J. Fluid Mech. (1969), vol. 37, part 3, pp. 491–496
Printed in Great Britain

Smoke observations of the formation of a Kármán vortex street

By M. M. ZDRAVKOVICH†
Engineering Department, Cambridge University

(Received 19 August 1968)

A smoke visualization technique was used to study the laminar wake behind a single cylinder. Observations of the wake revealed the nature of the process of formation of a Kármán vortex street: instability of the shear layers was coupled with the rolling up process induced by the concentration of vorticity.

An unexpected mass transfer was observed through the Kármán vortex street which cause mixing of the fluid surrounding the wake.

1. Introduction

Bénard (1908) produced photographs, and von Kármán (1911) proposed a theoretical model to explain and predict the spacing ratio of a vortex street. The first attempt to obtain some systematic experimental evidence concerning the formation of the vortices and the general characteristics of the generation of the vortex street was made by Nayler & Frazer (1917). They conducted experiments with the aid of a cine camera on the flow of water past a cylinder.

The details and the general character of the flow at a Reynolds number of about 120 were observed by introducing oil drops or a dilute solution of condensed milk into the fluid and illuminating them suitably. Velocity and direction measurements made at chosen epochs of the formation period were carefully collected into a simple diagram. The types of flow deduced in this way for different epochs are reproduced in figure 1. The series of ten figures (*a*) to (*j*) gives the life history of a single vortex formed behind the cylindrical model. The changes in the streamlines 1, 2, 3 and 4, 5, 6 are shown as an illustration. The manner of formation and development of the vortices shown in figure 1 reveals at least two significant features which will be confirmed later by a different visualization technique. These are: (i) at the very beginning (figure 1(*b*)–(*d*)) the lower vortex is formed by fluid from the upper side of the cylinder; (ii) later, a considerable amount of fluid from one side of the wake (figure 1(*f*)–(*h*)) finds its way between the vortices and reaches the opposite side of the wake.

Since 1917 numerous investigations have been made on the Kármán vortex street. Streaklines were photographed in the wake behind a circular cylinder in a stream of oil by Homann (1936) (pictures appeared in many text-books). The purpose of the present paper is to investigate the formation of the Kármán vortex street at different velocities. Smoke streaklines have been observed from

† On leave from the Department of Mechanical Engineering, University of Belgrade.

Reynolds numbers where the Kármán vortex street does not exist to those where it is fully developed. The second part of the investigation was devoted to the observation of mass transfer across the vortex street.

