Formation of Vortex Streets

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Flow visualization techniques were used to investigate the wake behind flat plates normal to the stream in the Reynolds number range $10 < R < 100$. Observations of the wake revealed the mechanism of vortex shedding in each flow regime and the process of formation of a vortex street.

It was observed that threre is a vorticity transfer in a vortex street, and a fully developed vortex in the vortex street embraces vorticity of opposite sign in the form of spirally coiled vortex-layer.

1. Introduction

Numerous investigations have been made on the problem of two-dimensional flow past a cylindrical body using a circular cylinder[1-7] or a flat plate.[8-14] The various flow regimes which occur when the Reynolds number is gradually increased have been classified and some explanations for the mode changes have been suggested.[4,14,16] However, the study of the wake structure is insufficient, and there remain some questions in the existing classification of the wake.

The present study has been undertaken to furnish detailed informations on the features of the wake behind a flat plate normal to the stream at low Reynolds numbers $R = Ub/\nu$ where U is the velocity of the plate, b the breadth of the plate and ν the kinematic viscosity. Flow visualization techniques were used, one being a dye method and the other the aluminium powder method. The experimental equipments are the same as those used in a previous work.[14]

The main purposes of this work are, (1) to observe the variation with Reynolds number of the wake, (2) to examine in detail the mechanism of vortex shedding, (3) and especially, to make clear the structure of vortex streets.

2. Straight-line wake with standing vortex-pair.

In a previous paper,[14] we discussed in detail that in the Reynolds number range $10 < R < 100$, the wake behind flat plates could be classified in the following three types: (1) standing vortex-pair and straight line wake, (2) oscillating vortex-pair and waving line wake, (3) degenerated vortex-pair and vortex street. In the previous paper, we presented the photographs which show the three different types of wake with Reynolds number. The streak-lines of the three types of wake can also be shown schematically as in Fig. 1.

For a Reynolds number below about 25, two thin sheer layers leaving the plate at each edge curl round on themselves with opposite circulations. The twin vortices are perfectly stable and symmetrical and the wake next to the vortices is a straight line as shown in Fig. 1. In this stage, the effect of increasing Reynolds number on the wake is only to change the size of the vortices, which become more and more elongated in the flow direction.

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It was observed that the dyed fluid leaving the plate at a edge went only into the wake on the same side and there was no transport of fluid across the center-line of the wake. The stagnation point at the back of the plate is always fixed and does not move along the surface of the plate.

