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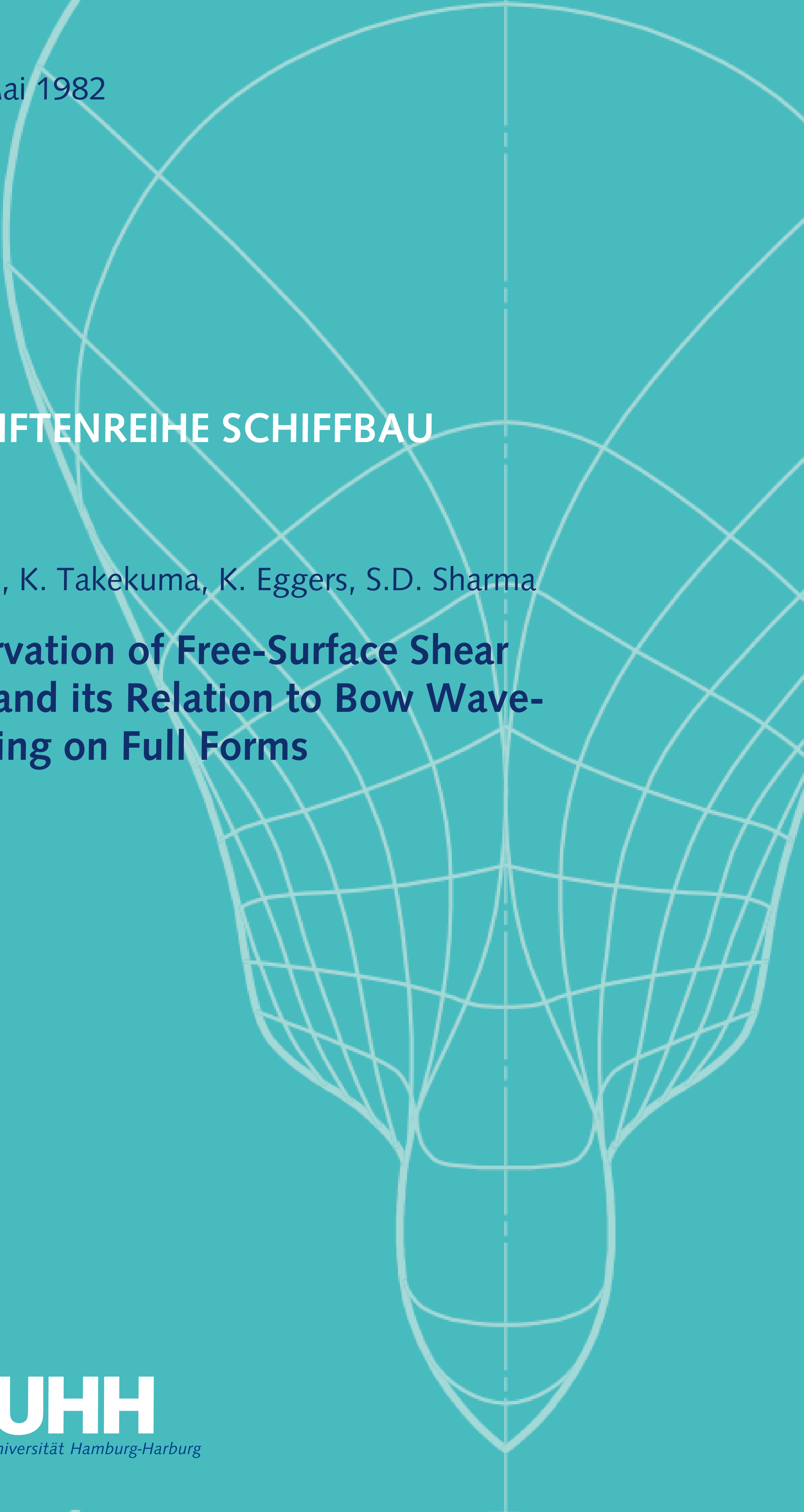

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Y. Kayo, K. Takekuma, K. Eggers, S.D. Sharma

Observation of Free-Surface Shear Flow and its Relation to Bow Wave-Breaking on Full Forms

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Joint Report

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May, 1982

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Abstract

In order to get a better understanding of the so called bow-wave-breaking phenomenon occurring on full-bodied hull forms, attempts were made to observe the flow fields around a horizontal and a vertical semi-submerged circular cylinder. It was verified that there apparently exists a shear layer beneath the free surface in front of the body, leading to the formation of trapped transverse vortices in front of the horizontal cylinder and of necklace vortices spiraling around the front of the vertical cylinder even at extremely slow speeds without any visible wave-breaking. At higher speeds there is a gradually increasing amount of visible wave breaking accompanied by intensive vortical motion beneath the free surface. The breaking bow wave and the necklace vortex around bluff bows thus seem to be closely realted phenomena.

Zusammenfassung

Um die an völligen Schiffsformen vorkommende Erscheinung der sog. brechenden Bugwelle besser verstehen zu können, wurden Versuche unternommen, das Strömungsfeld um halbgetauchte horizontale und vertikale Kreiszylinder sichtbar zu machen. Die Existenz einer Grenzschicht mit Scherströmung unmittelbar unter der freien Wasseroberfläche vor dem Körper konnte bestätigt werden. Sie führt zur Bildung vor dem Körper eingefangener Querwirbel beim horizontalen Zylinder bzw. dem Körper halskettenartig umgehängter Längswirbel beim vertikalen Zylinder, und zwar selbst bei extrem niedrigen Fahrtgeschwindigkeiten ohne jede sichtbare Wellenbrechung. Bei höheren Geschwindigkeiten beobachtet man eine allmählich zunehmende und von starker Wirbelbewegung unter der freien Oberfläche begleitete Wellenbrechung. Die brechende Bugwelle und der Halskettenwirbel um völlige Bugformen scheinen daher miteinander eng verwandte Vorgänge zu sein.

1. Introduction

Breaking bow waves around full forms are familiar phenomenon. However, it was only in 1969 that Baba(1) and Sharma(2) introduced a distinct component of resistance to full ships such as tankers and bulk carriers which is explicitly associated with the breaking wave. They also pointed out the importance of reducing this component in order to get a better performance for these ships at relatively high speeds, for instance by the use of suitably designed bow bulbs. Meanwhile, many more studies have been done to investigate this topic. However, one may say that we are still far from a satisfactory theoretical explanation of this phenomenon. In order to get an efficient theoretical tool to develop a hull form with less resistance due to breaking waves, therefore, further efforts are required.

Recently Kayo and Takekuma(3)(4) reported their findings about the effect of a shear layer on breaking bow waves. They observed that there exists a shear layer beneath the free surface in front of a moving full-form ship model and that the shear layer results in so-called necklace vortices. They also showed the important role of this shear layer in the breaking of bow waves by deliberately varying the intensity of the shear layer. The bow-wave breaking was intensified or attenuated according as the shear layer was artificially strengthened or weakened respectively.

The present investigation has been carried out to study in a more fundamental way the effect of the shear layer on vortices and the possible effect of vortices on the breaking bow waves.

The models used in this experiment were semi-submerged circular cylinders. The vertical cylinder was selected as one of the simplest models of a full ship. Additional observations were made on a horizontal cylinder as the extreme case of a full body where locally two-dimensional flow may be expected in front of the bow.

2. Experiments

The experiments were conducted in the towing tank of the Institut für Schiffbau der Universität Hamburg during August 10-15, 1981.

2.1 Models and test conditions

Two circular cylinders were towed at several speeds. The dimensions of the cylinders are as follows:

Table 1. Horizontal circular cylinder

Diameter 0.200 ^{m}

Length 2.09 ^{m} (10 ^{mm} less than the tank width)

Towing speed

V_m $^{m/s}$	F_{nT}	R_n (say WT = 24°C $\nu = 0.913 \times 10^{-6} m^2/s$)
0.55	0.05	1.095×10^4
0.10	0.101	2.190 × ″
0.20	0.202	4.38 × ″
0.25	0.252	5.47 × ″
0.30	0.303	6.57 × ″
0.35	0.353	7.66 × ″
0.40	0.404	8.76 × ″
0.45	0.454	9.85 × ″
0.50	0.505	1.095×10^5
0.60	0.606	1.31 × ″
0.80	0.808	1.75 × ″
1.00	1.010	2.19 × ″

Here $F_{nT} = V_m/\sqrt{gT}$ is Froude number based on draft T, and $R_n = V_m D/\nu$ is Reynolds number based on diameter D of the semi-submerged cylinder. In the test condition $T = D/2$.

Table 2. Vertical circular cylinder

Diameter 0.457 ^{m}

Drafts 0.114 ^{m} shallow draft : T_1

0.457 ^{m} deep draft : T_2

Towing speed	Froude number for shallow draft	Froude number for deep draft	Reynolds number
V_m m/s	F_{nT_1}	F_{nT_2}	R_n
0.053	0.05	0.025	2.65×10^4
0.106	0.10	0.05	5.30×10^4
0.212	0.20	0.10	1.60×10^5
0.423	0.40	0.20	2.12 × 〃
0.847	0.80	0.40	4.24 × 〃
1.060	—	0.50	5.30×10^5

where Froude numbers based on diameter for both drafts are the same as the F_{nT_2} for deep draft.

In the case of the vertical circular cylinder, the experiments were made on two different drafts to study the effect of the draft of the body on the phenomenon.

2.2 Kind of test

The flow in front of the models was observed by usual flow visualization techniques and recorded on half-inch video tape and on 16 mm film. Water color dye, aluminum powder and metal leaf flakes were used as tracers and injected into the fluid manually by means of a syringe held just above the free surface.

The free surface was skimmed several times carefully with a boom every morning before the test run.

Wave height measurements along several radial cuts in front of the vertical cylinder were carried out manually using a multi-pointer probe. A general arrangement of the test is shown in Fig. 1.

3. Test results

3.1 Observation of flow field in front of the horizontal cylinder

The upstream vortex in the case of a semi-submerged horizontal cylinder was reported by Honji(5). He explained in his paper that the forward movement of the free surface seems to be the cause of the formation of his upstream vortex. He also said that a free liquid surface behaves like a thin menbrane along which a boundary layer can be formed.

His original experiment was done on a small cylinder of 10 cm diameter at speeds below 0.11 m/s in a small towing tank of 6 m length. The present study was done to verify his result on a larger model in a larger tank over a larger range of speeds.

With the injection of water color dye, the shear layer beneath the free surface was visualized. The water surface immediately in front of the cylinder moved with the same velocity as the model itself up to a certain transverse line, which we could observe easily, and whose distance from the fore end of the cylinder was found to depend on the speed. When the dye, injected far ahead of the cylinder, flowed to this line, the upper most layer of the dye was trapped as if there was a solid plate on the free surface.

