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Petroleum & Petrochemical Engineering Journal
ISSN: 2578-4846

Environmental Issues of Transient Behavior

Gareev AA*

Niznesortymskneft Oil & Gas Production Division, Russia

***Corresponding author:** Adib Gareev, Niznesortymskneft Oil & Gas Production, Direktorate Surgut, Tyumtn region, 628447, Russia, Tel: +79324141618; Email: adibg@mail.ru

Review Article
Volume 5 Issue 4
Received Date: October 02, 2021
Published Date: November 12, 2021
DOI: 10.23880/ppej-16000284

Abstract

We are currently witnessing a high-rate of exploitation of oil fields at the stage of declining production. This decline is a result of the depletion of oil fields, which leads to the use of electric submersible centrifugal pumps (ESP) with dynamic head below saturation pressure. In this operating mode, the ESP's efficiency deteriorates, leading to the overheating of its working elements during operation. The boiling of water contained in the wellstream and salt deposition can take place in an overheated pump. This, in turn, can lead to a premature failure of the centrifugal pump and reduce the economic viability of this oil production method. To eliminate premature failure, such units must be transferred to an operating mode with periodic shutdowns. Yet, the planning of trip-out and restart time schedules is performed in the absence of a proper theoretical justification. Such planning often leads to ESP failures due to the reduction of the electric resistance of cable lines or salt deposition. To prevent salt deposition, oil production companies use different chemicals, which are pumped into the hole annulus and are expected to stop salt deposition when propelled into the pump pot. Chemical treatment practice shows that these reagents perform poorly and may not prevent salt deposition at all. In reality, chemical compounds can damage downhole equipment and its structural elements. Long-term use of these reagents may lead to ecological disaster – the contamination of productive formations and confined groundwater beds. This work investigates the possibility of ESP operation in periodic mode without salt deposition and the exploitation of oil fields without the application of chemical reagents. The development of a periodic operation method allowing for ESP operation without salt deposition could eliminate the use of reagents in oil production and thereby reduce the risk of ecological disasters.

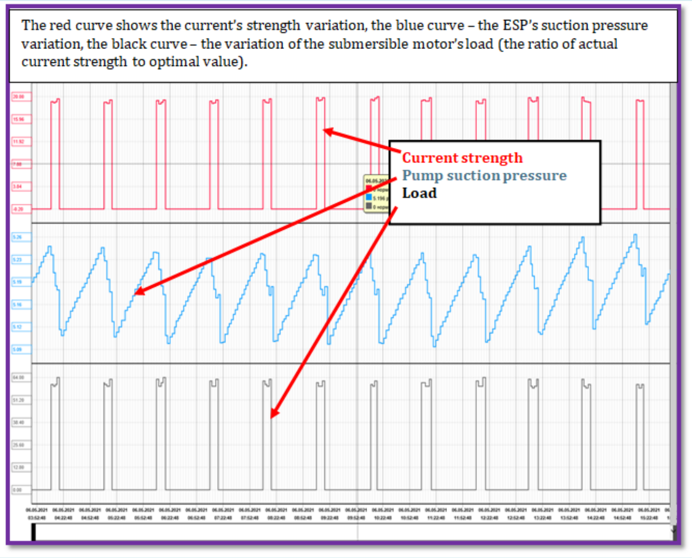
Keywords: Oil field; Exploitation of oil fields with electric submersible pumps operating in periodic mode; Salt deposition in a pump chamber; Use of reagents to stop salt deposition; Ecological destruction during oil production; Protection of subsurface resources against contamination; Prevention of ecological disasters

The Periodic Operation

The periodic operation of electric submersible pumps is a forced measure during oil well operation and, from the standpoint of thermodynamics, is represented by a series of transient processes involving heat transfer from a source inside the equipment assembly [1-3]. Figure 1 shows the variation trends of current strength, pump suction pressure and submersible motor load in periodic operation mode.

This mode is referred to as "short-term periodic operation," in which, over the course of an hour, the unit runs for 7 minutes and stays idle awaiting accumulation for 53 minutes. In this mode, the ESP suction pressure at which pumping should be performed is unknown and how such frequent stops and startups influence the pump's thermal behavior is unclear.

Why centrifugal pumps fail due to salt deposition or a reduction in the electric resistance of the "cable-motor" system to 0 milliohm also remains a mystery.



The red curve shows the current's strength variation, the blue curve – the ESP's suction pressure variation, the black curve – the variation of the submersible motor's load (the ratio of actual current strength to optimal value).