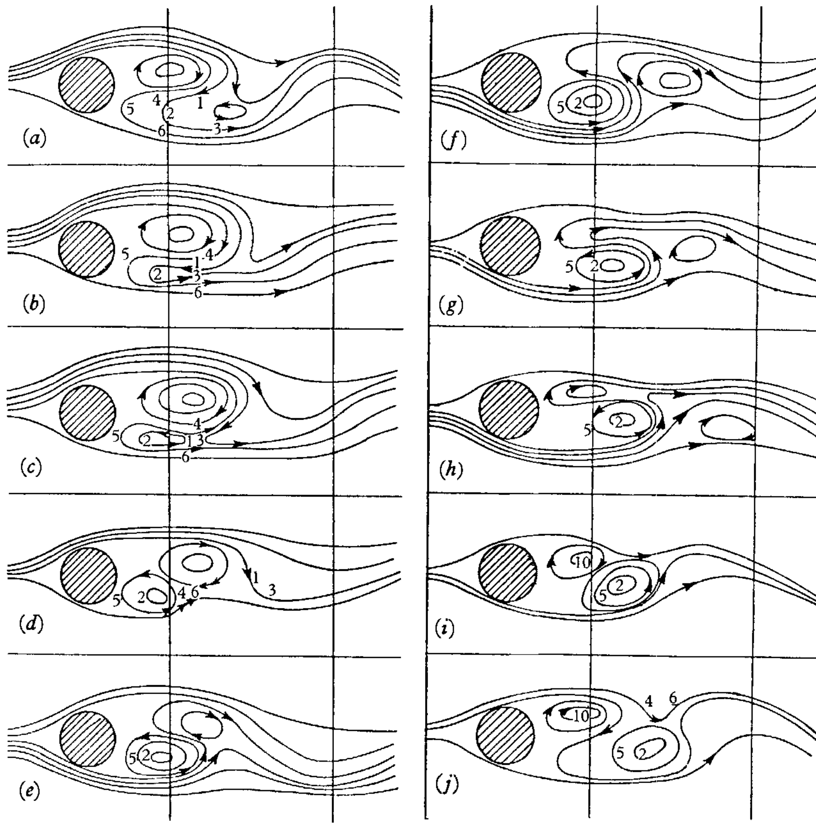

FIGURE 1. The development of vortices (Nayler & Frazer 1917).

2. Development of the vortex street with increasing Reynolds number

The investigation was conducted in the Aerodynamics Laboratory of the Cambridge University Engineering Department in a vertical low-speed wind tunnel with upward flow. The working section of the tunnel is 12×6 in. in cross-section and 20 in. long. A hollow cylinder of diameter 0·043 in., spanning the shortest dimension of the working section, was used to generate the vortex street.

The visible material in what is here called the smoke filament was actually liquid kerosene in the form of a fog of fine droplets; the smoke generator in which it was produced was of the Preston & Sweeting (1943) type. The wake configurations were recorded on ASA 400 film with a Nikon camera.

The Reynolds number was increased slowly from 30 to 90 and the photographs presented in figure 2(*a*)–(*h*), plate 1, show the appearance of the wake over this range. These flow régimes were obtained by simply adjusting a knob to increase the speed in the wind tunnel. The transient process occupied a finite time of the order of 6 sec, and all the photographs presented here were taken during that period. Some of the pictures obtained in this way are closely similar to those of Homann, indicating that in the present work the flow was effectively steady and not influenced by acceleration.

Figure 2 (*a*) was taken at the Reynolds number 30 when disturbances slightly distorted the smoke-filled shear layers in the wake. The black spot just behind the cylinder indicates the presence of attached vortices, sometimes known as the Foeppl vortices. The next figure 2 (*b*) shows only an increase in the disturbances, which are still irregular. Figure 2 (*c*) demonstrates the beginning of some regular patterns in the wake. Immediately behind the twin vortices the wake is remarkably straight and symmetrical. Some distances downstream a weak instability in the form of sinuous oscillations with small amplitude is noticed. This causes the appearance of what might be described as 'tongues' of smoke. The sinuous oscillations produce a displacement of the shear layers and bring some smoke into the zones of greater or less velocity. The accelerated smoke creates the observed smoke-tongues while the retarded parts form black intrusions.

Figure 2 (*d*) displays all the features so far described in more pronounced form. The sinuous oscillations begin nearer to the cylinder and also their amplitude is increased. It is evident that the staggered arrangement of the vortex rows is closely related to the sinuous oscillations. Figure 2 (*e*) reveals the further development of these instabilities of the shear layers. Close behind the cylinder we can still see the black spot, identified as the attached pair of vortices, as well as the nearly straight centre-line of the wake behind them. The smoke tongues grow; they acquire more of the smoke, and take what we may call a 'smoke-bud' form, while at the same time the middle of the wake becomes thinner. This trend continues in figure 2 (*f*). The middle line departs significantly from its previous shape, particularly at the wave crests, where sharp corners are established. On the other hand the shape of the smoke-buds is gradually rounded and there is a resemblance to pictures of the rolling up of a vortex sheet (Pierce 1961). This resemblance is not fortuitous because concentration of the smoke means at the same time concentration of the vorticity which has survived from the shear layers. Observing more closely the details of the smoke pattern over the visible part of the wake, going downstream along the wavy smoke-line, we see that the corners or joins move away from the rolled-up smoke-clouds and finally reach positions about midway between neighbouring smoke-clouds on opposite sides of the wake.

