrial heat pumps; (a) two-stage thermodynamic cycles in p-h diagram; (b) pressure limits of first and second stage ammonia screw compressors [Vilter-Emerson]

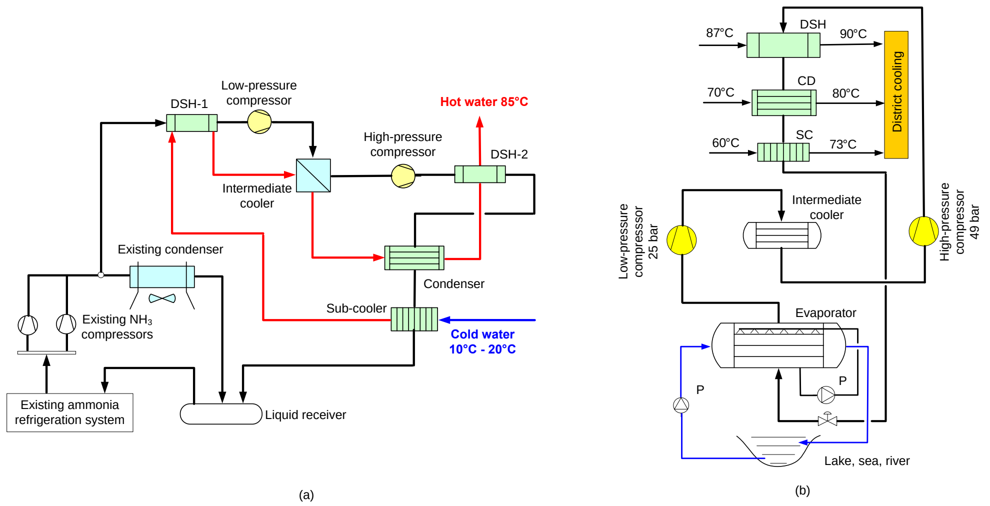


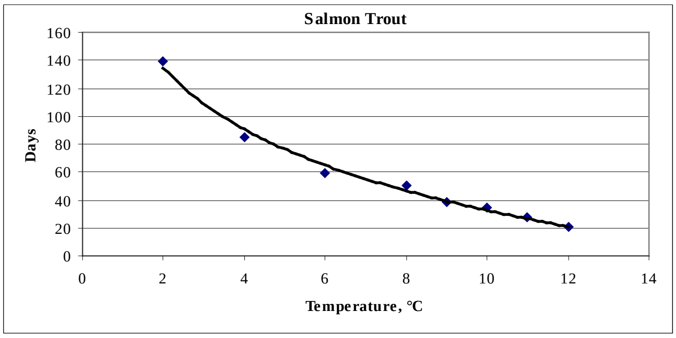
Figure 4-10: Heat recovery with high-temperature, double-stage ammonia heat pumps; (a) from refrigeration systems; (b) from lake, sea or river water [Vilter-Emerson]

4.4 Fish farms

Salmonid culture intended for the breeding, consumption and sport-fishing markets is growing in Canada. Conventional systems include oxygenation columns, plate heat recovery heat exchangers, water filters and pumps, and oil-fired water-preheating devices to improve productivity. Northern fishery companies use fresh, relatively cold surface or groundwater directly in incubation and fish nursery units, without any preliminary heating [Minea, 1996]. However, preheating the water would accelerate alevin growth.

In order to reduce and/or eliminate fossil fuel consumption and, thus, improve environmental performance, a six-month field study of a two-stage heat recovery system with passive heat exchanger (as a first stage) and water-to-water heat pump (as a second stage) has been conducted in a Canadian fish farming facility (Figure 4.11a) [Minea, 1998]. The main objective was to reduce energy consumption and costs, and increase the productivity of the industrial process by recovering and transferring heat between two high-flow rate streams, i.e. waste and fresh water. In other words, the cold groundwater, usually used in salmonid culture under cold climates, is heated with heat recovered from the process waste water in order to reduce the conventional alevin growth cycle. Figure 4.11b shows that, by increasing water temperature, for example, from 8 °C to 12 °C, the number of days required for 50% salmon trout hatching at a constant incubation temperature could be reduced from 50 to about 21 [Champagne, 1998].

(a)



(b)

Figure 4-11: (a) View of the fish farming building [Minea, 1998]; (b) number of days required for 50% salmon trout hatching at a constant incubation temperature [Champagne, 1998]

The fish nursery is the initial stage in the fish farming cycle, which leads to the production of young fish. The fry-rearing process begins when the eggs hatch and ends after about three months, when the fish reach a weight of about 5 grams or a length of 7.5 cm. For every cycle, several hundred thousand fertilized eggs are placed in incubation basins where water is generally maintained at a temperature varying between 6°C and 8 °C until hatching occurs. For incubation, water temperature is the most determining factor because the length of the process is inversely proportional to water temperature (see Figure 4.11b). Water temperature at the beginning of the alevins' rearing process is also important because it activates the metabolism and digestion, and stimulates the sac fry to eat more frequently and in greater quantities. The alevins' size also increases with both the oxygen saturation ratio and water-flow velocity. The fish nursery unit contains several breeding water pools with a total volume of 45 m^3 and a total water-flow rate of approximately 21 l/sec., about 50% of which is fresh groundwater.

In the two-stage heat recovery system implemented in Canada (Figure 4.12), about 10.5 l/sec. of fresh groundwater is pumped from deep ground wells through a plate heat exchanger, which raises its temperature by recovering energy from the waste water coming from the fish breeding pools. Then, the pre-heated fresh water enters the heat pump condenser where it is heated once again by the refrigerant, which recovers heat also from the waste water leaving the passive heat recovery heat exchanger. Therefore, the water-to-water heat pump uses waste water as a heat source and groundwater as a heat sink. Finally, the warmer fresh water is directed through an oxygenation system (not shown in Figure 4.12) where it mixes with the re-circulated water flow, prior to returning to the alevin basins. Waste water is discharged into an underground storage tank, and then to a river, without any environmental pollution. The vapor compression heat pump uses a HCFC-22 refrigerant and contains three parallel scroll compressors and a compact water-to-refrigerant evaporator and a condenser.

As can be seen in Figure 4.13a, the average temperatures of the groundwater entering the plate heat exchanger slightly decreased from 7.4 °C in October to about 6.8 °C in March, a normal but relatively negligible seasonal variation. The heat pump's monthly average coefficient of performance (COP), defined as the thermal energy provided to the process water supplied to the alevin basins divided by the total electrical energy consumed by the heat pump compressors, was about 6.1 during a continuous operation period of six months (Figure 4.13b), an excellent energy performance.

The average thermal efficiency of the first-stage heat recovery passive heat exchanger varied around 66%, and it provided more than 472,000 kWh of thermal energy to the groundwater, corresponding to an average seasonal thermal power of 109 kW.

In terms of energy, the fresh groundwater was first heated by the passive heat exchanger, which provided 64 % of the energy, and then by the heat pump, which provided 30.5 % over a six month production period (Figure 4.14). Heat pump heat recovery was made possible with a net power consumption of 45.8 %, while the water circulation pumps took 54.2 % of the total energy consumed. Consequently, the overall average coefficient of performance, calculated for the whole system, including both the passive heat exchanger and the heat pump, was 7.9 for two consecutive 3-month industrial production periods.

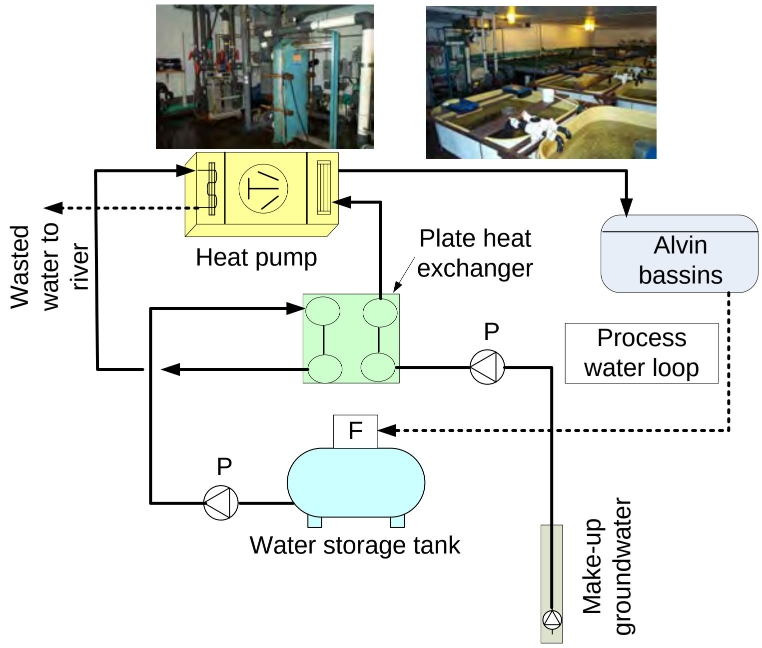


Figure 4-12: Two-stage heat recovery system implemented in a Canadian fish farming facility; T: temperature; P: pressure; W: power; HEX: plate heat exchanger; DE/RF: water & refrigerant flow meter [Morin 1996], [Collignon, 1998], [Minea, 1999]

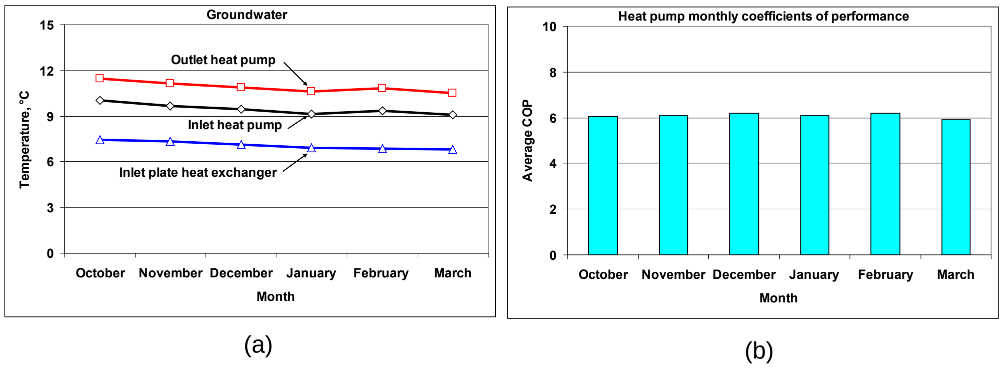


Figure 4-13:(a) Average monthly groundwater temperatures; (b) average monthly heat pump COP [Minea, 1998], [Minea, 1999], [Minea, 2002]

The comparison of the alevin growth rates with heated (10-12 °C) and unheated (7-8 °C) fresh water shows that the annual production of 5 gram rainbow trout increased by approximately 50 % using water that is 4 °C warmer. Moreover, the time period required for the rainbow trout to grow was 65 % shorter than that of conventional processes, leading to substantial improvements in the company's overall efficiency. In fact, with water temperatures increasing from 7 °C to 11 °C, the average alevin weight after a 90-day period increased from the usual 1.7 grams to 4.8 grams [Champagne, 1998]. Finally, the system simple pay-back period was estimated at 1.28 years, without taking the increase in fish production into consideration.

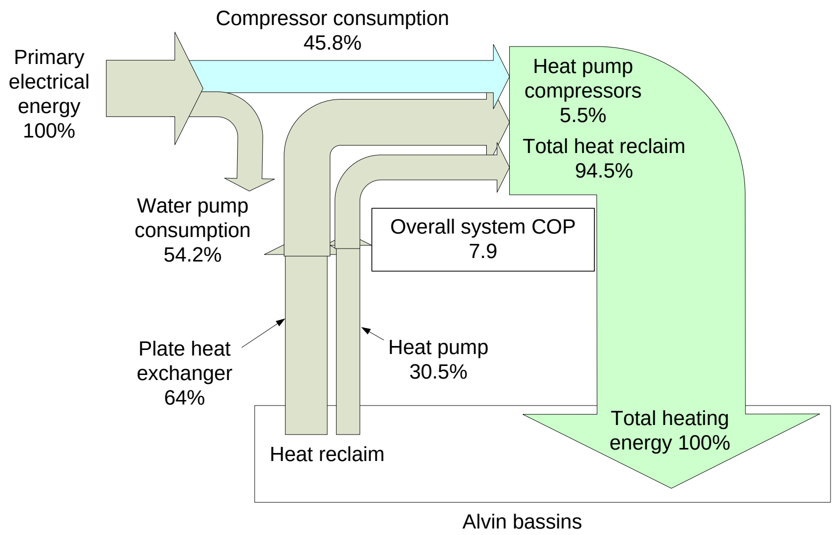


Figure 4-14: 6-month global energy balance of the two-stage heat reclaim system implemented in a Canadian fish farming facility [Minea, 1998], [Minea, 1999], [Minea, 2002]

4.5 Heat pump-assisted wood drying

About 45 % of the Canadian territory is wooded, representing 10 % of the planet's forests. The Canadian wood industry accounts for 3 % of the country's Gross Domestic Product, 10 % of total foreign trade, and 57 % of the annual commercial surplus. In Quebec (Eastern Canada), hardwood such as hard maple, yellow birch, oak, and white walnut represents 6.6 % of a market dominated by resinous species. Hardwood is usually dried at low temperatures (maximum 55 °C), a process that consumes up to 70 % of the total energy required for primary wood transformation. Usual energy sources for wood drying are fossil fuels (oil, natural gas, propane) and bark [Canada Statistics, 2002].

On the other hand, approximately 10 % of the Canadian soft wood production comes from the province of Quebec (Eastern Canada). About 2 % of this production is dried with *low-temperature* heat pumps and the rest through other technologies such as direct fire and the use of bark-, natural gas- or oil-fired boilers. Soft wood drying, highly profitable at high-temperatures, is essential to prevent warping and cracking. Usual energy sources for wood drying are fossil fuels (oil, natural gas, propane) and bark.

4.5.1 Low-temperature drying heat pump

Electrically-driven low-temperature heat pumps are usually used in combination with fossil fuels or electricity as back-up energy sources. About 25 % of hardwood dryers in Quebec are equipped with low-temperature heat pumps.

A 13 m^3 experimental forced air wood dryer with variable speed fans was equipped with a 5.6 kW low-temperature heat pump [Minea, 2006a], [Minea, 2011]. The heat pump (compressor, blower, evaporator, condenser, sub-cooler, refrigeration piping and controls) is installed inside a mechanical room next to the dryer chamber (Figure 4.15).The dryer contains steam and electrical heating coils. Steam is supplied at variable flow rates by a natural gas-fired boiler (with a thermal efficiency of 80 %). Inside the dryer, the air periodically flows in opposite directions to ensure uniform heating and drying.

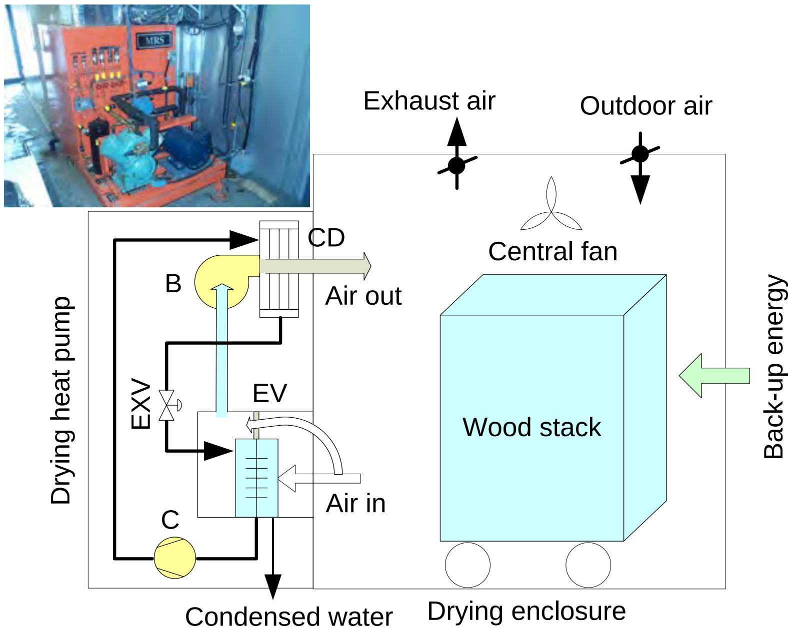


Figure 4-15: View of the low-temperature hardwood drying experimental heat pump [Minea, 2006a], [Minea, 2011]

4.5.1.1 Drying schedule and control

Dry- and wet-bulb temperatures inside the dryer, as well as the compressor running times, are scheduled based on the actual wood moisture content (Table 4.1). In the first step (preheating), the compressor is not running. The heating coils provide heat to increase the temperature of the wood stack. When the wet-bulb temperature reaches its set point, the heat pump starts and runs intermittently. For example, if the hourly operation percentage is set at 60 %, the heat pump will run for 30 minutes and will shut down during the next 20 minutes. The compressor running time increases when the actual wet-bulb temperature is higher than the upper set limit and decreases when it is below the lower set limit. When required, the dryer uses one of the back-up heating sources, i.e. electricity or steam. In addition, if the actual dry-bulb temperature is higher than its set point, the air vents open automatically and close when it drops below the set point.

Table 4-1: Example of a hardwood heat pump drying schedule

Drying step	Dry bulb	Wet bulb	Heat hump hourly running time
-	°C	°C	%
1 Preheating	37.8	32.2	-
2	37.8	32.2	100
3	40.5	33.9	85
4	43.3	34.4	75
5	46.1	34.4	65
6	54.4	34.4	75
7	57.2	35.0	85
8	60.0	35.0	100

4.5.1.2 Energy consumption and costs

Two all-electrical drying tests with a low-temperature heat pump and electrical back-up coils are presented (Table 4.2). The initial moisture content (dry basis), representing the weight of the water contained in the wood expressed as a percentage of its anhydrous mass, was 29.1 % (test #1) and 40.7 % (test #2) respectively. The total drying time, including the preheating steps, was 147.03 hours (6.12 days) (with yellow birch) and 240.67 hours (10 days) (with hard maple) respectively. The final moisture content (oven-measured, dry basis) was 7.4 % and 7.8 % respectively. The final moisture content is within normal ranges for hardwood drying. The heat pump (compressor and blower) accounted for 30% (test #1) (Figure 4.16) and 21 % (test #2) of the total electrical energy consumed respectively. The electric back-up coils accounted for 62 % (test #1) (Figure 4.16) and 61 % (test #2) of the energy consumed, and the dryer fan for 8 % (test #1) and 11% (test #2).

Two additional drying tests with the low-temperature heat pump and steam as back-up energy (hybrid test #3 and hybrid test #5), as well as a conventional drying cycle (test #4 - CONV), are also presented (Table 4.3). It can be seen that with hard maple, the total drying time of hybrid test #3, including the first (preheating) step, was 16.5 % longer than that of conventional drying test #4, while both final moisture contents were identical (7.5 %). However, the equivalent energy consumption of hybrid test #3 was more than 50 % lower than that of conventional test #4, which used natural gas as a heating energy source.

Table 4-2: All-electrical (heat pump with electrical back-up) drying tests

Test	Wood	Moisture content		Energy consumption			
-	-	MC_{in}	MC_{fin}	Heat pump		Dryer	
-	-	-	-	Compressor	Blower	Fan	Back-up electricity
-	-	%	%	kWh	kWh	kWh	kWh
#1	Yellow birch	29.1	7.4	747	151	229	1 828
#2	Hard maple	40.7	7.8	872	258	451	2 441

MC_{in} : initial moisture content; MC_{fin}: final moisture content

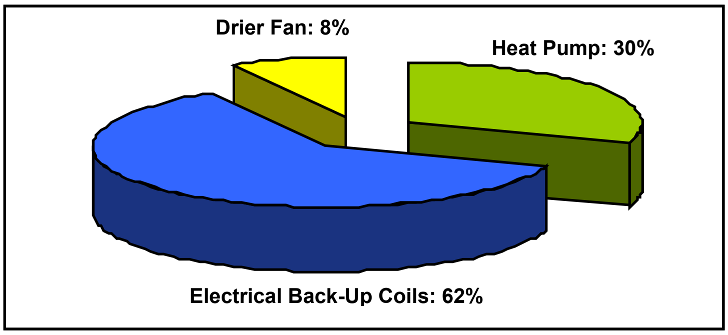


Figure 4-16: Electrical energy consumption distribution for all-electrical drying test #1 [Minea, 2006a], [Minea, 2011]

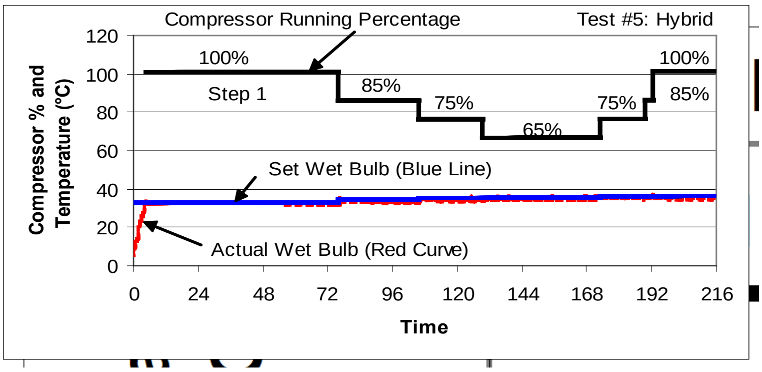
Table 4-3: Hybrid (heat pump with steam back-up) and conventional (steam) drying tests

Test	Hardwood species	Moisture content		Electrical energy consumption			Operation rate vs. cycle time	
-	-	MC_{in}	MC_{fin}	Heat pump		Dryer	Heat pump	Back-up
-	-	-	-	Compressor	Blower	Fan	Compressor	Steam
-	-	%	%	kWh	kWh	kWh	%	%
#3 - hybrid	Hard maple	31.1	7.5	650	129	360	65	39
#4 - CONV	Hard maple	36.4	7.5	-	-	638	-	70
#5 - hybrid	Yellow birch	75.9	7.6	902	201	400	84.7	40

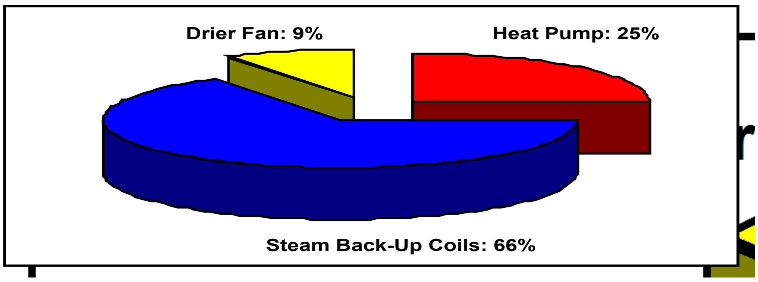
The intermittent operation of the heat pump was set prior to each step of the drying cycle. It was also frequently adjusted during the drying process in order to keep the actual wet-bulb temperature close to its set point. For hybrid test #5, Figure 4.17a shows the correlation between the heat pump's hourly percentages of operation and its settings and the actual wet-bulb temperatures. It can be seen that the actual wet-bulb temperature perfectly matched the set wet-bulb values with the intermittent operation of the compressor. Also, when the initial moisture content (MC_{in}) was relatively high (75.9 % - test #5), the compressor operated 84.7 % of the time. However, it ran only 65 % of the time when the MC_{in} was significantly lower (31.1 % - hybrid test #3). The heat pump (compressor and blower) accounted for 25 % of the total energy consumed, while the dryer fan and back-up heating (steam) accounted for 9 % and 66 % respectively (Figure 4.17b). The relatively high operating percentage of the steam coils can be explained by the poor thermal insulation of the experimental dryer and relatively high air leakage rates.

Compared to the energy consumed in conventional test #4 (719 m^3 of natural gas), the natural gas consumed in hybrid drying test #5 (350 m^3) was 56 % lower. Consequently, assuming a number of 40 drying cycles per year, natural gas savings would total about 15,000 m^3/year. Equivalent CO_2 emissions would consequently be reduced by 30.6 tons per year and per dryer. This takes into consideration approximately 40 kg of CO_2 emissions per year due to the additional electrical energy consumed by the heat pump. If 500 small-scale hardwood dryers with low-temperature heat pumps were installed, the annual reduction in CO_2 emissions would be 15,300 tons. This estimation was done for the Province of Quebec (Eastern Canada), where 97 % of the electricity produced is hydroelectric. In this case, the regional conversion factor is 0.00122 kg of CO_2 per kWh of electrical energy consumed.

Compared to the energy cost of the conventional drying cycle using natural gas (test #4 - CONV), the total energy cost (electricity and natural gas) of the drying cycles with low-temperature heat pumps is reduced by 20 % (all-electrical test #2) and by 23% (hybrid test #5) respectively (Figure 4.18).



(a)



(b)

Figure 4-17: Hybrid drying test #5; (a) compressor hourly running time (%) and set and actual wet-bulb temperatures; (b) distribution of energy consumption [Minea, 2006a], [Minea, 2011]

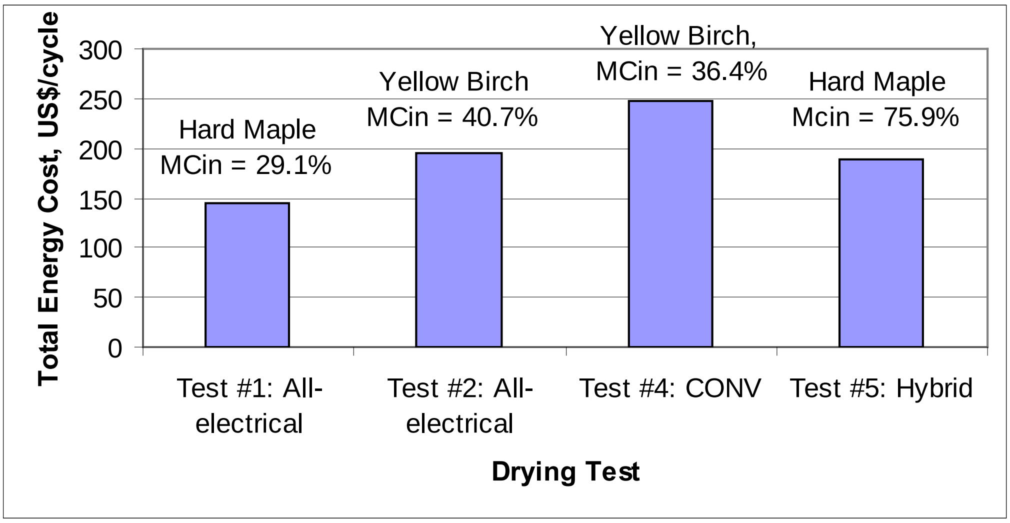


Figure 4-18: Drying cycle total energy cost (2007 US$); MCin: initial moisture content

4.5.1.3 *Water extraction*

The condensed water volume strongly depends on the wood initial moisture content (Figure 4.19). Test #1 (all electrical), with a relatively low initial moisture content (29.1 %), produced 2.5 times less water than hybrid test #5, where the initial moisture content was much higher (75.9 %). This result was obtained even though the initial quantity of dried wood (hard maple) was 33.6 % higher in all-electrical test #1 compared to the initial volume used in hybrid test #5.

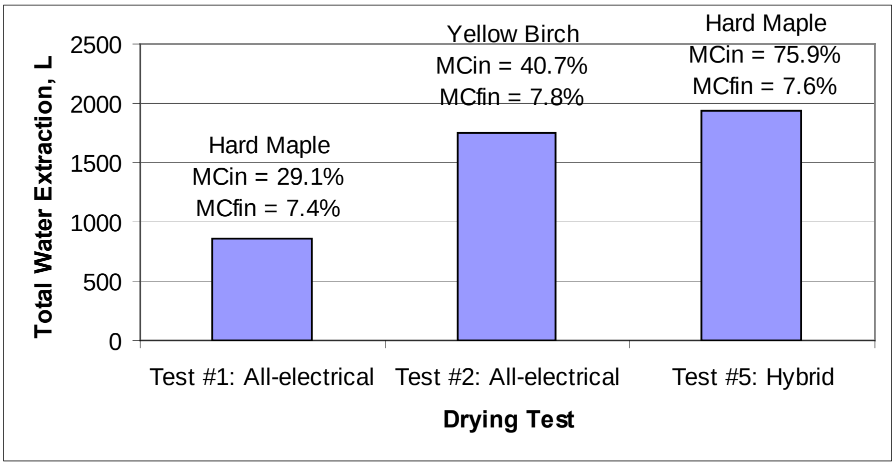


Figure 4-19: Total volumes of water extracted [Minea, 2006a], [Minea, 2011]

The fiber saturation point (FSP) is the physical state where the cell cavities are completely devoid of free water and their walls are still completely saturated. For hardwood, the FSP moisture content is about 25 % (dry basis). It can be seen that with an initial moisture content below 41 % (all-electrical test #1), the volume of water extracted below the FSP was much higher than the volume extracted above the FSP (Figure 4.20). However, when the initial moisture content was approximately 41 % (hybrid test #2), the volume of water that condensed above the FSP was practically equal to the volume removed below this point. Finally, when the initial moisture content was significantly higher than 41 % (75.9 % in hybrid test #5), the volume of water extracted above the FSP was about three times higher than the water volume removed below the FSP.

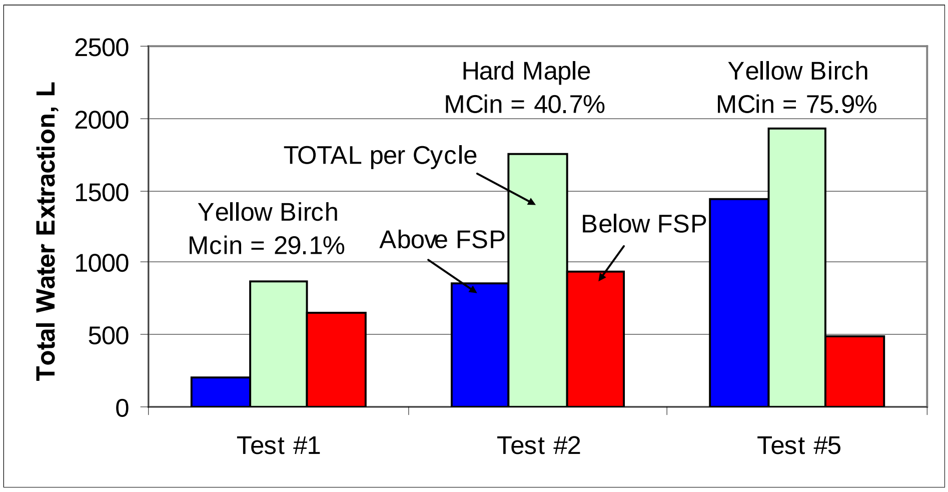


Figure 4-20: Total water extraction vs. the fibre saturation point [Minea, 2006a], [Minea, 2011]

4.5.1.4 Dehumidification rate

For every wood species and thickness, there is a safe drying rate at which moisture can be removed. In other words, there is a rate at which wood can be dried with little or no significant degradation or damage. On the other hand, the water evaporation rate depends on the amount of energy supplied and the capacity of the drying air to absorb moisture. To maintain a constant drying rate, the water molecules in the wood must be supplied with additional energy, or the drying air partial vapor pressure has to be lowered. This is achieved either by raising the temperature or reducing the relative humidity of the drying air. Exceeding a maximum safe evaporation rate increases the risk of drying defects (splits, cracks or checks). However, when drying is done at a rate substantially lower than the safe rate, there is also a risk of drying defects (increased warping, stains and uneven drying). For example, the safe drying rate for hard maple lumber in terms of moisture content loss per day is 6.5 %. Drying rates also provide a method of estimating drying cycle times. For conventional drying cycles, this parameter is usually expressed in terms of percent moisture content loss per day. Using a low-temperature heat pump as a dehumidifier, the drying rate is expressed in terms of average water extraction volume (L) per hour. In this case study the average water extraction rate per cycle slightly increased as a function of the initial moisture content. For example, with yellow birch, it increased by 10.3 % when the initial moisture content rose from 29.1 % (all-electrical test #1) to 75.9 % (hybrid test #5). However, the water extraction rates below the FSP decreased by a factor of 2.4 (test #1) and 3.4 (test #5) as compared to the respective rates above the FSP (Figure 4.21).The water extraction rate above the FSP is therefore not very sensitive to the total water volume removed. Actually, if we compare tests #1 and #5 with yellow birch, the water extraction rates above the FSP were practically similar (13 L/h and 14.5 L/h respectively), even though the total water volume removed during test #1 was more than five times lower than the volume extracted during test #5. On the other hand, below the FSP, the water extraction rates were proportional to the gap between the FSP and final moisture content (about 17.5 %), and practically equal (4 to 5 L/h), regardless of the dried species (yellow birch or hard maple) and the respective water volumes removed.

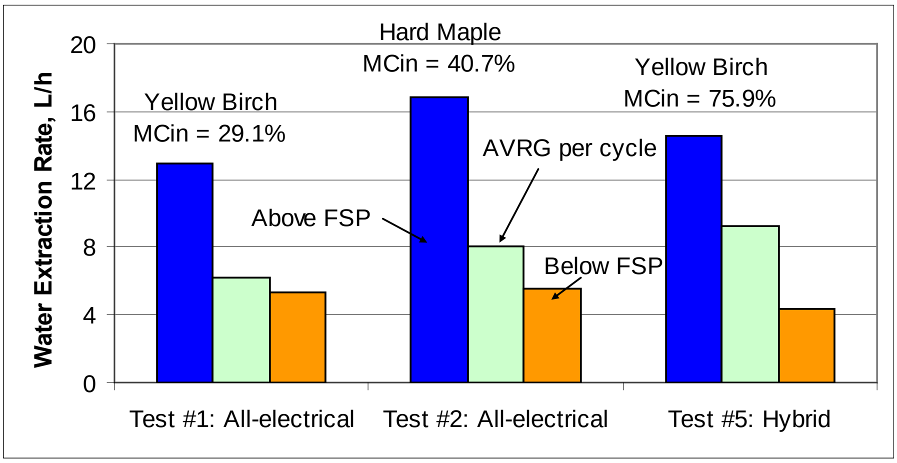


Figure 4-21: Water extraction rates vs. FSP; AVRG: average [Minea, 2006a], [Minea, 2011]

4.5.1.5 Dehumidification performance

The dehumidification efficiency of drying heat pumps is generally expressed in terms of the *Specific Moisture Extraction Rate* (*SMER*). This parameter represents the ratio between the mass of water extracted and the heat pump total electrical energy consumption (compressor and blower) (kg_{water}/kWh_{hp}). Laboratory tests show that above the FSP, the SMER was 2.5 kg_{water}/kWh_{hp} (Table 4.4), which is a very good performance for a dehumidification process. Table 4.4 also indicates at which moment, measured in hours, from the beginning of each drying cycle, the FSP was reached for each test. It depends on the initial moisture content. When MC_{in} was relatively low (29.1 % in test #1), the FSP was reached after 25 hours. When MC_{in} was higher (75.9 % in test #5), it was reached after 104 hours of operation.

Table 4-4: Dehumidification performance of low-temperature drying heat pumps

Test	MC_{in}	Specific moisture extraction ratio (SMER)			Comparison	-
-	Initial moisture content	Above FSP	FSP = 25%	Below FSP	Above vs. bellow FSP	Drying time
-	%	kg_{water}/kWh_{hp}	Hours*	kg_{water}/kWh_{hp}	Times	Hours
#1: all-electrical	29.1	2.06	25	0.82	2.5	138.3
#2: all-electrical	40.7	2.5	72	1.19	2.1	220.0
#5: hybrid	75.9	2.5	104	0.87	2.9	210.3

*From the beginning of the preheating step

4.5.1.6 Conclusions

A 5.6 kW low-temperature heat pump coupled to a 13 m^3 wood dryer was tested with electricity and natural gas (steam) as back-up energy sources. The heat pump electrical energy consumption (compressor and blower) varied between 25 % and 30 % of the total equivalent energy consumption during the all-electrical or hybrid drying cycles. The dryer fan generally accounted for 8 % to 9 % of the total drying energy consumed, and the electrical or fossil back-up energy between 62 % and 66 %. For initial moisture contents above 41 %, the total water quantity extracted above the fiber saturation point were up to 2.9 times higher than that removed below the FSP. Consequently, in these cases, the dehumidification efficiency of the low-temperature drying heat pump (SMER) was up to 3 times higher above the FSP than below that point. Finally, the hybrid drying cycles reduced natural gas consumption by 56 % and the equivalent energy costs by 21.5 %, compared to the conventional drying cycle with natural gas as a unique heating source.

4.5.2 High-temperature drying heat pump

High-temperature drying heat pumps offer many advantages such as lower energy consumption for each unit of water removed, accurate control of drying conditions, and enhanced product quality. Their limitations generally include the need for temperature resilient materials and fluids (refrigerants, oils, belts, etc.), regular maintenance, the risk of refrigerant leaks and higher initial capital costs compared to conventional dryers.

4.5.2.1 System configuration

The experimental site consists of two forced-air 354 m^3 wood dryers made of insulated panels, each equipped with 1500 kW steam heating coils (Figure 4.22). An oil-fired boiler with a 4,900 kW output capacity and 82% thermal efficiency supplies both dryers with high-pressure saturated steam for heating and spraying. One of these dryers is equipped with two 65 kW (compressor nominal power input) high-temperature heat pumps [Minea, 2011], [Minea, 2004]. A 56 kW multiple-blade fan with an outdoor motor forces the air flow through the stacks of wood at a rate of 1.5-2.0 m/sec. at the outlet. Wall deflectors and the inversion of the rotation of the dryer fan every 3 hours at the beginning and every 2 hours at the end of the drying cycles help maintain uniform ventilation.

To avoid air implosion hazards, three air vents open when the central fan rotation changes direction and, also, when the actual dry-bulb temperature exceeds the set point. High-temperature heat pumps HP-1 and HP-2 equipped with variable speed blowers, compressors, evaporators, as well as electric and electronic controls are installed within an adjacent mechanical room. However, the condensers of both heat pumps are remotely installed inside the drying enclosure. Designed for industrial processes, the open, belt-driven compressors are equipped with oil pumps, external pressure relief valves and crankcase heaters. The refrigerant (HFC-236fa) is a non-toxic and non-flammable fluid, with a relatively high critical temperature above the highest process temperature, and a normal boiling point below the lowest temperature likely to occur in the system. Moreover, the saturation vapour pressure at the highest design temperature is not so high as to impose design limitations on the system. Expansion valves are incorporated into the microprocessor-based temperature/process controllers that display both set points and actual process temperatures.

This case study presents some of the results achieved when drying *white spruce* (test #70 and test #88) and *balsam fir* (test #176) with high-temperature heat pumps and steam (oil) as a back-up energy source (see Table 4.5).

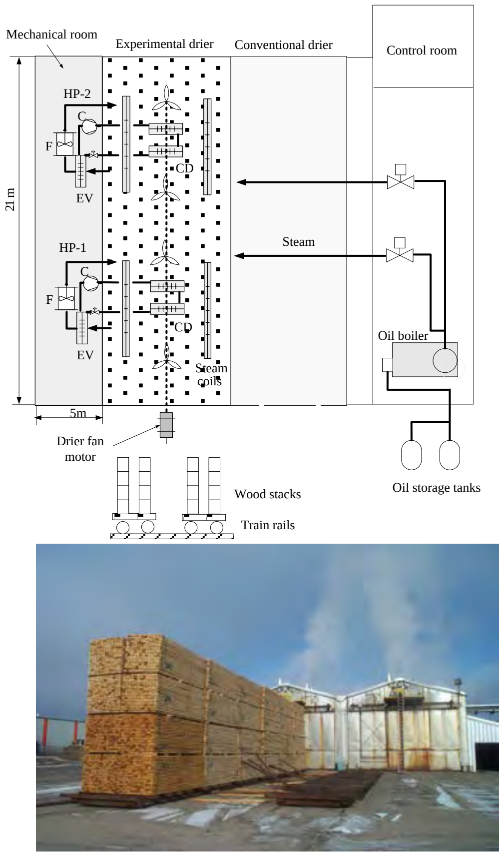


Figure 4-22: Schematic representation of the industrial-scale heat pump dryer and view of the site [Minea, 2011], [Minea, 2004]; C: condenser; CD: condenser; EV: evaporator; F: fan; HP: heat pump

4.5.2.2 Drying schedule and controls

All experimental drying cycles include 6 to 8 hour preheating steps at an average temperature of 93.3 °C in order to destroy the micro-organisms responsible for discoloring the sapwood. The drying conditions for each step were established based upon moisture content, type of wood species, dimensions and quality of the wood. For *white spruce*, which is normally easy to dry, when the initial moisture content was between 40 % and 25 %, the dry-bulb temperature was set between 82.2 °C and 85 °C and the wet-bulb temperature at 62.7 °C. At a moisture content below 25 %, the dry-bulb temperature was generally set at 79.4 °C and the wet bulb-temperature at 62.7 °C. With *balsam fir*, which is harder to dry, when the initial moisture content was above 30 %, the dry-bulb temperature was set at 82.2 °C and the wet-bulb temperature at 79.4 °C.

At moisture contents below 25 %, the set dry-bulb temperature reached 93.3°C whereas the wet-bulb temperature was 71.1°C. The dry- and wet-bulb temperature settings were changed at predetermined time intervals. For *white spruce*, steps 1 to 3 generally took 10 hours, step 4, 20 hours, and step 5, 10 to 20 hours depending on the wood actual moisture content. In the case of *balsam fir*, the first five drying steps each took 30 hours, while the 6th step took up to 15 hours. The goal was to stay within the average traditional drying cycle times for the same species of dried wood. Finally, when the indoor dry-bulb temperature was lower than the set point value, the steam valve opened gradually from 5 % to 100 % according to a time-based schedule to allow the temperature to return to the set point.

As can be seen in Figure 4.23a, the drying time for white spruce drying cycle #88 was 61.3 hours, without including the approximately 6 hour preheating step. The control strategy allowed the heat pump to shut down when the actual dryer wet-bulb temperature reached the set point (Figure 4.23b).

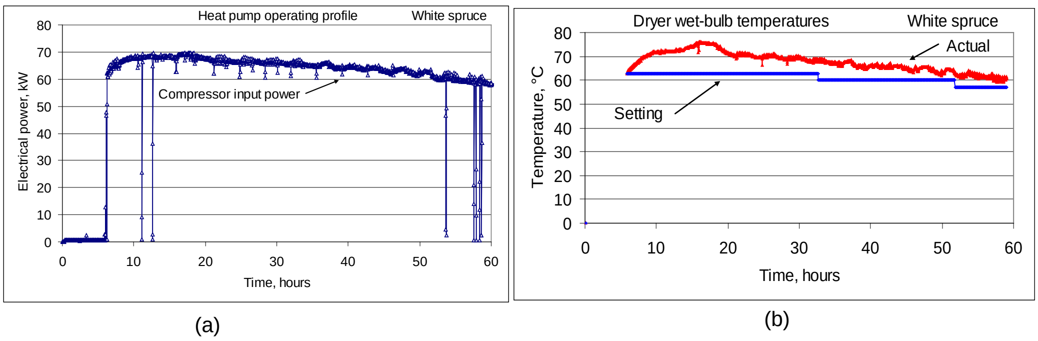


Figure 4-23: (a) Heat pump operating profile during test #88; (b) profiles of the dryer wet-bulb set and actual temperatures [Minea, 2011], [Minea, 2004]

The heat pump compressors ran with a 65 kW electrical power input, and average compression ratios of 5.5. Stable suction and discharge pressures as well as an average refrigerant sub-cooling temperature of 8 °C were achieved. Condensing temperatures varied around 105 °C, about 20 °C above the kiln dry-bulb temperature. Evaporating temperatures ranged between 41 °C and 45 °C. The average relative humidity of the air entering the evaporators varied widely because of the periodical changes in the rotation direction of the central fan, and also decreased continuously over time. However, the relative humidity leaving the evaporators was almost constant at around 74 % to 88 %, except at the end of the cycle when it dropped to 70 %.

4.5.2.3 Energy performances

The wood moisture content prior to each drying cycle was generally in the range of 35% to 45% (dry basis) (Table 4.5). The average coefficient of performance (COP) of the drying heat pumps, defined as the useful thermal power output (W) divided by the electrical power input (W), varied from 3 to 4.6.

The total water extraction rates were 313 kg_{water}/hour (batch #70), 263.2 kg_{water}/hour (batch #88) and 178.8 kg_{water}/hour (test #176). These numbers do not include any venting moisture losses (on average, 90 kg_{water}/hour), but account for 5% of condensed water losses. The Specific Moisture Extraction Rate (SMER), defined as the amount of water extracted by the heat pump (kg) divided by the total energy input (compressor and blower) expressed in kWh, ranged from 1.46 kg_{water}/kWh (test #176) to 2.52 kg_{water}/kWh (test #70). The Specific Energy Consumption (SEC) ranged from 0.4 to 0.68 kwh/kg_{water}. These values do not include the energy consumed during the pre-heating steps, nor any allowance for the energy consumed by the kiln central fan or the venting moisture losses.

Table 4-5: Energy performances [Minea, 2011], [Minea, 2004]

Test #	-	#70	#88	#176
Parameter	Unit	-	-	-
Timber	-	White spruce	White spruce	Balsam fir
Drying time (excluding preheating steps) (hours)	HP-1	61.00	61.3	151.4
	HP-2	61.00	61.3	151.4
Average compressor power input (kW)	HP-1	65.12	63.36	61.0
	HP-2	62.78	58.50	57.14
Compressor energy consumption (kWh)	HP-1	3,972	3,884	9,235
	HP-2	3,830	3,586	8,651
Blower energy consumption (kWh)	HP-1	13.42	16.6	28.7
	HP-2	14.03	39.5	107.5
Water extraction (Liters)	HP-1	9,454	8,263	13,550
	HP-2	9,655	8,478	13,531
Final moisture content (%)	-	17.2	20.6	20.7
Average COP* (-)	HP-1	4.23	4.6	3.46
	HP-2	3.70	4.07	3.00
Average SMER** (kg_{water}/kWh)	HP-1	2.38	2.13	1.46
	HP-2	2.52	2.36	1.54
Average SEC** (kWh/kg_{water})	HP-1	0.42	0.47	0.68
	HP-2	0.40	0.42	0.64

* Based on the compressor and blower energy consumptions

Energy consumption during the dehumidification cycles with high-temperature heat pumps was 27 % to 57 % lower than with conventional (steam) drying systems. The average reduction in specific energy costs, compared to the costs of conventional wood drying cycles, was estimated at approximately 35 %.

The heat pump (compressor plus blower) accounted for 72% and the dryer central fan for 28% of the total energy consumed. The drying time required to obtain white spruce with an approximate final moisture content of 17% to 19% was about 2.5 days, while for balsam fir it averaged 6.3 days. Despite a longer drying time, the balsam fir drying process was less focused on drying speed than the white spruce drying process, as the main operating focus was to produce a high quality product. The specific cost for drying about 39,600 m^3 of lumber was 14.75 US$/$m^3$, including kiln operation, electrical and fossil energy consumption, equipment depreciation, insurance, etc. Energy cost only was 6.86 US$/$m^3$. The objective was to reduce the specific energy cost by at least 40%.

4.5.2.4 Conclusions

As a clean energy technology compared with conventional heat-and-vent dryers, high-temperature heat pump dehumidifiers offer interesting advantages for drying soft timber wood. This paper presents the preliminary results of the development and field testing of two prototypes highlighting their thermodynamic parameters and preliminary energy performance as well as the first operating lessons learned. The average measured specific moisture extraction rate of the heat pumps was 2.35 kg_{water}/kWh (white spruce) and 1.5 kg_{water}/kWh (balsam fir), while the average coefficients of performance generally varied from 3.0 to a maximum of 4.6. Cycle time ranged from 2.5 days (white spruce) to 6.3 days (balsam fir), including the initial preheating steps. The refrigerant/oil mixture behaved well during more than 4000 hours of preliminary tests, showing good compatibility and chemical stability at condensing temperatures below 110 °C. Better insulated and well maintained dryers are necessary to obtain drying temperatures above 100 °C as well as reduce the drying time of resinous species by up to 25 % and total energy consumption by up to 50 %. The current goals of the study include using more corrosive resistant components and a variable speed central fan, as well as further optimizing the drying schedules and general dryer operation and maintenance. Finally, it is expected to help local Canadian equipment suppliers to promote research and development of the technology and develop an appropriate market strategy. Specifications for high-temperature heat pump dehumidifier kiln energy use and best-practice guidelines must also be produced.

4.6 Mechanical vapor recompression

A mechanical vapour recompression system has been studied, improved, and successfully implemented and tested in a Canadian metallurgical process consisting in transforming liquid copper into wire (Figure 4.24) [Bédard, 2002]. This MVR evaporator system is similar to a conventional steam-heated, single-effect evaporator, except that the vapour released from the boiling solution is compressed by the compressor. The compressor raises the pressure and saturation temperature of the vapour so that it may be returned to the evaporator as a heating medium. This reduces the steam needed to meet the evaporative load of the overall system.

The vacuum pump maintains a pressure of about 200 mbar inside the container, which corresponds to a water boiling temperature of 60 °C. The compressor (107.5 kW) increases the vapor pressure by 20 mbar and its temperature by 2°C between the evaporating and condensing sides. The evaporated water flow rate (15.8 m^3/h) represents about 97 % of the input product flow. At the same time, 3 % of the initial material quantity is discharged as a concentrated product. The metal recovery rate (copper, lead, sulphate) is as high as 95 %. The product is continuously re-circulated from the lower to the upper side of the container. Inside the heat exchanger, the compressed vapor condenses, and the liquid is pumped outside. A plate heat exchanger preheats the entering product by using heat from both the condensed and concentrated product leaving the container. The compressor consumes 7.8 kWh per ton of water evaporated, while the energy required by a conventional evaporation system is about 700 kWh per ton of water evaporated. Thus, the coefficient of performance, defined as the thermal energy supplied divided by the electrical energy consumed, is 86. However, during system operation, about 30 kW of thermal back-up power in the form of vapor (VIVE) is supplied on average to keep the temperature of the product being concentrated at a constant level. This operation increases the specific energy consumption to 9.9 kWh per ton of water evaporated. As a result, the system average COP drops to 68. However, this number doesn't include the energy consumed by the vacuum and other circulation pumps (total electrical power estimated at 60 kW) [Bédard, 2002].

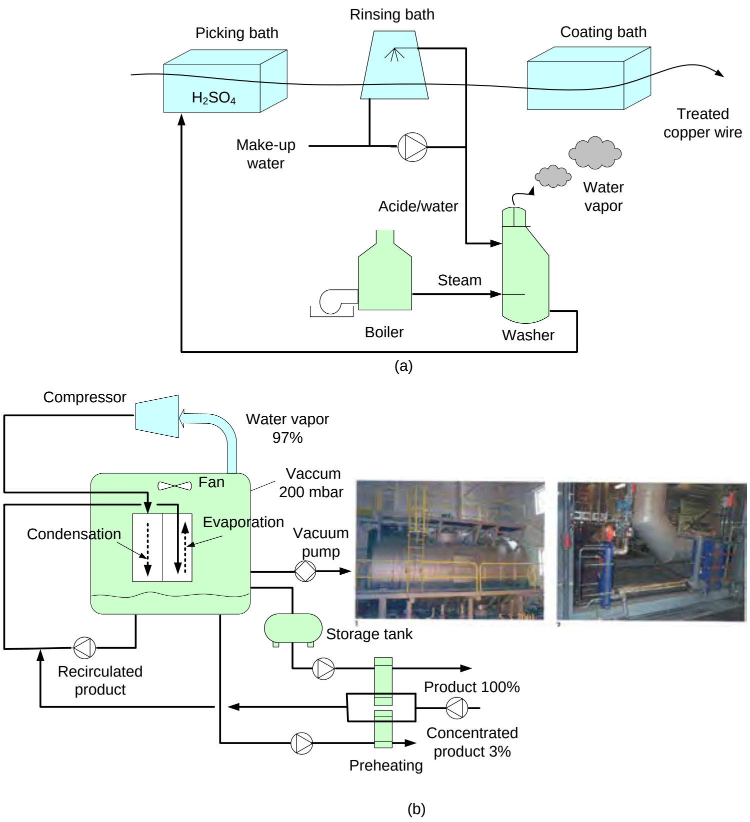


Figure 4-24: (a) Initial industrial process; (b) mechanical vapour recompression system [Bédard, 2002]

4.7 Poultry processing

For the industrial implementation of cascade heat pump systems, many practical options are available. As can be seen in Figure 4.25, the first stage of such systems may recover waste heat rejected by an industrial ice machine existing in a poultry processing plant [Caddet]. The cascade heat pump could therefore be the second stage of a heat recovery system, used to also recover heat from the condensers of an existing refrigeration plant through an intermediate closed loop. Cold water entering the system at 12 °C is heated up to 25 °C inside the pre-heating heat exchanger, and then up to 63 °C with the cascade heat pump, prior to being stored inside a storage tank and/or supplied to industrial processes or other consumers.

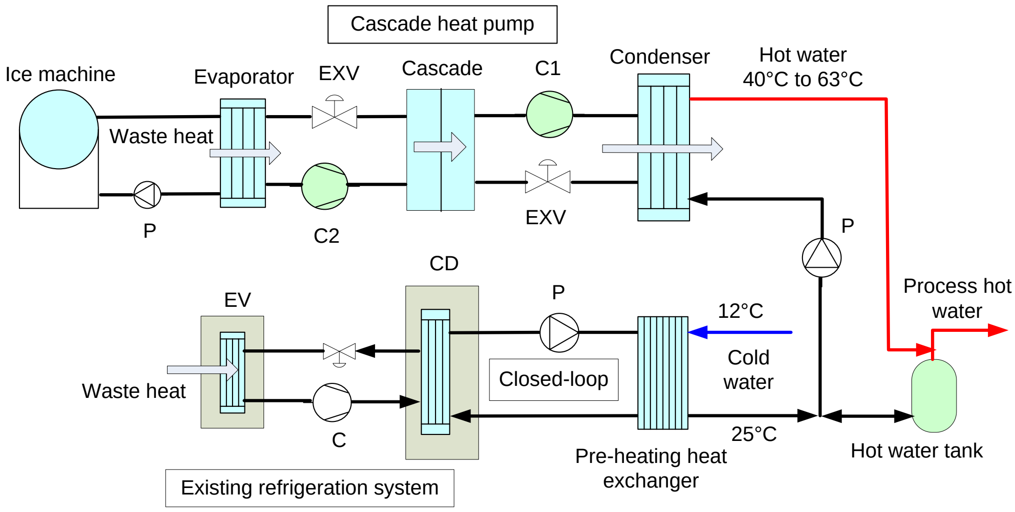


Figure 4-25: Schematic diagram of a cascade heat pump implemented in a Canadian poultry processing plant [Caddet]

The total investment cost of this heat recovery system (engineering, equipment, installation) was 165,000 US$ and natural gas annual savings of 330 m^3 have been achieved. The system overall COP has been estimated at 10.7, and the simple pay back period at 2.7 years [Caddet].

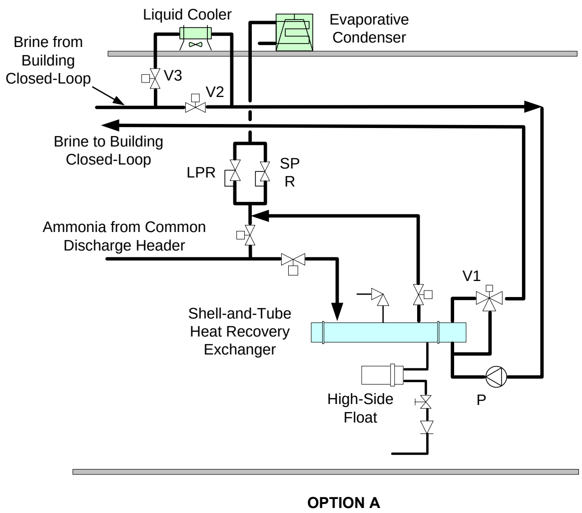
4.8 Cold warehouse

Ammonia refrigeration systems in small, medium and large cold storage warehouses operate with discharge and condensing temperatures that make it possible to efficiently recover heat normally rejected in the atmosphere by evaporative condensers. Heat recovered could be used for space (e.g. offices) and/or industrial hot water heating (e.g. neighbouring food processing plants).

Such a heat recovery system was developed to recover heat from new retrofit ammonia compressors installed in a cold warehouse [Minea, 2007]. Five old ammonia compressors, which had reached the end of their useful life, were replaced with five new single-stage screw compressors having a total nominal refrigeration capacity of 1600 kW. Four of them operate at -33 °C, and the fifth one at -44 °C evaporating temperatures. Oil cooling and injection help keep the common discharge header at a relatively low temperature (around 52°C). During the week, all five new compressors operate simultaneously but, on weekends and holydays, only two compressors generally run 24 hours a day.

To recover part of the available heat rejected, i.e. 2361 kW, from the new ammonia compressor common discharge header, a two-stage heat recovery system with a desuperheater (as a first stage) and water-to-air heat pumps (as a second stage) installed in a closed loop, was designed. About 33.5 % of the available thermal power is recovered and used for heating a building service and office spaces with a total area of 12,250 m^2. When at least two compressors operate simultaneously, all the available sensible heat and up to 93.9% of the condensing enthalpy are recovered to meet 100 % of the building peak heating demand.

The desuperheater is a heat exchanger installed on the common discharge header of the five new single-screw ammonia compressors and 21 water-to-air heat pumps with nominal capacities varying between 2 and 8 refrigeration tons (1 ton = 3.517 kW) are connected to the building reverse closed-loop (Figure 4.26). In addition, two 22.3 kW (heating capacity) brine-to-water heat pumps are used for preheating industrial (washing) hot water for a neighbouring food processing plant (Figure 27). Each of these heat pumps uses 0.6 L/s of brine as a heat source flowing from the building closed loop at temperatures ranging between 15 °C and 25 °C. The maximum temperature of the process hot water leaving the system storage tanks may reach 70 °C.



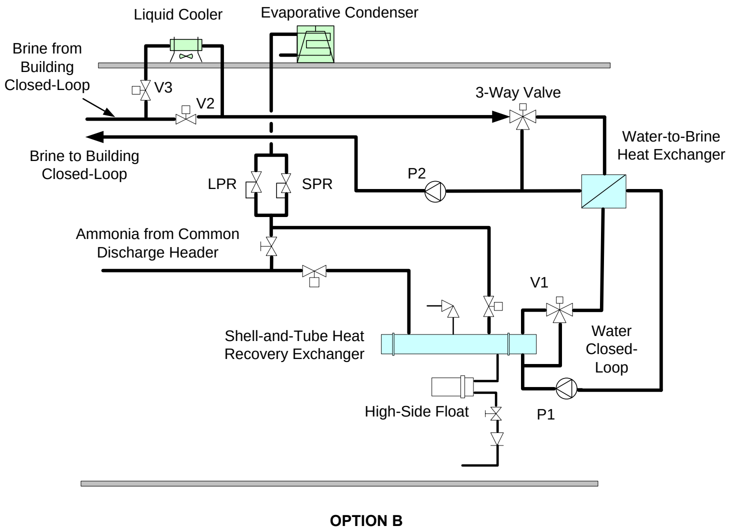


Figure 4-26: Refrigeration section of the two-stage heat recovery system [Minea, 2007]; (a) option A; (b) option B; V: motorized valve; P: water or brine circulating pump; NO: normally open; NC: normally closed; LPR: large size pressure regulator; SPR: small size pressure regulator.

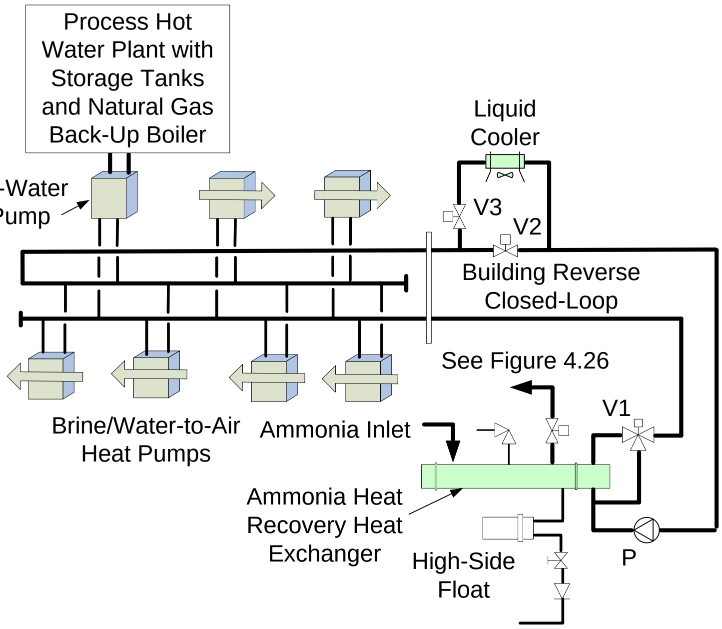


Figure 4-27: Configuration of the building brine closed loop [Minea, 2007].
V: 3-way motorized valve; P: brine circulating pump

4.9 Cooling towers

Relatively large amounts of low-grade waste heat are available in industrial cooling processes using cooling towers (or condensers). Cooling water entering the cooling towers at more than 30 °C year-around represents one of the most promising fields of application for industrial heat pumps. Several heat recovery system options have been studied and designed for a large Canadian metallurgical plant [Minea, 2006b].

In this metallurgical plant, exothermal chemical reactions occur in eight electrolytic reactors, while the evaporators and crystallizers are cooled by a water closed loop linked to three forced air-cooled cooling towers (Figure 4.28). The cooling water enters the cooling towers at an average temperature of about 40 °C and leaves them at 25 °C. The total flow rate of the cooling water is 2220 m^3/h, but about 1080 m^3/h are lost due to evaporation and 300 m^3/hr. due to purging [Salabery, 2003], [Salabery, 2004].

The heat recovery solution chosen was based on the assumption that 1066 m^3/h of cooling water, i.e. 48% of the total flow rate available on the site, would be used as a waste heat source for the plant heat pumps. In this case, two industrial water-to-water heat pumps are installed in parallel (Figure 4.29). By using about 4 MW of electrical input power, the thermal power recovered is 13.6 MW and the total thermal power delivered by the heat pump facility, is 17.6 MW. As a result, the total hot water flow rate supplied to consumers reaches 1536 m^3/h at a temperature of about 70 °C. The temperature of the return water is about 60 °C, and the heat recovery system overall coefficient of performance, is 4.33.

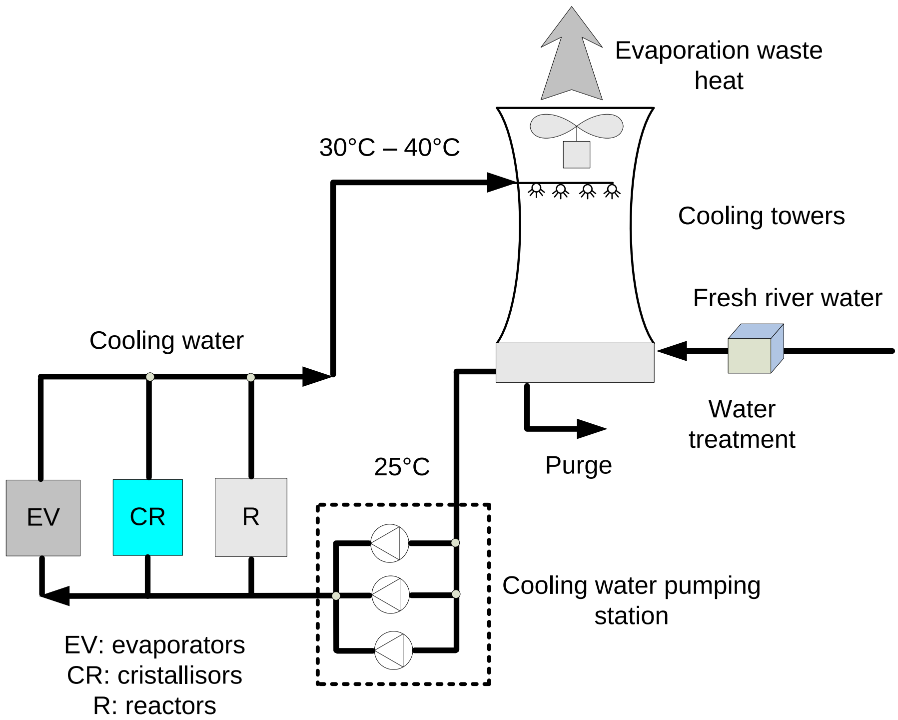


Figure 4-28: Schematic representation of the initial cooling water system of the plant [Salabery, 2003], [Salabery, 2004]

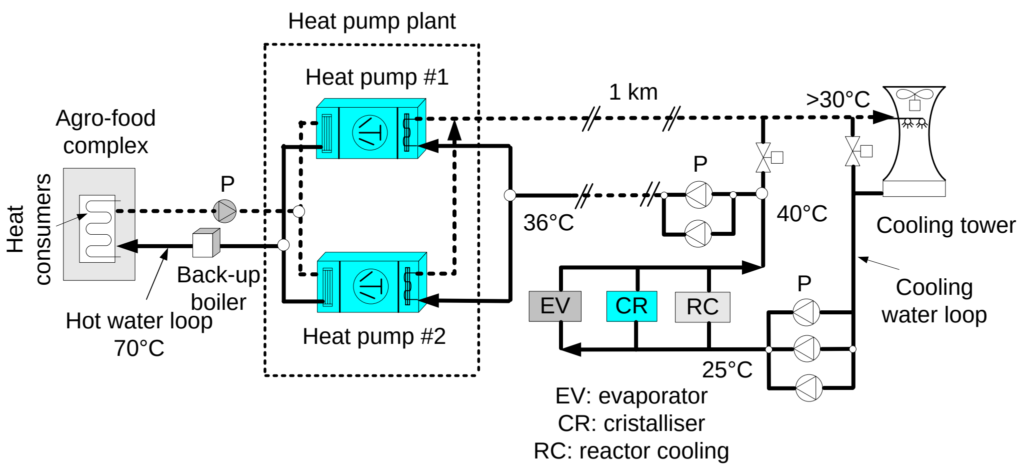


Figure 4-29: Heat recovery system with two parallel industrial water-to-water heat pumps at the agro-food complex [Minea, 2006]; P: water circulating pump

Another efficient option could integrate intermediate direct heat recovery heat exchangers and industrial heat pumps, as shown in Figure 4.30. In this case, the system could recover up to 100% of the available waste heat in order to meet all of the heating requirements of the industrial agro-food complex.

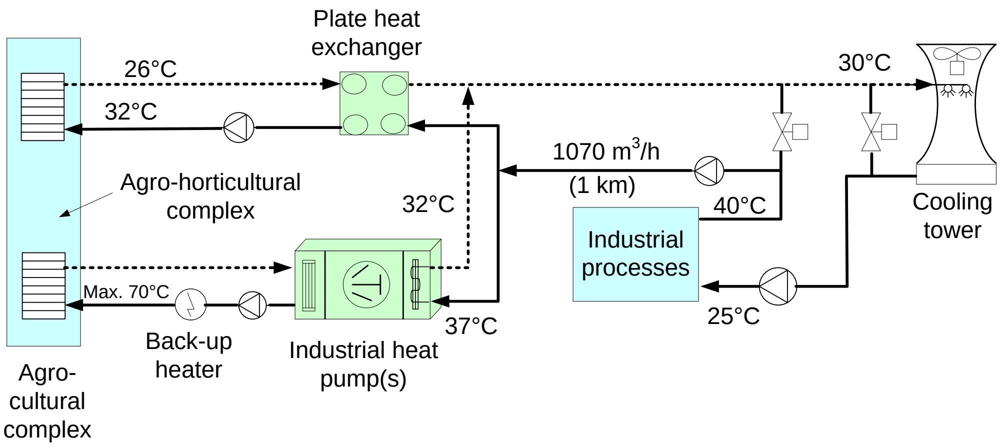


Figure 4-30: Combined heat recovery system with intermediate heat exchangers and industrial heat pumps at the agro-food complex [Minea, 2006b]

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5 Denmark

5.1 Hybrid heat pump at Arla Arinco

5.1.1 Summary

A heat pump of 1.25 MW was installed utilizing energy from 40° C cooling water – energy that was discharged to the environment prior to this project. The installed heat pump preheats drying air for milk powder to around 80° C through a water circuit.