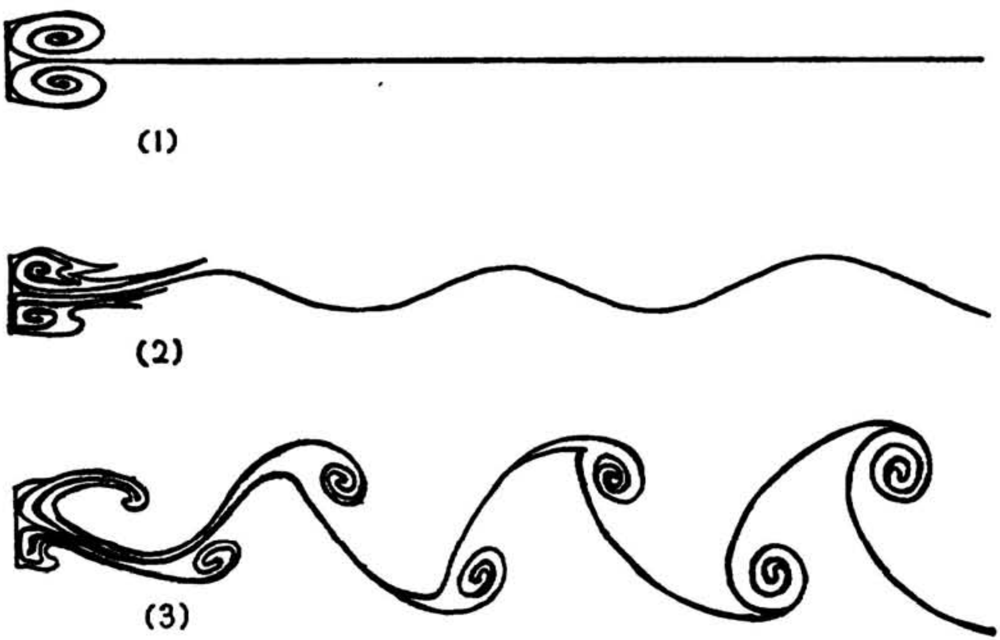

Fig. 1. Schematic diagram of streak lines of the wake behind flat plates.
(1) Straight-line wake with standing vortex-pair. $R<25$
(2) Waving-line wake with oscillating vortex-pair. $25<R<40$
(3) Vortex streets with degenerated vortex-pair. $40<R$

3. Waving-line wake with oscillating vortex-pair.

As the Reynolds number is raised beyond 25 the onset of instability of the wake takes place, that is, the faint periodic oscillations of the vortex-pair begin alternately and also the line wake next to the vortex-pair begings to oscillate very faintly corresponding to the oscillations of the vortex-pair (Fig. 1.).

In this stage, we can only notice a weak instability some distance downstream in the form of wavy line with very small amplitude. As the Reynolds number is increased, the amplitude of the waving-line wake increases and the oscillation of the vortex-pair becomes more and more conspicuous and then the rear part of the each oscillating vortex stretches alternately downstream outside the waving-line wake as a stretched 'whisker', or what we may call a 'tongue' of the layer.

The detached tongues from the vortex-pair are soon absorbed in the waving-line wake in such a manner that the tongues detached from the upper vortex of the vortex-pair join with the downstream side of the upper wave crests of the waving-line wake and those detached from the lower vortex join with the downstream side of the lower wave crests. These line vortex-sheets detached from the upper vortex rotate clockwise as they move downstream, and those detached from the lower vortex rotate counterclockwise. This means the effects of the line vortex-sheets on the wake are revealed only with distance downstream. It seems to be that this is the main reason for the facts that at a Reynolds number slightly beyond 25, a weak instability in the form of sinuous oscillations with small amplitude can only be seen at far enough distance behind the plate, and that at a comparatively higher Reynolds number, the amplitude of the waving-line wake is increased with distance downstream and the wave crests having sharp corners can be seen considerably far distance downstream.

Since the dyed streak-lines represent the shear layers, the tongues indicate the shedding of vorticity from the vortex-pair along the waving-line wake in the form of line vortex-sheet. The only thing is that these line vortex-sheets detached from the vortices are not strong enough to roll up themselves, so in this stage there is no shedding of vorticity in the form of vortex-street.

It was observed that almost all of the dyed fluid leaving the plate at a edge went into the wake on the same side, but a very small amount of fluid was transferred to the vortex on the other side along the surface of the plate. It seems that some cancellation of the vorticity will occur along the rear surface of the plate as well as along the waving-line wake. The stagnation point at the back of the plate moves along the surface of the plate corresponding to the oscillations of the vortex pair. There is no transport of matter across the waving-line wake.

4. Vortex streets with degenerated vortex-pair.

At a Reynolds number beyond about 40, an abrupt transition takes place in the behavior of the flow behind the plate. The oscillation of the vortex-pair becomes more and more pronounce and at the same time the periodic breaking-away of the circulating fluid within the vortices occurs, that is, vortices having an opposite rotation are shed alternately from the two sides of the plate, rolling up as an individual vortex, and moving downstream. The vortices arrange themselves in a double row and the typical Karman vortex street is formed. In this stage, most of the fluid within the vortex-pair is rapidly replaced by the fluid drawn around each edge of the plate. The shape of vortex-pair is far apart from its previous shape, taking what we may call a 'degenerated vortex-pair' form, and also the waving-line wake is absorbed into the vortices of the vortex street, and then becomes a part of them.