Figure 2 (*g*) supports the above description. The amount of vorticity in the wake is increased by the increase of speed. This is the first photograph in which it can be seen that the sinuous oscillations distort the shapes of the clouds. It is also the first in which the rotation within the smoke clouds is visible, showing that they are the embryos of future vortices. Going downstream they absorb more and more smoke and therefore more and more vorticity; the connecting smoke-lines are no longer seen to move to the middle position as in figure 2 (*f*). The rotation induced by this vorticity concentration, known as the rolling up process, leads finally to the emergence of all the visible smoke into the vortex cores, as can be seen for the last three vortex pairs in the photograph. The vortex street is formed in the wake downstream while the twin vortices next to the cylinder remain attached. This fact was also observed by Taneda (1956) and described in detail by Batchelor (1967).

The last photograph, figure 2(*h*), represents the vortex street in the classical sense. The twin vortices are no longer seen behind the cylinder. The strong sinuous oscillations which now appear immediately behind the cylinder have detached them, and they have been carried away downstream.

On the basis of these observations it is possible to propose a simple mechanism for the formation of a Kármán vortex street. The instability of the shear layers from a certain Reynolds number upwards leads to the initial staggered vorticity concentration. The rolling-up process reinforces both the concentration of vorticity and the circulation about the future vortex cores. It follows from this that in order to suppress the vortex street formation it is necessary and sufficient either to prevent the appearance of the instability or to decrease the rate of generation of vorticity. The first was successfully performed by a splitter plate by Roshko (1954) and the second by means of a perforated shroud enclosing a circular cylinder by Price (1956). Both were achieved with a high velocity jet by Poisson-Quinton & Jousserandot (1957) and with base bleed by Wood (1964). All these methods are consistent with the proposed model.

3. Mass transfer across the vortex street

The smoke filament was traversed across the wake in order to investigate the interaction of the fully formed vortex street and the neighbouring stream. The instantaneous streaklines behind a cylinder were photographed and are shown in figure 3(*a*)–(*g*), plate 2. In successive photographs the smoke filament has been moved down relative to the cylinder, beginning above and ending below it. The Reynolds number was approximately 100.

In figure 3(*a*) the smoke filament was adjusted to be four diameters above the cylinder. The resulting streakline did not interact with the wake because it was too far outside. The next figure, figure 3(*b*), reveals an interaction of the smoke-streakline with the vortex street. Smoke entered between neighbouring vortices and crossed to the other side of the wake, where the streakline was split and branched in two directions; one branch embraced the upper vortex and the other the lower one. There was no great change of the pattern further downstream. An unexpected result was that most of the smoke introduced above the cylinder found its way across and appeared in the lower part of the wake. This mixing was induced by the vortices and as they weakened further downstream the effect also decreased.

Figure 3(*c*) shows the smoke-streakline when it just touches the cylinder and is still above it. The upper vortex row is now seen to have black spots in the centres of the vortices. This means that the centres of the vortex cores are not filled with fluid from above the cylinder. Confirmation of this may be found if we look at the lower row of vortices: white spots indicate that the smoke introduced above the cylinder fills their centres. As in this case the smoke filament represents at the same time the shear layer, this shows the presence in the vortex core of some opposite vorticity, leading to some degree of cancellation of the vorticity there, as was observed in the experiments of Fage & Johansen (1927). This is also in accordance with the observations of Nayler & Frazer (1917) which were quoted above. Further downstream the smoke gradually surrounded the vortices in the lower row and this also contributed to the cancellation of vorticity as predicted by Hooker (1936).

Figure 3 (*d*) shows the usual pattern of the Kármán vortex street obtained when the smoke filament meets the cylinder symmetrically. Both rows of vortices are clearly seen as well as the connecting smoke lines, and the changes in them going downstream. With the aid of the preceding figures it is possible to imagine what happens in the black regions between the vortices. The widening of the smoke filament passing the cylinder and forming the vortex street displaces the neighbouring fluid and produces the observed mass transfer.

For the sake of completeness the next three, (figures 3 (*e*)–(*g*)) are added, showing the smoke-filament moving down below the cylinder. Figure 3 (*e*) shows a similar pattern to that in (*c*), although the filament in (*e*) was slightly beneath the cylinder and did not touch it. Figure 3 (*f*) is complementary to (*b*) and shows how smoke from under the cylinder finds its way across and appears in the upper part of the wake. If we imagine the superposition of (*b*) and (*f*) then the resulting picture represents the mechanism of the mass transfer through the vortex street. The last figure, figure 3 (*g*), was obtained when the smoke filament was three diameters below the centre plane.