The pay-back time of 2.3 years (1.5 years with energy grants included) indicates that large industrial heat pumps can be a profitable for both companies and society.

Another conclusion from the project is that engineering, design, construction, commissioning and operation of a heat pump plant of this size is comparable to that of industrial refrigeration plants.

5.1.2 Project information

Company	Arla Arinco
Location	Videbaek, Denmark
Process application	Drying air for milk powder
Type of heat pump	Hybrid NH_3/H_2O
Capacity	1.25 MW
Running hours	Approx. 7,400 per year
Year of operation	2012
Primary energy savings	Approx. 7.2 GWh per year
Reduction in CO_2 emission	Approx. 1,400 tonnes
Maintenance costs	Aprrox. 2 euros/MWh-heat
Manufacturer/supplier	Industri Montage
Pay back	1.5 years

5.1.3 Project characteristics and process design of installed system

The heat pump is installed in an application where ambient air is heated to 150 °C for drying milk powder. Previously this was done by a natural gas boiler. During the project the philosophy was to:

1. Minimize the energy demand
2. Incorporate direct heat exchangers as far as possible
3. Consider whether a heat pump is the best solution for the remaining energy demand

Following these steps it became obvious that the best solution would be a heat pump only doing part of the heating towards 150 °C. It was also noticed that pre heating of the ambient air was possible through direct heat exchanging utilizing cooling water from an evaporator. The installation was thus changed to consist of three stages where the first is preheating to 40 °C using cooling water, second stage is heating from 40-80 °C using the heat pump – also recovering heat from the cooling water and third stage is heating from 80-150 °C using the existing gas boiler. Due to fluctuations in cooling and heating demands, two buffer tanks have been installed eliminating variations in the cooling system and ensuring steady conditions for the heat pump.

The principle is shown on the figure below with the three heating stages on the right sight of the figure.

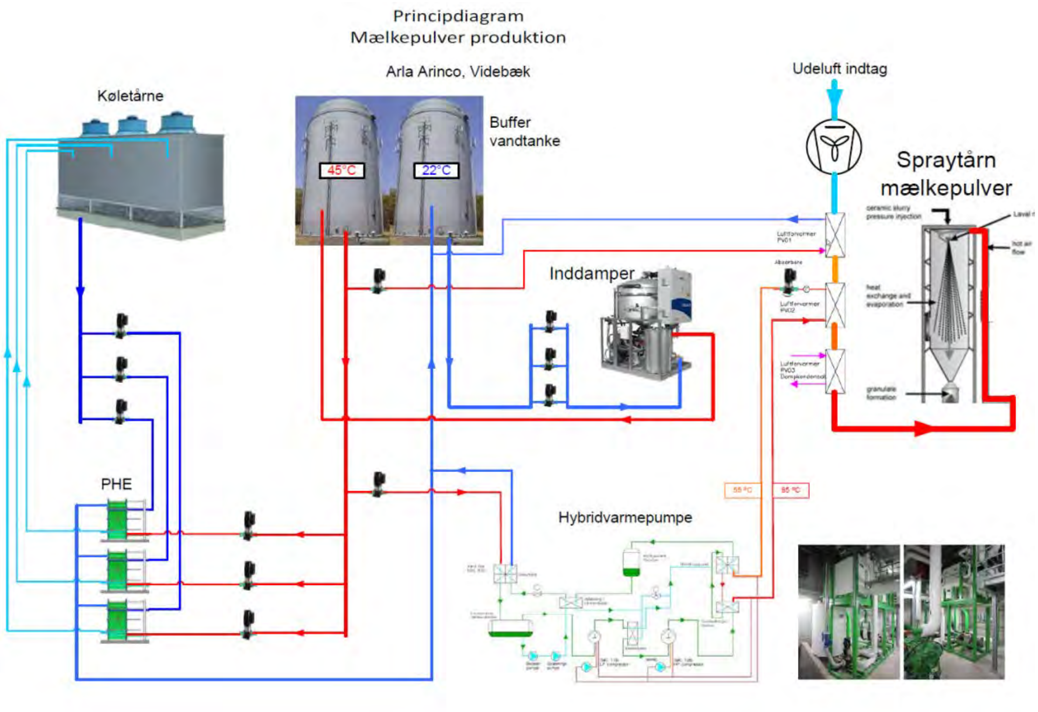


Figure 5-1: Principle

Existing cooling plants and NG boilers are kept for backup in case of failure or maintenance in the heat pump system.

5.1.4 Running experience, savings and economics

With a COP of 4.6 the heat pump approximately halves the energy cost compared to natural gas that is replaced. A high number of annual operation hours (around 7,400), ensures a considerable reduction in energy expenses. The analysis throughout the project also led to other energy reductions as well as direct pre heating of ambient air, thus the project as a whole caused substantial savings making this approach very profitable. Energy savings represent a tradable value in the Danish system for energy reductions. Because of the considerable amount of energy savings in this particular case, around half of the investment was financed through this value leading to a simple payback time of around 1.5 years and being very profitable from a life time perspective.

A few modifications were carried out during the first period of operation. This was primarily about the control strategy, where the heat pump itself and the surrounding part of the system did not correspond appropriate. Apart from this, the system has been functioning as planned.

5.1.5 Lessons learned and challenges

The owner is very happy with the system and the way this project was carried out. It has been clear that thorough energy analysis is crucial in these installations as reduced consumption and direct heat exchangers must be considered before installing heat pumps. This is very time consuming, but the direct savings found through this approach has paid for these working hours several times. If the analysis was not carried out the heat pump installed would have had twice the capacity and not be near as profitable.

5.1.6 Motive/grounds/rationale behind investment

Arla have ambitious goals to reduce energy consumption and CO_2 foot print. In order to assess possible solutions the company volunteered as a demonstration host in a heat pump project funded by the Danish Energy Agency. In this project a thoroughly energy analysis of the company's processes was conducted leading to direct energy savings as well as a basis for the heat pump installation.

5.1.7 Specifications of heat pump

Description	**Heat Pump**		**Back up**
Type	Two stage Hybrid NH_3/H_20		Gas boilers
Heating capacity	1,250 kW/unit (→°C, units)		
Cooling capacity	980 kW/unit (→°C, units)		
Power consumption	270 kW/unit (units)		
Heat source	Cooling water	45-20 °C 40 m^3/h	
Heat sink	Drying air (water circuit)	40-85 °C	
Refrigerant	NH_3/H_20 compression/absorption		
Compressor type	2 x standard reciprocating NH_3 compressors		
COP	4.6		
Operation hours	11,000		
Storage water tank	2 x 100 m^3	Temp 45-20 °C	
Manufacturer of heat pump	Industri Montage		
Supplier/consultant	Industri Montage		

5.2 NH_3 heat pump at Skjern Paper Mill

5.2.1 Summary

Skjern Paper Mill recovers waste heat from paper drying. The recovered heat is boosted to around 70° C using a heat pump and delivered to the district heating system in the city of Skjern. The paper mill use steam that is produced by natural gas boilers as a primary heat source. Apart from heat recovery at the drying process, heat is also recovered at the flue gas of the boilers. At the drying process heat is recovered through a combination of direct heat exchange and heat pumps. The heat pump system was put into operation in December 2012. Skjern Paper Mill supplies approx. 36,000 MWh of heat annually which equals 60 % of the consumption of the 3.000 households in the city of Skjern.

The heat pumps are installed at Skjern Paper Mill who also owns and operates the system. In this way the district heating plant has no operational responsibility for the heat purchased by Skjern Paper Mill.

5.2.2 Project information

Company	Skjern Paper Mill
Location	Skjern, Denmark
Process application	District heating
Type of heat pump	High pressure NH_3
Capacity	4.0 MW (5.4 incl. direct heat exchange)
Running hours	Approx. 8,000 per year
Year of operation	2012
Primary energy savings	Approx. 30 GWh per year
Reduction in CO_2 emission	Approx. 6.000 tonnes
Maintenance costs	Aprrox. 2 euros/MWh-heat
Manufacturer/supplier	Johnson Controls / Averhoff Energi Anlæg
Pay back	2.5 years

5.2.3 Project characteristics and process design of installed system

Skjern Paper Mill has been the developer of this project. The heat pump system recovers energy from moist drying air that was previously discharged directly to the ambient. Temperatures of the district heating system varies throughout the year but the district heating water is typically heated from approx. 37 °C to 68 °C. The moist drying air is between 50 °C and 55 °C with a relative humidity of 100 %. The temperature overlap between sink and source mean that the district heating water is preheated using a direct heat exchanger, while the heat pumps move energy in the temperature range which is not possible with direct exchange. The district heating network is coupled directly to the heat pumps and the system holds an accumulation tank to stabilize the production heat delivery. The heat pumps are three identical parallel coupled ammonia plants with a total output of approx. 4 MW. In combination with the direct heat recovery the total thermal output from the drying process is approx. 5.4 MW.

The principle is shown on the figure below.

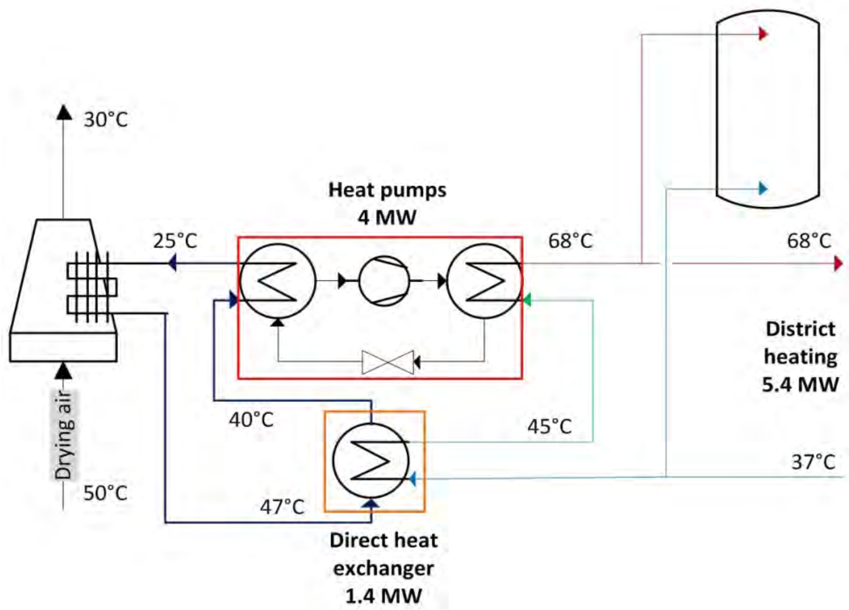


Figure 5-2: Principle

The district heating plant still holds the previous boilers as backup.

5.2.4 Running experience, savings and economics

Prior to installation of this system the Paper Mill and district heating company agreed on a fixed margin on top of the production cost. The Paper Mill guarantees a minimum COP of the system while the district heating company guarantees to purchase a certain amount of heat each year. This setup provides security for the investment at the Paper Mill, while the heat consumers in the city are guaranteed a low price for the heat.

The agreement between Skjern Paper Mill and Skjern district heating with this solid gross margin was settled in 2012 prior to commissioning of the plant in late 2012. In 2013 the tax system in Denmark was altered, meaning that a dynamic model of payment was preferable and chosen instead. In this approach the price is settled each month based on the actual production cost at the paper mill and the marginal heat production cost at Skjern district heating. The settlement price is always exactly in between, so that the profit at the paper mill corresponds to the savings at the district heating company.

5.2.5 Lessons learned and challenges

One of the components that have been particular important was the cooling surfaces, which cools moist drying air and recover heat. The air is corrosive and it was very important to find a product that can withstand aggressive environments. In addition the system is structured in a way which makes it possible to clean the heat exchanger in case of fouling.

One of the bigger challenges after start-up of the plant has been to ensure a delivery of heat from the paper mill to the district heating network. Due to unexpected stops such as a paper fracture that shuts the entire mill immediately when it occurs, it has been a challenge to ensure that there is no cold congestion in the district heating network. There have been some changes and adjustments in the first months after commissioning which solved the problems. Since the plant has not been operating for very long there is not sufficient experience of the service and maintenance to describe here.

The paper mill has become very aware of the temperature levels in the system as the heat pumps are an important source of income for the paper mill. In periods with extra high temperatures of the drying air or low temperatures in the district heating system, the COP of the total system have been as high as 11 while the capacity have been higher than the nominal 5.4 MW. The paper mill plans to establish a link between the heat pump system and the boilers. Heat recovery at the boilers happen at a much higher temperature than the district heating requires. By raising the temperature from the boilers and mix this with water from the heat pumps, COP and profit will be higher while the price of district heating is lowered.

5.2.6 Motive/grounds/rationale behind investment

The paper mill has ambitious goals to reduce energy consumption and CO_2 foot print. This solution meets these goals while being very profitable at the same time.

5.2.7 Specifications of heat pump

Description	**Heat Pump**		**Back up**
Type	3 x parallel coupled high pressure NH_3		Gas boilers
Heating capacity	1,335 kW/unit (→°C, units)		
Cooling capacity	1,065 kW/unit (→°C, units)		
Power consumption	270 kW/unit (units)		
Heat source	Drying air (water circuit)	40-25 °C	
Heat sink	District heating water	45-68 °C	
Refrigerant	NH_3		
Compressor type	3 x high pressure screw NH_3 compressors		
COP	5.0 (6.7 incl. direct heat exchange)		
Operation hours	10,000		
Storage water tank	1,250 m^3	Temp 37-68 °C	
Manufacturer of heat pump	Johnson Controls		
Supplier/consultant	Averhoff Energi Anlæg		

5.3 NH_3 heat pump at Knud Jepsen Nursery

5.3.1 Summary

Knud Jepsen is a Danish nursery with 120,000 m² green houses. The yearly energy consumption is 21 GWh of heat and 9 GWh of electricity. Heat and electricity is produced on natural gas CHP's, two oil boilers and one gas boiler. In the wintertime heat is added in the greenhouses and in the summer windows have to be opened to prevent high temperatures. Apart from the heat loss, opening the windows also allows pests to enter and CO_2 to escape.

The idea in this project was to utilize excess heat from the green houses via solar panels that can be angled to shade the greenhouses in warm periods. The solar panels are cooled by two heat pumps providing district heating for own use or for sale. Besides cooling the solar panels the heat pumps are also connected to flue gas coolers at the CHP's. The project was supported by the Danish Energy Agency and was initiated in 2012. The plants have been running since the summer of 2013 but as the heat pumps are only part of the installation concerning three different solar panel setups, focus so far have regarded the solar panels and operating experience of the heat pumps are not yet conclusive. A final report on the project can be expected within 2014.

5.3.2 Project information

Company	Knud Jepsen Nurcery
Location	Hinnerup, Denmark
Process application	Heating of green houses
Type of heat pump	40 bar NH_3
Capacity	2.0 MW
Running hours	?
Year of operation	2012
Primary energy savings	Approx. 3 GWh per year
Reduction in CO_2 emission	Approx. 600 tonnes
Maintenance costs	Aprrox. 2 euros/MWh-heat
Manufacturer/supplier	Johnson Controls / Averhoff Energi Anlæg
Pay back	?

5.3.3 Project characteristics and process design of installed system

The cooling circuit of the heat pumps is connected to both flue gas coolers and solar panels. The sink side is connected in series to the CHP's in order to use these for reheating after the heat pumps. The heat pumps take the heating water to around 60 °C while the CHP's increase the temperature to around 80 °C.

The system is sketched on the following figure:

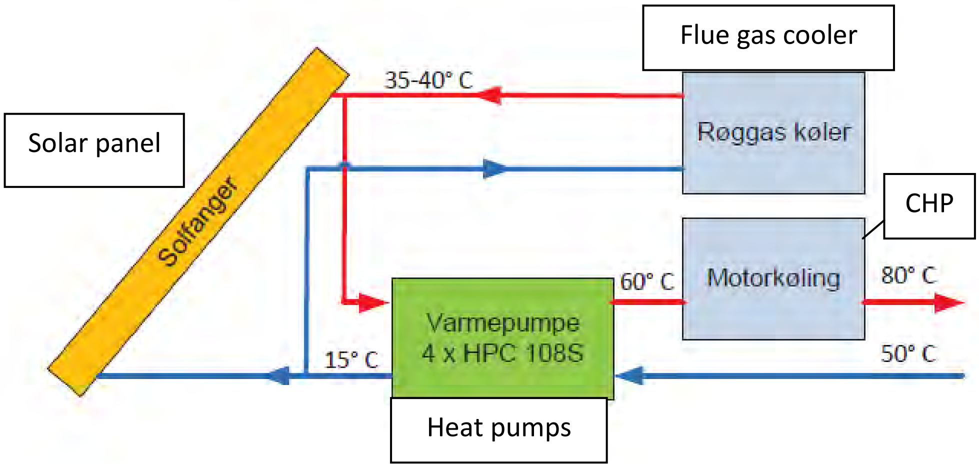


Figure 5-3: System

Depending on the solar radiation and capacity of the flue gas cooler, the cooling circuit is heated to around 35 °C. Utilizing the gas cooler enables the system to operate when there is no sun available. The water is heated through the heat pumps to 60 °C and then reheated to 80 °C in the CHP. The system is connected to two separate buffer tanks holding a total of 5,000 m^3. Two tanks allow separate storage of heat produced on heat pumps and CHP's, meaning that they can be operated individually to utilize fluctuating electricity prices.

The solar panels are fitted with wires so that they can be turned on or off like curtains whichever the plants in the greenhouse requires. In this way the panels can both collect the direct sun input and the convection heat from inside the green house.

5.3.4 Running experience, savings and economics

The system will reduce energy cost by lower heat production prices, reduced ventilation and less CO_2 consumption. The heat pumps have been running since the summer of 2013, but the system is not yet fully optimized as the fluctuating solar radiation and complex system layout require sophisticated control strategies. Due to this, economics and operating experience of the heat pumps are not yet conclusive. A final report on the project can be expected within 2014.

5.3.5 Motive/grounds/rationale behind investment

The project was initiated to reduce gas consumption and heat production cost due to low prices of electricity. Cooling of the greenhouses allow less ventilation thus less CO_2 consumption, which again reduce the gas consumption.

5.3.6 Specifications of heat pump

Description	Heat Pump		Back up
Type	2 x parallel coupled 40 bar NH_3		Gas boilers
Heating capacity	1,000 kW/unit (→°C, units)		
Cooling capacity	750 kW/unit (→°C, units)		
Power consumption	250 kW/unit (units)		
Heat source	Solar panels and flue gas	35-10 °C	
Heat sink	Water	50-60 °C	
Refrigerant	NH_3		
Compressor type	40 bar 8 cyl. reciprocating NH_3		
COP	4.0		
Operation hours	?		
Storage water tank	2 pcs. total 5,000 m^3	Temp 60 and 90 °C	
Manufacturer of heat pump	Johnson Controls		
Supplier/consultant	Averhoff Energi Anlæg		

5.4 Heat pumps in industrial washing applications

5.4.1 Summary

KSN Industries have been part of an R&D project developing heat pumps for the washing plants that KSN have been manufacturing for a number of years. KSN has seen an increasing focus from customers about energy optimization of production equipment. The washing processes are quite energy intensive and as they are usually electrically heated, there is a savings potential on energy cost. The project was carried out by KSN Industries, Grundfos and a number of advisers. Grundfos is the end user of a large number of these washing plants and very interested in this heat pump concept.

Through this project a demonstration plant was built and tested and it was verified that heat pumps in these applications can reduce energy consumption by 50 %. The heat pump is installed at one of Grundfos' washing plants in Bjerringbro. It recovers waste energy from the exhaust and recycles it back into the water of the same plant. The prototype is developed by the Danish Technological Institute in cooperation with KSN and the main challenges were finding suitable components, effective heat transfer and an optimal control system.

Other targets of the project were to uncover the potential for heat pumps in different types of washing processes and to disseminate this knowledge to manufacturers, energy consultants and end users.

5.4.2 Project information

Company	Grundfos
Location	Bjerringbro, Denmark
Process application	Washing metal items
Type of heat pump	R134a
Capacity	25 kW
Running hours	Approx. 5,000 per year
Year of operation	2011
Primary energy savings	Approx. 100 MWh per year
Reduction in CO_2 emission	Approx. 20 tonnes
Maintenance costs	Aprrox. 2 euros/MWh-heat
Manufacturer/supplier	KSN Industries
Pay back	2.5 years

5.4.3 Project characteristics and process design of installed system

The project focuses on washing plants for production companies where the washers are used to clean metal or plastic items after machining processes. The washers are typically located in direct continuation of processing machines, where the items are cleaned to remove oil residues and possible dirt from the machining. After washing the items are dried and proceed to further processing or assembly into the final product.

The idea is to design the heat pumps as independent units that can be applied in both existing and new plants. The heat pumps are located in their own cabinet and connected to washing plants via hoses or pipes. This requires only minimal interference with the washing plant, while the heat pump can be flexibly positioned near the washer.

The most common type of the washing plants are called “run through washers” as the items are led directly through after processing. The items are transported through the washer via a belt or a drum. The machines typically hold two washing areas – one with soapy water and one with rinsing water. And finally a drying zone. The picture below shows a “run through washer”.

Figure 5-4: „Run through washer"

Metal items leave the pressing machine on the right where they enter the washer and then exits on the left clean and dry. At the top right side of the washer is a ventilation system that removes moist air and keeps a slight negative pressure in the machine. This eliminates unwanted condensation around the machine.

The principle is illustrated in the figure below. However, with a flipped flow direction compared to the picture above.

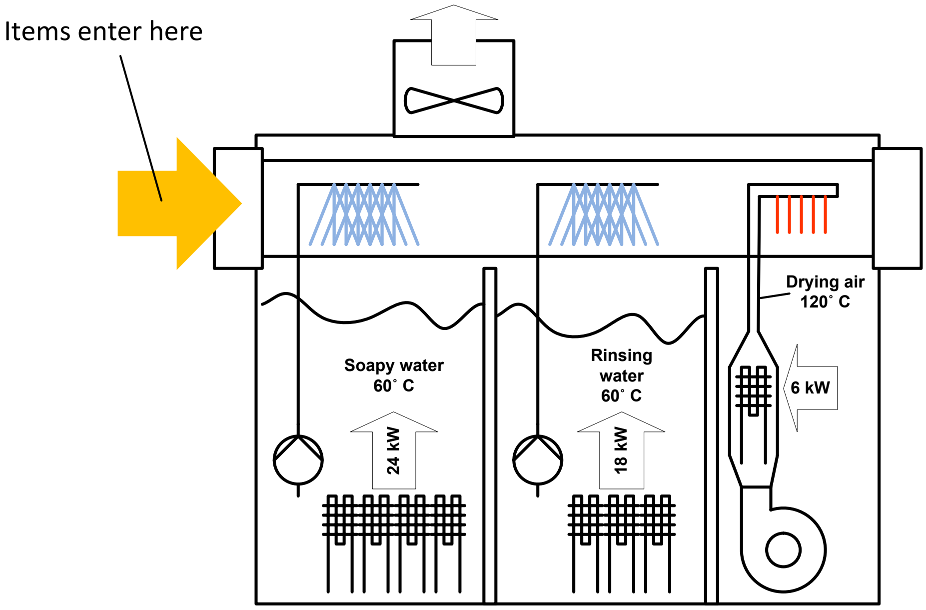


Figure 5-5: Principle

To maintain the set temperature of 60 °C in the two tanks, the washing plant is equipped with electrical heaters consuming a considerable amount of energy.

5.4.4 Implementation

In order to dimension the heat pump correctly it was important to know the exact energy consumption (and thereby average heat required) of the specific washing plant. The average energy consumption was logged during a representative period and the average heat demands of the two tanks were measured to 8 and 17 kW respectively.

To minimize refrigerant charge and risk of leaks, the entire cooling circuit is assembled inside the heat pump cabinet so that only hot and cold water enters the cabinet. A schematic drawing of the heat pump and washing plant is shown on the figure below:

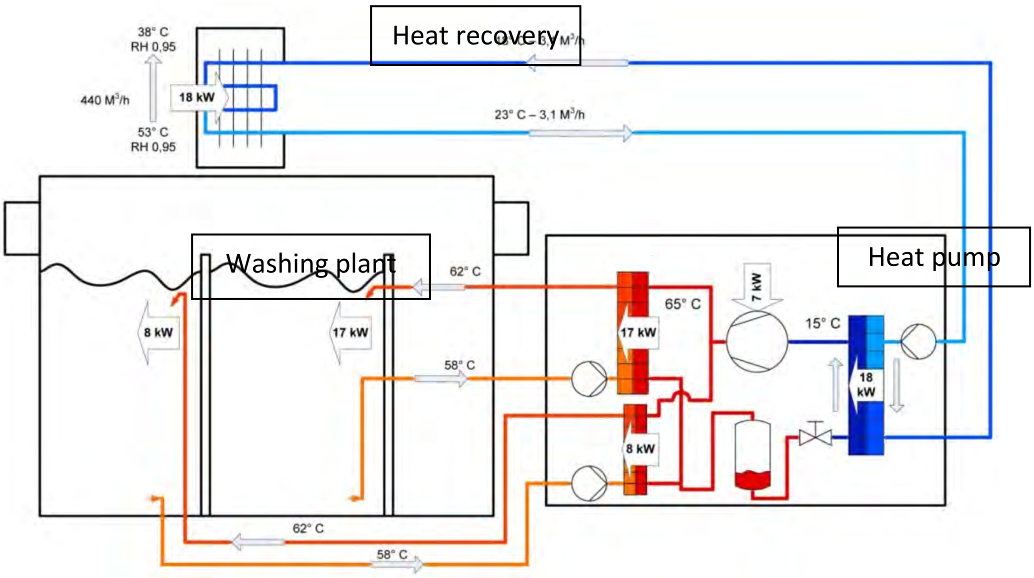


Figure 5-6: Principle

The two condensers in the heat pump are each connected to a tank at the washing plant. The evaporator is connected to a cooling surface that is installed at the filter mist of the washer.

The picture below shows the heat pump that is located next to a pressing machine and is connected to the washing plant through water pipes.

Figure 5-7: Heat pump

To verify the energy savings from the use of the heat pump, energy data for the washing process was recorded daily. In order to do a fair comparison it was important that the metal parts were the same throughout the period. At the same time, it is ensured that the water supply and temperatures are identical.

The results were showing that the heat pump reduced the total power consumption from approx. 31 kW to 15.7 kW equaling a reduction of 49 %. The heat pump has been tested under fluctuating conditions, and it has been proven that the chosen concept and control method have been successful. At the same time, it was proven that the expected energy savings of approx. 50 % can be achieved.

The cooling coil was expected to foul and lose capacity after a longer period of operation. This however has not happened. The coil has been inspected visually and still looks brand new. It is expected that the large amounts of water condensing at the cooling surface flushes dirt or particles off of it, thus cleaning it continuously.

5.4.5 Running experience, savings and economics

The demonstration project has shown that it is possible to apply heat pumps to halve the energy consumption of industrial washing plants. The function of the washing plants is very important for many manufacturing companies. Because of this the plant functionality has always been more interesting than low energy consumption, and it is only during the past few years, that the high energy consumption has been addressed. These washers have an average electrical consumption of 20-80 kW. With a high number of operating hours there is an economic incentive to reduce this consumption. Simple pay back periods will often be around 2 years. It is expected that there are about 3000 plants in Denmark alone.

5.4.6 Lessons learned and challenges

Throughout the project it became clear that correct dimensioning of the heat pumps and control strategy is important, however easy to assess following the correct approaches. In general these heat pumps are simple, easy to apply and reliable.

5.4.7 Motive/grounds/rationale behind investment

Most production companies have ambitious goals to reduce energy consumption and CO_2 foot print. These solutions meet these goals while being very profitable at the same time.

5.4.8 *Specifications of heat pump* (depending on application)

Description	**Heat Pump**		**Back up**
Type	Standard R134a using two condensers		Electrical heaters
Heating capacity	25 kW/unit (→°C, units)		
Cooling capacity	18 kW/unit (→°C, units)		
Power consumption	7 kW/unit (units)		
Heat source	Drying air (water circuit)	55-30 °C	
Heat sink	Washing water	60 °C	
Refrigerant	R-134a		
Compressor type	Copeland Scroll		
COP	3.8		
Operation hours	15,000		
Storage water tank	None		
Manufacturer of heat pump	KSN Industries		
Supplier/consultant	KSN Industries		

6 France

7 Germany

7.1 Introduction

As reported in Task 3, thermea. Energiesysteme GmbH (www.thermea.de) developed high-temperature high-power heat pumps with the refrigerant carbon dioxide. Since 2011 they were introduced to the market and since that time the company sold and put into operation a greater number of the machines.

In the actual report two selected applications are described to illustrate the energy and environmental benefits of CO_2 as natural refrigerant.

7.2 Heat Pump Plant at the Slaughterhouse Zurich

7.2.1 General

On 1 November 2011, a new thermeco$_2$ heat pump system for hot water generation and heating was put into operation in the slaughterhouse Zurich. With a capacity of 800 kW, the plant is the largest ever built in Switzerland. The thermeco$_2$ machines deliver the required 90 °C with better COPs compared to other refrigerants. The heat pump system is built up of 3 heat pumps thermeco$_2$ HHR 260.

Figure 7-1 shows the schema of this plant. The heat pump uses waste heat of an existing Ammonia refrigeration machine, an oilcooled air compressor plant and the installed fan-coil units as heat source. For this reason the heat is collected in a waste heat buffer storage connected with the heat pump evaporators. Because of the closed waste water circulating loop no special measures to avoid corrosion are necessary.

The warm side of the heat pumps is connected with a hot water buffer storage. The consumer (warm water for slaughtering and cleaning purposes, feed water for a steam generator and the heating system) are provided from this buffer storage using their consumer pumps tailored to the particular demand.

Because of the extremely low space requirement, this large heat pump system could be installed in a container system on the roof of the slaughterhouse in a short distance to urban residential development. Only authorized personal has access to the container and CO_2 sensors have been installed that activate an alarm when healthy concentration levels are exceeded.

7.2.2 Technical data:

Refrigerant:	R744 (carbon dioxide)
Machine type:	3 x thermeco$_2$ HHR 260
Capacity control via master CPU:	adjustable in 12 steps
Total heating capacity:	800 kW at 90/30 °C

Total refrigerating capacity:	564 kW at 20/14 °C
Electrical power consumption:	237 kW
Heat pump COP:	3.4
Annual heating output:	2200 MWh
CO_2 emission reduction:	510 tonnes/year

CO_2 has the advantage of minimal safety requirements. The avoidance of costs for foundations and noise control measures is due to the low-noise and low-vibration operation of the thermeco$_2$ machines.

The risk for leakage is considered small by the customer as the installed system has been certified and optimized for high pressures. A fine performance graduation without loss of efficiency and the high reliability are further advantages of the technology supplied. Maintenance and repair costs for the heat pumps are also low due to the use of virtually maintenance-free compressors and the remote monitoring and control system.

7.2.3 Energetic and environmental improvement by the heat pump application

All of the thermal energy for the slaughterhouse Zurich was previously provided with steam boilers. The customer's decision for a high temperature heat pump system with CO_2 as a refrigerant on this scale had several reasons. The efficiency advantages of the high temperature heat pump system clearly have priority. Running this heat pump plant the city of Zurich, represented by the Umwelt- und Gesundheitsschutz Zürich (UGZ) and the Elektrizitätswerk Zürich (ewz) as Contractor make an important contribution towards the "2000 Watt Society" of the city of Zurich. In the calculated overall balance of the slaughterhouse, CO_2 emissions can be reduced by approx. 30 %. By using the heat pump system, 2,590 MWh from fossil fuels can be saved per year, representing an annual reduction in CO_2 emissions of 510 tonnes.

The first measurements show that these values are lifelike. The operating company ewz and thermea will do further measurements and register all running costs as a basis of a long time evaluation.

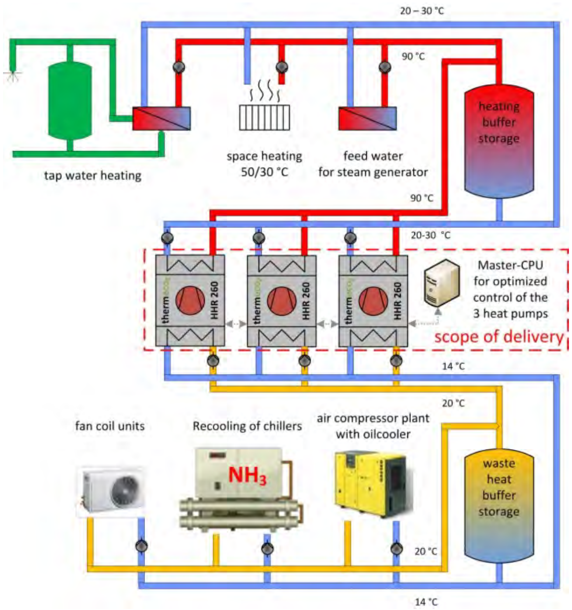


Figure 7-1: Function chart

7.3 Heat Pump Plant at the cafeteria at the University of Applied Sciences Soest, Germany

7.3.1 General

Using the example of the cafeteria at the University of Applied Sciences Soest with year-round warm water and occasionally heat supply by heat pump, 25% of heat costs are saved to the utmost satisfaction of the customer. Furthermore, the environmental impact was reduced to approximately 50%.

7.3.2 Technical Description

For the solution of the task, the machine type thermeco$_2$ HHR 45 in water/water conduction was selected in cooperation with the planner. It is the smallest type of thermeco2 HHR series, which consists of 10 basic types in the power range from 45 to 1,000 kW.

The high-temperature heat pump usable as a heat pump and for cold water/cold brine production is characterized by a robust design and a very compact construction. The machine is equipped with a frequency-controlled semi-hermetic reciprocating compressor operating on a transcritical CO_2 cycle with an internal heat exchanger. The special conduction with a frequency converter allows continuous power control with optimum adjustment of the supplied power to the power requirements.

The inner heat exchanger ensures high refrigerant inlet temperature into the compressor and with it also high outlet temperatures, which allow supply temperatures up to 90° C. In addition, some improvement in the coefficient of performance is achieved with the internal heat exchanger. The refrigerant injection into the evaporator is effected, as usual, by controlling the refrigerant superheat at the evaporator outlet. In addition, there is required a regulation of the high pressure, which is at transcritical process control determined by the refrigerant mass located on the high pressure side. The refrigerant receiver is installed on intermediate pressure level between the high-pressure control valve and the expansion valve. All the heat exchangers are designed as shell and tube devices, or in the lower power range, as a coaxial construction.

The hot water supply temperature is adjusted by a variable speed pump to the adjustable set point. Also with the variable speed pump in the heat source circuit it is possible to adjust to a constant chilled water supply temperature of 10 ° C.

A PLC integrated into the switchboard with a convenient touch panel takes over the control and regulation. The start screen of the touch panel displays the most important state variables. Additional sensor and control signals can be queried via an appropriate menu. Even via the touch panel, the parameterization of the heat pump (performance, temperatures, pressures) within the permissible limits is possible. Error messages or exceedances are recorded in a message list.

The heat pump is equipped with all necessary safety devices for a safe operation according to DIN EN 378-2.

The main technical data are listed in Table 7-1.

Table 7-1: Technical Parameters

➢ Machine type	1 x thermeco$_2$ HHR 45 mit FU
➢ Heating capacity	52,7 kW at water inlet/outlet temperature 20°C / 80 °C at gas cooler
➢ Cooling capacity	39,1 kW at water inlet/outlet temperature 12 °C / 6 °C at evaporator
➢ Electr. power input	14,3 kW at abovementioned water temperatures
➢ COP	3,7 at abovementioned water temperatures

7.3.3 Integration of the heat pump into the heat supply

The exhaust air from the ventilation system of the canteen and the waste heat of the industrial refrigeration system function as a heat source. The exhaust air registers and the heat recovery of the chiller are integrated in series to the heat source circuit (Figure 7-2).

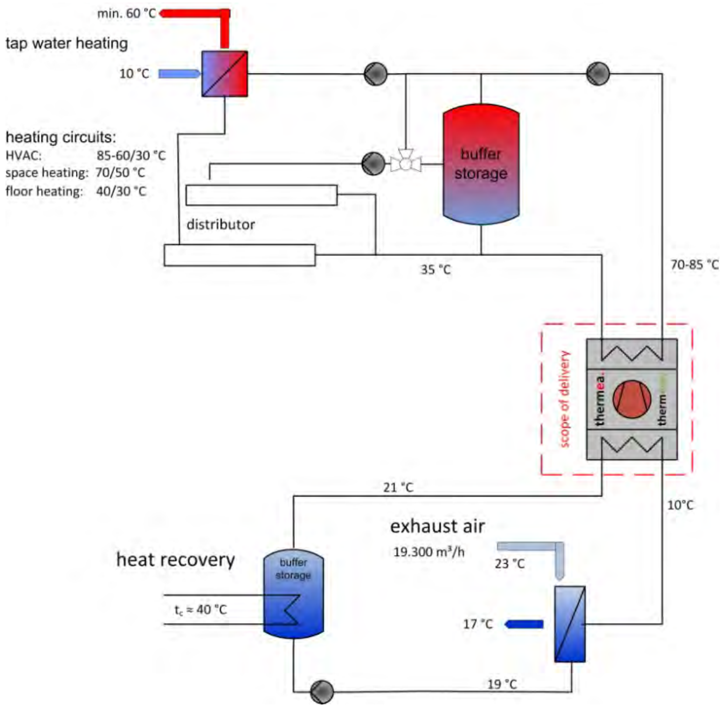


Figure 7-2: Function chart

The heat pump extracts heat from the source circuit, raises heat – depending on request - to a temperature level of 70° C to 85° C and loads hot water buffer storage. The storage decouples the overall system hydraulically and thermally.

The heat pumps works heat-conducted that means it is controlled by the charge state of the hot water storage. Demand-actuated, the consumer removes water for the heating distribution in the central section, while the water supply is coupled through an additional heat exchanger to the upper section of the storage. The planned consumer´s return temperature was on average 35 °C. By series connection with a floor heating at the end of the circuit, the return temperature could be lowered to about 5 K (measured values).

The heat pump system is running since March 2011 and operates reliably. In the future it will cover about 2/3 of the heat demand (Figure 7-3, yellow area). Moreover, the reduction of heat losses in the district heating network can be seen (Figure 7-3, red area). In summers, power losses do not occur any more. The achieved reduction of heat demand in the heating season 2010/2011 (Figure 7-3, blue area) is the result of previous modernization measures.

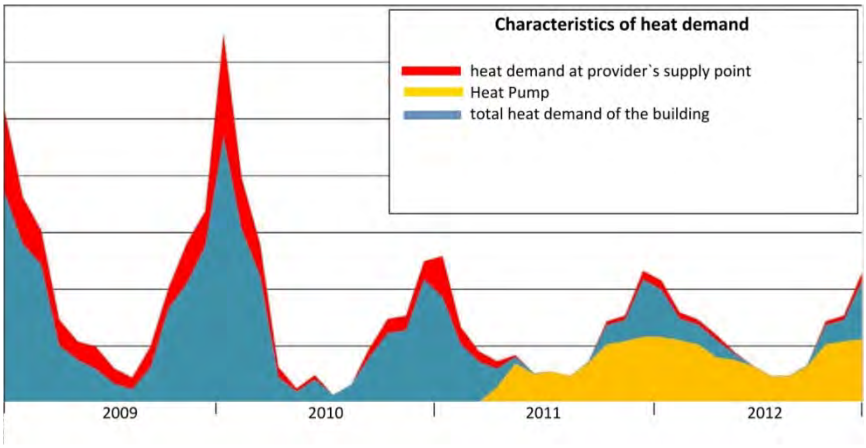


Figure 7-3: Gross margins of the heat pump

7.3.4 Heat cost savings and CO_2 emissions

In Figure 7-4 can be seen that the relatively high share of capital-bound costs is compensated by the lower consumption-bound costs. Taking into account a reasonable additional expense for maintenance of the heat pump, the annual full cost advantage is (including capital costs) for 15 years: 4.100 € / a. That means a saving of about 25 %. Basis for the calculation are heat costs from the district heating network to an amount of 70 €/MWh and 140 €/MWh of electric energy costs.

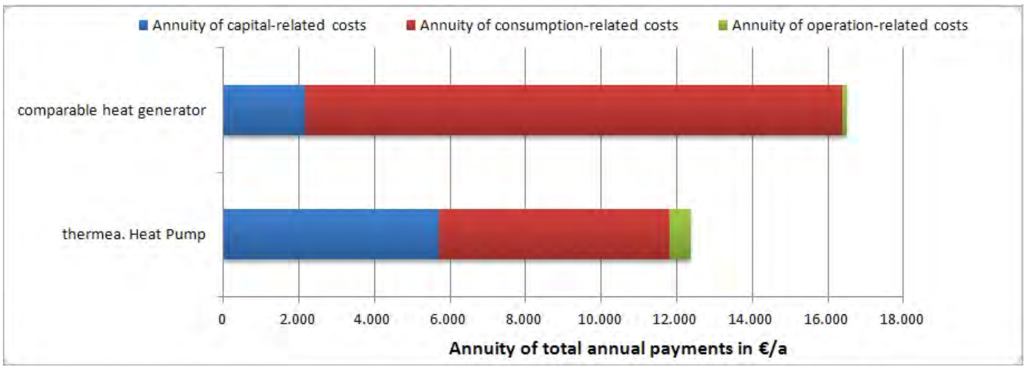


Figure 7-4: Comparison of costs

The specific CO_2 emissions in the heat supply from the district heating network are 0.39 kg CO_2/kWh. With the heat pump this value is reduced to 0.2 kg CO_2/kWh. That means approximately a halving.

The TEWI calculation according to EN 378-1 was made without consideration of the direct proportion with a conversion factor of 0.63 kg CO_2/KWh, and a seasonal performance factor of the heat pump of 3.2 for a lifetime of 15 years. The calculated emission for the heat pump is 400 tons of CO_2, while the district heating supply causes an amount of 790 t CO_2 for the same period. Thus, the use of heat pumps brings environmental discharge of 390 tons of CO_2.

7.3.5 Initial operating experience

After an operating time of about 2 years, there is satisfaction of the end user and the planner. The expectations regarding the technical parameters and the operating behavior are fully met and even exceeded them.

Figure 7-5 shows the behaviour of the most important temperatures over a period of 18 hours. The start of heating at 4 o´clock and the cafeteria´s closing at 16 o´clock are clearly visible. The temperature of the hot water forerun on the heating side is constantly 75 °C, while the return temperature varies according to the storage loading condition.

Additionally recorded curves are measured for control in the storage or in selected areas of the heat exchanger. The black curve of the hot water forerun represents the temperature behavior in the hot water storage above.

During the start-up time the behavior of the COPs at different operating states was precisely analyzed. It can be recognized that the COP is well above 3,5 at current operating conditions, heat source 20 °C / 10 °C at the evaporator and hot water 30 °C / 75 °C at the gas cooler. The coefficient of performance reaches a value of 3.2 as yearly average value.

The operator figures the major advantage of the heat pump thermeco$_2$ in comparison to other "conventional" machines in its flexibility. The heat pump can cover both evaporator and gas cooler-side an enormous temperature range, so that reserves for extreme operating conditions are always available. For example, in cold application a too small-sized cooler can be compensated by raising the flow just for a short time.

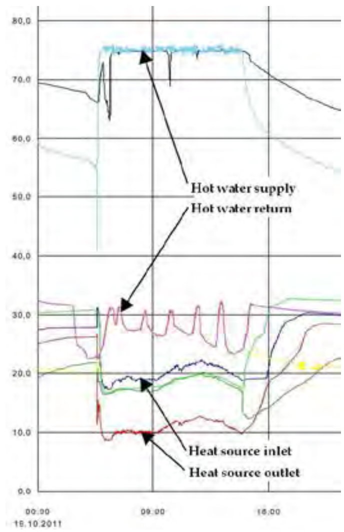


Figure 7-5: Selected temperatures

7.4 Summary

The two examples described show that at the current state of development of components for CO_2 as a refrigerant it is possible to build and operate reliable and energy-efficient high-temperature heat pumps. For the user the choice of CO_2 as a refrigerant means investment security because it is not affected by the increasingly stringent regulations of the so-called F-gases.

7.5 Heat pump installation in food and beverage industry: Dairy

(by P. Nellissen, Emerson Climates Technologies)

7.5.1 Background

Milk manufacturing process requires heating capacity for the process or also for some cleaning (pasteurisation, sanitary water, etc.). At the same time cooling capacity is required for some stage.

Norway's Dairy Cooperative Tine built a large new dairy in the Jæren region in the south west of Norway. It will be a gigantic facility covering 27,000 square meters, producing 200 million litres of milk annually mainly producing butter and cheese. Like most other industrialised processes, this facility will produce large amounts of waste heat. The concept was to initially install systems allowing heat recovery and also reducing CO_2 emissions by 30 - 40 % with this new dairy.

7.5.2 Company information

Category of industry Company	Food and Beverage processing: Dairy (butter and cheese)
Location	Jaeren, Norway
Year of installation	2011
Purpose	Heat recovery for hot water generation
Amount of production	200 million litres milk per year

7.5.3 Installed system

The heating plant is designed for not only fulfilling the dairies own demand of CIP water but is also connected to a local heating network which supply the heat to an adjacent new build green houses, which will be supplying 40 % of the cucumber and tomatoes to the Norwegian market. The heating system in the greenhouses are designed for a supply water temperature of 58 °C, this can be achieved with a heating COP above 9,0.

Using the waste heat to generate 25,000 MWh of cheap heat per year for the nearby greenhouses has secured a payback of the plant of less than 2.5 years. There are plans for connecting a local business estate to the heating network and increase the supply temperature to 73°C within the next couple of years. The heat pump is prepared for this increase in supply temperature.

Following capacities is required based on 3 low stage and 2 high stage compressors.

- 5400 kW @ -5°C required refrigeration duty, Condensing +37ºC

- 7200 kW @ 73°C required heating duty – COP 5.8
- 6900 kW @ 58°C required heating duty – COP 9.0

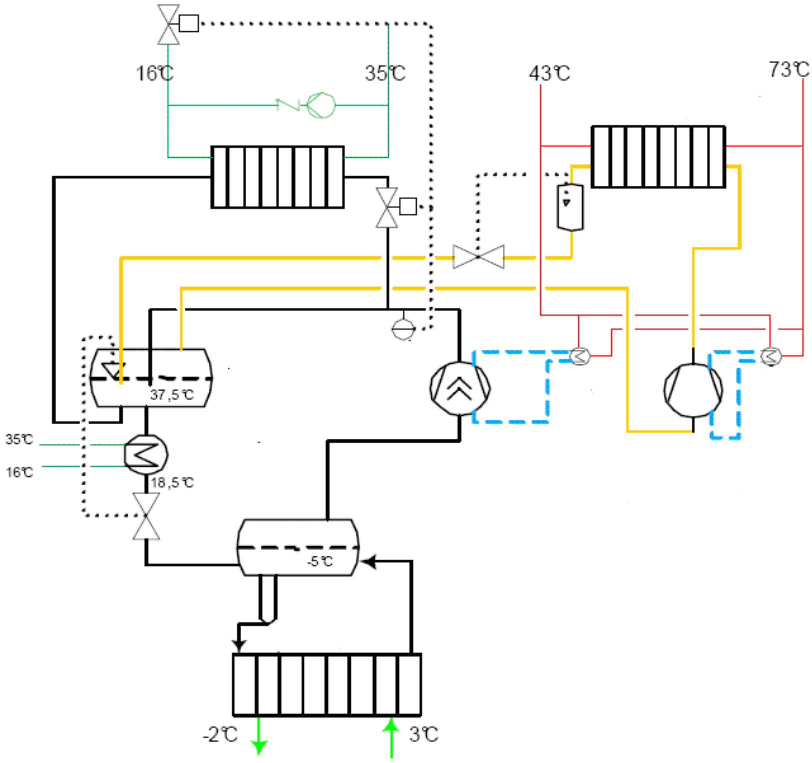


Figure 7-6: Configuration diagramme

Figure 7-7: Equipment appearance

7.5.4 Specification of Heat Pump system

The concept of the installations consists in combine cooling and heating systems. On one side, the cooling installation provides the cooling duty for the butter and cheese manufacturing process. On the other hand, the rejected heat from the refrigeration installation is used as heat source for the Neatpump.

Description	**Heat Pump**		**Back up**
Type	Combine heating and cooling installation		
Heating capacity	3450 kW(3600 kW)/unit (37.5→58 (73°C)°C, 2 units)		Boiler
Cooling capacity	760 kW/unit (-5°C→37.5 °C, 3 units)		
Power consumption	kW/unit (units)		
Heat source *Description and temp*	Condenser of the refrigeration installation	Temp 37.5°C °C	
		m^3/h	
Heat sink *Description and temp*	Hot water for the process and also for greenhouse heating	Temp. 58°C or 73°C	
		m^3/h	
Refrigerant	Ammonia		
Compressor type	Single Screw compressor		
Rated power of compressor			
COP	5.8 at 73°C and 9.0 at 58°C		
Operation hours			
Storage water tank	m^3	Temp. °C	
Targeted floor dimensions			
Manufacturer of heat pump	Star Refrigeration Ltd		
Supplier/consultant	Emerson Climate Technologies GmbH, Norsk Kulde		

7.5.5 Effects

NOT AVAILABLE AT THIS TIME

7.5.6 Challenges and prospects

This kind of installation proves that combined heating and cooling with an ammonia heat pump is a very attractive solution among existing only heating system.

This allows savings not only for heating cost but also

- in term of CO_2 emissions,
- in term water consumption
- On the total cost of energy per units manufactured
- for the future, the threat (F-Gas regulation in Europe) of using HFC in the refrigeration installation.

Combined heating and cooling can be applied on any industrial process requiring cooling and heating on different steps in their manufacturing process.

7.6 Heat pump in Food and Beverage industry - Combine heating and cooling in chocolate manufacturing

(by P. Nellissen, Emerson Climates Technologies)

7.6.1 Background

The existing cooling installation was using R22 as refrigerant which would be banned in the coming years. Previously one central coal fired steam generation plant served all of the individual end users, where high grade steam would be degraded to suit the processes. The Nestlé Halifax team completed an energy audit on their central coal fired boilers, the steam distribution and all of the end user heating systems throughout the factory. This enabled the team to clearly identify, grade and consolidate the various end user heating requirements which identified significant design and operational inefficiencies. The new concept was to simply heat the water to the desired process temperature and the heat pump would serve to provide hot water to end users requiring 60 °C and to preheat those operating in excess of 60 °C.

In parallel, the existing cooling installation, using R-22, would also have to be revamped because of the R22 future ban. Nestlé's global commitment to reduce the environmental impact.

7.6.2 Company information

Category of industry Company	Chocolate manufacturing Nestlé UK Ltd
Location	Halifax, UK
Year of installation	2010
Purpose	
Amount of production	2 x 600 kW

7.6.3 Installed system

Previously one central coal fired steam generation plant served all of the individual end users, where high grade steam would be degraded to suit the processes.

The chocolate manufacturing process also requires cooling capacity for certain steps of the process. These simultaneous demands for cooling capacity and heating capacity allowed the replacement of the heating and the cooling system by a combined cooling and heating installation. The idea was to install a Single Screw compressor Heat Pump combining Heating and cooling.

The Heat source consists in cooling process glycol from 5°C down to 0°C this evaporates Ammonia at -5°C and the heat pump lifts it to 61°C in one stage for heating. Process water is finally heated from 10°C to 60°C.

Based on the clients previously measured heating and cooling load profiles the analysis showed that to meet the projected hot water heating demands from the 'Total Loss' and Closed Loop' circuits, the selected heat pump compressors would have to produce

1.25 MW of high grade heat. To achieve this demand the equipment selected offers 914 kW of refrigeration capacity with an absorbed power rating of 346 kW. The combined heating and cooling COP, COP_{hc}, is calculated to be a modest 6.25. For an uplift of 17 K in discharge pressure the increase in absorbed power was 108 kW boosting the COP_{hi} to an impressive 11.57.

The diagram below describes the lay-out of the installation with the combined heating and cooling.

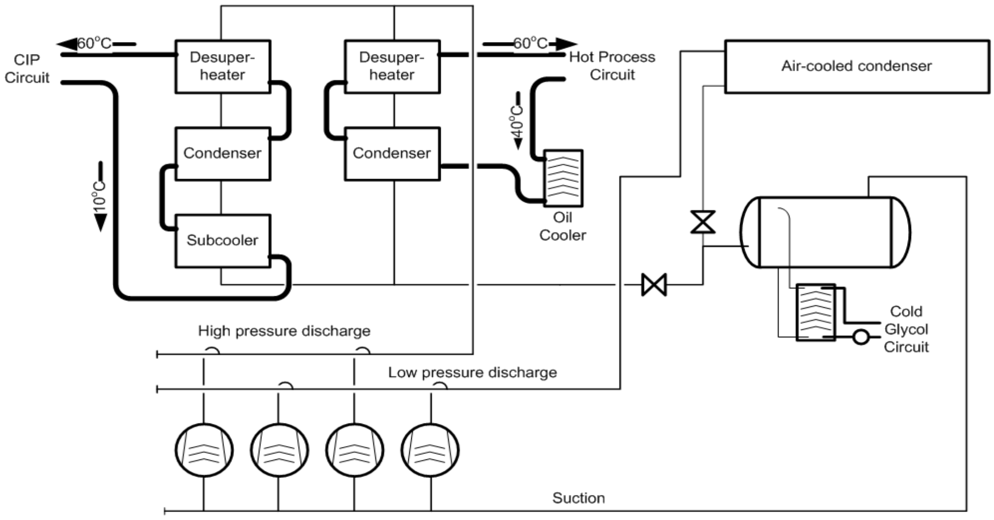


Figure 7-8: Configuration diagramme

The pictures below show the installations (the two compression units for the process cooling and the two heat pumps (with the full isolated oil separator in grey material).

7.6.4 Specification of Heat Pump system

A Pinch analysis was constructed that identified the major hot and cold streams for the factory. The stream data used for the Halifax analysis was stream lined to only include CIP water, high temperature closed heating and medium temperature closed heating.

Star Refrigeration, Vilter Manufacturing Inc (USA), Emerson Climate Technologies company, and Cool Partners (a Danish consultancy) formed a collaborative effort to devise a high pressure heat pump solution using ammonia and screws at 90°C. 60°C seemed a comparatively easy task by comparison but it was still ahead of it is time as it was asked to cover a wide operating pressure lift, taking heat from glycol at -5C and lift it to 60°C in one stage.

For the layout design and optimisation, software developed in collaboration with Cools Partners allows to rapidly and efficiently estimating the performances of the installation.

The table below provides more details about the heat pump installation:

Description	**Heat Pump**		**Back up**
Type	Single Screw heat pump		
Heating capacity	600 kW/unit (12→60°C, 2 units)		
Cooling capacity	1600 kW/unit (5→0°C, 2 units)		
Power consumption	kW/unit (2 units)		
Heat source *Description and temp*	With thenew system, heat can be taken from the 0°C process glycol and lifted to 60°C water in one stage for heating.	Temp 0 °C m^3/h	
Heat sink *Description and temp*	With the new system, heat can be taken from the 0°C process glycol and lifted to 60°C water in one stage for heating.	Temp. 60 °C	
Refrigerant	Ammonia		

Compressor type	Single Screw Compressor		
Rated power of compressor			
COP	Combined heating and cooling 5.46		
Operation hours			
Storage water tank	m^3	Temp. °C	
Targeted floor dimensions			
Manufacturer of heat pump	Star Refrigeration		
Supplier/consultant	Star Refrigeration, Emerson Climate Technologies		

7.6.5 Effects

The initial thinking for the customer was to get a 90°C hot water heat pump. Indeed, some application demand required 90°C. However the total demand for this temperature level was around 10% of the whole hot water consumption. Designing a heat pump installation for such temperature would not be interesting in terms of performances and efficiencies. It was decided to install the heat pump producing 60°C hot water. When the small amount of 90°C water is required, the incremental heat is supplied now by a small gas boiler heating up the water from 60°C up to 90°C.

In parallel, other alternatives for the heating were assessed like a central gas fired boiler, combined heat power or geothermal heat pump. Qualitative and quantitative assessments (cost, required existing installation upgrade, future site growth…) defined that the best alternative solution for this project was the heat pump. So a correct analysis and understanding of the real need for the installation allow installing the right answer to the real Nestle needs.

Nestlé can save an estimated £143,000 per year (166,000 € per year) in heating costs, and around 120,000 kg in carbon emissions by using a Star Neatpump.

Despite the new refrigeration plant providing both heating and cooling, it consumes £120,000 (140,000 €) less electricity per year than the previous cooling only plant.

Another impact of the complete project (combined heating and cooling, additional gas boiler for the 90°C water peak demand, etc.) decreased the total water consumption from 52,000 m^3/day down to 34,000 m^3/day.

The Nestlé system recently won the Industrial and Commercial Project of the Year title at the 2010 RAC awards.

7.6.6 Challenges and prospects

This kind of installation proves that combined heating and cooling with an ammonia heat pump is a very attractive solution among existing only heating system.

This allows savings not only for heating cost but also

- in term of CO_2 emissions,
- in term water consumption

- On the total cost of energy per units manufactured
- for the future, the threat (F-Gas regulation in Europe) of using HFC in the refrigeration installation

Combined heating and cooling can be applied on any industrial process requiring cooling and heating on different steps in their manufacturing process.

7.7 The World's Largest Natural District Heat Pump

(by P. Nellissen, Emerson Climates Technologies)

7.7.1 Background

Drammen is a town 40 km south west of Oslo (Norwegian Capital). During the last decade it has gone through a major transformation from being a rundown industrial town to a newly developed town centre with new hospital, housing, ice rink, hotels and shopping centre.

Drammen Fjernvarme KS was established in 1999, and is owned by Energiselskapet Buskerud (Buskerud Energy Company) and Fortum Holding. The same year Drammen Municipality decided to make connection to the district heating system mandatory in the concession area. This means that every new building larger than 1000 m^{2}has to be built with a water-based heating system connected to the district heating system. Today the area that receives district heating has been expanded, and includes most of central Drammen

These new developments have all been connected to a district heating network. The first district heating plant in Drammen was installed in 2002 using 8 MW biomass boilers.

Knowing that the European Commission has designated heat pumps a renewable technology for heating and cooling, Drammen decided to use heat pumps and had several additional goals in mind for this capacity increase project:

- The supply water temperature from the heat pump would be 90°C
- The highest coefficient of performance (COP) possible the ratio of heat extracted compared to energy consumed.
- A technology solution with low annual operating and maintenance costs.
- A system using a non-ozone depleting refrigerant with zero global warming impact.

With the second phase of the district heating network extension being a 13 MW of heat pump duty (for the base load) and additional 2 x 30 MW gas fired boiler (backup for the peak duties) have been installed. The maximum network peak heat demand is 45 MW duty.

7.7.2 Company information

Category of industry Company	Drammen Fjernvärme KS
Location	Drammen, Norway
Year of installation	2011
Purpose	Hot water generation for district heating application
Amount of production	13 MW heating capacity at 90°C hot water

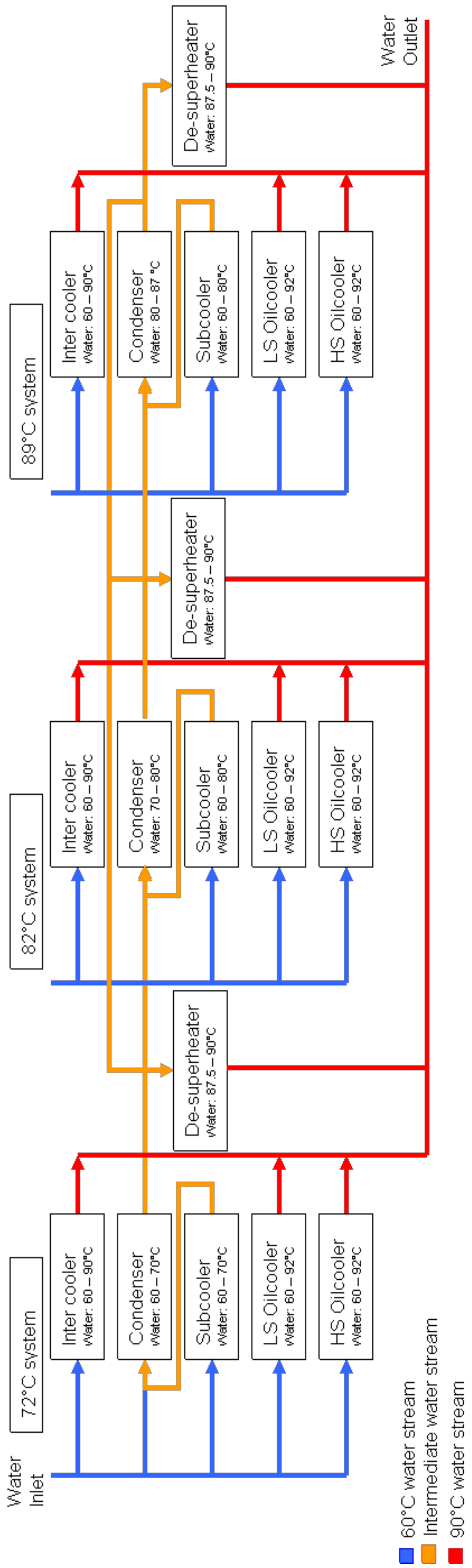
7.7.3 Installed system

The supply temperature of the district heating water varies across the year depending on the heat demand. In the summer time where there is a very small demand (less than 2 MW) the supply water temperature is 75°C, when the ambient temperature falls and there is an increase in heating demand, the supply water temperature increases up to 120°C at peak load. The return water temperature from the district heating loop is very steady at 60°C to 65°C all year around. When the gas boilers are being utilized they are working on a constant flow with temperature difference of 10°C between inlet and outlet. The water is then being mixed with the district heating water to achieve the desired outgoing temperature. To optimize the performance of the heat pump it was important to have variable flow system where the water is taken directly from the district heating return line as every degree subcooling is important and any degree overheating is wasted energy.

The heat source for the heat pump is sea water. Norway has a famous rocky coastline. The thermodynamic beauty of this landscape is that the water gets very deep just off the coast. When taking in the water at 40 m depth there is a constant water temperature of 8°C to 9°C most of the year. At this depth the water temperature is not affected by changes in the air temperature from +30°C in the summer to -20°C in the winter. The water intake pipe runs 800 m into Oslo Fjord and the return pipes are 600 m long to ensure that the 4°C outlet water is not mixed with the inlet water. The seawater pumps are situated on land but below sea level.

The seawater is cooled directly in spray chillers, where ammonia is sprayed across titanium pipes with the seawater inside.

The ammonia heat pump that has been installed on site consists of 3 x 2 stage single screw compressor systems in series each with a heating duty of approximately 4.5 MW.


72°C system
82°C system
89°C system
Water Inlet
Water Outlet
Inter cooler Water: 60 – 90°C
Condenser Water: 60 – 70°C
Subcooler Water: 60 – 70°C
LS Oilcooler Water: 60 – 92°C
HS Oilcooler Water: 60 – 92°C
De-superheater Water: 87.5 – 90°C
Inter cooler Water: 60 – 90°C
Condenser Water: 70 – 80°C
Subcooler Water: 60 – 80°C
LS Oilcooler Water: 60 – 92°C
HS Oilcooler Water: 60 – 92°C
De-superheater Water: 87.5 – 90°C
Inter cooler Water: 60 – 90°C
Condenser Water: 80 – 87 °C
Subcooler Water: 60 – 80°C
LS Oilcooler Water: 60 – 92°C
HS Oilcooler Water: 60 – 92°C
De-superheater Water: 87.5 – 90°C
60°C water stream
Intermediate water stream
90°C water stream

- Photo of equipment appearance

External view of the Drammen installation building

External view of the Drammen City

Internal view of the Drammen installation building: machine room

7.7.4 Specification of Heat Pump system - Design and installation process

For optimized performance of large scale heat pumps it is important to get the design right. The biggest challenge was to design the hot water flow through the heat pump to ensure that every kW is taken out of the system and at temperature where it is most useful.

With the water being heated from 60°C to 90°C the condenser part of the system is split into 3 off 2- stage systems working in series. The main water stream is being heated from 60°C to 69°C through the first condenser and from 69°C to 78°C in the second condenser and from 78°C to 87°C in the third condenser.

After the main flow has been heated to 87°C it is split into 3 streams going through the high stage desuperheater for each of the systems. The temperature is raised to 89°C through these heat exchangers.

Besides the main water flow there are separate streams of water going through subcoolers, high stage and low stage oil coolers and intercoolers. The intercoolers serve three purposes: they cool the superheated gas from the low stage compressors before entering the high stage compressors. Suction superheat reduces the isentropic efficiency of the compression. In addition the lower suction temperature gives rise to a lower discharge temperature thereby protecting the seals from too high a discharge gas temperature on the high stage compressors (maximum 135°C). The final reason of course is energy recovery.

With the main stream of water being mixed with the water from all auxiliary streams which has been heated to 92°C - 98°C the mixed outgoing water temperature from the heat pump is 90°C.

Although the three heat pumps are operating at different conditions the specifications for each of the three heat pumps are the same. This enables each of them to deliver 90°C water in case of a failure of one of the systems.

With 3 systems operating in a combination of series and parallel instead of simply parallel the average condensing temperature falls from 90°C to 80.5°C representing a 10% improvement in efficiency for the ammonia heat pump system.

Description	**Heat Pump**		**Back up**
Type	3 x 2 stage single screw compressor		
Heating capacity	4500 kW/unit (60→90°C, 3 units)		
Cooling capacity	kW/unit (10→5 °C, 3 units)		
Power consumption	kW/unit (2 units)		
Heat source *Description and temp*	Sea water	Temp 8°C m^3/h	
Heat sink *Description and temp*	District heating network	Temp 90°C m^3/h	
Refrigerant	Ammonia		
Compressor type	Single Screw		
COP	3.05		
Operation hours	8000 hours at different capacities		

Storage water tank	m^3	Temp °C	
Manufacturer of heat pump	Star Refrigeration Ltd		
Supplier/consultant	Emerson Climate Technologies/Vilter		

7.7.5 Effects

Based on 48,000 MWh per year at the following current gas prices in Norway are approximately £30 (35€) per MWh and the electricity prices is approximately £50 (58 €) per MWh. By using the ammonia heat pump: The total cost of electricity would be around 800,000 € per year vs. 2,000,000 € per year. There is an estimated saving of £1,042,289 (1,210,000 €) compared to using gas.

The global warming benefit of the ammonia heat pump is also significant. With a yearly equivalent CO_2 emission of 317 tons, this compares to burning gas which would give a CO_2 emission of 13,050 tons per year at the given usage profile.

Primary energy savings	1,210,000 €/year
Reduction in CO_2 emission	12,700 tons/year
Maintenance costs	
Manufacturer/supplier	Star Refrigeration Ltd.
Pay back	

7.7.6 Challenges and prospects

The main challenge for heat pump in general is to convert the heat source to the right heat level offering the best return on investment possible.

This type of installation shows that high temperature and also high heating capacity heat pump can be achieved using a natural refrigerant like Ammonia with the right compression technology.

This specific heat source (sea water at 8 °C) proves that the range of heat source for heat pump can be widened (sea water, river, waste process water, heat recovery,…) and can provide high COP allowing optimised return on investment. This type of installation is not limited to district heating applications but can be replicated to a large amount of installations with energy recovery/savings leading to operational costs decrease environmental positive impacts. **For example: distillation of ethanol or combined district cooling and desalination.**

<u>**References**</u>

- Emerson Climate Technologies + Star Refrigeration internal data
- Hoffman, & Pearson, D. 2011. Ammonia heat pumps for district heating in Norway 7 – a case study. Presented at Institute of Refrigeration, 7 April, London.
- http://www.youtube.com/watch?v=a6xMS_hBNKM
- http://www.youtube.com/watch?v=Imo-G7Dbito

7.8 Case Study – Surface Finishing

Finishing processes are used to influence the surface quality of work pieces. By the combined application of thin coatings, surface properties can be customized according to individual requirements. The range of surface treatments reaches from optical to technical finishes, like corrosion protection or an increased surface hardness.

