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Wind Tunnel Experiments on the Wake behind a Triangular Cylinder

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A wind tunnel of Göttingen type has been constructed at the Department of Physics of Ochanomizu University in 1955. The fan is driven by an electric motor of 5 HP. The test section is 50 cm × 50 cm square and the maximum air speed is about 24 m/sec.

Experiments on the wake behind a triangular cylinder were carried out both in an open jet and in a closed chamber. Pressure distributions on the surface of the cylinder and velocity distributions in the wake were measured and Schlieren photographs of the flow round the cylinder were taken. The relations between the base pressure, the drag, and the extension of the wake were discussed on the basis of these results.

INTRODUCTION

A wind tunnel of Göttingen type has been constructed at the Department of Physics of this university during March and June 1955. The outline of this tunnel is described first. The tunnel may be utilized for scientific research on aerodynamics, especially on the problems of turbulent flow.

As the first experiments to be carried on in this wind tunnel, we have made a plan for investigating the flow round and behind bluff cylinders.

The problem of the drag of bluff bodies has been one of the most important problems of hydrodynamics from a long time ago. As is well known, Kirchhoff's "free-streamline theory" and von Kármán's "vortex street theory" were both ingenious contributions and they elucidated two aspects of the essential features of the problem. Nevertheless, the former theory does not give the real value of drag and the latter cannot determine the drag without empirical data. In fact the flow behind a bluff cylinder is not so regular as considered in these theories but of very complicated turbulent nature except at extremely low Reynolds numbers. The structure of turbulent wake has been studied by many researchers. Especially severel years ago, Townsend investigated the turbulent flow in the wake of circular cylinders and established many important laws and facts of the wake in the region of the developed turbulence.(1) On the basis of these measurements, Batchelor presented new ideas about the mechanism of turbulence and its transferring effect across the wake.(2)

Recently Roshko has studied on the drag and the wake of bluff bodies. He observed how the turbulent wake developed from the vortex street behind an obstacle and how this process was affected by Reynolds number.(3) By the analysis of these results, he has found the so-called "bluff body simi-

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larity". On the other hand, he extended Kirchhoff's free-streamline theory by introducing a parameter k called "base pressure parameter", and derived analytical relations between the drag and the wake breadth for arbitrary base pressure.(4) These relations together with "bluff body similarity" establish a connection between free-streamline theory and vortex street theory and allow the drag to be determined from a measurement of one parameter, say, the shedding frequency of vortices. However, as Roshko himself stated, "the more understanding of the flow in the region of vortex formation is necessary for a really complete theory without empiricism."

Quite independently Imai has presented a new theory on the drag of bluff bodies.(5) It concerns with the drag of cylinders at very high Reynolds numbers and includes the "effective eddy viscosity" due to turbulent diffusion as a parameter. The theory has the advantage that it enables to picture the flow patterns in the wake in contrast to the free-streamline theory. In order to examine the validity of this theory and estimate the reasonable value of the "effective eddy viscosity", we must resort to experiments in the present state.

Considering these situations we have set up two purposes on our programme. Firstly we intend to determine the average flow characteristics, such as drag, base pressure, wake breadth, frequency of vortex shedding and mean flow patterns. Secondly, we are going to measure turbulent fluctuations in the flow round and behind a cylinder in order to investigate into the development and mechanism of turbulence in the wake. We have carried out some preliminary experiments on the flow past a triangular cylinder so far and the test results are described in this paper.

WIND TUNNEL

The tunnel is constructed in Göttingen type with single return passage arranged horizontally as shown in Fig. 1. The walls of wind ducts are wholly made of steel plates 3 mm thick and mounted on trusses.

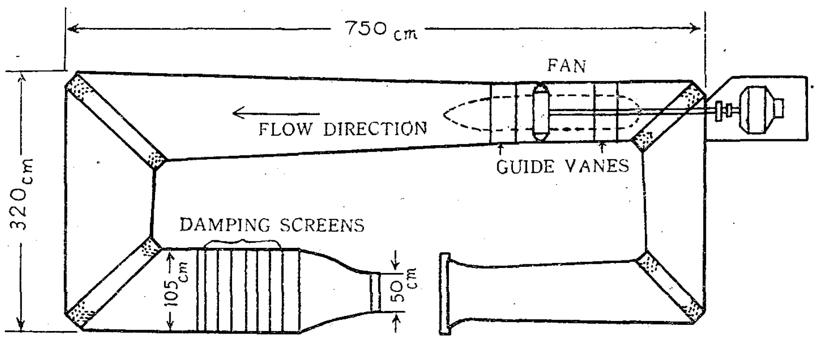


Fig. 1 Plan view of 50 cm × 50 cm wind tunnel.

The testing part is an open jet of 50 cm×50 cm square section and 80 cm long. In case of need side walls can be readily attached to this part, so that we may conduct experiments in a closed test section 200 cm long. (see Fig. 2).

Air flow is produced and maintained by an eight-bladed fan of 75 cm in diameter. The power is supplied by a 5 HP commutator motor of variable speed type. The speed of the motor is regulated continuously by a remote control device from rest to its maximum value 1800 r.p.m. The wind speed increases almost proportionally to the number of rotations of the motor and the maximum speed at the test section is about 24~26 m/sec, according to the arrangements of the test section and the settling chamber.

Owing to the limitation of space, we could not lay out the most desirable plan for reducing turbulence in the air stream ; contraction ratio at the passage from the settling chamber to the test section is small (4.41) and the length of diverging duct is unsatisfactory. In order to make up these defects, we have taken cautions as much as possible ; for example, careful design of fan and guide vanes, narrow spacing of deflectors, insertion of damping screens of fine meshes (three screens of 20 meshes and three of 25 meshes) into the settling chamber.