In order to study the growth of circulating flow immediately behind the plate and the details of the subsequent formation of vortices, consecutive photographs of the wake were taken. Photographs in Plate 1 and 2 were taken when the plate was accelerated from rest and maintained at a constant speed. The wake photographed in Plates 1, 2 are for $R=71.6$, $R=93.8$. Plate 1 is visualized by streak lines using the dye method and Plate 2 is visualized by streamlines using the aluminium powder method. By means of the reference quantities U and b, dimensionless time t^* can be expressed by $t^*=tU/b$.

Some of the photographs in Plate 1 are very similar to those of Harlow and Fromm[15] who obtained the flow-pattern development of the wake behind a rectangular cylinder through the use of a high-speed electronic computer.

When the plate is started from rest, as shown in Plate 1 and 2, in the initial stages two thin vortex-layers leave the edge of the plate and curl round on themselves, forming two symmetrical vortices and as their strength increases gradually with time they become longer and longer in the direction of flow. When the vortices have reached a certain strength, they begin to oscillate relative to one another and the oscillations become more and more conspicuous with time and then the vortex shedding from the vortex-pair into the field outside the waving-line wake takes place in the form of rolled-up vortices. Hereafter, the shedding of vorticity is repeated alternately from each of the pair of vortices, and the fully developed wake coresponding to the Reynolds number is established.

In a fully developed vortex street, the vortices in the initial stages consist of the vortex core which is formed by fluid coming from one of the degenerated vortex-pair and, of fluid, surrounding the core, coming from the same side of the wake, but latter on, as they move downstream a considerable amount of fluid from opposite side of the wake finds its way between the two neighbouring vortices bearing oppositely signed vorticity. The fluid is separated in two branches: one branch embraces the one vortex and the other embraces the vortex core itself of another one by the action of the growing vortices. That is to say, the wave crest having a sharp corner which reveals the movement of the fluid from opposite side of the wake coil round the already rolled-up vortex and finally becomes a part of the rolled-up vortex.

Fig. 2. Schematic diagram of fully developed vortices showing the transport of matter in a vortex street.

Fig. 2 shows the fully developed vortices in a vortex street. In a fully developed vortex of the vortex street, there is a region of vortex core which originated from the degenerated vortex-pair and surrounding the vortex core, there are two spiral vortex layers from each side of the wake which coil round each other alternately. It must be noted that, in the actual flow, a fully developed vortex in the vortex street

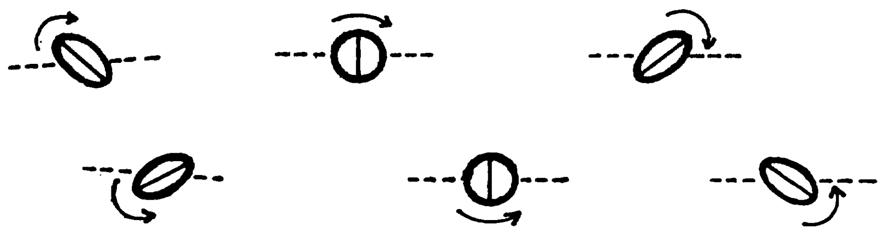

Fig. 3. Schematic diagram showing the variation with distance dounstream of the shapes of vortices in a vortex street.

is surrounded spirally by fluid of oppositely signed vorticity coming from the other side of the wake. As is described above, there is a mass transfer in a vortex street across the wake.