The position of the stagnant line, seen as a point when viewed from the side, seemed to be generally stable on any individual run, except for small pulsations at the higher speeds. Fig.2 shows the observed distances from the fore end of the cylinder to the stagnant line.

They scatter widely, especially at low speeds.

The highest value obtained at the speed of 0.05 m/s was gotten on the first run of the day when the water was very calm. On the other hand, the lower distances measured at the same speed were obtained while the carriage was going back to the starting point shortly after each run. It seems that this length may be affected by the residual current in the tank at very low speed. However, the distance to the stagnant line is longer at low speeds and decreases with increase of the towing speed to reach a constant value around $s/r = 2.0$ where s is the distance measured and r is the radius of the cylinder. This tendency is quite different from that obtained by Honji. (Fig.3) The tank length may also have some effect on the distance of this stagnant line.

The remarkable feature of the flow pattern in front of the cylinder is the formation of a dead water region with many alternating vortices as shown in Figs. 4-a~4-c. These vortices thus observed have some resemblance to the flow around a circular cylinder in unbounded fluid with a thin splitter plate attached to it.

The free surface, a boundary between air and water, in front of a moving body seems to be a source of vorticity and a kind of boundary layer may develop under the free surface.

However, a precise measurement of the velocity field in a proximity to the free surface is necessary for further discussion and the construction of a rational mathematical model.

3.2 Observation of flow field in front of the vertical cylinder

3.2.1 Wave height measurement

The wave height was measured for the conditions below.

draft	speed ($^m/_s$)			
$^1/_4$ D	0.106*	0.212*	0.423	0.847
D	0.106*	0.212*	0.423	0.847

* Wave height was too small to measure by a pointer

The results are shown in Figs 5,6. The non-dimensionalized wave heights on the longitudinal center line for each draft have little effect of speed except in the region near to the cylinder where a plateau is formed. However, it should be noted that in a proximity to the cylinder water can climb up to a stagnation pressure height and in some cases even exceed it by about 10% apparently violating Bernoulli's equation. This phenomenon also needs further investigation.(8)

3.2.2 Flow patterns

Flow visualizing technique was the same as used on the horizontal circular cylinder.

The flow pattern in the longitudinal center plane in front of the vertical circular cylinder resembles that of the horizontal circular cylinder except that there was no definite stagnant free surface region in front of the cylinder. In the case of three-dimensional flow the water surface moved continuously toward the cylinder as it could pass around both sides of the cylinder.

However, there exists a shear layer in front of the moving cylinder. The water color dye filament at far upstream is pointing forward as shown in Figs7a-7e. The uppermost water color dye particle then skews toward the cylinder due to the continuous movement of the free surface while the lower part is trapped by the vortices.

The vortices are similar to those known as a horseshoe vortex around a stubby circular cylinder on a plate.

It should be noted that the necklace vortices were found at any speed tested; that is the vortices existed even at extremely slow speed where no visible wave-breaking was observed.

Effect of towing speed on the vortices

A diameter of the nearest vortex and a keel depth of the wedge shaped region were measured from the video to analyse an effect of towing speed on the flow pattern in front of the vertical circular cylinder.

The results are shown in Fig. 8. At lower speeds the diameter of the vortex varies considerably even in the same test run. The smaller one was obtained at the after end of the run. They might have been affected by an end wall of the tank. (Fig.7-d)

The result of the deep draft seems to be rather stable and the diameter of the nearest vortex depends on the towing speed. The diameter is quite large at the lowest speed and it decreases with the increase of speed up to a certain point where visual breaking waves occur slightly. Then the vortex grows large again at higher speed accompanied with heavily breaking waves.

The present observation suggests a relationship between the intensity of vortices and the formation of breaking bow waves of full forms. However, it is desired to conduct more detailed experiments under well controlled conditions to get a conclusive understanding of the phenomenon.

Effect of draft of the cylinder on the vortices

It is commonly observed that full-form ship models experience heavier bow wave breaking at shallow draft conditions compared with their full-load conditions. Although the result varied at low speeds, the present experimental observations on the flow fields of two different drafts show a tendency that the vortex of the shallow draft cylinder is larger than that of the deep draft (Fig. 8). This may be interpreted as a possible cause of the difference between the bow-wave breaking on different draft conditions.

Effect of shear layer intensified artificially

A trial was made to observe the effect of strengthening the shear layer in front of the model on the intensity of vortical motion.

A thin foil was allowed to float on the water surface in front of the vertical circular cylinder and towed with the same speed as the model.

The vortex motion was exaggerated when this foil was on the free surface, as already observed previously in front of a ship model.(3) This result is also plotted in Fig.8.

Effect of surface tension on the vortices

Honji(6) reported that the upstream vortex was found to be smaller when the surface tension was reduced (Fig.9).

In the present experiment the water surface was treated with a kind of commercial detergent called 'Pril' to reduce the surface tension. Even a drop of 'Pril' pushed out the dust on the water surface and made the free surface clean within a certain neighborhood. This fact indicated that the surface tension was reduced considerably.

The test result showed that the detergent had the remarkable effect of intensifying the vortices at low speed. Namely the wedge shaped region extended far upstream, the vortices grew much larger and became unsteady when compared with the result obtained in water with naturally clean free surface (Figs.10,11). On the other hand the effect of the detergent became less at higher speed (Fig.8).

It is known(7,9) that even quite small amount of contaminants such as oil forms a surface film on water which causes considerable wave damping due to its resistance to compression. In our experiment the drops of detergent made a thin surface film with high resistance to compression so that the free surface might move more strongly.

These results seem to be quite different from that of Honji about the effect of surface tension on the formation of upstream vortex. Honji's experiment was done on two-dimensional flow whereas the present one was done on three-dimensional flow.

As the surface tension was not measured, no definite conclusion can be derived from a single observation. Further investigation is neccessary.

4. Conclusions and remarks

Based on the present investigations following conclusions may be derived.

1) There exists in principle a kind of shear layer in front of a moving body.

2) This shear layer beneath the free surface can produce vortices around the forebody.

3) The intensity of these vortices grows with the increase of towing speed .

4) The formation of the so-called breaking bow waves of a full form may be related to the intensity of the vortices mentioned above.

5) Further investigations, both of experimental and theoretical nature, seem to be necessary and worthwhile.

5. Acknowledgements

The authors wish to express their thanks to the staff of the Institute für Schiffbau for their cooperation in carrying out the experiments. Mr. D.L. Huang of the Dalian Technical Institute, currently visiting at Hamburg, also provided enthusiastic assistance. Moreover, we would like to acknowledge the stimulating discussions with Prof. K. Wieghardt, Dr. J. Kux, Dr. G. Collatz and Dr. E. Baba.

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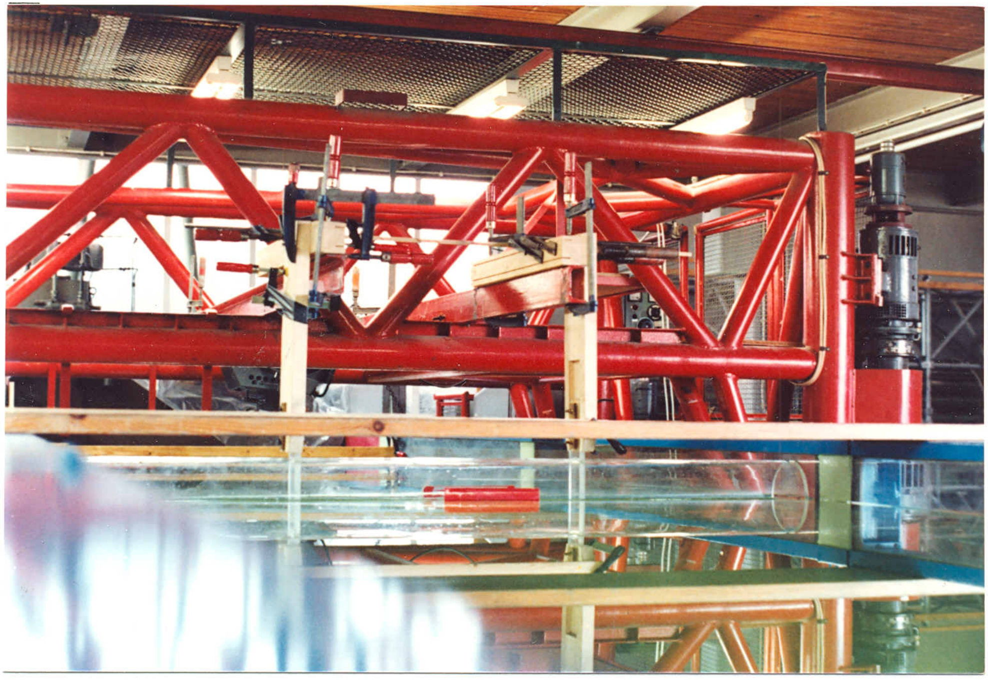