Figure 1: The "status list" dated May 6, 2021, shows the ESP's shutdowns and restarts. The pump's suction pressure P_{np} (see Figure 1) changes from 5.1 MPa to 5.26 MPa. The rundown time is about 7 minutes, while accumulation time is less than 53 minutes.

A Detailed Record

A detailed record of suction pressure variations of the centrifugal pump running in a different well is shown in Figure 2. The pump's suction pressure changes from 3.4 MPa to 4.5 MPa. Let's denote the rundown time as t_{rt}, and the accumulation time as t_{ac}. As the ESP starts up, the pump's temperature is T_l; prior to the ESP's stop – T_{rt}.

According to Gareev AA, Aleksandrov AA, Grigoryev B [1-5], the generation and propagation of heat in a centrifugal pump represents an energy dissipative process in the pump stages (and in the submersible motor as well). The intensity of heat generation depends on power input to the pump and the pump's efficiency. The study Gareyev AA [6] shows that the presence of gas in the mixture substantially reduces the pump's efficiency. The studies of failed units show that the highest temperature rise takes place in the first pump section; therefore, let's examine the behavior of this section and assume that the pump efficiency therein is constant and depends only on the content of gas in the mixture.

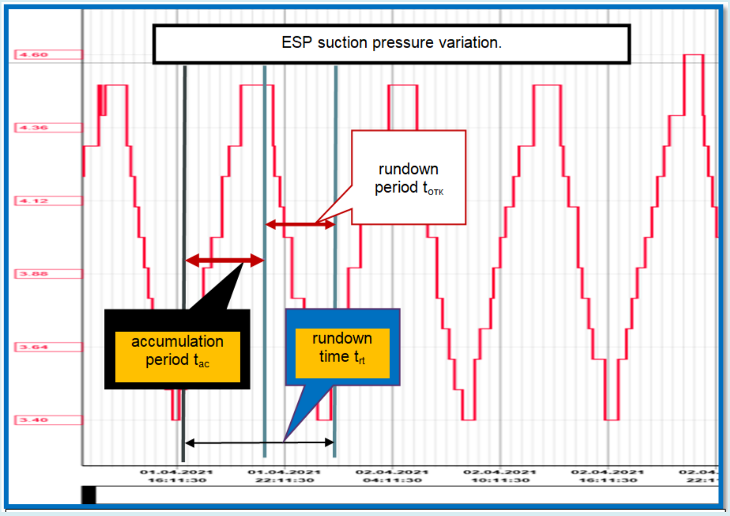


Figure 2: Time-based historical graphs of ESP suction pressure variation. Let's denote the fluid accumulation time at the centrifugal pump inlet as t_{ac} and the rundown time as t_{rt}.

During the Rundown

During the rundown of fluid in the well, ESP temperature increases from T_I to T_{rt} Gareev AA [7,8]. If we assume that T_I nearly matches the gas-fluid mixture temperature at the centrifugal pump's suction, it can be calculated on the basis of a known geothermic gradient in the wellbore, which is equal to = 0.03 °C/m. The unknown temperature T_{rt} can be determined on the basis of certain technical considerations: for example – the pump's temperature cannot exceed the boiling point of associated water and the maximum working temperature of the cable extension attached to the pump.

$$\grave{O}_{rt} < \grave{O}_{b} < \grave{O}_{cab} \quad (1)$$

where T_b – associated water boiling point at the pressure of P_{sp}, the permissible operating temperature of the cable extension T_{cab} is determined by experiment by studying the permissible leakage current value depending on the cable extension's temperature.

Thus, in planning periodic operation mode, it is essential to learn how to operate a centrifugal pump in such a way so as to eliminate salt deposition and protect the flat section of the cable line against overheating.