The survey of velocity distribution was made over the test section at various speeds of main flow and at several stations along the main stream. The variation of the local mean speed remains within 0.5% over the usual range for testing.

We have constructed a set of turbulence measuring equipment by the use of hot-wire anemometer. Tentative measurements show that $\sqrt{\overline{u^2}}/U$ is of the order of 0.1%. More accurate figures will be reported in a later paper.

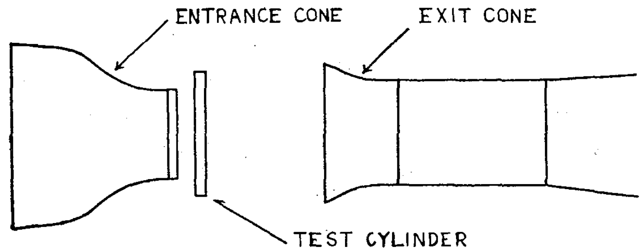
EXPERIMENTS ON THE WAKE BEHIND A TRIANGULAR CYLINDER

SCOPE OF EXPERIMENTS

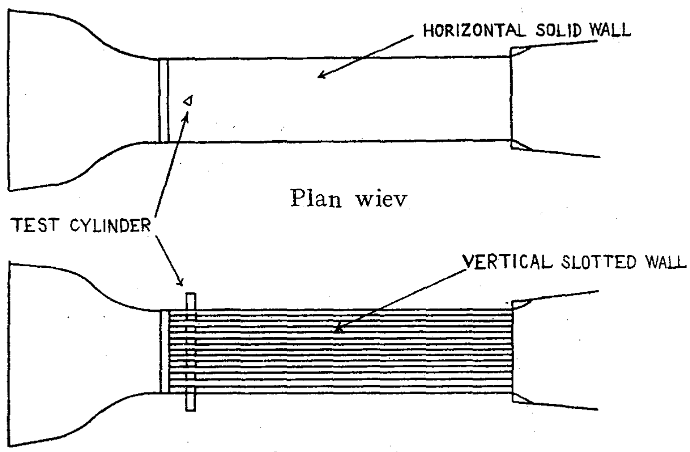
We have chosen an equilateral triangular cylinder as the testing body, since the separation point on the surface is fixed and this shape enables pressure holes and ducts to be installed into the cylinder. In order to investigate the flow close behind the obstacle in detail, we used a cylinder relatively large compared with the dimension of the test section.

Firstly we carried out measurements on the cylinder mounted horizontally crossing over the free jet as shown in Fig. 2, *Case* I. Of course it was ascertained by preliminary tests that the air stream around the cylinder was plane flow at least over the central half length along the span of the cylinder. However test results were found very different from the data published formerly including those due to Roshko; above all, the base pressure was very high and accordingly the drag was very small. After close examinations we have detected that there are remarkable inflows toward the central part in the very thin layers along the back side of the cylinder in the neighbourhood of either boundary of the free jet.

We have closed the test section with two horizontal solid walls and two vertical slotted walls as sketched in Fig. 2. Measurements taken in this closed section have shown that the flow past the cylinder is wholly two-dimensional and their results are consistent with the well-established data on the drag of bluff bodies. Although test results in the free jet deviate from those of ordinary two-dimensional flow, they seem to be very interesting from a viewpoint of Roshko's free-streamline theory. We describe the results of experiments in the free jet as well as in the closed test section, denoting as the "*Case* I" and the "*Case* II" respectively.

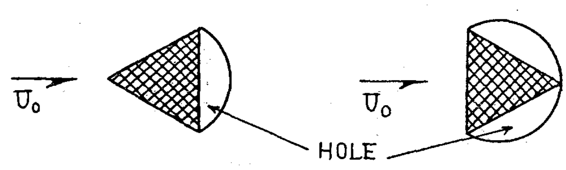


Case I Free jet.



Elevation view.

Cases II and III Closed test section.



Holes on the solid wall in the *Case* III.

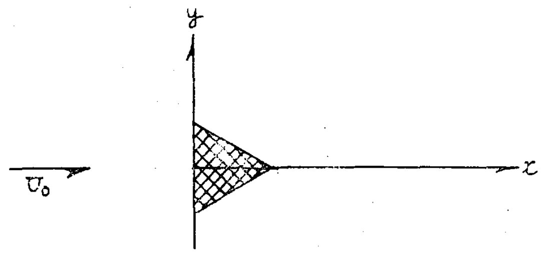
Fig. 2 Arrangements of test section.

Further we made a hole on each of the two solid walls round the test cylinder as shown in Fig. 2 and carried out similar tests. These results are considered to be corresponding to an intermediate flow between the *Cases* I and II, and they are denoted as the "*Case* III".

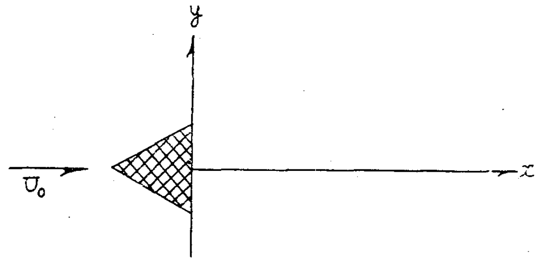
In each case the tests were made with either the apex or the flat surface of the cylinder toward the wind alternatively. (see Fig. 3). The results for these two kinds of setting may be compared with the calculated flows past a

60° wedge and a flat plate according to the free-streamline theory respectively. They are referred to as "facing forward" and "facing backward", or simply setting "*a*" and "*b*", respectively.