7.8.1 Process description

In the finishing process coatings are applied to the surfaces of work pieces by galvanic or chemical processes. One of the most common galvanic surface finishings is hard chromium plating, which is also the core competency of the company considered in this case study. Hard chromium plating is used to apply a thin layer of chromium to a surface to improve both wear and corrosion resistance of a work piece. This is achieved by an increase of the surface hardness. The thickness of the chromium layer can vary from 5 to more than 1,000 µm depending on the operating conditions. To apply the chromium layer, the work piece is immersed into a bath filled with chromium electrolyte. Between the work piece and an anode an electric DC voltage is applied. By the electric field chromium ions are forced to accumulate on the surface of the work piece. To achieve a good surface quality current densities of 50 A/dm² are needed. One of the disadvantages of the hard chromium process is its low efficiency. In industrial-scale chroming plants only 20% of the energy is used for the actual creation of the chrome layer /Zimmer 2010a/. The other 80% are transformed into heat. As the process temperature has to be kept between 50 and 60 °C, cooling is needed during the electroplating phase. In between the chromium electrolyte has to be heated to compensate thermal losses.

7.8.2 Initial situation

The company considered in this case study runs several hard chromium plants and a large chemical-nickel plant. Beside the galvanic and chemical surface finishing the company also offers mechanical surface finishing.

To cover the cooling demand of the chrome baths and the current rectifiers the company runs a large centralized cooling system. A scheme of this cooling system is shown in Figure 7-10. Two large tanks with a volume of 30 m³ each buffer peak cooling loads. Thus the cooling water temperature can always be kept below 37 °C. As there is no speed controlled circulation pump installed, the whole cooling system is designed for this operating temperature. This means that the tank temperature is not allowed to vary largely in order to maintain constant temperatures in the hard chroming process.

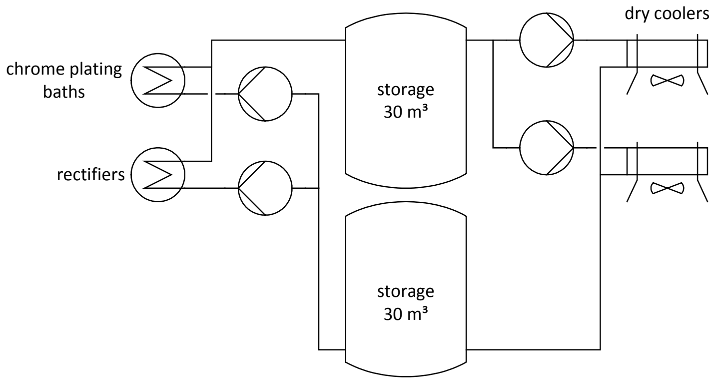


Figure 7-10: Scheme of the cooling system

The heat is emitted to the environment by means of two dry coolers. The cooling water flow and thus the cooling capacity can be adjusted to the cooling demand in six steps. Nevertheless the heat is rejected in short episodes from 5 to 10 minutes. As the storage temperature has to be kept in a range between 33 and 37 °C, the large volume of 30 m³ cannot create a large buffering effect.

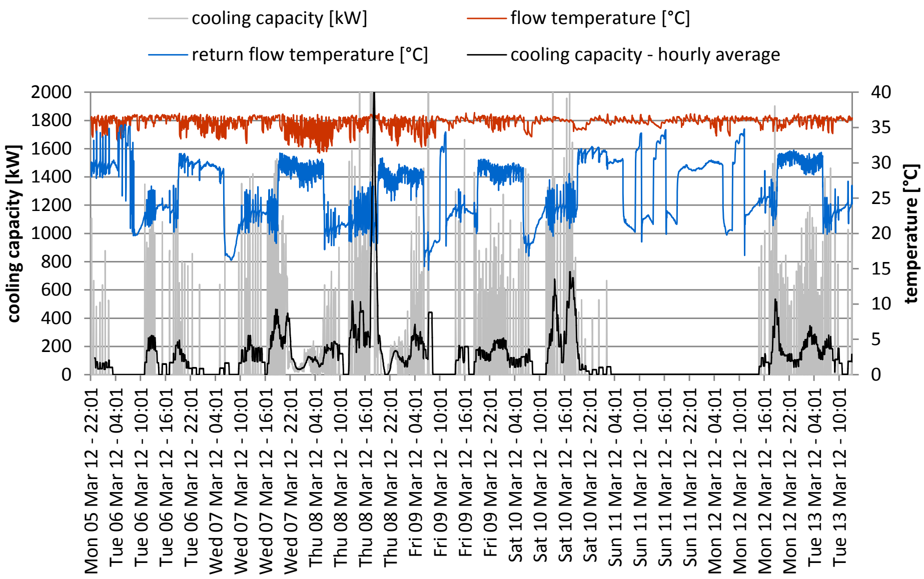


Figure 7-11: One week profile of the rejected heat of the cooling system

The rejected heat was measured over a time period of one week. The measurement results can be seen in Figure 7-11. The average hourly cooling capacity varies from 50 to 600 kW, while the absolute peak load reaches 3,290 kW. The average cooling load during the considered week was 376 kW. Assuming 2,500 operation hours per year, 671 MWh of waste heat are rejected to the environment. This estimate can be classed as conservative, as the company also produces on weekends, if large orders have to be processed.

While waste heat is rejected to the environment there is also a heat demand for space heating, hot water generation and process heat. Beside the chrome baths also the degreasing baths and the chemical-nickel plant need large amounts of heat at fairly low temperatures. An overview over process temperatures and the type of heating are shown in Table 7-2.

Table 7-2: Overview over possible heat sinks for a heat pump in the production line

process	temperature	type of heating
chemical-nickel bath	90 °C	hot water
degreasing bath	80 °C	hot water
chrome bath	55 °C	electric heaters

These processes are suitable heat sinks for a heat pump, because they have operating temperatures below 100 °C as well as an all-year heat demand. Since no data about the heat demand of these baths was available measurements had to be carried out for the chrome bath and the degreasing bath. The space heating demand is estimated based on the heating bills of the last 4 years.

- Degreasing bath: The bath is filled with 7.3 m³ cleaning solution. It has to be kept at a temperature of 80 °C for about 6,000 operating hours a year, since it is only shut off during weekends. In the start phase at the beginning of the week this bath has to be heated up within 4 hours according to strict factory specifications. The maximum heat performance measured in this starting phase was 180 kW. To maintain the operating temperature of 80 °C later on only 19.2 kW are needed. The bath is heated by a hot water circuit with a flow temperature of 115 °C and a back flow temperature of 100 °C. These high temperatures are only needed in the start phase. In the stationary phase, when only heat losses have to be compensated, heat is supplied in short bursts of 1 to 2 minutes in length. Considering the installed heat exchanger surface the flow temperature could be lowered to 90 °C during the stationary phase. In the course of one year 110 MWh are needed at 90 °C flow temperature.
- Chrome bath: The bath is filled with 12 m³ chromium electrolyte. Only during the chroming process a heat surplus is generated. In the intervening periods an electric heater maintains a bath temperature of 55 °C. For balancing the thermal losses a heating capacity of 20.8 kW is required. Since the chrome plating process takes just 23 % of the total operating time the yearly heat demand of the chrome bath amounts to 29 MWh. This heat is generated in a rather expensive way, as electric heaters are being used.
- Space heating: On the plant grounds there are two production halls and one administrative building that need to be heated in winter. An oil boiler covers the heat demand of 2.8 GWh per year. Since the air exchange rate of the production halls is fairly high due to toxic emissions of the chrome baths, there is also a large space heating demand. The space heating demand of production hall 2 amounts to 700 MWh/a. The heaters in the production hall are designed for a flow temperature of 70 °C. As this hall also houses the central cooling plant a

share of the space heating demand could be covered by a heat pump using the waste heat of the cooling system.

No measurements were carried out for the chemical-nickel bath because a hot water flow temperature of at least 110 °C is needed to keep the bath at its 90 °C operating temperature. Taking into account the 35 °C heat source temperature, there was no heat pump system available that would have matched neither technically nor economically.

7.8.3 Proposed measures

The previously unused waste heat can be utilized by a heat pump. The 30 m³ cold water storage can be used as heat source. A heat pump with a cooling capacity of 147 kW and a SCOP of 3.8 could cover 23 % of the cooling load. Since the cold water storage temperature has to be kept in a small range below 37 °C, the operation time of the heat pump is rather limited. The installation of a speed controlled circulation pump would allow a much broader temperature range which would multiply the storage capacity. This could raise the share of the heat pump up to 44 %. With reference to Figure 7-11 the needed cooling capacity would approach the black line representing the hourly average.

Based on the conducted measurements two options were suggested:

- Option 1: Installation of a speed controlled circulation pump for the cooling network and a heat pump with 200 kW heating and 147 kW cooling capacity. The heat pump would cover 44 % of the total cooling demand and 35 % of the space heating demand of production hall 2.
- Option 2: Installation of a speed controlled circulation pump for the cooling network, a heat pump with 200 kW heating and 147 kW cooling capacity and a 2 m³ hot water storage. Furthermore the electric heater of the chrome bath would be replaced with a heat exchanger. The heat pump would supply the chrome bath with heat all year long. In winter the excess heating capacity of the heat pump would be used for space heating of production hall 2.

7.8.4 Economic feasibility

For both options economic feasibility studies were carried out. For both options an optimistic and a pessimistic scenario were calculated. The calculation was carried out in accordance with VDI guideline 2076.

7.8.4.1 Option 1:

The proposed system only delivers heat during the heating period in winter. It can cover up to 35 % of the space heating demand of production hall 2. The payback period would be 7 to 8 years and the internal rate of return would be 6 to 11 %. Thus this option is considered not economically feasible (see Table 7-3).

Table 7-3: Results of the economic analysis of option 1

	scenario	
	optimistic	pessimistic
investment costs	70,000 €	90,000 €
increase of energy prices	4 % p.a.	3 % p.a.
oil price (2012)	7 ct/kWh	7 ct/kWh
electricity price (2012)	14 ct/kWh	14 ct/kWh
SCOP	3.8	3.8
heat generation	290 MWh/a	290 MWh/a
system life	15 years	15 years
internal rate of return	11 %	6 %
payback period	7 years	8 years

7.8.4.2 *Option 2*

In the second option the heat pump also supplies heat to the chrome bath. Since this bath is electrically heated, the economic advantage of the heat pump is considerably larger. The heat pump also generates about 90 MWh more heat, as it is supplying the chrome bath all-year long. These aspects are reflected by a significantly higher internal return rate of 20 to 26 % and a shorter payback period of 3.5 to 4.5 years.

Table 7-4: Results of the economic analysis of option 2

	scenario	
	optimistic	pessimistic
investment costs	90,000 €	110,000 €
increase of energy prices	4 % p.a.	3 % p.a.
oil price (2012)	7 ct/kWh	7 ct/kWh
electricity price (2012)	14 ct/kWh	14 ct/kWh
SCOP	3.8	3.8
heat generation	380 MWh/a	380 MWh/a
system life	15 years	15 years
internal rate of return	26 %	20 %
payback period	3.5 years	4.5 years

The second option was considered economical feasible. The results were given to a planner for a detailed cost calculation. Despite positive results the company decided not to implement the heat pump system due to internal restructuring measures.

7.9 Case study – Prefabricated house manufacturing

A prefabricated house consists of several components that are built in a factory and assembled on the construction site. These components are mostly built using a light-weight structure. Mainly timber is used to build the frameworks for walls. It is one of the most used materials in the construction of a prefabricated house.

7.9.1 Process description

The timber has to be dried before it can be processed. The residual moisture content has to be reduced to 10 to 20 % to avoid cracks. The wood is placed in a drying chamber in which it is exposed to a hot and dry atmosphere for several days. The water contained in the wood migrates to the surface where it evaporates. By forced convection, a good transition of the moisture to the air is achieved. During the drying process the air temperature is lifted stepwise from 50 to 80 °C. In between the temperature is held at a constant value for long time periods of up to several days. To prevent drying damage, temperature and humidity have to be maintained in a well-defined framework during the whole drying process. If the humidity hits the upper limit, dampers in the ceiling of the drying chamber open to replace the humid air with fresh dry air. The actual drying phase is followed by a conditioning phase. In this phase moisture gradients over the cross-section of the wood are compensated. Subsequently the wood must be cooled down to at least 40 K above ambient temperature to reduce internal tensions and to prevent the wood from cracking /Trübswetter/.

7.9.2 Initial situation

The prefabricated house manufacturer considered in this case study uses large quantities of wood. To achieve the most complete possible utilization of this raw material the company has set up a chain of exploitation from wood drying to the sawmill. The residuals are used to fire a biomass power plant. The power plant is composed of two blocks having a total net electric output of 8.2 MW. The net electrical efficiency of the blocks is 21.7 % and 23.8 %. Block 1 is equipped with an extraction-condensation turbine. Before the steam enters the low pressure part of the steam turbine, it can be partly drawn off to be used for the heat supply of the factory. Thus, up to 5 MW of thermal power can be provided. In both blocks the steam is condensed in an air cooler at a temperature of 55 °C.

The heat provided by the biomass power plant is used for 4 wood presses and 27 drying chambers. In addition to that it is also used for space heating of production halls and office buildings in winter.

Since the wood presses are operated at a temperature of 120 °C, they are not considered as a heat sink for a possible heat pump system. Therefore they are not investigated further. The drying chambers are also supplied with heat at 120 °C, although these high temperatures are only needed in the startup phase and when the process temperature has to be raised. Most of the time, the inlet flow is mixed down to 65 to 90 °C.

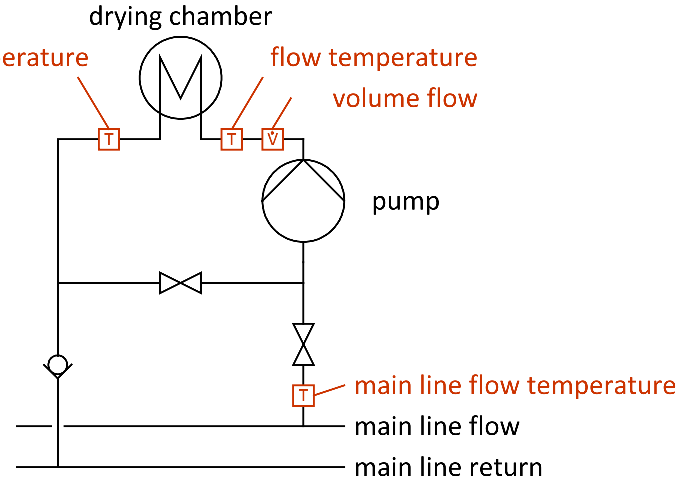


Figure 7-12: Heat supply system of the drying chamber

Figure 7-12 shows the heat supply system of the drying chamber. To prepare an energy balance, the temperatures and volume flows were measured in the points marked in red in Figure 7-13. These measurements had to be conducted since there was no data on the energy consumption of one single drying chamber available. A total of two drying runs were analyzed. The duration of the first run was 15 days, while the second run took 21 days. The time necessary for drying depends on the amount of wood, the moisture content and the ambient air temperature. The diagrams in Figure 7-13 and Figure 7-14 show the flow temperature and the heat demand of the drying chamber.

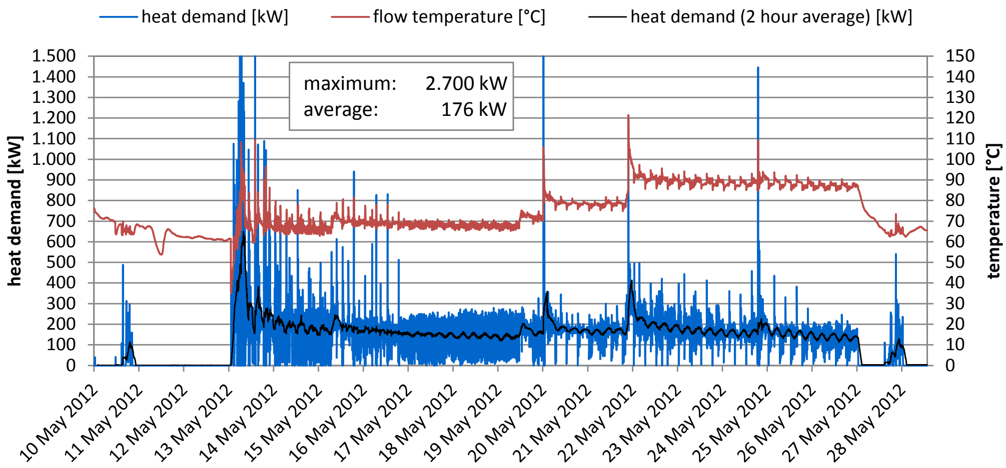


Figure 7-13: Measured data of the drying chamber – 1st drying run from 13th May 2012 to 28th May 2012

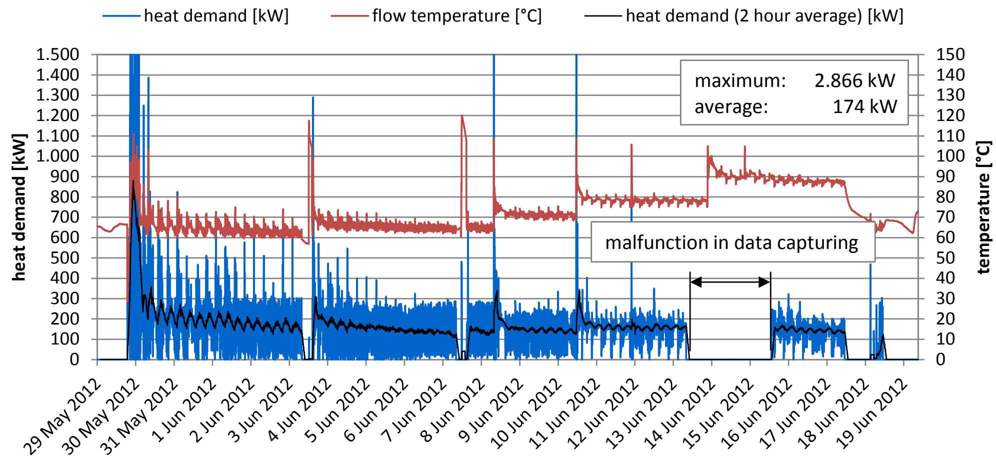


Figure 7-14: Measured data of the drying chamber – 2nd drying run from 29th May 2012 to 19th June 2012

High flow temperatures of more than 100 °C were only needed in the startup phase and when the process temperature had to be raised. During the startup phase, high temperature gradients between the heating circuit and the air temperature in the drying chamber lead to the transmission of high performances. The peak performance was as high as 2.9 MW. In the long-running drying phases the temperature is kept at constant values. In these periods an average heating power of 175 kW is needed. The flow temperature is raised in several steps from 65 °C to 90 °C.

7.9.3 Proposed measures

With an increase of the production, also the wood consumption and thus the heat demand for wood drying increased during the last years. Especially in winter the heat demand exceeds the maximum amount of heat that can be delivered by the biomass power plant. In this case an oil fired boiler would have to generate additional heat. To cover the additional heat demand in a more environmentally friendly and cost effective way, a heat pump system was proposed. The heat source for such a system would be the waste heat generated by the biomass power plant. The heat pump would be used to power the drying chambers during the long stationary phases in between the temperature lifts. Thus long running times with a constant load can be reached. The flow temperature during these phases varies between 65 and 90 °C. With a waste heat temperature of 55 °C, the heat pump would have to lift the temperature by 10 to 45 K. High temperature heat would only be needed during the startup and the temperature increase phases. During the long stationary phases a heat pump with a heating capacity of 180 kW could cover the entire heat demand of the drying chamber. Figure 7-15 shows the integration of the heat pump into the heating system of the drying chamber.

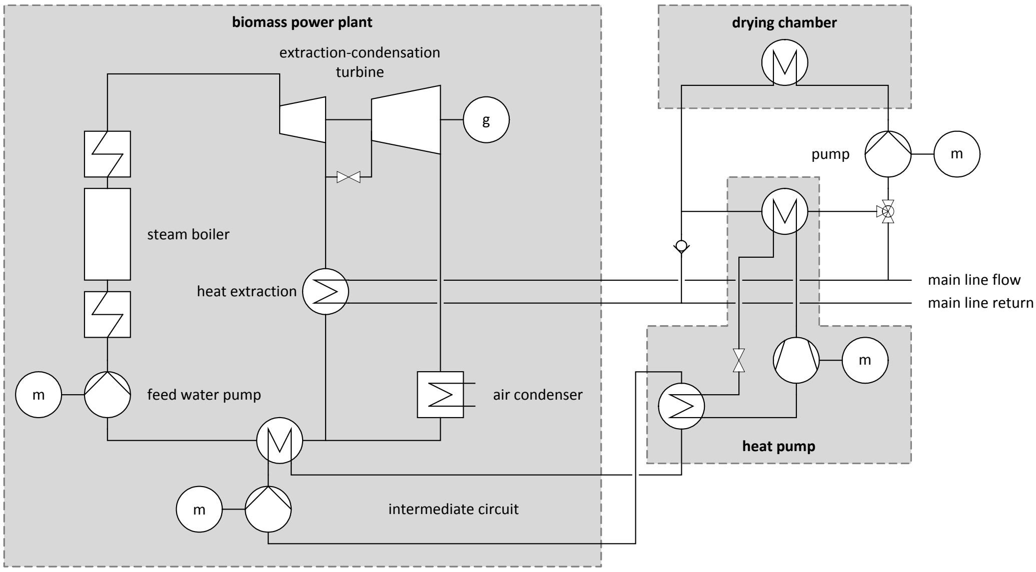


Figure 7-15: Integration of the heat pump into the heat supply system

7.9.4 Economic feasibility

The biomass power plant is currently generating the entire heat used in the company. Since the power plant is mainly fired with biogenic waste from the company's own production a heat pump could compete neither in economic nor in ecologic terms. Thus a heat pump could only be used to generate additional heat that is needed primarily in winter times. Here the heat pump system needs to compete with an oil fired boiler. Assuming a production expansion in conjunction with an increased heat demand, the heat pump could achieve a running time of 2,000 full-load hours per year.

For the described heat pump system an economic calculation was carried out according to the VDI Guideline 2067 /VDI 2010/. As reference heat source an oil fired boiler was considered. With a heating capacity of 180 kW the heat pump could cover up to 73 % of the drying chamber`s entire heat demand. To determine the influence of different assumptions a parameter variation was made. In Table 7-5 a pessimistic and an optimistic scenario are portrayed.

The internal rate of return of 16 to 24 % shows the economic feasibility of the heat pump system. Payback periods of 4 to 5.5 years could be reached.

Despite these positive figures the proposed heat pump system was not installed, because at the end of this analysis an increase of the heat demand was no longer assumed due to a prospected slight downturn of the order situation. Furthermore alongside the feasibility study for the integration of a heat pump other energy saving potentials were discovered that appeared to be more interesting from the economic point of view.

Table 7-5: Results of the economic analysis

	scenario	
	optimistic	pessimistic
investment costs	64,200 €	85,000 €
increase of energy prices	4 % p.a.	3 % p.a.
oil price (2012)	7.5 ct/kWh	7.5 ct/kWh
electricity price (2012)	9.5 ct/kWh	9.5 ct/kwH
SCOP	4.5	4.5
heat generation	360 MWh/a	360 MWh/a
system life	15 years	15 years
internal rate of return	24 %	16 %
payback period	4 years	5.5 years

7.10 Application of heat pumps in the German industry

A total number of 17 heat pump systems could be characterized in the German industry. These examples were picked, because they show opportunities for the application of heat pumps in different industrial branches and with a large variety of framework conditions. There are many more heat pump systems in operation, but they are either similar to the characterized systems or they are considered to be confidential parts of the production process. All of the characterized systems use industrial waste heat as heat source. Five of them provide process heat while the other eleven are used to generate hot water and space heating. The map in Figure 7-16 shows the geographic location of the surveyed companies.

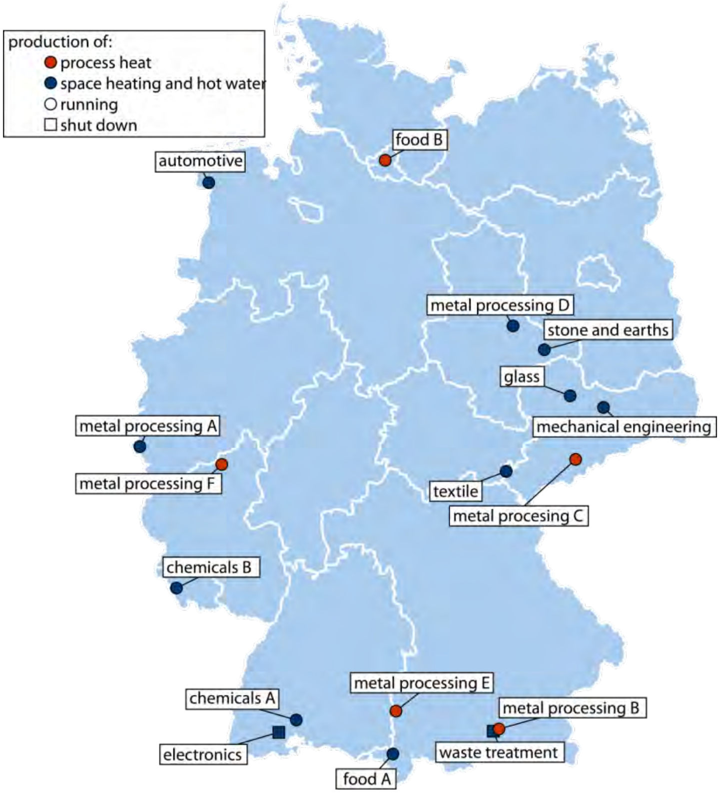


Figure 7-16: Heat pumps in the German industry

The surveyed companies can be subdivided into ten industrial branches. Figure 7-17 shows the number of companies per branch. With six examples the metal processing industry is more strongly represented than the other branches. Most of these six companies are using waste heat generated by machine tools especially laser cutting machines to generate heat for industrial processes or space heating.

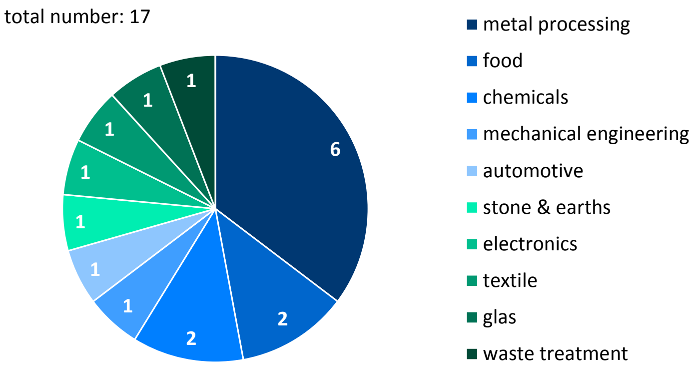


Figure 7-17: Represented industrial branches

Most of the surveyed systems have heating capacities between 100 and 500 kW. Figure 7-18 shows the distribution across different size classes. The largest heat pump is integrated into a malt production process. It has a heating capacity of 3.250 kW. The smallest heat pump has a heating capacity of 20 kW. It uses waste heat to generate hot water and space heating.

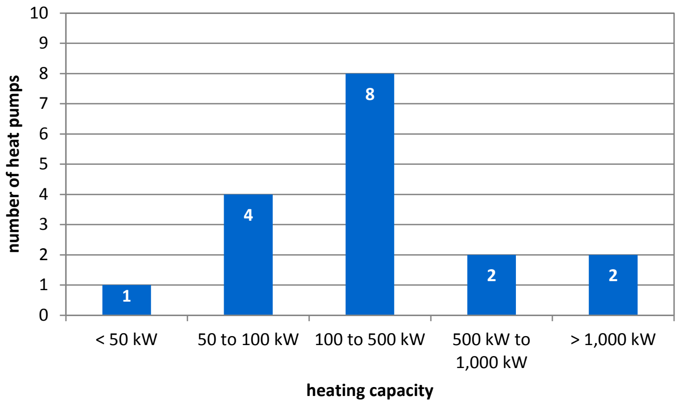


Figure 7-18: Heating capacity of the surveyed heat pump systems

Figure 7-18 gives an overview of all 17 characterized heat pump systems. It lists the name of the company operating the heat pump, the industrial branch, the kind of heat source and the heat pump manufacturer. The table is followed by descriptions of these heat pump systems. Those descriptions include pictures and integration schemes of the heat pumps as well as a standardized table for each heat pump that gives an overview of technical and economical key figures.

Table 7-6: Overview of the documented application examples

industrial branch	company	heat source	HP manufacturer
waste treatment	Vivo	composting plant	
automotive	Volkswagen	dip coating plant	Simaka
chemicals A	Emil Frei	powder coating production	Dimplex
chemicals B	Flavex	extraction plant	Junkers
electronics	Dunkermotoren	moulding machines	Combitherm
glass	Glasfabrik Thiele	workshop air	Dimplex
mechanical engineering	Gebr. Kemmerich	production processes	Klima Jentzsch
metal processing A	Flamm	production processes	SmartHeat
metal processing B	Ludwig Michl	production, servers	Robur
metal processing C	Purkart	lasers, furnaces	Combitherm
metal processing D	Schraubenwerk	induction press	Klima Jentzsch
metal processing E	Thoma	Chrome bath, rectifier	keine Angabe
metal processing F	Hennecke	laser	SmartHeat
food A	Hanspeter Graßl	cooling system, bottling plant	Arwego
food B	Tivoli Malz	malt kiln	
textile	Unternehmen	dyeing machine	Klima Jentzsch
stone and earths	Treibacher	electric furnace	Klima Jentzsch

7.10.1 Waste treatment (VIVO GmbH)

Vivo GmbH is a municipal waste management company. A yearly amount of 20,000 t of residual waste and 48,000 t of valuable and dangerous substances are disposed or processed by the company. In 1994 a bio waste composting plant was built in Warngau. This plant processes about 14,000 t of organic waste. The material is fermented for 21 days to produce biogas with a methane content of 55 %. This gas is collected and transported to a gasstorage. It is then used in a CHP plant to produce 2,500 MWh electricity per year. The heat generated by the CHP plant is used in the fermenters and to power a district heating network that supplies a nearby industrial park.

In addition to that an absorption heat pump was installed in 2005. The heat pump was run with natural gas and made use of the waste heat of a bio waste rotting plant on the same site. A cold water storage collected the waste heat generated at a temperature of 42 °C. The waste heat was upgraded to 82 °C to power the district heating network. The absorption heat pump provided a cooling capacity of 195 kW and a heating capacity of 500 kW. After the correction of minor malfunctions in the first months of operation, the heat pump reached 3,500 operating hours in the heating period from October 2005 to April 2006. Based on the heat input a COP of 1.47 was reached. Taking into account the combustion efficiency the over-all performance ratio was 1.31. The heat pump substituted a large part of the heat, formerly produced by a peak load oil boiler. With a heat production of 1,750 MWh per year, a payback period of 6.7 years was calculated. Furthermore CO_2 emissions were cut by about 160 t per year. The project was carried-out in cooperation with Bayerisches Zentrum für Angewandte Energieforschung e.V. (ZAE Bayern) and Ingenieurbüro J. Färber. It was funded by Deutsche Bundesstiftung Umwelt (DBU) with 60,000 €.

In 2011 the heat pump had to be shut down due to major corrosion problems. The very corrosive LiBr/water solution had destroyed the heat source heat exchanger and damaged the pipings. Due to the fact that the heat pump was manufactured by an Indian company major communication problems occurred. For repair and maintenance works a technician had to come from India. This technician didn't have sufficient knowledge of English, so an interpreter was needed to be able to communicate. Since VIVO GmbH was also not satisfied with the performance ratio, the heat pump was shut down /ZAE 2007; DBU 2008/. In modern absorption heat pumps however corrosion can be avoided by adding inhibitors to the LiBr/water solution. Furthermore a careful choice of materials also helps to avoid corrosion /ASUE 2009/.

Table 7-7: Fact sheet for Vivo GmbH

Industrial branch	Waste treatment – Composting of organic waste
Type of heat pump	Gas absorption heat pump
Heating capacity	500 kW
Heat source description	Waste heat from composting plant
Heat source temperature	42 °C
Heat sink description	District heating
Heat sink temperature	82 °C
COP	1,31
Refrigerant	not specified
Investment cost	174,200 €
Operating since	2005
Payback period	6.7 years
Contact	ZAE Bayern, Ingenieurbüro J. Färber, VIVO GmbH

7.10.2 Automotive (Volkswagen AG)

Volkswagen AG is one of the largest automotive manufacturing companies in the world. Its production site in Emden opened in 1964. It is mainly focused on the production of the model "Passat". The 8,200 employees produce up to 1,200 cars per day /Volkswagen 2013/.

Within the production line the paint shop is one of the main energy consumers. In a cathodic dip coating process items to be painted are immersed in an electrically conductive dipping varnish. A direct voltage field is applied between the items and a counter electrode. Hereby the binder is precipated at the item surface, in order to obtain a closed adhesive coating film. As this process has a positive energy balance, the paint bath has to be cooled continuously to keep the temperature at 30 °C. This cooling load is covered by a large heat pump with a cooling capacity of 1,188 kW. The heat is upgraded to a temperature of 75 °C. The maximum flow temperature offered by the heat pump is 88 °C at a hot gas temperature of 108 °C. The heat is used to provide hot water for different purposes. The heat pump achieves an integrated COP of 5.6 at an annual operation time of 6,720 hours. Apart from minor adjustments in the start-up phase, the heat pump works reliably and well /Volkswagen 2013/.

Table 7-8: Fact sheet for Volkswagen AG

Industrial branch	Automotive – paint shop
Type of heat pump	Electric compression heat pump
Heating capacity	1,683 kW
Heat source description	Cathodic dip coating
Heat source temperature	26 to 29 °C
Heat sink description	Hot water for different purposes
Heat sink temperature	65 to 75 °C
COP	5,6 (integrated)
Refrigerant	Fluid XPro II
Investment cost	not specified
Operating since	2012
Payback period	not specified
Internal rate of return	not specified
Contact	Volkswagen AG - Emden

7.10.3 Chemicals A (Emil Frei GmbH)

Emil Frei GmbH was founded in 1926 and developed from a wholesale for varnish and coatings to a producing company with five production sites. Two of them are situated in Germany. Main products are powder coatings, industrial coatings and electrodeposition coatings.

In 2009 the company was looking for a heating concept for their newly built logistics center in Bräunlingen. At the same location the company also produces powder coatings, what offered the chance to use a process cooling network as a heat source. In 2010 an integrated heating and cooling concept using a heat pump was implemented. The heat pump covers most of the heating demand of the production hall and the storage and shipping warehouse. The heating network runs at a temperature of 45 °C. At outside air temperatures below 0 °C an auxiliary oil heater is used to cover the rest of the heating load. As heat source for the heat pump a cooling water network is used. Through different production steps cooling water is heated up to 18 °C. The low temperature difference between hot and cold side of the heat pump ensures a heating COP of 5. In summer the heat pump is also used for cooling the production halls. Excess heat is then rejected to the environment. The payback period for this system is estimated to be 5 years. In 2010 23,000 € of fuel costs could be saved.

Table 7-9: Fact sheet for Emil Frei GmbH

Industrial branch	Other chemicals – Varnish and coatings
Type of heat pump	Electric compression heat pump
Heating capacity	240 kW
Heat source description	Coating powder production
Heat source temperature	18 °C
Heat sink description	Space heating
Heat sink temperature	45 °C
COP	5
Refrigerant	R404A
Investment cost	210,000 €
Operating since	2010
Payback period	5
Internal rate of return	18 %
Contact	Glen Dimplex GmbH

7.10.4 Chemicals B (Fkavex Naturextrakte GmbH)

Founded in 1986 Flavex Naturextrakte GmbH is now an expert in the production of plant and herb extracts. To protect the sensible active ingredients and aromatic substances the company uses the CO_2 extraction method. A scheme of the process is shown in Figure 7-10.

Supercritical CO_2 is used as extraction fluid, since it has a relatively low reactivity and the process temperatures can be kept low. The CO_2 gas is cooled and thereby liquefied. A pump raises the pressure to 500 bar. Before the liquid CO_2 enters the extraction chamber it is preheated. In the extraction chamber the CO_2 meets the plant material and active ingredients and aromatic substances are solved. This solution leaves the extraction chamber. An expansion valve reduces the pressure and the CO_2 evaporates while heat is supplied. Thereby the organic extracts are separated from the CO_2.

The extraction process needs cooling to liquefy the CO_2. A cooling water circuit supplies the plant with 16 °C cold water. The return flow has a temperature of 20 °C. The water is collected in a large storage tank with a volume of 30 m³. Since the temperatures were too low the waste heat was emitted to the environment until a heat pump was installed in 2009 to make use of this heat. It heats a new production building with a floor space of 2,000 m². To be able to supply the building with heat even on weekends and public holidays, when no waste heat from the process is available, a 45 m³ hot water tank was installed. The company was willing to accept a very long payback time of 10 years for the whole system, because it operates a similar heat pump system for 15 years now without any problems worth mentioning. In addition to that the new heat pump system saves up to 80 t CO_2 emissions per year /Bosch Thermotechnik GmbH 2011/.

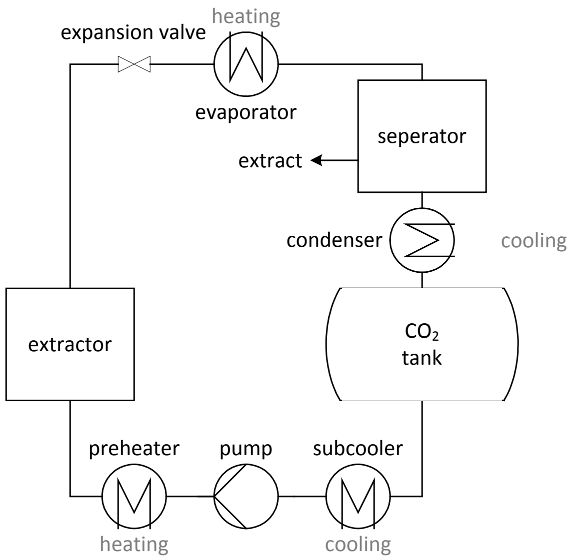


Figure 7-19: CO_2 extraction plant

Table 7-10: Fact sheet for Flavex Naturextrakte GmbH

Industrial branch	Chemicals – production of plant and herb extracts
Type of heat pump	Electric compression heat pump
Heating capacity	61,5 kW
Heat source description	CO_2 extraction plant
Heat source temperature	16 to 20 °C
Heat sink description	Space heating
Heat sink temperature	50 °C
COP	not specified
Refrigerant	R407c
Investment cost	210,000 €
Operating since	2009
Payback period	10
Internal rate of return	6 %
Contact	Junkers - Bosch Thermotechnik GmbH

7.10.5 Electronics (Dunkermotoren GmbH)

Dunkermotoren GmbH is a manufacturer of electric drives with 1,000 employees and an annual turnover of 150 million €. The company was acquired by Ametek in 2012.

In 2001 the company built a new production hall of 6,000 m² at their main site in Bonndorf. To cover the additional heat demand of the new building a heat pump was installed, so that the old oil powered heating system did not have to be extended. The heat pump recovered waste heat from injection moulidng machines at 25 °C and with a maximum cooling capacity of 66 kW. The temperature was lifted up to 70 °C to provide space heating in winter. To decouple heating and cooling demand, a large sprinkler tank was used to buffer peak loads. In the first year a monitoring of the heat pump system was monitored. The results showed that the heat pump system could cover 25% of the entire space heating demand. Due to restructurings of the company the injection moulding machines were taken out of service. With no heat source available anymore, the heat pump also had to be replaced by another heating system.

Table 7-11: Fact sheet for Dunkermotoren GmbH

Industrial branch	Electronics – Electrical drives
Type of heat pump	Electric compression heat pump
Heating capacity	90 kW
Heat source description	Injection moulding
Heat source temperature	25 °C
Heat sink description	Space heating
Heat sink temperature	70 °C
COP	3.7
Refrigerant	not specified
Investment cost	not specified
Operating since	2001
Payback period	not specified
Internal rate of return	not specified
Contact	Combitherm GmbH, Ingenieurbüro Jauch (Radolfzell)

7.10.6 Glass (Glasfabrik Thiele AG)

Glasfabrik Thiele AG was founded in 1984 in Schrotzberg and is now present in seven locations all over Germany. The company specializes on production and finishing of flat glass products. The company's largest production site with an area of 14,500 m² is situated in Wermsdorf. In 2007 the office building in Wermsdorf was extended from 200 m² to 450 m² office space. A heat pump system was installed to cover the resulting additional space heating demand. Furthermore the heat pump also generates 1,200 to 1,400 l of hot water per day.

Glass furnaces are emitting a lot of heat to the ambient air in the production hall. Therefore air conditioning is needed to keep the temperatures in a comfortable condition. To recover the heat emitted by the furnaces two air source heat pumps were installed directly next to them. These heat pumps suck in air at 25 °C and cool it down by 10 K. The heat pump system has a cooling capacity of 40 kW. At the condenser hot water is produced at 40 °C to be used for showers and space heating. Two thermal hot water storages of 400 l and 500 l are working as a buffer to decouple heating and cooling demands. The 500 l storage is used for space heating while the 400 l storage provides hot water for the showers. Pictures of the installation are shown in Figure 7-20. The investment costs for this system can be apportioned to 58,000 € for the heat pumps and 24,000 € for additional accessories and installation works. The total investment costs sum up to 82,000 € for the whole system /Dimplex 2012/.

Figure 7-20: Air source heat pump situated directly next to the glass furnace /Dimplex 2012/

Table 7-12: Fact sheet for Glasfabrik Thiele AG

Industrial branch	Glass – Glass finishing
Type of heat pump	Electric compression heat pump
Heating capacity	64 kW
Heat source description	Glass finishing, hot air near the production furnace
Heat source temperature	25 °C
Heat sink description	hot water, space heating
Heat sink temperature	40 °C
COP	3,8
Refrigerant	R404A
Investment cost	82,000 €
Operating since	2007
Payback period	not specified
Internal rate of return	not specified
Contact	Glen Dimplex GmbH

7.10.7 Mechanical Engineering (Gebr. Kemmerich GmbH)

Gebr. Kemmerich GmbH designs and produces metal parts. The company employs more than 1.000 employees at 5 locations. Since 1996 the tool-making division is settled in Niederau-Gröbern. In recent years the division specialized in metal forming processes.

In the production process CNC machines, laser cutters and eroding machines are used. These machines have been cooled by a conventional cooling system. In 2012 a heat pump was installed to recover the energy formerly wasted. The heat pump has a heating capacity of 20 kW and provides heat for space heating at 60 °C. When the heat demand exceeds the capacity of the heat pump an oil fired boiler is activated. Main focus of the system is to always provide enough cooling power. Therefore a cold storage was integrated into the cooling network. On the hot side storage for hot water was installed.

Figure 7-21 shows a scheme of the integrated heating and cooling system. With installation costs of 25,000 € a payback period of 2 years could be reached /Klima Jentzsch GmbH 2013; FORM + Werkzeug 2013/.

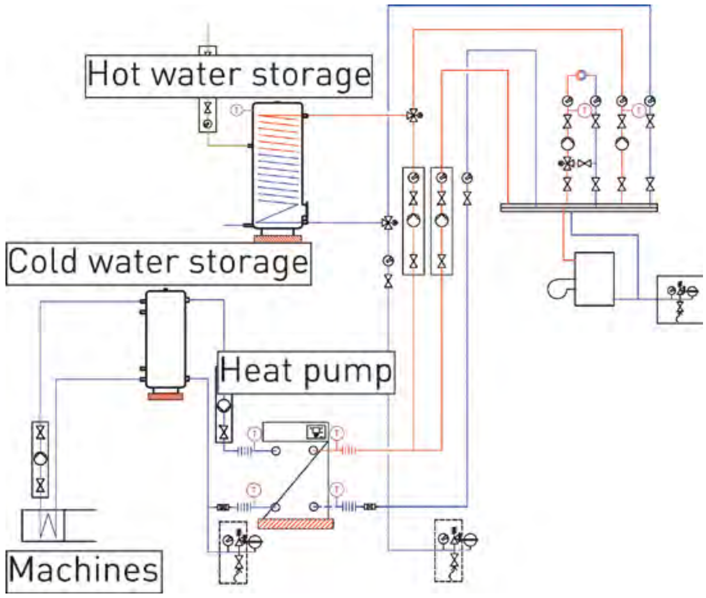


Figure 7-21: Integrated heating and cooling system at Gebr. Kemmerich GmbH /Klima Jentzsch GmbH 2013/

Table 7-13: Fact sheet for Gebr. Kemmerich GmbH

Industrial branch	Metal processing – tool manufacturing
Type of heat pump	Electric compression heat pump
Heating capacity	20 kW
Heat source description	Laser cutting, eroding and CNC machines
Heat source temperature	not specified
Heat sink description	Space heating
Heat sink temperature	60 °C
COP	3.7
Refrigerant	not specified
Investment cost	25,000 €
Operating since	2012
Payback period	2 years
Internal rate of return	50 %
Contact	Klima Jentzsch GmbH

7.10.8 Metal processing A (Flamm GmbH)

Flamm GmbH in Aachen is a manufacturer of precision wires for electronics industry and stamping and deep drawing parts for metal industry. The company was founded in 1982.

Today it employs 45 employees in three-shift operation. Production hall and warehouse have a total area of 8,000 m².

Different processes generate waste heat at 27 °C. It is used as heat source for a heat pump with a heating capacity of 230 kW. With a COP of 5 the heat pump lifts the temperature up to 55 °C and thus covers the entire heat demand of the company. The total investment amounts to 70,000 € with yearly savings of 22,000 €. This is reflected in the rather short payback period of 3.2 years and a large internal rate of return of 29 %.

Table 7-14: Fact sheet for Flamm GmbH /Schreier/

Industrial branch	Metal processing – Wires for the electronics industry
Type of heat pump	Electric compression heat pump
Heating capacity	220 kW
Heat source description	Process water
Heat source temperature	27 °C
Heat sink description	Space heating
Heat sink temperature	55 °C
COP	5
Refrigerant	R134a
Investment cost	70,000 €
Operating since	not specified
Payback period	3.2 years
Internal rate of return	29 %
Contact	Güstrower Wärmepumpen GmbH

7.10.9 Metal processing B (Ludwig Michl GmbH)

Ludwig Michl GmbH designs and manufactures metal products. With 80 employees the company processes 1,000 t of sheet metal per year and achieves an annual turnover of 9 to 10 million euro /Ludwig Michl GmbH 2013/. Motivation for a complete restructuring of the heating and cooling system was the acquisition of two new machines that needed to be cooled. Before the company installed a centralized cooling system each machine emitted its waste heat into the production hall. Especially in summers this lead to unpleasantly high air temperatures. The additional heat emitted by the new machines even lead to malfunctions in machine control units due to overheating.

When new machinery was procured in 2007 also a new centralized heating and cooling system was installed. The central unit of the system shown in Figure 7-22 are five absorption heat pumps, operated in parallel. Each of them has a heating capacity of 34 kW and a cooling capacity 16 kW and is equipped with a pump on both sides. These pumps for hot and cold water are controlled by the heat pump control system, which is connected to a higher-level control system via mod bus. The higher level system controls the distribution of heating and cooling. Cooling is supplied to two laser cutting and welding machines, to an edging machine, to a server room and the production hall. The heat sources are connected in parallel to ensure a supply temperature of 20 °C. A 3 m³ stratified cold water storage allows a decoupling of volume flows of the heat pump and the cooling circuit. The heat pumps can be switched on/off individually to adjust the cooling capacity. Hot water is produced at 60 °C to cover the heat demand of a chamber washing system and a hot air dryer. Both machines are connected in series as the dryer can also operate with lower temperatures. The chamber washing system, however, is very temperature dependent. If the temperature of the washing solution falls below a critical value, the solution starts to foam up. Like on the cold side volume flows of the heat pump and the heating circuits are decoupled by a 1 m³ storage. In case of a heat surplus, the heat can be emitted to the environment via an air cooler. To save space in the production hall, heat pumps, hot water storage and air cooler are housed in a sea container next to the building. As this container is neither heated in winter nor insulated sufficiently to inherently prevent freezing of the water circuits, the heat pumps are operated in an active anti-freeze mode in winter. The heating and cooling system is operated monovalent. Therefore system failures have to be patched immediately to prevent a production break down. By connecting the control system to an e-mail notification system staff is enabled to react quickly.

In the first months LPG was used to power the heat pumps. After the local gas supplier had connected the company to the gas network, the energy supply was switched to natural gas. The costs of 50,000 € for the extension of the gas network were covered by the local gas supplier. The investment costs for the integrated heating and cooling system amounted to 125,000 €. The Project was funded by Deutsche Bundesstiftung Umwelt (DBU) with 30,000 €. The payback period for the investment was 4 years. Compared to the old system up to 40 % of the CO_2-Emissions could be saved /Ludwig Michl 2007, Robur 2008; Lehnhardt 2008/.

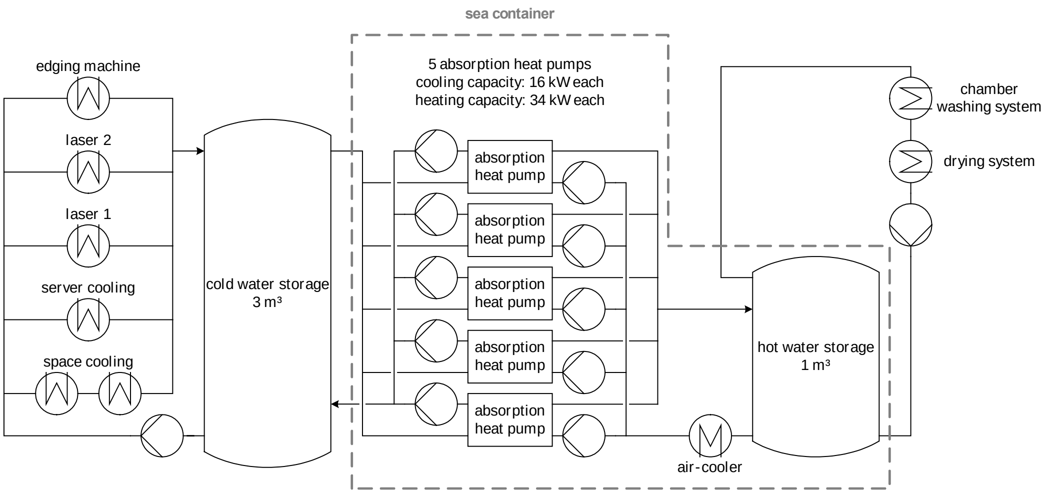


Figure 7-22: Heating and cooling system at Ludwig Michl GmbH

Table 7-15: Fact sheet for Ludwig Michl GmbH

Industrial branch	Metal processing – Sheet metal products
Type of heat pump	Gas absorption
Heating capacity	194 kW
Heat source description	Laser, server and space cooling
Heat source temperature	20 °C
Heat sink description	Washing process, drying process, space heating
Heat sink temperature	60 °C
COP	2,3 (integrated)
Refrigerant	R717 (Ammonia)
Investment cost	125,000 € (total investment)
Operating since	2007
Payback period	4 years
Internal rate of return	23 %
Contact	Ludwig Michl GmbH, Robur GmbH

7.10.10 Metal processing C (Purkart Systemkomponenten GmbH & Co. KG)

Purkart Systemkomponenten designs and manufactures metal products. In 2011 the company implemented a new integrated heat recovery system to reduce energy costs. Figure 7-23 shows a scheme of the new integrated heating and cooling network. Waste heat generated in production process is now used to cover the space heating and process heat demand. While waste heat from compressed air generation could directly be integrated into the heating network the temperatures of other heat sources are too low. Here a heat pump is used to upgrade the temperature to 60 °C to provide heat for space heating and industrial processes (e.g. phosphating and degreasing of metal parts). The heat pump extracts about 190 kW from a cooling network and cools down cooling water from 30 to 25 °C. Cooling is needed for a laser welding machine. To guarantee the cooling the old free cooling plant is kept as a backup system. In addition to the welding machine the exhaust gas from a curting oven is used as a heat source. The exhaust gas leaves the oven at temperatures of 200 to 300 °C. Formerly unused is it now condensed which raises the thermal efficiency of the oven to 99% based on the lower caloric value. In case there is no use for this heat can still be released by the old exhaust stacks. To buffer peak loads, a 16 m³ stratified storage is installed on both hot and cold side of the heat pump. Hereby heating and cooling demands are decoupled. The large volume of the tanks enables the system to run for 30 to 60 minutes without heat demand or supply. Monitoring and optimization of the plant performance could increase the operating time of the heat pump from 5 to 8 hours per day. Due to the high sensivity of the cooling of the laser welding machine hydraulic balancing had to be performed several times. The implementation of the heat recovery system now saves 33% of the total natural gas demand. Payback time for this system is expected to be 6 years assuming a return of 18% and an increase of energy prices of 3% per year /Preuß 2011; SAENA 2012; Brandenburg 2011/.

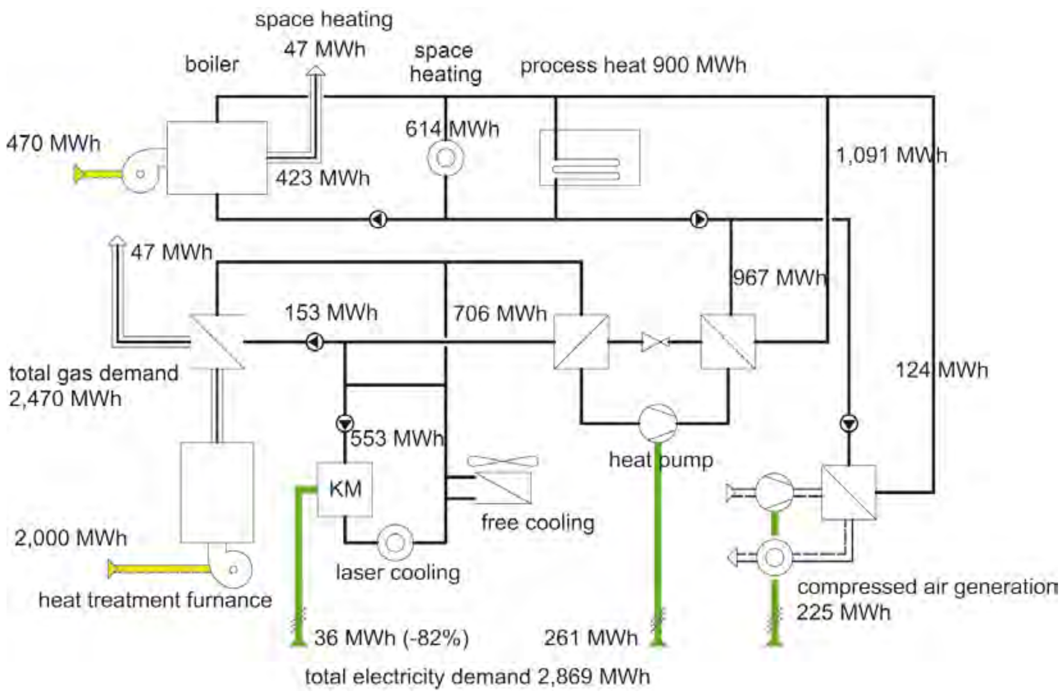


Figure 7-23: New heat recovery system with an integrated heat pump /Preuß 2011/

Table 7-16: Fact sheet for Purkart Systemkomponenten GmbH

Industrial branch	Metal processing – sheet metal products
Type of heat pump	Electric compression heat pump
Heating capacity	274 kW
Heat source description	Laser cooling and exhaust gas condensation
Heat source temperature	25 to 35 °C
Heat sink description	Space heating and process heat
Heat sink temperature	60 °C
COP	3.8
Refrigerant	R134a
Investment cost	570,000 € (for the whole system)
Operating since	2011
Payback period	6 years
Internal rate of return	15 %
Contact	FWU Ingenieurbüro GmbH, Combitherm GmbH

7.10.11 Metal processing D (Schraubenwerk Zerbst GmbH)

Schraubenwerk Zerbst is a producer of special screws with large diameters for rail fastening, wind turbines and other machinery. With 195 employees the company achieves a turnover of 38 million euro.

The production of screws starts with round rods that are pickled and degreased at first. An induction furnace heats the rods before a large press finally forms the screw head. The coils of the inductive furnace have to be cooled continuously. The cooling system supplies cooling water at 20 to 23 °C. The waste heat from the inductive furnace raises the temperature up to 25 °C. The cooling water is collected in a large basin before it is pumped to cooling towers that reject the waste heat to the environment.

To recover a large share of this waste heat (up to 436 kW) a heat pump system consisting of two heat pumps with a heating capacity of 292 kW per unit was installed. The heat pumps use the cooling water basin as heat source. To be able to adapt to heating and cooling demands the heat pumps are installed in parrallel. Therefore the heat pumps can adjust their heating capacity in 8 steps. To avoid an immediate circuit a special evaporator with a high contamination tolerance was designed. The heat pumps deliver hot water for space heating of production and administrative buildings. When there is not enough waste heat available (e.g. at weekends) a 300 kW gas boiler covers the heat demand of the building /Klima Jentzsch GmbH 2013; Schraubenwerk Zerbst 2013/.

Table 7-17: Fact sheet for Schraubenwerk Zerbst GmbH

Industrial branch	Metal processing – Screw production
Type of heat pump	Electric compression heat pump
Heating capacity	584 kW
Heat source description	Metal induction press
Heat source temperature	20 to 23 °C
Heat sink description	Space heating
Heat sink temperature	40 to 58 °C
COP	3,5
Refrigerant	not specified
Investment cost	180,000 €
Operating since	2011
Payback period	2 years
Internal rate of return	50 %
Contact	Klima Jentzsch GmbH

7.10.12 Metal processing E (Thoma Metallveredelung GmbH)

Thoma Metallveredelung GmbH is an electroplating company that offers a various surface treatments. The company is a very active driver for the rational use of energy in the electroplating industry. In a research project funded by Deutsche Bundesstiftung Umwelt (DBU) with 110.000 € a concept for a new energy saving hard chromium line was developed. Chromium plating is a technique of electroplating a thin layer of chrome onto metal objects. This is done by immersing the objects into a bath of chromium electrolyte. By applying direct electric current, chromium is plated out on the object´s surface. Usually only 20 % of the electric energy are used to create the chromium coating.

The remaining 80 % are converted into waste heat. As the electroplating process is very temperature-sensitive cooling has to be applied to the electroplating bath.

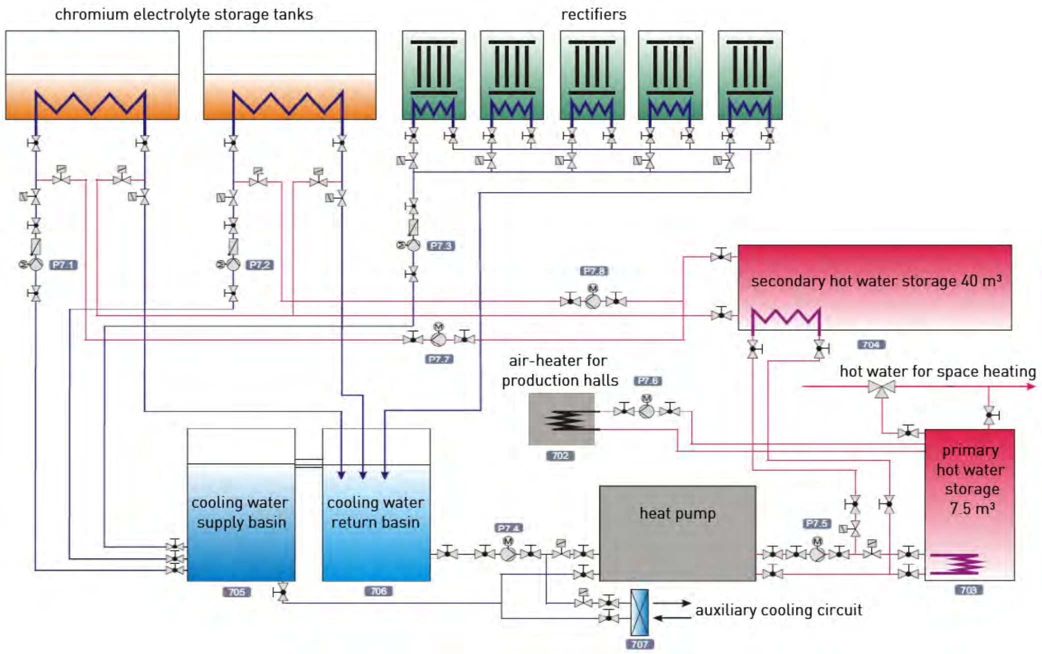


Figure 7-24: Circuit diagram of the heating and cooling system /Zimmer 2009/

Thoma Metallveredelung GmbH has increased the over-all efficiency of this process to more than 90 % by improving the electroplating process and integrating a heat pump to reuse the generated waste heat. By increasing the current density from 50 A/dm² to 90 A/dm² the efficiency of the electroplating process could be increased to 24 %. To maintain a good surface quality the temperature of the bath had to be raised to more than 60 °C. As the process still produces a large heat surplus, the electrolyte tanks as well as the current rectifiers are cooled by a water circuit. The cooling water returns to a collecting basin at a temperature of 60 °C. Because in the company there is no heat needed at 60 °C, the cooling water basin serves a heat source for a heat pump. The heat pump has a heating capacity of 143 kW and produces hot water at 75 to 80 °C. At this temperature level hot water is used for space heating and to supply others baths of the coating line. A 7.5 m³ storage serves as a buffer for space heating. Due to higher heating loads the process heat storage has a larger volume of 40 m³. Both heating and cooling system are operated bivalent. In case of a malfunction of the heat pump a groundwater well serves a heat sink for the cooling water, while an oil-fired heater covers the heating demand. The heat pump system covers 50 % of the heat demand and saves 150,000 l oil per year. Another positive effect of the new hard chromium line is significant process improvements. The coating hardness could be increased by 10%, while the plating rate could be increased by 80 %. For planning and implementation of the project experts from different engineering disciplines had to work together. The coordination of this work took a lot more effort than expected before. Nevertheless Thoma Metallveredelung GmbH is very satisfied with the result and plans to install similar heat recovery systems in their other coating lines. Furthermore the whole system was designed using standard components. In this way other electroplating companies can adapt the system without infringing property rights /Zimmer 2009, Zimmer 2010a, Zimmer 2010b; Hlavica 2010/.

Table 7-18: Fact sheet for Thoma Metallveredelung GmbH

Industrial branch	Metal processing – Electroplating
Type of heat pump	Electric compression heat pump
Heating capacity	143 kW
Heat source description	Process cooling
Heat source temperature	50 to 60 °C
Heat sink description	Space heating, process heat from bath heating
Heat sink temperature	75 to 80 °C
COP	3
Refrigerant	not specified
Investment cost	not specified
Operating since	2009
Payback period	less than 4 years
Contact	Thoma Metallveredelung GmbH

7.10.13 Metal processing F (Walter Th. Hennecke GmbH)

Hennecke GmbH is a metal processing company that offers a large spectrum of services from metal forming, surface treatment and welding to construction and logistics. In 2011 a new heat recovery system was installed. A 260 kW heat pump is the central element of this system. It provides cooling for 5 large CO_2 laser cutting machines that are operated all day long in three-shift operation. These machines have a power input of 80 kW each. More than 90 % of this power is turned into heat and has to be cooled. The five laser cutting machines together produce up to 375 kW heat at 27 °C. The heat pump provides a maximum cooling capacity of 180 kW and cools down the cooling water to 22 °C. It provides up to 260 kW heat at 65 °C to degreasing and phosphating machines. Two especially constructed stratified storages with a volume of 8,000 l buffer peak loads on the hot and the cold side of the heat pump. The old 400 kW gas heater is kept as an emergency reserve. The first months of operation showed that the heat pump could cover the entire heating demand at only 40 % load. To increase the operating hours the heat pump will also provide heat for showers and space heating for a newly built building with 1,400 m² of social and 2,500 m² of working space. In this final stage allows approximately 500 t of CO_2 to be saved /Hennecke 2013/.

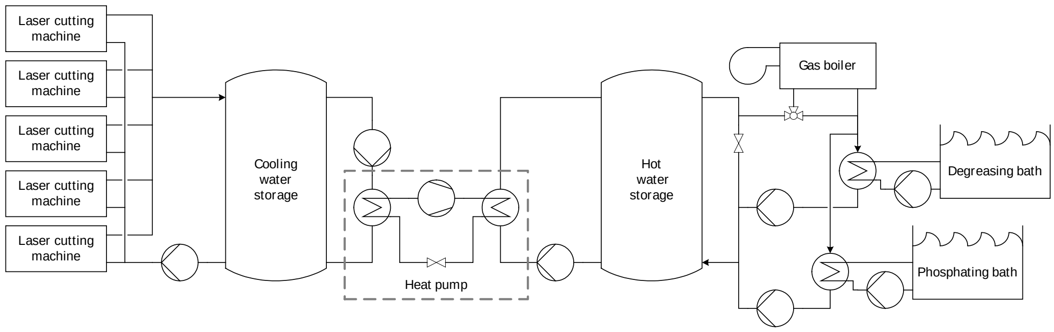


Figure 7-25: Integrated heating and cooling system at Hennecke GmbH

Table 7-19: Fact sheet for Hennecke GmbH

Industrial branch	Metal processing – sheet metal products
Type of heat pump	Electric compression heat pump
Heating capacity	260 kW
Heat source description	Laser cutting machine
Heat source temperature	27 °C
Heat sink description	Process heat for pretreatment for powder coating
Heat sink temperature	65 °C
COP	4
Refrigerant	not specified
Investment cost	85,000 € (heat pump only)
Operating since	2011
Payback period	3 to 4 years (whole system)
Internal rate of return	not specified
Contact	iQma energy GmbH & Co. KG; SmartHeat Deutschland GmbH; Henneke GmbH

7.10.14 Stone and earths (Treibacher Schleifmittel Zschornewitz GmbH)

Treibacher Schleifmittel GmbH is a producer of abrasives. The plant in Gräfenhainichen was acquired in 2001. Today the nearly 170 employees produce mainly zirconium oxide and corundum, which are needed for the production of abrasives or high temperature thermal insulations.

Reactive alumina is the basic compound for the corundum production. It is melted in an electric furnace that operates at 2,000 to 3,000 °C. The corundum is then cast into ingots. Once the ingots are cooled down, they are broken into smaller pieces. Further milling and sieving steps are necessary to achieve homogenous particle properties. Before packaging the corundum is mixed with additives and it is sieved for the last time.

To withstand the high process temperatures the electric furnace has to be cooled continuously. The cooling system is operating at 35 °C. Most of the heat is rejected to the environment by means of cooling towers. Since 2011 a small share of the cooling demand is covered by a heat pump with 80 kW cooling capacity. Due to impurities in the cooling water an immediate circuit was installed to protect the evaporator. On the hot side the heat pump provides heat for space heating at 60 °C. Two storages connected in parallel decouple heating and cooling demands. Figure 7-26 shows the integration scheme of the heat pump system. /Klima Jentzsch GmbH 2013/.

