PROCEEDINGS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Experiments on the Motion of Solid Bodies in Rotating Fluids

G. I. Taylor

Proc. R. Soc. Lond. A 1923 **104**, doi: 10.1098/rspa.1923.0103, published 1 September 1923

Experiments on the Motion of Solid Bodies in Rotating Fluids.

By G. I. Taylor, F.R.S.

(Received July 17, 1923.)

[Plate 25.]

Some years ago it was pointed out by Prof. Proudman* that all slow steady motions of a rotating liquid must be two-dimensional. If the motion is produced by moving a cylindrical object slowly through the liquid in such a way that its axis remains parallel to the axis of rotation, or if a two-dimensional motion is conceived as already existing, it seems clear that it will remain two-dimensional. If a slow three-dimensional motion is produced, then it cannot be a steady one. On the other hand, if an attempt is made to produce a slow steady motion by moving a three-dimensional body† with a small uniform velocity (relative to axes which rotate with the fluid) three possibilities present themselves :—

(*a*) The motion in the liquid may never become steady, however long the body goes on moving.

(*b*) The motion may be steady but it may not be small in the neighbourhood of the body.

(*c*) The motion may be steady and two-dimensional.

In considering these three possibilities it seems very unlikely that (*a*) will be the true one. In an infinite rotating fluid the disturbance produced by starting the motion of the body might go on spreading out for ever and steady motion might never be attained, but if the body were moved steadily in a direction at right angles to the axis of rotation, and if the fluid were contained between parallel planes also perpendicular to the axis of rotation, it seems very improbable that no steady motion satisfying the equations of motion could be attained. There is more chance that (*b*) may be true. A class of mathematical expressions representing the steady motion of a sphere along the axis of a rotating liquid has been obtained.‡ This solution of the problem breaks down when the velocity of the sphere becomes indefinitely small, in the sense that it represents a motion which does not decrease as the

* 'Roy. Soc. Proc.,' A, vol. 93, p. 99 (1917).

† *E.g.*, a sphere or any body except an infinite cylindrical body with its axis parallel to the axis of rotation.

‡ G. Taylor, 'Roy. Soc. Proc.,' A, vol. 102, p. 180 (1922).

velocity of the sphere decreases. It seems unlikely that such a motion would be produced under experimental conditions.

There remains the third possibility (*c*). In this case the motion would be a very remarkable one. If the liquid were contained between parallel planes perpendicular to the axis of rotation, the only possible two-dimensional motion satisfying the required conditions is one in which a cylinder of fluid moves as if fixed to the body. The boundary of such a cylinder would act as a solid body, and the liquid outside would behave as though a solid cylindrical body were being moved through it. No fluid would cross this boundary, and the liquid inside it would, in general, be at rest relative the solid body. This idea appears fantastic, but the experiments now to be described show that the true motion does, in fact, approximate to this curious type.

In these experiments, bodies were moved slowly through water contained in a rectangular tank which was rotating at a considerable speed. The stream lines relative to the rotating system were made visible by means of coloured fluid, and this was photographed by a camera placed on the axis of rotation (which was vertical) and aiming downwards through the plate-glass top of the tank. The arrangement is shown in fig. 1. In that diagram A is the tank,

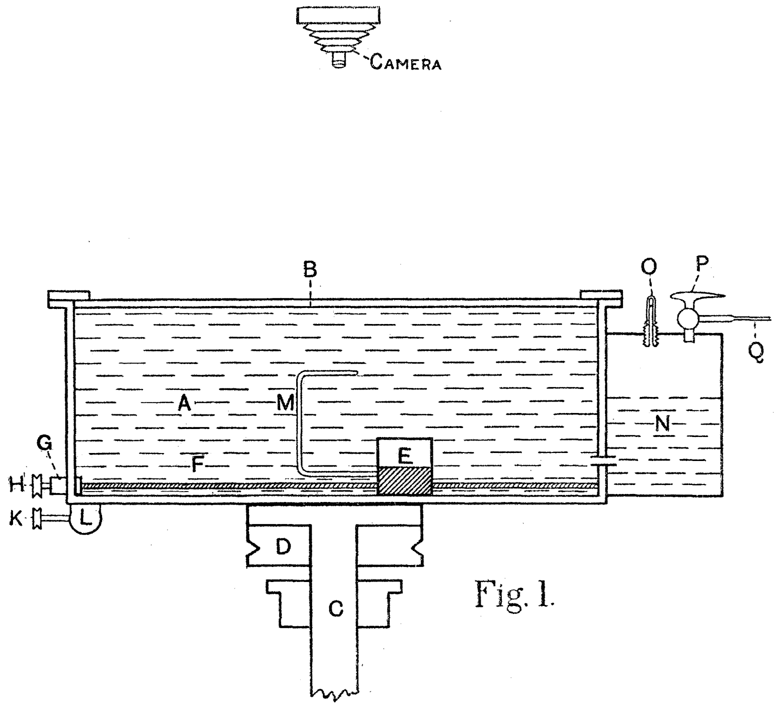

Fig. 1.