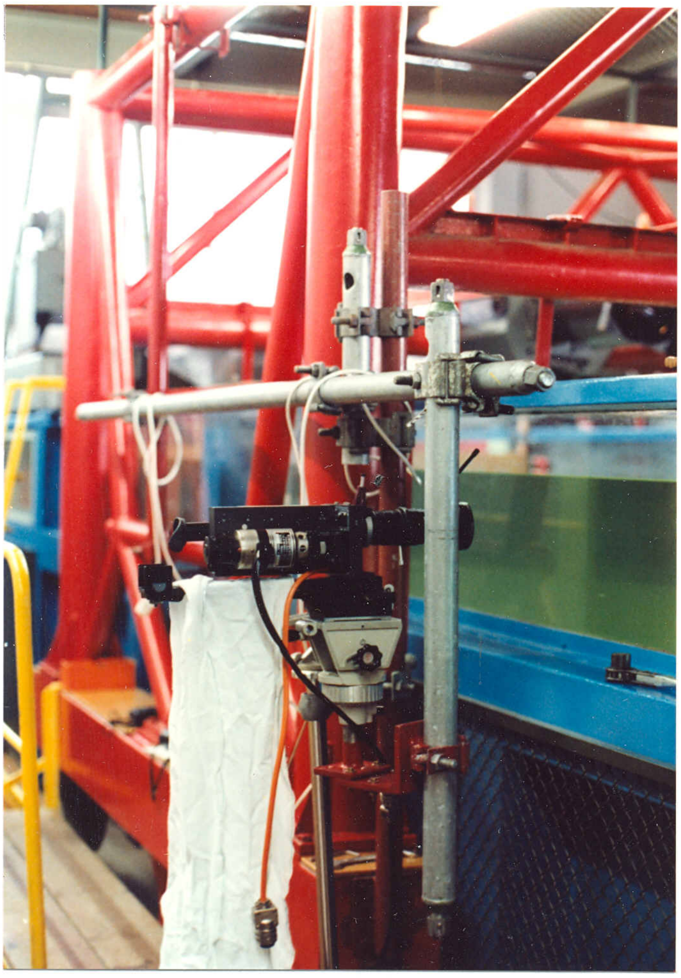


Fig. 1 General arrangement

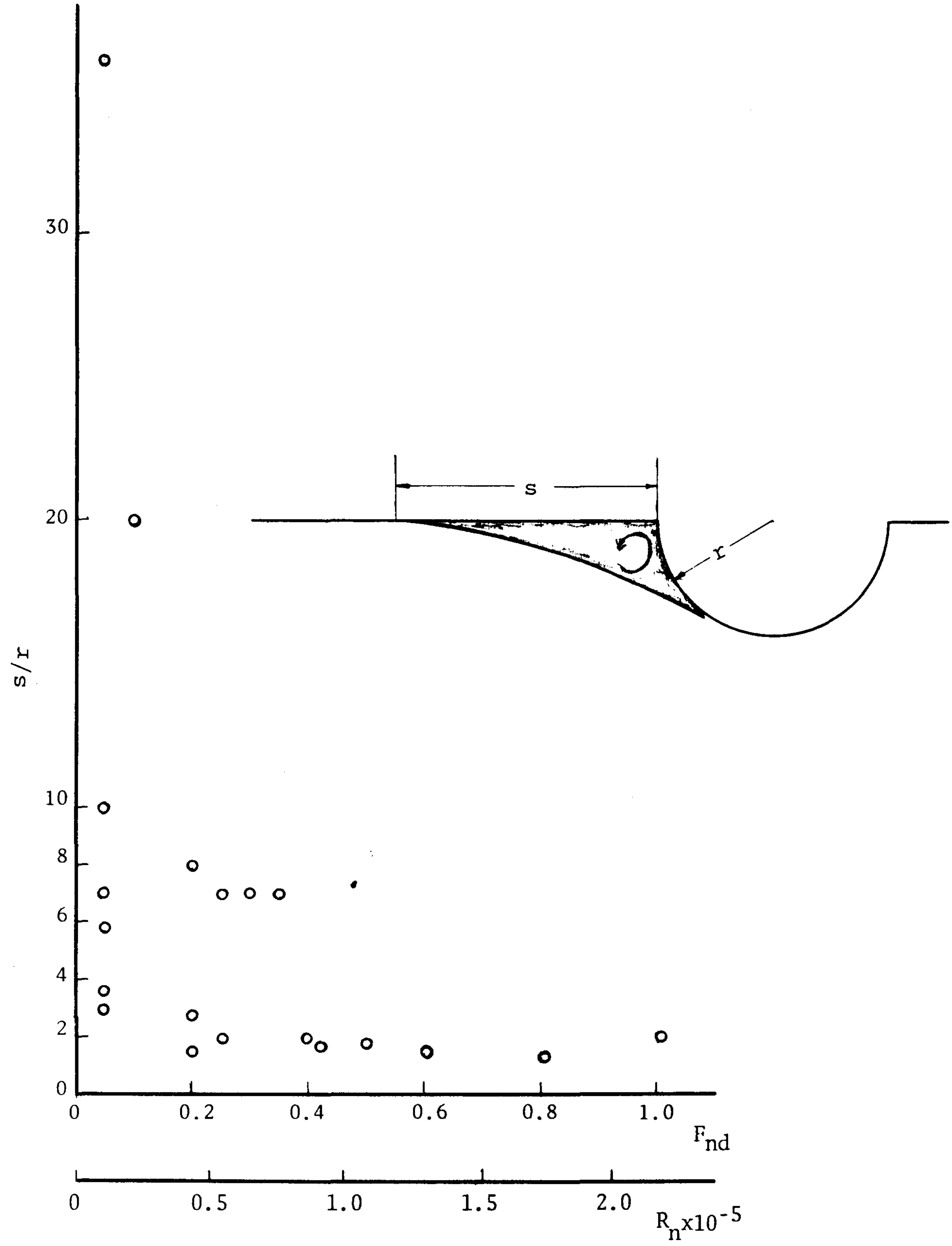


Fig.2 Distance s/r measured from the front of the cylinder to the stagnant line

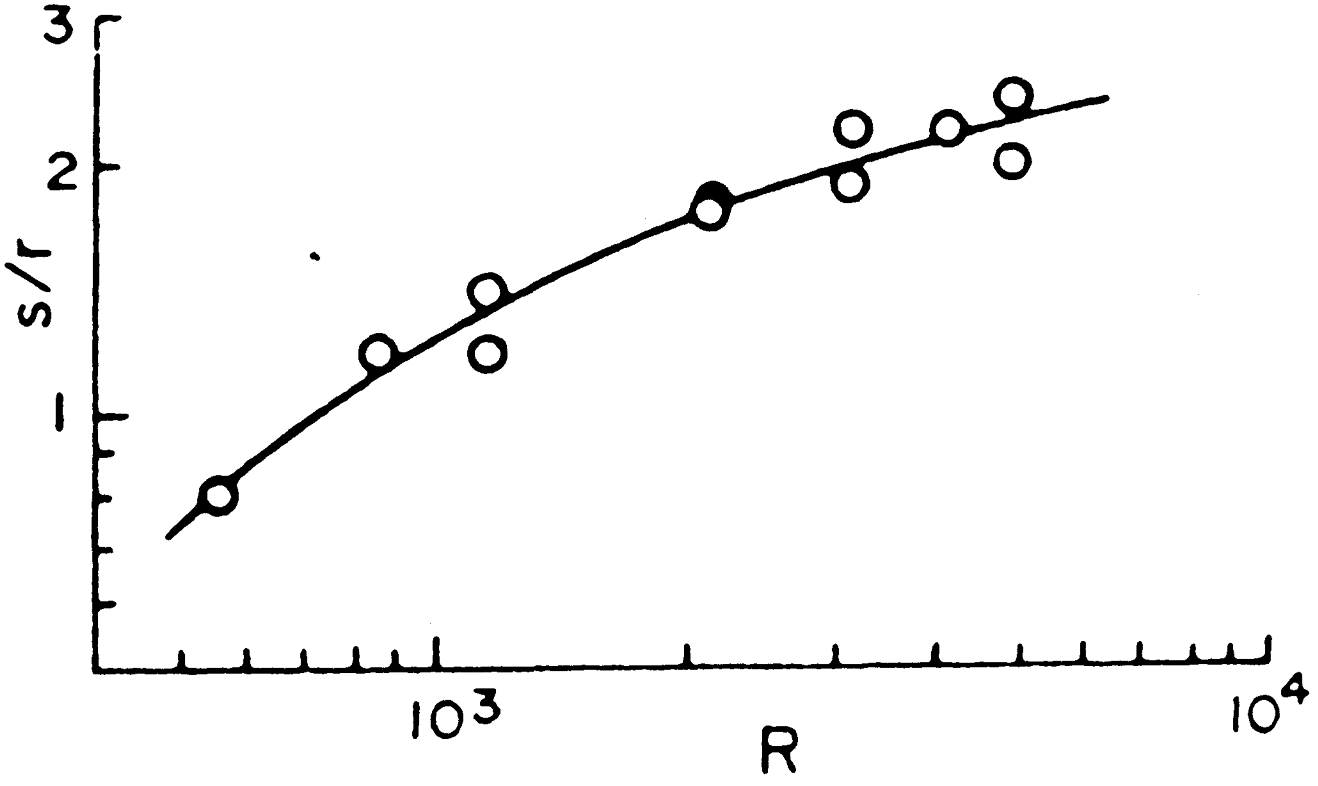


Fig.3 Distance s/r measured in Honji's(5) experiment

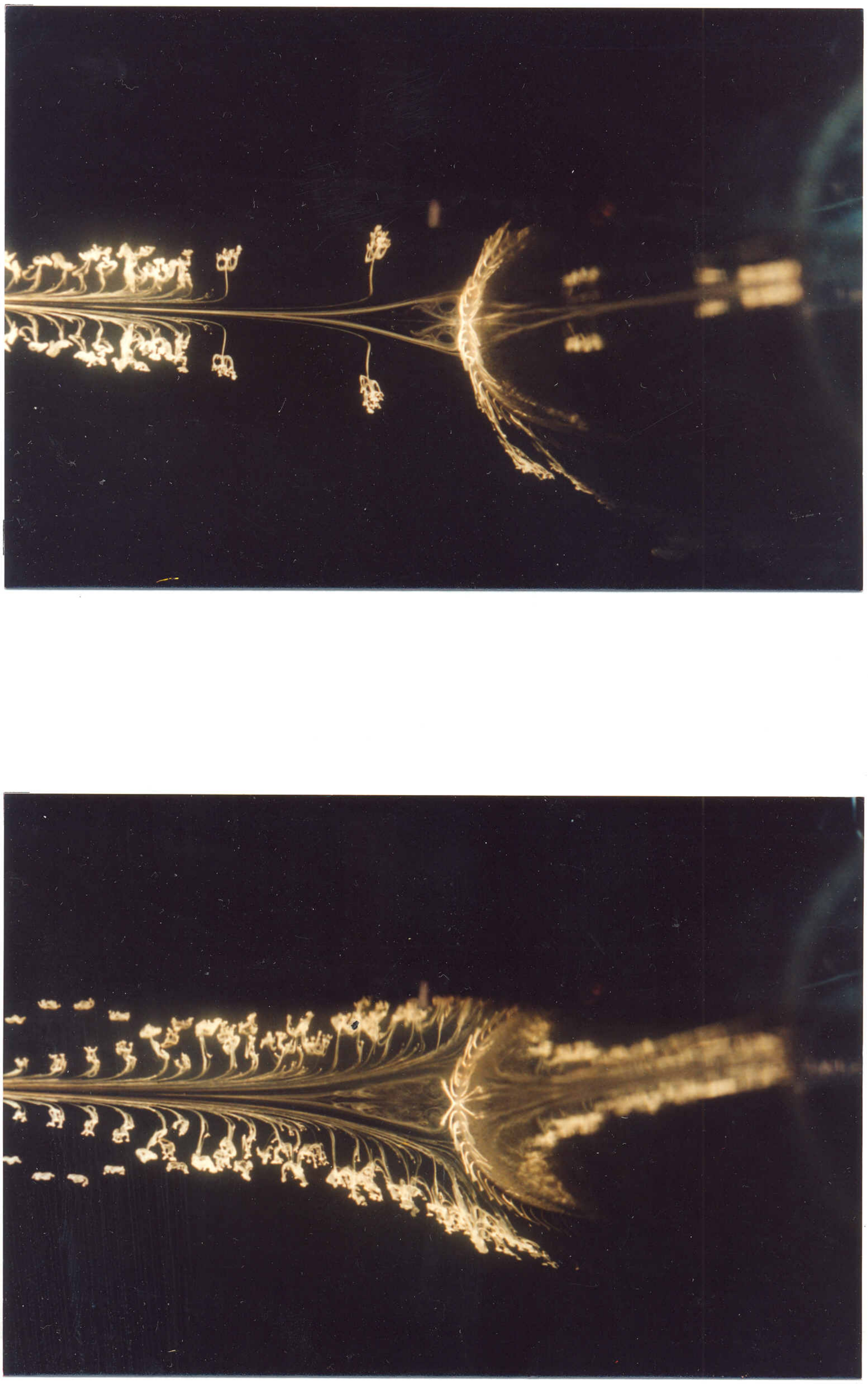
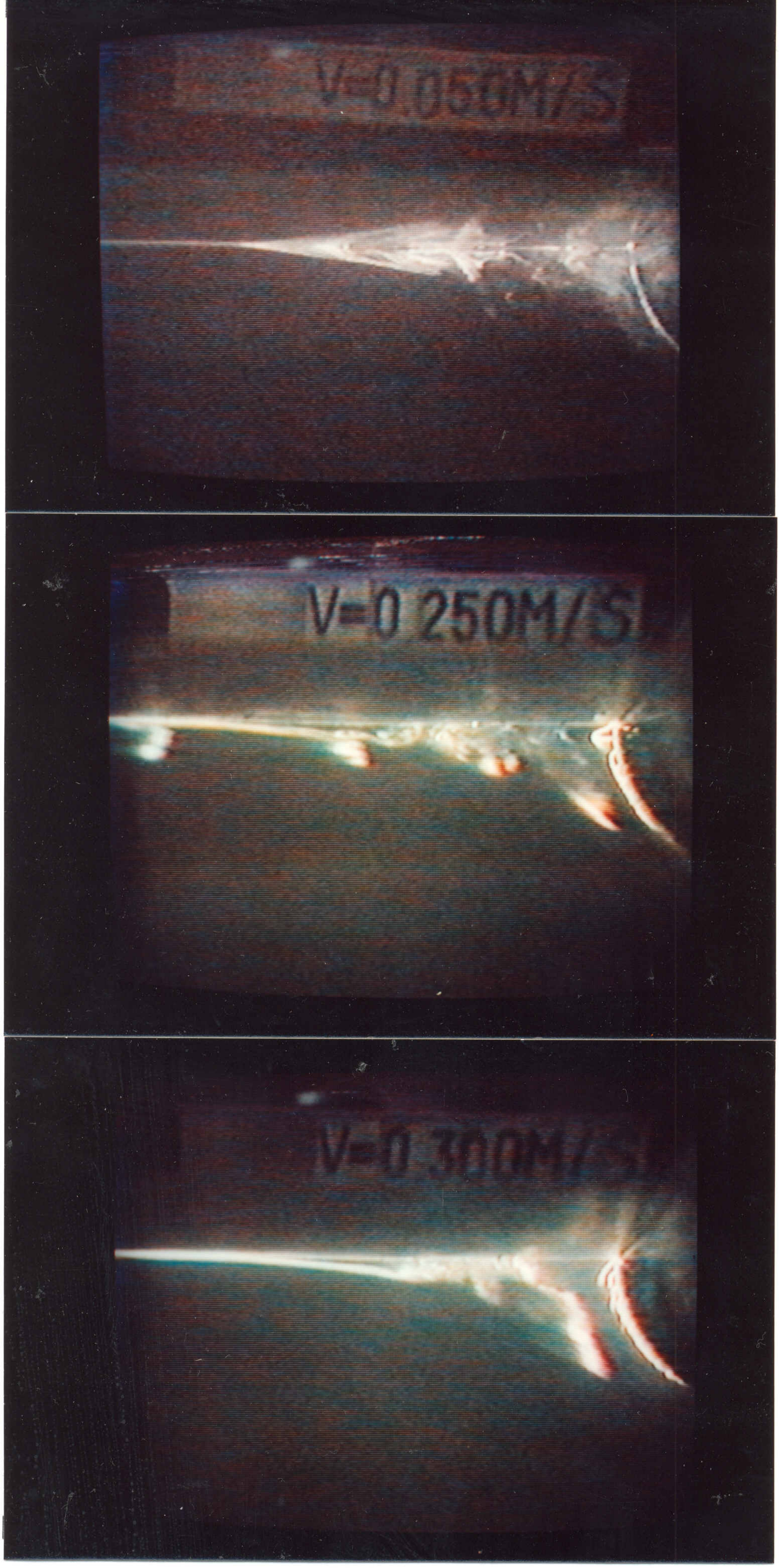


Fig. 4-a Flow pattern in front of semi-submerged circular cylinder (Vm = 0.05$^{m/s}$)



