Photographic evidence of the formation and growth of vorticity behind plates accelerated from rest in still air†

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The shedding of vorticity from the edges of a plate, which is accelerated normal to itself from rest in still air, is investigated experimentally by means of a new flow-visualization technique using spark-lighted shadowgraphs and heated air, benzene or other vapours to introduce sufficient changes in density along the surface of discontinuity.

The photographs show small-scale undulations and the formation of a number of centres of vorticity along the well known big-scale vortex sheets which roll up along their edges.

1. Introduction

Prandtl, in his well known paper of 1904, not only introduced boundary-layer theory but devoted the larger part of the discussion to the mechanism and consequences of boundary-layer separation. Using the example of the initial motion of a fluid as set up by a plate moved from rest at right angles to itself, he discussed the development of the shear layer which originates from the plate's edge, and which may be regarded as a Helmholtz surface of discontinuity, or vortex sheet, in the case of small viscosity. He pointed out that the vortex sheet tends to roll up along its free edge and, further, that such a sheet may be unstable in that small disturbances of its shape are likely to be amplified and lead to the formation of a series of centres of vorticity along the sheet. In this way, a small-scale undulation and vortex formation is superimposed upon a big-scale vortex sheet which itself may incorporate a rolled up edge with the formation of a vortex core there.

Prandtl described the flow mechanism and the resulting features from observations made in a water channel, and similar observations in water have since been made (Wedemeyer 1956). However, most of the later studies have been concerned with problems of the big-scale flow: the time-dependent development of this flow (Anton 1939; Wedemeyer 1956); the corresponding three-dimensional flow for the case of the flat triangular wing (Mangler & Smith 1959); and the features of the main core (Hall 1961). The small-scale undulations have been most extensively studied in the related case of the shear layer round a free jet (Wille 1960), and it has been noted that the formation of centres of vorticity and 'spots' in laminar layers may constitute an important phase in the mechanism of transition to turbulence.

The present study returns to Prandtl's original problem of a plate moved normal to itself from rest in still air. It is demonstrated how spark equipment, designed for the examination of unsteady supersonic flows, may be used to study time-dependent air flows at low speeds by the introduction of small quantities of a foreign vapour.

2. Equipment

The equipment used can be described in two parts: (*a*) that which concerns the acceleration of the plate from rest, and (*b*) that which enables the flow to be photographed.

2.1. *Plate acceleration*

The mechanism for accelerating the plate is shown in figure 1. The equipment consists essentially of three moving parts, with provision for the sudden application of pressure to two of the moving parts by the bursting of a diaphragm.

The plate under test is screwed to the web of a free piston which initially, by gravity, is in contact with a limited-stroke piston, as shown in figure 1. Pressure is increased in the compressed air chamber until the polyester film diaphragm

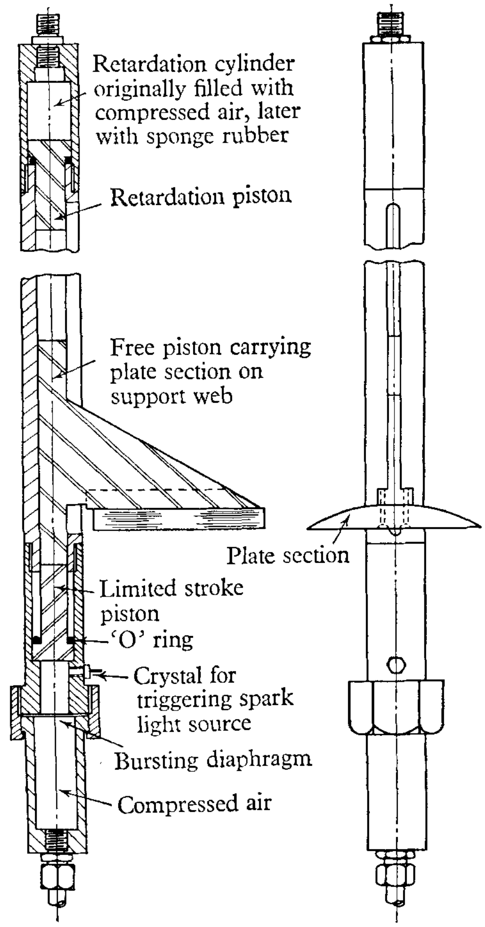

FIGURE 1. Equipment for accelerating the plate sections.

bursts and the pressure is suddenly applied to the limited-stroke piston. This piston and the free piston carrying the plate are accelerated together until the limited-stroke piston reaches the extent of its travel. The free piston carries the plate and continues to move with roughly constant velocity (it is decelerated slightly by gravity) until after moving for a few inches it is brought to rest by the retardation piston.