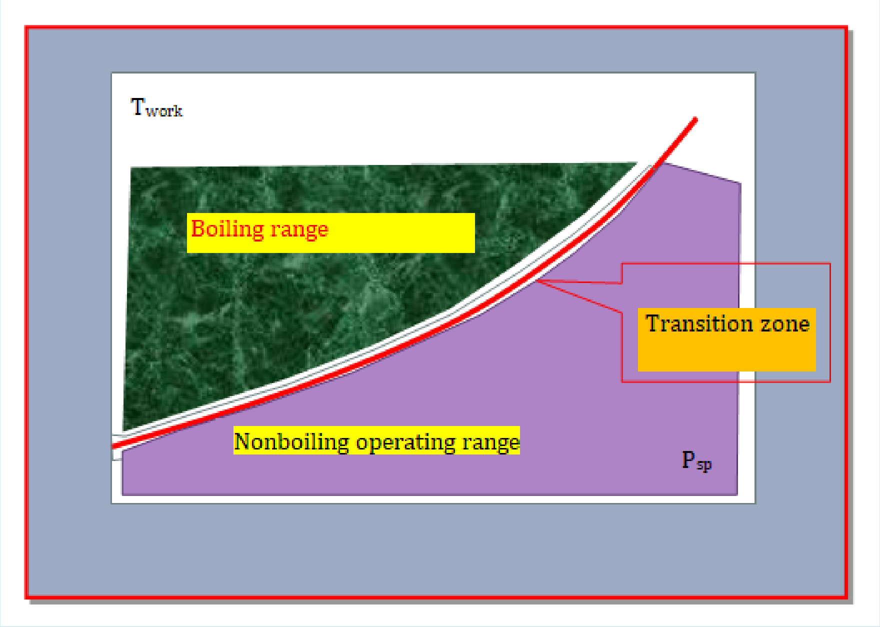


Figure 3: Oilfield water boiling point vs. pressure P_{sp} – ESP suction pressure, T_{work} – temperature inside the pump.

Figure 3 shows the plot of oilfield water boiling point [9] vs. pressure inside the centrifugal pump at constant saturation pressure, gas factor and WCO values. As the fluid pressure continues to grow, the boiling point increases and only slightly depends on the concentration of dissolved salts. Transition of the pump temperature from the oilfield water "nonboiling region" to the boiling range is characterized by the presence of a transition zone. The width of the transition zone shown in Figure 3 is conditioned by the minor dependency of the water boiling point at the given pressure on the concentration of dissolved salts (not exceeding 2-3°C) [10].

During ESP operation within the oilfield water boiling range, the salt deposition process begins. In this mode, the pump's service life depends on the content of water in the wellstream: the more the water, the lower the MTTF.

The pump's suction pressure can be determined on the basis of "pump starvation" – hydraulic closure of the centrifugal pump (say, during transition from constant duty to periodic mode) [11].