A close observation of the shedding of vortices behind the plate reveals that in the case of a few pairs of vortices in the initial stages, the vorticity is not concentrated in a well-defined circular-shaped area, but is concentrated in an elliptic-shaped area. The elliptical vortex on the upper side rotate clockwise as they move downstream, and those on the lower side rotate counterclockwise. During this rotation the vortices change their shapes gradually into the circular shapes and then, going far distance downstream, take again the elliptical shapes as shown in Fig. 3. This is accordance with the observation of Zdravkovich.[17]

5. Conclusions

An experimental investigation was carried out for the purpose of studing the behaviour of the wake behind flat plates normal to the flow at Reynolds numbers from 10 to 100. The more significant results of this study are the following : (1) The wake behind flat plates under consideration develops with Reynolds number following three different stages. (2) The process in which the wake develops downstream is quite different in the three stages. (3) There is no mass transport and no vorticity transfer across the straight-line wake and across the waving-line wake. (4) In a vortex street, there is a mass transport and also a vorticity transfer across the vortex street. (5) The fully developed vortices in a vortex street are surrounded spirally by the vortex-layer of oppositely signed vorticity. (6) The vortices in a vortex street change their shapes with distance downstream.

Throughout the series of observations, it was found that in the range of Reynolds number under consideration, no turbulent motion was generated and the flow was always laminar.

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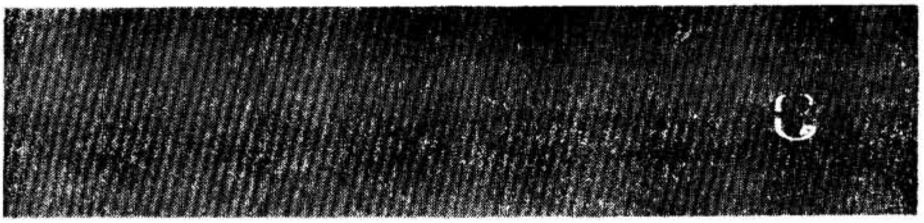
Plate 1. Growth of vortices behind flat plates visualized by streak lines. R=71.6
Plate 2. Growth of vortices behind flat plates visualized by streamlines. R=93.8



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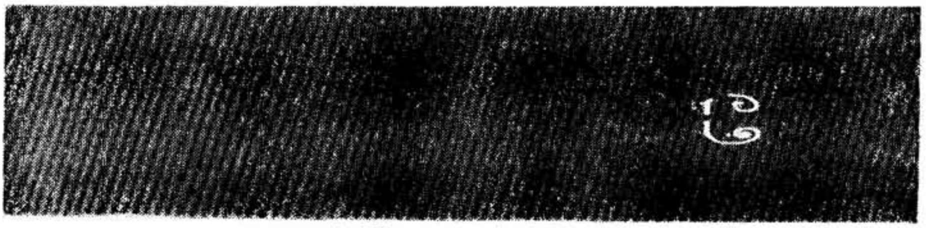

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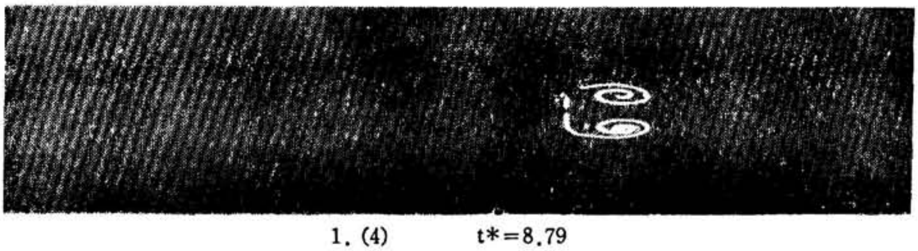

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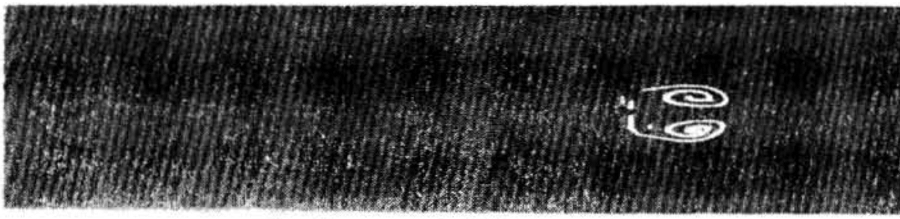