Originally the retardation cylinder was filled with air from the compressed air chamber so ensuring identical pressures for acceleration and retardation. Experiments, however, showed the retardation to be too severe and the air in the retardation chamber was replaced by sponge rubber. An O-ring on the limited-travel piston acts as a buffer for its retardation and as a seal to prevent the high-pressure air from escaping. This method of suddenly applying load to the piston obviates the necessity for any breaking link or quick-release mechanism, and it has been found that 0·00025 in. thick diaphragms consistently give plate velocities of 12–13 ft./sec and 0·0005 in. thick diaphragms give 23–24 ft./sec, the variation in velocity depending mainly on slight differences in weight of the various plate sections.

The total weight of the moving parts has been kept small and is approximately 2 oz. A piezo-electric crystal is mounted in the wall of the chamber between the diaphragm and the face of the limited-stroke piston to provide a means of triggering the photographic equipment. This acceleration system is clearly capable of further development, such as to enable the plate to be accelerated to the required velocity in a shorter distance and also to provide for an increased length of travel.

2.2. *Flow visualization technique*

The present experiments were undertaken in air at room temperature and pressure, i.e. roughly 65 °F and 29 in. of mercury, and a shadowgraph system was used together with spark photography to show the details of the vortex sheet.

A spark apparatus which produces an intense light flash with a duration of 1 μsec was available. This was used as the light source of a shadowgraph system in which the parallel light beam was directed over the plate section. The spark flash was triggered at an appropriate time by the signal from the piezo-electric crystal, the signal being first passed through a pre-set delay unit. Ilford H.P.S. photographic plates were used and positioned close to the moving plate to reduce any effects due to stray light. An ordinary shadowgraph technique cannot be used directly because the density changes in the flow are too slight. Thus density changes must be artificially introduced into the flow. Several methods of doing this successfully have been developed, and in all cases the change in density was made to coincide with the surface of discontinuity in velocity so that its effect on the flow may be assumed to be small.

The first method employs a column of air heated by passing over a hot soldering iron. With the plate stationary the column was arranged to pass just outboard of the edge of the plate and was then barely discernible in the shadowgraph pictures. When the plate is moving, the heated air is drawn behind the lee side of the plate to be on the inner side of the surface of discontinuity, which is then shown up with great clarity.

Other methods employ, on the surface of the plate, fluids which evaporate. A plate of balsa wood was used and a narrow band of benzene applied by paint brush to the upper and lower surfaces. The benzene soaks into the balsa wood and then starts to vaporize. When the plate accelerates, air flowing over the surface increases vaporization of the benzene and the vapour is drawn into the vortex sheet. Because of the difference in density between the vapour and the air, the paths of their boundaries are clearly seen in the shadowgraph pictures.

When the benzene is brushed on in a narrow band across the centre of the plate, normal to the light path, the resulting photographs have the effect of showing up the flow in a plane until the vortex and vapour sheet has moved far enough from the plate to be affected by end effects of the plate.

3. Results

The plates tested were all of 3 in. square planform and each had a cross-section which was constant in the direction of the light path. A variety of plates was used, these differing in their cross-sections as may be seen in the photographs, figure 6 (*a*)–(*e*). Also visible in each figure is a scale of pins at $\frac{1}{4}$ in. intervals, the initial position of the plate tip being opposite the bottom pin. This, together with the time intervals indicated, defines the motion of the plate. Care was taken to ensure that the undulations of the vortex sheet were not caused by vibrations of the model by testing plates of different stiffness; nor were they caused by any three-dimensional periodicity across the span of the model. The absence of such periodicity was verified by simultaneously taking pictures in two planes at right angles to one another.

The main sequence of pictures in figure 2 shows the growth of the edge vortex sheets behind a plate with a convex front surface and a flat rear surface as it accelerates to, and remains at, a speed of 24 ft./sec. Figure 3 shows the distance from rest of the plate as a function of the time taken. Figure 4 shows an enlarged section at $t = 5{\cdot}41$ msec.

