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By

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Summary.—In Part I of this paper, the possibility of obtaining lift on a body in a uniform stream independently of the incidence is discussed, and a practical method which obtains this effect is given. It is shown that a small thin 'flap' which may be moved about a well-rounded trailing edge through which, for example, continuous suction is applied will produce circulation about the aerofoil. A necessary feature of this method is the prevention of separation of flow by boundary-layer suction, which is also used to reduce substantially the width of the wake. The method uses principles quite different from those which have been proposed in the past for obtaining increased lift on aerofoils. The practical applications of the device are briefly discussed, and some interesting consequences pointed out. It will, for instance, be possible to fly with an aerofoil always at zero incidence. Again, the stall in which the flow separates from near the leading edge may be completely avoided, for as the circulation and lift increase, the incidence may be decreased so that severe adverse velocity gradients occur nowhere but near the trailing edge.

In Part II of the paper, a report is given of a preliminary experiment which was set up to investigate whether the theoretical predictions made about the efficacy of the Flap were largely confirmed. A wholly porous circular cylinder was fitted with the Flap and measurements were made of the pressure distribution round the cylinder for various positions of the Flap. These observations shewed that for angular deflection of the Flap of less than 20 deg, about 85 per cent of the theoretical value of C_L was realised : a maximum C_L of about 5·6 was obtained. These results are taken to shew that the physical principles of Part I are sound and that the Thwaites Flap does, in fact, enable lift to be generated independently of incidence.

PART I

Introduction.—The mechanism of flow whereby circulation is set up around a body is now well known, as is also the condition for a zero rate of vorticity transport into the wake, so that the circulation remains constant. These phenomena can take place only in a viscous fluid, and depend entirely on the existence of a boundary layer (at any rate after the beginning of the motion). There have been many attempts at increasing the lift of aerofoils so that the lift either approximates closely to the Kutta-Joukowski value, or actually exceeds substantially this value.

The most common device is the ordinary flap, in which a certain part of the aerofoil at the trailing edge is rotated about a hinge. This has the effect of not only altering the shape of the aerofoil but also of changing the incidence. It is possible, therefore, to calculate the effect of a flap in the ordinary way from potential flow considerations. Part of the effect of a flap at large angles of deflection is due to the confinement of separation of flow to the rear part of the aerofoil. The flap is a device for increasing the effective range of lift of an aerofoil although the lift does not exceed the value given by the Kutta-Joukowski condition (as applied to the changed shape of aerofoil and changed incidence).

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Another lift device depends on a type of boundary-layer control, that sheds downstream extra vorticity, so that the circulation reaches or exceeds the Kutta-Joukowski condition. This has been done by putting small strips along the trailing edge to disturb the symmetry of boundary-layer flow there. The practical applications of such a method of obtaining lift might be difficult, since there is no obvious way of controlling to any degree the circulation.

A third device has been tried by German investigators in which jets of air are expelled from close to the trailing edge. In this way, very high C_L's have been claimed as attained, but since no detailed reports have reached this country yet, it is difficult to understand either the mechanism of the flow or to estimate its economy.

None of these methods of obtaining lift, apart from the flap, is easy to control, whereas the method to be explained in this paper possesses control characteristics as simple as the ordinary aerofoil in flight as it changes incidence. Furthermore, the nature of this method enables various other improvements in performance of aerofoils to take place, which are desirable from considerations other than lift.

1. *Fundamental Idea.*—The strength of circulation about an aerofoil, provided the region of separated flow is not too great, is given to quite a good approximation by the condition that in potential flow the trailing edge is a stagnation point. This is the well-known Kutta-Joukowski condition. This approximation improves on thin aerofoils with the sharpness of the trailing edge and with increase of Reynolds number, but is nevertheless tolerably good, at any rate for small incidences, for bluff-ended bodies such as ellipses. However, nearly all aerofoils are designed to have fairly sharp trailing edges, for in this way a closer dependence of circulation on incidence is obtained which has been most desirable.

Suppose that this correspondence between incidence and circulation is no longer required, and that in fact the incidence and circulation are entirely independent. In potential flow, the rear stagnation point is no longer situated at a fixed point, and since singularities in the fluid flow must be avoided, the aerofoil shape must be wholly rounded with no cusps or sharp edges near the trailing edge.