Vm = $0.05^{m/s}$

Vm = $0.25^{m/s}$

Vm = $0.30^{m/s}$

Fig. 4-b Flow pattern in front of semi-submerged circular cylinder

Vm = 0.35$^{m/s}$

Vm = 0.40$^{m/s}$

Vm = 0.50$^{m/s}$

Fig. 4-c Flow pattern in front of semi-submerged circular cylinder

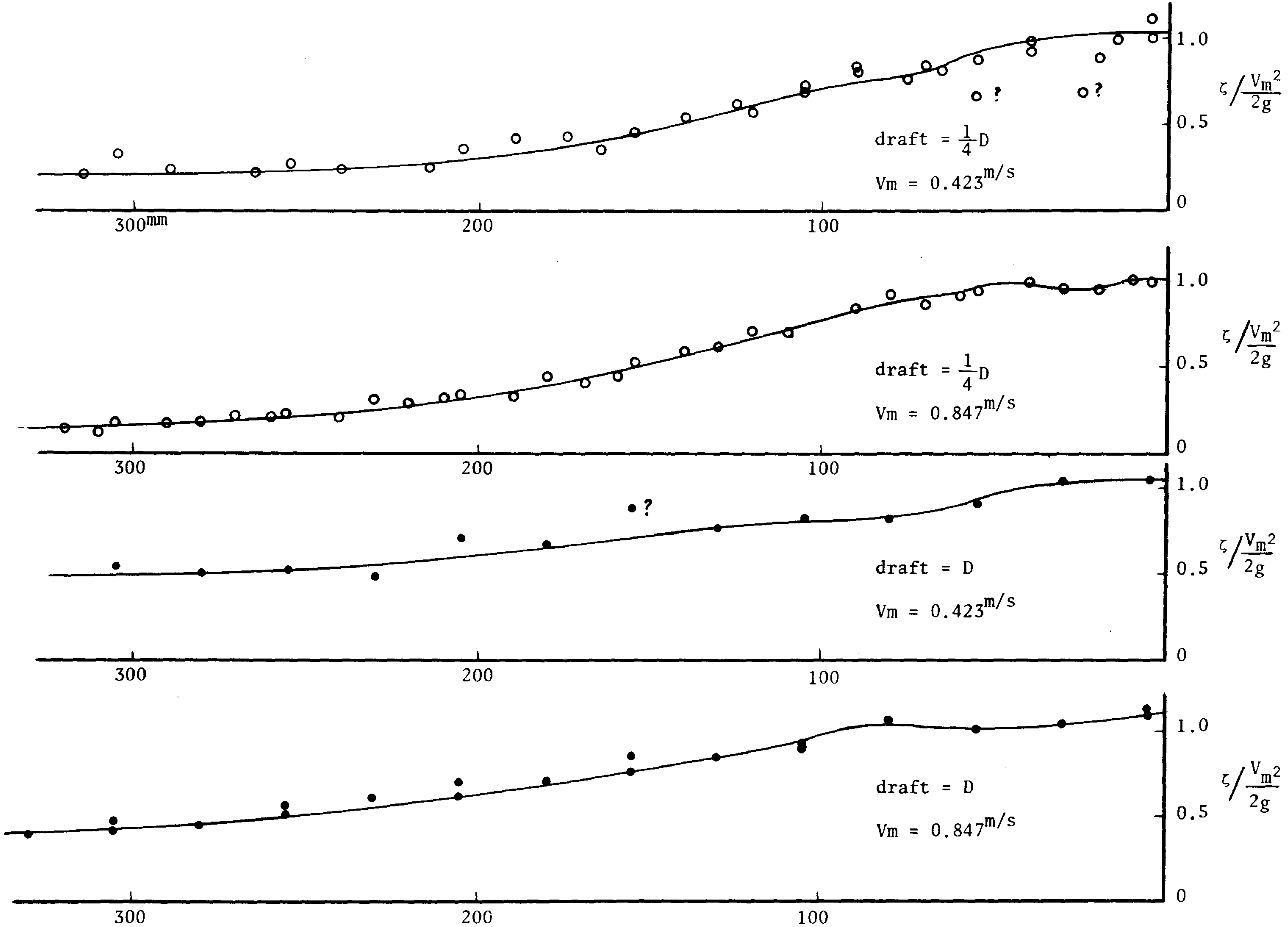


Fig.5 Wave height in front of vertical circular cylinder in the center plane (D = 457^{mm})