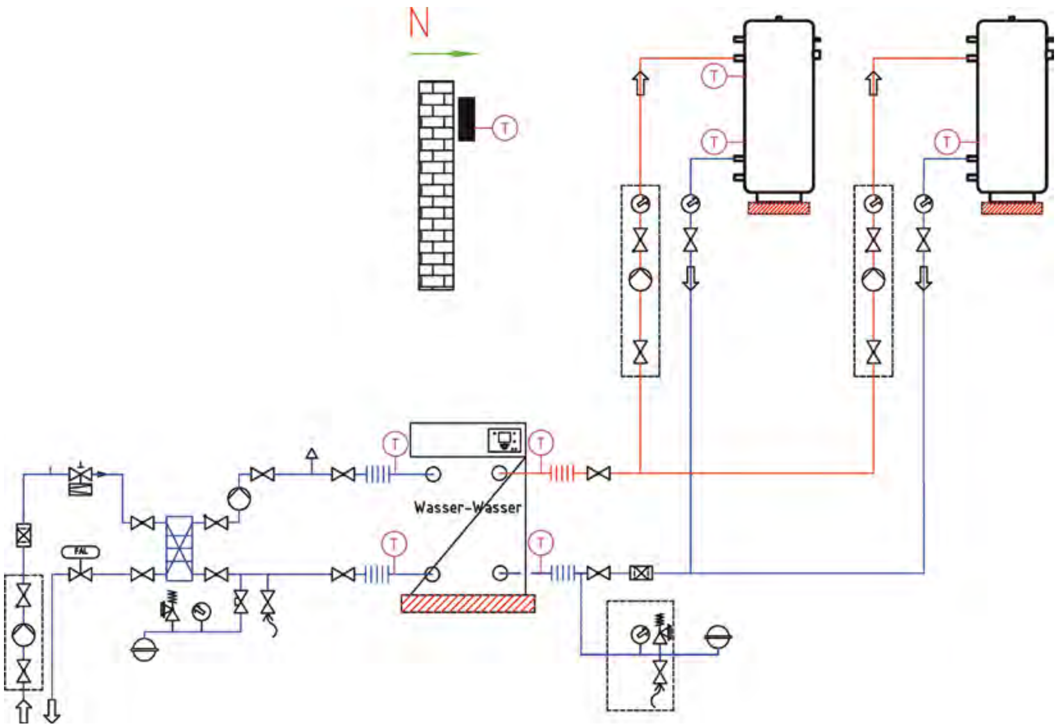


Figure 7-26: Integrated heating and cooling system at Traibacher Schleifmittel GmbH

Table 7-20: Fact sheet for Treibacher Schleifmittel GmbH

Industrial branch	Basic chemicals – Abrasives
Type of heat pump	Electric compression heat pump
Heating capacity	110 kW
Heat source description	Electric furnace
Heat source temperature	35 °C
Heat sink description	Space heating
Heat sink temperature	60 °C
COP	3.7
Refrigerant	not specified
Investment cost	72,760 €
Operating since	2011
Payback period	3.2 years
Internal rate of return	not specified
Contact	Klima Jentzsch GmbH

7.10.15 Food B (Tivoli Malz GmbH)

Tivoli Malz GmbH is holder of Global Malt GmbH & Co. KG and a mayor malt producer in Germany and Poland with an annual production of 400,000 t. At its production site in Hamburg the company installed a CHP plant in combination with a heat pump to lower energy costs. With an annual production of 105,000 t of malt the site accounts for more than one fourth of the company's production capacity /GlobalMalt 2013/.

Malt is a major ingredient for beer brewing. It is produced from cereal, which is left to germinate under humid conditions. The germination process is stopped by drying the germs in a kiln. This process typically needs a large amount of hot and dry air at 65 °C or above. Humid exhaust air is released at 28 °C. This waste heat stream can be used to preheat inlet air. This is usually carried out by means of recuperative glass tube heat exchangers. In addition to this branch technology standard Tivoli Malz GmbH integrated a heat pump to recover an additional amount of 2.7 MW waste heat. A very low temperature difference between heat source and heat sink leads to a high COP of 6. With Ammonia a natural refrigerant was chosen, because of its high volumetric capacity which results in a relatively little filling quantity and compact dimensions of the heat pump. The heat pump provides a heating capacity of 3.3 MW with about 6,000 operating hours at full load per year. Up to 3,000 l of water are condensed per hour. The inlet air is then further heated by a CHP plant that covers the total electricity demand of the production site. A gas powered auxiliary heater lifts the inlet air temperature up to 65 °C, before it enters the kiln /Mönch 2011; Tivoli Malz 2012; Brauwelt 2010/. The Project was funded with 340,000 € for 2.5 years by Deutsche Bundesstiftung Umwelt (DBU) /DBU/.

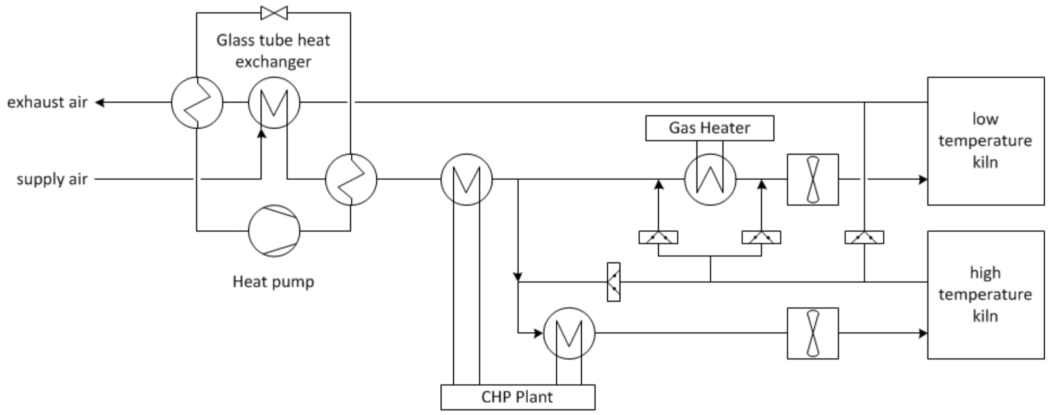


Figure 7-27: Process scheme of the energy supply for the kiln

Table 7-21: Fact sheet for Tivoli Malz GmbH

Industrial branch	Food – Malt production
Type of heat pump	Electric compression heat pump
Heating capacity	3,250 kW
Heat source description	Process exhaust air
Heat source temperature	23 °C
Heat sink description	Process heat for a kiln
Heat sink temperature	35 °C
COP	6.3
Refrigerant	R717 (Ammonia)
Investment cost	1,684,250 € (total investment for CHP, HX and heat pump)
Operating since	2010
Payback period	not specified
Internal rate of return	not specified
Contact	Tivoli Malz GmbH

7.10.16 Food A (Hanspeter Graßl KG)

Hanspeter Graßl KG is a small scale brewery that is marketing its beer under the brand name Schäffler Bräu in Missen.

Beer brewing is a multistage batch process. It is one of the most energy intensive production processes in the food industry. At first malt and water are heated in the mash pan. Stretch and enzymes are dissolved in the water. After the enzymes have turned the stretch into sugar the brew is heated up to 80 °C, which deactivates the enzymes. In the next step insolvable components are removed from the brew before it is cooked at 90 to 120 °C. A part of the water is evaporated in this step to concentrate the brew. After the cooking the brew is filled into fermentation tanks where yeast converts the sugar into alcohol. Since the fermentation process generates some heat the tank needs to be cooled to keep it at 5 to 15 °C. The temperature depends on the used yeast type. After the fermentation is completed the beer is filled into bottles.

In June 2012 the Schäffler Brewery installed a heat pump to recycle waste heat generated by the cooling plant and the bottle cleaning and filling plant. In case no waste heat is available the heat pump uses a ground water well as heat source. The heat pump system generates 200 MWh heat at 55 °C per year and covers about 80 % of the heat demand of a nearby restaurant and hotel. The investment cost of 31,667 € can be subdivided into the cost for the heat pump (26,667 €) and the cost for the heat exchanger (5,000 €). The payback period was calculated to be 6 years or less.

Table 7-22: Fact sheet for Hanspeter Graßl KG

Industrial branch	Food – Brewery
Type of heat pump	Electric compression heat pump
Heating capacity	77 kW
Heat source description	Waste heat from the cooling plant and the bottle filling plant
Heat source temperature	20 °C
Heat sink description	Space heating and hot water
Heat sink temperature	55 °C
COP	4.3
Refrigerant	R134a
Investment cost	31,667 €
Operating since	2012
Payback period	6
Internal rate of return	14 %
Contact	Arwego – Armin Schneider e.K.

7.10.17 Textile (PONGS Seidenweberei GmbH)

Pongs produces fabrics for technical and decorative purposes. Especially the dyeing of fabrics offers a large heat recovery potential. Exhaust air from the dyeing machine can be used as a heat source. In case of Pongs a special heat exchanger was designed to recover 110 kW heat for the 30 to 40 °C warm exhaust air. The heat pump delivers hot water for space heating at 50 °C with an average COP of 5.1. As the company is highly satisfied with the results, they already installed a second heat pump system for heat recovery /Klima Jentzsch GmbH 2013/.

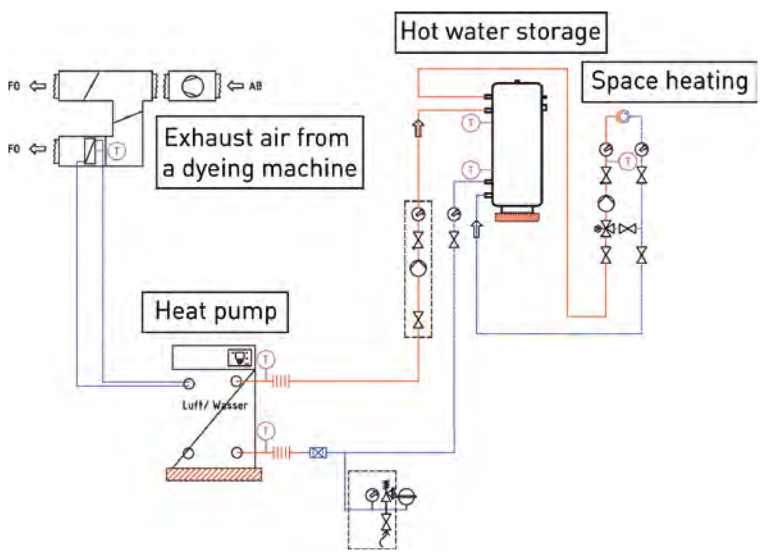


Figure 7-28: Air to water heat pump system at Pongs GmbH /Klima Jentzsch GmbH 2013/

Table 7-23: Fact sheet for PONGS Seidenweberei GmbH

Industrial branch	Textiles – printing and dyeing of textiles
Type of heat pump	Electric compression heat pump
Heating capacity	137 kW
Heat source description	Exhaust air from dying machine
Heat source temperature	30 to 40 °C
Heat sink description	Space heating
Heat sink temperature	50 °C
COP	5.1
Refrigerant	not specified
Investment cost	not specified
Operating since	2011
Payback period	not specified
Internal rate of return	not specified
Contact	Klima Jentzsch GmbH

7.10.18 Comparison and conclusion

The characterized heat pump systems show a wide range of application opportunities. Mostly industrial waste heat is used to generate heat for space heating. Therefore most heat pump systems generate heat at about 60 °C. The operation temperatures of the heat pump systems are given in Figure 7-29. The average heat source temperature is 28 °C. Heat source temperatures vary from 18 to 50 °C while the heat sink temperatures vary from 35 to 82 °C. The average heat sink temperature is 59 °C. The average temperature lift is 31 K. For one of the 17 examples data on temperatures was not complete.

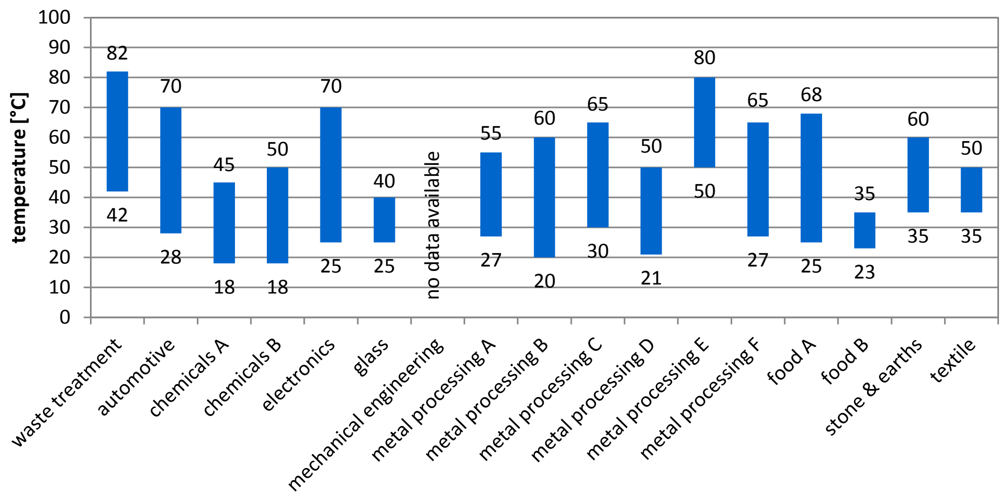


Figure 7-29: Operating temperatures of the surveyed heat pump systems

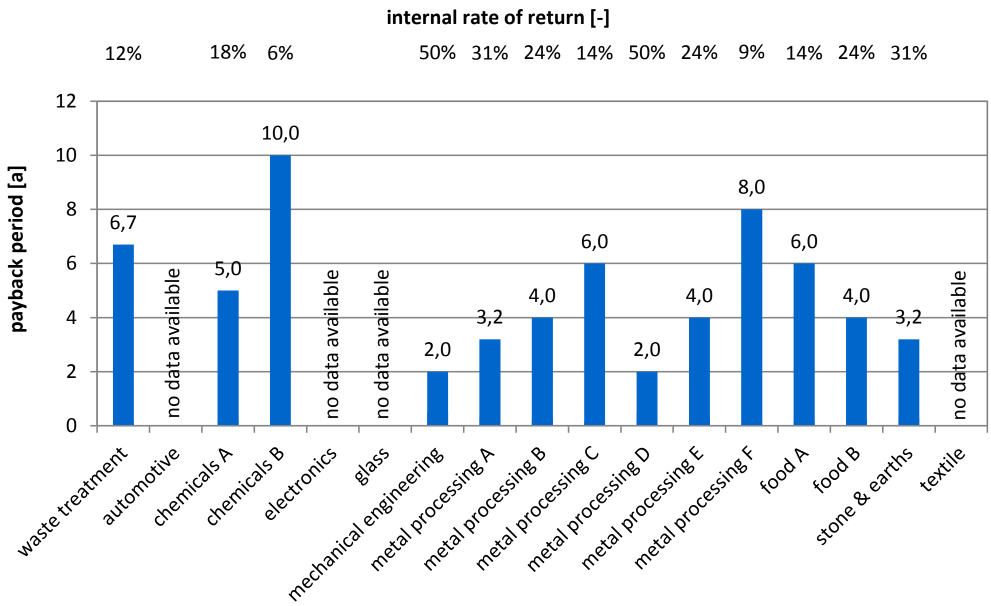


Figure 7-30: Economics of the surveyed heat pump systems

Economic data was just given by 13 companies, because it is often considered to be critical data. The documented payback periods are valid for the whole investment including peripheral components and planning and installation costs. Figure 7-30 gives an overview over payback periods of the documented energy efficiency measures. Payback periods vary from 2 to 10 years with an internal rate of return between 6 and 50 %. If looked at the internal return rate even a payback period of more than 6 years can be considered economical feasible.

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8 Japan

8.1 Introduction

In general, industrial heat pumps can be characterized by a high coefficient of performance (COP) achievable through the use of various types of exhaust heat, simultaneous supply of cold and hot energy, and long operating time through the year.

Heat pumps can be used for HVAC (heating, ventilation and air-conditioning), hot water supp supply, heating, drying, dehumidification and other purposes as shown in Table 8-1:

Table 8-1: Purpose of use of heat pumps

Purpose of use	Examples of application
HVAC	Factory HVAC, clean rooms, protected horticulture, plant factories
Hot water supply	Mechanical part washing, process liquid heating
Heating	Hot spring heating, snow melting, fish/eel farming, aquariums
Heating/cooling	Food manufacturing, electrocoating, plating, can manufacturing
Drying/dehumidification	Agricultural produce, marine products, printing, coating drying
Concentration/evaporation/distillation	Wort boiling, milk, sugar solution, amino acid
Heat recovery	Ethanol, cooling tower exhaust heat, rectifying tower exhaust heat

When heat pumps are used for industrial applications, the following considerations should be given:

- Clearly determine the temperature range and operating conditions of the heat utilization system
- Secure a good-quality absorption heat source, and pursue simultaneous usage of both heating (exothermic) and cooling (endothermic) as far as possible
- Supply heat at a proper temperature to the target process in a controlled manner
- Try to use the heat pump system in combination with a thermal storage system for effective operation

Figure 8-1 shows a chart of industrial heat pump applications:

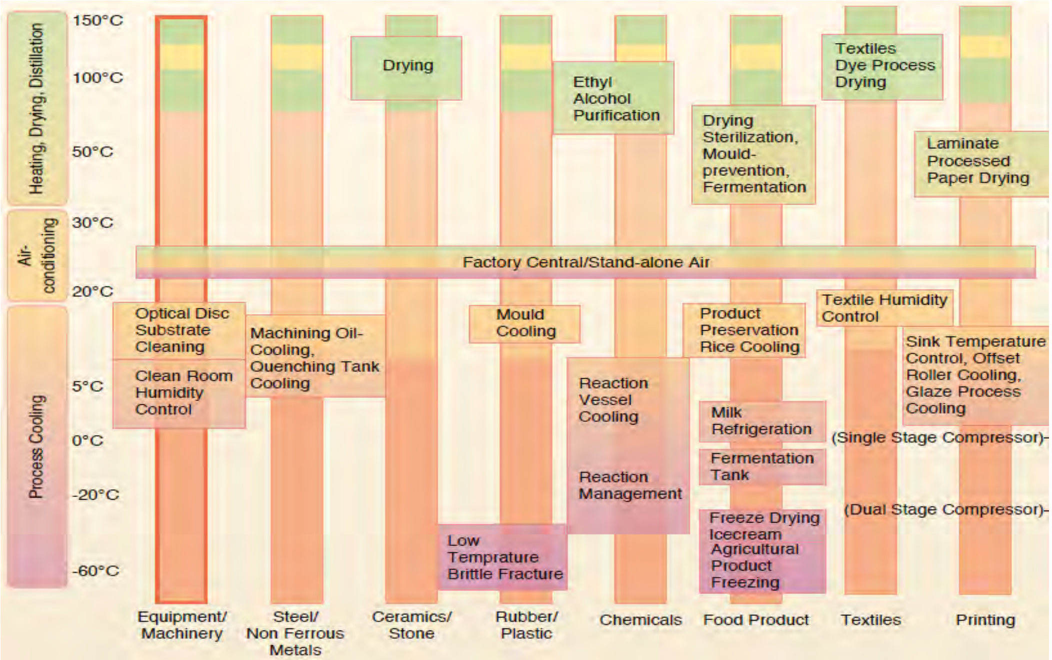


Figure 8-1: Industrial heat pump applications

Source: Masanori KANDO, Chapter 3, 'Examples of Application of Heat Pumps', Electro-Heat Handbook, "Recommended Electric-Powered Production Processes, Future Ages, Use More Electricity for Production", Japan Electro-Heat Center, 2010

Introducing heat pumps into the industrial sector can bring the following benefits:

1. “Steam reduction” by heat pumps

   - Factories generally use thermal energy in the form of steam. However, most manufacturers distribute steam from their energy center to individual production facilities through long steam piping. The steam system always involves heat loss from the piping and drain loss from the traps in addition to combustion loss in the steam boilers. It is said that only 30 to 50 percent of the steam generated in the energy center is effectively used.

   - Installation of a heat pump close to the place where heat is required can achieve more effective use of waste energy than the steam system.

   - Replacing conventional steam humidification of clean rooms with evaporative humidification (steamless) will save more energy than the steam system can do.

2. “Exhaust heat recycling”

   - Even exhaust heat, which has just been released to the atmosphere, can be collected and converted into higher-temperature thermal energy by heat pumps. Simultaneous cooling and heating with heat pumps will achieve substantial energy-saving.

3. "Thermal storage": Save heat and use it whenever necessary!
    - Storing cold and hot energy will allow supply of large amounts of heat at a constant temperature whenever necessary. Where both low- and high-temperature loads exist, the use of a simultaneous cold and hot water-producing heat pump in combination with cold and hot thermal storage tanks maximizes energy usage without wasting either.

Introducing heat pumps into the industrial sector can bring the following **economic** benefits:

1) Operating points of heat pumps

- A tip for successful operation of an exhaust heat recovery heat pump is to obtain a stable heat source. It is desirable that the heat pump can deliver thermal energy at a temperature as high as possible, and at a constant required flow rate.
- The temperature and flow rate of the hot water side are decided by the connected load. A hybrid system with boilers may be a good idea for better temperature control.

2) Operating condition

- With their high efficiency, heat pumps can bring benefits to running cost. A tip for maximizing the benefits is longer operating time (availability). Continual operation at as high efficiency as possible leads to a shorter payback period.
- Availability depends on the load balance between what is to be heated and what is to be cooled (exhaust heat). It is essential to design appropriate machinery and control systems that can be easily adapted to timing and variations (of temperature and flow rate) of both loads. If conditions are adequately satisfied, it would be possible to simultaneously produce cooling and heating energy, bringing substantial benefits.

3) Equipment and heat pump system

- The positional relationship between the loads to be cooled (exhaust heat) or heated and the heat pump substantially affects the initial cost of the overall heat pump system. If they are located close to each other, the piping system can be designed to be relatively small in scale.
- For some water quality or operating conditions, it may be necessary to plan supplemental devices such as indirect heat exchangers and thermal storage tanks. Careful preliminary discussion about coordination with existing equipment and overall system control is needed.

8.2 Examples of Recent Industrial Heat Pump Installation

We have many industrial heat pumps in practical use throughout Japan. Among the many installed cases, here we focus on heat pump technologies of simultaneous production of heating and cooling, vapor recompression, high temperature heat production and agricultural use because they are growing in sales and also expected further growth in the future.

In this section, 6 cases were picked out as typical examples of above mentioned prospective industrial heat pump technologies and their details, such as backgrounds of installation, system specifications and effects from economic and energy saving points of view, are explained.

A number of production processes require cold and hot water at the same time. A special feature of innovation surrounding the heat pump technology in recent years is a technology which can simultaneously produce hot water or hot air together with cold water effectively and easily. Good examples of the simultaneous cold water and 90 °C hot water production as well as the simultaneous cold water and 120 °C hot air production are shown in 8.3.1 and 8.3.3 respectively. In addition, chapter 8.3 explains an installation case of the heat pump system that can generate 65 °C circulating heating water and cooling water at the same time.

Effective use of less than 150 °C low-temperature waste heat still has much room to be developed. Vapor recompression systems are increasingly adopted to raise pressure and temperature of low-pressure vapor. However, when it comes to mechanical recompression systems, we have a problem of the large amount of power consumption. Therefore, an extensive use of the vapor recompression system has begun to be adopted by combining with the mechanical heat pumps. In relation to this, 8.3.2 is about the combined heat pump system of the mechanical and thermal vapor recompression reusing the low-pressure steam of 75 °C which is generated in distilling process. In addition, the adoption of heat pump systems with waste heat recovery is steadily growing in air-conditioning equipment. The 8.3.4 shows an example of the system for air-conditioning in 20 ~ 30 °C production processes.

Heat pump application in agriculture is one of the noteworthy features in recent years. The temperature and humidity control at a plant factory in ordinary commercial building is its good case example. However, residential heat pumps are mainly used for that purpose as the precise temperature and humidity control is strictly required and large heat loads are not necessary at most of the plant factories in Japan. On the other hand, in conventional outdoor greenhouses, the installation of heat pump systems is increasing as a replacement of heavy oil combustion boilers in accordance with increasing energy efficiency of heat pumps. The 8.3.6 shows the example for fruit cultivation which has high added values.

All the 6 cases picked out in this section succeeded in the great amount of reduction of energy consumption, running costs or CO_2 emission.

Appendix* is a factsheet that summarizes the cases from 8.3.1 to 8.3.5.

8.3 Examples of applications

8.3.1 Simultaneous hot/cold water producing heat pump for noodle-making

Background

Food processing consists of multiple processes at different temperatures such as cleaning, sterilization, boiling, cooling, freezing and drying. Traditionally, gas burners and heavy oil-fired steam boilers have been used as a heating source, and refrigerating machines have been used as a cooling source. Absorbing heat from the cold side and rejecting heat to the hot side is one of the most fundamental functions of heat pumps. If such absorbed heat and rejected heat produced by a heat pump are used simultaneously, the operating efficiency of the heat pump can be dramatically improved. To achieve this goal, heat pump systems that can produce hot and cold water simultaneously, and use them for cooling and heating, have been introduced in food processing plants. However, conventional compression heat pumps, which can only produce heat at around 60℃ at most on the hot side, can find only limited applications. Furthermore, the food processing industry faced an urgent problem of reducing heavy oil consumption, since the price of A-type heavy oil in Japan rose sharply from 2000 and reached a level as high as four times the 1999 price in 2008. Hence, a simultaneous hot/cold water producing heat pump capable of delivering water at 90℃ was developed, and is being introduced to sterilization and boiling processes in the industry.

Example of installation

8.3.1.1 Company Information

Location: Shikoku Island, Japan

Operation: Production of frozen noodles

Installed in: 2008

Purpose of installation: To reduce energy consumption for producing hot and cold water used in the noodle boiling process after noodle-making (80°C or higher), and the cooling process before freezing (around 5°C)

Production: Approx. 10,000 ton/year

8.3.1.2 Installed system

Frozen noodles are manufactured in production processes shown in Figure 8-2. The boiling process requires hot water not less than 80°C, which was traditionally supplied by steam boilers. The process is followed by a cooling process (5°C), which conventionally used a dedicated refrigerator.

Then, the noodle company introduced a heat pump that can produce hot water for the boiling process and cold water for the cooling process simultaneously. Figure 8-3 shows the flows of hot water, cold water and steam in the boiling and cooling processes. The process includes a steam boiler of 1500 kg/h, and two steam boilers of 1000 kg/h. There are two boiling pools having a capacity of about 3000L. The plant is operated over about 16 hours per day starting at 7 o'clock in the morning for about 250 days of the year.

Hot water (90°C) produced by the heat pump flows through a heat exchanger and is stored in a hot water tank. About 45 m^{3}/day of stored hot water (80 to 83°C) is delivered from the tank as demanded. The majority of the hot water in the tank is used to fill the boiling pools at the start of production in the morning. This helps reduce the peak load of the steam boilers. The boiling pools are reheated to the boiling temperature (98 °C) with steam from the steam boilers. The rest of the hot water in the tank is used to pre-heat the boiler feedwater. This brings benefits of lower steam boiler load as well as higher heat pump availability.

Cold water (5 °C) supplied by the heat pump is used to cool the additional water in the raw water tank (17 °C) for the cooling pools. This reduces the load of the refrigerating machine. Additional cooling to achieve the cooling temperature in the cooling pools (3 °C) is provided by the existing refrigerating machine.

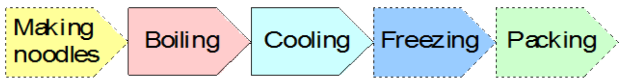


Figure 8-2: Production processes of frozen noodles

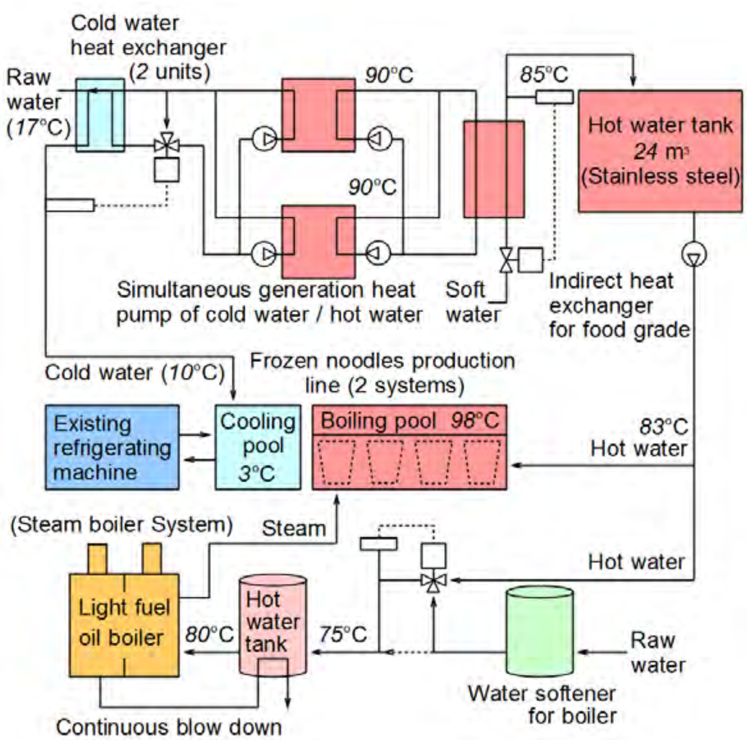


Figure 8-3: Heating and cooling system for producing frozen noodles

8.3.1.3 Specifications of heat pump

The appearance of the simultaneous hot/cold water producing CO_2 heat pump is shown in Figure 8-4. The heat pump specifications are listed in Table 8-2. The heat pump produces hot water through heat exchange between cold water, and CO_2 under supercritical pressure by the compressor. Cold water is used as a heat source for the heat pump evaporator to generate even colder water at the same time. The heat pump has a coefficient of performance (COP) of 3.0 on the heating side, and 2.1 on the cooling side. The total COP for simultaneous supply reaches 5.1.

Figure 8-4: Simultaneous generation CO_2 heat pump of cold water and hot water

Table 8-2: Specifications of CO2 heat pump refrigerator

Description	Specification
Heating capacity	71.9 kW/unit (20→90°C, 2 units)
Cooling capacity	50.1 kW/unit (10→5 °C, 2 units)
Power consumption	24.0 kW/unit (2 units)
Refrigerant	R744 (CO_2)
Compressor type	Reciprocating
Rated power of compressor	25 kW/unit (2 units)
Operating range	Delivery temperature of hot water 85 °C (3000 L/h) Delivery temperature of cold water 10 °C (5000 L/h)
Hot water tank	24 m^3

※Operating ranges are rated according to 17 °C entering-water temperature, 85 °C delivering-hot-water temperature, 10 °C delivering-cold-water temperature

8.3.1.4 *Effects of introduction*

Effects of introducing the simultaneous hot/cold water producing CO_2 heat pump are summarized in Table 8-3. The table compares the power required to produce hot water with the new heat pump against the required consumption of A-type heavy oil to produce the same amount of heat with steam boilers before installation of the heat pump. The hot water supply to the boiling pools from the heat pump reduces the heating load of the steam boilers, resulting in lower CO_2 emissions. The total CO_2 emissions reduction in the plant was estimated to be about 4 %. Placing importance on environmental performance, the company has introduced similar heat pump systems in three of its plants, other than this case, although the payback period is not short.

Table 8-3: Reduction of energy consumption and CO_2 emission (Only hot water supply)

Description		Heat pump installation	
		Before	After
Thermal balance of hot water supply	Additional light fuel oil without heat pump system [L/year]	93231	0
	Additional electric power with heat pump system [kWh/year]	0	307875
	Additional primary energy consumption [GJ/year]	3645	2965
	CO2 emission [t-CO_2/year]	253	100
Total energy balance	CO2 emission [t-CO_2/year]	325	185
	Initial cost for heat pump system[X10^3 Yen]	-----	45000
	Reduction of running cost [X10^3 Yen]	-----	5500
	Payout period of installation [Year]	-----	8.2

Conditions: Calorific valve - Light fuel oil: 39.1 MJ/L, Electricity: 9.63 MJ/kWh

CO_2 emission - Light fuel oil: 2.71 kg CO_2/L, Electricity: 0.326 kg CO_2/kWh

Unit price - Light fuel oil: 100 ¥/L, Electricity: 9.85 ¥/kWh

8.3.1.5 *Challenges and prospects*

Simultaneous supply of hot and cold water can enhance heat pump efficiency. However, the current heat pump system cannot deliver enough energy-saving to promote its introduction only from the viewpoint of energy efficiency. It is a must to improve performance and added value. The heat pump introduced in this case stores hot water during the night-time, and can deliver higher heating capacity during start-up in the early morning, allowing the steam boilers to be started up at a later time. One problem is that the heat pump has to be used as a preheating source for the steam boilers, because the upper limit temperature of hot water output is less than the 98℃ required by the boiling process. If a heat pump system with an even higher output temperature at a reasonable price were introduced into the plant, the production processes could be efficiently operated solely with the heat pump system, with an expectation for simpler facilities, safety achieved through electrification, and lower maintenance cost with no steam boilers.

8.3.2 Combined vapor re-compression system for alcohol distillation

Background

Steam boilers are popularly used as a heat source for production processes. Steam at lower pressure and temperature after use in production processes is usually released to the atmosphere. A vapor re-compression (VRC) system compresses pressure-reduced steam to regain the pressure and temperature suitable for the target production process. Japan promoted the introduction of VRC systems as an energy-efficiency technology after the oil crisis in the 1970's. Using VRC technology allows high-efficiency energy utilization. If there is a big difference in pressure between steam which is re-compressed and steam recycled for the process, however, more compression power is required. In some cases, electrical VRC cannot be introduced because of a receiving capacity limit of electricity. Therefore, as an attempt to expand VRC applications, a system which combines thermal vapor re-compression (TVR) and mechanical vapor re-compression (MVR) has been developed and is being introduced.

Example of installation

8.3.2.1 Company Information

Company name: Chita Distillery, Sungrain Ltd.

Location: Aichi Prefecture, Japan

Operation: Alcohol distillation

Installed: September 2002

Purpose of installation: To reduce the re-compression power for low-pressure steam recycled for heating of ethanol rectifying tower

Production: Distillation capacity 80 kL/day

8.3.2.2 Installed system

The company uses crude alcohol (95 % purity) and saccharine material to produce alcoholic beverage ethanol (not less than 95 % purity) and dehydrated ethanol (99.5 % purity) in production processes as shown in Figure 8-5. The production facility shown in Figure 8-6 used to consume as much energy as 10,000 kL/year in crude oil terms for 24-hour continual operation not less than 300 days a year. As shown in the illustration (a) of Figure 8-7, 95 vol.% ethanol solution with a condensation temperature of 78.3 °C was cooled and condensed at less than 75 °C to generate a large amount of hot water effluent at less than 75 °C, which was released to the atmosphere via a cooling tower. It was first attempted to modify the system as shown in Figure 8-7(b) so that ethanol condensation heat can be used to indirectly produce low-pressure steam, which can be re-compressed to have high pressure and high temperature for use as a heating source for the rectifying tower. In this VRC design, however, compression of low-pressure steam with an MVR system alone had a compression ratio of 3.5, which required a 700 kWh class motor. Finally the VRC design was suspended since the receiving capacity needed to be substantially increased to accommodate such a big motor. Another solution was therefore developed as shown in Figure 8-7(c). This new design includes a steam-driven TVR, which shares the heating boilers for the methyl tower, before the MVR to compress the vapor at a compression ratio of 1.7. The subsequent MVR further compresses vapor at a ratio of 2.1. The system can thus achieve vapor re-compression at a total compression ratio of 3.5. The MVR motor in this system consumes lower power than the previous design with MVR alone by 50 %. The company installed this system in one of its two distillation facilities with higher availability.

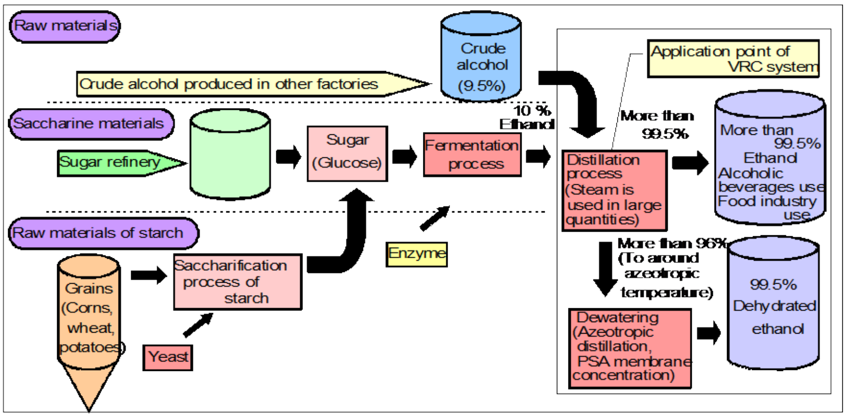


Figure 8-5: Alcohol production process

Figure 8-6:Appearance of rectifying tower

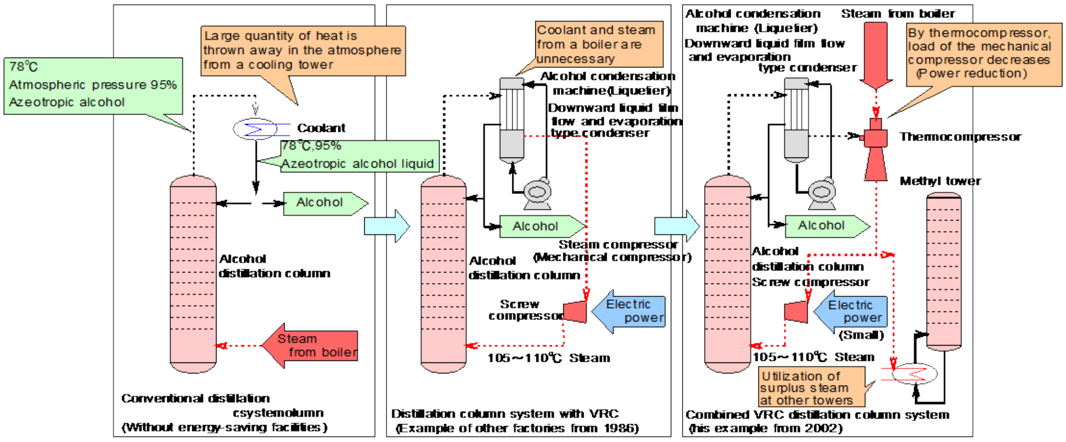


Figure 8-7: Applying RVC system to alcohol distillation process

8.3.2.3 Specifications of combined VRC system

Figure 8-8 and Figure 8-9 show the appearance of MVR and TVR which respectively make up the combined VRC system.

Table 8-4 shows the specifications of TVR and MVR. The MVR is installed after the TVR to make up the combined system. The TVR first compresses vapor at a compression ratio of 1.7, and then the MVR does the same at 2.1. The system can eventually deliver a compression ratio of 3.5 with both compressors.

Figure 8-8: Mechanical vapor re-compressor (MVR)

Figure 8-9: Thermal vapor re-compressor (TVR)

Table 8-4: Specifications of the combined VRC with MVR and TVR

Compressor	Description	Specification
TVR	Quantity of ejection steam	4.2 t/h
	Pressure of inhalation steam	0.039 MPa at 75°C
	Pressure of drive steam	1.5 MPa at 197°C
	Pressure of ejection steam	0.066 MPa at 88°C
MVR	Recovery quantity of steam	4.45 t/h
	Power consumption	350 kW
	Shaft power	250 kW
	Inlet pressure	0.066 MPa at 88°C
	Outlet pressure	0.137 MPa at 140°C

8.3.2.4 Effects of introduction

Table 8-5 shows energy consumption in crude oil terms and CO_2 emissions before and after introduction of the combined VRC system. The rectifying and methyl towers achieved a combined reduction of primary energy consumption and CO_2 emissions by 43%. The simple payout period is estimated to be three years.

Table 8-5: Reduction of energy consumption and CO_2 emission

Description		Installing combined VRC		Reduction effect [%]
		Before	After	
Primary energy consumption for steam [GJ/d]	Rectifying tower	338	218	▲56.3
	Methyl tower	161		—
Primary energy consumption for electric power [GJ/d]		0	68	—
Total primary energy consumption [GJ/d]		499	286	▲42.7
CO_2 emission [t- CO_2/d]		34.2	19.6	▲42.7

Conditions: CO_2 emission - Crude oil: 2.62 kg- CO_2/kL

8.3.2.5 Challenges and prospects

Combining TVR and MVR in the manner of this case can expand VRC applications, although both technologies were originally independent means to implement a separate VRC system. This combined VRC system has also been applied to beer breweries to recompress vapor from boiled wort. The system is expected to find application in other fields.

Combined systems are likely to involve higher design and installation costs, since their facility capacity and operating schedule often have to be adjusted on site for optimization. As more systems are installed, standardization and modularization may need to be considered.

8.3.3 CO_2 Heat Pump Air Heater for Drying Process

Background

A drying process is widely used in many production lines such as industrial material, chemical fertilizer, food and medical supplies, daily commodities, and so on. The drying operation and temperature depend not only on the physical properties or the condition of products, but also on the scale or the frequency of the process. As a way of shortening drying time, hot air at around 120°C is often used in the volatile dried type painting process. Boilers, burners or electric heaters were mainly used conventionally to generate hot air. If the heat source for the hot air is a heat pump which uses fluorocarbon as its refrigerant, applications were quite limited because the maximum output temperature of the heat pump was around 70°C. Then, heat pumps were developed to generate hot air up to 120°C with a CO_2 refrigerant, and have been gradually introduced to drying processes over 80°C.

Example of installation

8.3.3.1 Company information

Company name: Minami Electric CO., Ltd.

Location: Kagawa prefecture, Japan

Business: Manufacturing and painting of casings for electrical transformers

Amount of production: 35,000 units per year

Installed: September, 2009

Purpose of installation: reduction of fuel gas consumption for drying

8.3.3.2 Installed system

The painting and drying production process at the electrical transformer manufacturing factories is shown in Figure 8-10. Air circulated in the drying ovens after the electrodeposition process is heated up to about 170°C by LPG burners. The air circulated in the ovens after the top coating process is heated up to about 155°C. Partial ventilation is necessary to prevent the circulated air from contamination, which causes a decrease in the thermal efficiency of the facilities. In addition, exclusive chillers were used for keeping the temperature of the electro coating baths at 29°C. Hence, a heat pump that can pre-heat the fresh air and can assist cooling of the electro coating baths simultaneously and efficiently, was installed.

Figure 8-11 shows the flows of air and cooling water in the painting and drying system. Fresh air taken in from outside is first heated up to between 80 and 120 °C by the heat pump. After that, the air is heated further up to required temperatures by the LPG burners and used as drying air, as is shown in Figure 8-11. The pre-heating operation by the heat pump can provide a reduction of the heating load of the LPG burners. Water at 15 °C is supplied from the cold water tank to the evaporator of the heat pump as heat-source water, and is cooled. After cooling in the evaporator, cold water at 10° C returns in the reverse direction from the evaporator to the water tank.

This cooling action can reduce the chilling load of the chiller for temperature adjustment of the electrodeposition bath. If the cooling load of the electrodeposition bath is not sufficient to afford heat for the heat pump due to the low temperature of outdoor air in winter, it is designed to be able to recover waste heat from an air compressor as a supplemental heat source.

Figure 8-10: Painting and drying processes

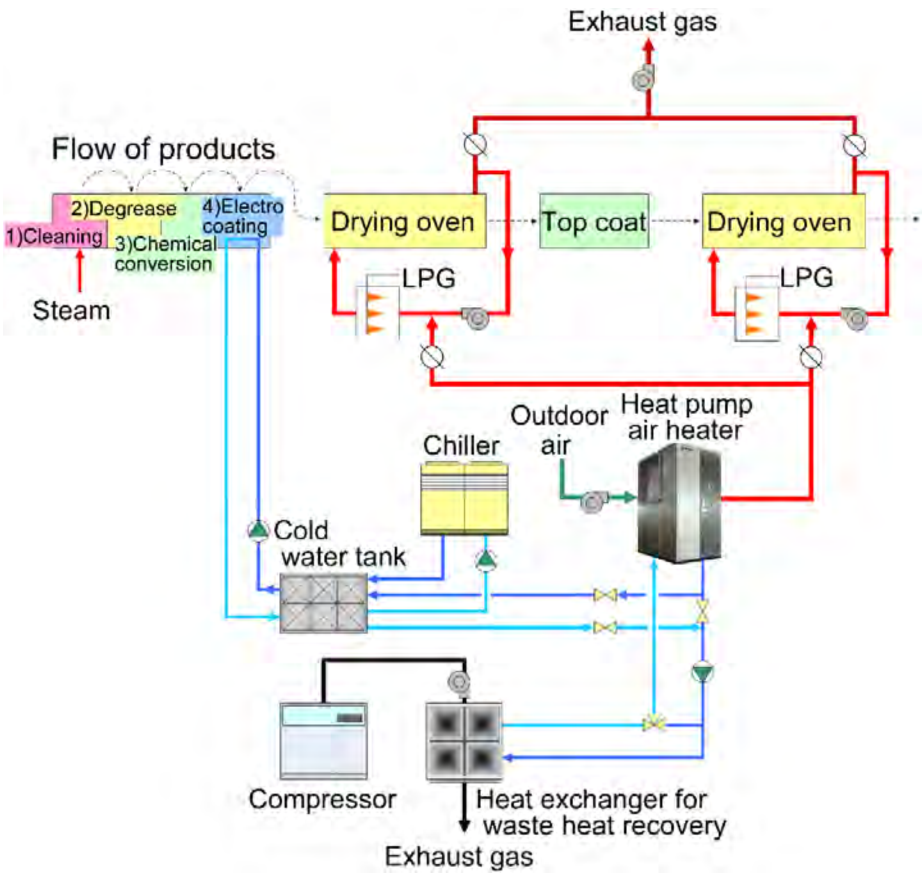


Figure 8-11: System flow diagram of drying process in painting application

8.3.3.3 *Specification of heat pump*

The specifications of the CO_2 heat pump air heater are listed in Table 8-6. Hot air is generated by heat exchange between supercritical CO_2 produced in the compressor, and fresh air for drying. Cold water can be simultaneously generated because the heat source of the heat pump is water. If there are demands for both hot air and cold water, the total COP can be further increased. Figure 8-12shows the relationships between the outlet temperature of the heat-source water, the heating capacity, and COP for heating when the inlet temperature of the fresh air is 20°C. Figure 8-13 shows the relationship between the outlet temperature of the heat-source water and the airflow rate. The heat pump system on site is shown in Figure 8-14.

Table 8-6: Specification of CO2 heat pump Air Heater

Description	Specification
Heating capacity	110 kW
Refrigerating capacity	35 kW (9.1 Refrigeration Tons)
Power consumption	32 kW
Refrigerant	R744 (CO_2)
Compressor type	Semi-Hermetic, Reciprocating, Two cylinders
Rated power of compressor	25 kW
Operating range	Delivery temperature of hot blast 80~120°C Delivery temperature of heat source water -9~35°C
Capacity control	Rotation control with inverter (30~65 Hz)
Dimensions	W1100×L1600×H2223 mm
Weight	Product weight 1948 kg （Operat

※Capacities are rated according to 20 °C entering-air temperature, 100 °C delivering-hot-blast temperature, 25 °C delivering-water temperature of heat source

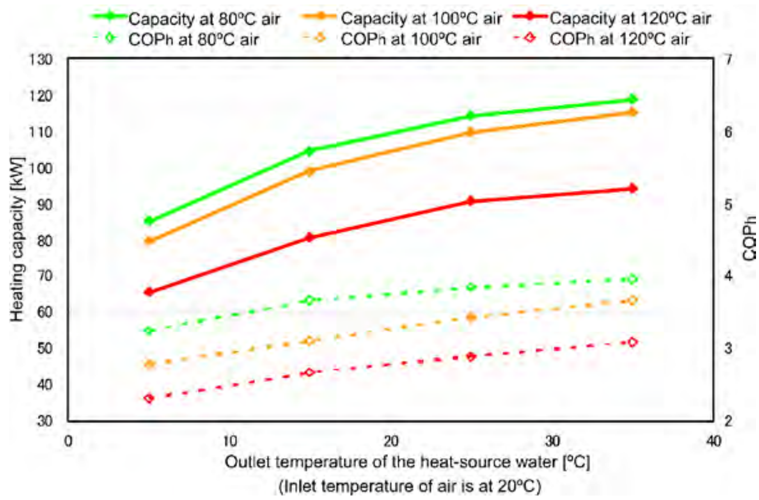


Figure 8-12: Relationships among the outlet temperature of the heat-source water, the heating capacity, and COP_h

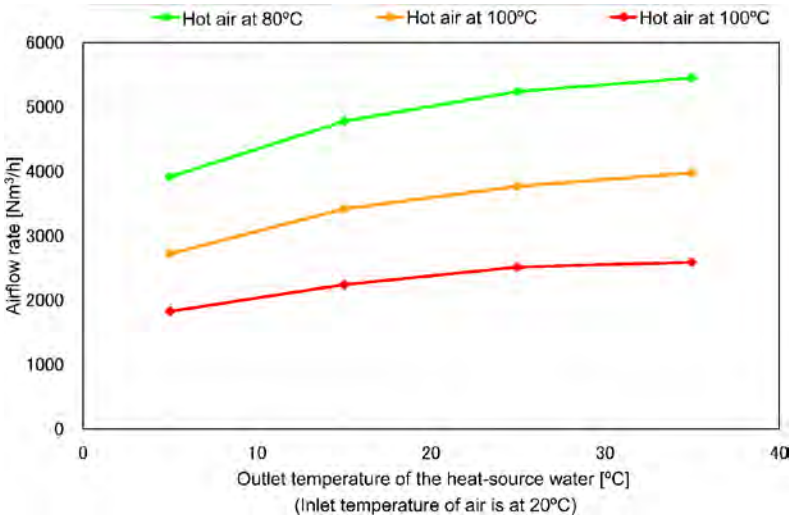


Figure 8-13: Relationship between the outlet temperature of the heat-source water and the air-flow rate

Figure 8-14: CO_2 heat pump air heater installation

8.3.3.4 Effect of introducing heat pumps

Energy consumption in the process before and after installation of the heat pump drying systems was measured to verify the effect of the installation. Conventional systems without heat pumps were measured on 7 and 8 December 2009, and the new heat pump systems were installed on 9 and 10 November 2009. Table 8-7 shows the results of the measured consumption of fuel gas and electric power. Energy consumption based upon primary energy equivalent was reduced by 3.0%, and the running cost could be reduced by 12%. Cold water in the tank is also used for cooling products after the drying process. Thus, the energy saving effect was improved by using the cold water and hot air more effectively.

Table 8-7: Reduction of energy consumption and CO2 emission

Description	Heat pump		Reduction effect [%]
	Not operated	Operated	
Operating time of drying furnace [h]	29.9	30.1	–
Gas consumption [Nm^3]	509.0	389.0	–
Average gas consumption [Nm^3/h]	17.0	12.9	▲24.1
Average electric energy consumption [kWh/h]	0.0	35.3	–
Primary energy consumption [GJ/h]	1.65	1.60	▲3.0
CO_2 emission [kg-CO_2/h]	103.7	90.2	▲13.1
Running cost [%]	100	88	▲12

Conditions: Performance of chiller for electro coating bath - Refrigerating capacity: 33.5 kW, Power consumption: 12.6 kW

Calorific valve - LPG: 97.0 MJ/Nm^3 (Density: 2.03 kg/Nm^3),

Electricity: Day 9.97 MJ/kWh, Night 9.28 MJ/kWh

CO_2 emission - LPG: 3.000 kg CO_2/Nm^3, Electricity: 0.326 kg CO_2/kWh

Unit price - LPG: 83 ¥/kg, Electricity: 9.85 ¥/kWh

8.3.3.5 Prospects

The efficiency of the CO_2 heat pump increases by operating with a large temperature range which includes the supercritical state of CO_2. In this installation example, the heat pump is used as a pre-heater because the required temperature of the drying air is higher than 120 °C. If the required temperature is lower than 120 °C, it would be possible to operate heat pumps alone, which also enables us to simplify the equipment and make it safer by using only electricity. Another possibility is to reduce the maintenance cost by using a boiler-less system if heat pumps could replace any steam heating system in the drying process.

8.3.4 Adoption of Heat Pump Technology in a Painting Process at an Automobile Factory

Background

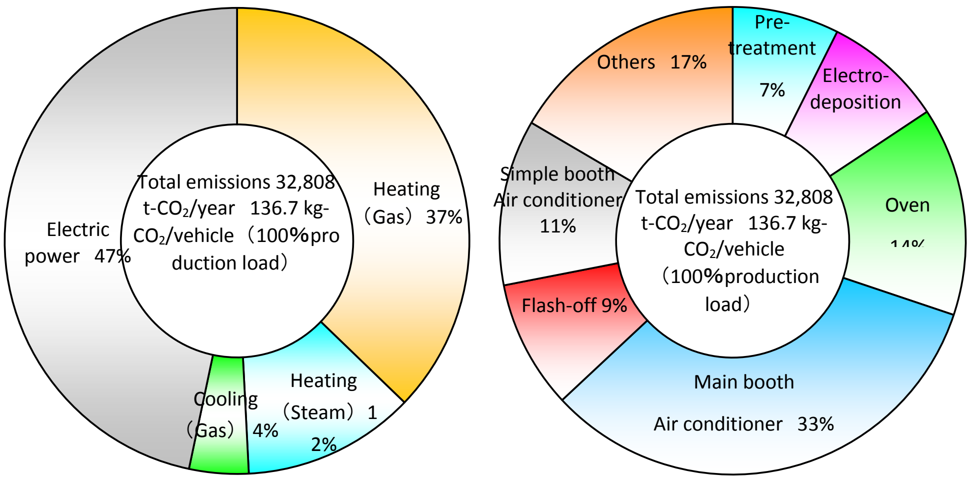
In a painting facility of an automobile factory, a great deal of energy is consumed by heating and cooling processes, the power supply, system controls, lighting, and so on. Generally, most primary energy sources are gas and electricity. Most heating and cooling needs in a painting process are supplied by direct gas combustion, steam, hot water, and chilled water generated by a refrigerator, most of the primary energy for which is gas.

In terms of energy efficiency ratio, electrical energy was believed to be lower in energy efficiency than gas energy, because electrical energy uses only around 40% of input energy while gas energy is able to use almost 100 % of direct gas combustion.

However, heat pump technology has greatly improved, and the energy efficiency ratio is increasing accordingly, so highly efficient heat pumps have been introduced also into industrial processes in recent years.

On an estimation basis, CO_2 emissions by heating gas were almost the same level as electric power in a painting facility model line where 24,000 cars a year were produced at an automobile factory in 2009 (Figure 8-15). Gas is mostly utilized as a heating source. If it is replaced by a highly energy-efficient system, it will save energy and reduce CO_2 emissions.

Further, according to CO_2 emissions by process, a large amount of emissions are from paint booth air conditioners which account for over 1/3 of the total.



a) Energy consumption by type (CO_2 basis) b) Emissions by process

Figure 8-15: CO_2 emissions in a Painting Process (estimated in 2009)

Figure 8-16 shows each process and its required heat temperature range in a painting process at an automobile factory. There are three main advantages which we can gain from heat pump technology. The first is the heat recovery system, the second is efficient heat source equipment, and the third is simultaneous usage of cooling and heating, which is believed to be the most efficient usage.

Simultaneous usage of heating and cooling can be applied to processes of pretreatment/electro-deposition, booth/working area air conditioning, and waterborne flash-off equipment. Hence, adoption of heat pump technology in this equipment is considered. The highest effect from adoption of heat pump technology in these cases is in booth recycled air conditioning and waterborne flash-off equipment.

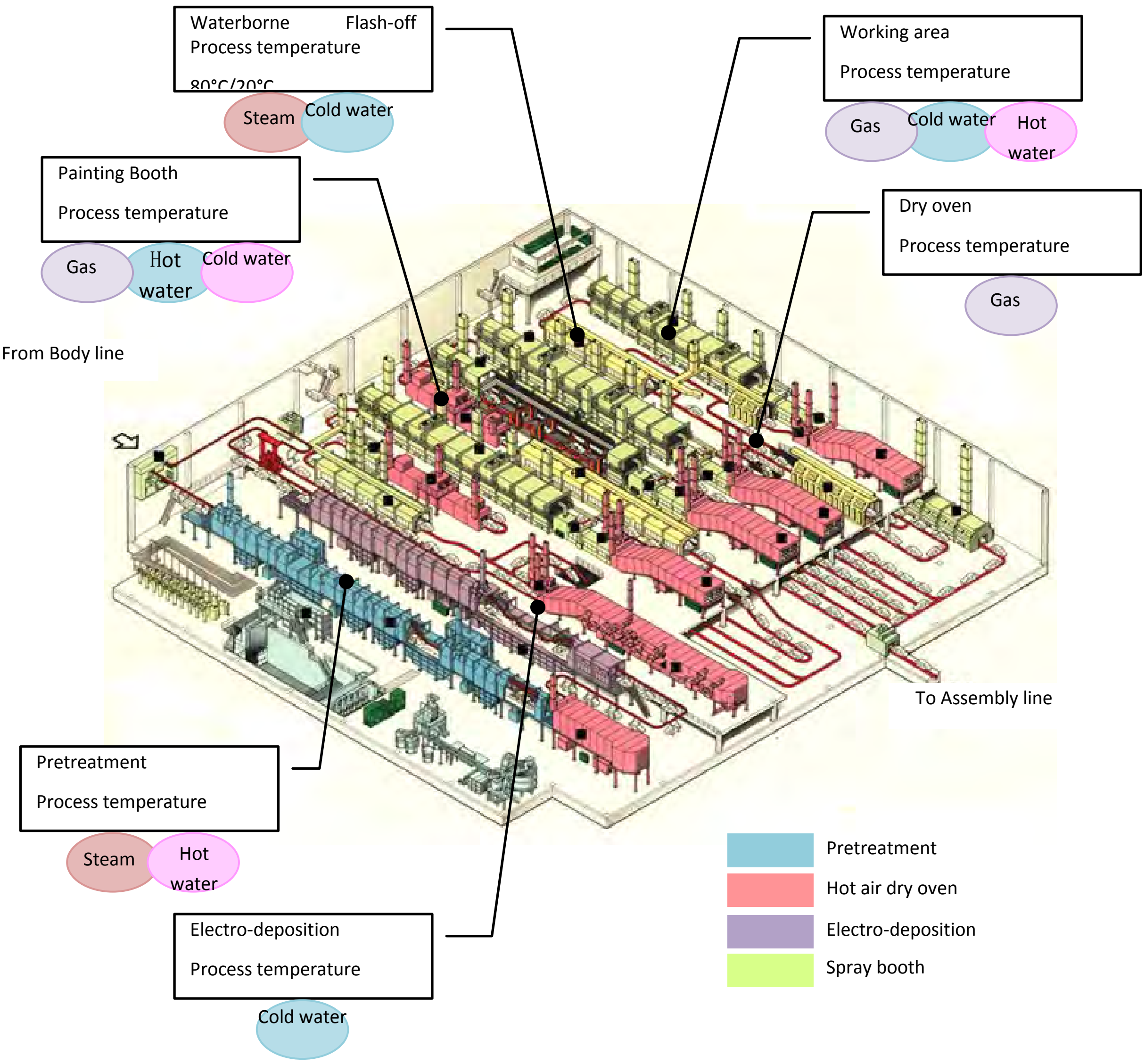


Figure 8-16: Required heat temperature ranges in a general automobile painting process

In this paper, heat pumps for booth recycled air conditioning are discussed along with energy conservation and reduction of CO_2 emissions.

Example of application

8.3.4.1 Company information

1 Place	Hino Motors, Ltd., Hamura No. 4 plant
2 Annual operating hours	4,880 hrs/year
3 Installed processes	Painting booth for finishing coat (base) and recycled air conditioning

Hino Motors, Ltd., is aiming to reduce CO_2 emissions on a company-wide level, and they paid attention to the painting process which occupied 40% of total CO_2 emissions in the Hamura plant in 2010. Three companies, i.e., Hino Motors, Ltd., an engineering company [1)] and an energy company [2)] shared their knowledge about painting technology - knowledge of automobiles from Hino Motors, design of the painting plant from the engineering company [1)], and efficient exploitation of energy from the energy company [2)], and successfully "adopted heat pumps as a heat source for painting (finishing coat) booth air conditioning".

8.3.4.2 Installed system and specification of heat pump

The paint booth consists of two booths - one is a manned booth where fresh air is supplied. And the other is a robot booth where exhaust air is re-used. As a mist of fine paint is contained in exhaust air from the manned booth, the air inside can be re-used via wet cleaning by using a circulating water shower, which is called the wet recycle system. Because the booth’s exhaust air is humidified via wet cleaning, the air is supplied to the robot booth with adjusted temperature and humidity after being dehumidified, and reheated in the recycled air conditioner. A schematic of the heat recovery heat pump system, its specification, and a photograph are shown in Figure 8-17, Table 8-8 and Figure 8-18 respectively.

Conventionally, the heat source system of a recycled air conditioner in the paint booth consists of a gas absorption refrigerator and a boiler. The recycled air conditioner was cooled by the gas absorption refrigerator, and reheated by boiler steam. In the meantime, the heat recovery heat pump enables us to supply both the heat for cooling and reheating concurrently. This modified system is provided to ensure system reliability and lower carbon emissions by utilizing existing equipment, such as the gas absorption refrigerator and the boiler, and also for backup purposes.

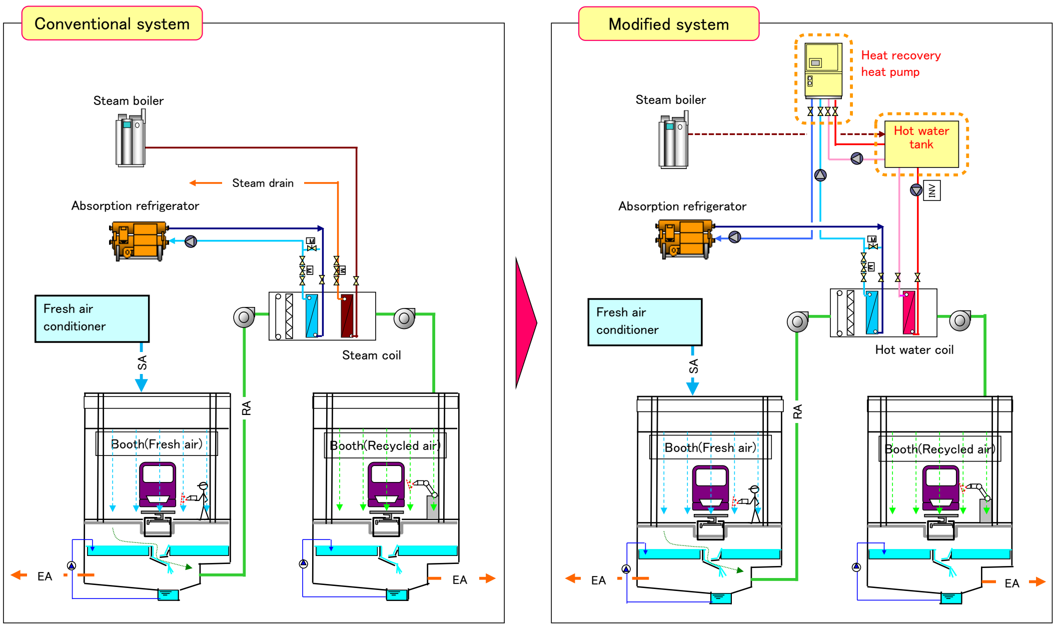


Figure 8-17: Schematic of painting system

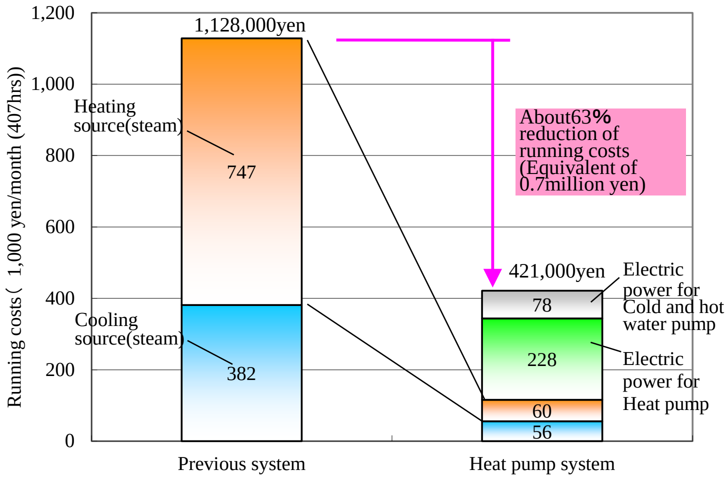
Table 8-8: Heat recovery heat pump specification

<table>
<tr><td colspan="2">Type</td><td>HEM-150 II</td></tr>
<tr><td colspan="2">Cooling capacity</td><td>456 kW</td></tr>
<tr><td colspan="2">Heating capacity</td><td>566 kW</td></tr>
<tr><td colspan="2">Refrigerant</td><td>HFC407E</td></tr>
<tr><td rowspan="3">Compressor</td><td>Startingsystem</td><td>Inverter</td></tr>
<tr><td>Type</td><td>Semi-hermetic Twin-screw</td></tr>
<tr><td>Input</td><td>110.1 kW</td></tr>
<tr><td rowspan="2">Rated COP</td><td>Cooling</td><td>4.14</td></tr>
<tr><td>Heating</td><td>5.14</td></tr>
<tr><td colspan="2">Quantity</td><td>1</td></tr>
</table>

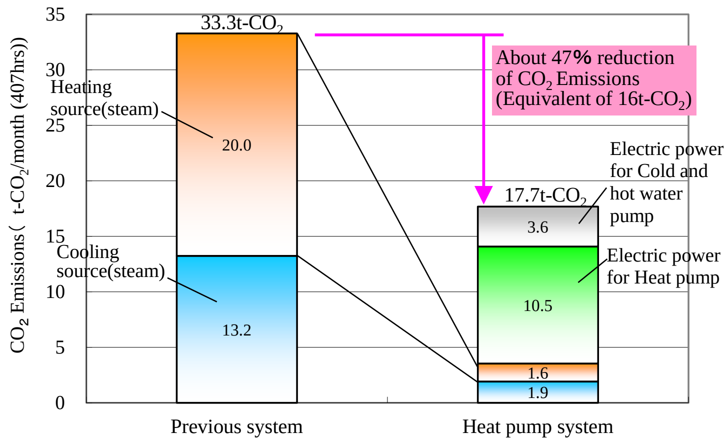
Figure 8-18: Heat pump equipment

8.3.4.3 Effect of introducing heat pumps

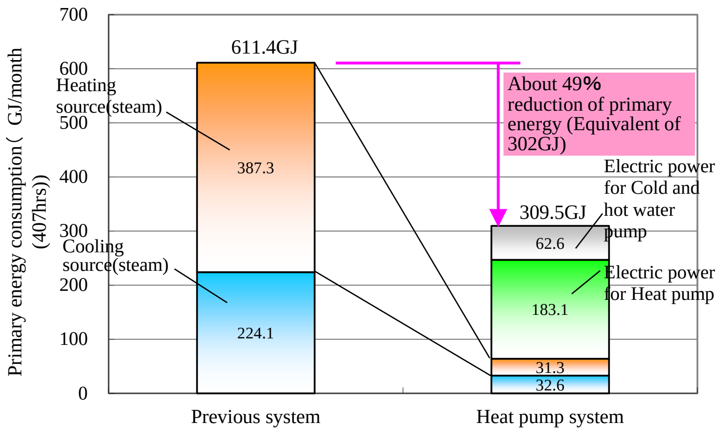
An estimation based on the measurement results on site after installation is shown in Figure 8-19. The heat pump makes it possible for the system to reduce running costs by about 63%, to reduce CO_2 emissions by about 47% per month, and to reduce primary energy consumption by about 49% per month as compared with the conventional boiler. Consequently, the pay-back period would be estimated at 3～4 years.



a) Running costs



b) CO_2 emissions



c) primary energy consumption

Figure 8-19: Effect of Adoption

8.3.4.4 Prospects

It was considered to utilize the existing boiler steam for the imbalance between cooling and heating loads when starting up the booth in winter. They have also installed a hot water tank so that they can have a heat source for providing steam directly.

In case of adopting a heat recovery heat pump system, it is common to install a cooling tower and for keeping the balance between cooling and heating loads. But in this case, they did not install a cooling tower, and instead utilized the existing refrigerator, aiming at the reduction of investment cost.

The adoption of heat pumps in recycled air conditioning is a case where full use was made of the heat pump's strengths - the good effects of installation, and easy introduction into the existing system - and it has well fitted the purpose of CO_2 reduction. When introducing heat pumps, it is indispensable to bring all the companies involved together. In this case, it was a collaboration between an automobile company, an engineering company, and an energy company.

References:

1. Taikisha Ltd. http://www.taikisha-group.com/
2. Tokyo Electric Power Company http://www.tepco.co.jp/en/index-e.html

8.3.5 Heat pumps for washing process

Background

Mechanical part manufacturing plants have a cutting process followed by a washing process where washing liquid is heated by an electric heater or hot steam from boilers to around 60°C (Figure 8-20). On the premises of some plants, the boiler room is located far from the building in which the washing process is installed. In this case, not only combustion loss and drain recovery loss but also huge heat loss from the steam piping substantially lowered total efficiency. To solve the problem, many of these plants desired to install high-efficiency heating equipment near the washing process for energy saving. However, a high-efficiency, oil mist resistant heat pump capable of delivering 60°C heating for production processes did not exist at that time. In this type of plant, the room temperature is higher than the outside air temperature because of heat generated by various devices within the plant. Thus, it is possible to implement a high-efficiency heat pump heating system using the air in the plant as a heat source. In the cutting process, cutting liquid was conventionally cooled by a small chiller. Exhaust heat from the chiller was released to the atmosphere, which further raised the ambient temperature in the plant. There was no system that used the cooling process exhaust heat for heating of the washing liquid as well. Then, General Heat Pump Co., Ltd. and Chubu Electric Power Co., Inc. jointly developed a heat pump for the washing process that could efficiently circulate and heat washing liquid used in the mechanical part washing process by using the exhaust heat in the plant.