The method by which this independence of circulation and incidence is obtained will be fully explained in the following paragraphs, and is briefly as follows. The potential flow around an aerofoil at a certain incidence and with a certain circulation is calculated, and the shape of the rear dividing streamline found. Continuous surface suction* is applied to those parts of the aerofoil over which the velocity decreases, so that separation of flow is completely prevented, and further the boundary layer is kept thin. A potential flow pattern may then be approximated to closely by the real viscous fluid. A plate or flap is now placed along some length of the rear dividing streamline as calculated. The flow will now adjust itself so that the aerofoil and flap are streamlines and also so that there are no singularities in the fluid. By the theorem of uniqueness, there is only one such flow, and that will be the flow calculated and required.

Such independence of circulation and incidence obtained by this means carries with it several advantages, some of which are briefly given below:—

(i) The sufficiency of symmetrical sections, with the consequent ease of manufacture.

(ii) The ability to fly at zero incidence.

(iii) Laminar flow over the whole upper surface by designing for a suitable velocity distribution.†

(iv) The avoidance of a violent stall associated with separation of flow from near the leading edge, by decreasing incidence as lift increases.

(v) No forces on the flap in steady flow.

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* Any other method of boundary-layer control, provided it prevents separation, would, of course, be sufficient: but the use of continuous suction appears to be the most suitable in a case, such as this, in which the velocity distribution may vary considerably.

† The design of sections for which the incidence is independent of the lift is discussed in R. & M. No. 2612, which also contains a discussion of the other properties of such aerofoils.

2. *Two Potential Flows with Circulation.*—Two simple cases of potential flow may be taken, those around a circle and ellipse (with the main stream flowing in the direction of the major axis in the latter case) with circulation. The velocity distributions over the bodies under such circumstances will be examined and these will display certain unfamiliar characteristics; the shape and position of the dividing streamlines will also be calculated so that some idea may be gained as to the size, shape and position of a flap as explained above to produce a certain lift. The parts of the surface over which it is necessary to use continuous suction may also be determined.

These two particular cases, the circle and the ellipse, have been taken for the simplicity of the mathematics, and also for the ability to calculate the dividing streamlines. In general, although it is possible to design shapes of bodies (as will be shown in a later report) to have pre-assigned velocity distributions, the flow away from the bodies is not readily determinable. However, this is only a slight disadvantage since for any aerofoil shape with, say, a rear half shaped as an ellipse the rear dividing streamline will lie close to the one corresponding to a whole ellipse. Our calculations, therefore, will give a good guide to the shape of dividing streamlines.

(i) *Circle.*—The complex potential, w, of flow around the circle $|z| = a$, due to a streaming velocity U parallel to the x-axis, and with circulation of strength K is

$$w = U\left(z + \frac{a^2}{z}\right) + \frac{iK}{2\pi}\log\frac{z}{a} \qquad (1)$$

in which the streamline $\psi = 0$ includes the circle.

The lift force is $K\rho U$ and is equal to $\frac{1}{2}\rho U^2 2aC_L$

thus $$K = UaC_L \qquad (2)$$

Equation (1), therefore, can be rewritten as

$$w = U\left(z + \frac{a^2}{z} + ia\,\frac{C_L}{2\pi}\log\frac{z}{a}\right). \qquad (3)$$

The velocity, q, on the surface of the circle at the point $z = ae^{i\theta}$ is

$$q = U\left(2\sin\theta + \frac{C_L}{2\pi}\right). \qquad (4)$$

The dividing streamlines are easily found as follows. From equation (3), at the point $z = Re^{i\theta}$, $R \geqslant 1$,

$$\psi = U\left(R\sin\theta - \frac{a^2}{R}\sin\theta\right) + \frac{C_L a}{2\pi}\log\frac{R}{a}. \qquad (5)$$

Since $\psi = 0$ represents the circle and the dividing streamlines, the dividing streamlines are given by the equation

$$\sin\theta = -\frac{C_L}{2\pi}\left(\frac{R}{a} - \frac{a}{R}\right)^{-1}\log\frac{R}{a}. \qquad (6)$$

The stagnation points $\theta = \beta$ are found from equations (4) or (6) to be given by

$$\sin\beta = -\frac{C_L}{4\pi}. \qquad (7)$$

Fig. 1 shows the shape of the rear dividing streamline near the circle for a range of C_L's from 0 to 4π. For values of $C_L > 4\pi$, there is only one stagnation point and that is away from the boundary.

It will be seen that for low C_L's the dividing streamlines lie closely to straight lines, so that for such C_L's a straight flap would be very suitable.

The whole motion is symmetrical about the diameter of the circle perpendicular to the main stream, and adverse velocity gradients occur over the rear half of the circle. Thus to maintain potential flow, it is necessary to use continuous suction over the rear half, sufficient to prevent separation of flow.