In all these cases and settings, the pressure distributions on the surface of the cylinder, distributions of mean velocity and its fluctuations in the wake were measured. Further we took a large number of photographs by the Schlieren method in order to visualize the flow patterns. The selected data of these measurements are presented in the following part, except those concerning velocity fluctuations or turbulence which shall be reported in a later paper.



(a) Facing forward.



(b) Facing backward.

Fig. 3 Setting of cylinder.

NOTATIONS

x, y	distances measured along and perpendicular to the main stream respectively from the center line of the vertical surface of the cylinder (see Fig. 3)
d	length of the side of the equilateral triangle of the cross section of the test cylinder (5 cm)
d'	half-value width of wake
ρ, ν	density and kinematic viscosity of air respectively
U_0, p_0	velocity and static pressure of the main stream respectively
U	local mean velocity of air flow
U_m	minimum value of U in each section of wake
p	pressure on the surface of the cylinder
p_s	base pressure on the back surface of the cylinder
C_p	pressure coefficient $((p-p_0)/\frac{1}{2}\rho U_0^2)$
C_{ps}	base pressure coefficient $((p_s-p_0)/\frac{1}{2}\rho U_0^2)$
C_D	drag coefficient (drag per unit width$/\frac{1}{2}\rho U_0^2 d$)
C_{D_f}	drag coefficient of front surfaces alone
k	base-pressure parameter $(\sqrt{1-C_{ps}})$
R	Reynolds numder $(U_0 d/\nu)$
N	frequency of vortex shedding
S	Strouhal number (Nd/U_0)

Arrangements of the test section (Fig. 2)

I denotes tests carried out in the free jet.

II denotes tests carried out in the test section with two horizontal solid walls and two vertical slotted walls and without hole on the wall.

III denotes tests carried out in the same test section as II, but with hole round the cylinder on each solid wall.

Setting of the test cylinder (Fig. 3)

a facing forward

b facing backward

TEST CYLINDER AND TEST PROCEDURES

Test cylinder and pressure distribution. The test cylinder is made of wood and 70 cm long. The cross section is an equilateral triangle and the length of its sides is 5 cm. There are laid two small tubes under each surface and seven pressure holes of 0.6 mm in diameter are drilled on each tube at the central part of the cylinder as shown in Fig. 4.

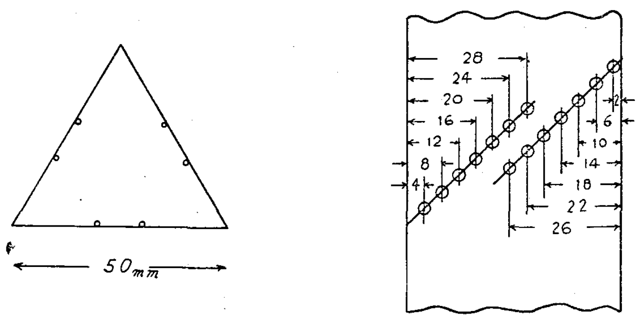


Fig. 4 Test cylinder and pressure holes.

Hot-wire anemometer and velocity distribution. In order to measure local mean velocity of air flow, a small Pitot-static tube was used at first, but in later experiments hot-wire anemometer was employed exclusively. A platinum wire of 15 microns in diameter and about 4 mm long placed perpendicular to the main stream was used. It was operated at about 150~200 °C by the constant-resistance method. As shown in the Schlieren photographs the velocity of air flow in the wake close behind the cylinder fluctuates very irregularly, its magnitude is very small, and its direction is even reversed. Although we cannot make reliable measurement of velocity by the hot-wire anemometer in such a region, we have recorded uncorrected data to get a general view of development of the wake near the cylinder.

Schlieren photograph and flow pattern. In order to visualize the streamlines we inserted small heat sources in the flow field and took photographs of their heat wakes by the Schlieren method. The heat sources are a pair of fine nichrome wires, 10 cm long and 1 cm apart, placed parallel to the axis of the cylinder and heated electrically. Schlieren system is of one-mirror type employing a reflecting mirror of which radius of curvature is 2 m.

TEST RESULTS

The preliminary tests were made for distributions of pressure on the surfaces and of local mean velocity in the wake by varying the velocity of main stream. It was ascertained that these test results, when represented in non-dimensional form C_p, C_D, and U/U_0, agreed with each other very well for the range of U_0 between 12 m/sec and 24 m/sec. Hence all measurements were carried out for a few kinds of main stream velocity and the average values were taken. These data apply to the range of Reynolds number between $4\times 10^4 \sim 8\times 10^4$. The Schlieren photographs were taken at the lower speed $U_0 =$ 5 m/sec for the convenience of experiments, and the flow pattern does not change appreciably at this speed in its essential features.