B is the removable plate-glass top which was screwed down with a water-tight joint capable of standing considerable pressure. The tank was 9 inches wide by 12 inches long and 4 inches deep. C is the vertical shaft about which the tank rotates, and D is the driving pulley. The apparatus was rotated at a uniform speed by an electric motor fitted with a governor, but this is not shown in the diagram.

Since it was necessary to give the whole system, including the water, a uniform rotation before starting the experiment, the mechanism necessary for moving the body through the water and for operating the apparatus used for making the stream-lines visible had to be fixed to the tank so as to rotate with it, but at the same time to be capable of being actuated from outside. This gave rise to the chief difficulty of the experiment. The body E (fig. 1) was moved slowly along a groove across the middle of the tank by means of a screw F of fine pitch, cut on a small steel shaft which passed through a stuffing-box G. This shaft was driven by a small motor L through two pulley wheels H and K connected by a fine endless silk thread. A small electric motor L was fixed to the under side of the tank, and was connected with a battery and switch through a wire, which dipped into a fixed annular trough containing mercury, and placed concentric with the axis of rotation.

On operating the switch while the tank was in motion, the body E could thus be made to move slowly across the middle of the tank.

To make the stream-lines visible it was necessary to have a source of coloured fluid moving with the body E. This end was attained by using the body itself as a reservoir for the coloured fluid whence it was led by a very fine metal tube M to the point at which it was desired to start the stream-line. In order to control the discharge of coloured fluid the upper part of this reservoir was filled with air, and the pressure of the water in the tank was gradually reduced while the experiment was proceeding. The reduction in pressure in the tank caused the air imprisoned in the upper part of the body E to expand and expel the coloured liquid through the tube M.

In order to get a steady stream of coloured fluid through M it was necessary to reduce the pressure in the tank at a uniform rate. This was accomplished by fixing a box N to the outside of the main tank, and the two were connected so that water could flow between them. The upper part of the box N was an air reservoir. The pressure in the tank could thus be raised by pumping air into N through a bicycle valve O which was soldered to the top of it.

In order to reduce the pressure at a uniform rate a fine capillary tube Q was fitted which allowed air to escape slowly out of N; and in order to keep the pressure up till the coloured liquid was wanted a stopcock P was inserted between N and Q. This stopcock was operated by a spring and trigger which could be released while the apparatus was in motion.

To photograph the stream-lines several mercury vapour spark gaps of the type used by Mr. C. T. R. Wilson were arranged in series round the apparatus, and to make a good background for the coloured streaks the bottom of the tank was silvered but not polished. Eosin was used as a colouring matter, and the eosin solution was made up to the same density as water by adding alcohol.

To perform an experiment the tap P was turned off and the trigger for releasing it was set. Air was then pumped into the reservoir N till the pressure was nearly, but not quite, sufficient to burst the glass top of the tank. The screw F was then turned till the body E was at the beginning of its path. The apparatus was then set rotating and left for some minutes till it was certain that all the water had attained a uniform rotation. When everything was ready to take a photograph the spring which turned the tap P was released. Directly the coloured liquid began to appear at the end of the tube M the switch operating the motor L was closed and the body E began to move. When the body got near the middle of the tank a spark was passed through the illuminating apparatus and an exposure made. Some practice was necessary before these operations could be performed in the correct order. The essential point aimed at in designing the apparatus was attained, for the speed of rotation was high while the speed of the body through the liquid was low.

Results of the Experiments.

In the first experiments the moving body was a cylinder 1·5 cm. diameter which extended from bottom to top of the tank. The tube M (fig. 1) was arranged so that the coloured stream emerging from it struck the cylinder centrally and divided into two. For reasons explained in a previous work,* the colouring matter remains in thin sheets, which appear as thin lines when seen edgewise from a point on the axis of rotation. These lines which were very visible in the photographs showed the well-known alternate vortices which are formed behind a cylinder moving in a fluid, but it must be remembered that these lines are not stream-lines in the mathematical sense of the words when the motion is not steady.