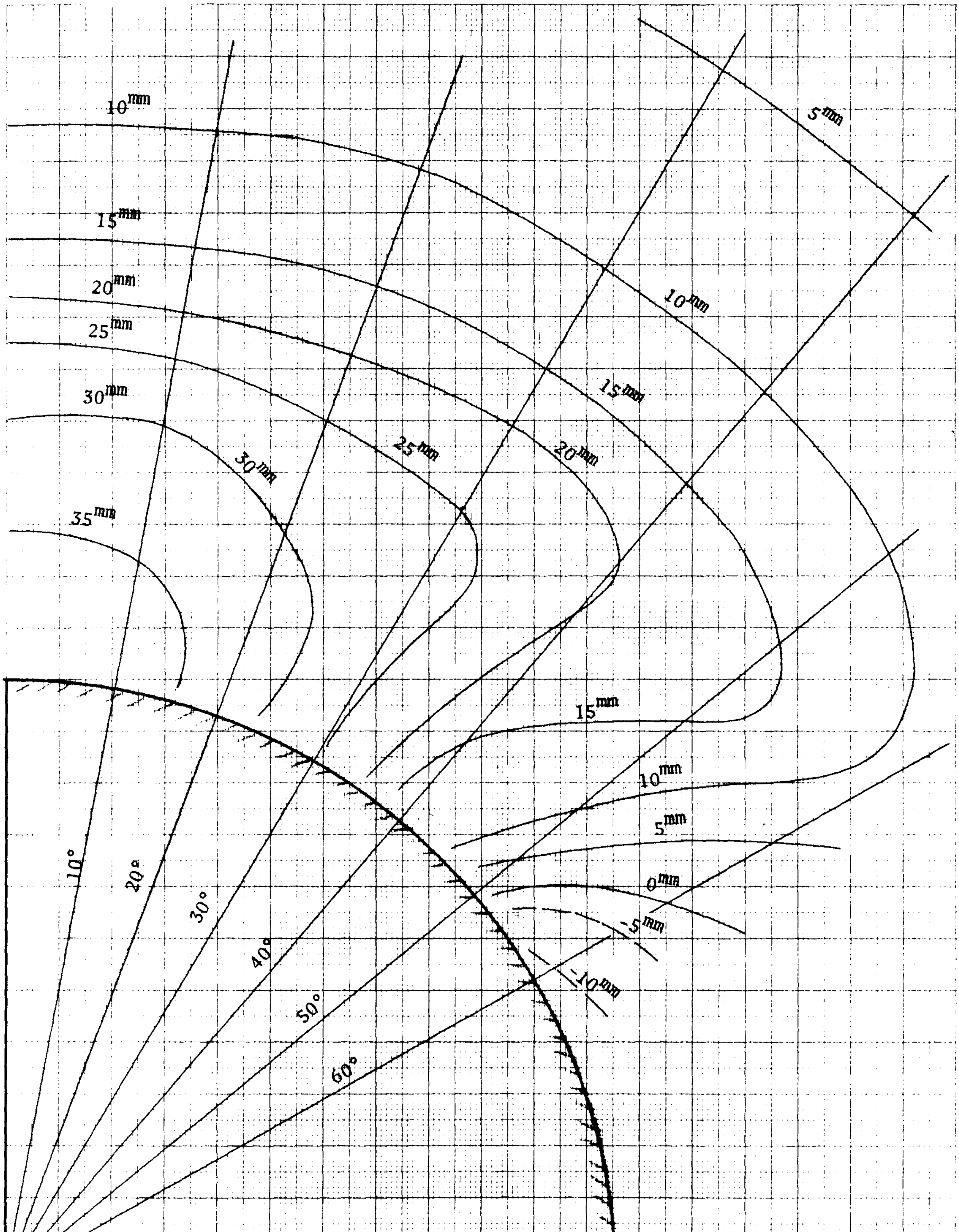
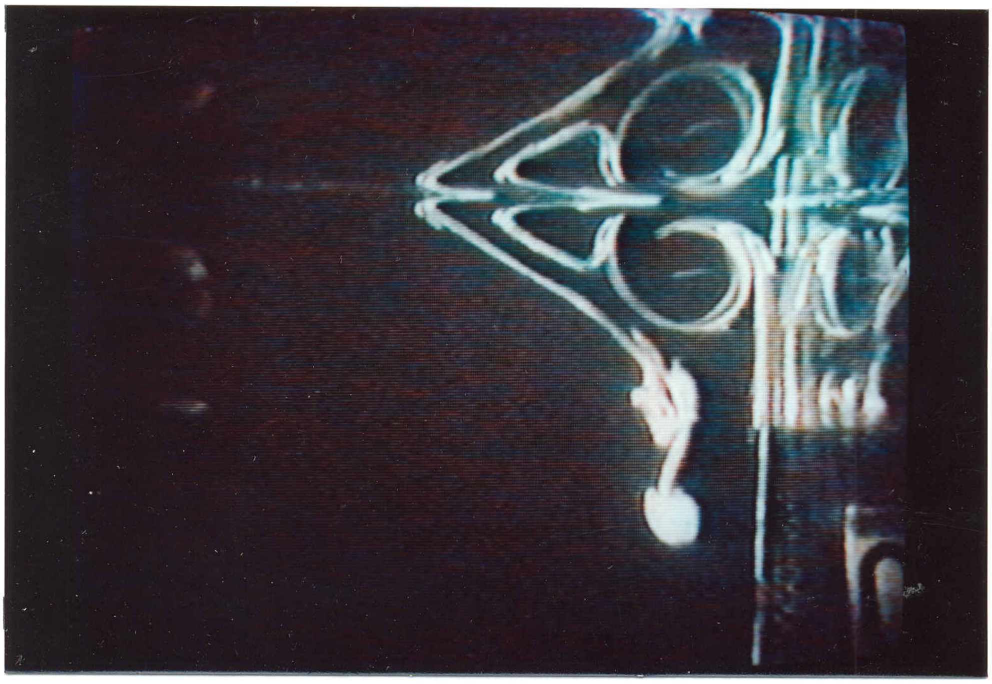


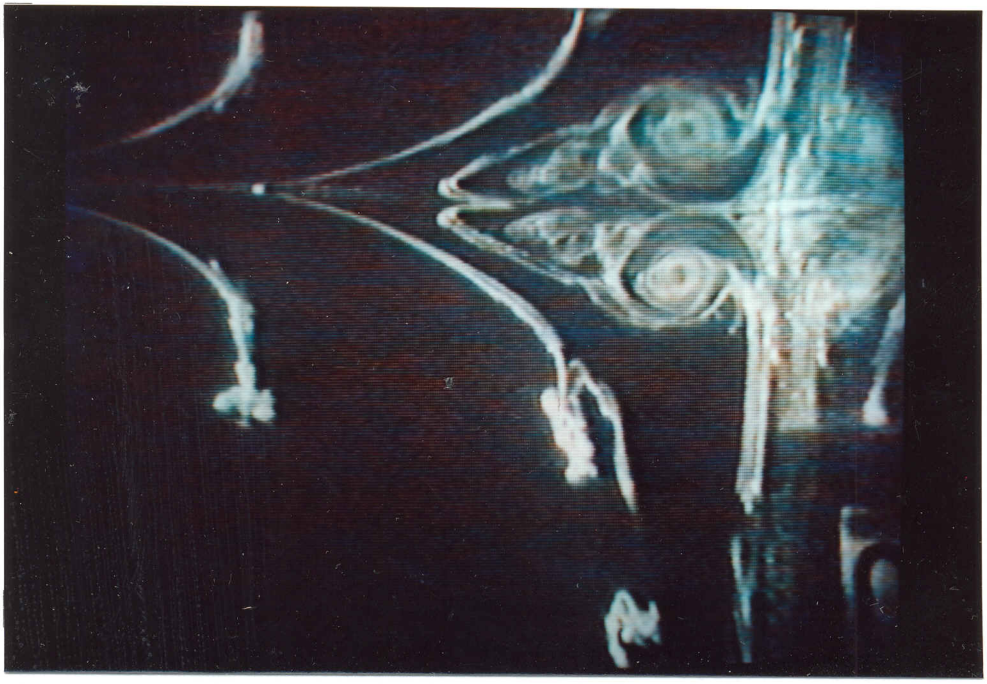
Fig.6 Wave contour line for a vertical circular cylinder with draft equal to 1/4 diameter

(Vm = 0.85 m/s)



$T = \frac{1}{4} D$

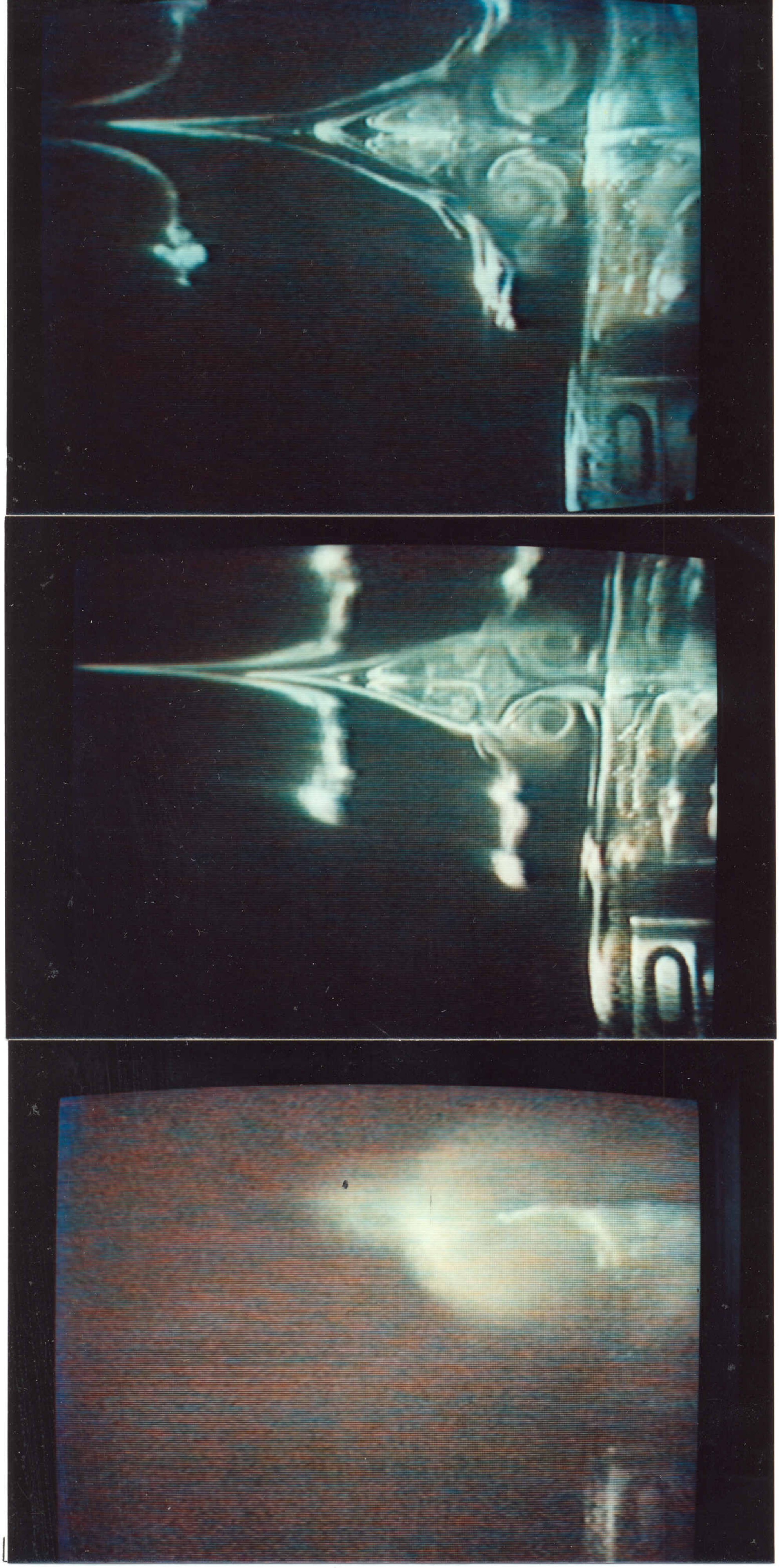
$Vm = 0.053^{m/s}$



$T = \frac{1}{4} D$

$Vm = 0.053^{m/s}$

Fig. 7-a Flow pattern in front of a vertical circular cylinder (draft $T = \frac{1}{4}$ D)