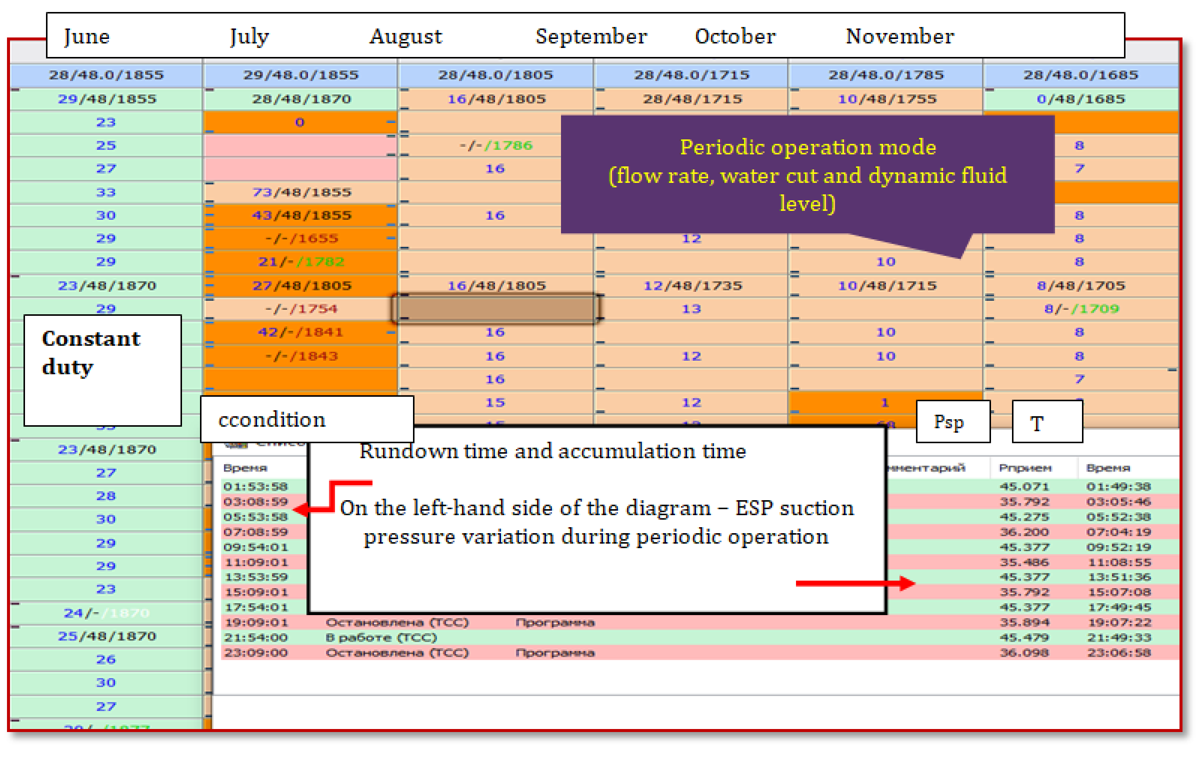


Figure 4: Transition of the ESP unit from constant operation duty to periodic mode in the month of June. The pump's suction pressure drops from 45.4 atm to 35.8 atm. The rundown time is 1h 15 min, the fluid accumulation time is 2 h 16 min. LCM 4, CM 4. Information on pump operation is provided in the Stock Flow software. Until the beginning of July, the ESP unit was running in constant duty with a flow rate of 30 m^3/d at a dynamic fluid level of 1,870 m. Producing water cut was 48%. Starting from early August, the unit was transferred to periodic operation mode: accumulation time (downtime) – 2 h 45 min, running time – about 1 h.

Figure 4 shows the ESP's operational process in constant duty in the month of June with further switch-over of the unit to periodic mode early this past July. That said, transition to periodic mode is a compulsory measure due to an imbalance between the pump's delivery and the productive strata. Let's choose the pump suction pressure P_{sp} from the operational data:

$$Ð_{sp} = \rho_{mix} * g * \left(Í_{v.d.} - Í_{v.d} \right) \quad (2)$$

where $H_{d.v.}$ – vertical depth of the dynamic fluid level; $H_{v.d}$ – vertical depth of the ESP location in the well; ρ_{mix} – density of the mixture; g – gravity acceleration.

Calculation of periodic operation mode

Let's calculate the pump's temperature at pump starvation pressure [1-5] using the equation: $T_w = T_{rt}$

$$T_{rt} = T_w = T_f + \frac{\varphi}{1-\varphi} \frac{q_0 P_{sat.p} * P_{sp} R_2}{2(1-B) * h * \Gamma * P_{atm}} \left\{ \frac{1}{\propto} + \frac{\delta_{t}}{\gamma th} \right\} \quad (3)$$

where: T_w– temperature on the pump surface; φ -share of free gas at ESP suction [6]; T_f– temperature of the liquid-gas mixture at ESP suction; B – share of water in the wellstream; $P_{sat.p}$ – bubble-point pressure; P_{sp} – ESP suction pressure; R_2 – ESP body radius, q_o– specific power rating; h – head generated by one pump stage; Γ – gas factor; ∝ – coefficient of heat transfer from the pump to the liquid-gas mixture inside the pump; δ_{th} – thickness of the gas blanket on the ESP surface in the well [10]; heat-conductivity factor of the gas blanket on the ESP surface [12]; P_{atm} – atmospheric pressure, γ_{th} - coefficient of thermal conductivity

Let's configure the data (from Figure 4) in a tabulated form for easier calculation (Table 1).

Data	Designation	Unit of measurement	Value
Submersible motor power intake	Ns.m.	W	15,000
Motor efficiency	hd	decimal fraction	0.835
Pump efficiency	hdec	decimal fraction	0.34
Number of pump stages	n	number	270
Radius of a centrifugal pump stage	Rcps	m	0.05
Height of a centrifugal pump stage	Δ	m	0.045
Number of expected cycles	n	units of measurement	24
Head of one stage	h	atm	0.3
Producing water cut	В	Decimal fractions	0.66
Power density	q_0	W/m^3	131,657
Saturation pressure	$P_{sat\,h}$	atm	94
Pump suction pressure	P_{sp}	atm	45
Well flow rate under daily measurement	Q_l	m^3/day	9.6
Gas factor	Г	m^3/m^3	103
Gas content in the wellstream	φ	Decimal fractions	0.37
Gas heat-conductivity factor	γ	W/(m*К)	5
Heat-transfer factor in the pump stage	∝	W/(m^2*К)	3,800
Gas blanket thickness	d_{th}	m	0.001
Temperature at pump suction	T_f	°К	67
Temperature on the pump surface	T_w	°К	290
Pump suction pressure before stopping	P_{sp2}	atm	45.4
Pump suction pressure before startup	P_{sp1}	atm	35.8

Table 1: ESP's operational process.

P *10-5, Pa	t_s, °C	P *10-5, Pa	t_s, °C	P *10-5, Pa	t_s, °C
1	99.64	56	271	140	336
3	133.54	60	275	144	338
5	151.8	64	279.8	148	341
7	164.96	68	283	152	343
9	175	72	287	156	345
11	184	76	291	160	347
13	191	80	294	164	349
15	198	84	298	168	351
17	204	88	301	172	353
19	209	92	304	176	355
21	214	96	307	180	356
23	219	100	310	184	358
25	223	104	313	188	360
27	228	108	316	192	362
29	231	112	319	196	364
32	237	116	322	200	365
34	241	118	323	202	366
36	244	120	324	204	367
38	247	122	325	206	368
40	250	124	327	208	368
42	253	126	328	210	369

44	256	128	329	212	370
46	258	130	330	214	371
48	261	132	332	216	372
50	263	134	333	218	373
52	266	136	333	220	373
54	268	138	335	Critical condition	

Table 2: Heat temperatures at different points by Mikheyev MA, Mikheyeva IM [13-14].