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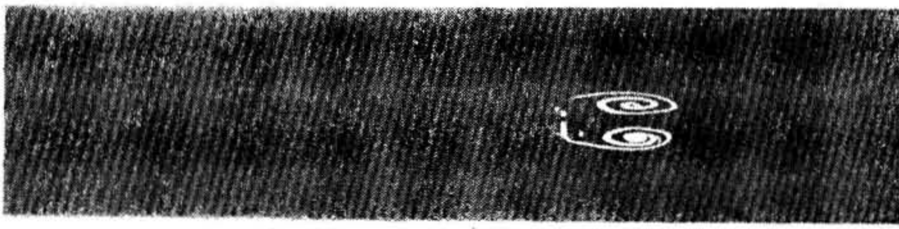

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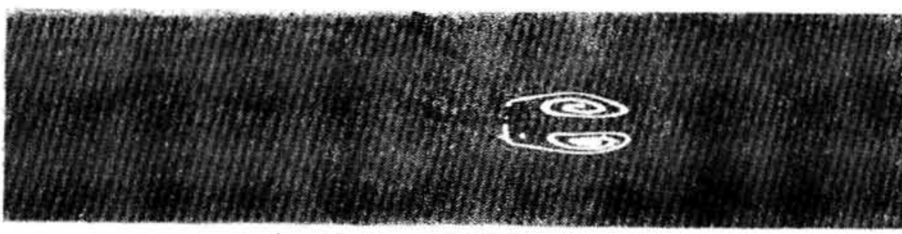

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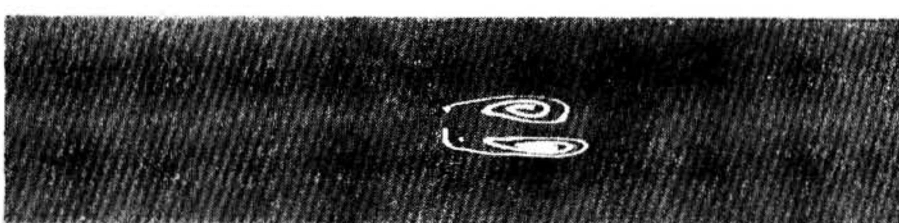

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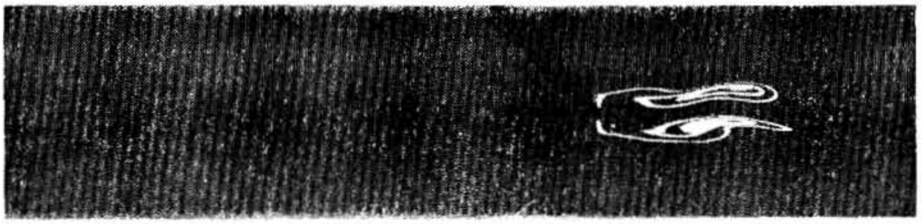

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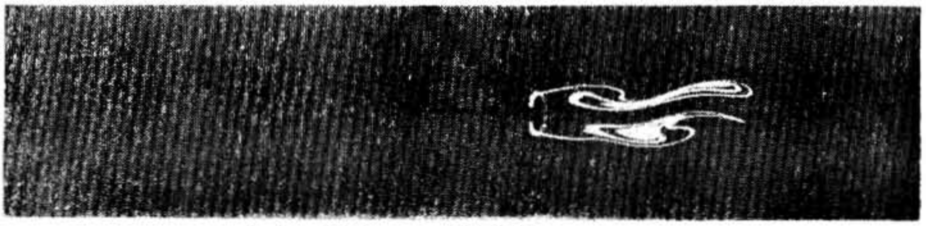