$T = \frac{1}{4} D$

$Vm = 0.106^{m/s}$

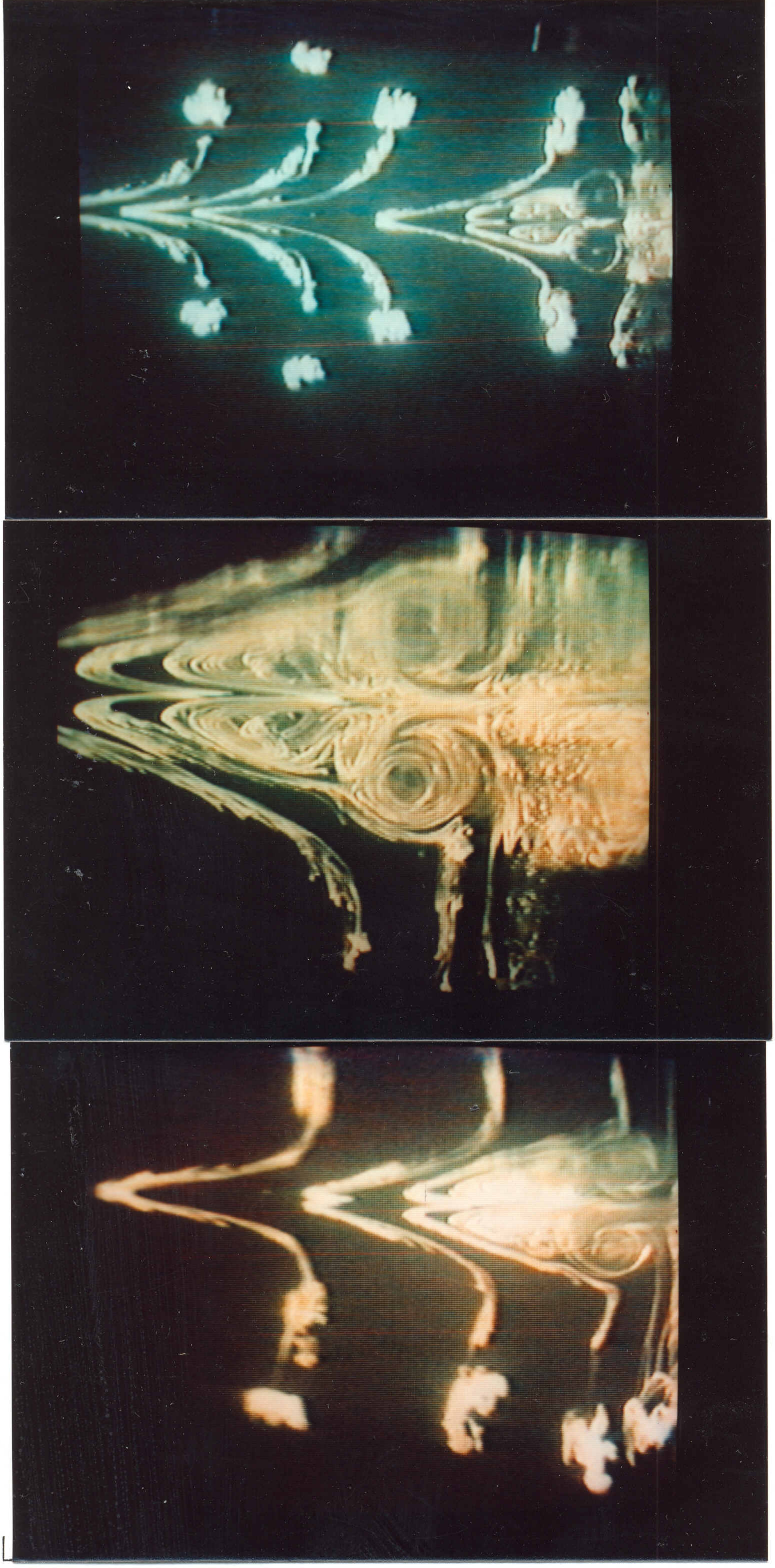
$T = \frac{1}{4} D$

$Vm = 0.212^{m/s}$

$T = \frac{1}{4} D$

$Vm = 0.423^{m/s}$

Fig. 7-b Flow pattern in front of a vertical circular cylinder (draft $T = \frac{1}{4} D$)



T = D

Vm = $0.053^{m/s}$

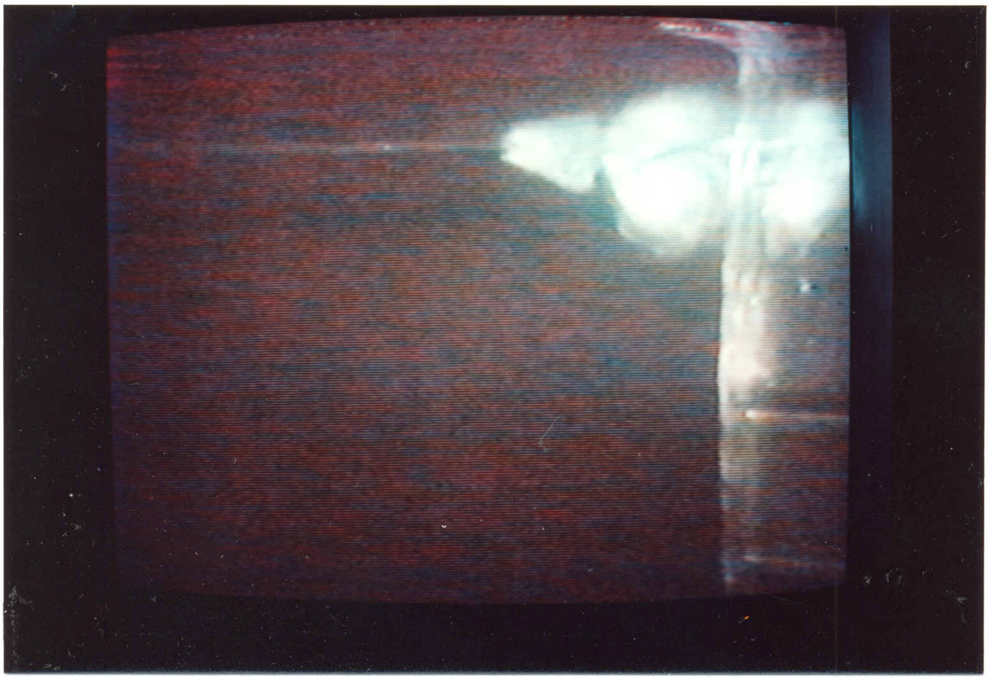
T = D

Vm = $0.053^{m/s}$

T = D

Vm = $0.106^{m/s}$

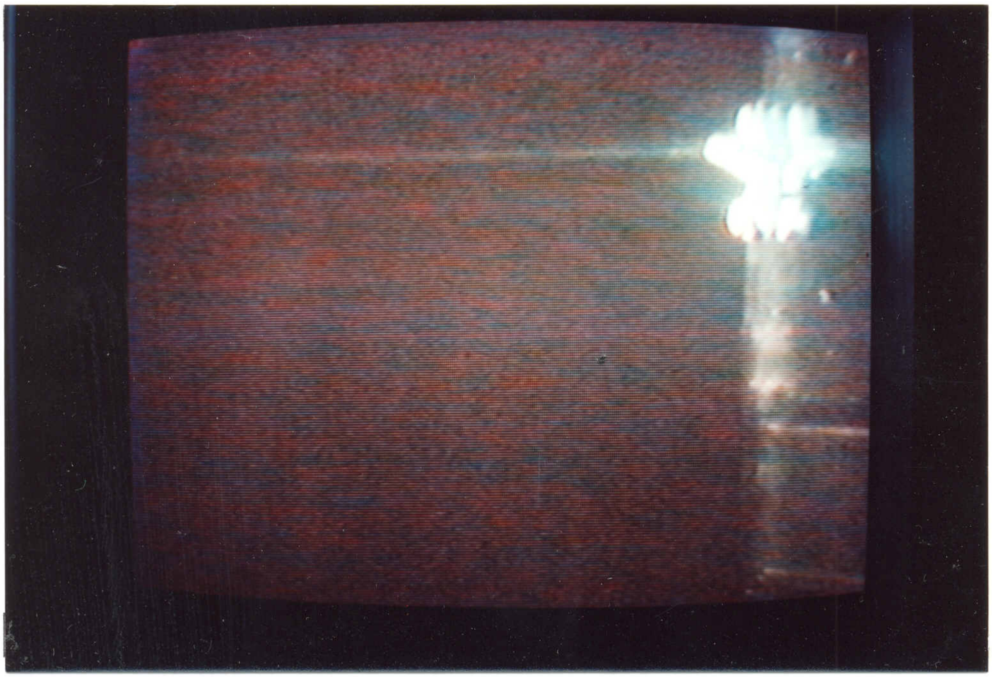
Fig. 7-c Flow pattern in front of a vertical circular cylinder (draft T = D)



T = D

Vm = 0.42$^{m/s}$

This picture was taken when the cylinder was in a steady motion shortly after it started