The sequence of photographs in figure 2 reveal the growth and the structure of the vortex sheets very clearly, and the small-scale formation of a large number of centres of vorticity within the big-scale rolled-up vortex sheet, in the manner described by Prandtl, is distinctly visible. The regularity of the process is noteworthy. Figure 3 also shows the movement of the core of the big-scale rolled-up vortex sheet. It is found that the velocity of the core is about half that of the plate. This is consistent with what is known about the corresponding three-dimensional flow past a rectangular plate of small aspect ratio where the upper edges of the tip vortex sheets are inclined to the mainstream at about half the angle of incidence (Bollay 1937, 1939; Mangler 1939; Küchemann 1955). This was also found to be the case when the plate was accelerated to half the speed, i.e. 12 ft./sec, although the initial undulations in the shear layer appear less pronounced as shown in figure 5. Future investigations may relate the change in the initial undulations to effects depending on the Reynolds number, which, at present, are not known.

The remaining photographs, figure 6, show the pronounced effect of the plate cross-sectional shape on the regularity of the distortion of the shear layer.† The differences in the flow are of secondary nature: a round edge, figure 6 (*c*), produces a less orderly flow with, possibly, two separation lines. A very pronounced shoulder, figure 6 (*e*), leads to a secondary separation. Sharp edges which fix separation lines produce clean flows.

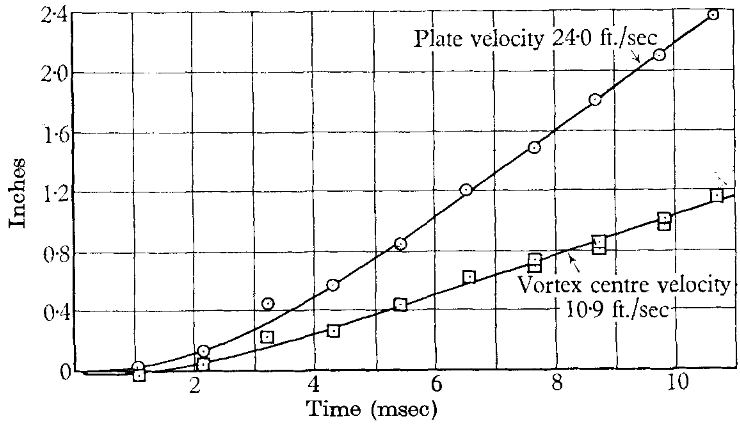

FIGURE 3. Movement of the plate and vortex centre from rest obtained from figure 2 (*a*)–(*j*).

4. Conclusions

A technique has been presented which should prove useful in the examination of the development of shear layers and other time-dependent flows at low speeds. Results obtained so far clearly show the distortion of a shear layer into regular vortex filaments and finally into turbulent motion. Further experiments are necessary to understand the dependence on the Reynolds number of the regular manner in which the shear layer breaks up.

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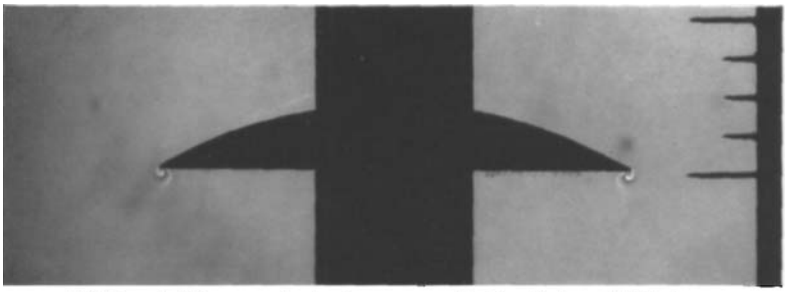
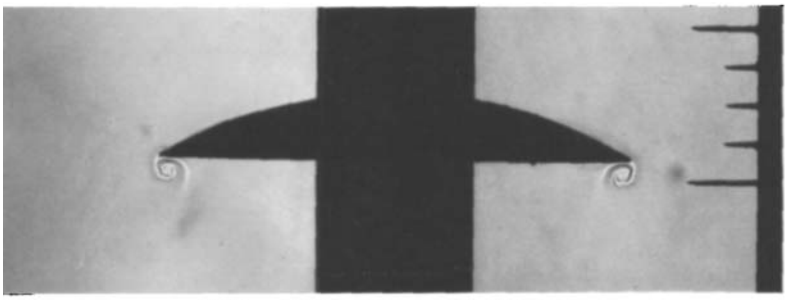
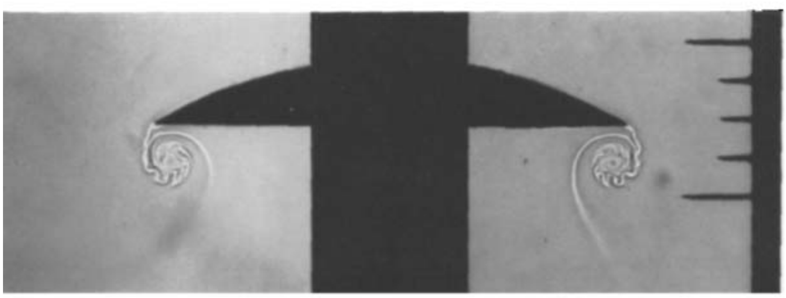
† In some of the pictures, particularly figure 6 (*b*), some particles of balsa dust are visible; these have been shed by the plate during the acceleration phase.