Pressure distribution. Fig. 5 shows the results of measurements for pressure distribution on the surfaces of the cylinder facing forward. The base pressure changes substantially according to the variations of the arrangement of the test section while the pressure distribution on the front surfaces remains almost the same. Integrations of these curves for pressure distribution give

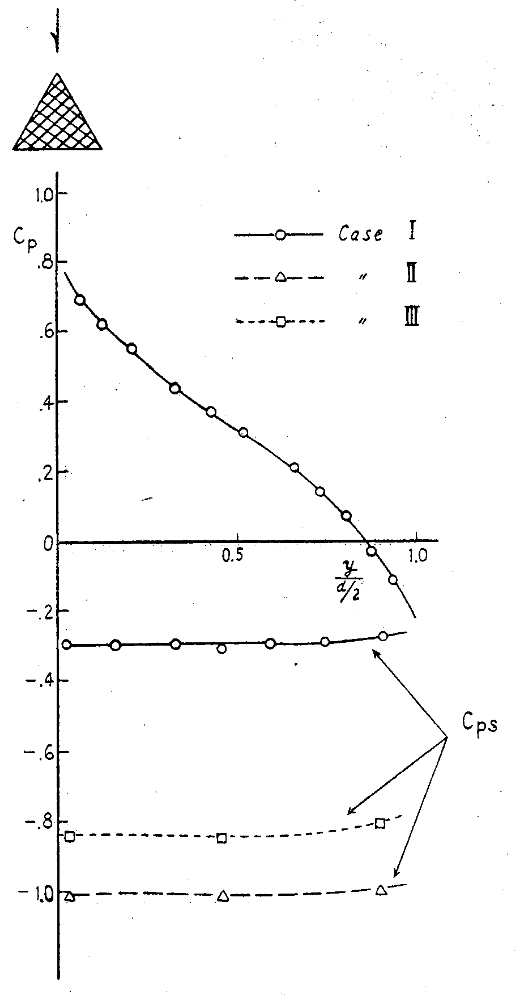


Fig. 5 Pressure distribution on the surface of a triangular cylinder facing forward.

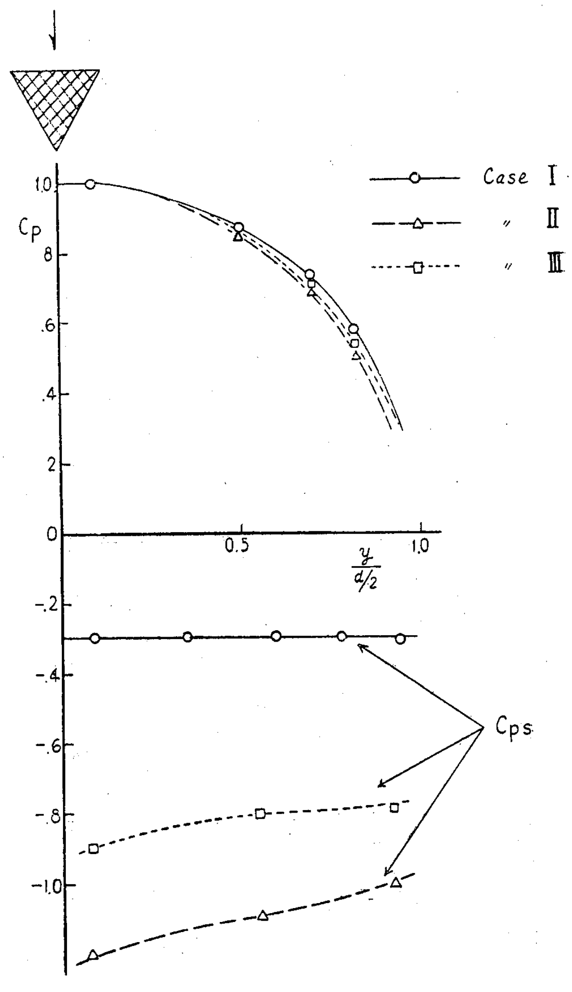


Fig. 6 Pressure distribution on the surface of a triangular cylinder facing backward.

the drag coefficients of the cylinder. The contribution of the front surfaces alone C_{D_f} is 0.33 irrespective of test conditions, while the total drag coefficient C_D is 0.62, 1.34 and 1.17 for the *Cases* I, II, and III respectively. The pressure at the trailing edges is not equal to the static pressure of the main stream but lower than it and this fact indicates that the velocity along the free streamline is higher than the velocity of the main stream in accordance with Roshko's theory.

Test results for the cylinder facing backward are shown in Fig. 6. General features of pressure distribution are quite similar to those for the cylinder facing forward. C_{D_f} is about 0.8 for each case and total drag coefficient C_D is 1.15, 1.84 and 1.54 for the *Cases* I, II and III respectively.

Velocity distribution in the wake. The local mean velocities U have been measured using hot-wire anemometer at five sections in the free jet and at three sections in the closed chamber, and their distribution curves in the wake are drawn in Figs. 7~10. Fig. 7 shows the variations of U in the wake behind

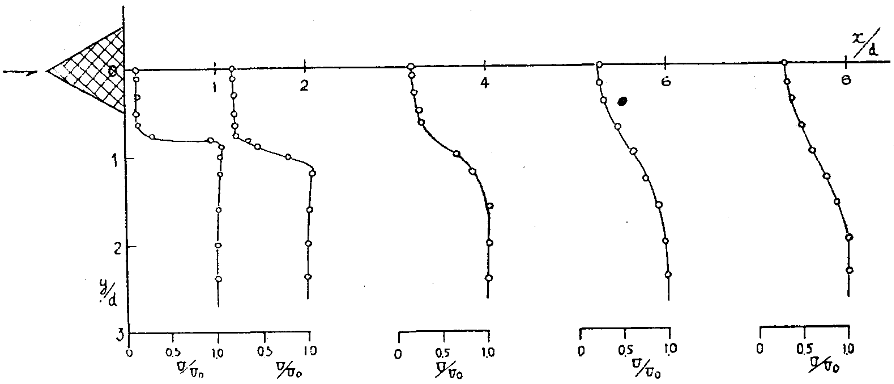


Fig. 7 Velocity distribution in the wake behind a triangular cylinder facing forward. (*Case* I.)