4. Downstream development

In figure 4 (*a*)–(*c*), plate 3, the development of the vortex street far downstream in the wake is shown. Figure 4 (*a*) was obtained 300 diameters downstream of the cylinder. The vortex cores, seen as smoke clouds, gradually change shape and become elliptical. In figure 4 (*c*) the Kármán vortex street is shown 600 diameters downstream. The elliptical vortex cores are more elongated but they are still distinct. In figure 4 (*b*) the region surrounding the vortex cores is shown 300 diameters downstream. It was obtained when the smoke filament was moved transversely to a distance of about two cylinder diameters from the axis. It is evident that the previously observed mass transfer is now suppressed.

Finally it is interesting to note that this mass transfer occuring in the Kármán vortex street was observed a long time ago. Professor W. R. Hawthorne has kindly pointed out to me the discussion following a lecture given by G. I. Taylor (1951, pp. 193–4) on the mechanism of eddy diffusion. Minchin (1951, p. 485) had studied the mixing of parallel streams of hot and cold air when they flow into a common duct. In the wake of a cylinder at the entrance, hot and cold eddies were interleaved, and two or three diameters downstream an even time-average temperature distribution could be obtained. That was followed further downstream by what appeared to be a weak reseparation of the hot and cold air and a reversed temperature variation.

5. Conclusions

The smoke visualization technique has revealed some features of the process of formation of a Kármán vortex street. The instability of the shear layers when the Reynolds number was not too low led to the initial staggered vorticity concentration. The rolling-up process reinforced both the concentration of vorticity and the circulation about these future vortex cores.

The visualization of the downstream development of the newly formed vortex street showed at first a strong interaction between the new vortices and the surrounding fluid; this interaction weakened as the strength of the vortices declined. The result was a mass transfer across the wake and its surroundings. Far downstream the vortex-cores were elongated in the elliptical shapes.

Thanks are due to Mr E. P. Sutton of Cambridge University for invaluable help during the preparation of this report.

REFERENCES

BATCHELOR, G. K. 1967 *An Introduction to Fluid Dynamics*. Cambridge University Press.

BÉNARD, H. 1908 Formation de centres de giration a l'arriere d'un obstacle en mouvement. *Comp. Rend.* **147**, 839–842.

FAGE, A. & JOHANSEN, F. C. 1927 On the flow of air behind an inclined flat plate of infinite span. *Proc. Roy. Soc.* A **116**, 170–197.

HOMANN, F. 1936 Einfluss grosser Zähigkeit bei Strömmung um Zylindern. *Forsch. Geb. Ing.-Wes.* **7**, 1–10.

HOOKER, S. G. 1936 On the action of viscosity in increasing the spacing ratio of a vortex street. *Proc. Roy. Soc.* A **154**, 67–89.

KÁRMÁN, TH. VON 1911 Ueber den Mechanismus des Widerstandes den ein bewegter Körper in einer Flüssigkeit erfahrt. *Gött. Nachr.* 509–517.

MINCHIN, L. T. 1951 Discussion on G. I. Taylor lecture (see Taylor). *Proc. Gen. Disc. on Heat Transfer*. Inst. Mech. Eng.

NAYLER, J. L. & FRAZER, R. A. 1917 Vortex motion. (i) Preliminary report upon an experimental method of investigating, by the aid of kinematograph photography, the history of eddying flow past a model immersed in water. *Advisory Committee for Aeronautics, R. & M.* (new series), no. 332.

PIERCE, D. 1961 Photographic evidence of the formation and growth of vorticity behind plates accelerated from rest in still air. *J. Fluid Mech.* **11**, 460–464.

POISSON-QUINTON, P. L. & JOUSSERANDOT, P. 1957 Influence du soufflage au voisinage du bord de fuite sur les caracteristiques d'une aile aux grandes vitesses. *La Rech. Aero.* **56**, 21–00.