(ii) *Ellipse—Zero Incidence.*—Suppose the ellipse has major and minor axes of length 2a and 2b respectively. Then the conformal transformation

$$Z = \tfrac{1}{2}(z + \sqrt{z^2 - c^2}) \quad \ldots \quad (8)$$

in which $c^2 = a^2 - b^2$, transforms the ellipse in the z-plane into the circle

$$|Z| = \frac{a + b}{2} = \frac{c}{2} e^{\xi_0}.$$

With elliptic co-ordinates, in which $z = c \cosh \zeta$, $\zeta = \xi + i\eta$, (8) gives $Z = \frac{1}{2} c e^{\zeta}$.

The angular distance η of a point on the circle then corresponds to the eccentric angle of the corresponding point on the ellipse.

In the elliptic co-ordinates, the potential flow about the circle is given by

$$w = U e^{\xi_0} c \cosh (\zeta - \xi_0) + i \frac{K}{2\pi} (\zeta - \xi_0). \quad \ldots \quad (9)$$

It is not difficult to obtain the velocity q of fluid at any point of the ellipse in the following form:

$$\frac{q}{U} = \frac{\left(1 + \frac{t}{C}\right) \sin \eta + \frac{C_L}{2\pi}}{\sqrt{\left[\left(\frac{t}{C}\right)^2 \cos^2 \eta + \sin^2 \eta\right]}}$$

in which t is the thickness, C the chord, U the stream velocity. The ellipse's ordinates x, y, are given by

$$\frac{x}{C} = \tfrac{1}{2} \cos \eta, \quad \frac{y}{C} = \frac{t}{2C} \sin \eta$$

and the relation between K and C_L is $K = \frac{1}{2} U c C_L$.

To obtain the ordinates of the streamlines, we find from equation (9) that

$$\frac{\psi}{UC} = \tfrac{1}{2}\left(1 + \frac{t}{C}\right) \sinh (\xi - \xi_0) \sin \eta + \frac{C_L}{4\pi} (\xi - \xi_0).$$

Hence the dividing streamlines $\psi = 0$ are given by

$$\sin \eta = - \frac{C_L}{2\pi \left(1 + \frac{t}{C}\right)} \frac{\xi - \xi_0}{\sinh (\xi - \xi_0)}$$

or $$\sin \eta = \sin \eta_0 \frac{\xi - \xi_0}{\sinh (\xi - \xi_0)}$$

where $\eta = \eta_0$ is the stagnation point on the ellipse.

The relation between the elliptic co-ordinate ζ and the z is $z = c \cosh \zeta$ which can be rewritten as

$$\frac{x}{C} = \tfrac{1}{2} \cos \eta \left[\cosh (\xi - \xi_0) + \frac{t}{C} \sinh (\xi - \xi_0)\right]$$

$$\frac{y}{C} = \tfrac{1}{2} \sin \eta \left[\frac{t}{C} \cosh (\xi - \xi_0) + \sinh (\xi - \xi_0)\right]$$

Fig. 2 gives the velocity distributions over one half of an ellipse, 20 per cent. thick, for some C_L's at zero incidence, and Fig. 3 shows the shape of some dividing streamlines. It will be noticed that the extent of adverse velocity gradients over which suction would have to be applied, is less for the ellipse than the circle.

(iii) *Ellipse—Other Incidences.*—Suppose now that the main stream is inclined at angle α to the major axis of the ellipse. Then the flow is given by

$$w = U e^{\xi_0} c \cosh (\zeta - \xi_0 - i\alpha) + i \frac{K}{2\pi} (\zeta - \xi_0).$$

The velocity, q, at a point on the ellipse is easily obtained in the form

$$\frac{q}{U} = \frac{\left(1 + \frac{t}{C}\right) \sin (\eta - \alpha) + \frac{C_L}{2\pi}}{\sqrt{\left[\left(\frac{t}{C}\right)^2 \cos^2 \eta + \sin^2 \eta\right]}}$$

and the dividing streamlines, $\psi = 0$, are given by

$$\sin (\eta - \alpha) = - \frac{C_L}{2\pi \left(1 + \frac{t}{C}\right)} \frac{\xi - \xi_0}{\sinh (\xi - \xi_0)} = \sin (\eta_0 - \alpha) \frac{\xi - \xi_0}{\sinh (\xi - \xi_0)}.$$

If the leading edge is a stagnation point, a case in which we shall be interested, $\eta_0 = 0$ or $C_L/2\pi(1 + t/C) = \sin \alpha$ and so the dividing streamlines are given by

$$\sin (\eta - \alpha) = - \sin \alpha \frac{\xi - \xi_0}{\sinh (\xi - \xi_0)}.$$

In this case, the velocity distributions over the ellipse are given in Fig. 4 for some C_L's and Fig. 5 shows the shape of the dividing streamlines for the same C_L's. We will discuss the application of this type of flow in the next paragraph.