The calculation according to (3) yields a pump temperature equal to 223°C + 67°C = 290°C. The cable line's working temperature is 230°C; therefore, long-term operation of the unit will result in its failure due to a reduction in the electric insulation resistance of the cable line. According to Table 2, the water boiling point is 256°C, i.e. when the pump temperature is 290°C, the boiling of water takes place in the wellstream (Table 2).

Thus, if we let the pump run in constant duty, the temperature inside the ESP unit will climb to the point where oilfield water boiling starts, accompanied by salt deposition. To avoid salt deposition in the pump, the unit must be switched over to periodic cooling or to periodic operation mode. As described in Gareyev AA [6], the process of the pump's temperature reduction from 200°C to 65°C takes several minutes. The calculations make it clear that operation under a pressure of in constant duty will lead to the premature failure of the centrifugal pump due to R=0 and salt deposition.

If we apply a reverse path and try to identify pump suction pressure on the basis of a known temperature, we can calculate the pressure at which long-term ESP operation without salt deposition becomes possible [8,12,15,16].

However, if geological considerations mandate that a centrifugal pump be operated with a suction pressure of , periodic operation mode must be scheduled.

Find the Centrifugal Pump's

Let's find the centrifugal pump's rundown time within a pressure range of 45 to 36 atm in periodic mode without salt deposition (Figure 5).

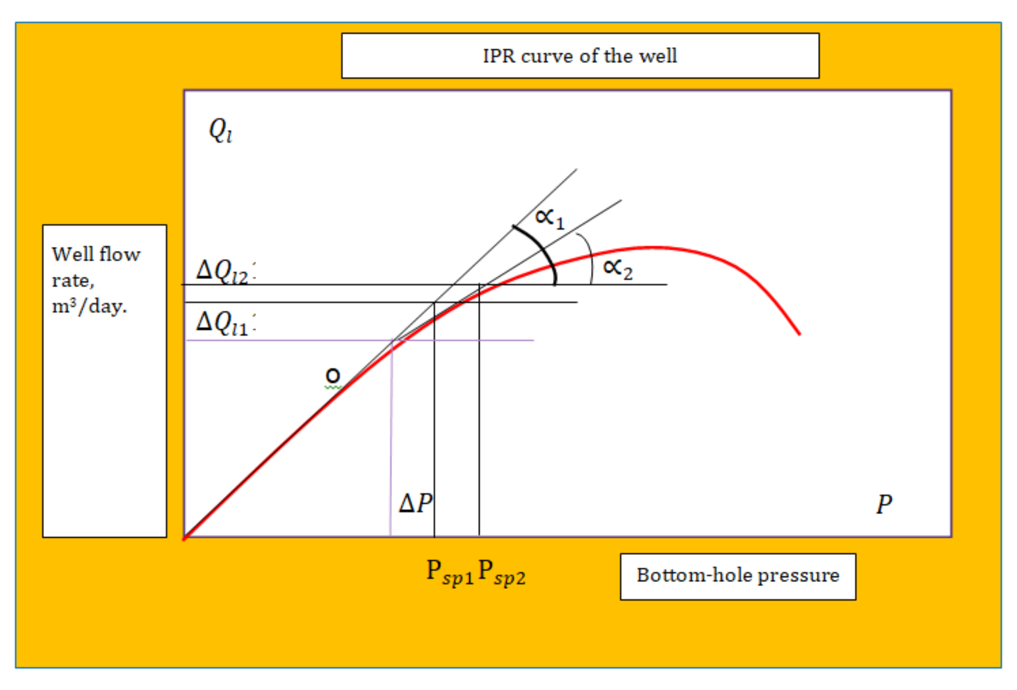


Figure 5: IPR curve of the well the slope of the curve with respect to the pressure axis characterizes the well's influx. Well flow rate change vs. BHP change is the well's productivity factor.