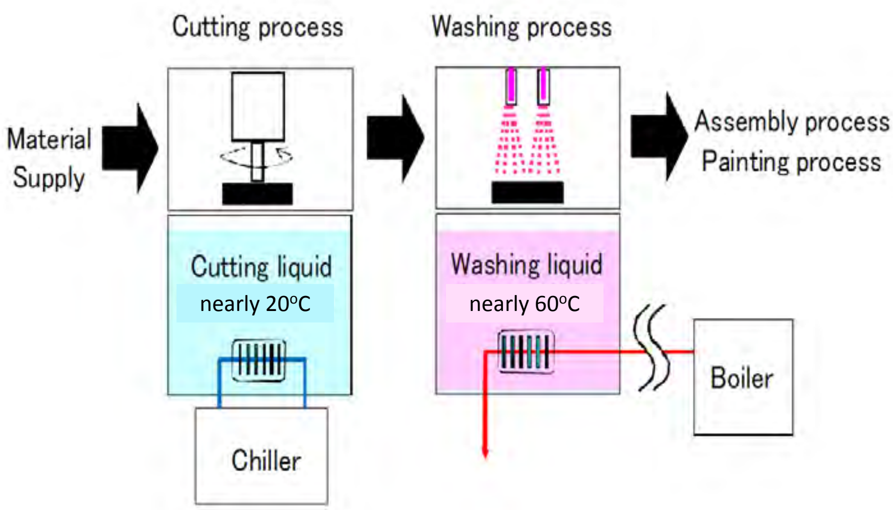


Figure 8-20: Cutting process and washing process

Example of application

8.3.5.1 Installed system and specification of heat pump

Figure 8-21 shows the appearance of the heat pump for the washing process. There are two types of heat pumps for a washing process: heating only, and cooling/heating. Table 8-9 shows the basic specifications of cooling/heating type heat pumps. Although not shown in Table 8-9, the heating-only heat pump has the same specifications (heating capacity, electric consumption and heating COP) as those of the cooling/heating type, except that the heating-only type cannot deliver cooling, and is slightly lighter than the cooling/heating type because it has no heat exchanger for water cooling.

In a popular mechanical part cutting process, cutting liquid is cooled and the temperature is maintained at around 20°C. After the cutting process, mechanical parts are subjected to a washing process where washing liquid is heated and the temperature is maintained at around 60°C. The heat pump for the washing process can simultaneously deliver heat energy of not less than 60°C for heating the cooling liquid, and cold water at 15°C suitable for cooling the cutting liquid. This simultaneous heating and cooling supply can only be achieved by absorbing the heat released during cooling of the cutting liquid, and then re-using the heat for heating of the washing liquid. The heat pump can use a refrigerant (R-134a), whose performance has been proven in large refrigerators and vehicle HVAC applications, to deliver high-efficiency circulation heating for the mechanical part washing liquid (washing liquid inlet temperature 60°C and outlet temperature 65°C). Further, as a countermeasure against oil mist that is generated in the cutting process and may lead to lower heat pump efficiency, a filter is installed in the heat exchangers so that the heat pump can be installed near the washing process (within the plant building). Figure 8-22 shows a proposed installation of cooling/heating type heat pumps. A desirable operation mode can be selected from simultaneous cooling & heating, cooling only and heating only to support any combinations of cutting liquid cooling, and washing liquid heating.

Figure 8-21: Heat Pump for Washing Process

Table 8-9: Specification of Heat Pumps for Washing Process

Heating※1	Capacity	22.3 kW	43.5 kW
	Electric Consumption	7.5 kW	14.8 kW
	Heating COP※2	3.0	2.9 kW
Cooling※3	Capacity	20.5kW	39.7 kW
	Electric Consumption	4.0 kW	7.9 kW
	Cooling COP※2	5.1	5.0
Simultaneous Cooling and Heating※4	Cooling Capacity	15.0 kW	29.1 kW
	Heating Capacity	21.8 kW	42.5 kW
	Electric Consumption	7.1 kW	14.0 kW
	Total COP※5	5.2	5.1
Refrigerant		R134a	R134a
Size (L×W ×H)		1.3m× 0.7m× 1.9m	1.6m× 0.7m× 1.9m
Weight		600 kg	700 kg

※1 Ambient Temperature: 25°C DB/21°C B; Heat Pump Inlet Temperature:60°C,Outlet:65°C

※ 2 Heating COP = Heating Capacity (kW) / Electric Consumption (kW),

Cooling COP = Cooling Capacity (kW) / Electric Consumption (kW)

※3 Ambient Temperature: 25°C DB; Heat Pump Inlet Temperature 20°C, Outlet: 15°C

※4 Heat Pump Inlet Cool Water Temperature: 20°C, Outlet: 15°C

Heat Pump Hot Water Inlet Temperature 60°C,Outlet: 65°C

※5 Total COP = {Heating Capacity (kW) + Cooling Capacity(kW) } / Electric Consumption (kW)

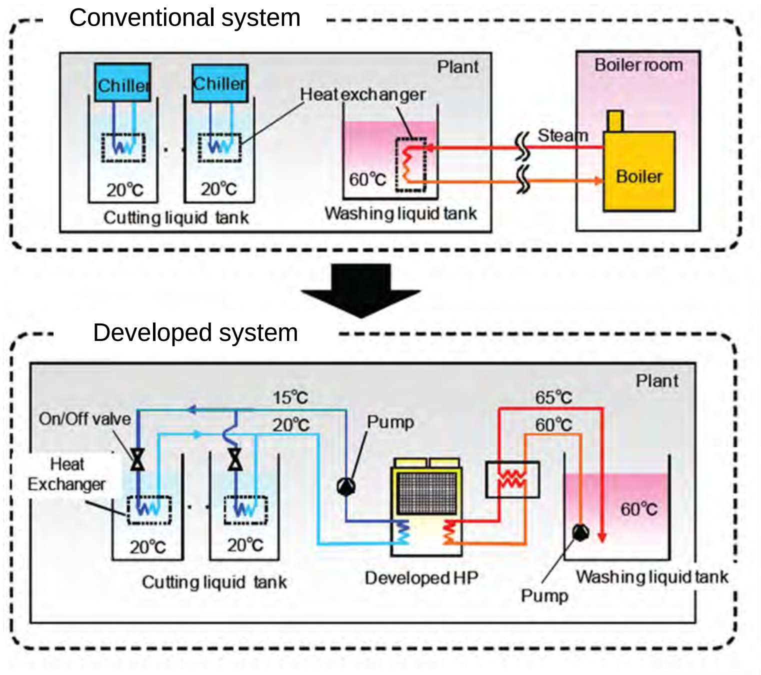


Figure 8-22: Developed Heat Pump System for Cutting and Washing Process

The heat pump for a washing process has the following features:

① Circulation heating suitable for heating of washing liquid

The use of the refrigerant R-134a, which is ideal for heating of washing liquid, achieved high-efficiency circulation heating of the washing liquid to maintain the temperature at 60°C (washing liquid inlet temperature 60°C and outlet temperature 65°C). Indirect heat exchangers such as immersion heaters can be used to accommodate even low-quality washing liquid.

② Substantial energy saving

The heat pump achieved a total COP of 5.2 under the simultaneous cooling and heating condition shown in Table 8-9. Figure 8-23 shows measurements of total COP under simultaneous cooling and heating conditions with various combinations of cold and hot water temperature. Raising the cold water temperature and lowering the hot water temperature within their respective allowable temperature range can substantially improve the COP. With its high total COP, the heat pump for a washing process allows you to substantially reduce energy consumption, CO_2 emissions and running cost from the level achievable by conventional thermal systems using boilers and chillers.

③ Oil mist-proof, and more user-friendly

In many plants, the washing process is located adjacent to the cutting process where high-speed tools are lubricated with cutting liquid, releasing oil mist in the building. If deposited on the air heat exchanger of the heat pump, oil mist may lead to reduction of efficiency. To prevent this, an easily removable filter has been added to the heat exchanger. Further, a touch-panel operator console provides better user-friendliness.

④ Accommodating unbalanced cooling and heating demands

The balance between cooling load and heating load in plants always changes with time, although the variation depends on the type of production process. For an application where a single heat pump is used to deliver cooling for cutting liquid and heating for washing liquid, how to accommodate such a load imbalance was an issue. With the simultaneous cooling & heating type, just switching between three modes, i.e., simultaneous cooling & heating, heating-only and cooling-only, can accommodate load balance variations.

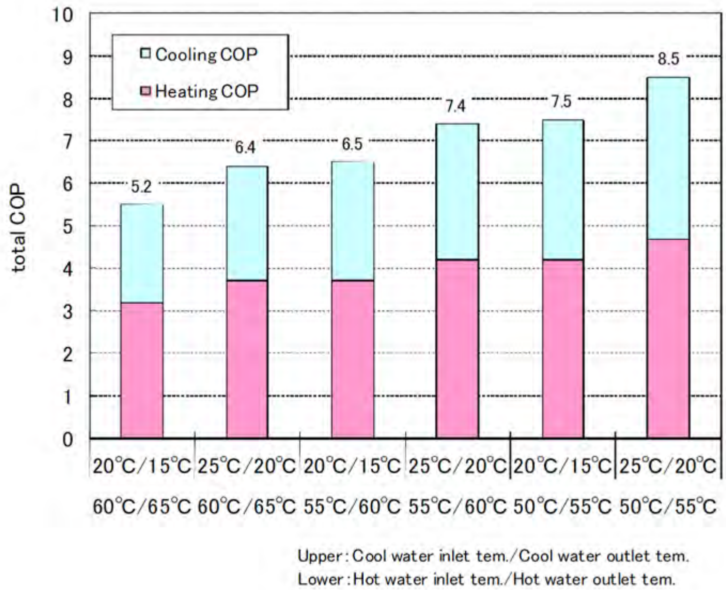


Figure 8-23: Relation between total COP and cooling/heating temperature

8.3.5.2 Effect of introduction

Aisin AW Co., Ltd., a Japanese automobile part manufacturer, introduced heat pumps for a washing process into its Gamagori Plant (Gamagori City, Aichi Prefecture) to apply them to the mechanical part production line including cutting and washing processes. Conventionally, the plant used air-cooled chillers to cool cutting liquid for the part cutting process and steam boilers to heat washing liquid for the washing process, which is located immediately after the cutting process. The existing thermal system using steam boilers had a long piping system and could only deliver very low energy efficiency due to huge heat and drain losses. Then, Aisin installed heat pumps for a washing process in a place very close to the production line. To begin with, a heat pump for a washing process was installed in 2009 as shown in Figure 8-24. After the effect was verified through field tests, 13 more heat pumps were installed in 2010. These 14 heat pumps consist of six cooling/heating type with a heating capacity of about 22 kW, and eight heating-only type with a heating capacity of about 43 kW. By introducing these heat pumps, the company realized a steamless thermal system for the overall plant. Table 8-10 shows the annual energy consumption and CO_2 emissions calculated from actual measurements. Although there is no significant difference in power consumption before and after the introduction of the heat pumps, the energy consumption, CO_2 emissions and running cost were respectively reduced by 73%, 86% and 89% from the level achieved by the existing system because the new system no longer uses heavy oil to burn the steam boilers.

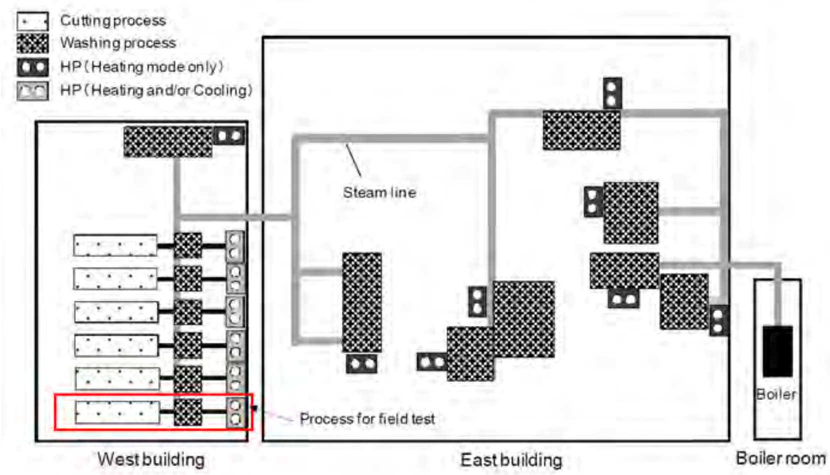


Figure 8-24: Ground Plan of a Mechanical Parts Factory where heat pump has been installed

Table 8-10: Effects of Introduction of Heat Pumps for Washing Process in a Factory

	Energy Consumption [GJ/year]	CO_2 Emission [ton CO_2/year]
Before Introduction of Heat Pumps	20,238	1,340
After Introduction of Heat Pumps	5,515	194
Reduction Rate	73%	86%

8.3.6 Applying the heat pump technology to agricultural production

Background

In Japan, about 73 % of the land is occupied by mountains. With the limited arable land, farmers try to raise the unit production and profitability by positively using greenhouses and plant factories to supply agricultural products regardless of the season (i.e., throughout the year). The energy consumption by agricultural production is shown in Figure 8-25. A-type heavy oil and kerosene, both of which are fossil fuel primary energy, jointly account for 85 % of total energy consumption. In particular, greenhouse cultivation consumes large amounts of energy, usually A-type heavy oil, for heating.

As heat pump technology has been substantially improved to offer higher energy efficiency in recent years, high-efficiency heat pumps available at a relatively inexpensive price have been introduced to production of flowers, fruit and other high-value-added products as an alternative to existing greenhouse heating technology. In addition to lower energy consumption and lower CO_2 emissions, the use of heat pumps in these applications can deliver quality-related benefits, i.e., a wider temperature setting range, and disease suppression by dehumidification.

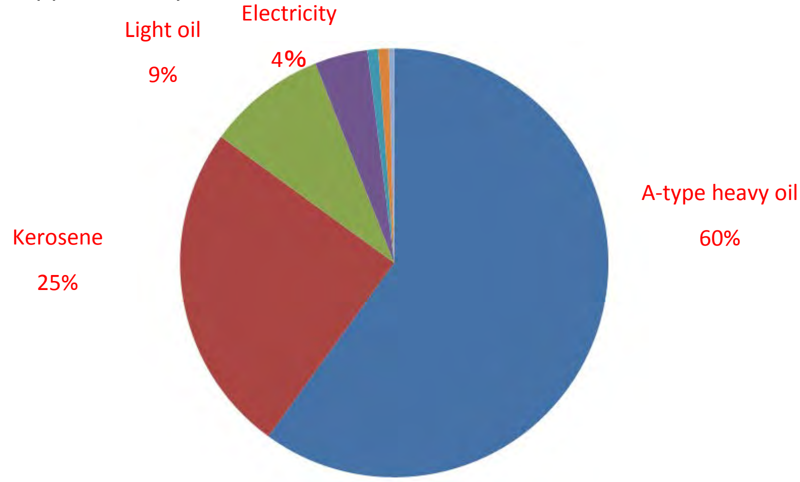


Figure 8-25: Energy consumption by agriculture and forestry (2008) 1)

Japan today has commercial greenhouses occupying a total area of about 50,000 ha. These greenhouses are heated by three major means: burning of petroleum fuel, using groundwater heat sources, and using petroleum substitutes such as gas and electricity. Figure 8-26 shows greenhouse installations by heating systems. According to the figure, 95 % of total installations are heated by hot-air heaters burning A-type heavy oil[2)].

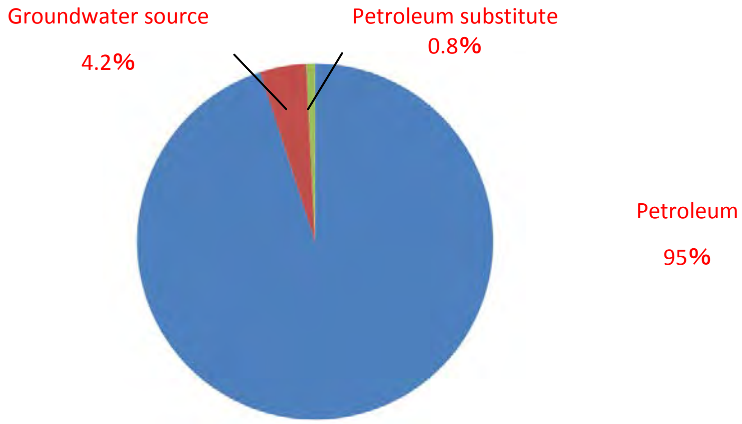


Figure 8-26: Greenhouse heating systems 2)

Since around 2008, agricultural heat pumps for greenhouse heating have been available in the market. Before introducing heat pumps, it is important to look into the power consumption, heating capacity and initial equipment cost of the product, to determine whether they can be used in combination with fossil fuel-fired heaters to deliver efficient operation, whether they provide easy humidity control, and whether they can be easily inspected and repaired. Particularly, it is more advantageous to apply heat pumps to high-temperature applications in which heating to 15 °C or higher is needed such as when growing roses, mandarin oranges or melons. This is because the higher the required heating temperature is, the larger the difference in heating cost between fossil fuel-fired heaters and heat pumps.

In the case described in the following, the company introduced greenhouse heat pumps with highest energy efficiency to achieve energy saving and CO_2emissions reduction.

Example of application

8.3.6.1 Company information

1	Company name:	Morita Farm, Kimitsu Horticulture (1173 Aoki, Futtsu City, Chiba Prefecture)
2	Completed in:	December 2010
3	Greenhouse information:	Three-quarter glass greenhouse (77 to 168 m^2): 7 houses
4	Product:	Melon
5	Design heating temperature:	20 °C
6	Existing heater:	A-type heavy oil-fired hot water boiler (thermal output 290.7 kW, 1 unit)
7	Heat pump installed (E'z Inc.):	"Aguri mo Guppy 55", twin type: 6 sets "Aguri mo Guppy", single type: 1 set

8.3.6.2 Installed system, and specification of heat pump

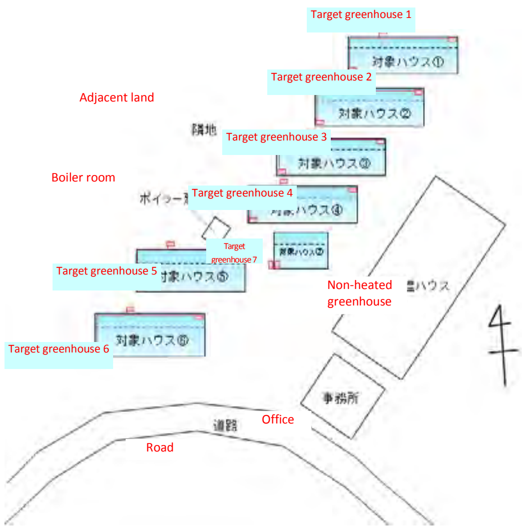
The purpose of introduction is to operate high-efficiency heat pumps for heating melon greenhouses so that existing fossil fuel heaters can be used just as an auxiliary option. The farmer aimed to reduce fossil fuel (A-type heavy oil) consumption by shortening the operation time of the existing heaters.

From the E'z Inc. catalogue 2008[3)], the company selected an agricultural heat pump with the highest COP and installed seven units in total. Based on the concept that the greenhouse indoor environment is equivalent to the usual outdoor environment, a housing of an "air-conditioner outdoor unit for shop/office applications" was combined with the heat exchanger and a high air-flow fan for usual outdoor units. With this design, a single type heat pump includes two fans, and a twin type has two indoor units so that they can be installed in separate places. Thanks to the "larger area" and "higher air flow" for heat exchange, the heat pump can deliver dramatically improved efficiency in heat exchange with air, achieving a high COP of 4.9 and substantially higher heating efficiency.

The heat pump also provides a wide temperature setting range: 7 to 30 °C for heating and 10 to 30 °C for cooling. By diverting the outdoor unit housing for air-conditioners, the heat pump can be operated even under the dusty environment in the greenhouses, showing high environmental resistance. The splash-proof and washability features made it possible to design a filterless heat pump.

The cultivation greenhouses have different roof heights on the north and south sides to let more sun shine in through the transparent roof panels, which is called "three-quarter greenhouse" (Figure 8-28). In Figure 8-28, greenhouses [1] to [6] have two twin type indoor units on the diagonal line each, and greenhouse [7] has one single type indoor unit in the same layout (Figure 8-28). Hot air from the heat pump indoor unit is driven by a circulating duct fan (3,600 m^3/h) into the main perforated polyethylene duct (ϕ450). Hot air then comes out of the many openings of its branch ducts (ϕ200), and spreads evenly over to make the temperature uniform within the greenhouse (Figure 8-29 and Figure 8-30, right). The outdoor unit for twin heat pumps is installed almost at the mid-point of the two indoor units (Figure 8-30, left). The specifications of the greenhouse heat pumps which were installed are shown in Table 8-11.

Heat pumps generally involve higher installation cost than fossil fuel heaters. To suppress the installation cost, the farm has established a hybrid heating system that uses fossil fuel heaters to meet the energy demand during the hours of peak load in a day, and uses heat pumps to cover the energy demand by the base load, successfully downsizing the total heat pump capacity. This hybrid heating system allows improving the shortcoming of air source heat pumps that the COP is lower at a lower outside air temperature.

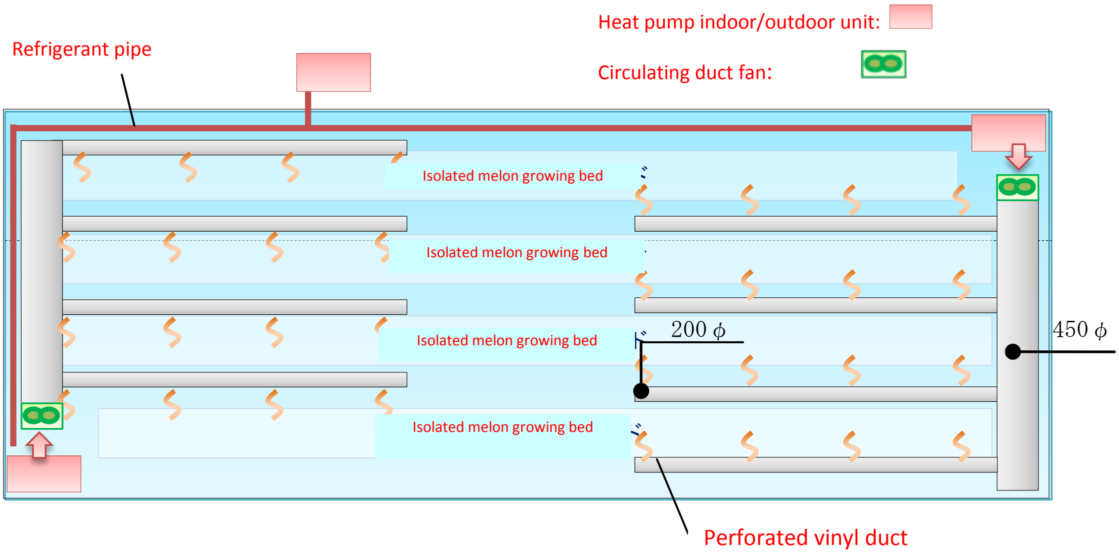


Target greenhouse:

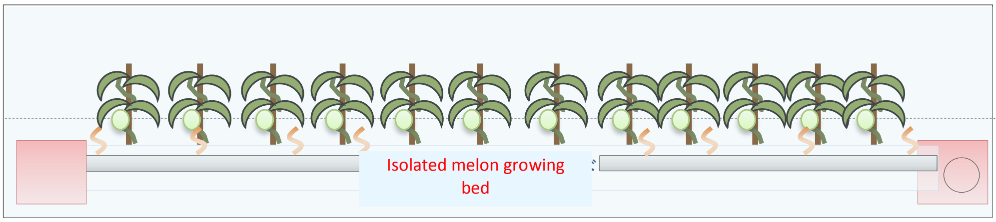
- ① to ④ 147m^2
- ⑤ and ⑥ 168m^2
- ⑦ 77m^2

Figure 8-27: Three-quarter greenhouse

Figure 8-28: Outdoor facilities and heat pump installations



a) Plan view



b) Cross section

Figure 8-29: Heat pump and duct layout in the greenhouse

Figure 8-30: Heat pump outdoor unit (left), Heat pump indoor unit and circulating duct fan (right)

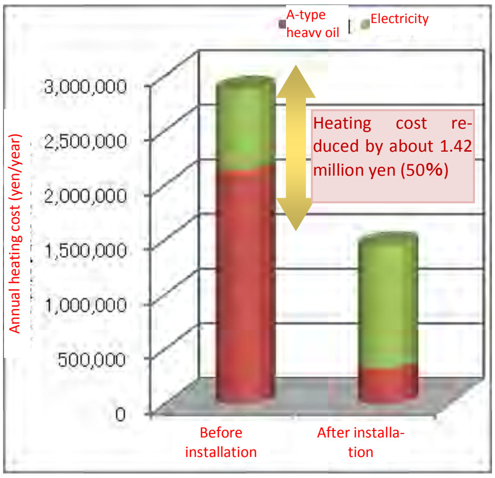
Table 8-11: Specifications of greenhouse heat pumps [3)]

		Aguri mo Guppy 55, Twin type	Aguri mo Guppy, Single type
Model		SPW-AGCHVPP180EN	SPW-AGCHVP180E
Cooling capacity		16.0 kW (12.5 to 28.0)	16.0 kW (7.3 to 21.3)
Heating capacity	Standard	18.0 kW (9.0 to 31.5)	18.0 kW (6.8 to 25.0)
	Cold climate	18.0 kW	18.0 kW
Refrigerant		HFC (R410A)	
Compress or	Capacity control	Inverter	
	Type	Totally enclosed rotary type	
	Output	5.5 kW	4.2 kW
COP	Cooling (standard)	5.48	3.86
	Heating (standard)	5.50	4.90
	Heating (cold climate)	3.77	3.20
Number of units		6 sets	1 set
Operating conditions (according to JISB8616)		● Cooling: Indoor suction air temperature 27°C DB, 19°C WB, Outdoor suction air temperature 35°C B ● Heating (standard): Indoor suction air temperature 20°C DB, 15° WB or less, Outdoor suction air temperature 7°C DB, 6°C WB ● Heating (cold climate): Indoor suction air temperature 20°C DB, 15°C WB or less, Outdoor suction air temperature 2°C DB, 1°CWB ● Amount of refrigerant: As shipped from factory	

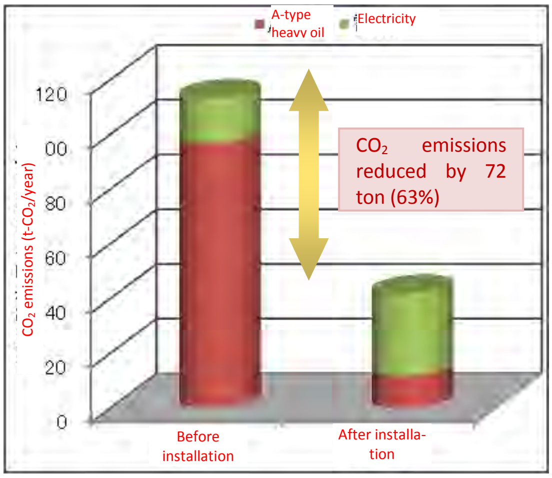
8.3.6.3 Effect of introduction heat pumps

The effect of introducing determined from the result of measurement after installation is shown in Figure 8-31. The transfer of heat source from A-type heavy oil to electricity has successfully reduced the annual operating cost by about 50 %, the annual CO_2 emissions by about 63% and the primary energy consumption by about 49 %. This means that the project investment of around 7,700,000 yen can be recovered in about 5.4 years through compensation by operating cost reduction.

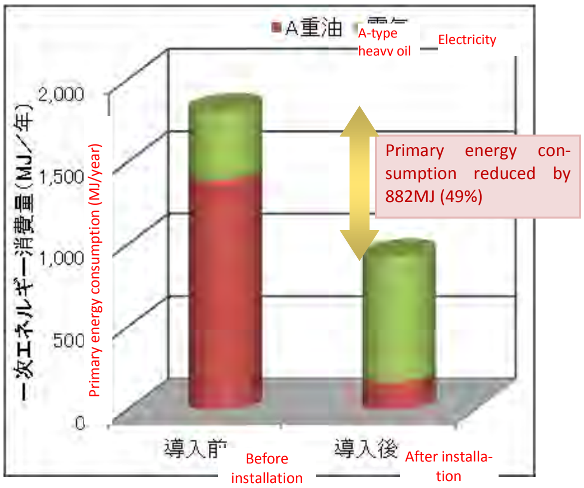
The temperature setting of melon greenhouses is as high as 20 °C. The longer the period in which melons are grown at a low outside temperature, the more the energy consumption reduction. The farm in this case cultivates melons even during the winter season. With this long cultivation period, the farm has successfully reduced A-type heavy oil consumption by about 88 %. On the other hand, power consumption increased by 82 % after the heat pumps were installed. The existing heating facility used a unit type hot water heating system with central hot water boilers and, if at least one of the seven greenhouses needed to be heated as shown in Figure 8-26, the boilers and circulating pumps had to be started, resulting in a very large thermal loss and very high power consumption by the thermal transport system. Actually the power consumption by the thermal transport system was about 55 % of that after installation of the heat pumps. However, now hot water is transported less frequently than before, so about 50 % of the apparent power consumption is eventually balanced out.



a) Operating cost



b) CO_2 emissions



c) Primary energy consumption

Figure 8-31: Effect of introducing heat pumps

8.3.6.4 Prospects

Before applying a heat pump to greenhouse cultivation, it is important to consider whether the heat pump can be efficiently operated in combination with fossil fuel-fired heaters for lower initial equipment cost, whether humidity can easily be controlled, and whether the heat pump can be inspected and repaired. In the case cited in this report, the installation brought substantial reduction effects, since the existing thermal facility used a unit type hot water heating system with central hot water boilers. It is desirable that heat pump technology will be further improved to feature even higher efficiency and lower installation cost.

Due to recent rising concern over the increasing risk of energy prices, renewable energy technologies have had a higher advantage and are expected to be more widely used. Further, it is important to enhance the public subsidy system for heat pump installation so that the high initial cost, which has impeded their introduction, can be recovered in a shorter period of time.

The biggest benefit of using heat pumps is controllability of both temperature and humidity, which allows year-round cultivation. This benefit can lead to higher yield of general product. Particularly, flower and fruit greenhouses are applications in which heat pumps have been increasingly installed, with an expectation for higher quality and higher yield of these high value-added products.

Source

"Analysis on CO_2 emissions of agricultural production, and effect of installation of heat pumps - Case study in Ibaraki Prefecture-", Master's thesis, March 2011, Graduate School of Systems and Information Engineering, University of Tsukuba

References

1) Edited from "Energy Balance Table", Statistics, Agency for Natural Resources and Energy, Ministry of Economy, Trade and Industry

2) General Government Statistics, Actual Area of Installed Heating Systems by System Type - Vegetable Greenhouses, Greenhouse Installations, and Statistics by Prefecture, Ministry of Agriculture, Forestry and Fisheries

3) E'z Inc. http://www.esinc.co.jp/agri/

8.4 Prospects

To increase the use of industrial heat pumps, it is essential to build up a track record of installation by promoting partial replacement of existing heat source equipment with heat pumps for the time being. Scheduled operation of production processes with heat pumps cannot be realized without ensuring the reliability of heat pumps. It is also important to prepare ourselves for the next step to promote R&D and commercialization of next-generation heat pump systems for which the use of heat pumps as a heat source is a prerequisite. To encourage replacement of existing heat source equipment, the support programs described in section 8.2.2, as well as the following discussion and development, are needed:

- Determining the actual waste heat and thermal demand
- Improving the heating efficiency of circulating hot water

- Improving heat transport and thermal insulation techniques
- Improving refrigerant leakage prevention, leakage detection and waste refrigerant recovery techniques, and enhancing their efficiency
- Reducing usage of rare metals (such as neodymium and dysprosium) and copper
- Enhancing efficiency of temperature control technology for agricultural applications

To commercialize and increase the use of next-generation heat pump systems, it is necessary not only to raise the output temperature and efficiency, and diversify heat sources, but also to discuss and develop the following points:

- Simulation and evaluation techniques of system characteristics
- Establishing safe use of mildly flammable refrigerants, and applying natural refrigerants to more applications
- Rare metal substitutes.

Basically, many manufacturers do not disclose their production processes. Hence, it is difficult to make examples of heat pump installation open to the public, or share information across industries. The cases introduced above could not be included in this report without understanding the arrangements made by heat pump users and manufacturers. We would like to express our gratitude for provision of information by those concerned. We expect that building up a track record of installation and information-sharing, as far as possible, will promote improvement of heat pump functionality and enhancement of efficiency, and create a virtuous cycle which will bring increasing benefit to the industrial society.

9 Korea

9.1 Introduction

Since the unique characteristics of Korean market such as wide-spread network of natural gas supply, low electricity price and floor heating culture, heat pump penetration rate is relatively low compare to other nations. However, recent environmental challenges of society, especially for the challenges related with energy security, have brought consensus on the energy saving potential of heat pump. In the industrial sector, as a solution for energy saving, the number of heat pump installation and operation increases. In this chapter, representative heat pump installation and operation cases in industrial sector will be presented.

9.2 Cases of heat pump systems that utilize waste heat (heat recovery)

9.2.1 Reduction in usage of steam for DI water heating by installing heat pump and heat exchanger

This case is about the reduction in steam and electricity used for heating process of DI (Deionized) water through installing waste heat recovery device of coolant in factory and heat pump and using the waste heat for the heating process of process water and DI water. In order to clean glass substrate which is main element of TFT-LCD, DI water is produced and used. The temperature level of water was classified as 28 °C and 45 °C depending on the target process. For the maximization of the efficiency of RQ (reverse osmosis) process which is one of main processes of DI water production, the temperature of industrial water need to be raise up to 28 °C before RQ process and 45 °C DI water is produce through 28 °C DI water heating. DI water is made from industrial water that is supplied by K-water.

In previous process for DI water heating, waste heat through heat exchanger from chilled water of a refrigerator which produces cold water of 5 °C is used. In case of emergency, water is heated by steam using LNG boiler. Used DI water is transferred to waste water disposal plant and rejected after physicochemical /biochemical treatment. When cold water is required in factory, chilled water is used to lower the temperature of high pressure side refrigerant and it then is circulated to the cooling tower to release gained heat to the atmosphere.

A heat pump is installed and by utilizing waste heat as low temperature heat source it generates hot DI water (15 °C) in the improved process. This is different from conventional method that uses heat from steam in order to produce hot DI water. In the conventional process, 45 °C DI water is produced from 28 °C DI water through steam heating and the refrigerator that used to produce cold water has waste heat that is rejected to the atmosphere through cooling tower. In the improved process the refrigerator is removed and a heat pump is introduced to reduce energy use by recycling waste heat that is used to release to the atmosphere before. The installation of heat pump cuts the LNG usage for steam production which is needed for 45 °C DI water generation. In addition, the waste heat of coolant that used to be rejected to the atmosphere maximizes heating effect by connecting it to the heat exchanger that already existed at refrigerator coolant heat recovery cycle.

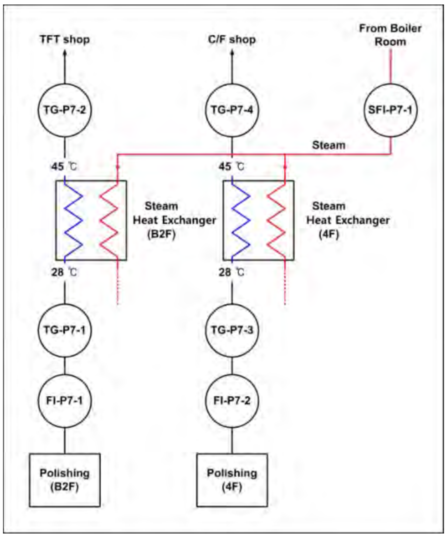


Figure 9-1: Previous process diagram

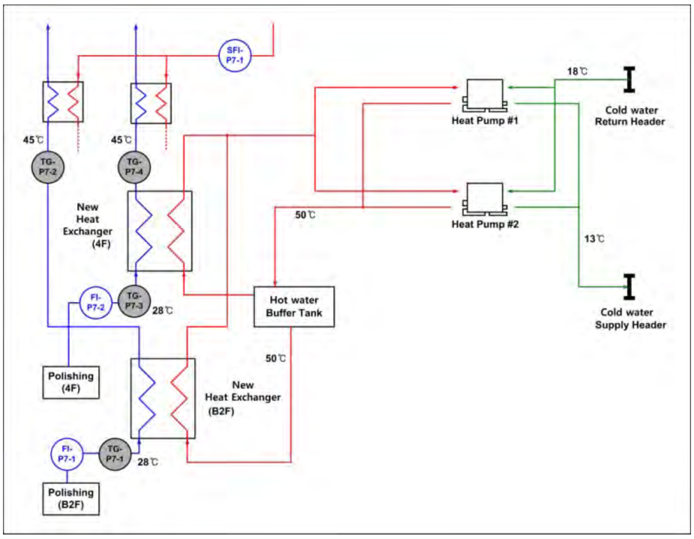


Figure 9-2: Improved process diagram

9.2.2 Energy saving through installation of waste heat recovery heat pump

This case is about generation of cold water and hot water of 60 °C through heat pump. This system was applied to textile factory. In conventional process, a refrigerator was used to produce cold water and steam from boiler was used to produce hot water. The Installation of a heat pump before steam heat exchanger preheats process water and reduces steam usage of existing steam heat exchanger, thus saving energy. In this case, the average annual reduction of CO_2 emission is expected to be 1,047 ton CO_2-eq.

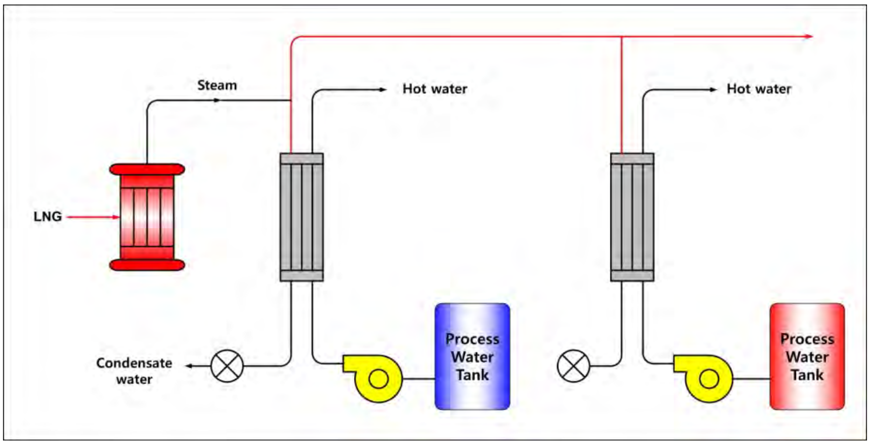


Figure 9-3: Previous process diagram

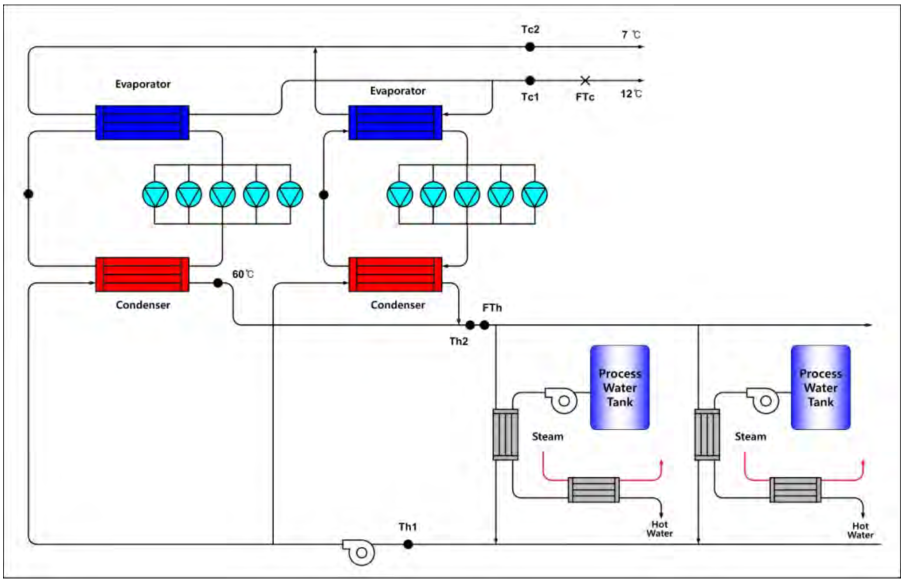


Figure 9-4: Improved process diagram

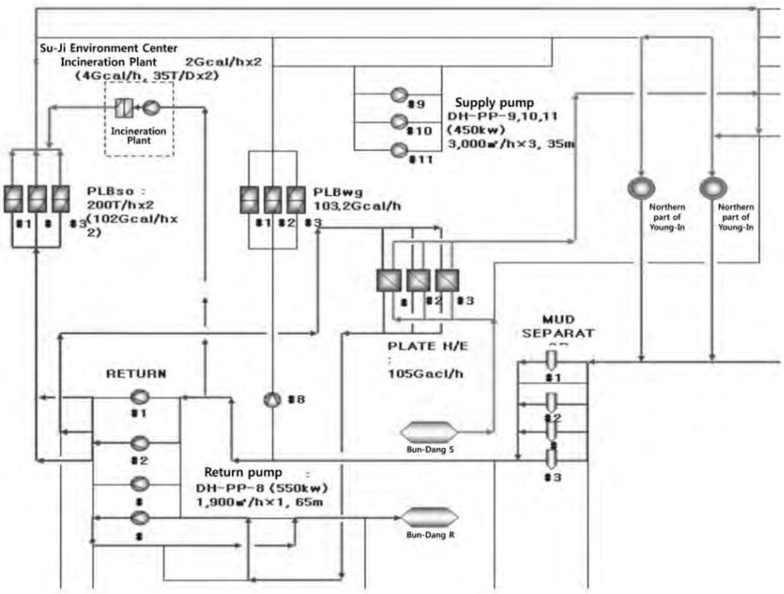
9.2.3 Sewage heat source heat pump (renewable energy facility) installation case in Yong-in

A plan was suggested for a partial utilization of wastewater from Respia in Suji in order to prevent local stream (Seongbok stream) depletion and scenery improvement. This plan was progressed for reduction of energy usage and active response for the Convention on Climate Change by using unused wastewater energy as a heating source through installing and managing related facilities.

A district heating system of Respia in Suji provides steam of 100~110 °C to deal with the heating demand in Yong-in area using boiler system. After circulation, hot water of 50 °C is recovered which is transferred to heat exchanger of boiler again. The total area of the facility is 124,573 m² and the distance between the facility and heat source in Yong-in is 2 km.

Yong-in city established a plan of releasing treated sewage from Suji sewage treatment plant into the upper Seongbok stream in order to prevent dry stream and improve scenery. As a part of the plan, a heat pump was installed which utilizes Suji Respia unused energy as heat source for district heating in wastewater. This converts low-temperature and widely spread thermal energies such as geothermal energy, stream water, seawater, wastewater and other energies into high-temperature and intensive energy. Moreover, with a heat pump system, it is possible to produce hot and cold water simultaneously or independently. This system has a weak point that electric energy consumption is required to run compressor for gas compression. The annual CO_2 and power reduction were expected to be 5,719 t and 20,530,289 kW respectively.

Process schematic diagram before improvement



Process explanation:
System that provides heat of 100~110 °C to the places that require heating in Yong-in area through heat exchanging process with the steam from boiler. After the circulation, hot water of 50 °C is collected and transferred to the heat exchanger again.

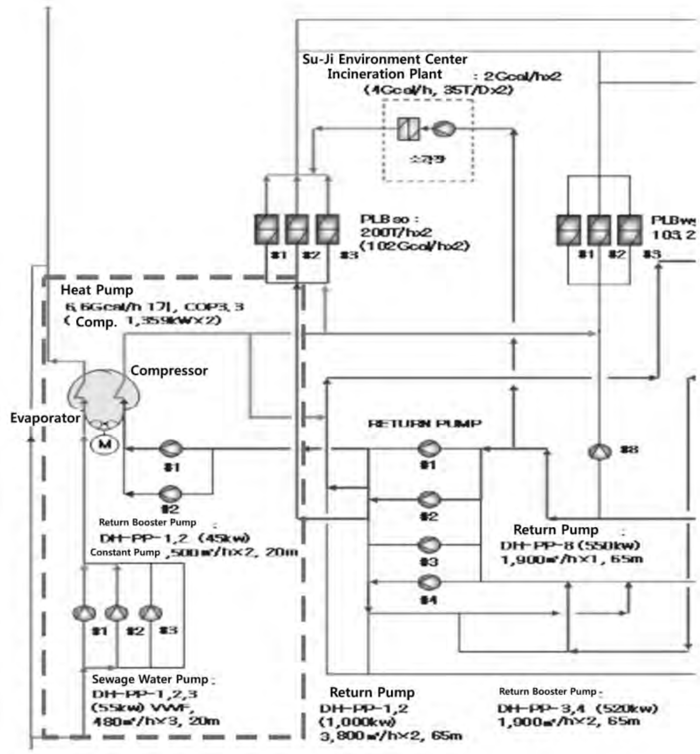
Process schematic diagram after improvement

Process explanation: The recovered heat from sewage releasing place is transferred to the heat pump as a low temperature heat source. The generated hot water is supplied to the heating demand place in Young-in area.

Figure 9-5: Installed heat pump

9.2.4 Energy saving case by utilizing a heat pump which collects waste heat from cooling system in IDC (Internet Data Centre) server room

A heat pump was used for hot water supply and heating in this case. The waste heat of coolant from IDC cooling system in computer room was collected and used as a heat source of AHU (Air Handling Unit) that controls temperature and humidity level of IDC server room.

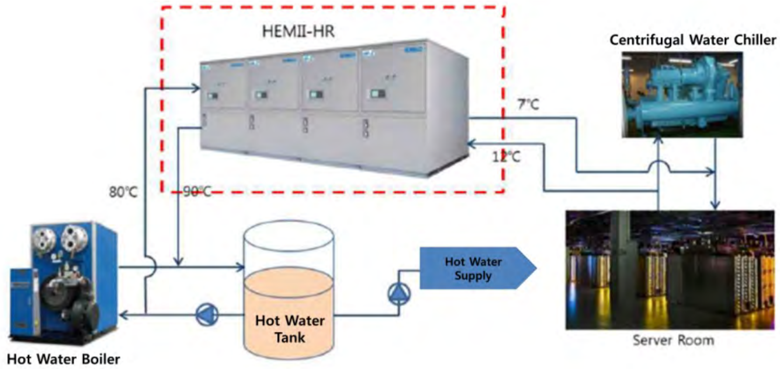


Figure 9-6: Diagram of cooling system of IDC server room with heat pump

9.2.5 Energy saving through change from TVR (Thermal Vapour Recompression) concentration facility to MVR concentration facility

TVR concentration system is waste heat recovery-type concentration system that takes high pressure steam as driving force for steam compression and reuses compressed steam as heat source for the discharge process. This process fits for the process, which concentrates materials of high boiling point. In addition, it also fits for high capacity processing. Since it evaporates circulating material by utilizing latent heat of evaporating steam, it can be applied to treat high concentration materials which have high possibility of scaling.

Improved process is high efficiency concentration system with MVR that intakes low-temperature waste steam as heat source into turbine-driven type compressor, compresses the steam, and reuses the output steam as a heating source of the production process. Due to the large available space inside of the heat exchanging tube and high vapour specific volume it is easy to separate vapour and liquid. In addition, a concentrated material drops in form of film inside the tube which yields high overall heat transfer coefficient and heat transfer efficiency. Moreover, it is suitable for evaporative concentration of materials of high sensitivity to thermal degradation because low-temperature concentration is possible and the product stays only for short time inside the tube as the velocity of fluid is increased by the evaporated vapour.

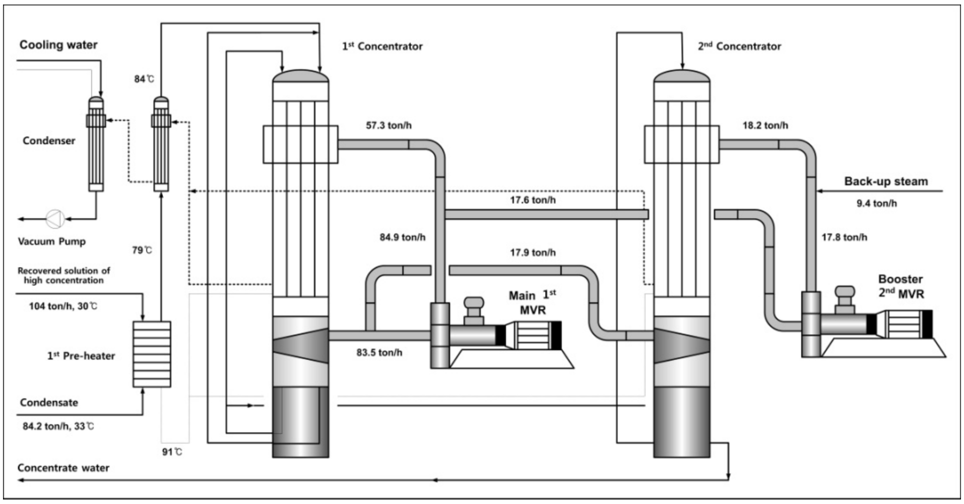


Figure 9-7: Improved concentration process with TVR

9.2.6 Energy saving case of the steam generation through TVR and MVR for heat recovery

This case is to reduce thermal loss from cooling tower where waste steam condenses by recycling waste steam through the installation of TVR and MVR and using recycled steam as the heat source of M,T-Line Stripper.

The MVR and TVR are installed to collect waste gas which is exhausted during the separation process of solvent in synthetic rubber production process. They generate usable low-pressure steam and substitute it with the supply steam from cogeneration plant. The main feature of conventional and improved process is represented in following table.

Previous Process	Improved Process
∘ Insert raw material/solvent during reaction (polymerization) process → ∘ Insert steam in order to separate solvent during reaction process → ∘ Lower part of stripper → hot water discharge → transfer to production process after striper insertion	∘ Same as the previous process
∘ Upper part of stripper → vapour discharge → cooling tower → rejected as waste water after condensation	∘ Upper part of stripper → vapour discharge → plate heat exchanger → vapour-liquid separator → MVR (3-stages) → TVR → steam generation → reinsertion to M,T-Line separator

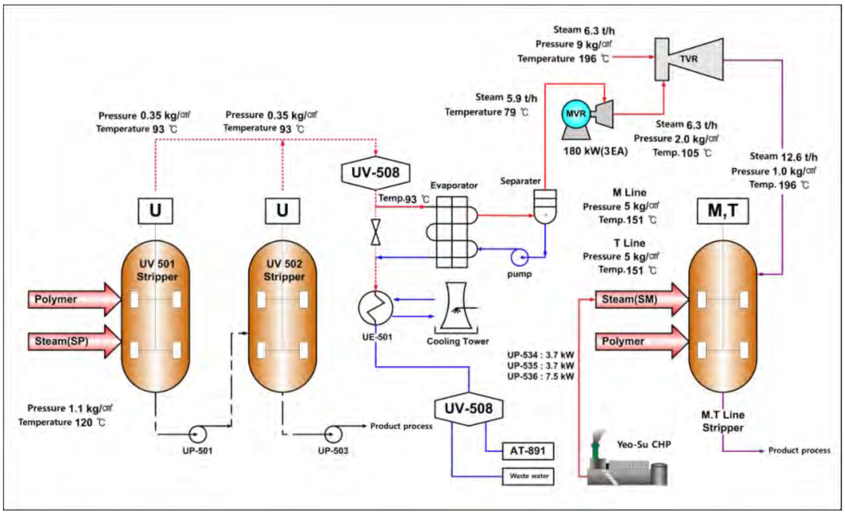


Figure 9-8: Diagram of energy saving process with MVR and TRV

9.2.7 Application case of high efficiency thin film dropping type concentration tube and MVR to a sugar refinery factory

In conventional process, a concentration tube is double effect tube of rising film type and is used as vacuum concentration of sugar solution. Waste steam which is generated from concentration tube is recycled as hot water generation for factory and condensate water is used as supply water to the boiler or rejected as waste water.

The improved process uses 1st MVR to recompress waste steam which is generated from 1st concentration tube and inserts the steam into 1st concentration tube again. A certain portion of waste steam from 1st concentration tube is recompressed by 2nd MVR and used as heat source of 2nd concentration tube and generated waste steam from 2nd MVR is and recompressed by 1st MVR and sent back to 1st concentration tube. Such utilization of MVRs that recycle waste steam from concentration tubes reduces input energy to entire process.

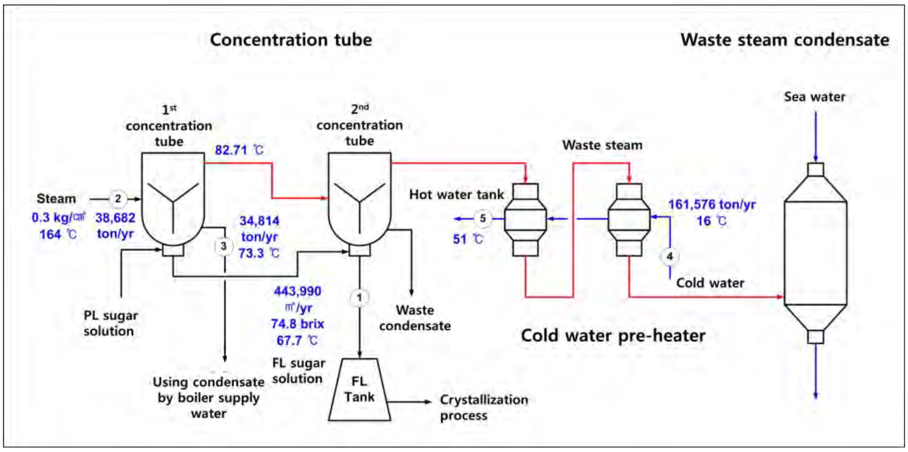


Figure 9-9: Diagram of previous process of sugar concentration

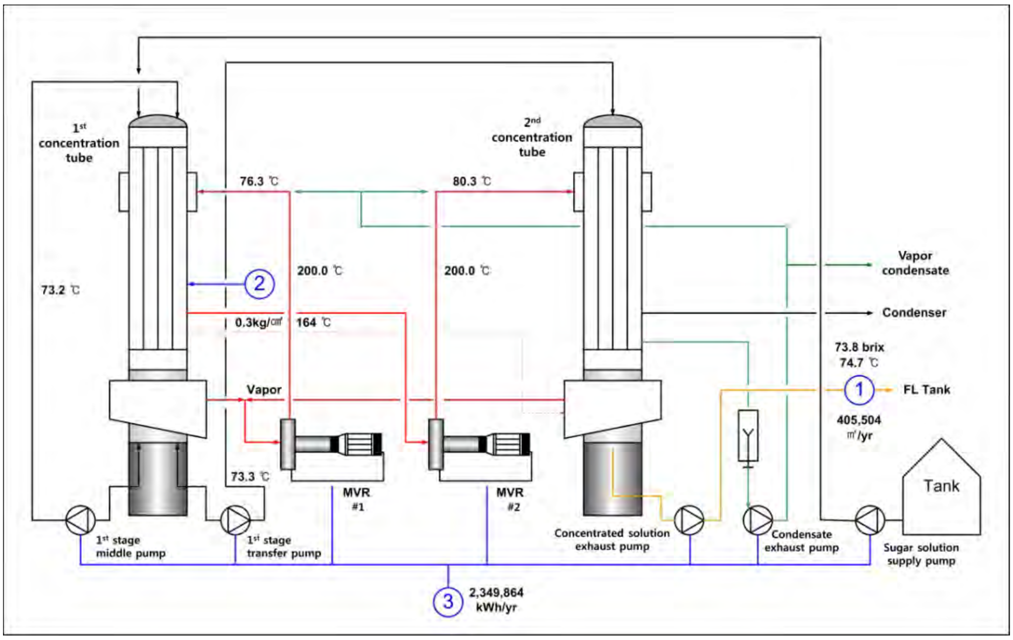


Figure 9-10: Diagram of improved process with MVR

9.2.8 Reduction of greenhouse gas emission through installation of heat recovery MVR in reaction tower

With the waste heat from the processes in a PC (Polycarbonate) factory, steam of the pressure of 1.9 kg/cm² is generated. This steam is recompressed up to 4.2 kg/cm² through mechanical vapour recompression (MVR). This makes it possible to contribute energy cost reduction and prevent global warming by stopping steam boiler operation of existing factory and cutting fossil fuel usage.

Yeo-su branch of Che-il Industries Inc. consists of an old factory that produces ABS, EPS resins and other product and a PC factory that manufactures PC (polycarbonate) which is made from DPC (diphenyl carbonate) by processing DMC (dimethyl carbonate) as a raw material. The old existing factory uses 3 steam boilers (Capacity: 25 tons/hr, pressure: 7 kg/cm²) to generate required amount of steam in production processes. The required steam of the PC factory is produced by one steam boiler exclusively for PC process (Capacity: 100 tons/hr, Pressure: 40 kg/cm²).

DPC process in PC factory produces DPC by inserting raw materials purchased from the outside and steam of temperature of 155 °C and pressure of 0.7 kg/cm² is discharged at the upper part of DPC reaction tower. The high-temperature discharged steam is cooled by cold water (CW) through a heat exchanger. After that, a certain amount of the steam re-circulates to the reaction tower and the rest is sent to the RP tank. Even though the high-temperature discharged steam of the upper part of DPC reaction tower has high thermal energy capacity of 14 million kcal/h, this energy is not efficiently reused because of the forced cooling process with coolant at cooling tower.

For the OVER-HEAD waste heat collection facility at DPC reaction tower, a steam generator and an MVR were introduced which intake steam of 1.9 kg/cm² and pressurize this steam up to 4.2 kg/cm². This system was proposed by Everland that is specialized for ESCO (Energy Service Company) investment.

The specification of PC process waste heat collection facility system is shown below. For the first localization of MVR facility in Korea, the turbo compressor, STG-1300 MVR from SeAHENT (Korean company) was chosen and construction was done as an ESCO investment.

The improvement through MVR is like followings. Above all, for the amount of annual energy cost, 6.05 billion wons ($5.64 millions) are saved through alternation of steam and 550 million wons ($0.51 millions) are added for power consumption. Therefore the net energy saving cost is 5.5 billion wons ($5.13 millions) per year. The energy saving amount through alternation is 8,476 TOE and additional power consumption is 1,668 TOE per year which makes net energy saving amount of 6,808 TOE annually. The expected payback period is 0.9 year.

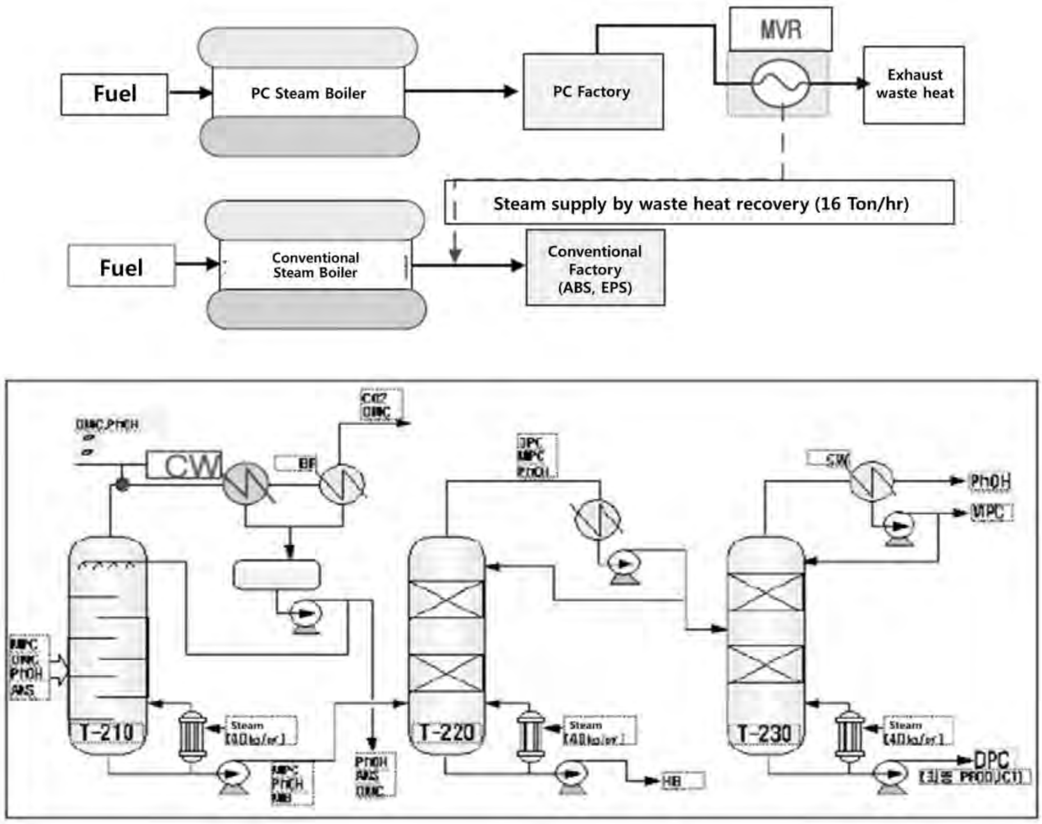


Figure 9-11: Process diagram

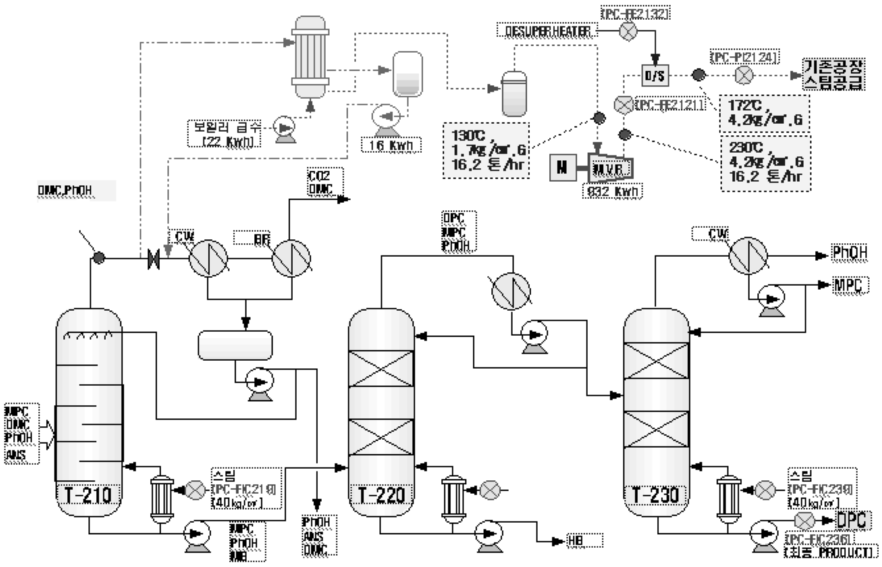


Figure 9-12: Improved process

9.2.9 Recycle of re-evaporated steam by installation of variable-type thermal vapour recompressor (TVR)

A thermal vapour recompressor (TVR) was installed to crumb slurry tank to collect re-evaporated steam and utilize it as heat source for Stripper (Solvent collector). So the amount of supply steam for Stripper heating was reduced.

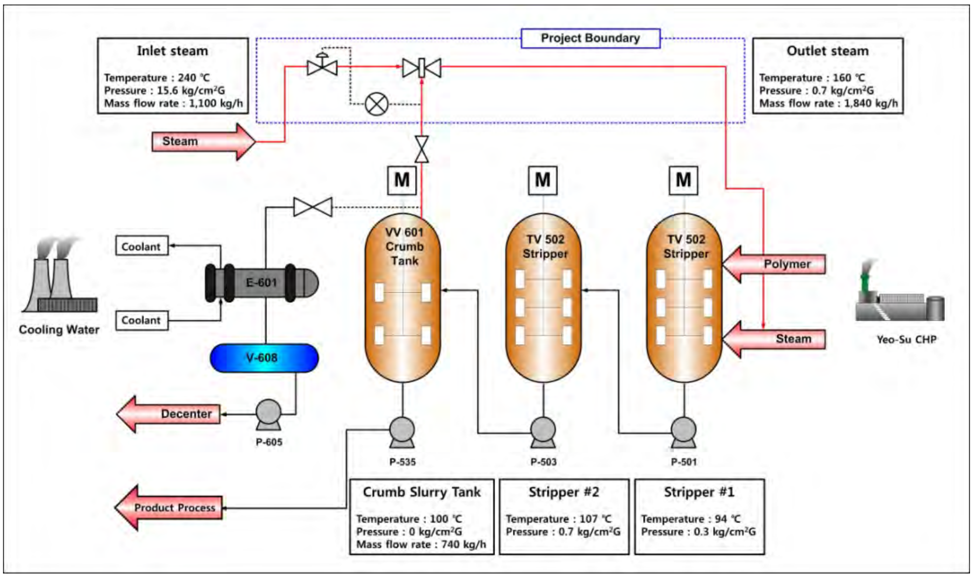


Figure 9-13: Improved process

9.2.10 Reuse of waste steam to the process steam by TVR

Previously, a plant received steam for the production process from a neighbouring co-generation plant. When there was need for additional steam, a steam boiler installed in a factory was used. The steam is provided to each process and recovered as a form of condensate water after its usage.

In the improved process, input energy can be reduced by recycling generated air vent steam (1 kg f/cm²) from condensate water collection system of plant and recompressing the steam up to 3 kg f/cm² through TVR (Thermo-Vapour Recompression).

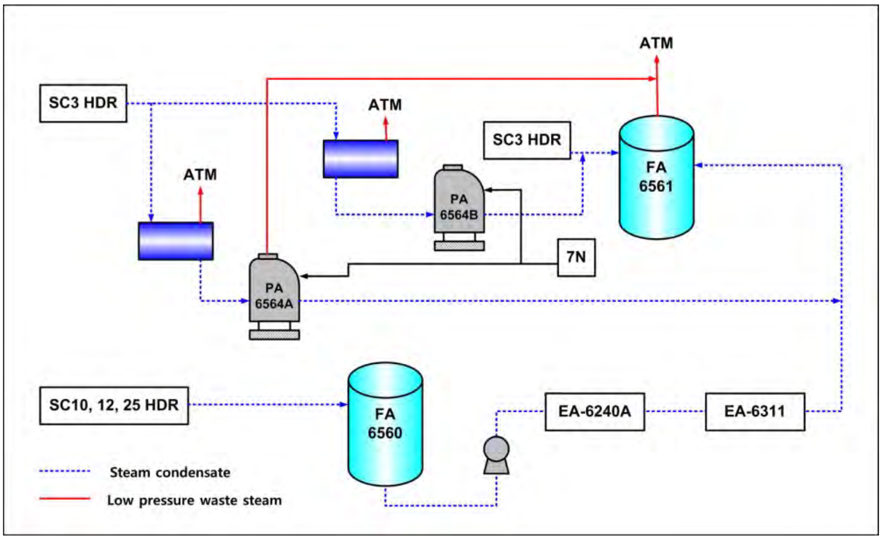


Figure 9-14: Improved process

10 The Netherlands

10.1 Example projects in Netherlands

Developing and dissemination of knowledge is important for successful growth of the application of heat pumps. To stimulate the application of heat pumps it is useful to analyze heat pumps which have been placed in the past and analyse how they operate in practice.

In this study the operation of these "older" heat pumps is analyzed. The research has been performed through contacts by phone and e-mail. In this study an inventory was made about; the experiences of the companies, if there have been any changes of the design over time, whether operating & maintenance of the installation is difficult (high level of knowledge, complexity, etc.), if promised energy savings are achieved and whether there are remarks which can be defined as lessons learned.

Over the past 20 years several feasibility studies and project realizations of heat pump projects have been performed. These are evaluated in this study.

The table below provides a summary of the results, which heat pumps are still in use and which are not. The reason is indicated when heat pump have been taken out of use.

All companies, whose heat pumps were described in the examined literature (22 cases) participated in this evaluation study. 5 projects were never realized, despite the fact that acceptable payback periods and significant energy savings were calculated in the feasibility studies.