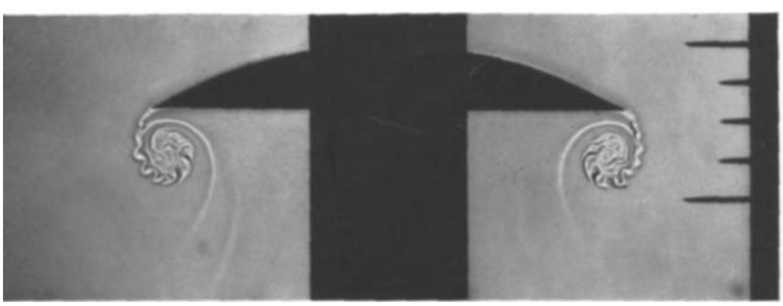
(*a*) t = 1·05 msec; instantaneous velocity (v_1) = 5·5 ft./sec.



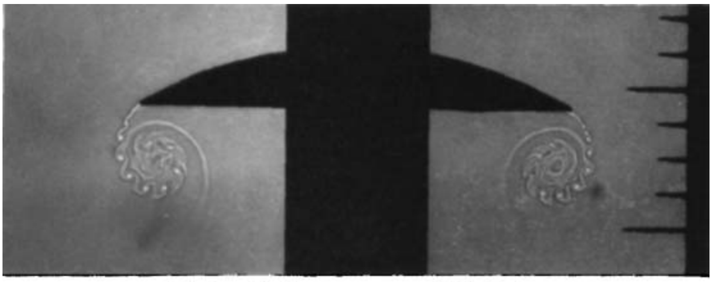
(*b*) t = 2·14 msec; v_1 = 11·1 ft./sec.



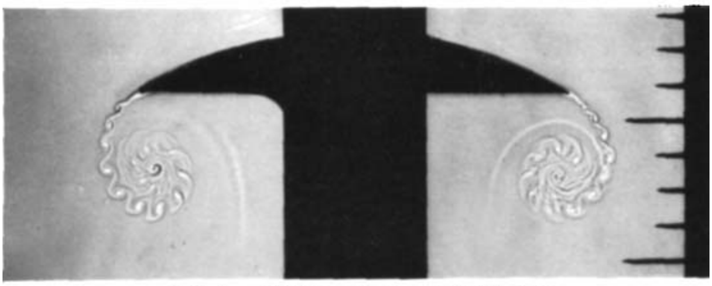
(*c*) t = 3·22 msec; v_1 = 16·9 ft./sec.



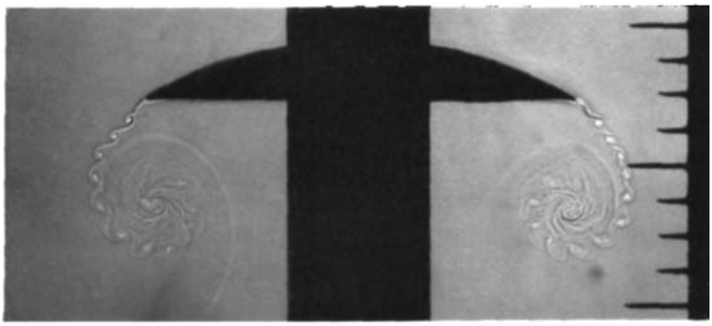
(*d*) t = 4·30 msec; v_1 = 21·0 ft./sec.



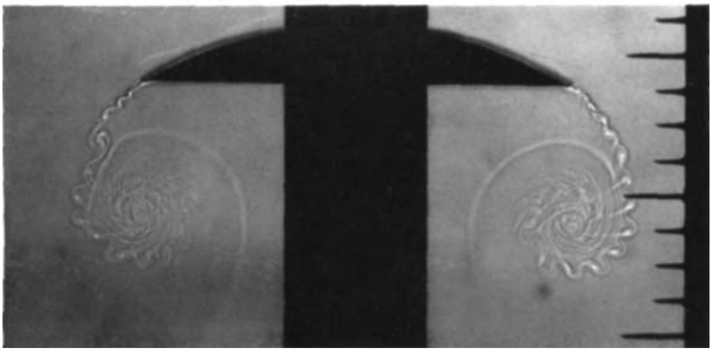
(*e*) $t = 5{\cdot}41$ msec; $v_1 = 23{\cdot}2$ ft./sec.