For this purpose, let's develop an IPR curve for the well (crossplot of drawdown vs flow rate). On the IPR curve, we identify the optimal flow rate at a certain drawdown:

$$Q_l = f\left(\Delta P\right) \quad (5)$$

Let's calculate the unit's service life for pumpout at optimal flow rate:

$$t_{rt} = \frac{Q_{l.rt.}}{Q_{o.f.ESP}\left(\varphi\right)}, \text{ day} \quad (6)$$

where the type of dependency $Q_{o.f.ESP} = f\left(\varphi\right)$ must be determined by experiment in down-hole conditions.

Well productivity factor, determined on the linear part of the curve:

so that

$$tg \propto_2 < tg \propto_1 \text{ and } \Delta Q_{l2} < \Delta Q_{l1}. \ (7)$$

on the basis of economic feasibility:

Let's assume: *, where* (8)

Point "o" is the point of inflection on the IPR curve satisfying the condition (7).

To determine rundown time according to (6), it's essential to know

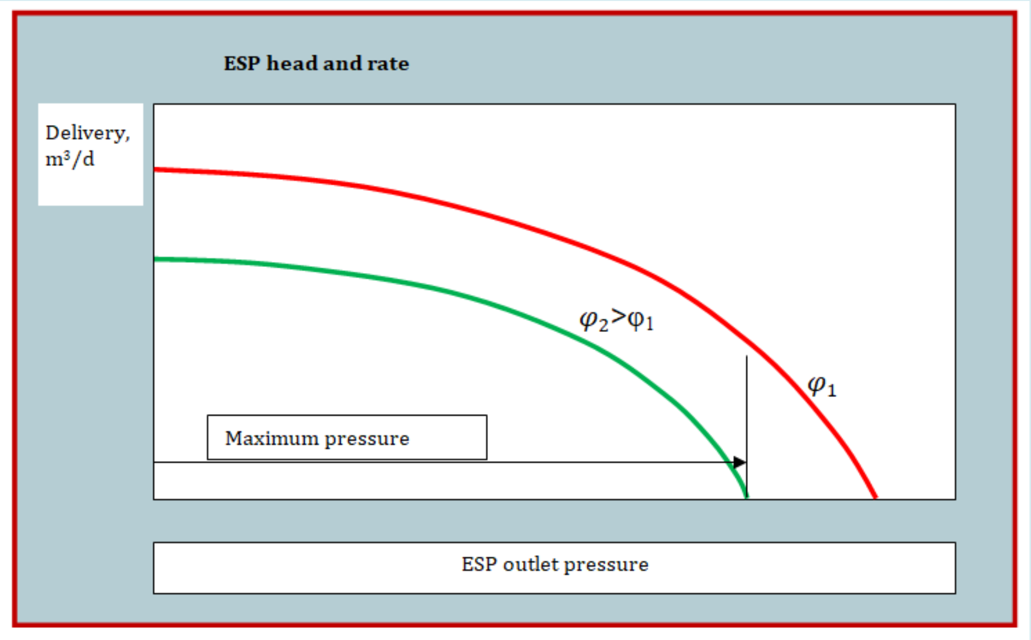


Figure 6: Centrifugal pump characteristics vs. gas content in the pumped fluid. As gas content increases φ the ESP head-and-rate curve closely approaches the y axis [12].

ESP head and rate $Q_{o.f.ESP}\left(\varphi\right)$ during the pumping of liquid-gas mixtures with account for suction pressure and well flow rate. Such studies can be performed in the field using ESP units equipped with pressure sensors. Therefore, let's assume that the ESP's performance has been studied under real-world conditions, as displayed by the curves in Figure 6.

The ESP's operating mode can be determined from (6) using the rundown time t_{rt} and the accumulation time:

$$T_{ac} = T_{per.} - t_{rt} \quad (7)$$

Where T_{per} represents a cycle of the periodic process.

It's Essential to Calculate

It's essential to calculate the ESP rundown time during which pump temperature does not exceed the water boiling point under real-world conditions at pump suction. Let's consider an approximate solution of the problem.

The amount of heat generated by the centrifugal pump is equal to:

$$\Delta Q_{con} = N_{con.ESP} * \eta_{ESP} * \left(1 - \eta_{dec} * \left(1 - \varphi\right)\right) * \tau_{work} \quad (10)$$

where τ_{work} – the ESP's running time.

Heat generation Q_{con} depends on the centrifugal pump's efficiency η_{dec}, which in turn depends on the content of gas in the mixture [6].

Let's assume in our calculations that η_{f} depends on gas content and remains constant along the full length of the pump [1-4].