PRESTON, J. H. & SWEETING, N. E. 1943 An improved smoke generator for use in the visualization of airflow, particularly boundary layer flow at high Reynolds numbers. *Aero. Res. Counc. R. & M.* no. 2023.

PRICE, P. 1956 Suppression of the fluid-induced vibration of circular cylinders. *J. Engng. Mech. Div. ASCE,* paper 1030, **82**, EM 3.

ROSHKO, A. 1954 On the development of turbulent wakes from vortex streets. *NACA* TR 1191.

TANEDA, S. 1956 Experimental investigation of the wakes behind cylinders and plates at low Reynolds numbers. *J. Phys. Soc. Japan,* **11**, 302–307.

TAYLOR, G. I. 1951 The mechanism of eddy diffusivity. *Proc. Gen. Disc. on Heat Transfer*. Inst. Mech. Eng.

WOOD, C. J. 1964 Effect of base bleed on a periodic wake. *J. Roy. Aero. Soc.* **68**, 477–482.

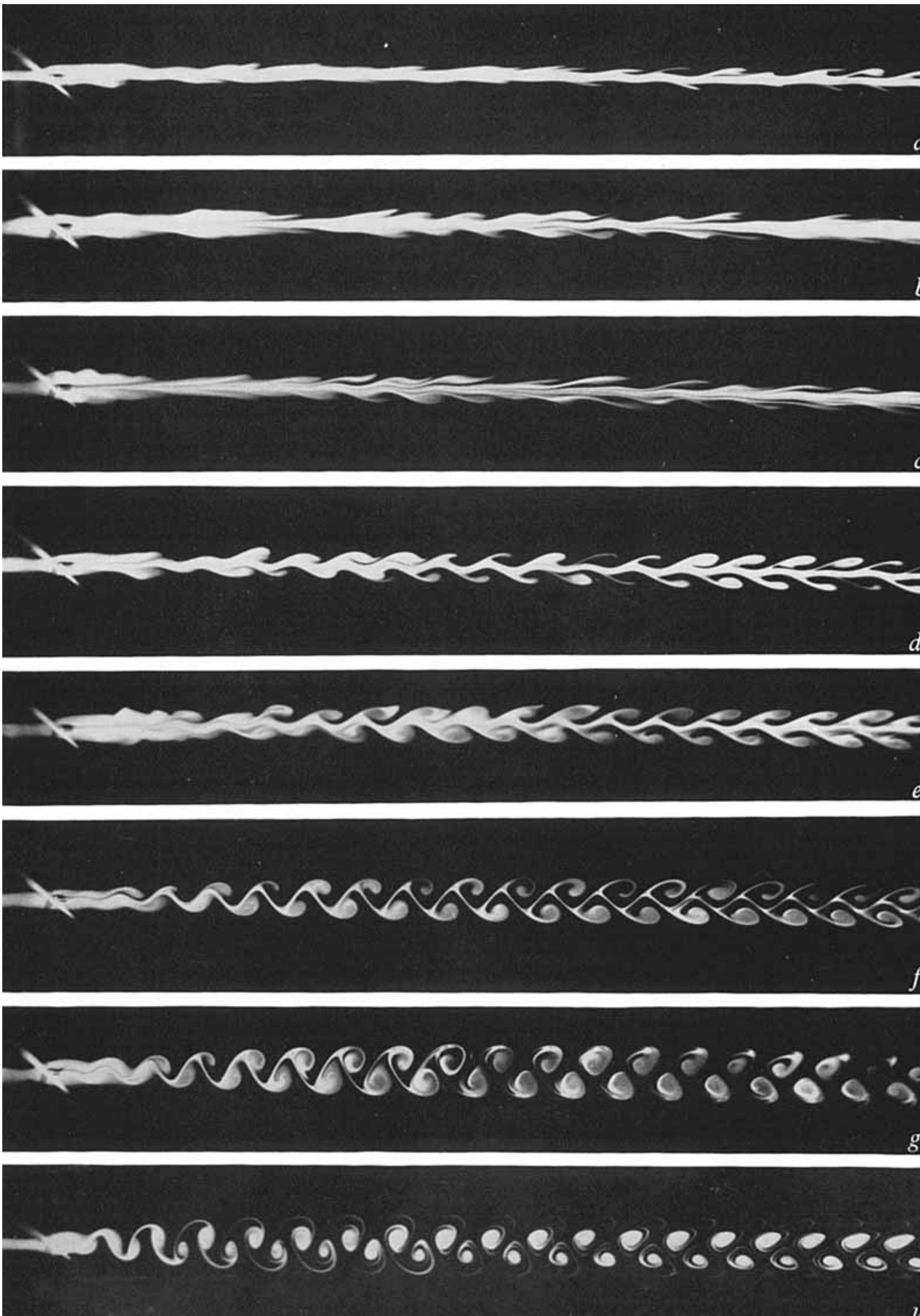

FIGURE 2. Formation of the Kármán vortex street.

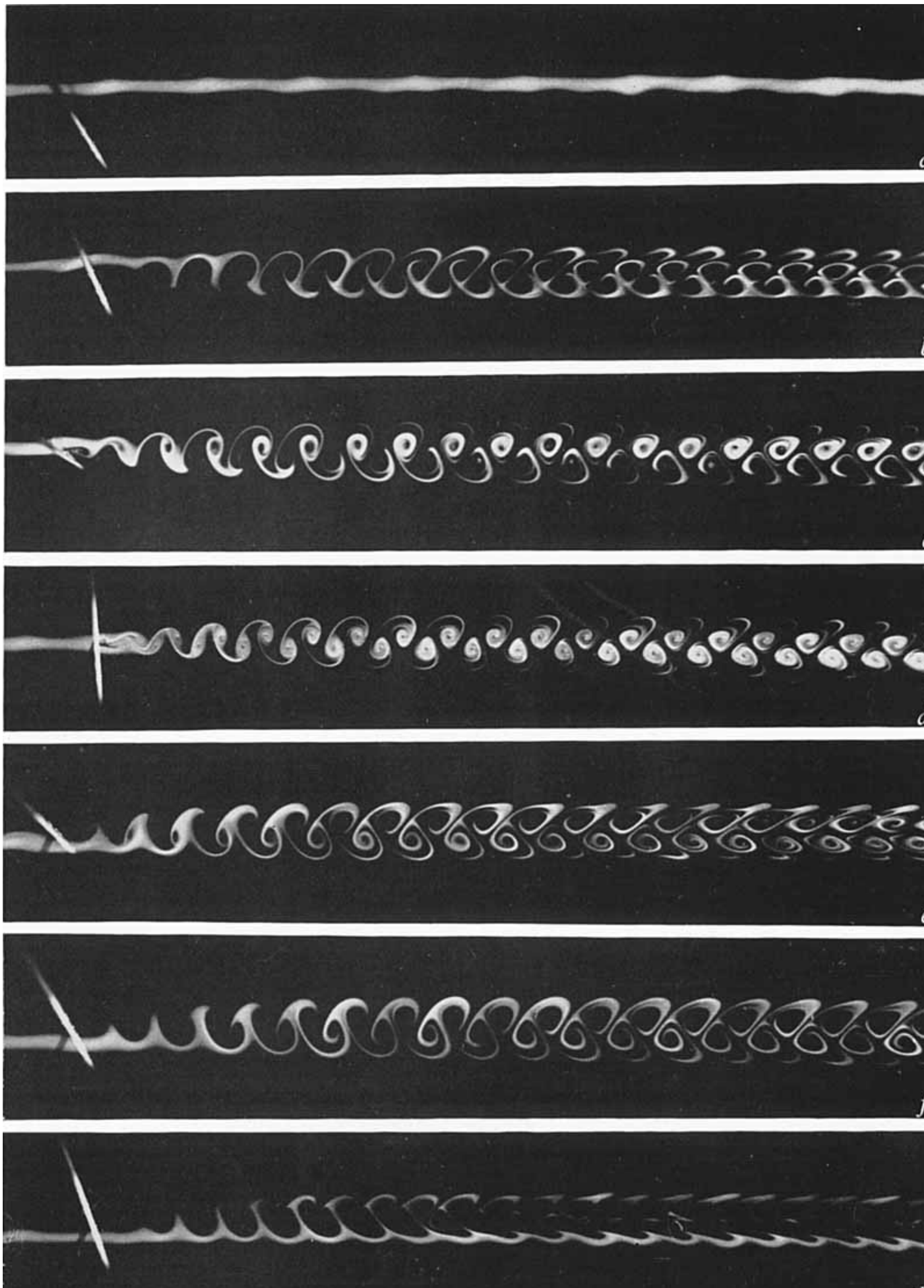

FIGURE 3. Mass transfer across the Kármán vortex street.