The next experiment was made with a sphere, and the stream of coloured

* "Experiments with Rotating Fluids," 'Roy. Soc. Proc.,' A, vol. 100, p. 114 (1921).

fluid was discharged from a point in front of its centre. The coloured streaks were very similar to those obtained with a cylinder, except that the line of the wake of alternate vortices did not lie directly behind the sphere; on the other hand, increasing speed of rotation made the wake appear more and more like that of a cylinder. This experiment seems to suggest that the motion is something like that outlined in the third alternative (*c*) (p. 213), a cylinder of fluid of the same diameter as the sphere moving with it and acting towards the rest of the fluid as if it were a solid cylinder.

To test this the apparatus was arranged so that a stream-line at some height above the body E could be examined. The body E consisted in these experiments of a short cylinder, about 1 inch high by $1\frac{1}{4}$ inches diameter. This rested on the bottom of the tank, and there was thus about 3 inches of water between the top of it and the top of the tank. The coloured liquid was led by the pipe M to a level $1\frac{1}{2}$ inches above the top of the moving body. Under these circumstances the coloured liquid would, if there were no rotation, pass over the middle of the top of the body. The arrangement is that shown in fig. 1.

In the first of the experiments made with this body the coloured liquid was discharged from a point 1 inch in front of the imaginary vertical cylinder enclosing the body, as shown in fig. 1. It was found that the coloured stream flowed straight towards this imaginary cylinder to a point vertically above the foremost point of the body. At that point the stream divided as though it had struck a solid obstacle. The fact that this virtual "solid obstacle" coincided with the imaginary cylinder enclosing the body can be seen in the photograph (Plate 25, fig. 2). The point from which the coloured stream emerges is shown at A. The point at which the stream divides is marked with an arrow B. At this point part of the coloured stream passes to the right and collects in a sheath C (fig. 2) which seems to remain close to the surface of the imaginary cylinder. The rest of the coloured liquid flows round the imaginary cylinder to the left and breaks away from it, forming large eddies D. The top view of the body E can be seen in the photograph, and it will be seen that the water contained in the cylinder vertically over the body E is quite clear. The broad black line which passes under it is the driving screw F (figs. 1 and 2). This line accordingly shows the direction of motion of the body.

In order to make certain that the liquid inside the imaginary vertical cylinder enclosing the body does in fact move with it, an experiment was next made in which the coloured liquid was discharged from a point inside this cylinder.

A photograph taken under these conditions is shown in fig. 3 (Plate 25). In that photograph the end of the tube from which the coloured liquid issued is at A. It will be seen that it is almost exactly over the foremost point of the edge of the moving body E. The coloured liquid remained in a small compact mass D (fig. 3) which travelled with the body. In this experiment the discharge of coloured fluid and the motion of the body were started simultaneously at the end of the tank, which is just outside the right-hand end of the photograph. Though the point from which the coloured liquid was issuing had travelled more than half the length of the tank, none of this fluid had escaped from the imaginary vertical cylinder containing the moving body E, although it was $1\frac{1}{2}$ inches above the level of the top of E.

This result confirms and supplements the observation previously recorded* that in the case when a sphere is moved slowly *along* the axis of rotation the motion tends to become two-dimensional, owing to the formation of a cylindrical dead-water region extending above the body and moving with it. On the other hand, no theoretical work has so far given any indication as to how such a motion could be established. The calculations of Mr. S. F. Grace† on the motion of a solid sphere projected slowly in a liquid of the same density as itself, show that at one stage, at any rate, the disturbance in the surrounding fluid is greater in the region which lies above and below the sphere than it is in other directions. This may have some bearing on the subject, and it is to be hoped that some further light will be thrown on it when Mr. Grace applies his method of analysis to the case of a sphere which is constrained to move uniformly along, or perpendicular to, the axis of rotation.

These experiments were carried out in the Cavendish Laboratory through the kindness of Sir Ernest Rutherford to whom the writer wishes to express his thanks.

* *L.c.*, p. 189.
† 'Roy. Soc. Proc.,' A, vol. 102, p. 89 (1922).