(*f*) $t = 6{\cdot}53$ msec; $v_1 = 24{\cdot}0$ ft./sec.



(*g*) $t = 7{\cdot}65$ msec; $v_1 = 24{\cdot}0$ ft./sec.



(*h*) $t = 8{\cdot}69$ msec; $v_1 = 24{\cdot}0$ ft./sec.

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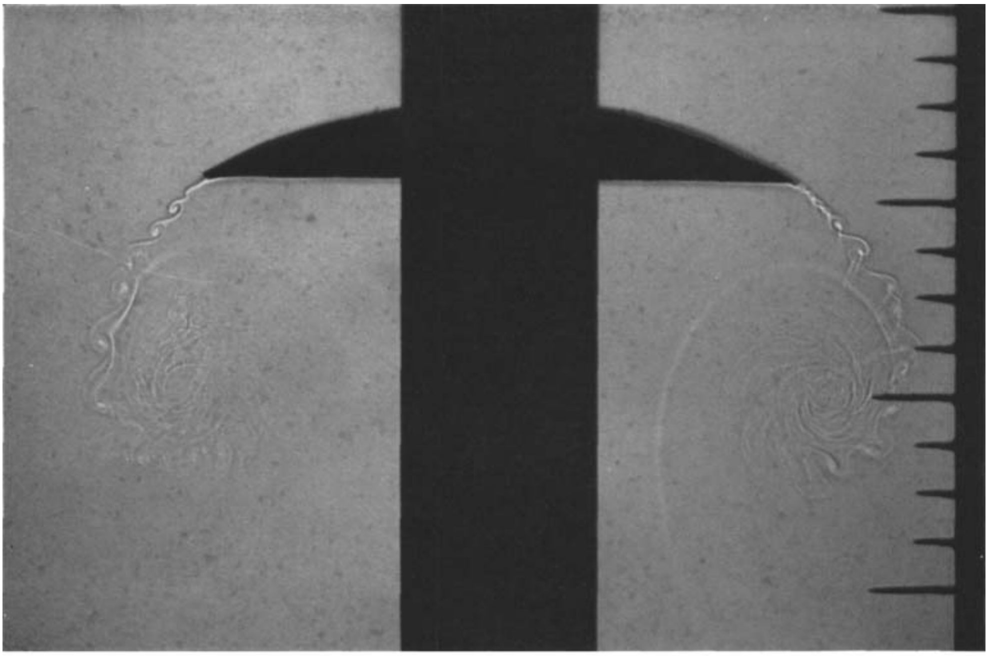
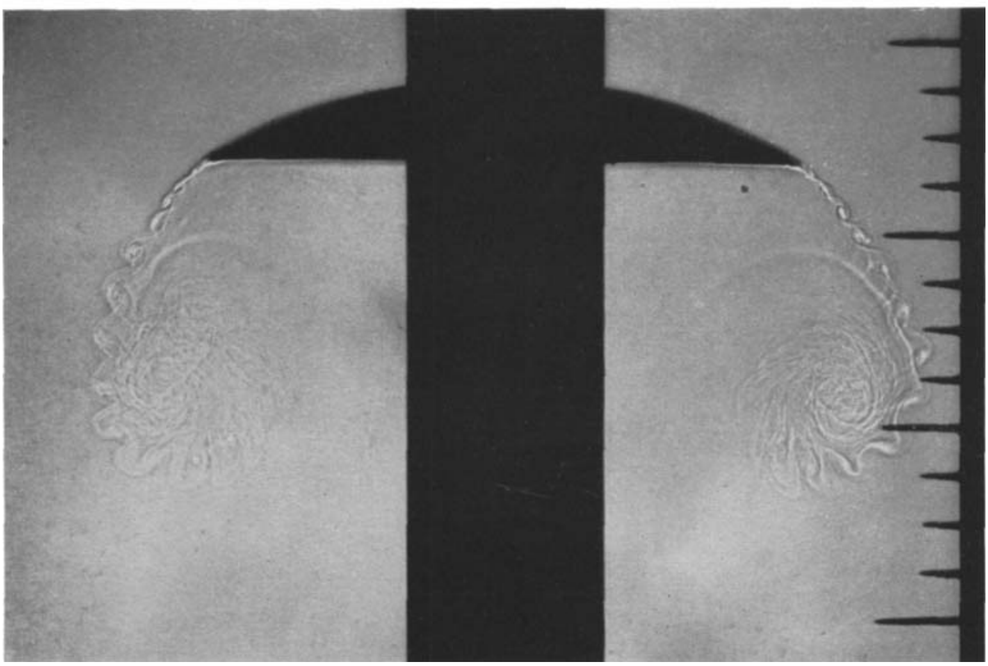