3. *Details of Device and its Applications.*—In Section 1, the action of the device for obtaining lift independently of incidence was briefly described, and we now enunciate it clearly and go on to suggest the various advantages to be obtained by its use.

We assume that a flow round any body can be obtained which approximates very closely to the theoretical potential flow by the use of boundary-layer suction.* The amount of suction

* While the author's opinion is that continuous surface suction is likely to prove the best way of obtaining this result, it should be noted that suitable arrangements of slots may also be effective.

therefore must be sufficient to prevent any separation of flow, and possibly sufficient also to obtain a boundary layer whose thickness does not exceed a certain value. These requirements might be stated a little differently by saying that the wake of the body, under any conditions which may be required, should be small.

The aerofoil shape on which the device is to be used must be everywhere rounded, so that there are no cusps or edges where theoretically the velocity of fluid would become infinite and which in practice impose a dependence between incidence and circulation.

A flap of suitable shape, of small thickness and of length large* compared with the boundary layer, is now placed touching and normal to some point of the aerofoil near the trailing edge.

The fluid flow must adjust itself so that not only the aerofoil but also the flap is part of a streamline and so that there are no singularities in the fluid. This can be done only by the presence of a circulation, whose strength depends entirely on the position of the flap. By suitable positioning of the flap any circulation can, presumably, be obtained provided it is not so great that there is no stagnation point on the aerofoil.

The method of obtaining circulation independently of incidence having been described the associated advantages may be enumerated:

(i) It is possible to fly with the wings at constant incidence, which is especially an advantage at high C_L's for which the usual high incidence is sometimes an embarrassment.

(ii) The usual combinations of flaps and ailerons may become necessary, since not only may high lift be obtained but the lift of the two main planes may be varied independently to produce banking.

(iii) If at very high C_L's there is a danger of the flow separating from the leading edge, incidence can be decreased. Suppose, in fact, the incidence is adjusted so that the leading edge is a stagnation point, the velocity increases over most of the upper surface. In this way not only is there no danger of separation but also the boundary layer is so thin when it reaches the trailing edge that no great amount of suction will be required to prevent separation between the trailing edge and the flap. Fig. 4 shows the type of velocity distribution obtained under these conditions. It would be necessary to use suction over approximately the rear half of the lower surface.

(iv) By proper design, laminar flow can be achieved over nearly the whole of the upper surface, and at least half the lower surface. The mathematical design of such aerofoils is discussed in R. & M. No. 2612.

(v) Symmetrical sections may be used without loss of aerodynamic efficiency, and therefore, manufacture is very considerably simplified.

(vi) If sections are employed which are symmetrical about the line perpendicular to, and through the mid-point of, the chord and are used at zero incidence, the centre of pressure is fixed in position for all C_L's at the mid-chord point. Thus no change of trim is required and further, if the section is symmetrical about the chord, the moment coefficient is always zero.

(vii) Since the flap is thin, and lies along a streamline, the velocities of fluid at corresponding points on either side of it are equal, and so there are no forces on the flap. Forces will act on the flap when it is moved, but their magnitude will depend on the speed of flap movement.

4. *The Mechanism of Flow.*—It is interesting to see how circulation is set up by the method described, although, of course, there is no fundamental difference between this case and the ordinary one in which an aerofoil changes incidence. Two cases will be described, in which the flow starts from rest with the flap set in a deflected position and in which the flap changes position when the flow is fully developed. The mechanism of flow for a circular cylinder will be described.

* The condition is intuitively necessary, but clearly may be modified in the light of experimental results.

(i) *Flow from Rest* with the flap inclined to the stream's direction. Suction is applied over the rear half of the cylinder where adverse velocity gradients occur, so that no separation takes place. As the velocity of the main stream increases from zero, flow approximating to potential flow takes place round the cylinder and flap and there is a stagnation point on the upper surface of the flap, with a very large velocity round the edge of the flap. There is now a force on the flap, tending to increase its deflection. Owing to the suction over the cylinder, no eddies will be formed in contact with it, but a small eddy will soon appear between the stagnation point, and the edge of the flap. This eddy will be swept off downstream, leaving circulation in the opposite sense, about the cylinder and flap. Meanwhile, a boundary layer will have grown about the cylinder and along the flap, which sheds vorticity of opposite signs from the upper and lower surfaces of the flap. The circulation will be continually adjusted in this way, by the total amount of vorticity shed in the wake, until a steady condition is reached in which the velocities at each edge of the boundary layer at the end of the flap are roughly equal (which is the approximate condition for the total rate of vorticity transport into the wake being zero). In this steady condition, the velocities on each side of the flap are the same, and there is no force on the flap. This development of the flow from rest is pictorially represented in Fig. 6.