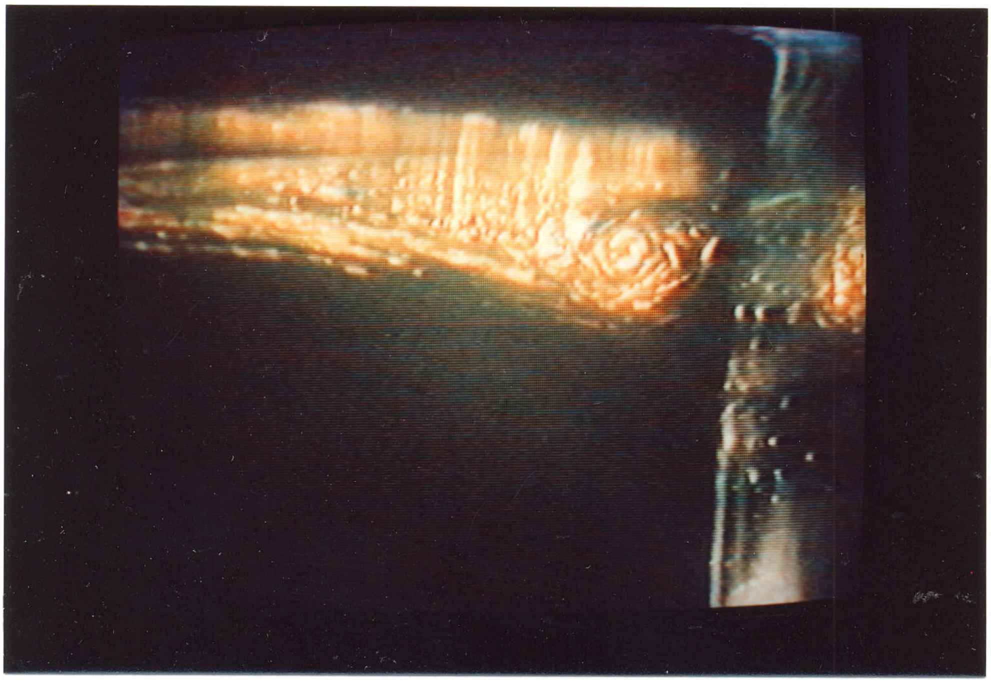


T = D

Vm = 0.42$^{m/s}$

This picture was taken when the cylinder was close to the tank end.

Fig. 7-d Flow pattern in front of a vertical circular cylinder (draft T = D)



$T = D$

$Vm = 0.84^{m/s}$

Fig. 7-e Flow pattern in front of a vertical circular cylinder (draft $T = D$)

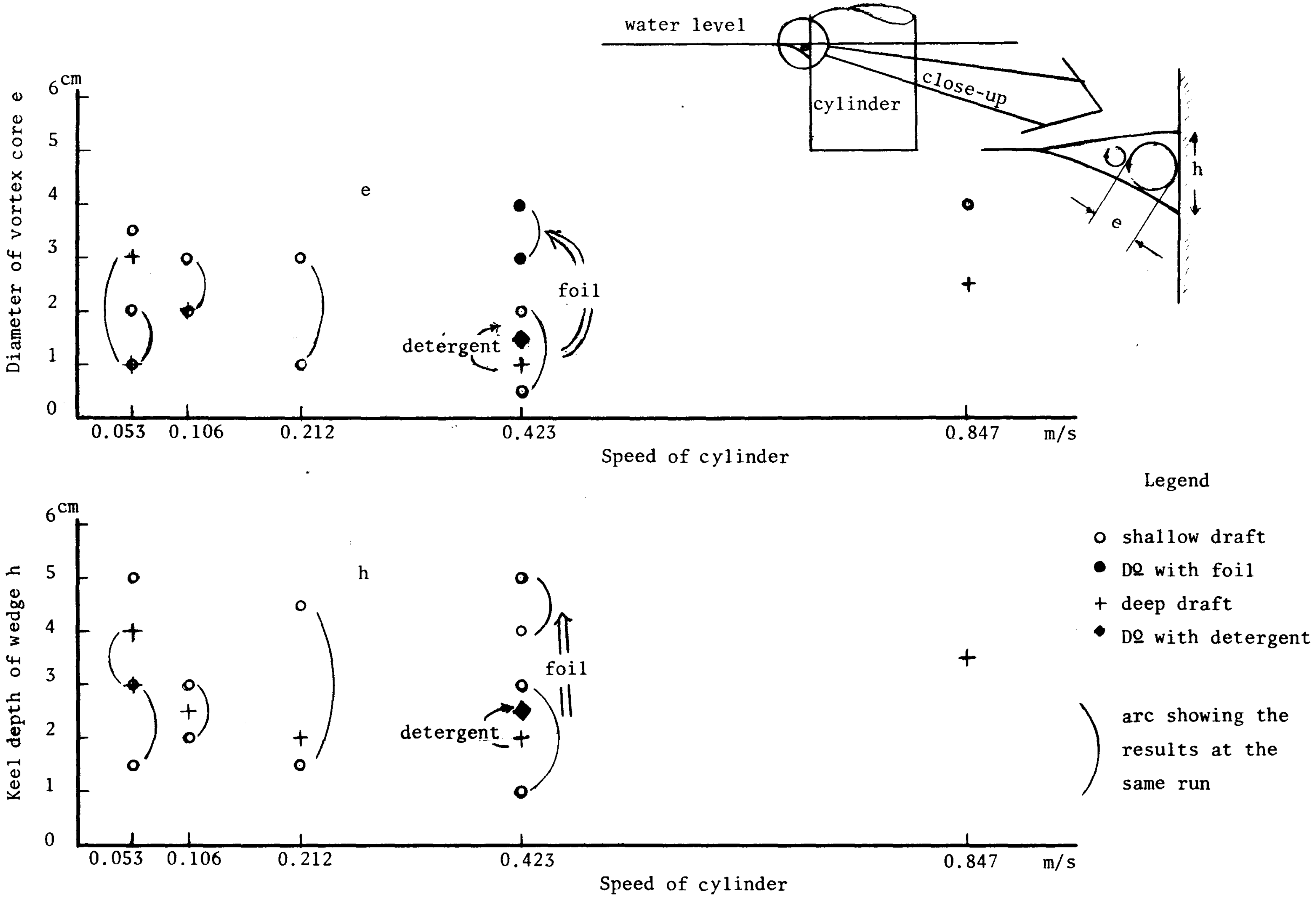
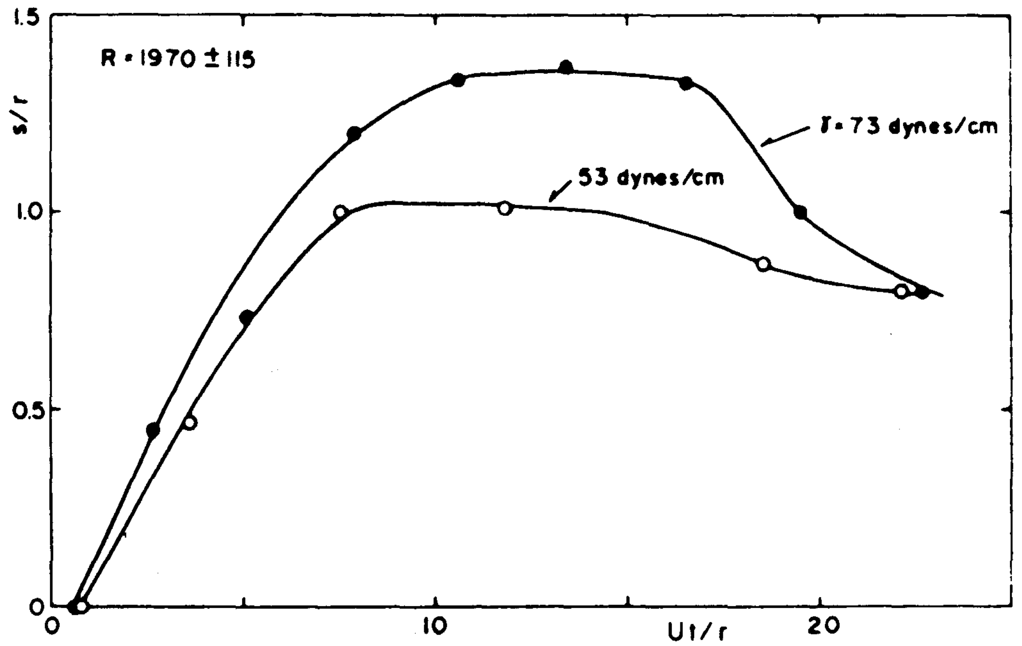


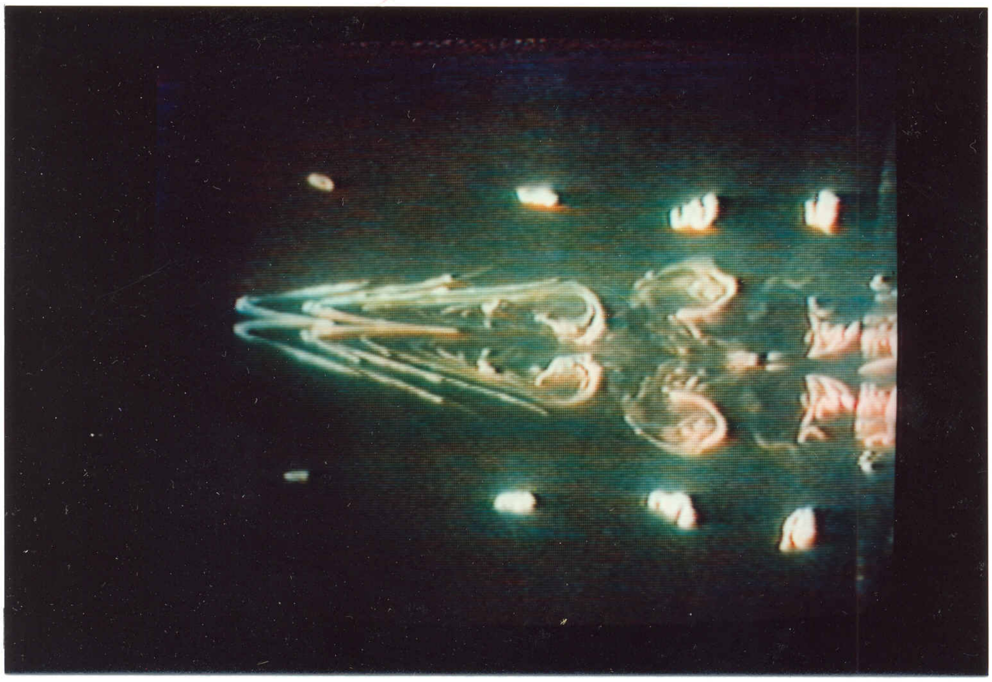
Fig. 8 Diameter of the nearest vortex and keel depth of the wedge shaped region