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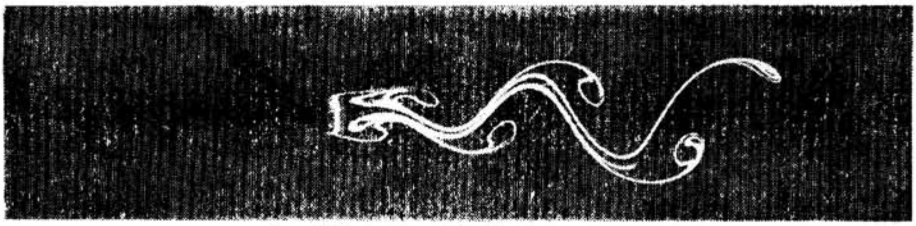

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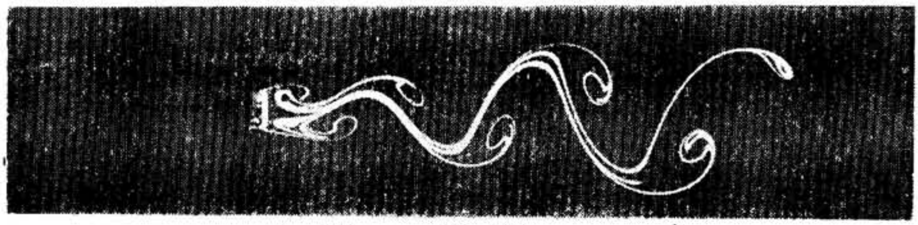

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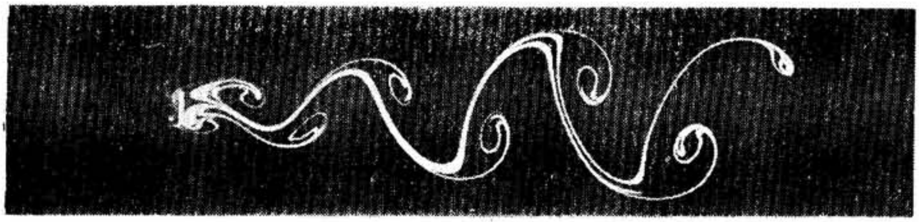

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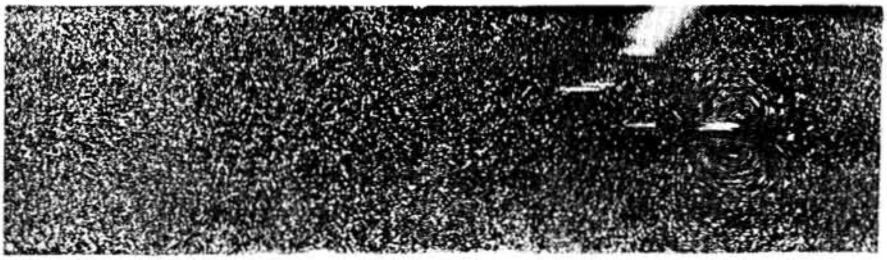

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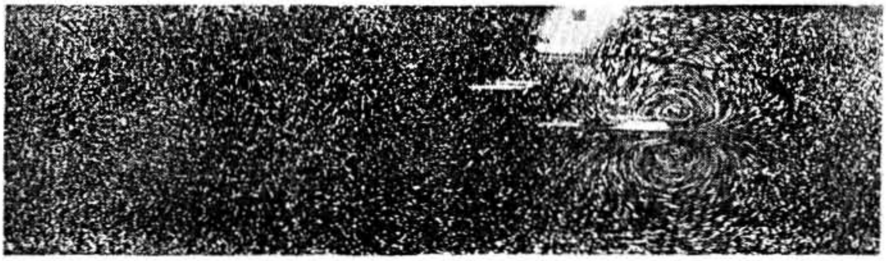