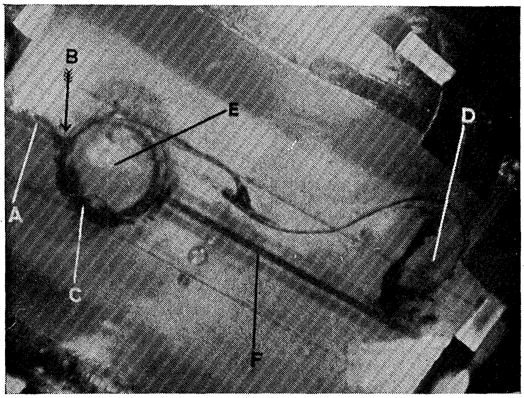

FIG. 2.

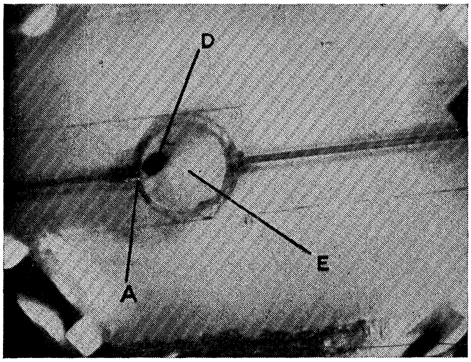

FIG. 3.

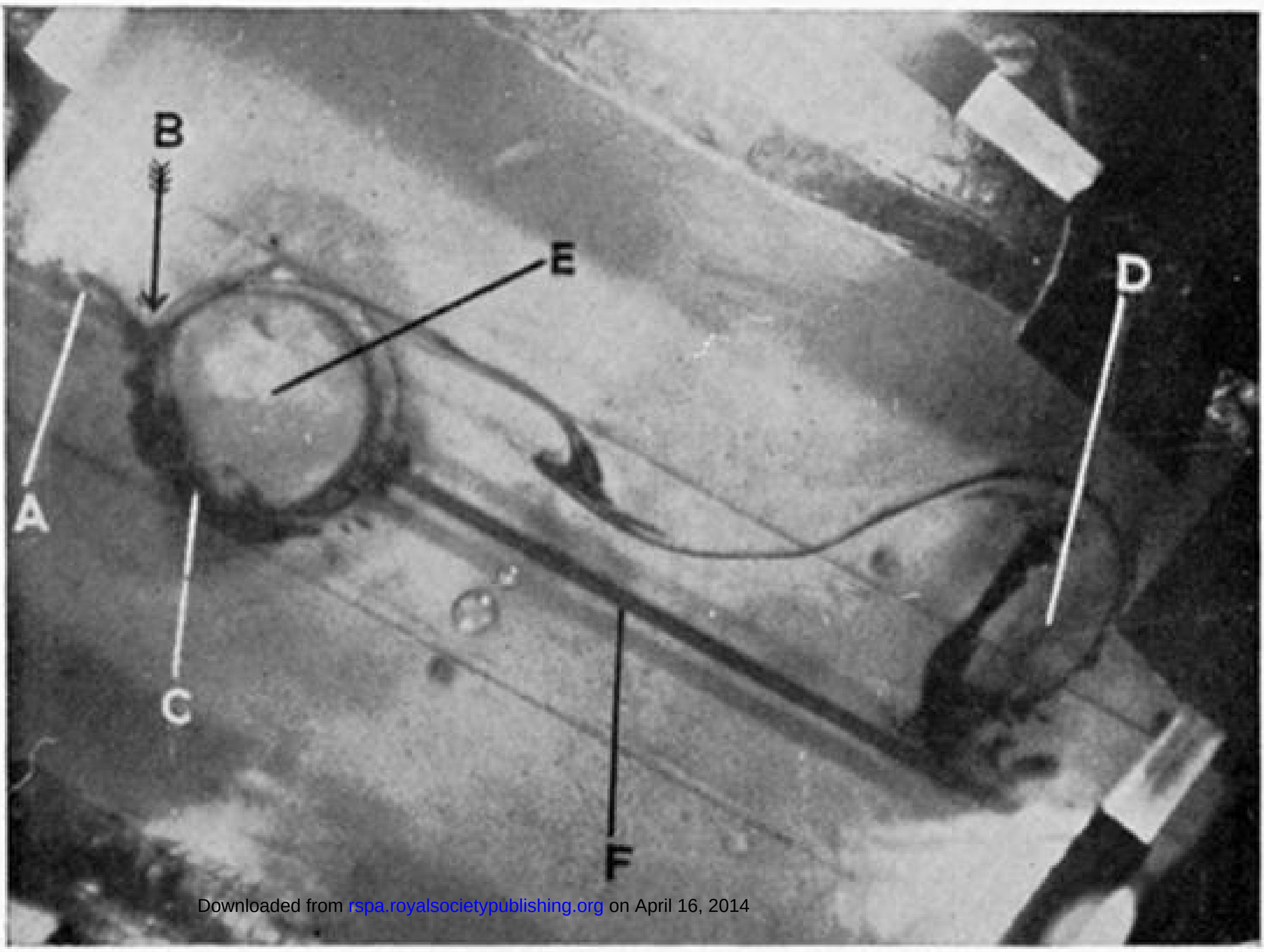

Fig. 2.