the cylinder facing forward in the free jet. Close behind the cylinder ($x/d=1.0$) the wake is of almost the type predicted by the free-streamline theory and at its boundary on either side exists a very thin layer of discontinuity

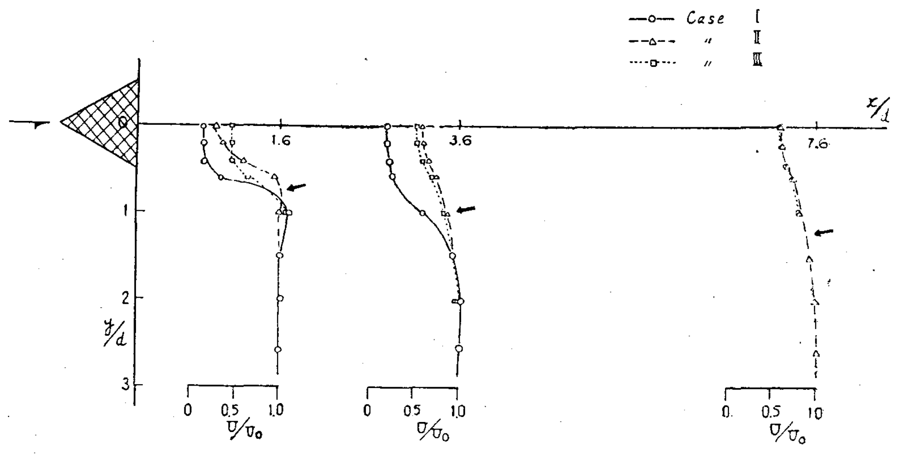


Fig. 8 Velocity distribution in the wake behind a triangular cylinder facing forward. (*Cases* I, II and III.)

in velocity. This layer is the succession of the limiting streamline at the trailing edge of the cylinder and the velocity just outside it exceeds the velocity of the main stream. As the distance from the cylinder increases, the trough of velocity distribution becomes shallower and broader.

Fig. 8 represents the velocity distributions in the wake in the closed test section together with the distributions measured in the free jet at the same distances from the cylinder for the sake of comparison. It is remarkable that the minimum velocities in the closed test section are considerably higher than those in the free jet and the breadths of the wake are smaller in the former case than in the latter. The effect of the hole on the solid wall (*Case* III) is noticed near the cylinder but it soon disappears as the distance from the cylinder increases.

The results of the survey in the wake behind the cylinder facing backward are shown in Figs. 9 and 10. The essential features of the wake and the differences due to the changes of test condition are very similar to those for the cylinder facing forward.

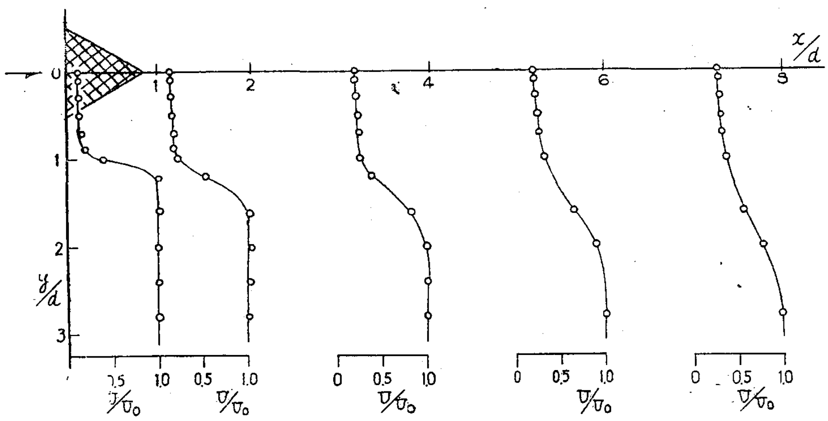


Fig. 9 Velocity distribution in the wake behind a triangular cylinder facing backward. (*Case* I.)

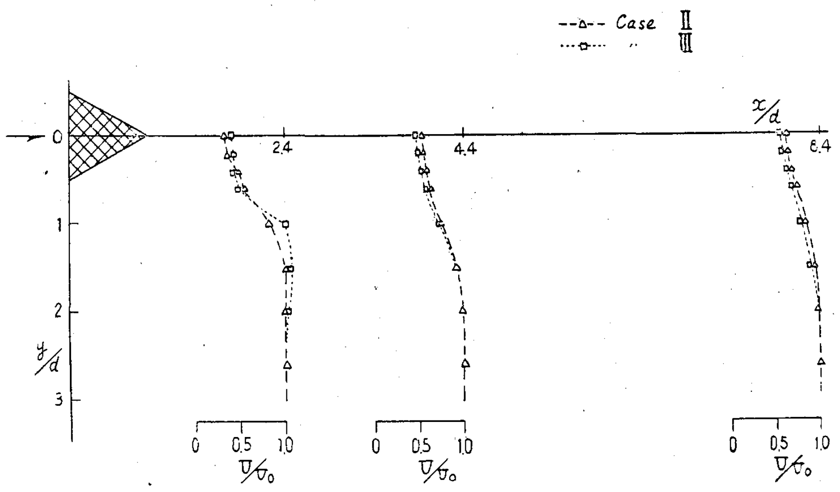
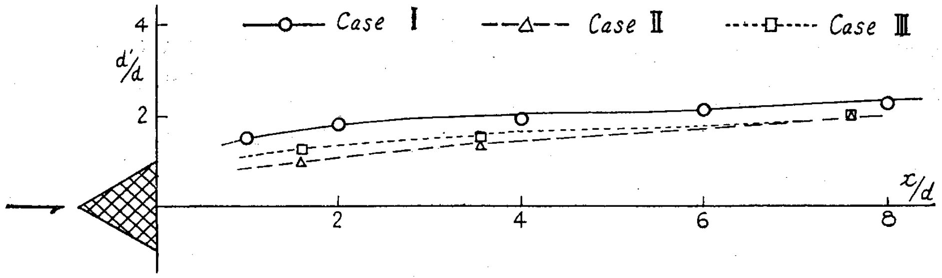
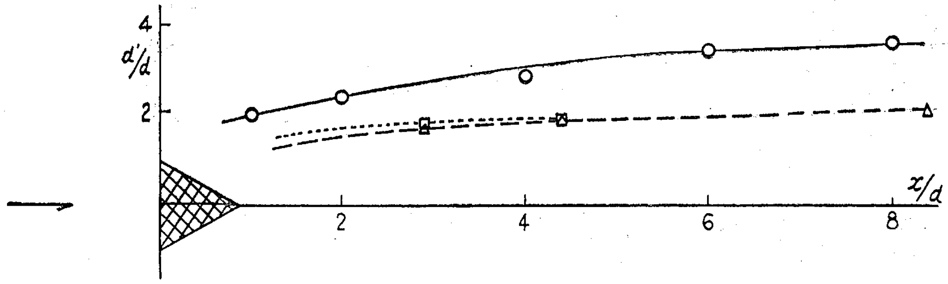