Much has changed in the companies in the past 20 years like the closure of the plant, moving production abroad, no demand for the product produced, changes in operations, etc. As a result, 6 of the analyzed heat pumps have been removed. This had nothing to do with any possible malfunction of the heat pumps.

Factsheet	Company old/new name	location	process	Condition
	Oriental Foods	Landgraaf	Drying of Tahoe	Company closed
	Plukon	Asten Ommel	Slaughterhouse	Feasibility only
	Solphay/Dishman	Veenendaal	MDR on Aceton	End of production
	Purac Biochem	Gorinchem	MDR on lactose	End of production in NL
	Hartman/Jardin	Enschede	Garden furniture	Feasibility only
	ITB		Plastics	Feasibility only
	Quality Pack	Kampen	Crate washing	Company closed
	Beukema/Eska Graphic Board	Hoogezand	Paper drying	Feasibility only
	Huwa Bricks factory	Spijk	Brick drying	Feasibility only
	Frico	Sint Nicolaasga	Cheese evaporative drying	Company closed
	Hoogovens/Tata steel	IJmuiden	Heat Transformer	Corrosion problems
	ARCO/Lyondell	Botlek	MDR on Distillation	no data available
NL-01	Shell	Pernis	MDR on Distillation	running
NL-02	Unichema/Croda	Gouda	MDR on Distillation	running
NL-03	Hoechst	Vlissingen	MDR on Distillation	End of production in NL
NL-04	Campina	Veghel	MDR on evaporation	running
NL-05	De Graafstroom	Bleskensgraaf	MDR on evaporation	running
NL-11	Dommelsch Brewery	Dommelen	MDR on wort	running
NL-13	GPS	Nunspeet	Heating from condensor	running
NL-15	AVEBE	Ter Apelkanaal	MVR on patatoe starch	running
NL-16	Cerestar/Cargill	Sas van Gent	MVR on	replaced by new MVR
NL-17	Fapona/Berendsen	Apeldoorn	Laundry drying	running

Of the 11 remaining heat pumps, 10 are still in use. These are 8 Mechanical Vapour Recompressors (MVR), a Thermal Vapour Recompressor (TVR) and a heat pump, which uses the heat from the condenser of the refrigeration installation for process heat.

When the heat pump are still in use, the companies have, no more insight into why there ever was chosen for the heat pump given the long period since the investment decision. The heat pumps which are still in use are generally still running in their original design. They are running relatively many hours a year (5,000-8,000), usually at full load.

In several cases the maintenance is outsourced for reasons of complexity, high operating hours and capacity problems in the technical department. Operating the installation is generally regarded as a relatively simple. The installations have few problems and / or malfunctions. Companies have no insight on whether the system achieves its efficiency, or whether the intended energy savings have been obtained. They have no reference, given the initial situation is so far in the past. Below are a couple of remarks which have emerged from this study which should be taken into account for the application of heat pump technologies.

- When a steam-powered evaporation process is switched to an MVR, which is electrically powered, it must be taken into account that the ratio between heat and electricity demand shifts towards electricity. This is unfavourable for the use of gas turbines, when a company has these in use.
- A point of interest for heat pump installations which processes polluted water is that the heat exchangers require relatively high-maintenance when they have to process large quantities of polluted water.
- An additional advantage of a TVR, or a MVR is that these systems reduce the emission of odours, since all vapours are condensed.

The heat pumps generally run satisfactorily, this study provides no indications to suggest that there are major risks associated with the use of heat pumps in industrial environments.

Example projects are listed in factsheets as Appendix of this report.

10.1.1 Chemical industry[1]

Distillation is by far the most widely practised technique for separating mixtures in the chemical and petrochemical industry. Distillation columns are in many chemical plants the largest energy consumers. In a conventionally operated distillation plant, energy is used to heat in the reboiler and about 95% of this is released at the top of the column in the air or water cooled condenser. This energy is in most cases wasted.

The application of heat pumps is one of the most efficient technologies to reduce the energy requirement of distillation. Sulzer Chemtech has applied various types of heat pumps successfully in a number of industrial processes.

The energy costs can be reduced in several cases by 30 – 70%, involving less than two years payback time for the additional capital investment related to the installation of the heat pump. The environmentally friendly character of the heat pump process is apparent from the lower amount of CO_2 emitted while generating the electrical power required for the process. It is found that the CO_2 emission can be reduced by 60-80% depending (*a*) on the thermodynamic efficiency of the heat pump and (*b*) on the type of primary energy employed for power generation. In each investigated application of a heat pump, the additional investment costs compared to conventional distillation is paid back in less than two to three years thanks to the lower energy consumption. Moreover, in some cases the expansion of auxiliary facilities, like the cooling tower, the chilled water system or the boiler house can be avoided.

Heat pump systems can be implemented for new distillation units, as well as for revamp of existing plants.

In the process of direct vapor recompression (see Figure 10-1) the pressure of the vapor leaving at the top of column (C-1) is elevated in a compressor (T-1). This raises the dew point of the vapor following which it can be condensed in the reboiler (E-1). There are, however, applications where the medium in the column, and thus the vapor from the column top, is not suitable for compression (due to, for example, polymerization and corrosion). In these cases an additional, separate working fluid like water can be selected (see Figure 10-2). The water is evaporated in the condenser (E-2) of the column (C-1), the generated steam will be compressed in a compressor (T-1) and condensed in the

[1] I. Mészáros, Sulzer Chemtech Ltd,

reboiler (E-3). The water condensate is circulated back through a throttle valve into the condenser where it will be evaporated again.

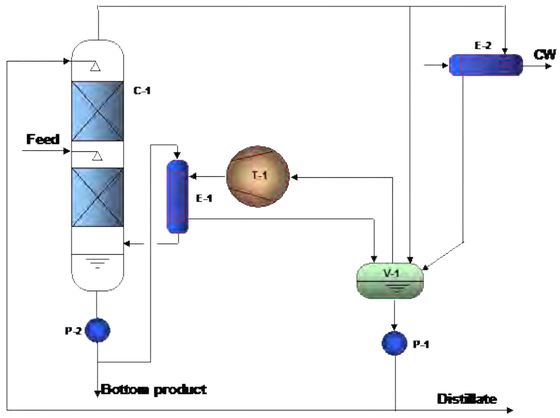


Figure 10-1: Scheme of distillation with direct vapor compression

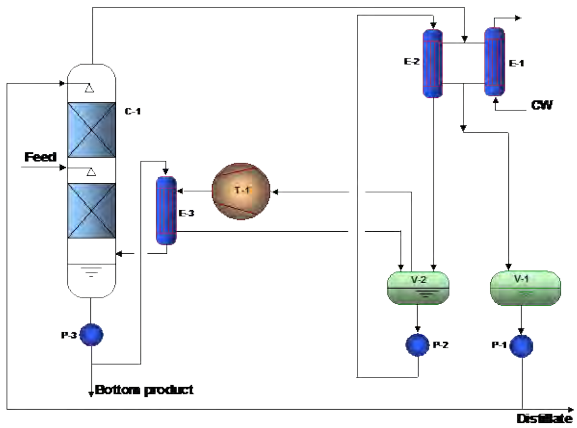


Figure 10-2: scheme of distillation with an indirect heat pump

Practical application criteria are given in Appendix 2, where also six cases are described [Kleefkens, 1996].

Three example projects are discussed. A fourth large example project which was already published in a paper in 1995 did not get the allowance to be published as according to the new management there was too much confidential and competative process information in the sheet.

NL-01 MVR for chemical process at PP-splitter for Shell in Pernis

At Shell Nederland Chemie on the location at Pernis (NL) products such as cleansers, solvents, fibres, resins and polymers are produced. These products are manufactured from raw materials produced in the refinery on the same site. Propylene is a key material in the production of a number of chemical products including polypropylene (PP) and solvents. It is obtained by distillation separation of propylene and propane in a so called PP-splitter column. In a conventional distillation the reboiler is heated by low pressure steam and the overhead vapours are cooled with cooling water.

In 1995 as a part of the modernisation of the whole propylene distribution system within the Shell site at Pernis, a new propylene-propane distillation column was built with the application of mechanical vapour recompression (MVR), built by Mannesmann Demag AG. This was done to save energy, reduce the use of cooling water and increase the yield of the distillation.

The heat pump as described is still running in line with the original design at 8650 hours per year at fixed speed. Maintenance is done by an external party as specific knowledge is required.

NL-02 - Croda in Gouda

Croda is produces special oleochemicals and derivates for a broad market of applications. In the separtion process for oleïne and stearine an MVR heta pump is used since 1994. The heat pump as decribed in the factsheet is till running to the design at 90% full load for 8000 hours/year.

Maintenance and service is contracted as a high level of expertise, not present at Croda, is needed. Once a year the process is stopped for that overhaul where mostly only cleaning of the system is needed and no parts are broken down or have to be replaced.

NL-03 Hoechst Vlissingen

Since 1982 three steam recompression systems have been in operation at the Hoechst production plant in Vlissingen. The heat pumps are a part of the process for the production of dimethyl-terephthalate (DMT). With the application of steam recompression, steam pressure is increased from 1.14 bara to 3 bara, which can be used in the low pressure steam system. The main goals for the application have been cost reduction and the possibility to work with a smaller steam production plant. Due to the recline in the PMT market worldwide the Hoechst plant was closed in 2007.

10.1.2 Food industry

Evaporators in dairy industry

The GEA handbook on Milk Powder Technology states that the transforming of a liquid product into a dry powder requires means the removal of practically all water, the amount of which often exceeds the weight of the final product. During the water removal the processed product is undergoing deep changes of physical structure and appearance, starting with thin water-like liquid and terminating with dry powder at the end of the process. Therefore, one single method of water removal cannot be optimal throughout the whole process, as also the product composition is different from one food product to another. In the food and dairy industry the following dehydration methods have been adopted:

- Evaporation:
- Spray Drying:

- Vibrating Fluid Bed Drying:
- Integrated Fluid Bed Drying:
- Integrated Belt Drying:

Each method should be adjusted to the properties of the processed material at each processing step. The more difficult the product, the more complex the plant.

As the development went on, the concentration was carried out in forced recirculation evaporators. In this evaporator the milk streams upwards through a number of tubes or plates. On the outside the heating medium, usually steam, is applied. The heating surface is thus increased in this system, but the evaporation surface is still limited, as the tubes and plates remain filled with product, which therefore becomes superheated in relation to the existing boiling temperature. Not until the product leaves the top of the tubes, are the vapours released and the product temperature decreases. For the separation of liquid and vapours, centrifugal separators were preferred. In order to obtain the desired degree of evaporation the product was recycled in the system. The concentration was thus controlled by the amount of concentrate discharged from the plant.

NL-04 Campina in Veghel

FrieslandCampina DMV in Veghel installed an energy-efficient evaporator that is the only one of its kind. It evaporates water from whey, allowing the lactose to crystallise spontaneously. By using smart technology, the current combination of mechanical and thermal evaporation techniques can be replaced by a single mechanical technique to cut energy consumption by an additional 60%. The heat released using this new technique is used so efficiently that cooling water is no longer needed. The discharged condensate is cooled until it reaches a temperature of 15°C. Approximately 35 technicians work on the installation. The new evaporator will become fully operational in October 2013. The construction and installation of the new evaporator is part of an extensive capital expenditure programme at Veghel, in which FrieslandCampina is investing over 60 million euros. The knowledge gained in developing this evaporator will also be put to use in future projects where there are similar cost savings to be achieved.

NL-05 De Graafstroom

The Cheese & Butter group produces and sells semi-hard Gouda cheeses in a number of varieties (Campina Holland Cheese) which is produced in Bleskensgraaf. Since 1992, Campina has supported the Dutch Long-Term Energy Efficiency Agreements for Industry (LTA-1 and LTA 2) covenants between the private sector and the government to realise the goals of (inter)national climate policy.

NL-06 McCain

In the summer of 2012, a heat pump is installed at a plant of a French fries producer. This heat pump will provide the majority of the energy needed for drying of French fries before they are baked. The used dryer type is a belt dryer that operates at a maximum temperature of 70 °C. The innovative application of a heat pump connected to a French dryer, invented by De Kleijn Energy Consulting, is the first of its kind. Energy savings as high as 70 % on the dryers energy consumption will be realized.

Refrigeration

Most of the waste heat is available from the condensing heat of refrigeration plants. The temperature level is between 30°C and 40°C. This energy source amounts to 28 PJ a year. Similarly the heat consumers have been investigated showing that 14 PJ is consumed by various processes at temperature levels between 60°C to 110°C. Some information of example projects is available, where one of the projects is a UK project by Grenco.

UK-01 Wiseman Dairies

> The company of Robert Wiseman in UK was confronted by the choice of replacing the refrigerant R22 by a more environmentally friendly solution, or of investing in a completely new plant based on ammonia as refrigerant. Although planning revealed that an ammonia plant would operate more efficiently, the customer initially did not accept this solution owing to the long amortization period. Yet, in the end, GEA Refrigeration Technologies made an investment so attractive by an add-on, in the form of a heat pump, that Wiseman could not resist. The new system allows using the heat emitted by the refrigeration plant to be used for pasteurization of the milk – and the entire plant will now amortize itself in less than two years (Source: Grenco).

NL-08 Blue Band margarine factory Unilever Rotterdam

The Blue Band factory from Unilever, at the Nassaukade in Rotterdam is over 120 years old and at the moment the world largest factory for margarine with an output of more than 200.000 tonnes of margarine and 10.000 tonnes of peanut butter. Over that period of 120 years many changes in building, expansion and machinery have been done and a large overhaul of the complete production and building has never been undertaken creating a complex onoverzichtelijke situation. When in 2009 the boiler-room was going to be renovated the 40 years old steam boiler had to be replaced. Of the installed capacity more than 40% was not used because the new production lines have a lower energy use. As production had to go on a new boiler-house was designed near the old existing one.

NL-09 Thermal vapour recompression heat pump at Heineken Den Bosch

Heineken Den Bosch has installed a heat pump in the wort boiling house during a renovation. The heat pump is a thermal vapor recompression (TVR) type placed on the wort boilers. The TVR is used to reduce the energy consumption of the wort boiling process. The heat pump started operation early 2005. The savings on gas consumption and CO2 emission are considerable.

NL-10 Dommelsche Bierbrouwerij

NL-11 Export Slachterij Apeldoorn (Slaughterhouse)

The slaughterhouse at ESA for veal requires large amounts of hot water for room and machinery cleaning and for removing hair from veal skin, and a smaller amount for sterile water (90 °C). The heat pump has been installed in a slaughter house at a moment that the steam boiler had to be replaced. This created the opportunity to improve the hot water system efficiency. The heat pump is a 45 bar reciprocating compressor coupled to the high pressure side of a refrigeration plant with ammonia as refrigerant (see figure 1). The heat pump condenser heats up water up to 62.5 °C. The installation is running more than one year with great satisfaction and reliability.

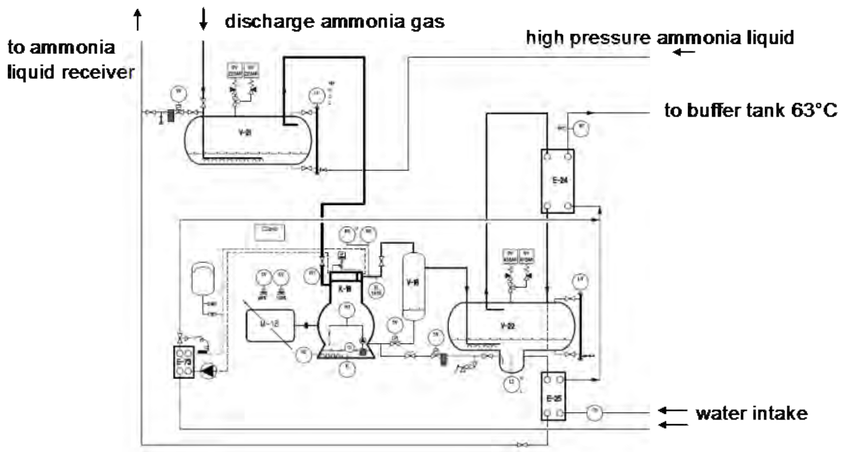


Figure 10-3: Cycle process

NL-12 GPS (Gecombineerde Pluimvee Slachterijen)

GPS in Nunspeet is a slaughterhous for poultry. The condenser heat from cooling and refrigeration is used for process and space heating. The heat pump as described is running since 1994 with 3,750 hours/year of operation often in 65% partial load. Running the heat pump is simple, but maintenance is more complex and contracted out. There are no data available on the energy savings as there are no reference data.

NL-13 Sonac

Sonac in Suemeer processes animal offal and carcasses. The feedstock is after breaking an crushing to small particles heated to remove the liquids and water. MVR is used to heat this process. The heat pump is running since 1996 for 6,000 hours/year in full load. Running, servicing and maintenance are simple and robust done by the in house technical group. As the system is running to design the company expects that the foreseen energy savings are achieved.

NL-14 AVEBE Ter Apelkanaal

AVEBE is one of the largest potato starch producers in Europe with a yearly output of 500,000 tons of starch. The waste water streams from the production process are evaporated to the stage of protamylasse. A overall of 2,475.000 tons of water is evaporated in the process per year. In this part of the process AVEBE already in 1990 invested in energy efficiency measures where a mechanical vapour recompression heat pump was installed in the first phase of a three phase evaporator. The heat pump runs 5,000 – 6,000 hours/year largely in partial load of 65%.

Running is simple but servicing is contracted out. AVEBE estimates that the expected savings are largely achieved.

10.1.3 Misceleneous

Under this heading several industries are clustered which are of various types of processes.

NL-15 MVR for sludge drying at Sophus Berendsen Textiel in Apeldoorn

Berendsen Textiel in Apeldoorn is an industrial washing plant for industrial cleaning cloths. The evaporation of watery sludge streams is done through a process of mechanical vapour recompression and has replaced a process of water treatment with reversed osmosis. The heat pump as described in the original factsheet and in its original design is stil in use and makes 6000 running hours per year. It is running at 50 – 100% partial load. Every week the heat pump is stopped to be able to clean the heat exchangers while once a year the heat exchanger are replaced by new ones. Maintenance is done by in-house technical service department with the main attention at the heat exchangers and the composition of the waste water.

NL-17 Ahrend

No details available.

NL-18 SCM-TDC in Kampen

No details available.

NL-19 Brinks Metaalwaren

Brinks is specialist in: drilling, milling, thermal deburring and cleaning in serial batches ranging from 500 to 200,000 units. Maximum unit weight 20 Kgs. In the chain of production Brinks performs the role of process-supplier with the specialism of multispindle CNC processing, thermal deburring (TEM) and the specifically custom-made cleansing of products.

NL-20 Icerink in Enschede

In October 2008 a new indoor skating rink was opened in the city of Enschede. The refrigeration plant for this skating rink was designed, delivered and installed by IBK. CO2 was chosen as the secondary refrigerant. CO2 is easily detectable, sustainable and - above all -very energy efficient, since less pumping energy is required and pipes with a smaller diameter can be used. The residual heat of the refrigeration plant is used for the Zamboni, for the CH block and for the unique floor heating system, which is located under the skating rink.

NL-21 Wastewater treatment in Raalte

The temperature of the effluent of the wastewater treatment plant varies from 8 to 20 °C and thus contains thermal energy. Effluent is discharged into surface water. This is not an ideal situation, because the thermal energy has a negative effect on surface water. Furthermore, a potential source of energy is lost. In this project the water board Groot Salland and the municipality of Raalte want to use thermal energy from the effluent to heat the nearby swimming pool Tijenraan.

NL-22 LIDL Distributiecentrum Heerenveen

Lidl has built a large distribution centre near Heerenveen of 46.000 m². The project is one large building with several subsections like distribution centre, offices and technical rooms. The building was nominated 4 stars being Excellent in BREEAM according to the Dutch Green Building Council (DGBC).

Also for their supermarkets they have their strategy on renewables, which is actually the case with Lidl all over Europe. Their communication manager: Marcel Ganzeboom: “*Ik vind eigenlijk dat iedereen zo moet denken. En vaak is duurzaam helemaal niet duurder. Je moet gewoon niet bang zijn om nieuwe technieken te onderzoeken en te gebruiken. Wij geven echt niet meer geld uit dan hoeft. Als je een winkel moet koelen én verwarmen, waarom zou je dan niet twee vliegen in een klap slaan met een warmtepomp? De eerste keer is dat een proefondervindelijk stapje en nu is het standaard. Wij bouwen al zes jaar geen winkels meer met een cv-installatie. Een warmtepomp is gewoon een stukje techniek waarmee je het gasverbruik terugdringt – hoe moeilijk kan het zijn?”*

No further information or specification of technologies is given.

10.1.4 Industrial areas

In the Netherlands other industrial areas are getting more and more sustainable. Information can be found on: www.energiezuinigebedrijventerreinen.nl.

NL-23 Ecofactorij industrial area

Ecofactorij in Apeldoorn is an industrial business area south of the City of Apeldoorn. The local authorities have the policy to develop this area as sustainable as possibly by creating the right boundary conditions for settling new companies. This has been described in the “Kwaliteitsplan Ecofactorij” (Qualityplan Ecofactorij). By investing in sustainability and renewables points are given with which rebates were given on the price of land.

Energy is within this sustainability approach an important topic as almost 40% of the point could be gained by investing in these. This has resulted in the fact that 80% of the companies and buildings are equipped with heat pumps and 20% with bio-pellet heating. As the business area is near the traffic junction A1/A50 in the middle of the country, logistic service providers like Sandds, Sils, Harbers and Grolleman Cold Store are settled at the Ecofactorij.

Initially the idea was to cluster companies on connecting to a common infrastructure of heat, waste heat and annual thermal energy storage with heat pumps. In the end the slower than expected development of the area and the larger than expected attraction for logistic distribution centres changed into an approach to individual sustainable and renewable solutions.

NL-24 Bakker Barendrecht – freezing store

A large distribution centre for fruit and vegetables requires a cooling capacity to maintain temperatures at 2ºC and 12ºC during the year. At the same time heat is required for ripening of bananas, defrosting of air coolers and water heating. Industrial heat pumps have been installed for cooling and simultaneously heating. The heat pumps increase the energy efficiency of the total plant and have reduced the investment costs for electricity supply equipment and heating installations.

NL-25 Bovendeert Shoes

The warehouse and headquarters of shoe store chain Bovendeert in Boxtel, contains, besides thousands of colourful shoeboxes and shoes, also an installation with highlighted technical features. Besides the accompaniment of an international automation standard type KNX to link an innovative and energy saving heat pump installation from LG Electronics on an advanced controlled electrical installation, a durable and comfortable installation concept arose.

10.1.5 Agriculture

The major energy user in the agricultural sector are greenhouses where heat pumps are becoming state of the art. Other sectors in agriculture are of interest too.

NL-27 Greenhouses

Since 1998 when the first idea wars reported on the ‘closed greenhouse’ concept several projects and experiments have been started. Some failed as there are different crops which have to be handled differently, but in the end the concept is now broadly accepted for most of the types of crops. All these applications are feasable because of the broad experience built up with ATES systems. Under NL-27 five examples are generally described.

In the period 2003-2013, in Dutch horticulture approximately 40 growers of various crops have implemented heat pumps in their greenhouses. In the following, we present 5 factsheets concerning the application of heat pumps in Dutch horticulture in the production of roses, tomatoes and orchids.

NL-27 a	Themato
NL-27 b	Anthura in Bleiswijk
NL-27 c	Hecostek in Biezenmortel
NL-27 d	Ermstrang
NL-27 e	Entius in Heerhugowaard
NL-27 f	Hoorn - Grenco

NL-28 ECO 200

No further information or specification of technologies is given.

NL-29 Onion at Broer in Creil

No further information or specification of technologies is given.

10.2 Integrated heat pump technologies

A very important part of the market is where suppliers of turnkey unit operations integrate heat pumping technologies into their product to make these more energy efficient. GEA-Grenco is one of the best examples where they have there drying processes almost always equipped with MVR type of heat pumps [Westergaard]. Sulzer Chemtec from Winterthur does the same for their distillation columns.

Smaller companies in Netherlands not so prominent in the market do the same. Examples are Reinders Droogtech, applying heat pumping technologies integrated in many of their dryers and Rhima integrate heat pumps in their crate wash units.

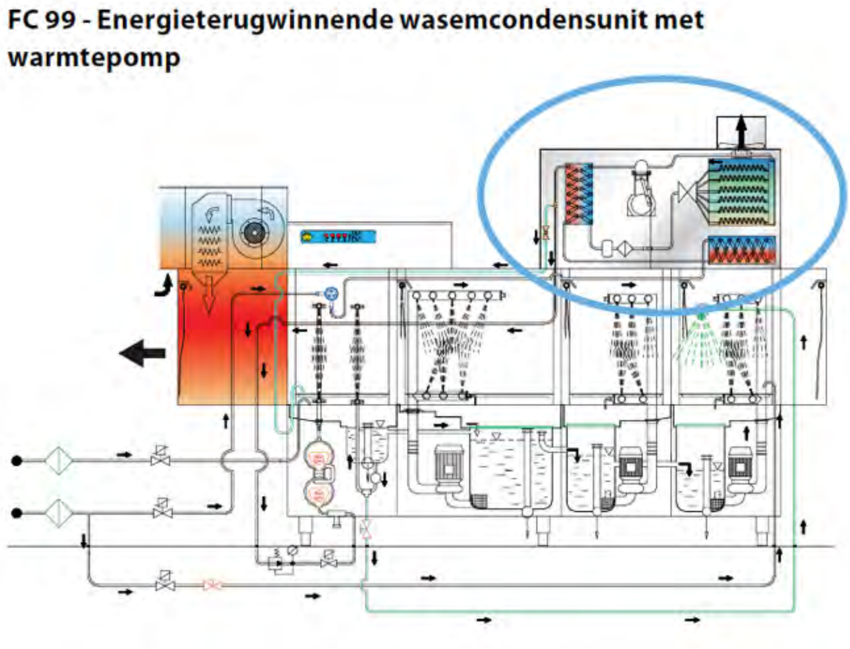


Figure 10-4: *Rhima crate washer*

Due to competative markets details of the two applications are not given. Information at:

www.droogtech.nl (Reinders Industrial; Plesmanweg 17; 7602 PD Almelo)

www.rhima.nl (RHIMA Nederland; Energieweg 4-6; 3762ET Soest)

10.3 What happened with projects on older factsheets?

This is to inform about some older projects that were published on factsheet in de mid nineties.

10.3.1 Efficient cooling system with heat recovery for Tofu production[2]

At the Lin Tahoe plant, tofu is produced by allowing soya bean milk to curdle at a temperature of 95°C. The process takes place in open vessels, which are checked visually. During the curdling process, a considerable amount of water vapor is released, which tends to condense inside the production hall. After the curdling, the product is pressed

[2] CADDET Project no. NL-92-011

into blocks and cooled, originally from about 60°C to 14°C by pouring cold water over it, and then to 5°C in a cold storage chamber.

Stricter demands from the health authorities mean that the product now has to be cooled to 7°C in one single stage, and that condensate from the production hall can no longer come into contact with the product. To meet these demands, a new, energy-efficient cooling system has been installed. A heat pump prevents condensation forming on the factory walls on cold days.

The cooling installation in the main production line consists of two parallel cooling vessels containing circulating cold water, through which blocks of tofu are passed by a conveyor belt. It takes about three hours to cool the blocks from their production temperature of about 60°C to their maximum storage temperature of 7°C. The water in the vessels is kept at a temperature between 2°C and 4°C by cold glycol flowing through the double wall of the steel cooling vessels.

The glycol in turn is cooled in an external cooling unit to a temperature of -2°C. In the cold season, the heat from the condenser of this cooler is used to heat the ventilation air of the factory hall. Apart from the improvement in the indoor climate of the factory, the enhanced temperature prevents the condensation of evaporated water. This condensate could otherwise make contact with the product and cause contamination.

The total investment for this project was USD 200,000 (1992), of which 60% is attributed to the new cooling system. Compared to the previous situation, the cooler saves 140 MWh/year and the heat pump 235 MWh/year. At an electricity price of USD 0.1/kWh, the investment resulted in a payback period of 5.5 years.

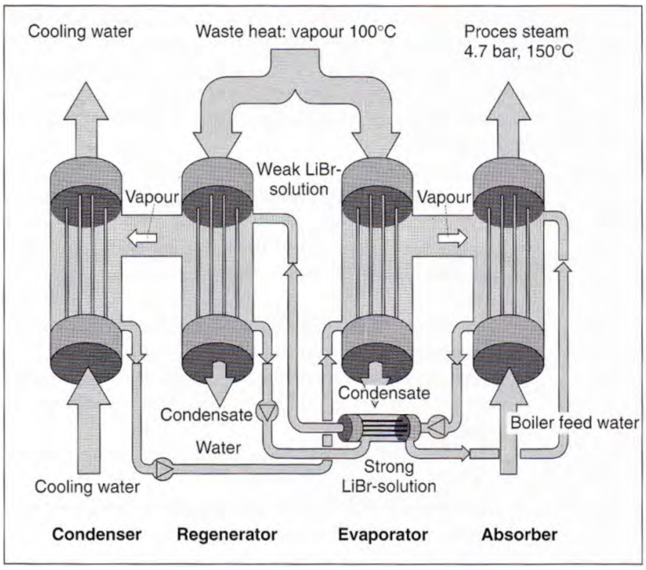
The heat pump was installed in 1991. The Lin Tahoe plant has since then been sold to Alpro Soja which in the end stopped production at the site.

10.3.2 Absorption Heat Pump, Type II Heat transformer in the chemical industry

The heat transformer was in operation with Dealmine in Delfzijl in an ethylene amine plant. It produced 11 tonnes of saturated steam at 145 °C and 4.6 bar at full load, and used saturated steam at 100°C to drive the system. The measured heating capacity was 6.7 MW at 11 tonnes of steam per hour, whilst 13.7 MW of waste heat was needed to drive the unit. The measured COP of was 0.49. The total power needed for circulating pumps etc. is 53 kW (less than 1 % of the output). At the time the system was installed (1985) the payback period was two years.

Prior to filling the system, the equipment was cleaned and tested for air leakage. Chromate-hydroxide was used as inhibitor in the LiBr circuit. The equipment operated for six months without problems, before interruptions occurred due to corrosion. Corrosion was first noticed in the heat-recovery heat exchanger, circulation pumps and steel tubes. Later, corrosion problems developed in the other heat exchangers. Due to the corrosion, performance and heat output decreased. The lower output was due to clogging of passages by corrosion products.

The heat-recovery heat exchanger is of the plate type, with titanium plates and ethylene propylene diene methylene gaskets. In the heat exchanger, crack corrosion occurred in the structure housing the gasket.



When the leakage became too great, a new heat exchanger with Ti/Pd plates was installed. That heat exchanger corroded after only a few hours of operation, due to flow-induced vibration causing stress corrosion. A new heat exchanger with Ti plates and safeguards to eliminate the plate vibration was later installed. During operation, clogging of the heat exchanger occurred due to the settling of corrosion particles. To reduce the extent of corrosion particles in the system, two filters have been installed. However, corrosion and fouling continue, and plates have to be replaced twice a year. The principal corrosion type is deposit attack. This causes the plate material to become brittle locally, and extremely sensitive to cracking.

In the evaporator, after seven months of operation, four stainless steel tubes were found to be leaking, and other tubes had suffered from pit corrosion. A new evaporator equipped with Ti tubes and CuNi-clad inner shell was then installed to tackle the problem. Inspection of the absorber showed that all unalloyed steel parts which were in contact with LiBr were covered with crusty corrosion products. Carbon steel parts, such as the shell, had suffered from galvanic effects. The absorber was again replaced, and carbon steel piping, which was in direct contact with the LiBr solution, was replaced with CuNi.

The canned weak solution pump had to be replaced after five months of operation. Stainless steel parts such as the inducer had broken, and the adjustment ring had cracked. The inducer had probably suffered from cavitation during operation, which led to stress corrosion. The same type of corrosion occurs in the pump as in the heat-recovery heat exchanger, i.e. deposit attack.

The heat transformer at the Hoogovens site was the second one installed in the Netherlands. The first one, at Delamine Delfzijl is definitively taken out of operation due to serious internal corrosion problems caused by the LiBr-solution and air-leakage. This corrosion phenomenon was studied extensively under a European project and has led to the following measures adapted in the Hoogovens design:

- minimize number of materials; exclusively CuNi, carbon steel and, for the plate heat exchanger, titanium are used.
- regular testing for high air tightness.

- flange connections are avoided to a maximum.
- continuous measuring of the oxygen content in the condensate (may not exceed 5 ppb).
- regular control of the composition of the working fluid and corrosion inhibitors
- continuous measuring of corrosion rates
- continuous filtering of LiBr-solution and condensate
- only N2 is permitted to fill up the vacumized part of the installation.

The heat transformer consists of four vertical shell and tube heat exchangers which are open connected in pairs (evaporator + absorber, regenerator + condenser). A rich LiBr-solution (63%) is mixed with water vapor in the absorber. The released heat is used to produce steam (2.7 bar, 130 °C) from boiling feed water (110 °C). The water vapor used in the absorber is produced in the evaporator at a pressure of 0.05 bar with waste heat of 90 °C. The lean LiBr-solution (60%) from the absorber is sent to the regenerator at a pressure of 0.5 bar to create a rich solution by evaporating water with waste heat of 90 °C. The rich LiBr-solution is directed to the absorber. The water vapor is condensed in a fourth heat exchanger with cooling water and pumped back to the evaporator. As well as the four large shell and tube heat exchangers, a compact plate heat exchanger is used to exchange heat between the rich and lean solution. The efficiency of the heat transformer is determined by the temperatures of cooling water, waste heat and steam.

At the Hoogovens site, large quantities of waste heat are released in the hot rolling strip mill. The furnaces are cooled with water of which the temperature is increased to 90 °C. Since 1991 the duty of this cooling water is no longer cooled in a cooling tower but is partly used in a heat transformer. Therefore transportation of cooling water takes place through pipelines to the heat transformer at 800 meters distance. The heat transformer cools the water from 90 down to 85 °C and produces steam at 130 °C and 2.7 bar. With 1,700 tonnes per hour waste water it is possible to generate 6.5 tonnes low pressure steam per hour. The saturated steam is superheated to 136 °C with middle pressure steam from the existing boiler and used in several processes at the cold rolling strip mill. The heat transformer is supplied by Rinheat OY from Finland. This company has great experience with this type of heat exchangers used for the heat transformer.

Economics: The heat transformer takes up 9 MW_{th} from the waste heat from the hot rolling strip mill. The produced steam is equal to 4.1 MW_{th}. The other part is cooled by cooling water (4.9 MW_{th}) of which the temperature increases from 20 to 26 °C. The power consumption of the several pumps is only 60 kW_e. The energy savings are 4.8 million m^3 natural gas when assuming an annual operation time of 8,000 hours.

The total investment was approximately 3.4 million €, of which 60% was spent on the heat transformer. The transportation system for 90 °C cooling water and adaptations in the existing steam system were 25 and 15 % respectively. The European Union and Novem have sponsored the project.

The heat transformer has only been in operation for several years as the high maintenance costs and the low availability and reliability made further operation in-economic. Due to process-changes where the temperature of the cooling water for the furnace was lowered, the heat transformer did not run optimally.

10.4 Literature

Westergaard — Milk Powder Technology, Evaporation and Spray Drying, ed. Vagn Westergaard, 5th Edition, GEA Process Engineering

Kleefkens, 1996 — Kleefkens O., Industrial Heat Pumps, MVR/TVR-systems in chemical industry, Dv3.4.39 96.11, ©Novem, Utrecht 1996.

APPENDIX

Japan

The Netherlands

1 A1 - Japan

1.1 Challenges and Necessary Support for Increasing the Use of Industrial Heat Pumps

1.1.1 Challenges for increasing use

Energy consumers in Japan can be roughly divided into three sectors: industrial, residential/commercial, and transport, which respectively consume about 44 %, 23 % and 33 % of the total energy (in FY2010). In terms of the increase rate of final energy consumption, the residential/commercial sector shows a much higher increase rate than that of the industrial and transport sectors. It is important to curb the consumption of the residential/commercial sector. However, the industrial sector still consumes most energy, which implies that the encouragement of energy efficiency technologies remains an important issue. About 90 % of the consumption of the industrial sector is the consumption by manufacturers, which mainly use energy for heating in production processes and their associated HVAC. Therefore, popular use of heat pumps by the industrial sector could be an extremely effective energy-saving measure in Japan. The sector is increasingly expected to introduce and encourage the use of heat pump systems.

The introduction of industrial heat pumps involves many challenges to be overcome. Technical challenges include higher system output temperature, lower heat source temperature, higher system capacity and efficiency, lower environmental load of refrigerants, and lubrication countermeasures. Social and economical challenges include lower system price, generalization/standardization, diversification of heat sources, public communication, and development/relaxation of laws and regulations. Particularly, price is very likely to be against performance. Appropriate planning of measures for developing and introducing industrial heat pumps with balanced price and performance is also important. For example, hot-water supply CO_2 heat pumps have been subsidized for installation in the residential/commercial sector. Thanks to the government subsidy, 3 million units were shipped in the decade from 2001.

In Japan, the introduction of industrial heat pumps has just begun mainly as a substitute for existing small once-through boiler systems. This means that these heat pumps are used for the production of high-temperature hot water or steam. To reach a stage in which new heat pump systems are designed and introduced, not as a replacement of existing boiler systems, public support, particularly by the government for research & development (R&D), commercialization and initial introduction, may be a key factor for wide spread use of the systems.

1.1.2 Current government support programs

R&D of heat pump technology is an important key factor for energy conservation in the residential/commercial, transport and industrial sectors including plant HVAC, humidification and drying applications. R&D in Japan has been positively supported by the government, particularly the Ministry of Economy, Trade and Industry (METI) and New Energy and Industrial Technology Development Organization (NEDO). For example, NEDO has specified key energy efficiency technologies to be intensively addressed (Figure 1-1), and annually subsidized about 10 billion yen for R&D of the technologies. Among these, next-generation heat pump systems were selected as a "cross-sector key technology" to be widely used because it increasingly found more applications in all of the industrial, residential/commercial and transport sectors.

Specific R&D challenges for the next-generation heat pump system include developing a high-efficiency refrigeration cycle, a new refrigerant, and innovative fundamental technologies related to high-efficiency heat exchangers and compressors. In addition, unused heat utilization, high-efficiency heat recovery/storage (simultaneous production of heating and cooling), expansion power recovery, light-load efficiency optimization, CFC-free refrigeration/air-conditioning systems, and other various system-related technologies including securing of heat sources and secondary circuit control methods, have been selected as R&D themes.

To achieve the prime target of enhancing the heat pump system efficiency to 1.5 times the current level in 2030 and double in 2050 (*1), a national project aimed at developing a super-high-efficiency heat pump is being separately promoted. As technologies for successful development, use of various types of unused heat, annual efficiency enhancement according to actual loads, maximizing the use of generated heat, and efficient production of high-temperature water/ steam or air were selected, and about 800 million yen was spent for the R&D subsidy in the year (FY2012). Furthermore, a high-temperature heat pump that uses exhaust heat or simultaneously produces high-temperature steam and low-temperature water as a substitute for existing boilers in factories was selected as a specific technical development theme, and is waiting to receive a subsidy. (*1. According to the Technology Development Road Map of "Cool Earth Innovative Energy Technology Program", industrial heat pumps producing 120℃ high-temperature heat should be targeted to achieve higher efficiency by 1.3 times the current level, and those producing 180℃ high-temperature heat targeted to exceed the efficiency of existing heating systems (such as boiler systems)).

One example of subsidy programs for introduction of heat pumps is the "Urgent project for promoting the introduction of next-generation heat utilization systems" (total budget 15.5 billion yen) by METI between 2012 and 2013. This project supports plants and facilities to introduce a next-generation heat utilization system to recover and re-use low-temperature waste heat at 300 °C or less released to the atmosphere from their running equipment. For example, low-temperature exhaust heat-driven absorption refrigerating machines and steam generating heat pumps are covered. The subsidy rate is up to a half of the applicable expense for recovery of waste gas/ steam at less than 140 °C, or up to one third of the same between 140 °C and 300 °C. The subsidy is expected to expand system demand by private companies and to make the system available at a lower price from mass production, leading to further demand expansion.

For Japan, with only limited fossil fuel resources, increasing the use of renewable energy is also an urgent matter. The country is promoting the development of a heat pump system utilizing unused thermal energy. In recent years, the government launched a subsidy program and conducted legal reform to encourage the development of heat pump systems using geothermal or sewage heat as a heat source. Sewers are expected to also serve as thermal ducts that crisscross all cities. While the residential/commercial sector mostly needs cold water supply during summer and hot water supply during winter, industrial processes require cold and hot water supply at a relatively constant balance throughout the year, which however depends on the type of process. Using sewage heat for industrial processes could help moderate the sewage temperature variation. Thus, expectation for industrial heat pump systems using sewage is gaining ground.

For example, the Ministry of Land, Infrastructure and Transport established the Act on Special Measures concerning Urban Reconstruction (which came into operation on July 25, 2011) to permit the use of sewage heat by private operators. The Ministry also launched the Water Environment Creation Project under the New Generation Sewage Support System and Next Generation Urban Improvement Projects to promote the introduction of heat pump systems using sewage heat, and the Town Making Subsidy to promote the introduction of regional cooling and heating facilities. The Ministry of the Environment conducted the Cool City Promotion Project [Underground Water and Ground Source Utilization] (2009), and Ground Source/Sewage Heat Pump HVAC Demonstration Test (from 2010) to promote the use of renewable energy with heat pumps, which was also expected to serve as heat island countermeasures. One example is a food product plant (Hokkaido) where a simultaneous cold (2℃) and hot (65℃) water-producing heat pump recovering geothermal heat as well as exhaust heat from refrigerators and septic tanks, was installed to supply cold water for vegetable washing, and hot water as a low-quality water supply for plant cleaning.

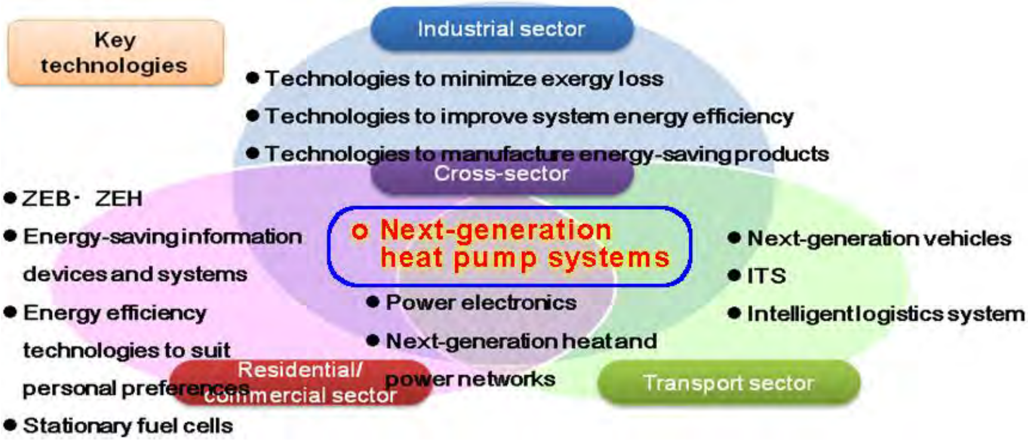


Figure 1-1: Thirteen “Key technologies” in “2011 Strategy for Energy Efficiency Technologies”

1 Appendix A2 - Japan

The tables below show a list of recent installations of industrial heat pumps. Shaded cases are detailed in the following sections.

Industry	Plant	Process	Heat use	Application	Purpose	Installed in	System overview	Effect
Food	Nakashibetsu Plant, Meg Milk Snow Brand Co., Ltd.	Cheese production	Thermal storage	Milk sterilization at 75 °C Quick milk cooling at 30 °C Cheese cooling (HVAC) at 10 °C	Strict temperature control for cheese production Power load levelling and higher-efficiency management through introduction of thermal storage systems	2007	Turbo refrigerator 1,395 kW (for ice making): 2 units Water-cooled chiller 240 kW: 2 units Ice storage tank 84 m^3	Daytime power use of approx. 3,700 kWh per day was shifted to night-time use to achieve power levelling. Utility contract power was reduced by 600 kW (approx. 2,600 kW -> approx. 2,000 kW)
Food	Sanda Plant, Cosmos Foods Company	Freeze-dried food product manufacturing	Steam reduction	Food boiling Production line cleaning: hot water at 85 °C Building HVAC: cold water at 10 °C	Installation of 90 °C water producing equipment Hot/cold water supply to HVAC and processing lines from simultaneous hot/cold water producing heat pumps	2010	・Simultaneous hot/cold water producing heat pump (water source heat pump (WSHP) with CO_2 refrigerant): 3 units Heating capacity 92 kW (90 °C) Cooling capacity 69 kW (10 °C) ・Hot water tank 37.5 m^3 ・Chilled water tank 500 m^3	Hot water supply for food processing and plant HVAC were simultaneously achieved to reduce both CO_2 emissions and energy cost by 80 % or more.

Examples of Recent Industrial Heat Pump Installation

Industry	Plant	Process	Heat use	Application	Purpose	Installed in	System overview	Effect
Food	Tamura Noodle-Making Corporation	Noodle production	Thermal storage	90 °C hot water supply for preheating the noodle boiling pool (98 °C) Boiled noodle cooling: cold brine (-5 °C) for cooling ice storage tanks that supply cold water at 2 °C	Hot/cold water supply to noodle production processes CO_2 emissions reduction and energy cost-cutting with heat pumps	2008	・Simultaneous hot/cold water supply heat pump (WSHP with CO_2 refrigerant): 1 unit Heating capacity 56 kW (90 °C) Cooling capacity 38.2 kW (-2 °C) ・Hot water tank 15 m^3 ・Ice storage tank 4.1 m^3	・Heavy oil consumption was reduced by 70 %. ・CO_2 emissions were reduced by 31 %. ・Energy cost was reduced by 25 %.
Food	Plant in Shikoku Island	Noodle production	Steam reduction, Waste heat recovery	Hot water supply (83 °C) to noodle boiling pools (98 °C) and cold water supply (10 °C) to noodle cooling pools (3° C)	Hot/cold water supply to noodle production processes, CO_2 emissions reduction and energy cost-cutting with heat pumps	2008	・Simultaneous hot/cold water producing heat pump (WSHP with CO_2 refrigerant): 1 unit, Heating capacity 72 kW (90 °C), Cooling capacity 50 kW (5 °C) ・Hot water tank 24 m^3	・Primary energy consumption was reduced by 19 %. ・CO_2 emissions were reduced by 43 %.

Examples of Recent Industrial Heat Pump Installation

Industry	Plant	Process	Heat use	Application	Purpose	Installed in	System overview	Effect
Food	Osumi Plant, Kagoshima Kumiai Chicken Foods Co., Ltd.	Chicken product manufacturing	Steam reduction	Heating the hot water supply to steam boilers: 65 °C	Effective heating of high-volume water supply To eliminate dependence on steam boilers, and reduce the environmental load by introducing heat pump water heaters	2008	・Air source heat pump (ASHP) with CO_2 refrigerant: 1 unit Heating capacity 80 kW (65°C) ・Hot water tank 10 m^3	・CO_2 emissions were reduced by 65 %. ・Energy cost was reduced by 88 %.
Plant factory	Yasaikobo Co., Ltd.	Lettuce growing	Thermal storage	Plant factory HVAC (dry-bulb temperature 20-24 °C, relative humidity 60±10 %)	To install highly temperature/humidity controllable heat pumps to maintain the environment in the plant factory in a constant state.	2008	ASHP (cooling capacity 28 kW): 4 units	・Stable production ・High quality product ・Maintenance-free
Beverage	Kyushu Nitta Plant, Sapporo Breweries Ltd.	Beer production	Waste heat recovery	Hot water supply for cleaning and sterilizing tanks/ovens (70 °C) Cooling the heat by fermentation (-5 °C)	To recover heat by fermentation of beer, which has been wasted, produce hot water, and use it for cleaning and sterilization of tanks and ovens	2009 to 2010	Waste heat recovery heat pump 35 kW: 4 units Hot water supply capacity (70 °C): 111.6 kW Cooling capacity (-5°C): 81.6 kW	・Annual hot water supply energy was reduced by 18 %. ・Annual cooling energy was reduced by 14 %.
Beverage	Chita Distillery, Sungrain Ltd.	Whisky and material alcohol production	Steam reduction Waste heat recovery	Vapor re-compression	Energy-saving through re-compression, and reuse of vapor from alcohol distillation facilities	2002	Combined VRC system (mechanical and thermal vapor re-compression, vapor flow rate: approx. 4 t/h)	・Primary energy consumption was reduced by 43 %.

Examples of Recent Industrial Heat Pump Installation

Industry	Plant	Process	Heat use	Application	Purpose	Installed in	System overview	Effect
Paper making	Iwabuchi Facility of Tokai Mill, Oji Specialty Paper Co., Ltd.	Paper manufacturing by recycling broke	Thermal storage	Hot water supply to water tanks for supplying hot water to broke pulpers: 75 °C	Hot water supply to broke recycling process Reduction of waste vapor by supplying hot water from heat pump water heaters	2009	・ASHP with CO_2 refrigerant: 8 units Heating capacity 40 kW (75 °C) ・Hot water tank 25 m^3	・CO_2 emissions were reduced by 50 %. ・Primary energy consumption was reduced by 42 %.

Examples of Recent Industrial Heat Pump Installation

Industry	Plant	Process	Heat use	Application	Purpose	Installed in	System overview	Effect
Chemical	Saiden Chemical Industry Co., Ltd.	Adhesive production	Thermal storage	Cold water supply to reaction ovens: 9 °C	Stable supply of cooling water to reaction ovens To enjoy various benefits including CO_2 emissions reduction by introducing a chilled water storage system.	2005	・ASHP modules: 1 set Cooling capacity 800 kW ・Hot water tank 1,000 m^3	・CO_2 emissions were reduced by 50 %. ・Primary energy consumption was reduced by 32 %.
Plastic	Diachemical Co., Ltd.	Styrofoam molding production	Steam reduction Waste heat recovery	Hot air: 90 °C Cooling of hot effluent (70 to 80 °C)	Hot air supply at up to 120 °C To apply a hot air heat pump to drying process To contribute to lower CO_2 emissions and higher safety	2010	Hot air WSHP with CO_2 refrigerant: 1 unit Heating capacity 110 kW (90 °C) Operating range Hot air outlet temperature: 80 to 120 °C Heat source water outlet temperature: -9 to 35°C	・CO_2 emissions were reduced by 63 %. ・Primary energy consumption was reduced by 48 %.
Glass	Osaka Facility of Kansai Plant, Asahi Glass Co., Ltd.	High-quality glass production	Clean rooms	Hot and cold (7 °C) water supply for clean room HVAC	To improve the environmental performance and cost efficiency	2007	Turbo refrigerator (for cooling only): 2 units Turbo refrigerator (double bundle, hot/cold water supply): 1 unit	・CO_2 emissions were reduced by 26 %. ・Primary energy consumption was reduced by 16 %. ・Energy cost was reduced by 18 %.

Examples of Recent Industrial Heat Pump Installation

Industry	Plant	Process	Heat use	Application	Purpose	Installed in	System overview	Effect
Pharma-ceutical	Tsukuba Research Laboratories, Eisai Co., Ltd.	R&D of new drugs	Steam reduction Thermal storage Waste heat recovery Clean rooms	Hot water supply to reheating coils of HVAC using outside air equipped with evaporative humidifier: 30 °C	To replace steam humidification with evaporative humidification Use steamless air-conditioners to achieve energy-saving and cost reduction by breaking the "common sense for HVAC" in the pharmaceutical industry.	2008	・Steamless HVAC (using outside air), capacity 33,000 m^3/h: 2 units ・Small water source heat pump unit and others	・CO_2 emissions were reduced by 77 %. ・Energy cost was reduced by 82 %.
Pharma-ceutical	Daito	Pharmaceutical production	Clean rooms	Cold water supply for clean room HVAC (dry-bulb temperature 20 °C, relative humidity 50 %)	HVAC, production process temperature and humidity control To meet various applications and needs with modular heat pumps	2008	Modular ASHP Cooling 380 kW: 1 set Cooling 635 kW: 1 set Cooling 715 kW: 1 set	・CO_2 emissions were reduced by 67 %. ・Primary energy consumption was reduced by 53 %.

Examples of Recent Industrial Heat Pump Installation

Industry	Plant	Process	Heat use	Application	Purpose	Installed in	System overview	Effect
Pharma-ceutical	Tokushima Itano Plant, Otsuka Pharmaceutical Co., Ltd.	Pharmaceutical production	Waste heat recovery Clean rooms	Hot (45 °C) and cold (7 °C) water supply for clean room HVAC (room temperature 23 °C, relative humidity 40-60 % or low humidity 25-40 %)	Hot/cold water supply for clean room HVAC To realize advanced air rooms and energy- saving in the pharmaceutical plant using a simultaneous hot/cold water producing heat pump	2009	Simultaneous hot/cold water producing heat pump: 1 unit Hot 247 kW (45 °C) Cold 180 kW (7 °C)	Heavy oil consumption was reduced. ・CO_2 emissions were reduced by 24 %. ・Primary energy consumption was reduced by 24 %.
Mecha-nical	Fujinomiya Plant, Amada Co., Ltd.	Metalworking machinery production	Thermal storage	Cooling water supply (25 °C) to laser oscillators for laser machine operating test	To supply cooling water to laser machines To substantially reduce CO_2 emissions and primary energy consumption with turbo refrigerating machines and chilled water storage system	2007	Turbo refrigerator Cooling capacity 563 kW: 2 units	・CO_2 emissions were reduced by 81 %. ・Primary energy consumption was reduced by 68 %.
Mechanical	Togane Technical Center, Takubo Engineering Co., Ltd.	Coating machine production	Steam reduction Waste heat recovery	Simultaneous supply of hot/cold water to HVAC using outside air equipped with evaporative humidifier	To achieve higher air quality, CO_2 emissions reduction, cost- cutting and higher safety by making coating booths steamless	Unknown	Connected three ASHP modules (total cooling capacity 255 kW), Evaporative humidifier: 1 unit	・CO_2 emissions were reduced by 45 %. ・Primary energy consumption was reduced by 31 %.

Examples of Recent Industrial Heat Pump Installation

Industry	Plant	Process	Heat use	Application	Purpose	Installed in	System overview	Effect
Electric	Kami Plant, Terasaki Electric Co., Ltd	Circuit breaker production	Thermal storage	Hot water supply (65 °C) for heating plating baths (max. temperature 50 °C) and water baths (60 °C)	Heating of plating baths and hot water supply to water baths Lower energy consumption and lower maintenance by introducing heat pump water heaters	2009	・ASHP water heaters: 2 units Heating capacity 55.8 kW (65 °C) ・Hot water tank 4 m^3, 12 m^3	The use of the heat pump water heaters improved energy-saving and cost performance. ・CO_2 emissions were reduced by 19 %. ・Energy cost was reduced by 11 %.
Electric	Minami Electric Co., Ltd.	Transformer case production	Waste heat recovery	Hot air supply to drying process of high-durability coated transformers (80 to 120 °C) Cold water supply to electropainting process (5 to 32 °C)	Preheating (120 °C) of gas drying tower (170 °C)	2009	Hot air WSHP with CO_2 refrigerant: 1 unit Heating capacity 110 kW Operating range Hot air outlet temperature: 80 to 120 °C Heat source water outlet temperature: 5 to 32 °C	・CO_2 emissions were reduced by 19%. ・LPG consumption was reduced by 24 %. ・Energy cost was reduced by 12 %. ・Cold water can be recycled.
Automobile	Hamura Plant, Hino Motors, Ltd.	Production of trucks, buses, cars and other automobiles	Steam reduction	Hot/cold water supply for plant HVAC Heating of washing tanks	To raise the plant HVAC heat source efficiency To reduce environmental load and cost by replacing existing steam equipment with heat pumps	2007 and 2009	2007 ASHP Cold 90 kW: 5 units Cold 85 kW: 10 units 2009 ASHP Cold 95 kW: 6 units	The change of heat source brought a synergistic effect of lower steam demand and lower steam loss. ・CO_2 emissions were reduced by 30 %. ・Primary energy consumption was reduced by 32 %.

Examples of Recent Industrial Heat Pump Installation

Industry	Plant	Process	Heat use	Application	Purpose	Installed in	System overview	Effect
Automobile	Hamura Plant, Hino Motors, Ltd.	Production of trucks, buses, cars and other automobiles	Steam reduction Waste heat recovery	Simultaneous supply of hot/cold water to coating booth circulating HVAC	Energy-saving by simultaneous supply of hot/cold water	2010	Heat recovery heat pump (cooling capacity 456 kW, heating capacity 566 kW): 1 unit	・CO_2 emissions were reduced by 47 %. ・Energy cost was reduced by 63 %.
Automobile	Kameyama Plant, Koyo Heat Treatment Co., Ltd.	Production of automobile parts including bearings and steering	Steam reduction	Vapor re-compression	To reduce environmental load of effluent To reduce CO_2 emissions and improve environmental conservation by introducing heat pump vacuum evaporator	2005	Heat pump vacuum evaporator: 1 unit Evaporation capacity 300 kg/h	The treatment of water recyclable in the plant resulted in lower CO_2 emissions and better environmental conservation. ・CO_2 emissions were reduced by 79 %. ・Primary energy consumption was reduced by 77 %.
Automobile	Suzuka Factory, Honda Motor Co., Ltd.	Automobile production	Waste heat recovery	Plant HVAC	To replace deteriorated gas burning refrigerators with high-efficiency equipment	Unknown	High-efficiency turbo refrigerator, Cooling capacity 3,252 kW Heating capacity 3,755 W Hot/cold water tank	・CO_2 emissions were reduced by 48 %. ・Energy cost was reduced by 25 %.

Examples of Recent Industrial Heat Pump Installation

Industry	Plant	Process	Heat use	Application	Purpose	Installed in	System overview	Effect
Automobile	Gamagori Plant, Aisin AW Co., Ltd.	Automobile part production	Steam reduction Waste heat recovery	Heating of washing liquid in the washing process (65 °C) Cooling of cutting liquid in the cutting process (15 °C)	・To eliminate low energy-efficiency steam use for heating of washing liquid ・To use waste heat for cooling of cutting liquid	2010	・Circulating ASHP (Heating only type, heating capacity 43.5 kW): 8 units ・Waste heat recovery circulating heat pump (Cooling/heating type, heating capacity 22.3 kW): 6 units	・CO_2 emissions were reduced by 86 %. ・Primary energy consumption was reduced by 73 %. ・Energy cost was reduced by 89 %.
Electronics	Aizu Wakamatsu Plant, Fujitsu Facilities Limited	Pure steam, cold water and other utility supply to semiconductor plants	Steam reduction Waste heat recovery Clean rooms	Hot water supply to pure water manufacturing plants, production process HVAC, and cold water supply to manufacturing equipment	Waste heat recovery from turbo refrigerators Lower environmental load through the use of high-efficiency turbo refrigerators and waste heat recovery	2004 to 2006	Turbo refrigerator (heat recovery type): 3 units Cold: 4,219 kW/unit	Existing turbo refrigerators were replaced with the latest model. CO_2 emissions were reduced by 33 %. Primary energy consumption was reduced by 31 %.
Electronics	Chiba Plant, Showa Denko K.K.	Production of small hard disk media	Thermal storage Waste heat recovery Clean rooms	Cold water supply to clean room HVAC, and recirculation of waste heat hot water to pure water production facilities	High-performance HVAC for precision instrument production sites To use an ice storage system for clean room HVAC Energy-saving and cost reduction	2006 to 2007	Turbo refrigerator 3,516 kW: 3 units Ice storage tank 237 m^3	The ice storage system achieved HVAC with high cost efficiency and reliability.

Examples of Recent Industrial Heat Pump Installation

Industry	Plant	Process	Heat use	Application	Purpose	Installed in	System overview	Effect
Electronics	Yokkaichi Plant, Toshiba Semiconductor & Storage Products Company	Semiconductor memory production	Steam reduction Waste heat recovery Clean rooms	Cold water supply to fan coil units in clean rooms, and hot/cold water supply to clean room HVAC using outside air	Waste heat recycling in the plant To recover waste heat released from HVAC and production processes to substantially reduce CO_2 emissions and achieve a steamless HVAC system	2005	Turbo refrigerator	All waste heat within the plant can be effectively used. Steamless HVAC was achieved.
Electronics	Ise Factory, Panasonic Corporation	Control equipment assembly	Clean rooms	Clean room HVAC	To raise clean room HVAC efficiency To improve environmental conservation and energy-saving with high-efficiency heat pumps	2009	ASHP Cold 950 kW: 2 sets	CO_2 emissions were reduced by 59 %. Primary energy consumption was reduced by 31%.

Examples of Recent Industrial Heat Pump Installation

Industry	Plant	Process	Heat use	Application	Purpose	Installed in	System overview	Effect
Printing	Nikkei Tokyo Newspaper Printing Center, Inc., and Nikkei Kawasaki Annex, Inc., Nikkei Inc.	Newspaper printing	Thermal storage Waste heat recovery	Hot/cold water supply to HVAC systems for newspaper printing plants	To supply hot/cold water to HVAC systems for newspaper printing plants To achieve strict temperature and humidity control, CO_2 emissions reduction and energy- saving with thermal storage systems	2006	・Brine turbo refrigerator: 2 units Cold: 762 kW/unit (for ice making) ・ASHP (simultaneous hot/cold water producing): 1 unit Cold: 315 kW Hot: 355 kW ・ASHP （hot/cold water selectable): 1 unit Cold: 355 kW Hot: 425 kW ・Ice storage tank 135 m^3 ・Hot water tank 175 m^3	The two load peaks per day were leveled out to achieve CO_2 emissions reduction and energy-saving.

Source:

1. "Examples of heat pump installation in the industrial sector", Heat Pump & Thermal Storage Technology Center of Japan, Japan Electro-Heat Center

2. "Recommended Electric-Powered Production Processes, Future Ages, Use More Electricity for Production", Japan Electro-Heat Center, 2010

3. 'Possibility of energy-saving and carbon dioxide emissions reduction with vapor re-compression system -Ethanol distillation cases-', Maekawa Mfg. Co., Ltd., "Electro-Heat" No.155, 2007,

4. “LOWER CO_2 IN INDUSTRIAL PRODUCTION PROCESSES THROUGH THE ADOPTION OF HEAT PUMPS”, YUKIYASU DAIMON etc., 10th IEA Heat Pump Conference 2011, 16 - 19 May 2011, Tokyo, Japan

Task 4 report – Factheets on industrial heat pumps in Netherlands

NL-01 MVR System at Shell PP-splitter in Pernis

Summary

Propylene is a key material in the production of a number of chemical products including polypropylene (PP) and solvents. It is obtained by distillation separation of propylene and propane in a so called PP-splitter column. In a conventional distillation the reboiler is heated by low pressure steam or hot condensate and the overhead vapours are cooled with cooling water.

In 1995 as a part of the modernisation of the whole propylene distribution system within the Shell site at Pernis, a new propylene-propane distillation column was built with the application of mechanical vapour recompression (MVR), built by Mannesmann Demag AG. This was done to save energy, reduce the use of cooling water and increase the yield of the distillation

Project summary/information

Company	Shell
Location	Pernis, Netherlands
Process application	Distillation in PP-splitter
Type of heat pump	MVR
Capacity	5.8 MW
Running hours	8650/year
Year of operation	October 1995
Primary energy savings	1,2 PJ/year
Reduction in CO_2 emission	67 kton/year
Maintenance costs	
Manufacturer/supplier	Mannesmann DEMAG AG
Pay back	2 years

Process description

Propylene is a key ingredient in a number of chemical products, including polypropylene and solvents. It is produced by the distillative separation of propylene and propane in a so called PP-splitter column. The splitter became into operation in October 1995 and produces polymer grade propylene with a purity of 99.5%. In a conventional distillation the reboiler is heated with low pressure steam or hot condensate and the overhead vapours are cooled with water.

With the application of MVR on the distillation column the overhead top vapours are used to heat the column at the bottom. In the MVR an electrically driven two stage fixed speed compressor, manufactured by Mannesmann DEMAG AG, increases the pressure of the top vapours which are then condensed in a condenser/reboiler with UOP Hi-flux double enhanced tubes to heat the bottom stream from the PP-splitter. The main part of the condensed overhead vapours is returned to the column as reflux, the remainder providing feed stock to downstream chemical plants.

Because the column can operate independently from a cooling fluid the temperature can be reduced and thus the column pressure can be reduced giving a better split between propylene and propane, increasing the relative volatility. The operating pressure is one of the primary process variables in optimizing the design for the separation of propylene and propane by distillation. The volatility ratio is significantly greater at pressures in the range of 3 – 10 bars, compared to the traditional values at 15 – 20 bars. The use of lower pressure prevents the use of cooling water and this problem is solved by using MVR. Because the column can operate independently of a cooling fluid, the column pressure can be reduced resulting in a better split between propylene and propane by the increase of relative volatility. The splitter thus produces polymer grade propylene with a purity of min. 99.5 wt%.

High reliability of the system has been achieved by the advanced process control system developed by Shell (Shell Multivariable Optimization Control). The SMOC process control system adjusts several parameters periodically. It sets the variables at given targets, taking into account the steady state and dynamic interactions between the variables.

Starting up procedure is initiated by purging with nitrogen and brought up to operational pressure by feeding in with propylene vapour generated in the de-ethanizer column from propylene storage.

Energy savings

Energy Heat pump drive energy (kWh/year):	50 400 MWh/year
Fuel:	Electricity
Energy output, useful heating (kWh/year):	401 600 MWh/year
Energy output, useful cooling (kWh/year):	352 000 MWh/year
Energy cost (EUR/kWh):	136 EUR/kW demand charge

The net yearly energy savings thus are 1,2 PJ/year (equivalent to 37.8 Mill m^3 of gas per year) at an operating time of over 8650 hours per year. CO_2 emissions reduction of 67 kton/year. In this calculation electricity is generated at an efficiency of 40% by gas-fired power plants.

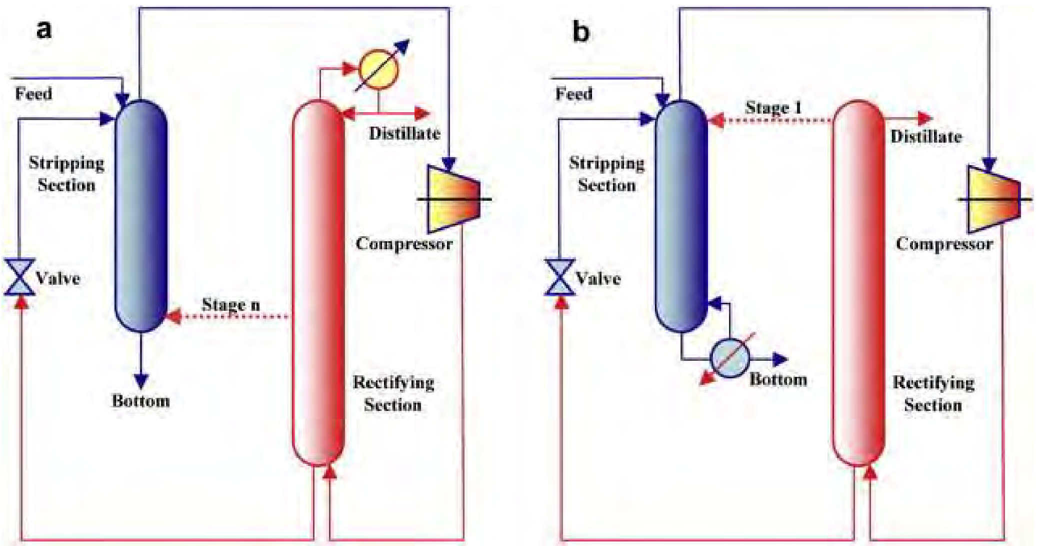
Operating experience

The heat pump as described is still running in line with the original design at 8650 hours per year at fixed speed. Maintenance is done by an external party as specific knowledge is required.

The system has a sophisticated level of automatic controls through the SMOC process control system. When it runs it does not require much human effort to run. The start-up procedures are due to the process requirement rather complex but do seldom occur.