This means that:

$$\eta_{dec} = f(\varphi) = const \quad (11)$$

The amount of heat $\text{Ä}Q_{con}$ is spent for the temperature rise of the pump assembly from T_{ent} to the current value of .

$$\Delta Q_{con.ESP} = c_p * M_p * (T_x - T_{ent}) + c_{mix} * M_{mix\text{м}} * (T_x - T_{ent})$$

(12)

where: $\tilde{n}_{mix} = \left[\tilde{n}_w * \hat{A} + \tilde{n}_{oil} * \left(1 - \hat{A}\right)\right] * \left(1 - \varphi\right) + \varphi * c_g$

where c_p– specific heat capacity of the pump metal; M_p– pump weight; T_x– measured temperature; T_{ent}– temperature at the pump level before startup; c_{mix}– specific heat capacity of the mixture; M_{mix}– weight of the mixture; c_w– specific heat capacity of water; c_{oil}– specific heat capacity of oil; B – producing water cut; c_g– gas heat capacity. Insofar as the heat capacity of gas is hundreds of times lower than that of the fluid, we'll ignore it from now on.

The mixture's weight can be determined by the formula:

$$Q_w = \kappa * (P_{ac} - P_{sp})$$

$$\grave{I}_{mix} = \rho_{mix} * Q_l \quad (13)$$

$$\rho_{mix} = \rho_{oil} * \left(1 - \hat{A}\right) + \rho_w * \hat{A}$$

Let's calculate the heat capacity of the mixture using the formula:

$$\tilde{n}_{mix} = \tilde{n}_w * \hat{A} + \left(1 - \hat{A}\right) * \tilde{n}_{oil} \} * \left(1 - \varphi\right) + \tilde{n}_g * \varphi \quad (14)$$

A centrifugal pump is always surrounded by homogeneous oil and covered by gas bubbles [6], whose thickness is equal to δ_f . Under approximate calculations, heat dissipation from the pump surface can be ignored due to the low heat-conductivity factor of the gas blanket [5].

Therefore, at a first approximation, the heat flow equation with account for (12-14) can be composed as follows:

$$N_{con} * \eta_{MOTOR} * (1 - \eta_{oil} * (1 - \varphi) * \tau_{work} = (c_{oil} * M_{oil} + c_{cmix*} M_{mix}) * (T_x - T_w)$$

(15)

thus, the pump's temperature rise during its operation is:

$$\grave{O}_{\tilde{o}} = \grave{O}_w + \frac{\Delta Q_{con}}{(\tilde{n}_{oil} \grave{I}_{oil} + \tilde{n}_{mix} \grave{I}_{mix})} \quad (16)$$

Having experimentally determined the recycle delay time τ_{gp} of the dynamic fluid level from P_{sp1} to P_{sp2}, let's formulate the process regulations for ESP operation in periodic mode without salt deposition.

Let's consider a case study of theoretical computation.

Let's calculate well flow rate during pumpout of the fluid from P_{sp2} to P_{sp1}:

$$Q_{\text{ж}} = k * (P_{sp2} - P_{sp1}) \quad (17)$$

Let's calculate gas content at the centrifugal pump's suction [12]:

$$\varphi = \frac{V}{V + Q_l}$$

where $V = Q_l * (1 - B) * \Gamma * (1 - \frac{Psp1}{Psat.p}) / P_{sp1}$ (18)

$$V = 5{,}04 * \left(1 - 0{,}66\right) * 114 * \frac{\left(1 - \frac{45}{94}\right)}{45} = 1{,}62$$

φ%	Capacity of the ESP unit, m³/d (m³/s)			
	30	**35**	**50**	**80**
	0.000347	0.000405	0.000579	0.000926
15%	0.000289352	0.000347	0.000520833	0.00081
30%	0.000115741	0.00024306	0.0003125	0.000405
45%	3.47222E-05	6.9444E-05	9.25926E-05	0.000139

Table 3: Head and rate of ESP units with a capacity of 30, 35, 50 and 80 m³/d (table compiled on the basis of processed experimental data relating to the ESP units).

From which V = 1.62 m^3/d and the gas content at pump suction is equal to: $\varphi = 0,24$

Let's choose the ESP's performance according to its head and rate depending on the gas content shown in Table 3.

Let's find the ESP unit's rundown time from the pressure Рпр2 to Рпр1 and show the result in tabulated form (Table 4):

Gas Content φ%	**Rundown Time in Seconds**			
	30	35	50	80
30%	1,814.40	864.00	672.00	518.40
45%	6,048.00	3,024	2,268	1,512

Table 4: Approximate calculations of the liquid-gas mixture's pumpout time by centrifugal pumps depending on gas content.