Fig. 10 Velocity distribution in the wake behind a triangular cylinder facing backward. (*Cases* II and III.)

The development of the wake is shown in Fig. 11. Here, d' is the distance between two points at which $U=\frac{1}{2}(U_0+U_m)$ and may be called half-value width of the wake.



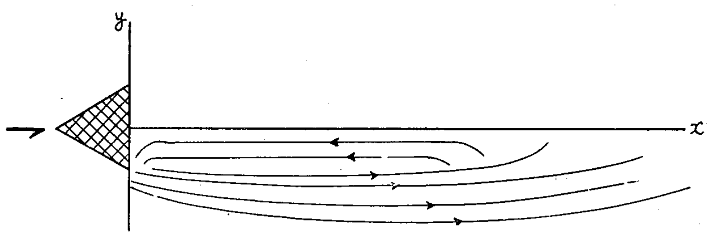
(a) Cylinder facing forward.



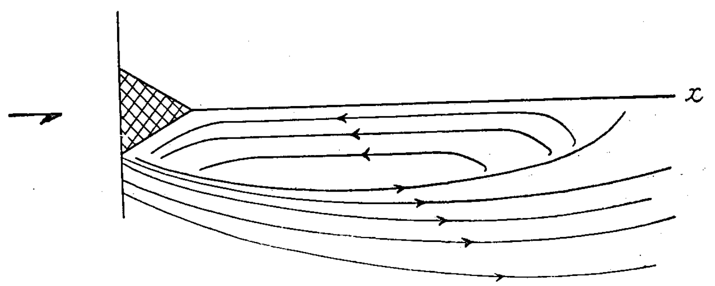
(b) Cylinder facing backward.

Fig. 11 Half-value width of wakes.

Streamlines and frequency of vortex shedding. A large number of Schlieren photographs were taken all over the flow field behind the cylinder in the free jet. Several samples of these photographs are reproduced in Plates I and II. Pictures in short exposure show the instantaneous flow, while those in long exposure represent the mean streamlines. There exists a highly turbulent region of backward flow behind the cylinder. Based on these photographs we may draw mean streamlines as shown in Fig. 12.



(a) Cylinder facing forward.



(b) Cylinder facing backward.

Fig. 12 Mean streamlines behind a triangular cylinder.

← Flow direction

Exposure 1/500 sec. Exposure 1 sec.