The energy conservation can be calculated if compared to another smaller PP-splitter at the same location which is run on hot condensate feed and top cooling water. This splitter needs 2.2 GJ per ton feedstock while the MVR-equipped splitter needs only 0.5 GJ per ton, being a savings of 77%.

Maintenance problems have not occurred during the years of operation. The company has experienced the systems to have a very high reliability. Next to saving on heating, a considerable saving on cooling energy has been achieved, thus also reducing the use of surface water and disposing of waste heat on surface water.



NL-03 MVR at Hoechst Chemicals Vlissingen

Summary

Since 1982 three steam recompression systems have been in operation at the Hoechst production plant in Vlissingen. The heat pumps are a part of the process for the production of dimethyl-terephthalate (DMT). With the application of steam recompression, steam pressure is increased from 1.14 bara to 3 bara, which can be used in the low pressure steam system. The main goals for the application have been cost reduction and the possibility to work with a smaller steam production plant.

De produktie van de DMT-fabriek in Vlissingen-oost is sinds enkele maanden op een lager pitje gedraaid in verband met de teruglopende DMT-markt. DMT is een grondstof voor de chemische industrie.

Project summary/information

Company	Hoechst
Location	Vlissingen
Process application	production of dimethyl-terephthalate (DMT).
Type of heat pump	MVR
Capacity	
Running hours	
Year of operation	1982
Primary energy savings	
Reduction in CO_2 emission	
Maintenance costs	
Manufacturer/supplier	
Pay back	

Industry/process

The base chemical for the production of polyester is paraxylene (“PX”). Through an oxidation process, PX is transformed into pure terephthalic acid (“PTA”) or dimethyl terephthalate (“DMT”), two forms of terephthalic acid. An amorphous polyester polymer (“APP”) is then created by reacting either PTA or DMT with a di functional alcohol, most often mono-ethylene glycol (“MEG”). APP is used to generate a variety of end products, which can be segmented into six general categories:

- polyester packaging resin (“PPR”)
- industrial fibres
- textile fibres
- non-wovens
- PET film
- engineering plastics.

DMT and PTA are terephthalates derived from PX. For nearly all end-uses, DMT and PTA are interchangeable. DMT is easier to recover and to purify but PTA needs lower capital and operating costs (less of raw material and by-product handling). Thus, DMT and PTA should be considered together in any relevant market assessment. Hoechst is active in the production of DMT only. Its share of the total terephthalate market (DMT and PTA taken together) was approximately [<10%]. Even if one would consider a separate market for DMT, the share of Hoechst of the 1997 Western European merchant market for DMT was only [between 10% and 20%]. In 1997 take over and cahnge to Invista and in 2007 end of production.

Description of the process: In the production of dimethyl-terephthalate (DMT) the first step is the oxidation of para-xylene C6H4(CH3)2 with air. The second step is the esterification of the oxidation product (paratoluic acid) with methanol, towards para-toluic acid, methyl ester. This intermediate is oxidised and esterified once again to the resulting DMT (second and third steps). To produce a product with a purity of 99.96%, the DMT is partly purified by distillation. The remaining impurities are removed by crystallisation. In the condenser of the methanol distillation column, steam is generated at 1.14 bara by condensation of the methanol reflux (15 tons/h, 106ºC, 4.2 bar). The generated steam is compressed to 3 bar in a two-stage centrifugal compressor (Linde GT040T2K1, 760 kWe) and supplied to the low pressure steam system. Interstage cooling between the two stages takes place and additional condensate is injected after the second stage of the compressor. A total of 7 tons/h of steam is delivered to the 3 bar steam system. The two-stage compressor is directly driven by a radial centripetal expansion turbine (Atlas Copco, ET410NS). Exhaust gases (19,000 Nm3/h) from the oxidation section of the DMT reactor (mainly N2 and CO2) are expanded from 5.5 bara to 1.25 bara. The outlet temperature is controlled by a by-pass over the expander. Besides this steam compression system, another system is in operation. Steam generated in two oxidators (4.2 and 3.9 bara) is compressed to 5 bara in two electric-driven centrifugal compressors (Atlas Copco GT026T1K, 131kWe and 132kWe). A total of 20 tons/h of steam is produced at 5 bara (=163ºC), which is delivered to the steam grid.

Energy savings

1 year 3 months. This is calculated roughly from the following: Steam driven system: investments EUR 295 000 with cost savings of approximately EUR 270 000 per year. The second system (two compressors): investment EUR 155 000 with cost savings of EUR 725 000 per year. These systems were newly built, so the investment costs are calculated on extra costs compared with traditional systems in a new plant.

CO2 emissions reductions are 5.3 and 14.2 kton/year. These figures are calculated at assumed efficiencies for the steam boiler of 90% and gas fuelled power generation of 52% and at a running time of 8 000 hours. Energy savings are for the steam driven heat pump calculated at 3 million m3/year of gas equivalent and for the two electric driven systems at 8 million m3/year.

Operational experience and other comments

The systems are considered as very reliable. Although heat pumps in general are seen as difficult and not very reliable, the heat pumps at Hoechst were not really recognised as such because maintenance costs are extremely low. There have been no operational problems. Extremely short payback times can be achieved by installing heat pumps at new-built plants from the beginning. Heat pumps should in the case of MVR systems be marketed as compressors, integrated in systems.

NL-07 HT-HEAT PUMP AT THE BLUE BAND FACTORY IN ROTTERDAM

Summary

The Blue Band factory from Unilever, at the Nassaukade in Rotterdam is over 120 years old and at the moment the world largest factory for margarine with an output of more than 200.000 tonnes of margarine and 10.000 tonnes of peanut butter. Over that period of 120 years many changes in building, expansion and machinery have been done and a large overhaul of the complete production and building has never been undertaken creating a complex onoverzichtelijke situation. When in 2009 the boiler-room was going to be renovated the 40 years old steam boiler had to be replaced. Of the installed capacity more than 40% was not used because the new production lines have a lower energy use. As production had to go on a new boiler-house was designed near the old existing one.

Project information

Company	Unilever
Location	Rotterdam; Netherlands
Process application	
Type of heat pump	Compression add on heat pump
Capacity	1400 kW
Running hours	5000
Year of operation	2011
Primary energy savings	
Reduction in CO_2 emission	1.600.000 kg
Maintenance costs	
Manufacturer/supplier	Grenco
Pay back	2 years

Project characteristics and process design of installed system

The production line for margarine and peanut butter uses various heat and cold streams for the process:

- Hot water at several temperature levels
- Steam
- Warm water for space heating
- Ice water
- Freezing from an ammonia system at -23°C

All of the hot water and steam is generated by the old steam boiler on which the heat demanding processes run independent from each other and can run on partial load. The complete energy demand of the existing factory has been mapped and simulation and pinch models were used to design the new heat generating process. The basic thought is to make the plant as energy friendly as possible and robust for the next decade with a focus to use as much waste heat when occurring as possible. The heat demand could be split into low temperature heat (<70°C) and high temperature heat (>90°C).

For the low temperature heat the condenser heat from the NH3 chiller is used in a Grenco add-on heat pump to generate temperatures up to 80^{o}C.

This construction is called an add on heat pump. It is a mechanical heat pump that uses the refrigerant of an existing refrigeration system, in this case Ammonia. With the use of an add on heat pump the pressure of the gaseous Ammonia is increased. This causes the refrigerant to condensate at a higher temperature. In this case the add on heat pump is used to heat a water circuit up to 65 °C. Application of a heat pump enables several processes to benefit from the waste heat of the refrigeration system. Therefore energy savings can be realized as well as a reduction in CO_2 emission.

In this project a COP (coefficient of performance) of 5 is realized, or: every kW that is used by the compressor delivers 5 kW of useful heat. An additional advantage of the add-on heat pump is that the load of the existing condenser is reduced.

The installation has the following specifications:

- Heat capacity: 1400 kW at a temperature of 65 °C of the heated water
- Heating COP: 5,5
- Annual hours of operation: 6.000
- Annual energy savings: € 220.000
- Annual reduction of CO_2 emission: 1.600.000 kg
- Pay back time: ca. 2 years

De Energy Enhancer add-on heat pump is a GEA Grenco innovation. They won the NVKL cooling award 2012 with this innovation. The system is especially designed to be integrated in existing cooling or refrigeration systems with Ammonia as a refrigerant. At this moment the condensation temperature can be increased to a maximum of 90 °C with the use of a heat pump. Through a heat exchanger this energy is delivered to the medium that requires it.

For the high temperature heat a cogeneration gas engine is used with a steam boiler as back up. In partial load situations heat can be exchanged between the two systems

Door middel van een WKK van Caterpillar wordt 1,6 MW elektrisch vermogen en 2 MW aan thermisch vermogen opgewekt. De warmte wordt gebruikt om de fabriek te voorzien van 90 graden proceswater. Tevens is er voor de bij- of noodver warming een stoomketel geïnstalleerd. Deze levert 6,5 ton stoom per uur bij 12 bar.

Kantoorgebouw De Brug van Unilever, Rotterdam

Kantoorgebouw De Brug van unilever Bestfoods Nederland in Rotterdam heeft landelijke bekendheid vanwege de bijzondere architectuur en de prominente ligging aan de Maas. Wat velen echter niet weten, is dat het pand een schoolvoorbeeld is van de toepassing van lagetemperatuurverwarming (LTV, door Low-H2O techniek) in combinatie met radiatoren. Sterker nog: er komt geen wand- of vloerverwarming aan te pas. Het gebruik van uitsluitend LTV-radiatoren van Jaga is samen met de plafondkoeling voldoende voor een aangenaam binnenklimaat.

Al bij de ontwikkeling van het gebouw in 2001 werd bepaald dat duurzaamheid centraal moest staan in het project, ook bij het verwarmen en koelen. Geen eenvoudige opgave, want de stalen constructie met 15.000 m² kantoorruimte, verdeeld over vier verdiepingen, heeft gevels die vrijwel uitsluitend uit (HR++-)glas bestaan. De oplossing werd gevonden in het toepassen van LTV-radiatoren die de koudeval van de ramen geheel opvangen: de Mini van Jaga, specialist in klimaatbeheersingsoplossingen.

Is De Poort ook duurzaam verwarmd met warmtepomp??

Running experience, savings and economics

The overall steam demand is reduced by 80%. To reduce efficiency losses in heat generation hot water storage tanks were installed.

The heat pump, chp and steam boiler are running since 2010 getting into a 25% energy conservation. This exactly according to the design of the system.

Are there figures available??

- Energy cost savings
- Energy savings
- Reduction of CO2 emissions
- Other savings i.e. less use of water (ground water), higher performance or yield of the system
- Running and maintenance costs, servicing and reliability

Lessons learned and challenges

- Overall view of owner/user of the system: are they happy, would they do it again?
- Do’s and don’t’s, attention for pit holes, etc.

Motive/grounds/rationale behind investment

On what basis was the decision made and why did the company invest in the heat pump?

NL-11 Drying French fries at McCain in Lelystad (NL)

Summary

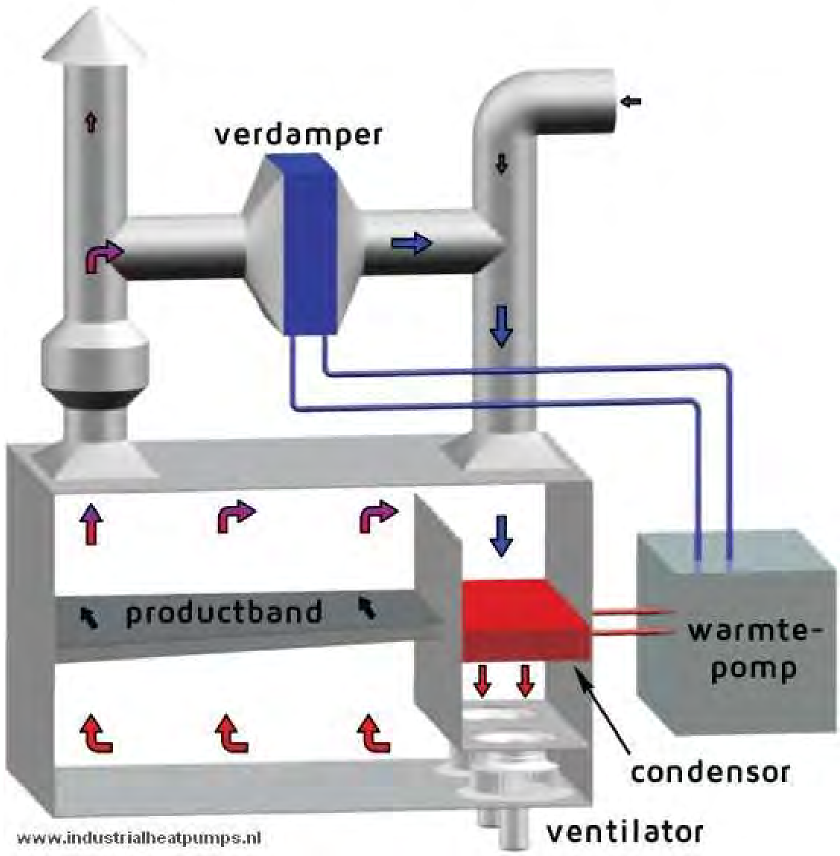
In the summer of 2012, a heat pump is installed at a plant of a French fries producer. This heat pump will provide the majority of the energy needed for drying of French fries before they are baked. The used dryer type is a belt dryer that operates at a maximum temperature of 70 °C. The innovative application of a heat pump connected to a French dryer, invented by De Kleijn Energy Consulting, is the first of its kind. Energy savings as high as 70% on the dryers energy consumption will be realized.

Project information

Company	McCain Foods
Location	Lelystad
Process application	Dying of patatoes
Type of heat pump	Compression Heat Pump
Capacity	880kW
Running hours	4000
Year of operation	2012
Primary energy savings	
Reduction in CO_2 emission	
Maintenance costs	
Manufacturer/supplier	Kleijn/Gea Grenco
Pay back	4 years

Process design of installed system

The principle of operation for drying in conventional dryers can be divided in two parts. The first step concerns fresh outdoor air that is being brought inside the dryer and heated. Secondly, the air is circulated over the wet product. During circulation it picks up moisture from the wet product due to which its humidity increases and its temperature decreases. The energy contained in this humid air flow may make it a useful heat source. Standard procedure is to exhaust this used air or dehumidify



it. Most of the humid and cold air is recirculated when the innovative heat pump is applied. The air is cooled below condensation point and thus dehumidified at the evaporator of the heat pump. The pressure and temperature of the refrigerant are increased with the use of a compressor. This energy is released into the dryer air, at the condenser site. Due to the application of a heat pump large energy savings can be obtained. Furthermore, the drying process is less influenced by outdoor air conditions. A more stable drying process increases the quality of the French fries.

The heat pump uses Ammonia as its refrigerant. This is a natural refrigerant with which high efficiencies can be obtained. Another advantage is the fact that considerable knowledge about this refrigerant is present in the food industry: Ammonia is very commonly applied there.

Two reciprocating compressors are used; a Grasso 45 HP and a Grasso 65 HP. These compressors have a continuous capacity control. Their COP in this process depends on the drying conditions and varies between 5 to 8.

The heat pump dryer is designed as an ammonia pump system. In the engine room, compressors, separator and pumps are situated. Evaporators are situated on the roof and connect the ducting for exhaust and fresh air with each other. Condensers are installed inside the dryer.

Running experience, savings and economics

The heat pump is designed to condensate 1.500 kg of water per hour. If this quota is reached an annual energy saving of 800.000 Nm^3 of natural gas is obtained. The payback time is than 4 years. This particular project has a shorter payback time since financial support is given by the so called SBIR program of AgentschapNL (the Dutch government).

Een half jaar na de in bedrijfname van de installatie kan geconcludeerd worden dat de warmtepomp boven verwachting presteert. Uit intensieve monitoring blijkt dat een besparing gerealiseerd wordt van 67 % op het primair energieverbruik van de droger. Dit wordt bereikt door de hoge COP van gemiddeld 7,9. COP staat voor Coefficient Of Performance en is een maat voor het rendement van de installatie. Een COP van 7,9 betekent dat bij elke kW elektriciteitsopname van de warmtepomp 7,9 kW warmte wordt afgegeven in de droger. Bij voldoende draaiuren en een goede belasting van de droger is de installatie dan ook binnen 4 jaar terug te verdienen.

Minstens zo belangrijk als de hoge efficiency is dat de warmtepomp moeiteloos de gewenste droogcondities bereikt. Het is zelfs mogelijk gebleken om de droger binnen 5 minuten opgestart te krijgen zonder hiervoor externe warmte te gebruiken. Vervuiling van de warmtewisselaars was een aandachtspunt. Echter zelfs na een half jaar zonder reiniging blijkt de vervuiling gering te zijn.

Foto: Kanaalwerk op het dak, met op de voorgrond de 3 recirculatiesecties voorzien van verdampers

Enkele kengetallen van de warmtepomp installatie bij McCain:

- De totale warmtecapaciteit van de warmtepomp bedraagt 880 kW;
- De maximale luchttemperatuur in de droger bedraagt 70°C;
- Op de warmtepomp zijn twee zuigercompressoren met toerenregeling toegepast;
- Het systeem is gevuld met het natuurlijke koudemiddel ammoniak;
- Er is veel aandacht besteed aan veiligheid en betrouwbaarheid van de installatie;
- COP van de warmtepomp is 7,9 (over gemonitorde periode).

De warmtepomp is geïnstalleerd op de bestaande droger bij McCain, waar de conventionele interne stooomverwarming is vervangen door de condensors van de warmtepomp.

NL-12 Slaughterhouse for veal, The Netherlands

Summary

Export Slachterij Apeldoorn, part of the Alpuro Group, produces a broad selection of veal products for the retail business worldwide. This production needs large amounts of hot water for the cleaning of production rooms and machinery and for removing hair from veal skin, and a smaller amount for sterile water (90°C). The heat pump has been installed in a slaughter house at a moment that the steam boiler had to be replaced. This created the opportunity to improve the hot water system efficiency.

The heat pump is a 45 bar reciprocating compressor coupled to the high pressure side of a refrigeration plant with ammonia as refrigerant (see figure 1). The heat pump condenser heats up water up to 62,5°C. The installation is running more than one year with great satisfaction and reliability.

Project information

Company	Export Slachterij
Location	Apeldoorn, Netherlands
Process application	Slaughterhouse for veal
Type of heat pump	Electrical compression heat pump
Capacity	440 kW
Running hours	
Year of operation	September 2009
Primary energy savings	/year
Reduction in CO_2 emission	/year
Maintenance costs	
Manufacturer/supplier	IBK Koudetechniek
Pay back	years

Project design

A new system was designed with three smaller warm water boilers and a high temperature heat pump on top of the refrigeration plant operating at -10°C refrigerating temperature.

This refrigerating plant has a cooling capacity of 1200 kW, at a condensing temperature of 23°C, which is the suction pressure of the high temperature heat pump. The condensing temperature of this heat pump is 65°C, producing hot water at 62,5°C. The COP on heating appeared to be approximately 6,7. The heat pump compressor is a 6 cylinders piston type compressor, frequency controlled, extracting only part of the discharge gasses. The heat produced at 65°C amounts to 500 kW. This heating capacity heats up a water flow from 15°C up to 62,5°C.

The superheated discharge gasses of the regular refrigerating installation have to be cooled down to almost saturation at 23°C in order to avoid extreme discharge temperatures of the heat pump. This gas desuperheater (= heat pump suction gas cooler) is cooled by high pressure ammonia liquid (23°C) from the condensers of the regular refrigeration plant (see figure 2 upper left vessel). The discharge gas of the heat pump is cooled by heat pump condensate (65°C) in vessel V22. The municipal water intake is heated up from 15°C to 62,5°C in two stages, first by a liquid subcooler E25 and compressor head cooler E70 and secondly by the condenser E24. The water is stored in a 100 m3 insulated water tank.

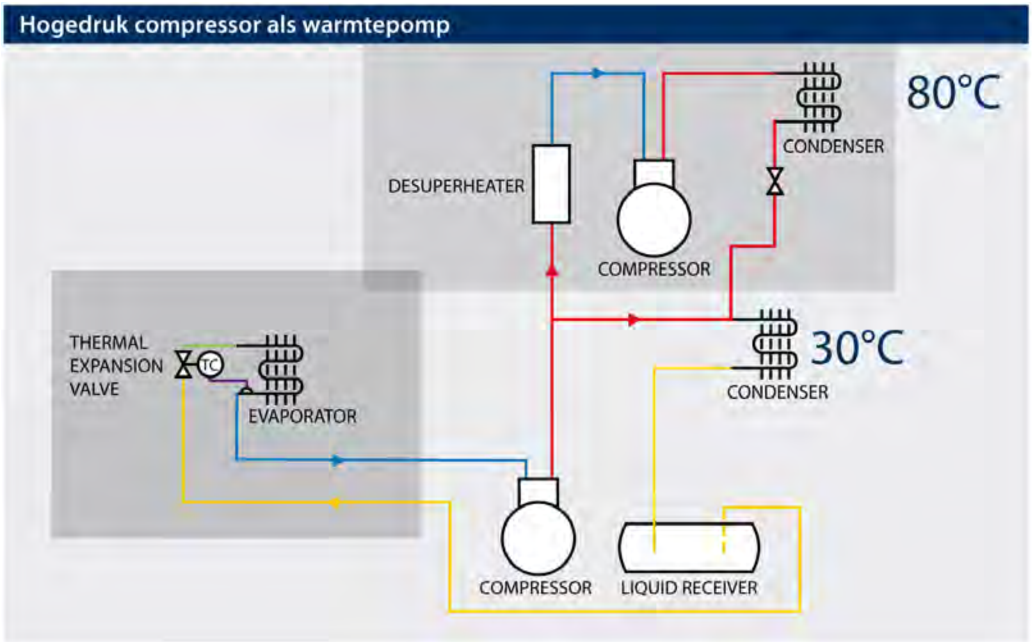


Figure 1: Principle of a high temperature heat pump on top of a refrigeration plant for process heating

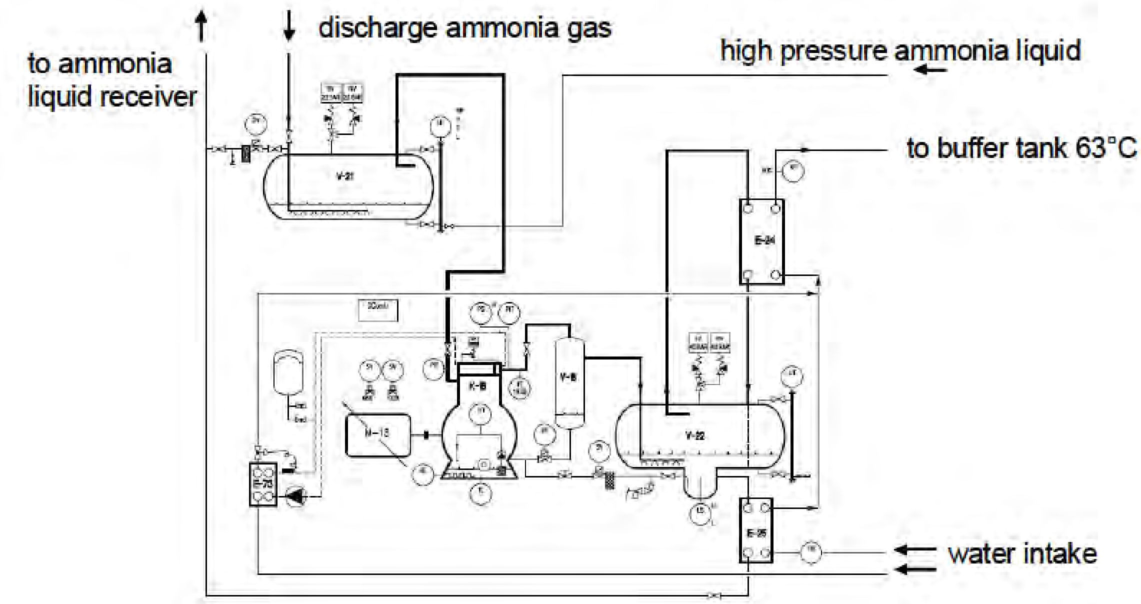


Figure 2: Heat pump layout in practice, ammonia high temperature compression and water flow from intake to buffer tank.

The slaughter house requires a hot water flow for dehairing and cleaning of the production areas at the end of the day. The water demand varies a lot during the day. The storage hot water tank is sufficiently large to cope with the variations.

Hot water boilers are connected to the water system of the heat pump as back up system and to heat the water up to 90°C for sterilization water for knives cleaning.

The water flow circulating in the boilers however is separated by a plate heat exchanger from the water flow running through the heat pump. This heat exchanger appears to be required since the warm water boilers became damaged by severe calcification.

The heat of the heat pump is released into a water cooled condenser. The discharge temperatures are above 90°C causing severe calcification of the heat exchanger surfaces. This is prevented by the use of the desuperheater heat exchanger cooled by the condensed ammonia liquid at 65°C. This heat exchanger has been installed in the discharge line of the heat pump.

The heat pump started operation in September 2009 and is running 16 hours per day, approximately 4000 hours per year at almost 100% capacity. By comparing gas consumption figures during the last years, it showed that the gas consumption was reduced by 50%.

On theoretical basis the energy saving by the heat pump is 65% compared with a hot water boiler for this field application as shown in table 2. The electrical energy consumption of the heat pump is included in this calculation. The CO2 emission is reduced by 50%.

Table 1: MJ primary energy and CO2 emission reduction by the heat pump in comparison with a hot water boiler

Heat production options		Heat pump 23°C/65°C	Hot water boiler
Heat demand	kW	500	500
COP heat pump		6,7	
Boiler efficiency	%		90
Operating hours	hours/y	4.000	4.000
Primary energy use	MJ/y	2.686.600	8.000.000
CO_2 emission	kg/y	200.150	450.000

The electricity consumption is increased by the operation of the heat pump but the condensing temperature of the refrigeration plant is reduced by 4K, resulting in a better efficiency and energy savings of the refrigeration plant. In addition, the heat pump reduces the load on the evaporative condenser of the refrigeration plant. This creates a saving in water and chemical water treatment costs of approximately euro 6.000,-- per year.

Organization

The project is implemented by IBK Koudetechniek B.V. (IBK Refrigeration) in Apeldoorn.

Financially

The simple pay back time is approximately 4 to 5 years. The project is subsidized by reduction of companies taxes according to a Dutch energy efficiency investment program.

Lessons learned

The three boilers were initially integrated in the hot water system of the heat pump. Severe calcification took place in these boilers, causing break downs. For this reason the boiler water loop and the fresh water loop through the heat pump were separated by a plate heat exchanger. Water quality have to be checked to be able to control calcification of heat exchangers during heating.

NL-17 MVR for sludge drying at Sophus Berendsen Textiel in Apeldoorn (NL)

Summary

Berendsen Textiel in Apeldoorn is an industrial washing plant for industrial cleaning cloths. The evaporation of watery sludge streams is done through a process of mechanical vapour recompression and has replaced a process of water treatment with reversed osmosis.

Berendsen handles 200.000 cleaning cloths per day. The processes are ISO 9001:2000 and ISO 14001 certified and the company has been awarded the FTN energy award and the MVO innovation award.

Project summary/information

Company	Sophus Berendsen
Location	Apeldoorn, Netherlands
Process application	Sludge drying process for cleaning cloths
Type of heat pump	MVR
Capacity	
Running hours	8650/year
Year of operation	October 1998
Primary energy savings	40T/year
Reduction in CO_2 emission	kton/year
Maintenance costs	
Manufacturer/supplier	
Pay back	2 years

Process description

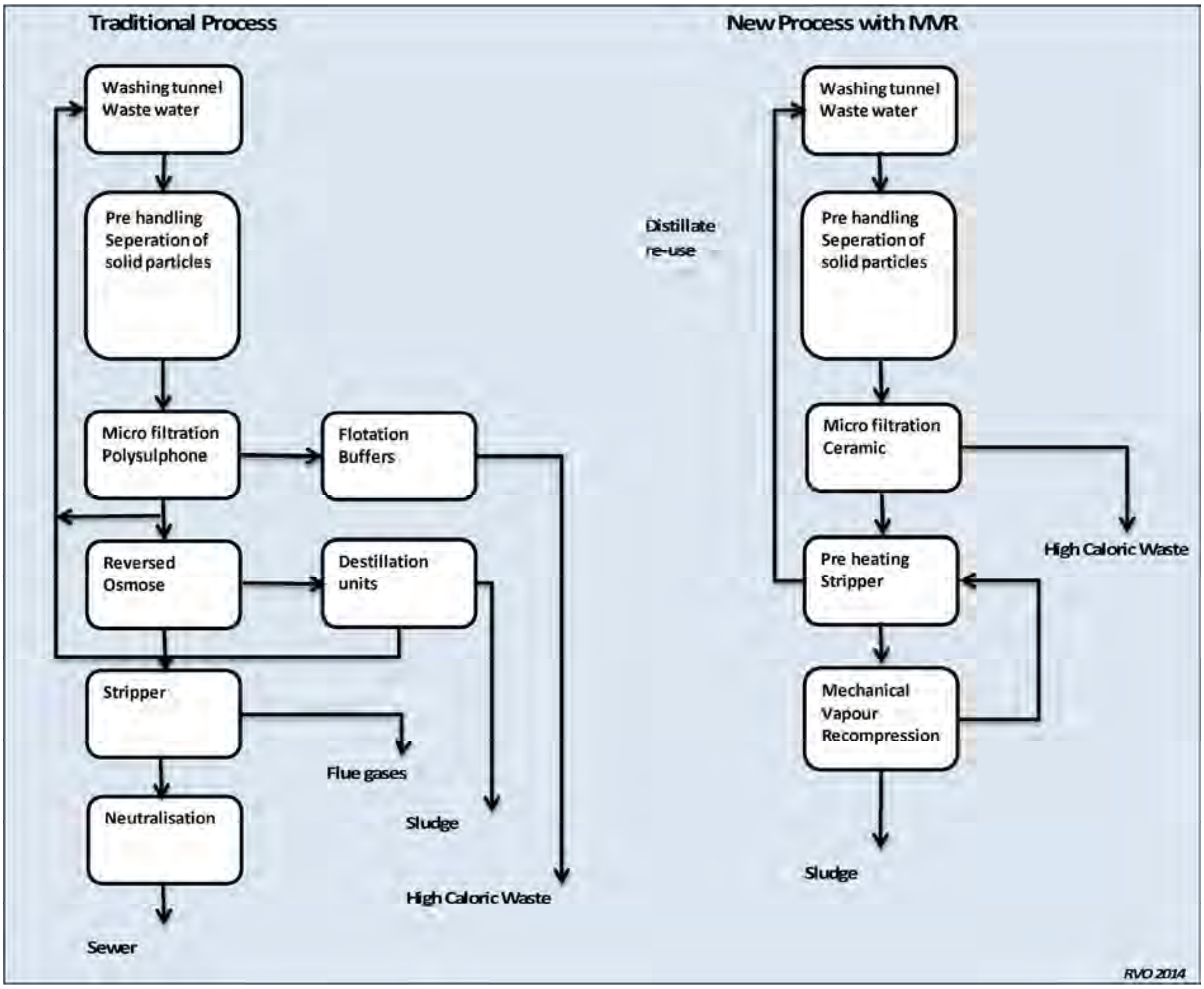
At the moment of renovation the company was looking at expansion from 1200 tonnes to 3000 tonnes of cloth handling with technologies that could increase the economy by reducing operational and energy costs with a special focus on the waste water streams.

At the industrial washing process waste water streams are released containing heavy metals, hydrocarbons and other polutants, like chemicals. These waste water streams are purified first by pre-cleaning units consisting of polysulphone micro-filtration and reversed osmose untill the needed effluent quality is achieved. The sludge concentrate from the reversed osmose, with a 33% concentrate, was further condensed by a steam driven evaporator. Per m^3 of effluent about 1 ton of steam is needed. The the waste water from the osmose stage is drained to the local sewer system. This original process was state of the art in the nineties, but was energy intensive and highly sensitive and costly on maintenance, especially on the cleaning of the membrane section. The overall energy use at a capacity of 1200 tonnes cloths handled was 586.000 m^3 of gas (20TJ).

In the new process the polysulphone micro filtration is replaced by ceramic filtration which gives considerable reduction in maintenance. Next to that the steam driven evaporator is replaced by an evaporator with mechanical vapour recompression. The condensate from the MVR is used as pre-heating for the washing process. The new process saves 90% on the use of water and 1.162.000 m^3 of gas, being 86%.

The total investements in the project for extension of the process were € 1.434.250, whereas the additional investments for the MVR was € 454.550. The savings on energy are € 221.150 and on operational costs € 172.750. Additional gain is the lesser use of cleansing agents in the process.

Technical development by USF Waterbehandeling Zoetermeer and MVH Partners in Pollution Control at Uden.



Evaluation of heat pump

The heat pump as described in the original factsheet and in its original design is stil in use and makes 6000 running hours per year. It is running at 50 – 100% partial load.

Every week the heat pump is stopped to be able to clean the heat exchangers while once a year the heat exchanger are replaced by new ones.

Maintenance is done by in-house technical service department with the main attention at the heat exchangers and the composition of the waste water. The company does not have figures on the running efficiency of the heat pump.

In the start up the main problems were with the fouling of the heat exchangers

NL-24 Bovendeert warehouse in Boxtel Netherlands

Summary

The warehouse and headquarters of shoe store chain Bovendeert in Boxtel, contains, besides thousands of colourful shoeboxes and shoes, also an installation with highlighted technical features. Besides the accompaniment of an international automation standard type KNX to link an innovative and energy saving heat pump installation from LG Electronics on an advanced controlled electrical installation, a durable and comfortable installation concept arose.

Project summary/information

Company	Bovendeert Shoes
Location	Boxtel
Process application	Warehouse
Type of heat pump	Air Source compression
Capacity	224 kW Cooling 252 kW Heating
Running hours	8650/year
Year of operation	2013
Primary energy savings	n/a yet
Reduction in CO_2 emission	n/a yet
Maintenance costs	n/a yet
Manufacturer/supplier	LG – Centercon B.V. – Elin Installations
Pay back	Less than 5 years when compared to conventional installation with gas boiler and cooling only air-conditioner

Process description

The applied LG Electronics Multi V Heat Recovery system plays an important role in the concept. It is a three -pipe heat-recovery heat pump system that can simultaneously cool and heat different rooms. The heat extracted in the cooling mode, is directly used for indoor spaces with a heating requirement. In total 4 LG Multi V outdoor units are situated on the roof and all connected as one system.

The outdoor unit is connected to 23 ceiling concealed duct units, which are connected to tailor made discharge jets. The system is also connected to 4 LG Hydro kits that are located indoor in the technical area of the property. The Hydro units provide warm water to feed the low temperature underfloor heating system. In this way the total climate system and the warm water preparation for the entire building is provided by the combined heat pump system and no gas is required.

Thanks to the advanced heat pump technology with inverter controlled compressors, this system with Hydro Kits saves up to 77 % energy compared to conventional heating systems. Due to hydro kits a 50%reduction of CO_2 emission is made. In order to ventilate the building efficient and effective, Elin Installations also installed 7 pieces of 1000 m^3/h CO_2-controlled LG ECO-V heat recovery ventilation units.

The logical choice for the Multi V Heat Recovery system was done keeping in mind the heat and cooling demand of the warehouse as per the offices, loads may vary. Thus, this system can make the offices warm and comfortable and at the same time keep the shoes in the warehouse at a lower temperature and minimum humidity because they thrive better at it.

It was decided to optimize the control and operation of the units and climate system to be integrated into a building management system that is based on the globally standardized KNX protocol. The link between the heat pump system, underfloor heating and KNX has not previously been achieved in Europe. All system's parts are working together to optimize comfort, control and energy savings. For example, the ventilation units are controlled by KNX controlled CO_2 sensors. Presence and motion detection controls both the lighting and the climate, for each room or area individually. If there is no one in for an hour, the climate system is switched off or the heating system is switched to "low settings".

In the evening the "all off" function switches the system to "Night mode", the lights and the air conditioning off and the alarm is triggered. In the morning, intelligent cooperation between systems provides an achievement of the desired temperature at the desired start time. When the underfloor heating system will not get to the desired value at the right time, the concealed duct units will support to reach the required temperature settings. System integrator Elin also created separate summer and winter settings in the system. In the summer the system does not heat, but the air conditioning cools all rooms. Such integrated smart control strategy is even more energy -saving than the also energy saving control strategy of LG Electronics Heat Pump system it selves.


LG

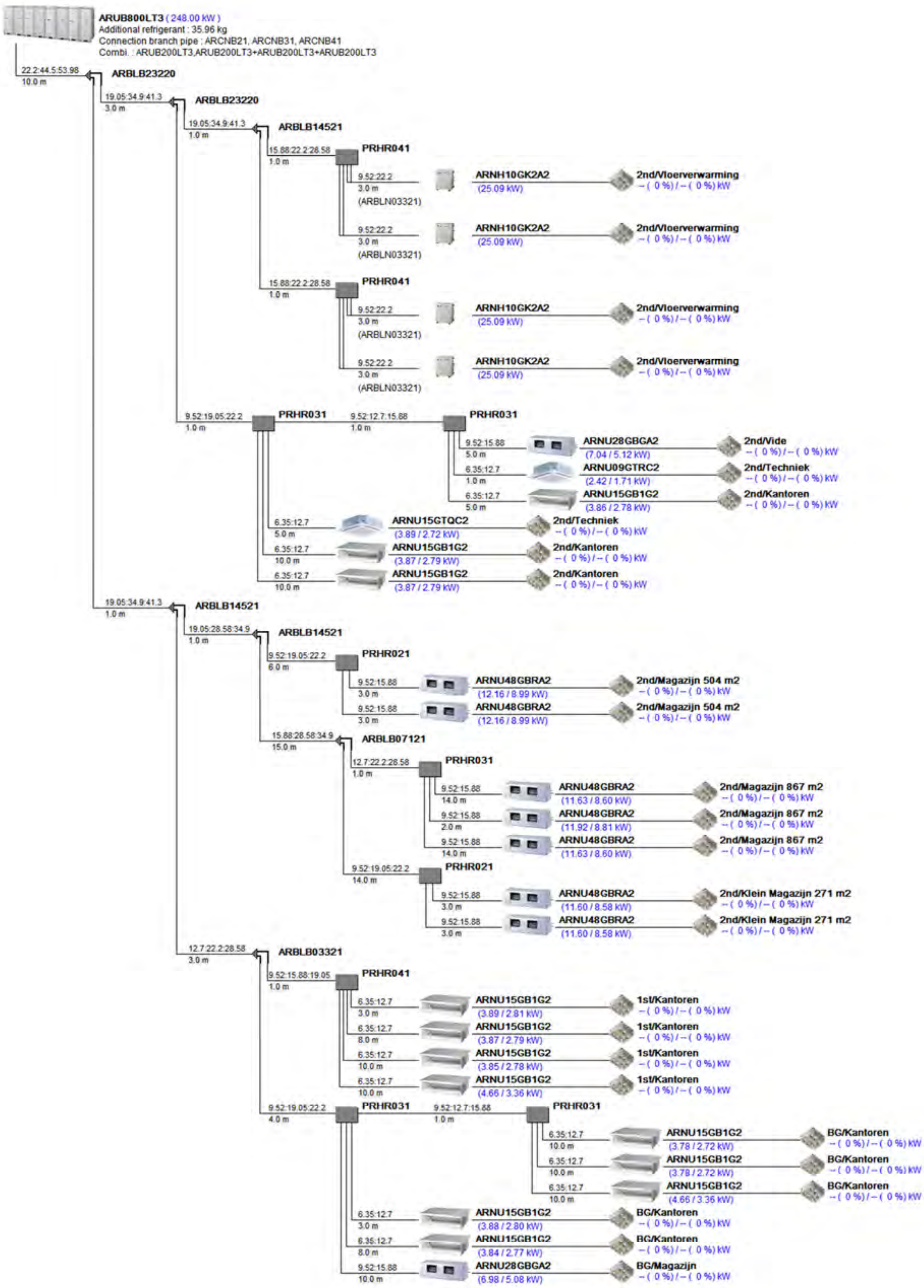
Specifications of heat pump

Description	Heat Pump			Back up
Type				
Heating capacity	252 kW (Outside Air 7°C Inside Air 20°C)			
Cooling capacity	224 kW			
Power consumption	63 kW			
Heat source	Outside air minimal -25°C	Temp	°C	
Refrigerant	R410a			
Compressor type	Hermetic Inverter Scroll 12pcs			
COP	4,18			
Operation hours	24hrs a day			
Storage water tank	1 m^3	35 Temp	°C	
Manufacturer of heat pump	LG Electronics, Korea			
Supplier/consultant	Centercon B.V. Rotterdam, Elin Boxtel			

Project characteristics and process design of installed system

- New build warehouse and office.
- Ability to fully exchange heat inside the building. Cooling offices and heating warehouse and vice versa.

- Figure



ARUB800LT3 (248.00 kW)
Additional refrigerant : 35.96 kg
Connection branch pipe : ARCNB21, ARCNB31, ARCNB41
Combi. : ARUB200LT3,ARUB200LT3+ARUB200LT3+ARUB200LT3
22.2:44.5:53.98
10.0 m
ARBLB23220
19.05:34.9:41.3
3.0 m
ARBLB23220
19.05:34.9:41.3
1.0 m
ARBLB14521
15.88:22.2:28.58
1.0 m
PRHR041
9.52:22.2
3.0 m
(ARBLN03321)
ARNH10GK2A2
(25.09 kW)
2nd/Vloerverwarming
--(0 %) / --(0 %) kW
9.52:22.2
3.0 m
(ARBLN03321)
ARNH10GK2A2
(25.09 kW)
2nd/Vloerverwarming
--(0 %) / --(0 %) kW
15.88:22.2:28.58
1.0 m
PRHR041
9.52:22.2
3.0 m
(ARBLN03321)
ARNH10GK2A2
(25.09 kW)
2nd/Vloerverwarming
--(0 %) / --(0 %) kW
9.52:22.2
3.0 m
(ARBLN03321)
ARNH10GK2A2
(25.09 kW)
2nd/Vloerverwarming
--(0 %) / --(0 %) kW
9.52:19.05:22.2
1.0 m
PRHR031
9.52:12.7:15.88
1.0 m
PRHR031
9.52:15.88
5.0 m
ARNU28GBGA2
(7.04 / 5.12 kW)
2nd/Vide
--(0 %) / --(0 %) kW
6.35:12.7
1.0 m
ARNU09GTRC2
(2.42 / 1.71 kW)
2nd/Techniek
--(0 %) / --(0 %) kW
6.35:12.7
5.0 m
ARNU15GB1G2
(3.86 / 2.78 kW)
2nd/Kantoren
--(0 %) / --(0 %) kW
6.35:12.7
5.0 m
ARNU15GTQC2
(3.89 / 2.72 kW)
2nd/Techniek
--(0 %) / --(0 %) kW
6.35:12.7
10.0 m
ARNU15GB1G2
(3.87 / 2.79 kW)
2nd/Kantoren
--(0 %) / --(0 %) kW
6.35:12.7
10.0 m
ARNU15GB1G2
(3.87 / 2.79 kW)
2nd/Kantoren
--(0 %) / --(0 %) kW
19.05:34.9:41.3
1.0 m
ARBLB14521
19.05:28.58:34.9
1.0 m
ARBLB14521
9.52:19.05:22.2
6.0 m
PRHR021
9.52:15.88
3.0 m
ARNU48GBRA2
(12.16 / 8.99 kW)
2nd/Magazijn 504 m2
--(0 %) / --(0 %) kW
9.52:15.88
3.0 m
ARNU48GBRA2
(12.16 / 8.99 kW)
2nd/Magazijn 504 m2
--(0 %) / --(0 %) kW
15.88:28.58:34.9
15.0 m
ARBLB07121
12.7:22.2:28.58
1.0 m
PRHR031
9.52:15.88
14.0 m
ARNU48GBRA2
(11.63 / 8.60 kW)
2nd/Magazijn 867 m2
--(0 %) / --(0 %) kW
9.52:15.88
2.0 m
ARNU48GBRA2
(11.92 / 8.81 kW)
2nd/Magazijn 867 m2
--(0 %) / --(0 %) kW
9.52:15.88
14.0 m
ARNU48GBRA2
(11.63 / 8.60 kW)
2nd/Magazijn 867 m2
--(0 %) / --(0 %) kW
9.52:19.05:22.2
14.0 m
PRHR021
9.52:15.88
3.0 m
ARNU48GBRA2
(11.60 / 8.58 kW)
2nd/Klein Magazijn 271 m2
--(0 %) / --(0 %) kW
9.52:15.88
3.0 m
ARNU48GBRA2
(11.60 / 8.58 kW)
2nd/Klein Magazijn 271 m2
--(0 %) / --(0 %) kW
12.7:22.2:28.58
3.0 m
ARBLB03321
9.52:15.88:19.05
1.0 m
PRHR041
6.35:12.7
3.0 m
ARNU15GB1G2
(3.89 / 2.81 kW)
1st/Kantoren
--(0 %) / --(0 %) kW
6.35:12.7
8.0 m
ARNU15GB1G2
(3.87 / 2.79 kW)
1st/Kantoren
--(0 %) / --(0 %) kW
6.35:12.7
10.0 m
ARNU15GB1G2
(3.85 / 2.78 kW)
1st/Kantoren
--(0 %) / --(0 %) kW
6.35:12.7
10.0 m
ARNU15GB1G2
(4.66 / 3.36 kW)
1st/Kantoren
--(0 %) / --(0 %) kW
9.52:19.05:22.2
4.0 m
PRHR031
9.52:12.7:15.88
1.0 m
PRHR031
6.35:12.7
10.0 m
ARNU15GB1G2
(3.78 / 2.72 kW)
BG/Kantoren
--(0 %) / --(0 %) kW
6.35:12.7
10.0 m
ARNU15GB1G2
(3.78 / 2.72 kW)
BG/Kantoren
--(0 %) / --(0 %) kW
6.35:12.7
10.0 m
ARNU15GB1G2
(4.66 / 3.36 kW)
BG/Kantoren
--(0 %) / --(0 %) kW
6.35:12.7
3.0 m
ARNU15GB1G2
(3.88 / 2.80 kW)
BG/Kantoren
--(0 %) / --(0 %) kW
6.35:12.7
8.0 m
ARNU15GB1G2
(3.84 / 2.77 kW)
BG/Kantoren
--(0 %) / --(0 %) kW
9.52:15.88
10.0 m
ARNU28GBGA2
(6.98 / 5.08 kW)
BG/Magazijn
--(0 %) / --(0 %) kW

Motive/grounds/rationale behind investment

The newly build warehouse and office needed to be very energy efficient, no use of gas boilers. No gas connection in the building. Full electric heat-pump

Design and installation process

The installation was done by Elin installations in Boxtel who has don the Electrical Mechanical installation including the system integration and control in the KNX standard

Running experience, savings and economics

- With the power consumption of about 200000 kWh is not a big number compared to the size of the building with around 5000m² on three floors.

Lessons learned

Customer is very happy with the installation and the energy consumption. Temperatures in the building are very good with the combination of floor and air heating and cooling. This ensures a stable temperature in the building. All excess heat can be used in the warehouse to heat the air.

NL-27 Heat Pumps in Greenhouses

Summary

In the period 2003-2013, in Dutch horticulture approximately 40 growers of various crops have implemented heat pumps (most of them in combination with ATES – Aquifer Thermal Energy Storage) in their greenhouses. They comprise the following crops a.o.:

- Roses (2x)
- Tomatoes (3x)
- Orchids (Phalaenopsis) (8x)
- Freesia (2x)
- Anthurium (2x)

In the following, we present a factsheets concerning the application of heat pumps in Dutch horticulture in the production of tomatoes.

a. Heat pump application at a commercial nursery for tomatoes

Project description

Company name *)	Commercial nursery for tomatoes
Location / production area	Berkel & Rodenrijs; 54.000 m2
Process / Application	Growing tomatoes
Type of Heat Pump	30HXC285 Carrier
Capacity	1250 kW-th per heat pump, 3x HP in total
Operational hours	15000 hours = average of 5000 per heat pump; 3 heat pumps operating
Year of commissioning	2003
Energy savings	29%
CO_2 emission reduction	40-60%
Maintenance costs **)	N/A
Manufacturer / supplier	Innogrow
Simple Pay Back Time **)	14,9 years

*) Companies cooperated in this project on the basis of anonymity
**) if such data are available

Specifications of the heat pump

Type		water-cooled, condenserless chillers using screw compressors	
Heating capacity (total)		1250x3=3750	kW/unit (3 units)
Cooling capacity (total)		1100x3=3300	kW/unit (3 units)
Power consumption		240x3=720	kW/unit (3 units)
Heat Source	Temperature	20 °C	
	Flow	240 m3/h	
Supply Temperature		42-50 °C	
Refrigerant		R134a	
Compressor type		twin-screw compressor	
COP		5,2	
Buffer tanks		1800 m3 (3x 600 m3) at 55 °C (maximum)	

Specifications of back up system

Gas fired boilers are used to provide additional heat when the capacity of the other systems (ATES) is insufficient. It is also used to provide backup in the event of any breakdown. Two gas engines (CHP's of 650 and 300 kWe respectively) were used to generate electricity to power the heat pump and fans. The relative high temperature water produced by the CHP was used to heat the conventional (open) part of the greenhouses. However, due to market conditions in The Netherlands (low electricity prices / feed in tariffs) the CHP is used less and less.

Project characteristics of the company

- Description of the existing situation

Until 2003 this horticulturist grew his tomatoes in a traditional ('open') greenhouse using a combination of a gas fired boilers and CHP to generate the required heat. The total area of this greenhouse was 54.000 m2. No lighting is applied during the production, so the electricity consumption is relatively low.

- Description of the implementation of the heat pump

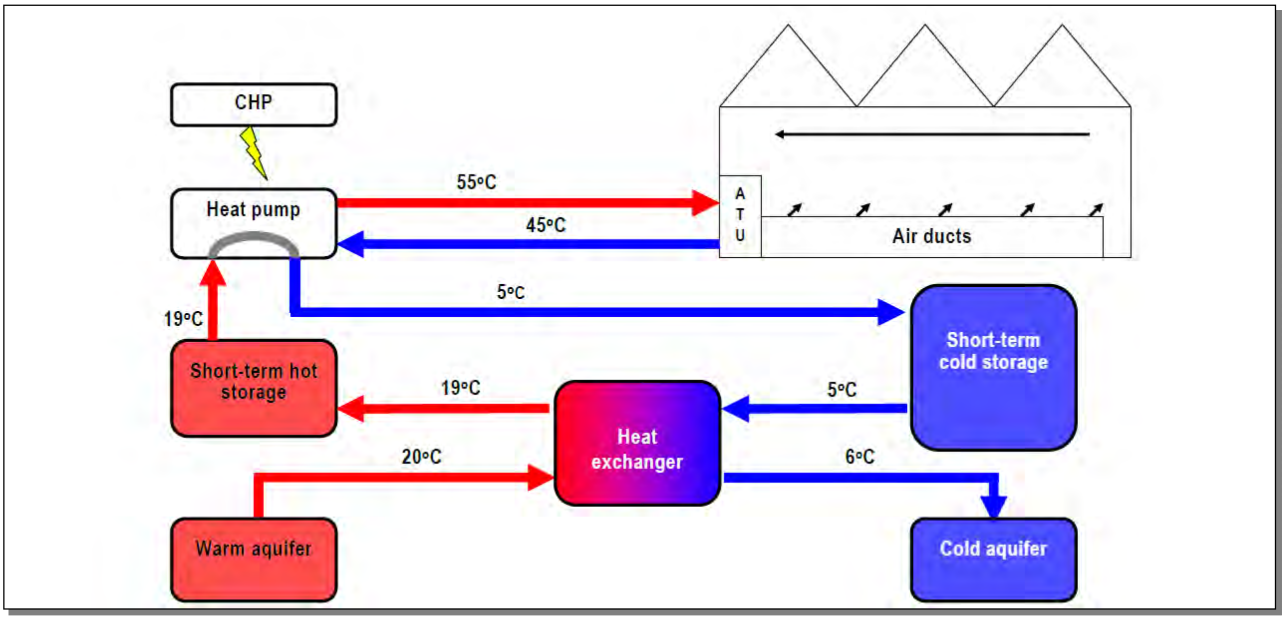
Cultivation of tomatoes in the new situation takes place in a (semi-)closed greenhouse, using a heat pump and ATES. This new concept is applied on 14.000 m2 of the total area of 54.000 m2 (40.000 m2 remaining as it was). By the end of 2003 this horticulturist –as the first grower in The Netherlands!- began to operate his ATES-system. The heat sink/source used at this company is an aquifer. Air humidity and temperature are controlled by a ducted ATU (Air Treatment Unit, see picture), using low temperature heat exchanger/heaters.

The company originally utilized the closed greenhouse (Gesloten Kas®) concept that was developed by the Dutch environmental/engineering consultancy Innogrow B.V.. The concept utilizes the fact that during the summer a greenhouse vents off more heat (solar gain) than it requires in the form of fossil fuel heat during the winter. Therefore, if the summer heat can be captured and stored until it is required during the winter significant reductions in fossil fuel use can be achieved. In the summer cold water (6˚C) is drawn from a borehole and passed through water-to-air heat exchangers in the greenhouse. The recovered warm water (around 20˚C), is returned to the aquifer via a second 'warm' borehole. When heat is required during the winter a heat pump recovers the heat from the warm aquifer water boosting it to 45-55˚C. This in turn leads to the production of cold water (6˚C) that is stored in the aquifer and used the following summer for cooling. The concepts results in a heat excess in the closed section of the greenhouses which –after seasonal storage- is used in the other (open) sections of the greenhouse and is partially supplied to an adjacent greenhouse farmer (from October to April).

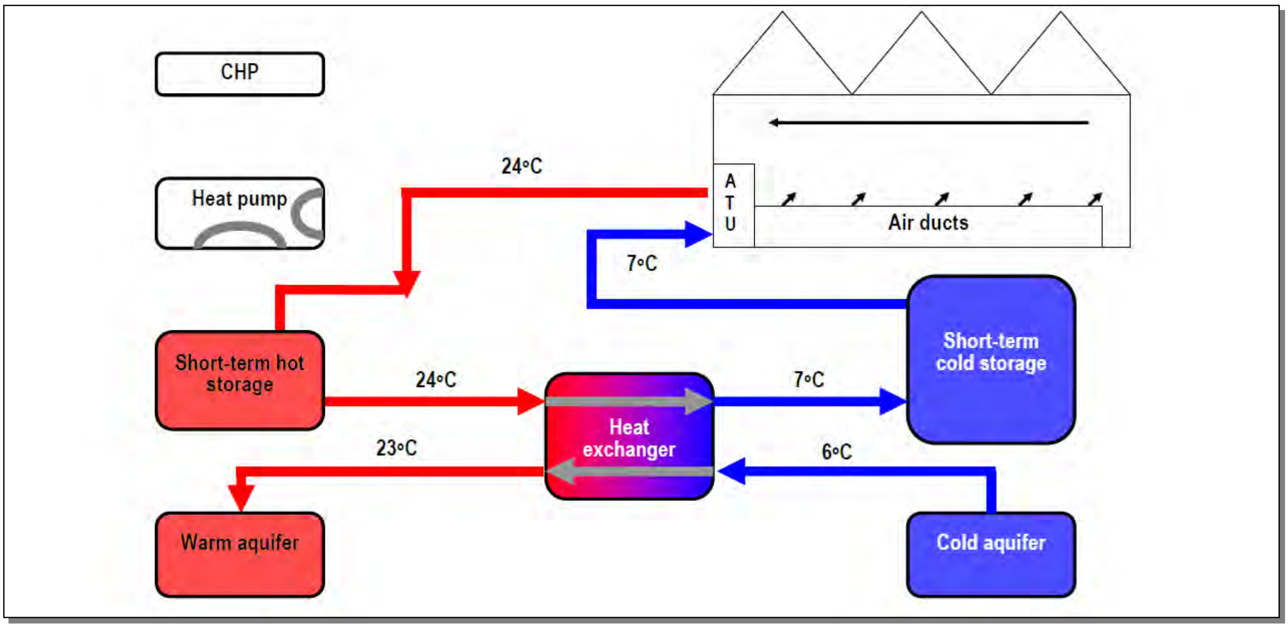
An important benefit of cooling in this way is that the vents do not open in the summer and CO2-levels can therefore be maintained at higher levels than would normally be possible. A significant yield (17%) increase results. A reduction in pest and disease incidence is also claimed due to reduced pest invasion (no venting) and more reliable, accurate and uniform temperature and humidity control.

- **Graph (simple schematic of the installation)**

Installation at heating mode (during winter)



Installation at cooling mode (during summer)



Running experience, savings and economics

- Energy cost savings: approximately 29%
- Energy savings: approximately 30-40%
- Reduction of CO2 emissions: approximately 40-60%

ITEM	
Investment costs	**EURO/m2**
CHP & aquifer ATU & heat storage Total investment costs	75 40 115
Operating costs	**EURO/m2 per annum**
Energy saving – 200 kWh/m2 (36% for entire nursery) Increased yield (9% for entire nursery) Minus extra annual costs (entire nursery)	5,00 3,50 6,50
Net gain	2,00

- **Other savings i.e. less use of water, higher performance or yield of the system**

  The closed greenhouse concept results in better temperature and humidity control of the cultivation process and hence in an improved crop management. It also enables higher CO2-concentrations inside the greenhouses, which in turn results in higher crop yields (17% increase) and better crop quality. This also results in a 80% reduction of pesticide use, reduced pest and disease incidents.

Lessons learned

Overall view of owner/user of the system: are they happy, would they do it again?

- In the next project the horticulturist would refrain from all unnecessary technology which makes the project needlessly complicated . For example, an additional “TSA” (heat exchanger) that allows him to add condenser excess heat to the warm side of the aquifer would not be installed in a next project.
- Essential to the success of the project is the quality of the aquifer and boreholes. Therefore, it is important to select an experienced and trustworthy “manufacturer” of boreholes.
- The application of an (ducted) ATU (for heating, cooling and dehumidification) instead of the traditional rail heating system enables the horticulturist to generate more air movement inside his greenhouse. These increased dynamics result in a more homogeneous climate in the

greenhouse and especially a different **micro-climate (relative humidity; RH!) at the micro-level of the plants themselves.** The measured RH in the (bulk of the) closed greenhouse can therefore be maintained at a higher level than in traditional greenhouses: in this 'static' situation the plant itself experiences a higher RH than measured. Due to this the productivity can be increased by higher CO2-concentration, higher temperature and controlling towards maximum photosynthesis.

- The 'trick' of crop production in a (semi-)closed greenhouse is that it requires a totally different way of operating and production philosophy than in a traditional greenhouse: the horticulturist needs to learn to grow all over again.
- Cultivation with a few % "over pressure" in the greenhouse (especially in winter) reduces the 'drop of coldness' from the glass and contributes to a more homogeneous climate as well. Also, it is more difficult for insects and pests to enter the greenhouse.
- All in all this horticulturist is very satisfied with his ATES-heat pump system, because –on top of the resulting energy savings (29%) and increases in crop yield (17%) ánd quality- it gives him much more flexibility to deal with the dynamic energy markets.
- For a new project, this horticulturist would certainly apply ATES and heat pumps again in his greenhouse .

<u>Do's and don'ts, attention for pit holes, etc.</u>

- It is important for any horticulturist who's new to these type of systems to invest serious time -starting with the first days of operation- to thoroughly learn to operate the system and the new settings of the climate computer in close cooperation with the supplier/installer of the ATES-system. Only then, the horticulturist will learn to understand the consequences and possibilities of cultivation under higher temperatures, CO2-concentrations and relative humidity. This will enable him to understand the complex interactions between crop/plants and greenhouse climate and allows him to truly optimize and control his production and crops.
- It is important to select an installer/system supplier (and/or a consultant) who has his roots in the horticultural sector and not just some installer only with experience with heat pumps, CHP and other energy systems.

Literature & sources

Interview with Theo Ammerlaan by Krijn Braber & Charles Geelen (Infinitus Energy Solutions)

Raaphorst M., (2005) Optimale teelt in de gesloten kas – Teeltkundig verslag van de

gesloten kas bij Themato in 2004

http://www.hdc.org.uk/sites/default/files/research_papers/PC%20256%20final%20report%202007.pdf

NL 27 f Greenhouse for breeding and propagating Anthuria

Summary

The installation consists of a heat pump and an aquifer thermal energy system and is applied to provide heating and cooling to create a temperature and humidity controlled environment for the critical stage in the propagation of Anthuria.

Project information

Company	Anthura
Location	Bleiswijk
Process application	Climatisation of pot plants in greenhouse
Type of heat pump	Ground source compression heat pump with Aquifer Thermal Energy Storage (ATES)
Capacity	2x1300 kW heating 4 MW total cooling capacity with ATES system
Running hours	6000 hrs/yr heat pump heating 4000 hrs/yr ATES cooling
Year of operation	2009
Primary energy savings	30 TJ/yr
Reduction in CO_2 emission	1600 ton/yr
Maintenance costs	40.000 euro/yr total guarantee
Manufacturer/supplier	Energy Total Projects b.v. (ETP)
Pay back period	4 years, excluding subsidies

Project characteristics

A new 100.000 m^2 greenhouse was built by Anthura in 2009 to produce the small Anthurium plants that are supplied to growers all over the world.

30% of the greenhouse consists of a climate controlled 'closed greenhouse' environment where the young plants are subjected to a temperature treatment in order to promote the formation of leaves and flower butts. During this critical phase a tight control of humidity levels is required to achieve optimal quality and minimum process time.

The heat pumps have been developed for high efficiency, using frequency controlled compressors and economisers to achieve a 20% higher efficiency than standard available units.

The ATES system consists of 3 cold wells and 3 warm wells. The water is pumped back and forth between the warm and the cold wells, with each well providing 90 m^3/h of ground water.

For heating, cooling and dehumidification of the air in the greenhouse, 120 custom built air treatment units where fitted in the 30.000 m^2 closed greenhouse with heating and cooling coils and frequency controlled fans with air streamers.

Energy Total Projects (ETP) designed the heat pump system and the aquifer thermal energy system along with the air treatment units and supplied this as an entire operational system.

Compared to the conventional alternative with chillers and a gas fired boiler, 60% energy is conserved while increasing production and quality of the plants.

Supplier characteristics

ETP is a systems supplier of specialised heat pump technology for several applications in buildings, industry and agriculture. The heat pumps are supplied with a variety of heat source modules, ranging from aquifer systems and deep geothermal wells to exhaust gasses and surface water.

In the last 10 years, ETP has fitted their special developed heat pumps and source modules in almost 200 projects with a total capacity of ca. 100 MWth.

Application of Industrial Heat Pumps

IEA Industrial Energy-related Systems and Technologies Annex 13
IEA Heat Pump Programme Annex 35

Task 5: Communication

Final Report

(Status: 01.09.2014)

Prepared by
Participants of Annex 35/13

Contents

1 Introduction

Communication strategy has to be developed (target groups, objectives and means) based upon learning curves by continuous consolidation of the created content through extensive monitoring of projects

- Awareness of potential (energy conservation, greenhouse gases, eco footprint, etc)
- Develop independent information that can be used for policy developments on energy, environmental legislation
- Give recommendation on future developments
- Execute targeted workshops with relevant stake holders, conference presentations
- Communicate directly with manufacturers and end users
- Create a Web site with database – Best practice, overview of technologies
- Give input for training courses in relation to existing organizations.

These dissemination and communication activities should be openly available to every potential user in order to attain the essential objectives of the Implementing Agreements.

Task 5 “Communication” includes also publications of the participants referring to the topics of this Annex.

2 Country-Reports

2.1 Austria

2.1.1 Communication in Austria concerning HPP Annex 35

Within the Austrian cooperation and contribution on the HPP-IETS Annex 35/13 a communication strategy has been developed in order to attain the essential objectives of the Implementing Agreements. The Austrian dissemination and communication activities include papers/presentations and other publications concerning the topic industrial heat pumps (see chapter 2.1.1). Furthermore, the national communication strategy focused on giving and getting important information on the issue concerning the Annex 35/13 to and from relevant national stake holders:

- Within a national workshop the Austrian heat pump manufactures and community has been involved in the potential, application possibilities, challenges and technology trends of industrial heat pumps (see chapter 2.1.2).
- To reach the end users (the Austrian industrial and commercial companies), presentations of the benefits at relevant conferences as e.g. Zotter & Rieberer (2014) (see chapter 2.1.1) has been held, as well as a questionnaire (see chapter 2.1.2) has been developed and sent to the Austrian industry to indicate them to the possibility of using an industrial heat pump in their production.
- Involving relevant decision maker to this important topic, a national report about the activities and the results about the HPP-IETS Annex 35/13 will be prepared at end of the Annex and sent to the Federal Ministry for Transport, Innovation and Technology of Austria (see chapter 2.1.4).
- This national report will be free and publicly available at the web site www.nachhaltigwirtschaften.at/iea/ to grant a broad access. At this website further information about the aims and activities of the HPP-IETS Annex 35/13 are available (see chapter 2.1.4).

As a highlight of the Austrian communication activities, which have to be mentioned, is the successful initiation - based on the experience of the HPP Annex 35 - of a national R&D project (FFG-Pr. Nr.: 834614) concerning the development of a high temperature hybrid compression/absorption heat pump with an alternative working pair for recovering industrial waste heat.

2.1.2 National Workshop

A national workshop about the activities and issues concerning the HPP-IETS Annex 35/13 was held on Oct. 11, 2013 within the 9th Austrian Info-Day for Heat Pump Manufactures (see Figure 2-1).

Within this workshop the Austrian heat pump community has been informed about the activities of the HPP-IETS Annex 35/13, the application possibilities at relevant industrial branches, the economical and ecological potential, the technical issues and needs, as well as about the actual R&D trends of industrial heat pumps (see Figure 2-2). The work shop ends with a discussion about the economical objectives and future trends of industrial heat pumps. As recommendation on future developments, it has been summarized that the Austrian industry needs high-temperature heat pumps. Within this discussion, it was also pointed out, that beside the industry commercial buildings in Austria offer also a large potential for heat pump applications, as e.g. hotels.

Figure 2-1: Members of the 9th Austrian info-day for heat pump manufactures

Figure 2-2: *Presentation of the aims and activities of the IEA HPP Annex 35*

2.1.3 Questionnaire

In order to get in contact to the end users of industrial heat pumps a questionnaire have been developed and sent to the Austrian industrial and commercial companies. The sent questionnaires have two major aims, both to determine an overview of the actual energy consumption on the one hand and on the other hand to involve the industry with this topic.

Preliminary, about 360 companies in whole Austrian have been contacted via telephone. The questionnaires have been sent to all the companies, which have agreed to join with. But unfortunately, the number of completed, returned questionnaires has been rather poor despite repeated contact. Therefore, a branches selected analysis was not possible. However, according to the results of the questionnaire, for about 90 % of the asked companies (40#) measures to reduce the energy consumption are considered. The most important criteria for or against a measures for saving energy in the industry are the economical rentability and the reliability of the production process. For Austrian industry payback time should be no longer than 3 years and in exceptional cases no longer than 6 years at all.

According to this analysis, about 67 % of industrial companies know about the possibility to use heat pumps for their heat supply. But, the percentage of Austrian companies knowing about industrial waste heat recovery by heat pumps is lower. However, based on these results the relatively high investment costs and “long” payback periods were seen as the most important barriers by the industry. Furthermore, there is skepticism about the reliability of such systems, since experience of already installed plants are missing. Other barriers are a lack of know-how in Austria regarding the integration and operation of high-temperature heat pumps in different production processes, as well as a previously unattractive energy price situation. But, with an expectable increase in fossil fuel prices in future and a gain in experience the industrial heat pump will become much more attractive for the industry compared to conventional boilers.

2.1.4 National report (web site)

After the end of the IEA HPP-IETS Annex 35/13, a national report will be written to give a detailed overview of all the results, the Austrian contributions and activities of this Annex. This national report will be published by the Federal Ministry for Transport, Innovation and Technology of Austria (bmvit) via the public domain web site "www.nachhaltigwirtschaften.at/iea/" to grant a broad and generally access to reach a relevant spin-doctors and policy-maker. This web site also gives further information about the aims and activities of the HPP-IETS Annex 35/13.