Using the data from Table 1, let's calculate the amount of heat:

$$\Delta Q_{con} = N_{con.MOTOR} * \eta_{MOTOR} * \left(1 - \eta_p * \left(1 - \varphi\right)\right) * \tau_{work}$$

$$\Delta Q_{con} = 15000 * 0,835 * \left(1 - 0,3 * \left(1 - 0,37\right)\right) * 864 = 8776317 \text{ J}$$

This amount of heat is generated during pumpout. The pump's temperature increases by:

$$\grave{O}_{\tilde{o}} = \grave{O}_{w} + \frac{\Delta Q_{con}}{(\tilde{n}_{oil*}\grave{I}_{oil} + \tilde{n}_{mix}\grave{I}_{mix})} = 63 + \frac{8776317}{450 * 100} = \left(63,2 + 195\right)^{o} C = 258^{o} C$$

This means that in 864 seconds (14.4 minutes), the pump's temperature rises to 258°C. At the end of the pumping process, the water in the wellstream starts boiling and the cable line adjacent to the pump (cable extension) is affected by thermal impact (the working temperature of the cable line is 230°C).

The maximum rundown time t_{ultim}, when salt deposition begins and water reaches its boiling point T_b, can be calculated as follows:

$$t_{ultim} = \frac{\left(\grave{O}_b - \grave{O}_w\right) * \left(c_{pump} M_{pump} + c_{mix} M_{mix}\right)}{N_{sp.MOTOR} \eta_{MOTOR} \left(1 - \eta_{pump} * \left(1 - \varphi\right)\right)} \quad (20)$$

Substituting the values from formula (19), we determine maximum rundown time t_{ultim}:

$$t_{ultim} = \frac{\left(256 - 63\right) * 450 * 100}{10157} = 855 \text{ seconds}$$

Having performed the calculations according to the formulas (18-20), rundown time must be adjusted to 855 seconds (14.25 minutes). With account for approximation, let's assume a rundown time of 14 minutes and determine the accumulation time t_{ac} by experiment on the well.

Conclusions

1. The thermal state of a centrifugal pump during intermittent operation is a complex thermodynamic process.
2. The determining parameter of the thermal state of a centrifugal pump is the content of free gas in the gas-liquid mixture.
3. Periodic operation of a centrifugal pump can be predicted based on its thermal state.
4. Prediction of the periodic operation of the centrifugal pump can be programmed.

References

1. Gareev AA (2009) Regarding maximum-permissible gas content at centrifugal pump intake. Equipment and Technologies for the Oil & Gas Sector 2: 21-25.

2. Gareev AA (2011) Regarding the thermal behavior and thermal-shock phenomenon of electric centrifugal pumps. Oil Facilities 3: 122-126.

3. Aleksandrov AA, Grigoryev BA (1998) Thermal and physical properties of water and water vapor. MEI Publishing Company, Russia, pp: 423.

4. Gareev AA (2009) Regarding gas-separation coefficient at pump intake. Oil Facilities 6: 90-93.

5. Gareev AA (2013) Calculation of gas-separation coefficient at pump intake. Oil Facilities 3: 82-85.

6. Gareyev AA (2018) Investigation of ESP unit temperature and pressure in transient behavior. Surgutneftegaz Engineer 1: 39-43.

7. Gareev AA (2010) Regarding the thermal behavior of electric submersible pumps. Equipment and Technologies for Oil-and-Gas Facilities, Oilfield Engineering, Moscow: Vniioeng, 6: 35-41.

8. Gareev AA (2017) Regarding the salt-deposition mechanism. Oilfield Engineering 4: 35-45.

9. Gareev AA (2009) Regarding the significance of thermal condition in electric centrifugal pump units (ESP). Equipment and Technologies for the Oil & Gas Sector 1: 23-29.

10. Tsivilev RP (2004) Introduction to the Physical Chemistry of Gases and Fluids. Ukhta, pp: 72.

11. Gareev AA, Sharafutdinov RF, Valiullin RA (2012) Regarding the significance of pressure at electric centrifugal-pump intake. Oil Facilities 10: 128-131.

12. Gareev AA (2011) Current problems of low-capacity electric centrifugal pump operation during oil production. Printing and Publications Center, Bashkir State University, Russia.

13. Drozdov AN (2008) Methods and technology for oil extraction by submersible pumps in abnormal conditions. M. MAKS-Express, Russian State University of Oil and Gas, Russia, pp: 245.

14. Mikheyev AA, Mikheyeva IM (1977) Heat-conductivity principles. Energiya-M.

15. Gareev AA (2009) Regarding maximum gas content at electric centrifugal pump intake. Equipment and Technologies for Oil-and-Gas Facilities, Oilfield Engineering, Moscow, Vniioeng, 2: 21-25.

16. Gareev AA (2019) Regarding the thermal behavior of a centrifugal pump for oil recovery. Engineering Science 4(2): 28-33.