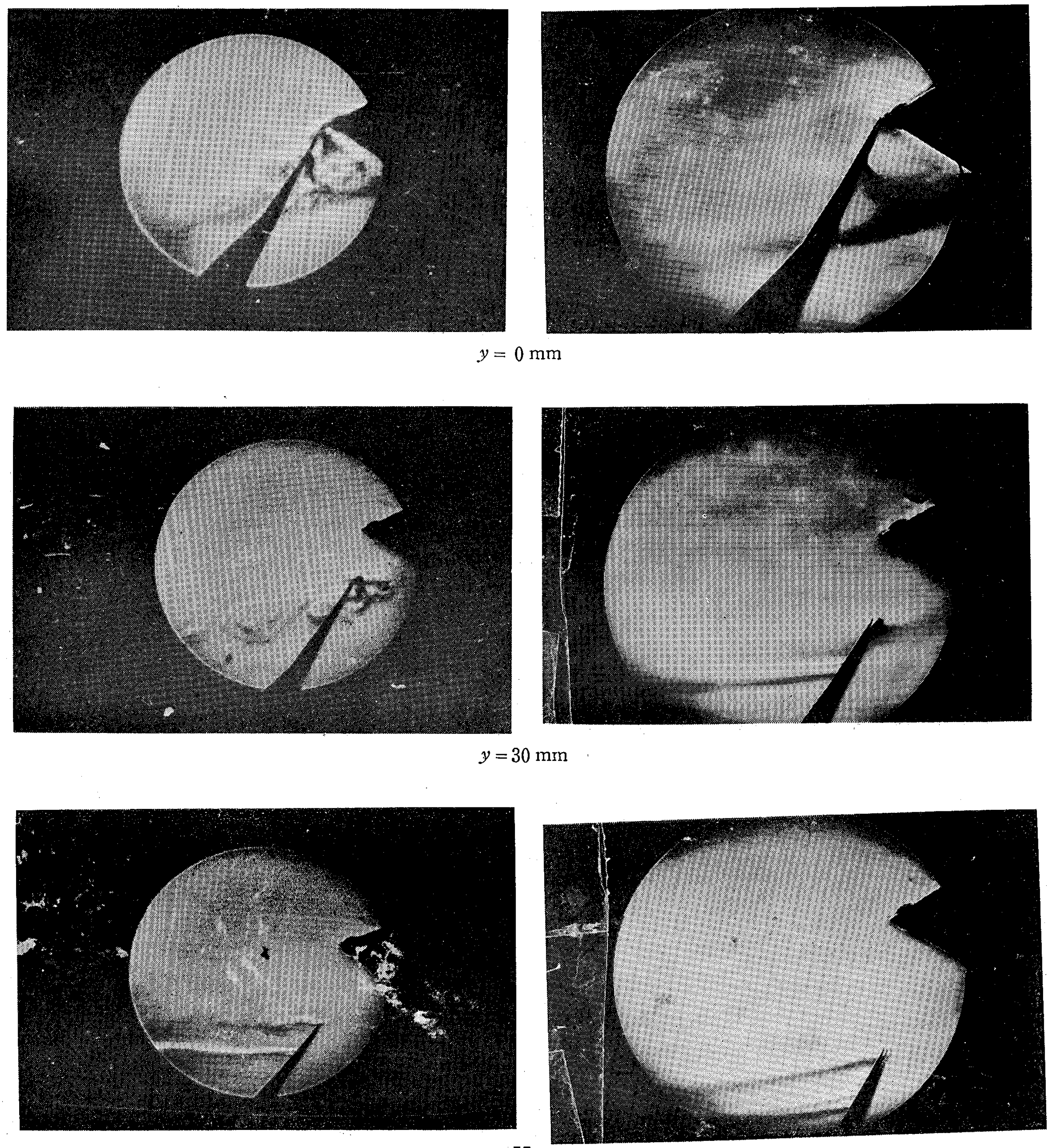
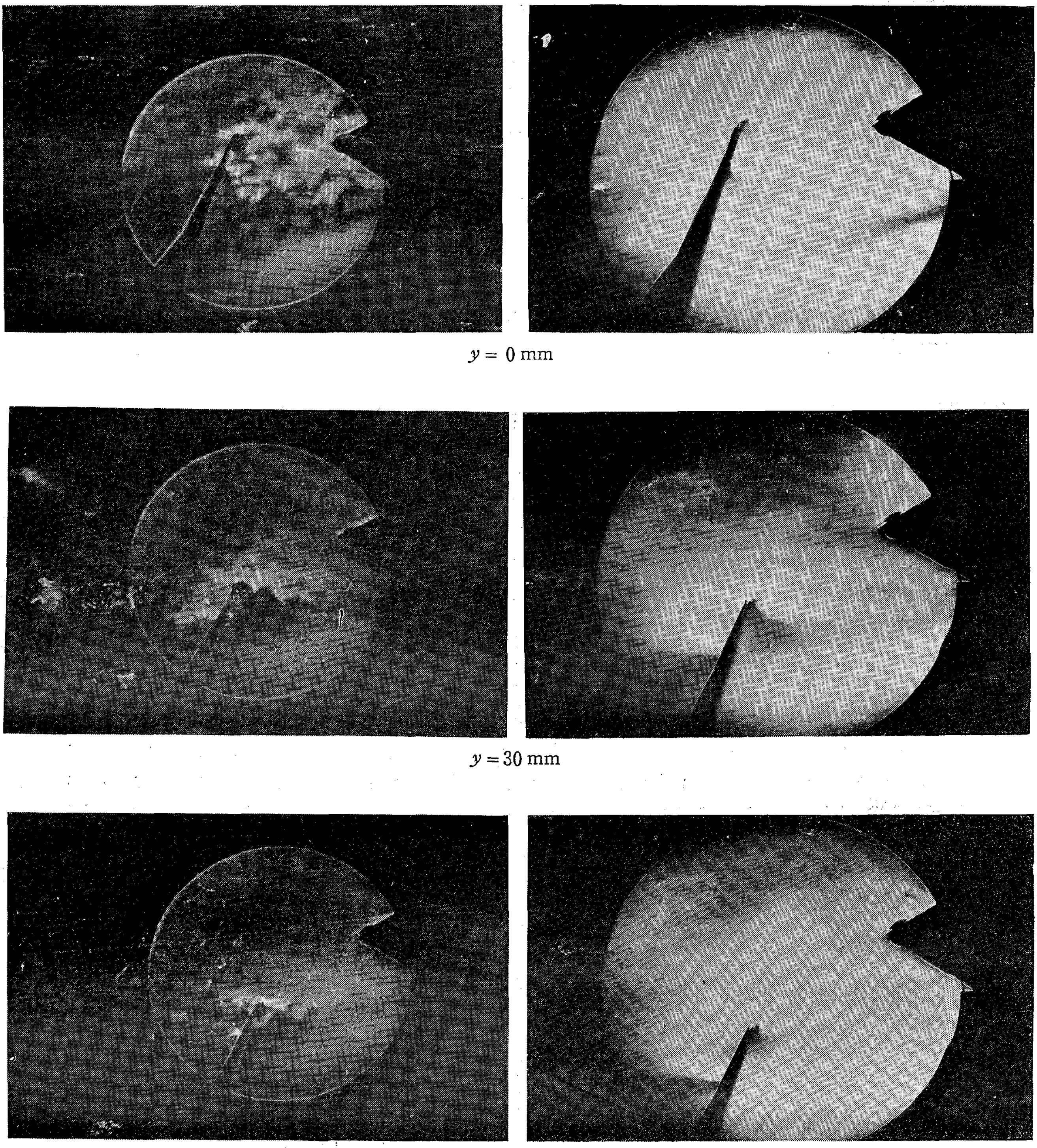


Plate I. Flow behind a triangular cylinder facing backward (in the vertical plane at the trailing edge).