(i) t = 9·77 msec; v_1 = 24·0 ft./sec.



(j) t = 10·66 msec; v_1 = 24·0 ft./sec.

FIGURE 2. Sequence of shadowgraphs of convex plate section with final velocity 24 ft./sec.

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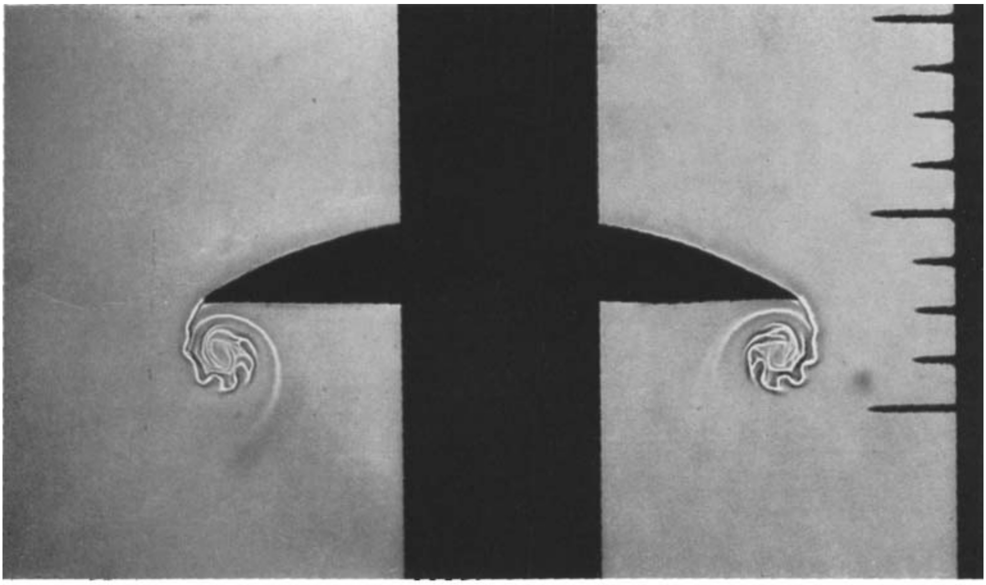
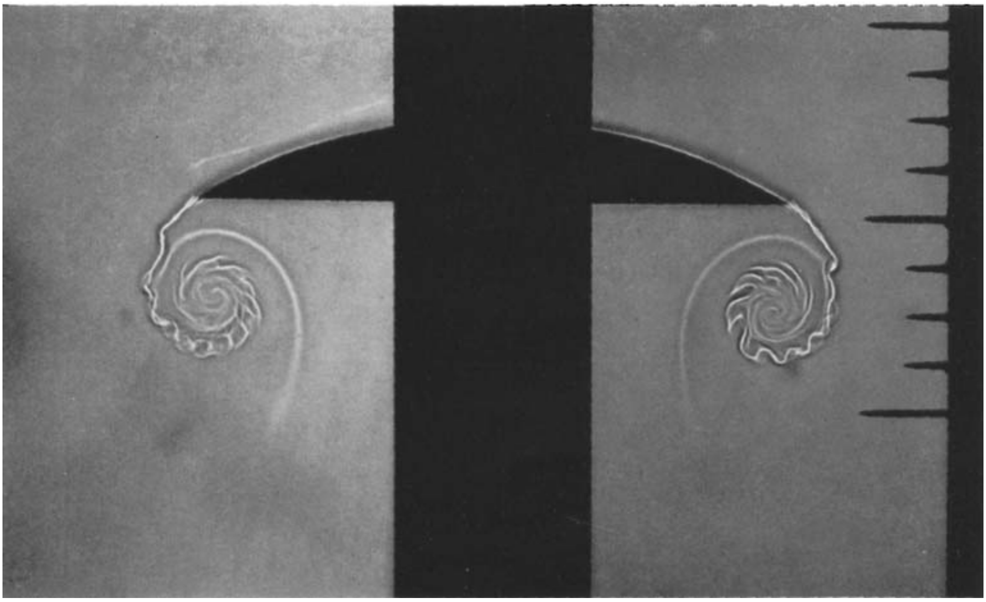
FIGURE 4. Enlargement of figure 2(*e*), $t = 5{\cdot}41$ msec, $v_1 = 23{\cdot}2$ ft./sec.