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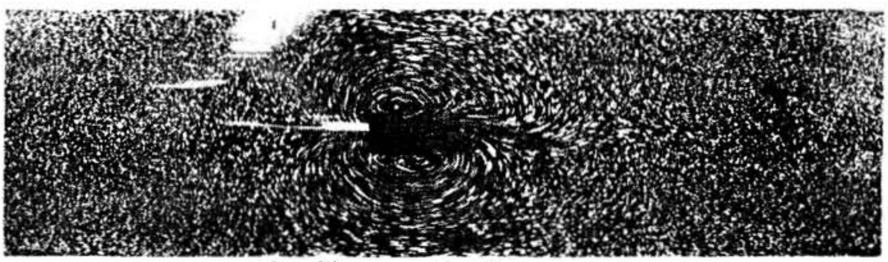

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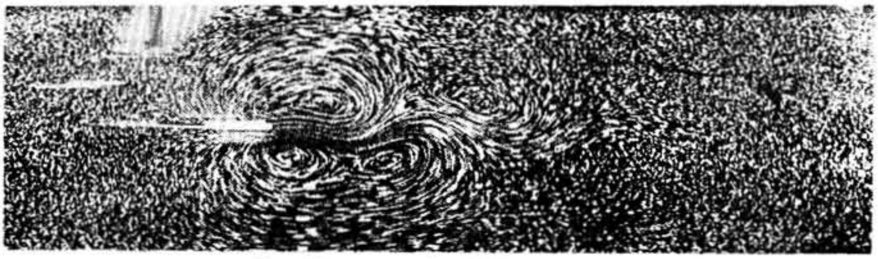

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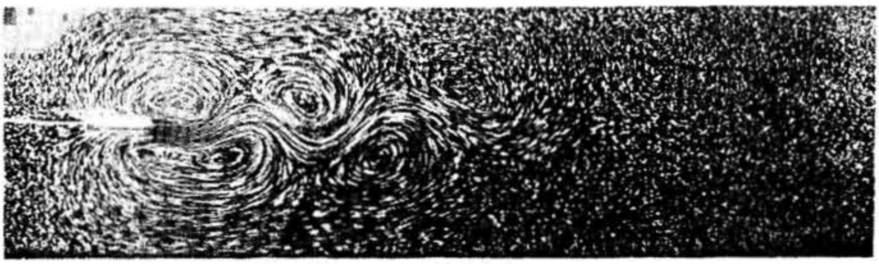

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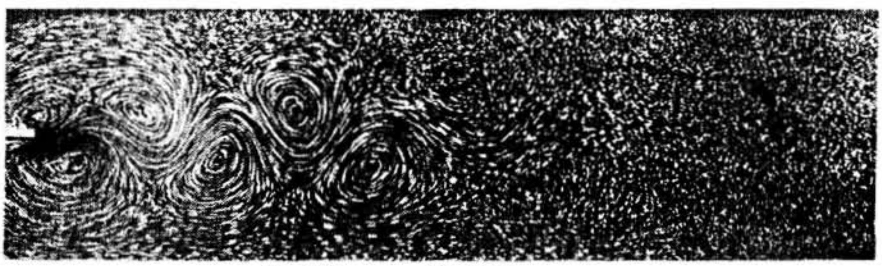

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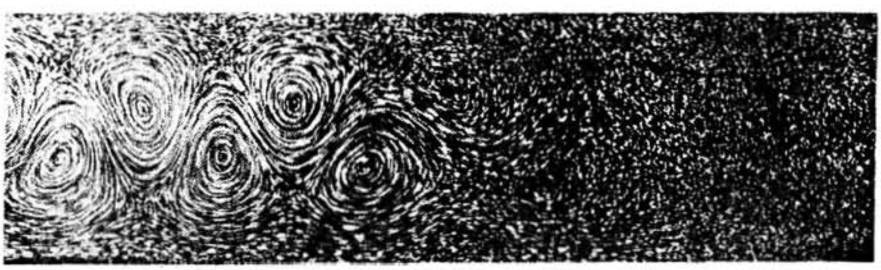

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