The national report will include an overview of the energy situation in Austrian industry, the potential for reducing CO_2-emission in the industry using heat pumps and an overview of the available heat pump technology and R&D trends suitable for the industry. Furthermore, also an overview of possible barriers, legal standards as well as funding guidelines in Austria concerning the application of industrial heat pumps will be part of this report. A main part of the report will be related to application possibilities in different industry branches and processes, as well as the documentation of some realised plants in Austria.

The major aim of this national report is to overcome the mostly relevant barriers like e.g. missing experience and know-how., which hinder a wider field of heat pump applications in Austrian industry up to now.

The national report will be mainly addressed to the heat pumps manufacturer, the industry, consulting engineers and installers as well as policy makers for input to directives and legislation.

2.2 The Netherlands

The Legal Text for the Annex had Task 5 titled Communication in a broad sense of the definition. The goal was to develop a communication strategy (target groups, objectives and means) based upon learning curves by continuous consolidation of the created content through extensive monitoring of projects.

The objective of the Annex to reduce the use of energy and emissions of greenhouse gases by the increased implementation of heat pumps in industry, is to be reached by:

- Generating information for policy makers.
- Developing information for key stake holders in industry and its supply and consulting chain and for policy makers.
- Getting insight in business decision processes.
- Increasing the knowledge and information about IHP's, database and getting existing information available.
- Applying new technologies and identifying the needs for technological development
- Creating a network of experts.
- Finding synergy with renewable energy production to increase flexibility of the grid.

The dissemination and communication activities should be based upon a set of activities defined as:

- Awareness of potential (energy conservation, greenhouse gases, eco footprint, etc)
- Develop independent information that can be used for policy developments on energy, environmental legislation
- Give recommendation on future developments
- Execute targeted workshops with relevant stake holders, conference presentations
- Communicate directly with manufacturers and end users
- Create a Web site with database – Best practice, overview of technologies
- Give input for training courses in relation to existing organizations

On international IEA level within the Annex unfortunately, although the Annex 35/13 project had been prolonged by one year, nearly none of the deliveries could be finished as foreseen, due to the fact that most participants in the Annex are more involved with R&D than with marketing

The report on The Netherlands will handle the topics as mentioned under the activities in the Legal Text, where an analyzes by the National Enterprise Agency in 2009 was the basis for the approach using traditional tools accepted in the market. A Dutch National Team with the main stakeholders supported this approach. As 'work in progress' this report is not the final stage of the work.

2.2.1 Introduction to the market

Technological development, the development tariffs for natural gas and electricity, the need to promote a green image and the increased government attention for excess heat will increase the interest for industrial heat pumps. Frontrunners in the market ranging from Lidl to Shell are well aware of the need for sustainable development and are already committed to highly ambitious goals. Dairy industry has developed their program on an Energy Neutral production chain. But what about the others?

In the approach of industry we must be conscious as reported under Tasks 1&2 of the fact that decisions in industry are based upon information that will be of different and tailor made contents. The energy conservation policy for industry from government has been largely based on the Voluntary Multi-Year Agreements (MYA) between Industrial Sectors and the Ministry of Economic Affairs. This approach is tailor made and worked out in Road Maps.

As a consequence four or even five different levels of information and approach can be distinguished in which heat pumping technologies can play an important role, being:

- Chemical industries active under the R&D innovation contract of ISPT (http://ispt.eu/roadmap/) is actively involved in developments of technologies as described under Task 3.
- Paper and pulp and other large sectors are approached through the MYA are also partly involved in ISPT. An important topic for these sectors is the bad economic situation of cogeneration through the negative spark spread giving new opportunities for process integration.

- Food industry is active on MYA-roadmaps and there is notable increase in applied heat pumps. An important topic is the F-gas regulation through a large renovation process is needed for the refrigeration and cooling in these sectors.
- Miscellaneous industries have a potential for heat pump applications which not yet structurally approached by policy or market suppliers. The number of applications is also growing but those are coincidences.
- Industrial areas with mixed occupants are almost all approached through local authorities, an approach which can be successful.
- Agriculture and the Greenhouse sector have already shown a lot of successful applications.

In general there two major obstacles which already noted in the start of the IEA Annex which is the fact that the knowledge of pinch and process integration is not broadly spread and almost lost for a large part of industry, nor the knowledge of heat pump applications and heat pumping technologies. It is not normal the policy and even within the capacities of RVO/Government to approach individual industries to convince these towards sustainability, nor is it possible within the framework of policy programs to give a long term commitment to an information structure. In order to reach the individual industries a closely knit network has to be developed and a process approach of a long distance runner is needed. Commissioned by RVO, Energy Matters therefore has analysed how market introduction of heat pumps in special but reduction of energy for making heat in general can be accelerated without continued support from the government. To overcome the barriers a voluntary program is basically as described under the Legal Text of the Annex:

- Information of the key users, to raise awareness of the saving potential and the potential for renewable energy
- Education, trainings of key users and Energy Auditors, where standardized methodologies and supporting tools are used within an integral approach based upon the Onion model for heat conservation;
- Develop best case studies and publish factsheets, conduct pilot audits and develop monitoring and a set of sector specific tailor made solutions;
- Partly financed company specific Energy Efficiency Plans based upon energy audits, which is a program run under the MYA. This program should focus on the re-use of waste heat within the process.
- Development of Long Term Sectorial plans (i.e. Roadmaps)
- Support scheme for tax reductions on the resulting investments
- Work with suppliers, as ideal partners to distribute information and specific know-how
- Roll out of newly developed technologies through support of demonstration and pilot projects.

Therefore as discussed under Task 2 checklists, software tool and standardized reports are developed. But also information of key users, pilot audits, case studies, education of auditors are addressed.

2.2.2 Market analyses

Most energy users are unaware of the large savings potential, both technological and economic, to reduce energy consumption. Therefore time and budget devoted to optimize energy efficiency of other systems than the key-production process is often zero. According to the energy managers of industrial companies these two points – lack of time and lack of budget – are the main barriers for implementing energy saving measures.

It is stated that information for the key users, to raise awareness of the saving potential and the potential for renewable energy is an important step in the process.

Very often the management does not realize the real costs of the energy consumption in their company and the possibilities of savings which can be achieved, but also the technical staff has low awareness of potential energy savings in industry. The costs of detailed energy audits are considered as too high. Therefore most companies are not willing to pay for audits, unless they already have a specific idea of certain measures to be implemented.

It is important to envisage in a communication strategy on heat pumps, that industrial companies only become active if one of its staff members is convinced and is able to present the heat pump as a sound and attractive business case to the decision makers within the company. Heat pumps can be part of the solution for a new project or renovation project in which excess heat is part of the challenge to be solved. As excess heat is often not seen as an economical problem, it will be the first challenge to get this topic on the agenda of the project engineers and decision makers within the company. Then the threshold for a company becoming aware of the solution with heat pumps should not be too high or too time consuming in the learning process.

Information should be readily available, tailor made and have easy tools for a first calculation or estimation.

Persons to be informed in the first stage are most likely project or process engineers, managers of the utilities or persons responsible for quality, working conditions and the environment (permits).

The next aspect to consider in a communication strategy on heat pumps is that it is impossible for one organization only, like RVO, to approach thousands of employees, hundreds of companies with tailor made communication on the advantages of heat pumping technologies for different processes. An intermediary organizational structure is needed. The question will have to be answered how such an organization can work and continue to work without financial support from government after the start and build up phases. Key stakeholders in the market will have to be attracted to join forces. It seems logical to involve heat pump suppliers/manufacturers and to let them take the lead. However these companies are often more active in refrigeration with limited knowledge of industrial processes.

Consultants have a common interest in the development of this market, are accustomed to process analyses and sometimes have basic awareness of pinch models.

The market deployment for industrial heat pumps already fosters successful new projects since the last five years as technological developments enter the market and boundary conditions are changing through environmental legislation and tariff developments of energy prices. These developments are often sector and process specific and need a tailor made approach to find the right leverage for interest in the heat pump solution. It is interesting to know that heat pumps are attractive to a certain part of the intensive greenhouse industry as it was possible to get a higher yield with less risk for plant diseases [snap niet wat hier staat]. This added value was the leverage needed. For industrial processes it will be the challenge to find similar strategies.

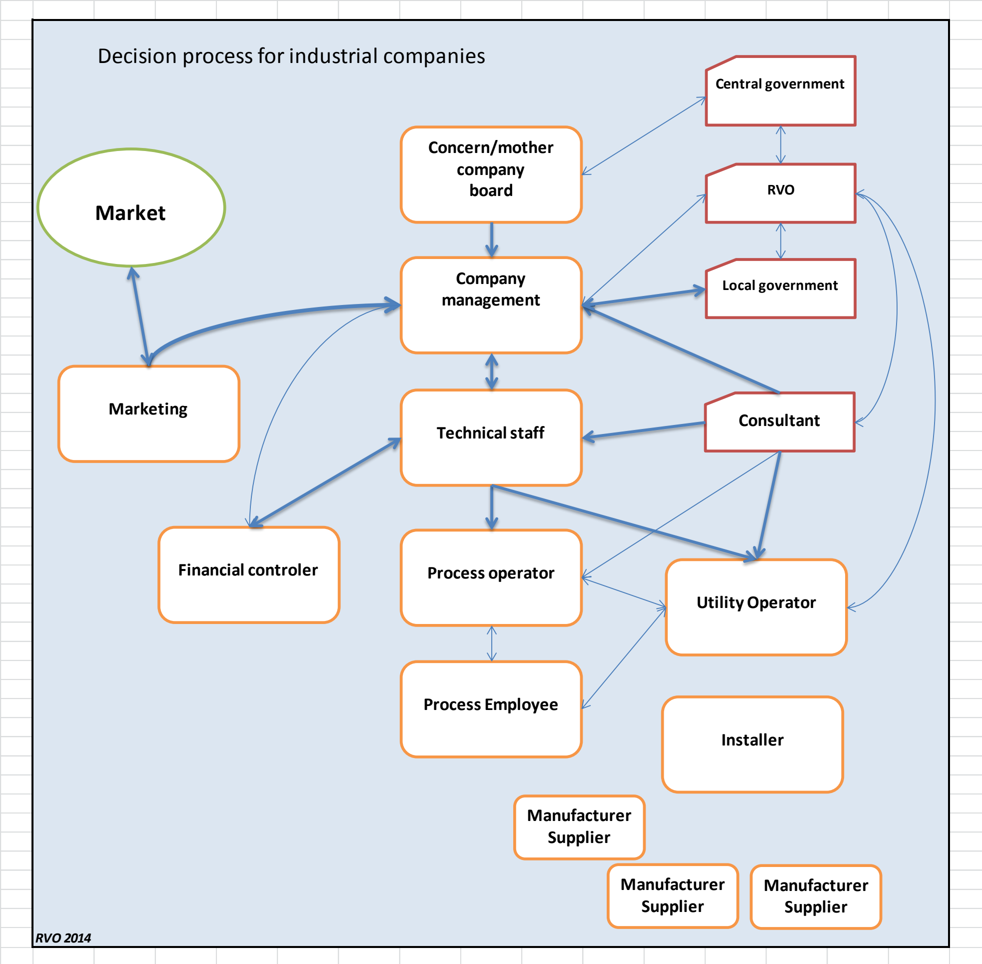


Figure 2-3: ***Communication network in industry***

Heat pumps are only economically viable when aligned with the business process and not compete with simple measures such as direct heating. The basic message is that 'Heat pumps offer opportunities in situations where excess heat is available which cannot be used directly'.

A basis for communication is and will be the availability of objective and unambiguous information. Information which is needed in order to evaluate the odds as well as give the characteristics of the available heat pump equipment which can be stored in a database and made available through a web site.

In the Einstein project parallel to the RVO analyses several factors are named that hinder further energy optimization of processes:

Competition of suppliers and trade companies: Suppliers of equipment for industry are very active on the market but are looking for sale of equipment and not for assistance to reduce energy consumption. Furthermore energy audits are conducted by design companies and wholesale trade enterprises. These companies do not have practical and professional experiences for an energy audit as this is not their core service.

Data acquisition problems: In many cases factories are unwilling to disclose energy-related data which are considered confidential, sometimes inadequate or unreliable measuring equipment is installed in factories. Furthermore companies often are not aware of the energy flows of their own processes and therefore they do not store properly relevant data and are not able to deliver reliable information as they have not the appropriate knowledge. For energy auditors it is difficult to get support of technical employees: sometimes they are considered as competitors or as a danger for their own job.

Evaluation: Sometimes neither the auditor nor the company have the measurement equipment necessary for evaluation of the saving measures and it is difficult to identify the characteristics of the machines and technical equipment on site. For the evaluation of the processes in different industrial sectors it is difficult for energy auditors to know all the relevant technologies and collect experience in all technical processes. All those problems make economical assessment and evaluation of selected options very challenging.

Implementation: At the end of the decision process expectations of short investment pay-back period and reluctance to implement changes because of possible impact on the processes are the main barriers to the implementation of saving measures. At the end clients simply do not implement proposed measures.

Problems on personnel level: Personnel may not be trained or experienced in energy saving measures. Furthermore the personnel have insufficient time to implement measures. The person responsible for energy any energy efficiency is not a part of the management team. Therefore, (s)he has limited organizational power and budget. Those problems may also be seen as barriers from management: reluctance to adopt current managerial procedures for energy efficiency and lack of a culture to make energy efficiency ‘business as usual’, i.e., to make energy management an integrated part of the management processes.

Cost evaluation case by case: Universal information on the cost of energy efficiency investments does not exist. Instead, each energy-saving measure has its individual cost depending on the local situation and is determined by the amount of supplementary work (rebuilding etc.) that has to be done to implement it.

Inexistent follow up: The follow-up after the energy audits or the implementation projects thereafter may have been inexistent. Supervision and maintenance work may have been neglected and, as a result, their energy performance has fallen.

2.2.3 Market developments and communication strategy (tailor made approach)

There a number of market developments which widens the opportunities for industrial heat pumps. An increase in the application of heat pumps is noticeable in the last five years after more than a decade of stand-still. External influences as well as technological developments can be credited:

- Process industry, mainly chemical industry with a focus on process intensification using advanced highly specific software models by large specialized engineering companies. Under the ISPT-program these companies are effectively collaborating on new processes and new innovative heat pumping technologies as described under Task3. The roll-out of these technologies are supported by governmental programs.
- Large industrial processes for specific sectors where large excess heat streams are produced like paper and pulp industry are often multi-nationals which have their own priorities and react on market changes, energy and feedstock prices with decisions often made at concern level. Due to the decline of the so-called spark spread, the difference in operating costs between CHP and heat pumps is considerably narrowed. A lot of CHP-installations after depreciation will therefore not be replaced as the investment will have an insecure economical basis. Paper and Pulp industry being an example. In those cases, there is more attention to the internal use of process heat and thus for heat pumps where drying processes and washing hot water processes are the logical applications. The approach in the Netherlands can be sector specific as companies are part of sectorial multi-year agreements with government. This approach has been piloted in paper and pulp and is based upon general and specific analyses of processes, workshops and training courses. Experience on this can be applied in other sectors. Especially in the greenhouse sector the combination of heat pumps and CHP increases the heating capacity and decreases the electricity output to the grid, therewith increasing the economy.
- In line with the requirements for the EU F-gas regulation many companies have to adapt their system or replace their refrigeration and/or cooling systems. This conversion, which has to be done before the end of 2015, and not to forget the new EU F-gas proposal (additional phase out in 2020), offers the opportunity to simultaneously use the heat from chillers for heating purposes. Manufacturers like IBK and Grasso are actively marketing this solution with the support of Netherlands Enterprise Agency and workshops/training courses for installers. For food industry Dairy industry is already on a pathway to Energy Neutral for the complete supply chain from cow to end user. Other sectors like meat industry have heat pumps defined as key technology. This approach should be broadened to other sectors. The first projects using condenser heat from cooling with add-on heat pumps are built but not yet common practice. The focus for communication is to catch up in closing the knowledge gap at to get the use of excess heat from cooling for heating purposes state of the art in industry by the end of 2015. A ‘taskforce heat from cooling’ is set up. This taskforce creates a website with project cases, hold seminars in the regions and workshops and training courses. The startup of this task force is funded by RVO and will be continued on commercial basis by consultants, installers and manufacturers.
- A large application potential of industrial heat pumps is still not used because of the limited supply temperatures of about 100 °C of commercially available heat pumps.

If these supply temperatures could be increased, more industrial processes could be improved in their energy efficiency. The main reason for the limited temperatures has been the absence of adequate working fluids. By using other than the traditional working fluids for refrigeration and new technologies heat pumps can lift to reach 120 °C and even higher. Both working fluids and new technologies are now getting out of the development phases into practice through first pilots and real life applications:

- New refrigerants with low GDP and high temperatures are becoming available from international manufacturers.
- Through the use of so-called "temperature glides" the heat/electricity ratio (COP) is significantly improved and the introduction of chillers with an additional compression step, which are perfect for the heating of hot water or cleaning process in process industries.
- The early development of acoustic and thermochemical heat pumps and heat transformers the path towards even higher temperature ranges up to 250 °C.

- Increased performance, reliability and availability of heat pump technologies for commercial and domestic buildings make the application in business parks more attractive, the first industrial A+++ buildings with BREEAM appearing on the market. Business parks where small manufacturing companies and warehouses are located have a large potential which can be realized with the examples like Ecofactorij in renovation and development process of the area within the boundary conditions of Municipalities, developing master plans.

In general the Multi-Year Agreements with other sectors then the above should focus on pathways and on re-use of waste heat within the process. The existence of cooling towers within the industrial process shows where heat is wasted. A program focusing on ‘no more cooling towers’ can be developed

2.2.4 Conclusions

In line with the Legal Text of the Annex the undertaken activities focus on:

- *Awareness of potential (energy conservation, greenhouse gases, eco footprint, etc*) which is reported under Chapter 1 (Task 1) as follows:
    - Chemical Industry is active in ISPT-program and well aware of and active with innovative heat pumping technologies as described under Chapter 3/Task 3.
    - Paper and Pulp is extensively approached with regular sectorial works shops supported by the R&D-program of ISPT (Chapter 3/Task 3) and the KCPK (Knowledge Expert Centre for Paper and Pulp).
    - Food Industry is active under the MYA’s and within their Energy Conservation Roadmaps heat pumping technologies are taken up when relevant. Examples being meat processing, dairy and cheese making, greenhouses, etc.

  - Miscellaneous industries on clustered areas are approached through the website and by informing local city councils with information successes like Ecofactorij. Workshops are held on the Information Centre
  - Large forerunners are advertised as example like Lidl and Campina
- *Develop independent information that can be used for policy developments on energy, environmental legislation*. The Management summary of the report on Industrial Heat in the Netherlands is sent to the ministry of Economic Affairs which is developing a Long Term Vision on the heat infrastructure in the Netherlands.
- *Give recommendation on future developments*, this is described in the Management Summary and in the next paragraphs. These recommendations are discussed and being programmed in the activities of Netherlands Enterprise Agency.
- *Execute targeted workshops with relevant stake holders*, This is taken up by education and trainings of key users and Energy Auditors through their branch organization FEDEC, where standardized methodologies, like EPS, and supporting tools, like EINSTEIN, are used within an integral approach based upon the Onion model for heat conservation;
- *Communicate directly with manufacturers and end users.* As stated in the analyses of the market the scope of the approach and the target audience is large and cannot be covered by the Netherlands Enterprise Agency on the long term.
  - The market is approached through tailor made activities is described in paragraph 5.5.
  - Intermediaries are used a discussion platform ‘Industrial Heat’ is created organizing targeted workshops and seminars.
  - Partly financed company specific Energy Efficiency Plans based upon energy audits, which is a program run under the MYA. This program should focus on the re-use of waste heat within the process. This is not yet the case and Long Term Sectorial plans (i.e. Roadmaps) can be used for this attention.
  - There have been extensive discussions with manufacturers where during the Annex two manufacturers were awarded the NVKL-Innovation Award, therewith getting country wide attention.
- *Create a Web site with database*, two websites have been created during the Annex.
- *Best practice, overview of technologies*. At the start of the Annex it has been difficult to get sufficient information best practice applications, but running the Annex more and more information got in. A list of over 30 projects exists for which 20 Factsheets have been written. This database will be filled continuously and information will be spread to the target audience.

The Communication strategy is work in progress and not yet fully established.

Several approaches for process optimization in industry can be met with based upon the TRIAS Energetica. In chapter 2 it is discussed how to approach the different industrial sectors/companies. The Energy Potential Scan developed by Philips/Novem is a partici-pative model to start the analyses of the industrial process. Unlike traditional energy audit approach, in EPS, company and energy consultants work together to analyze the possibility to conserve energy. This model is used in many countries worldwide to get awareness within companies to work on energy conservation.

In general the approach through the Multi-Year Agreements and the approach by local authorities should give permits for investments in new processes and technologies only upon the Best Available Technologies and process energy investments only on the TRI-AS-Energetica. A short list of sector specific technologies can be developed by RVO.

Supporting actions for this strategy are:

- Training courses on Energy Potential Scan and process integration through Einstein for consultants through Energy Matters and FEDEC.
- Data of technology in models within input from manufacturers. Several specific heat pump models and databases have become available in the Netherlands during the work on the Annex. These models must still be extended on international level in order to get The heat pump model based upon Excel would ideally be available on the Internet and could further be developed as a WIKI-approach where the market itself would fill in further details in the model and in the end applications could be hinged as factsheets to the model. This stage of development is not reached yet during the process of the Annex.
- Factsheets for several types of best practice applications have become available and will be published in linked to the mentioned heat pump model. This collection of fact sheets will be extended
- Training and education on process modeling based upon exergy and pinch at basic high school level and universities should be intensified and partly re-introduced.
- Workshops with key stake holders and decision makers can give a basic understanding of the real costs of the energy consumption in companies and the possibilities of savings which can be achieved.

These supporting activities should be clearly shown on a Web site which is not part of a governmental program but ideally supported and financed by the market.

3 Publications

The participants of this Annex published the following articles, reports etc.

3.1 Austria

Following a list of all Austrian papers/presentations or other publications on the issue concerning Annex 35/ 13 "Application of Industrial Heat Pumps" is given:

Fleckl T., Zottl A., 2013: *„Simulation tools for the integration of heat pumps in complex systems“* 9. Info-Tag für Wärmepumpenhersteller, Vienna, Austria, 11.10.2013 (in German: *Simulationstools zur Integration von Wärmepumpen in komplexe Systeme)*

Hoff C., 2011: *„High temperature heat pumps for industrial waste heat recovery”*– Bachelor Thesis at the Faculty of Mechanical Engineering and Economic Sciences, University of Technology Graz, written at the Institute of Thermal Engineering of , University of Technology Graz, Austria, 2011 (in German: Hochtemperaturwärmepumpen für industrielle Abwärmenutzung)

Moser, H.; Rieberer, R., 2010: ***„****Waste heat recovery due to flue gas condensing systems of biomass cogeneration plants“*- in: Cluster Forum "Abwärmenutzung in der Industrie". Nuremberg, Germany, 19.11.2010 (in German: Wärmerückgewinnung mittels Rauchgaskondensationsanlagen biomassebefeuerter Heizkraftwerke)

Rieberer R., 2013: *„IEA HPP Annex 35 – Industrial Heat Pumps – Overview“* 9. Info-Tag für Wärmepumpenhersteller, Vienna, Austria, 11.10.2013 (in German: *IEA HPP Annex 35 – Industrial Heat Pumps – Übersicht)*

Schachner T., 2012: *„Industrial heat pump applications in Austria - An ecological and economic comparison with conventional heat generators”* - Bachelor Thesis, Faculty of Mechanical Engineering and Economic Sciences, University of Technology Graz, written at the Institute of Thermal Engineering of , University of Technology Graz, Ausria, 2012

Zotter, G.; Rieberer, R., 2013: ***„****Technical, ecological and economical analyse of a heat pump application for waste heat recovery in a metal-working industrial plant“* – in Proc.: DKV-Tagungsbericht 2013. Deutscher Kalte- und Klimatechnischer Verein Hannover, Germany, 20-22.11.2013, ISBN: 978-3-932715-49-5 (in German: Technische, ökologische und ökonomische

Analyse des Einsatzes einer Wärmepumpe zur Nutzung von industrieller Abwärme in einem metallverarbeitenden Betrieb)

Zotter G., Rieberer R., 2013: „*Industrial heat pumps – possibilities and potentials of in-plant waste heat recovery by heat pumps*“ 9. Info-Tag für Wärmepumpenhersteller, Vienna, Austria, 11.10.2013 (in German: *Industrielle Wärmepumpe - Möglichkeiten und Potentiale der innerbetrieblichen Abwärmenutzung mittels Wärmepumpen)*

Zotter, G.; Rieberer, R., 2014: „Increase of the energy efficiency in Austrian industry due *in-plant waste heat recovery with heat pumps* by two examples*“* – in Proc.: Symposium Energie Innovationen 2014. Graz, Austria, 13-15.02.2014, ISBN: 978-3-85125-310-8 (in German: „Steigerung der Energieeffizienz in Österreichs Industrie durch innerbetriebliche Abwärmenutzung mittels Wärmepumpsystemen anhand zweier Beispiele

Zotter, G.; Rieberer, R., 2014: „In-plant utilization of waste heat by heat pumping systems“; in Journal: KI-Kälte-, Luft-& Klimatechnik, published 22.05.2014 (in German: „Innerbetriebliche Nutzung von Abwärme mittels Wärmepumpen*“*)

3.2 France

Sapora, 2010 Sapora, E.: Heat Pump Integration in a Dairy. Workshop Industrial Heat Pump. Chillventa 2010, Nuremberg, 2010.

Bobelin, 2011 Bobelin, D.: Experimental results of a heat pump using R245fa as working fluid. European Heat Pump summit, Nuremberg, 2011.

Pereux, 2012 Peureux, J. L.: Very high temperature heat pump applied to Energy efficiency in Industry. ACHEMA 2012

3.3 Germany

3.3.1 thermea. Energiesysteme GmbH

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Wobst, 2008 Wobst, E., Oberländer, S., Nestler, W., CO2-Wärmepumpen großer Leistung – unverzichtbar für eine nachhaltige Wärmeversorgung, KI Kälte Luft Klimatechnik, December 2008

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Hübner, 2012	Hübner,.J., Oberländer, S., Wobst, E.: Energiekosten- und CO2-Emissionsreduzierung mit CO2- Hochtemperaturwärmepumpen thermeco2, HLH, Bd. 63, March 2012
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Hübner, 2014	Hübner, J., Energieeffizienz und Nachhaltigkeit in der Produktion und Gebäudetechnik TWK 10. Karlsruher Wärmepumpensymposium, February 2014

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Wolf, 2012	Wolf, S.; Lambauer, J.; Blesl, M.; Fahl, U.; Voß, A.: Industrial Heat Pumps in Germany: Potentials, technological development and market barriers. Proceedings of the Eceee 2012 Summer Study on energy efficiency in industry, S. 543-550
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Wolf, 2013b	**Wolf, S.; Fahl, U.; Voß, A.:** Zukunftsträchtiger Markt: Hochtemperaturwärmepumpen für den Einsatz in Industrie und Gewerbe. In: IKZ Fachplaner (2013), Nr. 7, S. 14-16
Wolf, 2014	**Wolf, S.; Fahl, U.:** Fortschritte beim Wärmepumpeneinsatz in der Industrie: Enorme Chancen nicht nur bei der Prozesswärme. In: Die Klima + Kältetechnik (2014), Nr. 2, S. 26-29

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Lambauer, 2010 Lambauer, J.; Ohl, M.; Blesl, M.; Fahl, U.; Voß, A.: Large scale industrial heat pumps – market analysis, potentials, barriers and Best-Practice-Examples, Vortrag gehalten anlässlich des Kick-off Meetings IEA IETS HPP Annex 13/35 „Application of industrial Heat Pumps“ am 26. April 2010 in Maintal, veranstaltet von IEA IETS HPP Annex 13/35, Information Centre on Heat Pumps and Refrigeration IZW e.V., Karlsruhe

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Minea, 2012a	Minea, V.: Using industrial heat pumps in sawmills for lumber drying. IEA HEAT PUMP CENTRE NEWSLETTER, VOL. 30, No. 1/2012, pp. 19-25.
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Watanabe et al, 2014	Pioneering Industrial Heat Pump Technology in Japan, Choyu Watanabe et al. 11th IEA Heat Pump Conference, 2014, Montreal.
Zotter, 2013	Technische, ökologische und ökonomische Analyse des Einsatzes einer Wärmepumpe zur Nutzung von industrieller Abwärme in einem metallverarbeitenden Betrieb. Gerald Zotter, René Rieberer, Technische Universität Graz, DKV-Tagung 2013, Hannover.

4 Policy paper

The main results of ANNEX 35/13 are summarized in a policy paper. The concept was to have a brochure, summarising the main results of the annex work explained in a generally intelligible manner, which can be used by the members of the Annex and the IEA Heat Pump Centre.

The policy paper consists of

- Description of industrial heat pumps
- Applications
- Barriers and solutions
- The integration of IHP into process
- Case studies
- Research and development projects
- Contacts.

The members of Annex have the possibility to change the examples of R&D-projects and the case studies with examples representing their countries and regions or technologies, referring to them.

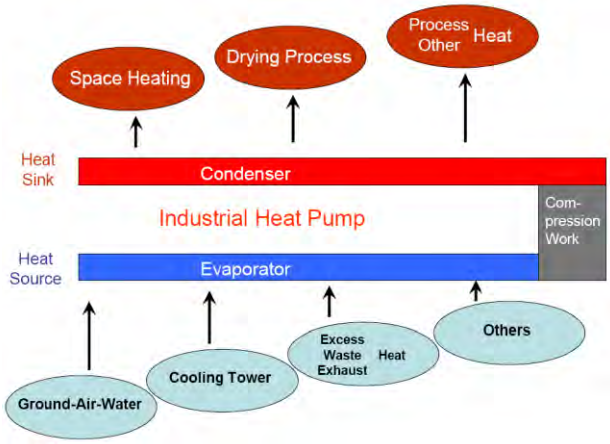
The complete policy paper is attached to this report.

APPENDIX

Application of Industrial Heat Pumps

Securing a reliable, economic and sustainable energy supply as well as environmental and climate protection are important global challenges of the 21st century. Renewable energy and improving energy efficiency are the most important steps to achieve these goals of energy policy. While impressive efficiency gains have already been achieved in the past two decades, energy use and CO_2 emissions in manufacturing industries could be reduced further, if best available technologies were to be applied worldwide.

Industrial heat pumps (IHP) are active heat-recovery devices that increase the temperature of waste heat in an industrial process to a higher temperature to be used in the same process or another adjacent process or heat demand

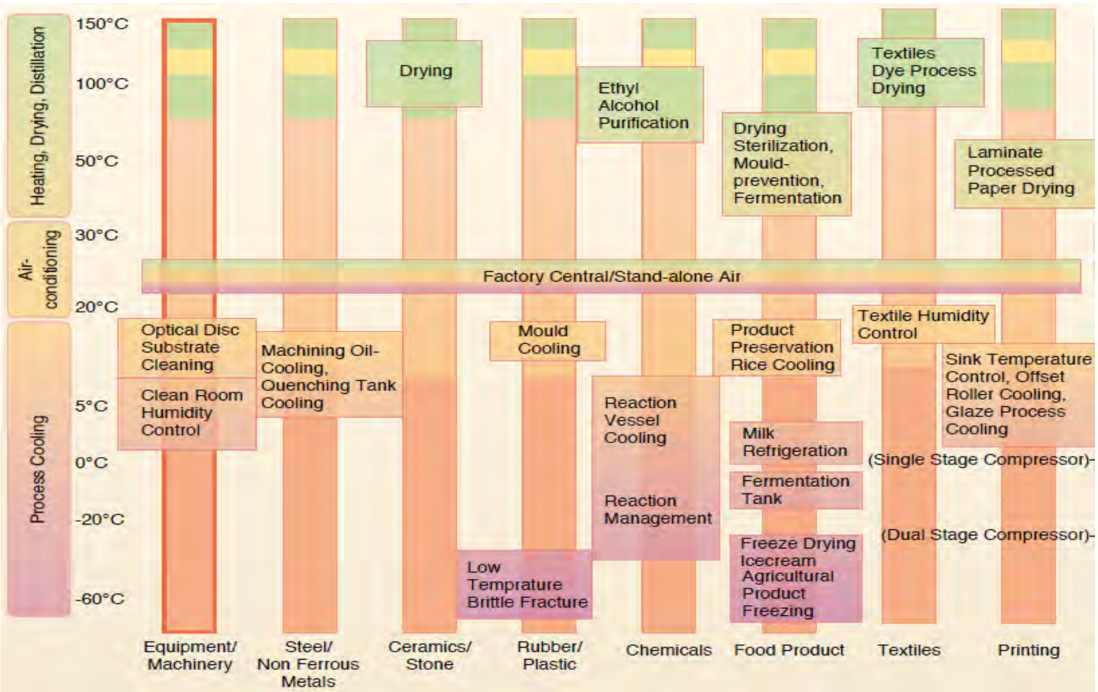


Annex 35 / 13

The IEA HPP-IETS Annex 35/13 "Application of industrial Heat Pumps", a joint venture of the International Energy Agency (IEA) Implementing Agreements "Industrial Energy-Related Technologies and Systems" (IETS) and "Heat Pump Programme" (HPP) has been initiated in order to actively contribute to the reduction of energy consumption and emissions of greenhouse gases by the increased implementation of heat pumps in industry.

The Annex 35/13 started on 01. April 2010 and expired on 30. April 2014, with 15 participating organisations from Austria, Canada, Denmark, France, Germany (Operating Agent) Japan, The Netherlands, South Korea and Sweden.

Industrial Heat Pump Applications



Barriers for application and solutions

Heat pumps for the industrial use are available on the markets in the participating countries in recent years, just very few carried out applications can be found. To distinguish the reasons were a part of the survey in the annex:

- Lack of knowledge:
  The integration of heat pumps into industrial processes requires knowledge of the capabilities of industrial heat pumps, as well as knowledge about the process itself. Only few installers and decision makers in the industry have this combined knowledge, which enables them to integrate a heat pump in the most suitable way.
- Low awareness of heat consumption in companies:
  In most companies knowledge about heating and cooling demands of their processes is quite rare. This requires expensive and time consuming measurements to find an integration opportunity for an industrial heat pump
- Long payback periods:
  Compared to oil and gas burners, heat pumps have relatively high investment costs. At the same time companies expect very low payback periods of less than 2 or 3 years. Some companies were willing to accept payback periods up to 5 years, when it comes to investments into their energy infrastructure. To meet these expectations heat pumps need to have long running periods and good COPs to become economical feasible.
- High temperature application
  Many applications are limited to heat sink temperatures below 65°C. The theoretical potential for the application range of IHP increases significantly by developing energy efficient heat pumps including refrigerants for heat sink temperatures up to and higher than 100°C.

The barriers can be solved, as shown in the results of the Annex: short payback periods are possible (less than 2 years), high reduction of CO_2-emissionen (in some cases more than 50%), temperatures higher than 100°°C are possible, supply temperatures < 100°C are standard.

The integration of industrial heat pumps into processes

The methods of integration IHPs in processes range from applying rules by hand to far advanced mathematical optimization and are discussed in the literature. The Task 2 Report outlines specifically how the integration of IHPs in processes is supported by computer software, i.e. by modeling.

In order to ‘update’ the Annex 21 screening program in the sense of a modern development retaining the original goals, a proposal has been made that allows a consistent integration of a heat pump into a process based on pinch analysis. The basic elements of this concept are:

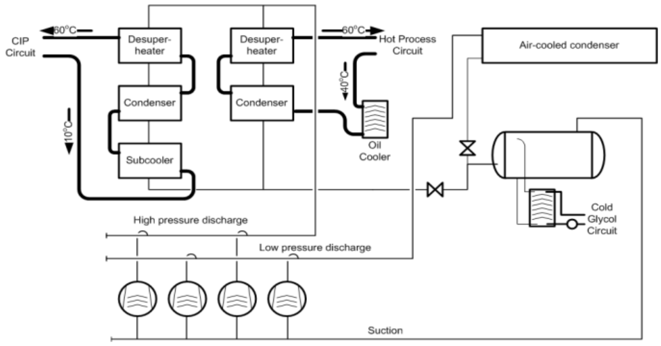
- Substitution of the problem table algorithm in pinch analysis by an extended transshipment model which allows a simultaneous optimization of utilities and heat pump.
- Approximation of the heat exchanger network as in the standard pinch analysis.
- Development of an algorithm for selecting of a hot and cold stream (may be of several hot and cold streams) to which the heat pump could be connected.
- Development of a heat pump data base to be used within the simultaneous optimization. Since this optimization is nonlinear a special algorithm needs to be developed that enables convergence.

This concept of integrating a heat pump into a process is ‘below’ sophisticated mathematical optimization models and could therefore be considered as an **add-on** to the widely used programs based on pinch analysis enhancing their capabilities.

Examples of existing Installations

Heat pump in Food and Beverage industry - Combine heating and cooling in chocolate manufacturing (UK)

The chocolate manufacturing process also requires cooling capacity for certain steps of the process. These simultaneous demands for cooling capacity and heating capacity allowed the replacement of the heating and the cooling system by a combined cooling and heating installation. The idea was to install a Single Screw compressor Heat Pump combining Heating and cooling.



The Heat source consists in cooling process glycol from 5°C down to 0°C this evaporates Ammonia at -5°C and the heat pump lifts it to 61°C in one stage for heating. Process water is finally heated from 10°C to 60°C.

Based on the clients previously measured heating and cooling load profiles the analysis showed that to meet the projected hot water heating demands from the 'Total Loss' and Closed Loop' circuits, the selected heat pump compressors would have to produce 1.25 MW of high grade heat. To achieve this demand the equipment selected offers 914 kW of refrigeration capacity with an absorbed power rating of 346 kW. The combined heating and cooling COP, COP_{hc}, is calculated to be a modest 6.25. For an uplift of 17 K in discharge pressure the increase in absorbed power was 108 kW boosting the COP_{hi} to an impressive 11.57.

The initial thinking for the customer was to get a 90°C hot water heat pump. Indeed, some application demand required 90°C. However the total demand for this temperature level was around 10% of the whole hot water consumption. Designing a heat pump installation for such temperature would not be interesting in terms of performances and efficiencies. It was decided to install the heat pump producing 60°C hot water. When the small amount of 90°C water is required, the incremental heat is supplied now by a small gas boiler heating up the water from 60°C up to 90°C.

In parallel, other alternatives for the heating were assessed like a central gas fired boiler, combined heat power or geothermal heat pump. Qualitative and quantitative assessments (cost, required existing installation upgrade, future site growth…) defined that the best alternative solution for this project was the heat pump. So a correct analysis and understanding of the real need for the installation allow installing the right answer to the real Nestle needs.

Nestlé can save an estimated £143,000 per year (166,000 € per year) in heating costs, and around 120,000 kg in carbon emissions by using a Star Neatpump. Despite the new refrigeration plant providing both heating and cooling, it consumes £120,000 (140,000 €) less electricity per year than the previous cooling only plant.

Another impact of the complete project (combined heating and cooling, additional gas boiler for the 90°C water peak demand, etc.) decreased the total water consumption from 52,000 m^3/day down to 34,000 m^3/day.

The Nestlé system recently won the Industrial and Commercial Project of the Year title at the 2010 RAC awards.

Hybrid heat pump at Arla Arinco (Denmark)

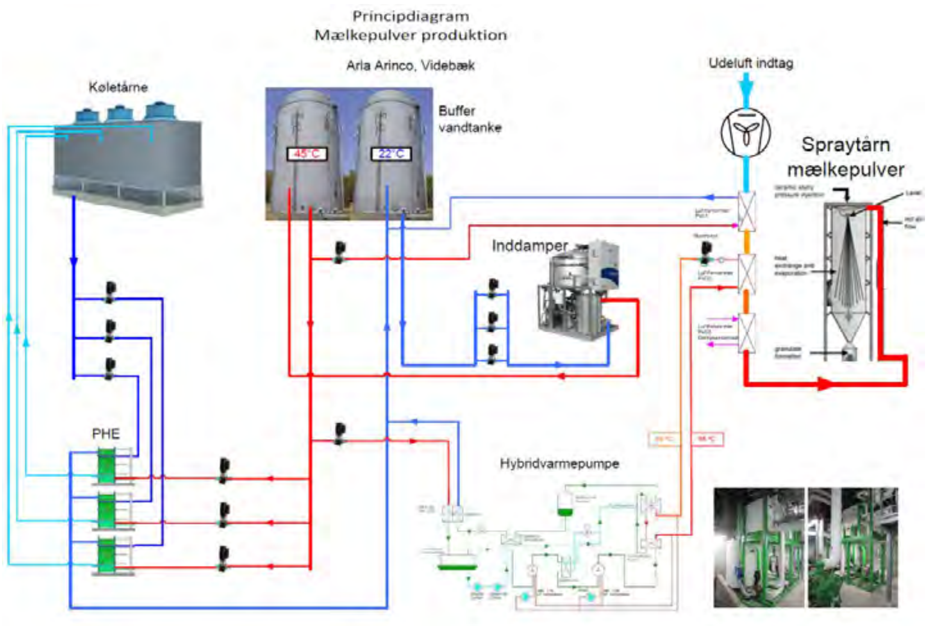
A heat pump of 1.25 MW was installed utilizing energy from 40° C cooling water – energy that was discharged to the environment prior to this project. The installed heat pump preheats drying air for milk powder to around 80° C through a water circuit.

The heat pump is installed in an application where ambient air is heated to 150 °C for drying milk powder. Previously this was done by a natural gas boiler. During the project the philosophy was to:

1. Minimize the energy demand
2. Incorporate direct heat exchangers as far as possible
3. Consider whether a heat pump is the best solution for the remaining energy demand.

The type of the heat pump is a Hybrid (compression/absorption) with the refrigerant NH_3/H_2O with a capacity of 1.25 MW.

Following these steps it became obvious that the best solution would be a heat pump only doing part of the heating towards 150 °C. It was also noticed that pre heating of the ambient air was possible through direct heat exchanging utilizing cooling water from an evaporator. The installation was thus changed to consist of three stages where the first is preheating to 40 °C using cooling water, second stage is heating from 40-80 °C using the heat pump – also recovering heat from the cooling water and third stage is heating from 80-150 °C using the existing gas boiler. Due to fluctuations in cooling and heating demands, two buffer tanks have been installed eliminating variations in the cooling system and ensuring steady conditions for the heat pump.



With a COP of 4.6 the heat pump approximately halves the energy cost compared to natural gas that is replaced. A high number of annual operation hours (around 7,400), ensures a considerable reduction in energy expenses. The analysis throughout the project also led to other energy reductions as well as direct pre heating of ambient air, thus the project as a whole caused substantial savings making this approach very profitable. Energy savings represent a tradable value in the Danish system for energy reductions. Because of the considerable amount of energy savings in this particular case, around half of the investment was financed through this value leading to a simple payback time of around 1.5 years and being very profitable from a life time perspective.

Another conclusion from the project is that engineering, design, construction, commissioning and operation of a heat pump plant of this size is comparable to that of industrial refrigeration plants.

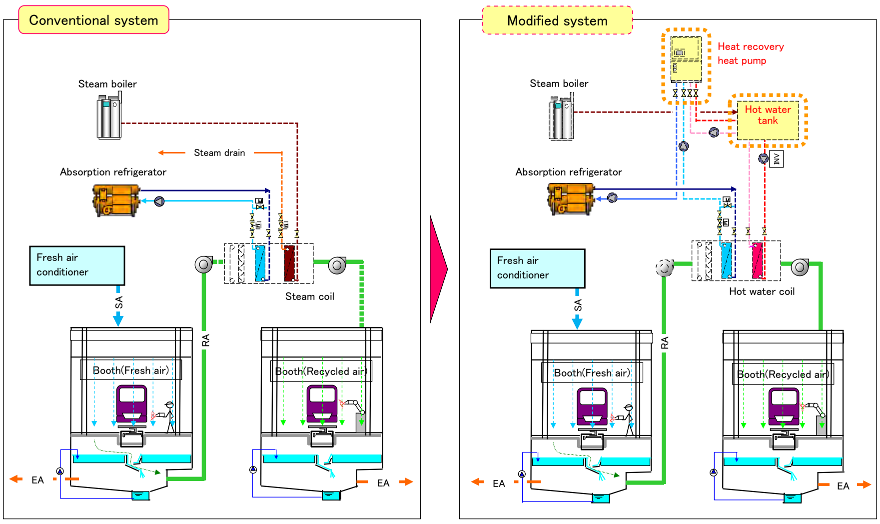
Adoption of Heat Pump Technology in a Painting Process at an Automobile Factory (Japan)

In a painting facility of an automobile factory, a great deal of energy is consumed by heating and cooling processes, the power supply, system controls, lighting, and so on. Generally, most primary energy sources are gas and electricity. Most heating and cooling needs in a painting process are supplied by direct gas combustion, steam, hot water, and chilled water generated by a refrigerator, most of the primary energy for which is gas. In terms of energy efficiency ratio, electrical energy was believed to be lower in energy efficiency than gas energy, because electrical energy uses only around 40 % of input energy while gas energy is able to use almost 100 % of direct gas combustion. However, heat pump technology has greatly improved, and the energy efficiency ratio is increasing accordingly, so highly efficient heat pumps have been introduced also into industrial processes in recent years.

There are three main advantages which we can gain from heat pump technology. The first is the heat recovery system, the second is efficient heat source equipment, and the third is simultaneous usage of cooling and heating, which is believed to be the most efficient usage. Simultaneous usage of heating and cooling can be applied to processes of pretreatment/electro-deposition, booth/working area air conditioning, and waterborne flash-off equipment. Hence, adoption of heat pump technology in this equipment is considered. The highest effect from adoption of heat pump technology in these cases is in booth recycled air conditioning and waterborne flash-off equipment.

Conventionally, the heat source system of a recycled air conditioner in the paint booth consists of a gas absorption refrigerator and a boiler. The recycled air conditioner was cooled by the gas absorption refrigerator, and reheated by boiler steam. In the meantime, the heat recovery heat pump enables us to supply both the heat for cooling and reheating concurrently. This modified system is provided to ensure system reliability and lower carbon emissions by utilizing existing equipment, such as the gas absorption refrigerator and the boiler, and also for backup purposes.

The heat pump makes it possible for the system to reduce running costs by about 63 %, to reduce CO_2 emissions by about 47 % per month, and to reduce primary energy consumption by about 49 % per month as compared with the conventional boiler. Consequently, the pay-back period would be estimated at 3〜4 years.

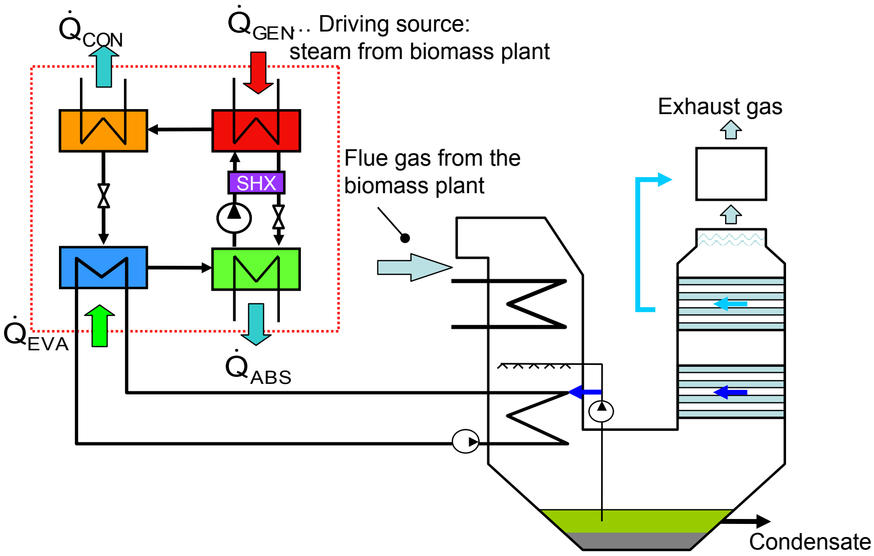


Absorption heat pump for flue gas condensation in a biomass plant

Schweighofer Fibre GmbH in Hallein (Austria) is a woodworking industrial company and part of the Austrian family enterprise Schweighofer Holzindustrie. Their core business is the production of high-quality cellulose and bioenergy from the raw material wood by an efficient and environmentally-friendly use. A biomass power plant including a steam generator supplies the in-house steam grid and covers the company's energy demand at the site. The capacity of this cogeneration plant, which is fired by 77 % of external wood and 23 % of in-house remants, amounts to about 5 MW_{el} and 30 MW_{th}. Beside the in-house power supply of Schweighofer Fibre GmbH the biomass plant also delivers electricity for about 15,000 households and heat for the local district heating grid.

The AHP offers the possibility to use the condensation heat of the flue gas by upgrading its temperature level, even thou the return flow temperature of the existing district heating grid is higher than the dew point temperature of the flue gas. At evaporating temperatures of the AHP lower than 50 °C the flue gas gets sub cooled below the dew point temperature. Hence, the temperature level of the condensation heat of the flue gas is lifted up to a useful level for the district heating. Otherwise, the condensation heat of the flue gas could not be used and would be dissipated to the ambient.

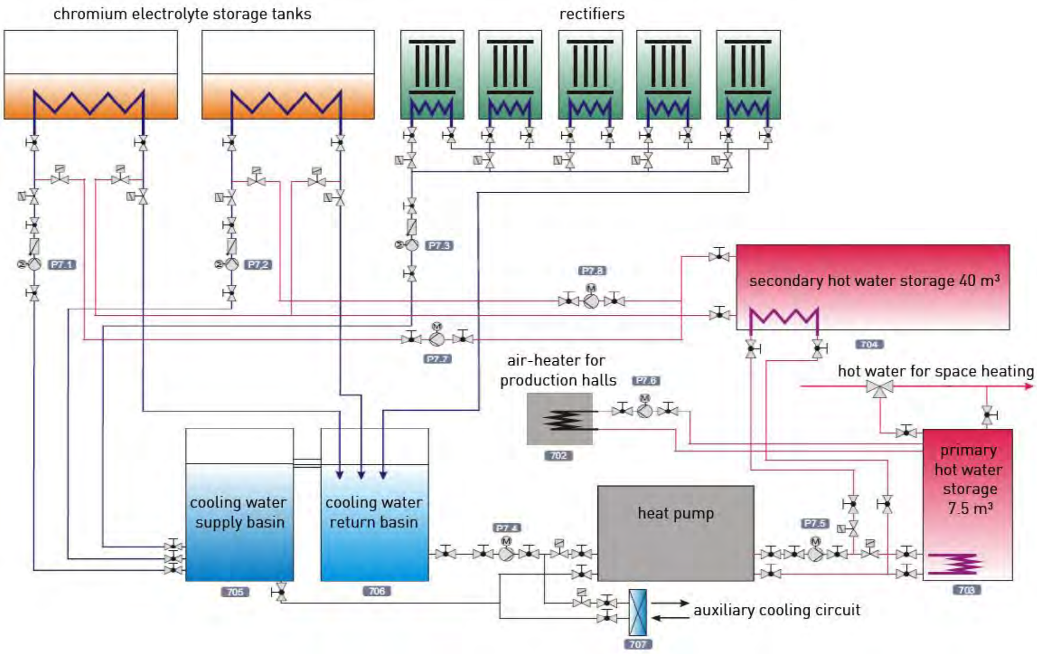
The applied AHP is a single-stage Water/LiBr absorption heat pump with a solution heat exchanger (SHX) and a heating capacity of ca. 7.5 MW. The driving source of the AHP is steam from the biomass heating plant at ca. 165 °C. According to the existing monitoring system the AHP operates with a seasonal performance factor (SPF) of about 1.6. Due to the high efficiency and the high operating hours of the AHP this industrial heat pump application enables a significant fuel and emission reduction. Additionally to the ecological advantages this application offers an economical benefit for the operator of the plant.



The benefits are energy savings of ca. 15,000 MWh/a, a higher performance and no vapour discharge system is required.

Metal processing (Germany)

Thoma Metallveredelung GmbH is an electroplating company that offers a various surface treatments. The company is a very active driver for the rational use of energy in the electroplating industry. In a research project funded by Deutsche Bundesstiftung Umwelt (DBU) a concept for a new energy saving hard chromium line was developed. Chromium plating is a technique of electroplating a thin layer of chrome onto metal objects. This is done by immersing the objects into a bath of chromium electrolyte. By applying direct electric current, chromium is plated out on the object´s surface. Usually only 20 % of the electric energy are used to create the chromium coating. The remaining 80 % are converted into waste heat. As the electroplating process is very temperature-sensitive cooling has to be applied to the electroplating bath.



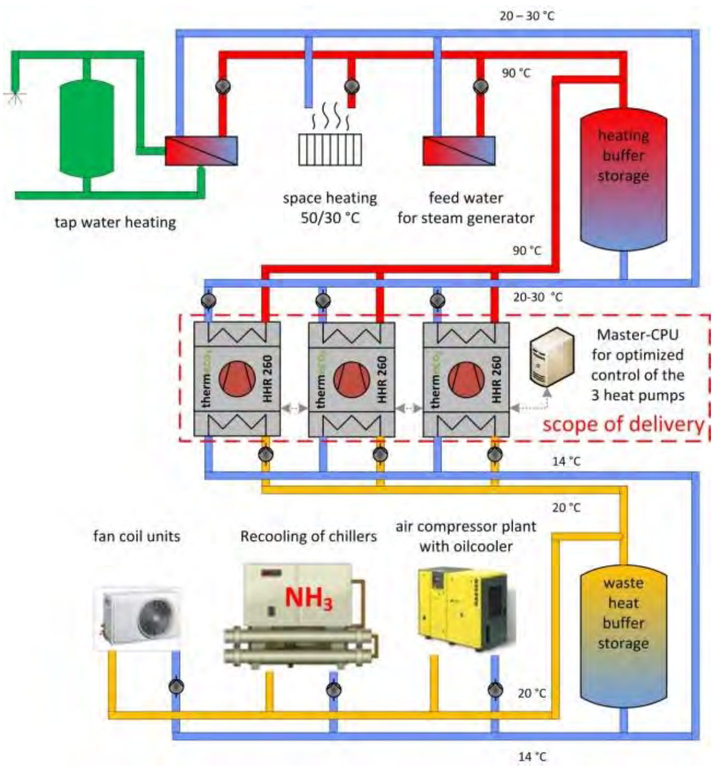
The company has increased the over-all efficiency of this process to more than 90 % by improving the electroplating process and integrating a heat pump to reuse the generated waste heat. By increasing the current density from 50 A/dm² to 90 A/dm² the efficiency of the electroplating process could be increased to 24 %. To maintain a good surface quality the temperature of the bath had to be raised to more than 60 °C. As the process still produces a large heat surplus, the electrolyte tanks as well as the current rectifiers are cooled by a water circuit. The cooling water returns to a collecting basin at a temperature of 60 °C. Because in the company there is no heat needed at 60 °C, the cooling water basin serves a heat source for a heat pump. The heat pump has a heating capacity of 143 kW and produces hot water at 75 to 80 °C. At this temperature level hot water is used for space heating and to supply others baths of the coating line. A 7.5 m³ storage serves as a buffer for space heating. Due to higher heating loads the process heat storage has a larger volume of 40 m³. Both heating and cooling system are operated bivalent. In case of a malfunction of the heat pump a groundwater well serves a heat sink for the cooling water, while an oil-fired heater covers the heating demand. The heat pump system covers 50 % of the heat demand and saves 150,000 l oil per year. Another positive effect of the new hard chromium line is significant process improvements. The coating hardness could be increased by 10%, while the plating rate could be increased by 80 %. For planning and implementation of the project experts from different engineering disciplines had to work together. The coordination of this work took a lot more effort than expected before. Nevertheless Thoma Metallveredelung GmbH is very satisfied with the result and plans to install similar heat recovery systems in their other coating lines. Furthermore the whole system was designed using standard components. In this way other electroplating companies can adapt the system without infringing property rights.

Slaughter House in Zurich (Switzerland)

In 2011, a new thermeco$_2$ heat pump system for hot water generation and heating was put into operation in the slaughterhouse Zurich. With a capacity of 800 kW, the plant is the largest ever built in Switzerland. The thermeco$_2$ machines deliver the required 90 °C with better COPs compared to other refrigerants. The heat pump system is built up of 3 heat pumps thermeco$_2$ HHR 260.

The heat pump uses waste heat of an existing Ammonia refrigeration machine, an oilcooled air compressor plant and the installed fan-coil units as heat source. For this reason the heat is collected in a waste heat buffer storage connected with the heat pump evaporators. Because of the closed waste water circulating loop no special measures to avoid corrosion are necessary.

The warm side of the heat pumps is connected with a hot water buffer storage. The consumer (warm water for slaughtering and cleaning purposes, feed water for a steam generator and the heating system) are provided from this buffer storage using their consumer pumps tailored to the particular demand.



Because of the extremely low space requirement, this large heat pump system could be installed in a container system on the roof of the slaughterhouse in a short distance to urban residential development. Only authorized personal has access to the container and CO_2 sensors have been installed that activate an alarm when healthy concentration levels are exceeded.

All of the thermal energy for the slaughterhouse Zurich was previously provided with steam boilers. The customer's decision for a high temperature heat pump system with CO_2 as a refrigerant on this scale had several reasons. The efficiency advantages of the high temperature heat pump system clearly have priority. Running this heat pump plant the city of Zurich, represented by the Umwelt- und Gesundheitsschutz Zürich (UGZ) and the Elektrizitätswerk Zürich (ewz) as Contractor make an important contribution towards the "2000 Watt Society" of the city of Zurich. In the calculated overall balance of the slaughterhouse, CO_2 emissions can be reduced by approx. 30 %. By using the heat pump system, 2,590 MWh from fossil fuels can be saved per year, representing an annual reduction in CO_2 emissions of 510 tonnes.

R&D high temperature heat pumps

EDF France in cooperation with industry is working on the development of high temperature industrial heat pumps with new working fluids to reach temperatures higher than 100 °C:

Alter ECO Project

This project includes the development and industrial testing of HPs capable of operating at 140 °C in condensation mode, equipped with scroll compressors and working with a new blend.

Publication: Experimental results of a newly developed very high temperature industrial heat pump (140 °C) equipped with scroll compressors and working with a new blend refrigerants.

The compressor power is 75 kW. The machine performances have been characterized to demonstrate the technical feasibility. For each evaporation temperature (from 35 to 60 °C by step of 5 °C), the condensation temperature is increased by step of 5 °C from 80 up to 140 °C.

Test campaigns over 1,000 hours were carried out in industrial-like conditions to demonstrate the reliability.

The efficiency of heat recovery up to 125 °C is demonstrated. Good performances are obtained. For higher temperatures, the technological feasibility is demonstrated but some further developments have to be carried out to increase the efficiency and the economic viability: 2 stage compressors (it is designed for a given pressure ratio), expansion valve, etc.

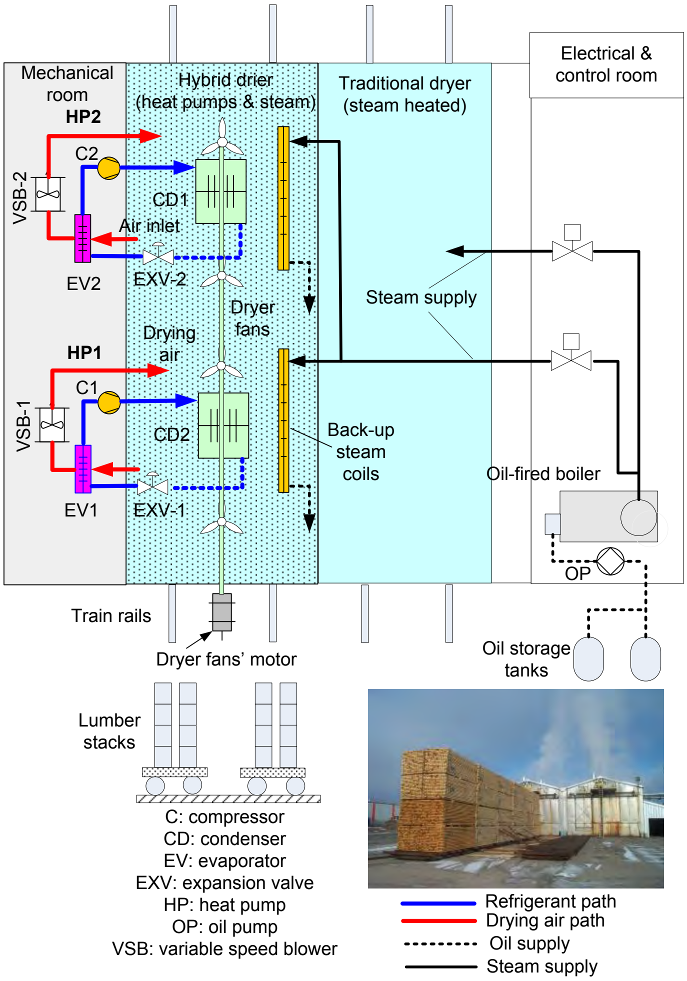
All this demonstrates the prototype reliability and the capacity to use this newly developed machine for industrial purposes.

PACO Project

Heat pump using water as a refrigerant is an interesting solution for waste heat recovery in industry. Water is nontoxic, non-ignitable and presents excellent thermodynamic properties, especially at high temperature. Water HP development is complex, notably due to water vapor compression. The compression ratio of centrifugal and lobe compressors is low. It prevents gas temperature from rising more than 20 °C. For now, the only technical solution able to overcome this drawback with moderate costs is to put two lobe compressors in series. However, theses compressors are less reliable than the others and their efficiency is low. Thus, the development of a novel water compressor is needed. Screw and centrifugal compressors on magnetic bearings seem to be the most promising technology. Discussions with the compressor manufacturers, and the numerical simulations show that the COP can be increased up to 80 % if such a compressor is integrated on a water heat pump. The price of this prototype compressor is very high, but it should decrease with the development of the market. Thus, the payoff would be guaranteed and the water heat pump would become an industrial reality.

High-temperature drying heat pump

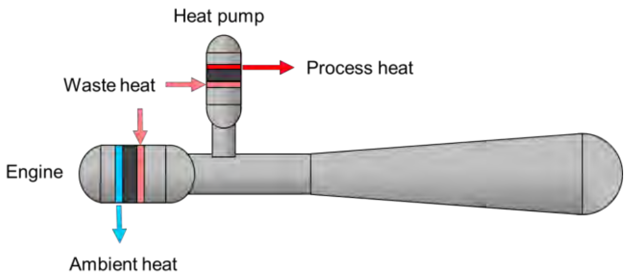
An industrial-scale, high-temperature heat pump-assisted dryer prototype, including one 354 m^3 forced-air wood dryer with steam heating coils and two high-temperature heat pumps (see Figure) has also been studied in Canada. Finished softwood lumber is produced in standard sizes, mostly for the construction industry. Softwood, such as pine, spruce and fir (coniferous species), is composed of vertical and horizontal fiber cells serving as a mechanical support and pathway for the movement of moisture. These species are generally dried at relatively high temperatures, but no higher than 115 °C, and thus high-temperature heat pumps coupled with convective dryers are required. An oil-fired boiler supplies steam for wood preheating and supplemental (back-up) heating during the subsequent drying steps. The dryer central fans force the circulation of the indoor drying air and periodically change their rotation sense to make more uniform and, thus, to improve the overall drying process and the wood final quality. Each heat pump includes a 65 kW (nominal electrical power input) compressor, an evaporator, a variable speed blower and electronic controls located in an adjacent mechanical room. Both remote condensers are installed inside the drying chamber. The high-temperature refrigerant (HFC-236fa) is a non-toxic and non-flammable fluid, having a relatively high critical temperature compared to the highest process temperatures. Expansion valves are controlled by microprocessor-based controllers that display set points and actual process temperatures. The industrial-scale prototype demonstrates that, as a clean energy technology compared with traditional heat-and-vent dryers, the high-temperature heat pump-assisted dryers offer very interesting benefits for drying resinous timber. Its actual energy consumption effectively is between 27.3% and 56.7% lower than the energy consumed during the conventional (steam) drying cycles, whereas the average reduction in specific energy costs, compared to the average costs of the Canadian conventional wood drying industry (2009), is of approximately 35 %.



Thermo Acoustic Heat Transformer

Thermo acoustic (TA) energy conversion can be used to convert heat to acoustic power (engine) and to use acoustic power to pump heat to higher temperature levels (heat pump). The systems use an environmentally friendly working medium (noble gas) in a Stirling-like cycle, and contain no moving parts.

Although the dynamics and working principles of TA systems are quite complex and involve many disciplines such as acoustics, thermodynamics, fluid dynamics, heat transfer, structural mechanics, and electrical machines, the practical implementation is relatively simple. This offers great advantages with respect to the economic feasibility of this technology. When thermal energy is converted into acoustic energy, this is referred to as a Thermo acoustic (TA)-engine. In a TA-heat pump, the thermodynamic cycle is run in the re-verse way and heat is pumped from a low-temperature level to a high-temperature level by the acoustic power. This principle can be used to create a heat transformer, as shown below.



The TA-engine is located at the left side and generates acoustic power from a stream of waste heat stream at a temperature of 140 °C. The acoustic power flows through the resonator to the TA-heat pump, located on top of the resonator. Waste heat of 140 °C is upgraded to 180 °C in this component. The total system can be generally applied into the existing utility system at an industrial site.

Basic characteristics of refrigerants suitable for high temperature heat pump

Some development of the industrial heat pump using R-134a, R-245fa, R-717, R-744, hydro carbons, etc. has been made recently. However, except for R-744 and the flammables R-717 and HCs which are natural refrigerants with extremely low global warming potential (GWP), HFCs such as R-134a and R-245fa have high GWP values, and the use of HFCs are likely to be regulated in the viewpoint of global warming prevention in the foreseeable future. Therefore, development of alternative refrigerants with low GWP has been required.

At present, as substitutes of R-134a, R-1234yf and R-1234ze (E) are considered to be promising, and R-1234ze (Z) is attractive as a substitute of R-245fa. R-365mfc is considered to be suitable as a refrigerant of heat pump for vapor generation using waste heat, but its GWP value is high. Therefore, it seems that development of a substitute of R-365mfc should be furthered. The table below shows basic characteristics of the present and future refrigerants for IHPs.

Refrigerant	Chemical formula	GWP	Flammability	T_c °C	p_c M Pa	NBP °C
R-290	CH3CH2CH3	~20	yes	96.7	4.25	-42.1
R-601	CH3CH2CH2CH2CH3	~20	yes	196.6	3.37	36.1
R-717	NH3	0	yes	132.25	11.33	-33.33
R-744	CO2	1	none	30.98	7.3773	-78.40
R-1234yf	CF3CF=CH2	<1	weak	94.7	3.382	-29,48
R-134a	CF3CH2F	1,430	none	101.06	4.0593	-26.07
R-1234ze(E)	CFH=CHCF3	6	weak	109.37	3.636	-18.96
R-1234ze(Z)	CFH=CHCF3	<10	weak	153.7	3.97	9.76
R-245fa	CF3CH2CHF2	1,030	none	154.01	3.651	15.14
R-1233zd		6	none	165.6	3.5709	n. a.
R-1336mzz		9	none	171	n. a.	n. a.
R-365mfc	CF3CH2CF2CH3	794	weak	186,85	3.266	40.19

Operating Agent: Annex 35/13 Application of industrial Heat Pumps

Information Centre on Heat Pumps and Refrigeration (IZW e.V.)

IZW is a German society for the promotion of research and development of heat pumps and refrigeration, to contribute to the reduction of the primary energy consumption and CO_2 emissions and the improvement of the energy-efficiency and environmental protection at the heat production, refrigeration and in the manufacturing industry.

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What is the IEA Heat Pump Programme?

The Programme is a non-profit organisation funded by its member countries. It is the foremost worldwide source of independent information and expertise on environmental and energy conservation benefits of heat pumping technologies.

What is the aim of the Heat Pump Programme?

The aim is to achieve widespread deployment of appropriate practical and reliable heat pumping technology systems that can save energy resources while helping to protect the environment.

Why is that important?

The world's energy and climate problems are well known. The buildings sector is responsible for a very considerable proportion of greenhouse gas emissions. Heat pumps are a key technology in the solution to break this trend.

What needs to be done?

By disseminating knowledge of heat pumps worldwide, we contribute to the battle against global warming. In order to increase the pace of development and deployment of heat pumps for buildings and industries, we need to increase R&D efforts for heat pumps, and we need to implement long-term policies for further deployment of heat pumps.