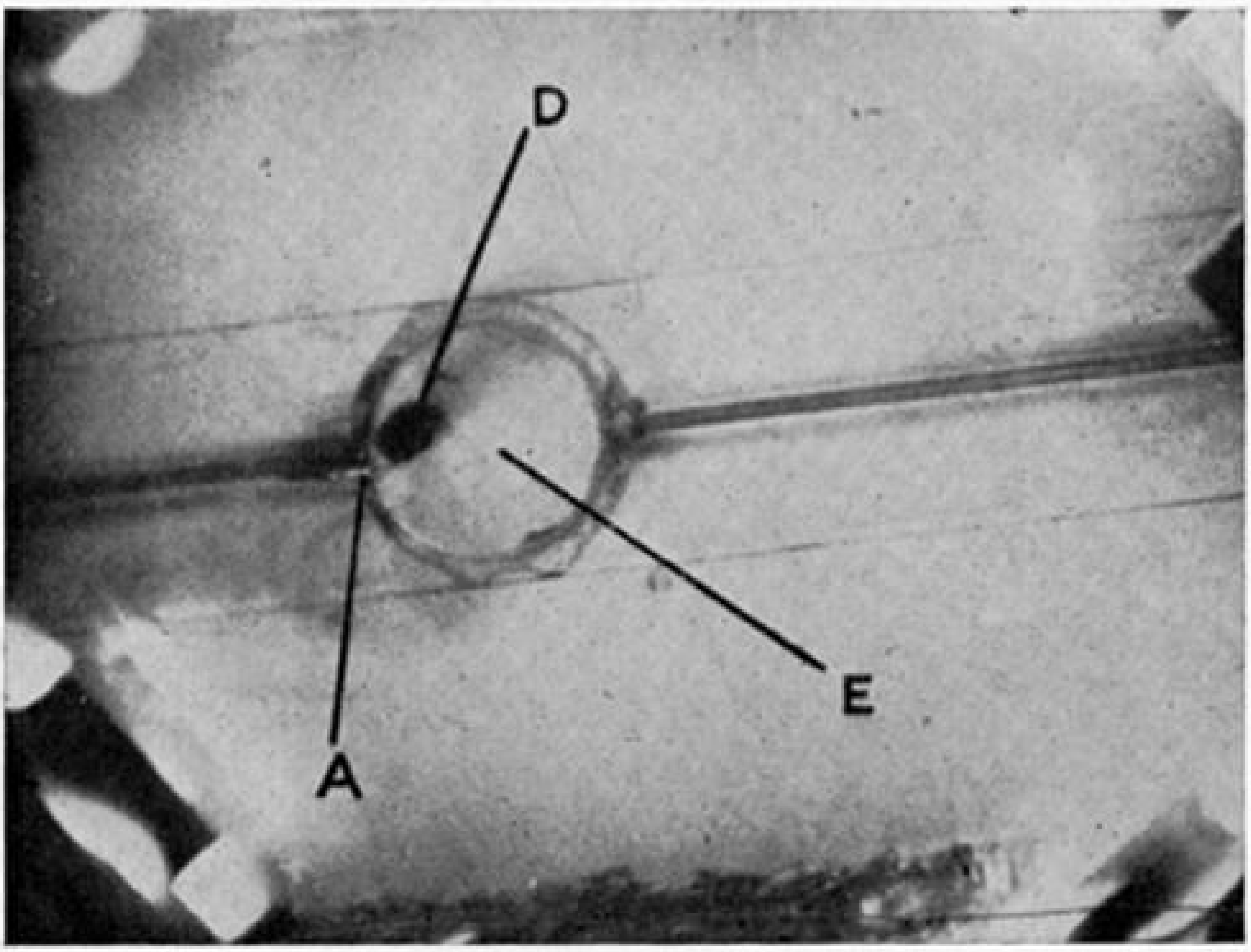

Fig. 3.