ZDRAVKOVICH

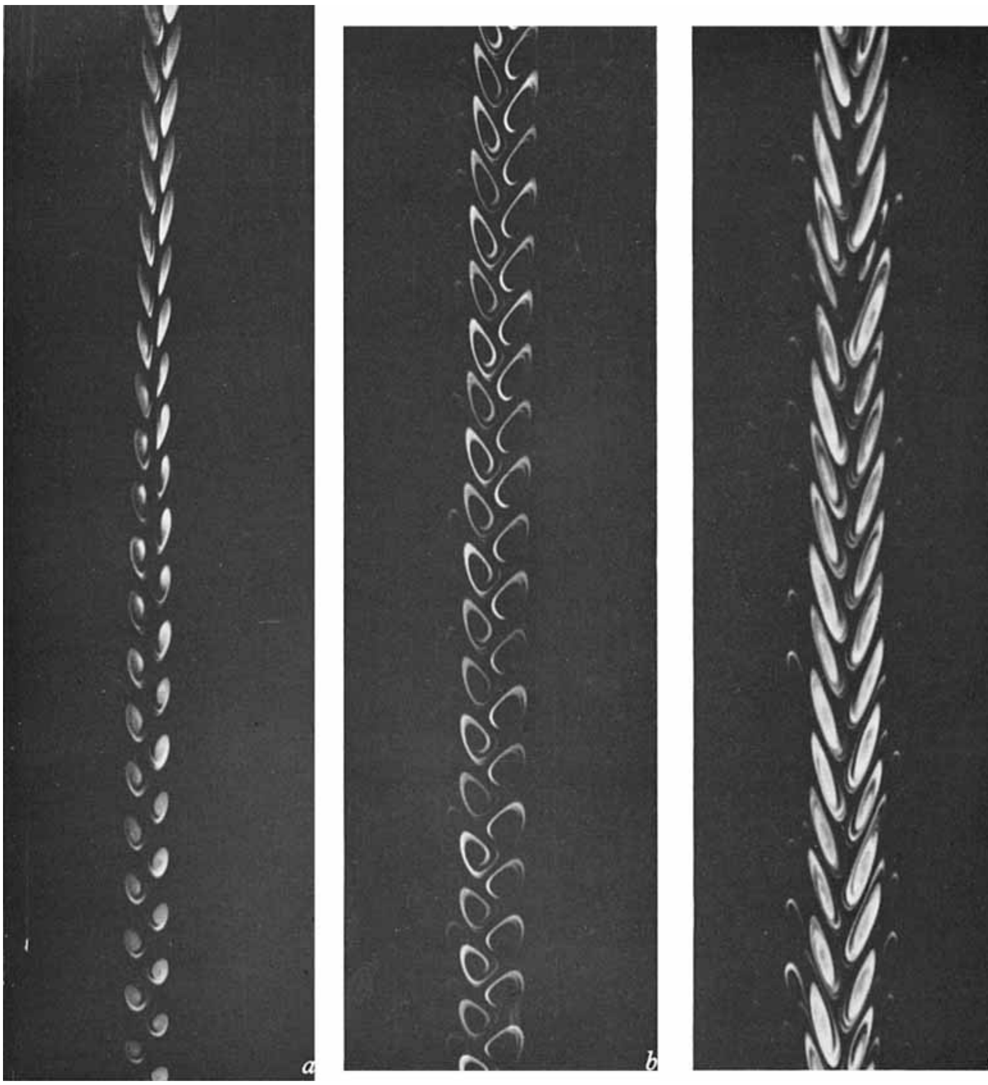

FIGURE 4. Downstream development of the Kármán vortex street.