← Flow direction

Exposure 1/500 sec. Exposure 1 sec.



$y = 40$ mm

Plate II. Flow behind a triangular cylinder facing backward (in the vertical plane 100 mm downstream the front surface).

Near the trailing edge the flow exposes periodic patterns very clearly. This vortex layer is nothing but the shear layer mentioned above. It decays out very soon. The periodic fluctuations of velocity must be readily recognized by the usual technique of hot-wire anemometry. However, we could hardly observe the regular oscillations by this method all over the flow field.

We have not yet carried out Schlieren photography for the flow in the closed chamber since it requires some modifications of the apparatus. For the present we have surveyed the flow field using the hot-wire equipment in this case and we have found that the vortex layers prevail in the fairly wide regions outside the turbulent core in contrast to the case of free jet. The central positions of the region where the regular oscillation dominates are marked with arrows in Fig. 8. The frequency of vortex shedding can be determined within two or three cycles per second since it fluctuates a little. This frequency is almost proportional to the velocity of the main stream and Strouhal number is 0.22 and 0.14 for the cylinder facing forward and backward respectively.

DISCUSSION OF RESULTS AND FURTHER INVESTIGATIONS

The test results in the closed chamber are in good agreement with the previous measurenents by several authors and regarded to correspond to the two-dimensional flow, while the results in the free jet show that the general features of the wake in this case differ substantially from those of the normal plane flow as described above in detail. It seems likely that in free jet the air current along the back surface of the cylinder raises the base pressure and in consequence the drag is reduced and the wake becomes broader. The test cylinder is so large compared with the dimension of the jet that such deviations might have been exaggerated. Nevertheless our results are very interesting because they suggest how the drag and the width of the wake of a cylinder would be related to its base pressure. The base pressure parameter k is calculated from the observed value of C_{ps} in each test condition and the drag

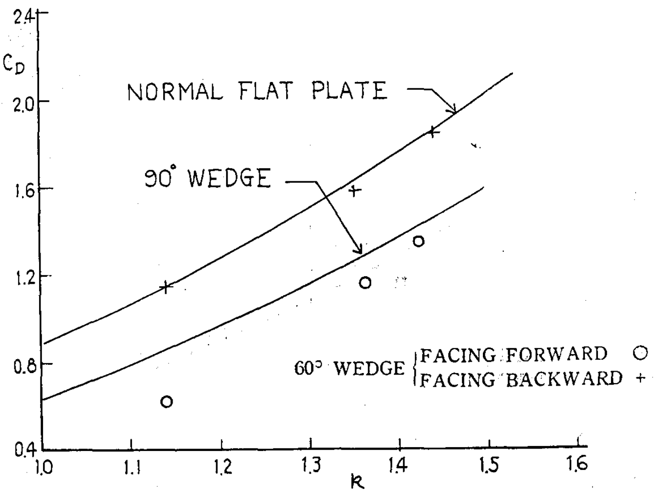


Fig. 13 Drag of cylinders.

coefficient is determined according to Roshko's theory.[4] These values are compared with the test data in the Table and in Fig. 13. The values for flat plate are in good agreement. If this relation between C_D and k (or C_{ps}) would hold for wider range of k, we might control the drag or the width of the wake by changing the base pressure intentionally, say, with injection or suction of air at the back surface. We expect to verify this inference by further experiments.

TABLE

Cylinder	facing forward			facing backward		
Case	I	II	III	I	II	III
C_{ps}	−0.29	−1.01	−0.84	−0.30	−1.08	−0.81
k	1.14	1.42	1.36	1.14	1.44	1.35
C_{D_f}	0.33	0.33	0.33	0.85	0.76	0.77
C_D obs.	0.62	1.34	1.17	1.15	1.84	1.58
C_D cal.	—	—	—	1.14	1.83	1.62
S	—	0.216	0.217	—	0.136	0.138

Although the air is almost at rest close behind a cylinder as assumed in the free-streamline theory, Schlieren photographs show evidently that there exist backward flows in this region. Such a flow pattern seems to promise the validity of Imai's theory on the drag of bluff bodies mentioned above. More accurate investigations of flow field, that is, measurements of the magnitude and direction of mean local velocity in this highly complicated region would be a valuable check on the theory and we are preparing for the devices for these measurements.

Schlieren photographs and the measurements of local velocities and their fluctuations show that the flow behind and near the cylinder ($x/d<10$) is far from the fully developed turbulent wake and liable to be affected by the conditions of the outer flow. For example, the regular periodicity can hardly be observed in the free jet, while it distinctly prevails near the cylinder in the closed duct. In general the formation of regularly oscillatory flow behind an obstacle and the development of turbulent wake from it are the essential points of the bluff body problem and many interesting questions concerning them still remain to be answered.[3] Further investigations should be promoted in these lines.

The wind tunnel has been constructed on funds for research equipments by the Ministry of Education. We wish to express our sincere gratitude to Professors I. Tani and F. Tamaki for the conveniences for experiments offered by them. Our cordial thanks are due to Misses Yûko Nagasawa, Kyôko Satô and Mitsuko Watanabe, who assisted us persistently during this work.

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