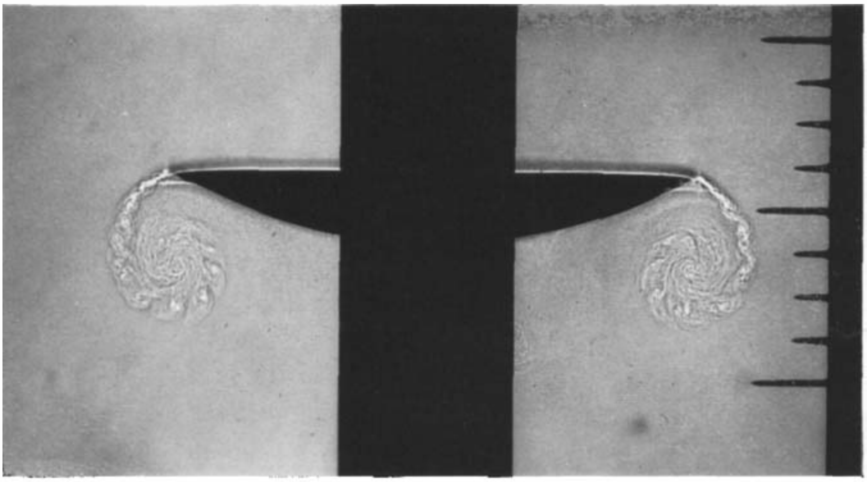


(*a*) $t = 6{\cdot}53$ msec, $v_1 = 12{\cdot}1$ ft./sec.

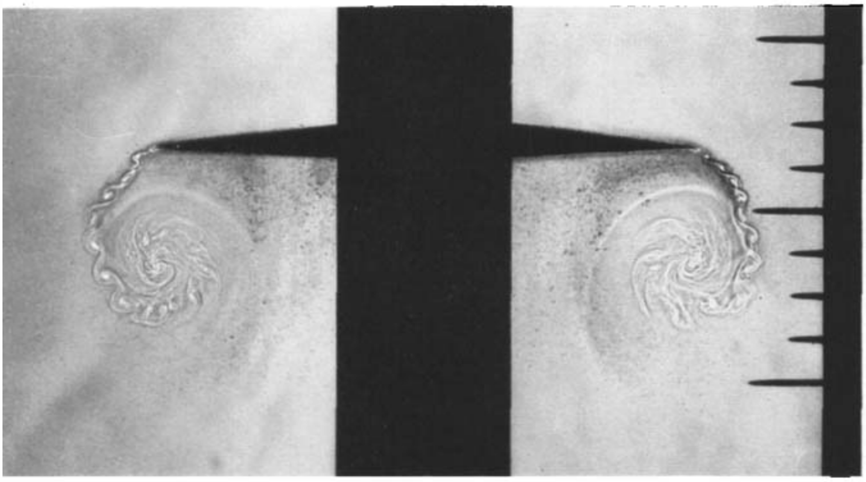


(*b*) $t = 10{\cdot}66$ msec; $v_1 = 12{\cdot}1$ ft./sec.

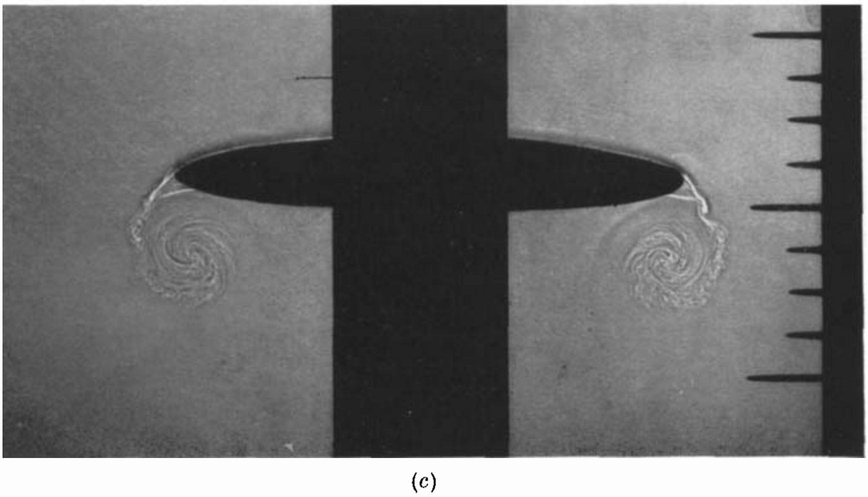
FIGURE 5. Shadowgraphs of convex plate section with final velocity 12·1 ft./sec.