● $W=1.63$, ○ $W=2.24$,

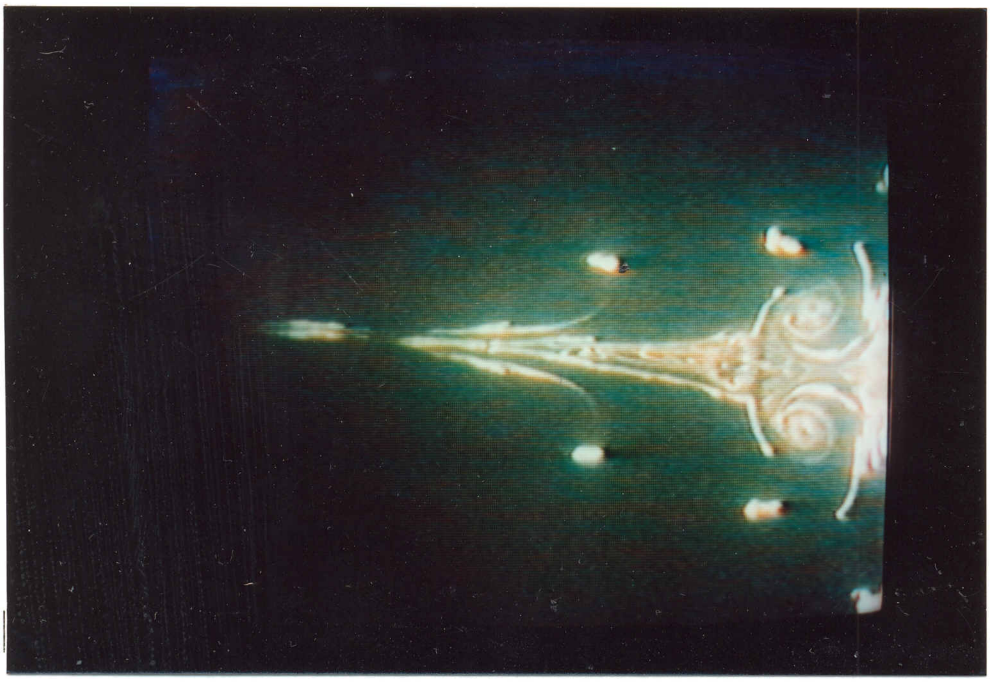
$U=4.88$cm/s, $r=5.00$cm, $l=29.7$cm.

Fig.9 Effect of surface tension on an upstream vortex in Honji's experiment(6)



T = D

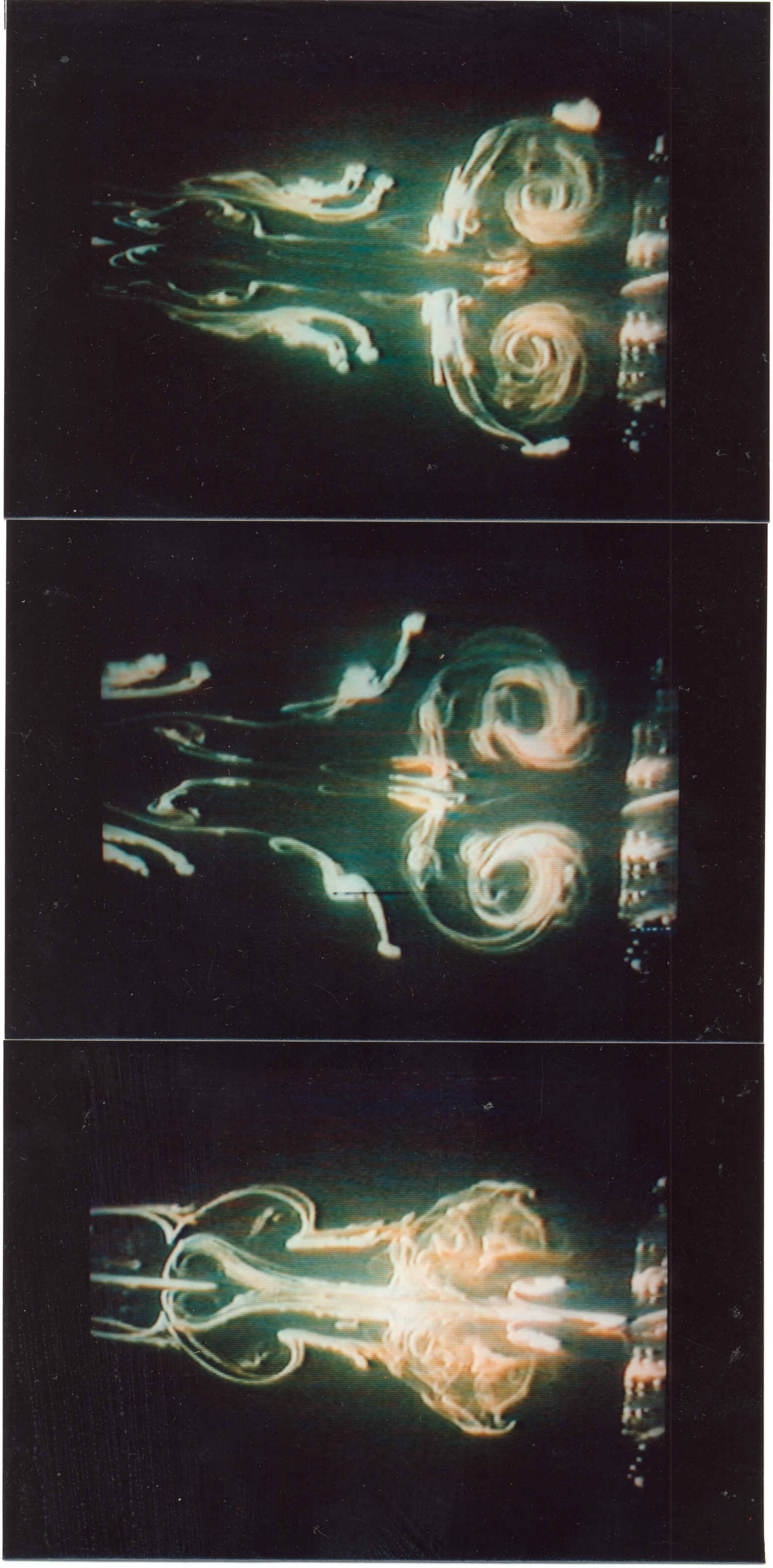
Vm = $0.053^{m/s}$



T = D

Vm = $0.053^{m/s}$

Fig. 10 Effect of surface tension on vortices - over all view in front of a vertical circular cylinder (Flow pattern is unsteady)



T = D

Vm = 0.053$^{m/s}$

free surface
is treated
with a
detergent

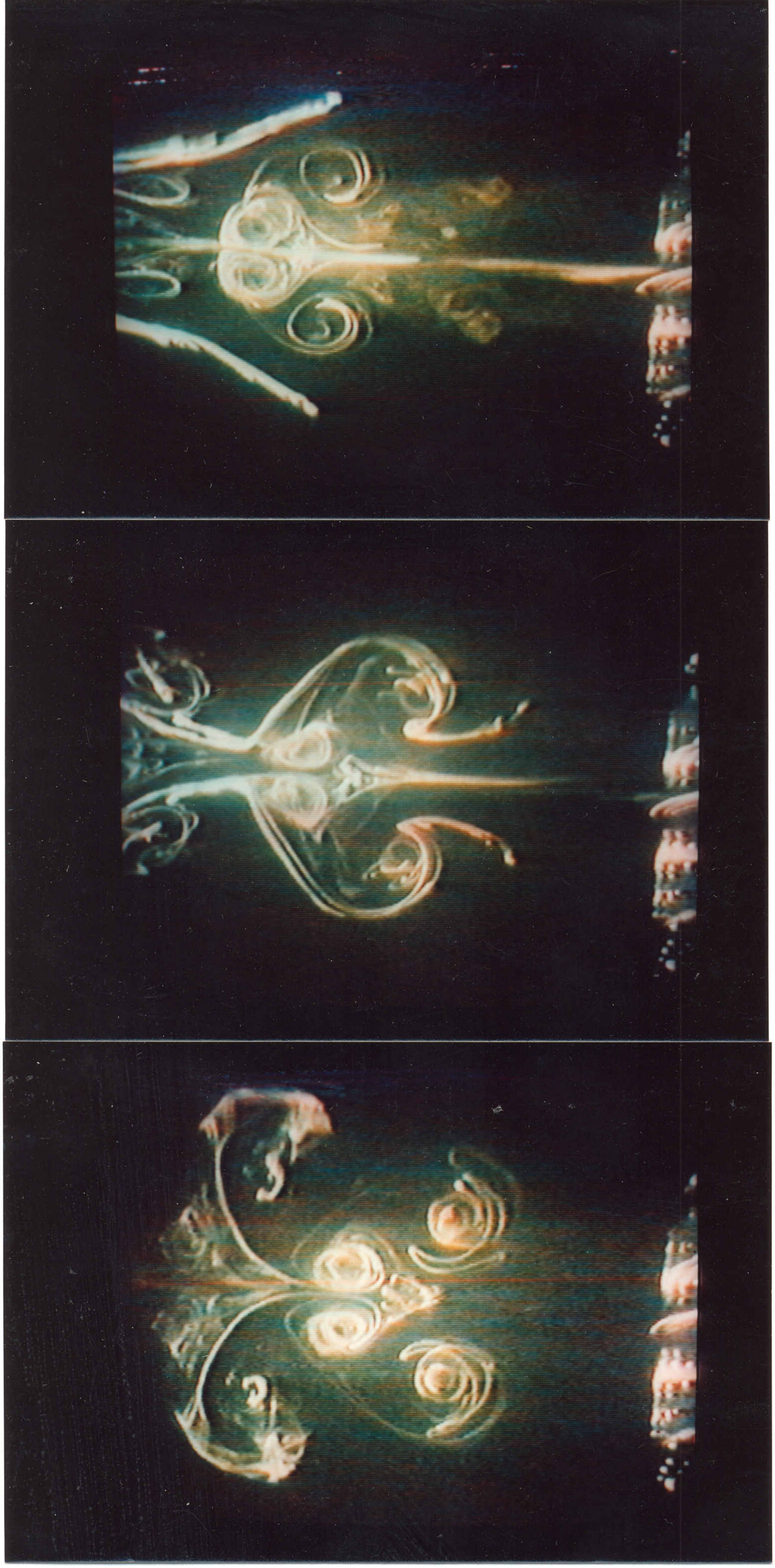
T = D

Vm = 0.053$^{m/s}$

T = D

Vm = 0.053$^{m/s}$

Fig. 11-a Unsteady flow pattern in front of a vertical circular cylinder (close-up)



T = D

Vm = 0.053$^{m/s}$

free surface
is treated
with a
detergent

T = D

Vm = 0.053$^{m/s}$

T = D

Vm = 0.053$^{m/s}$

Fig. 11-b Unsteady flow pattern in front of a vertical circular cylinder (close-up)