(*a*)



(*b*)



(*c*)

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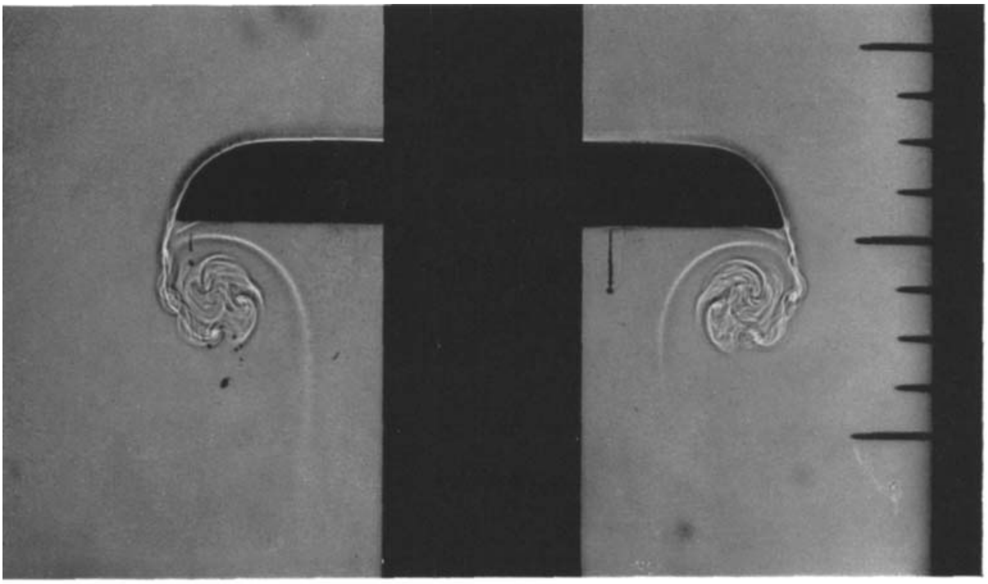
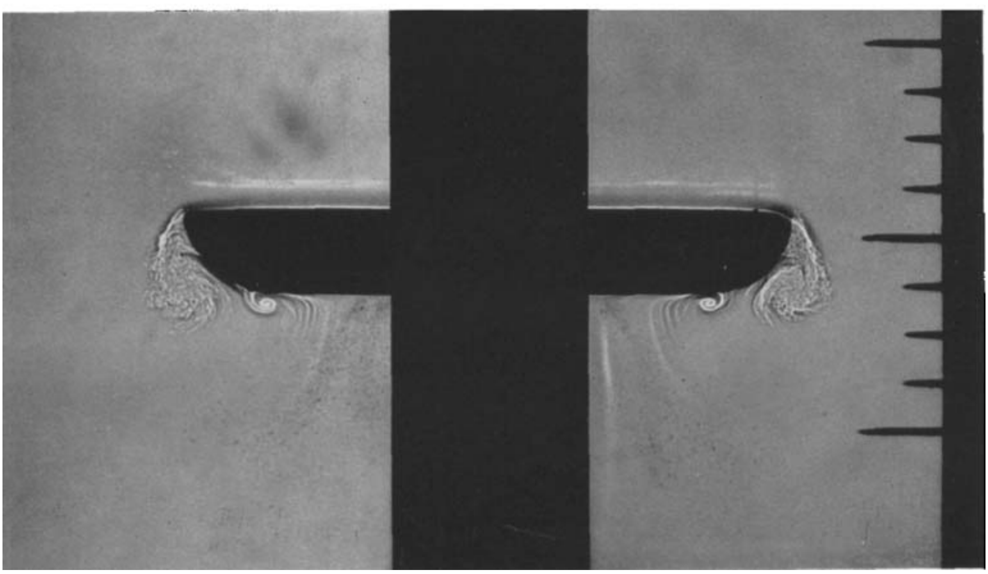


(*d*)



(*e*)

FIGURE 6. Shadowgraphs of various plate cross-sections at $t = 6{\cdot}53$ msec. All velocities 24 ft./sec approximately.