(ii) *Deflection of Flap* in fully developed flow. In the steady developed flow, as above, the velocities at the edge of the boundary layer at the end of the flap are equal, and vorticity is shed at equal rates from the upper and lower surfaces of the flap. The flap is now deflected further, which upsets this condition. The velocity increases on the under surface of the flap and decreases on the upper. Thus more vorticity is shed from the lower than from the upper surface which increases the circulation about the cylinder and flap, which in turn tends to equalise the velocities at the edge of the boundary layer at the end of the flap. In this way, the circulation is increased until, once more, there is a steady flow, in which there is a total of zero vorticity being shed into the wake. The development of this flow is diagrammatically explained in Fig. 7.

Conclusion.—In this paper, a method has been explained by which circulation can be produced about an aerofoil or body in a stream independently of the incidence. An essential part of the method is the use of boundary-layer suction to prevent separation of flow. There would appear to be several advantages in the use of this method of obtaining lift on an aerofoil.

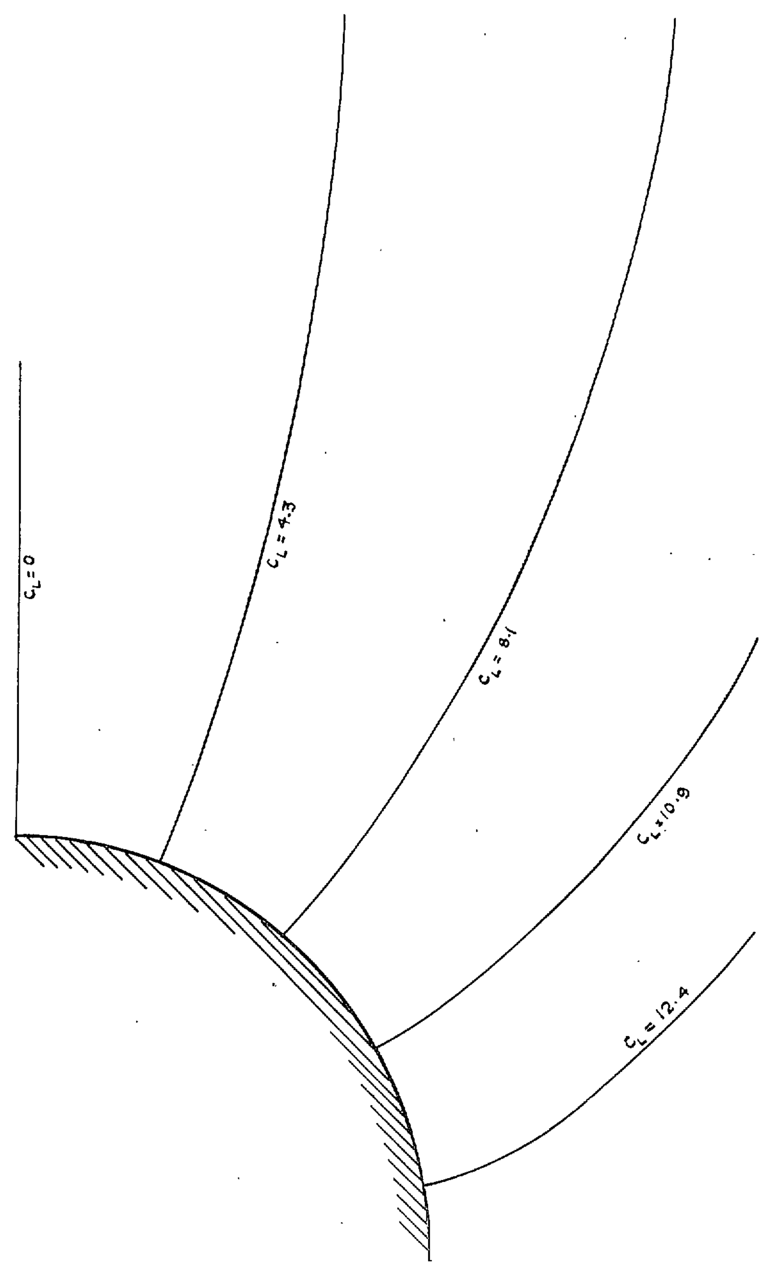

Fig. 1. Dividing streamlines at the rear of a circular cylinder, for various C_L's.

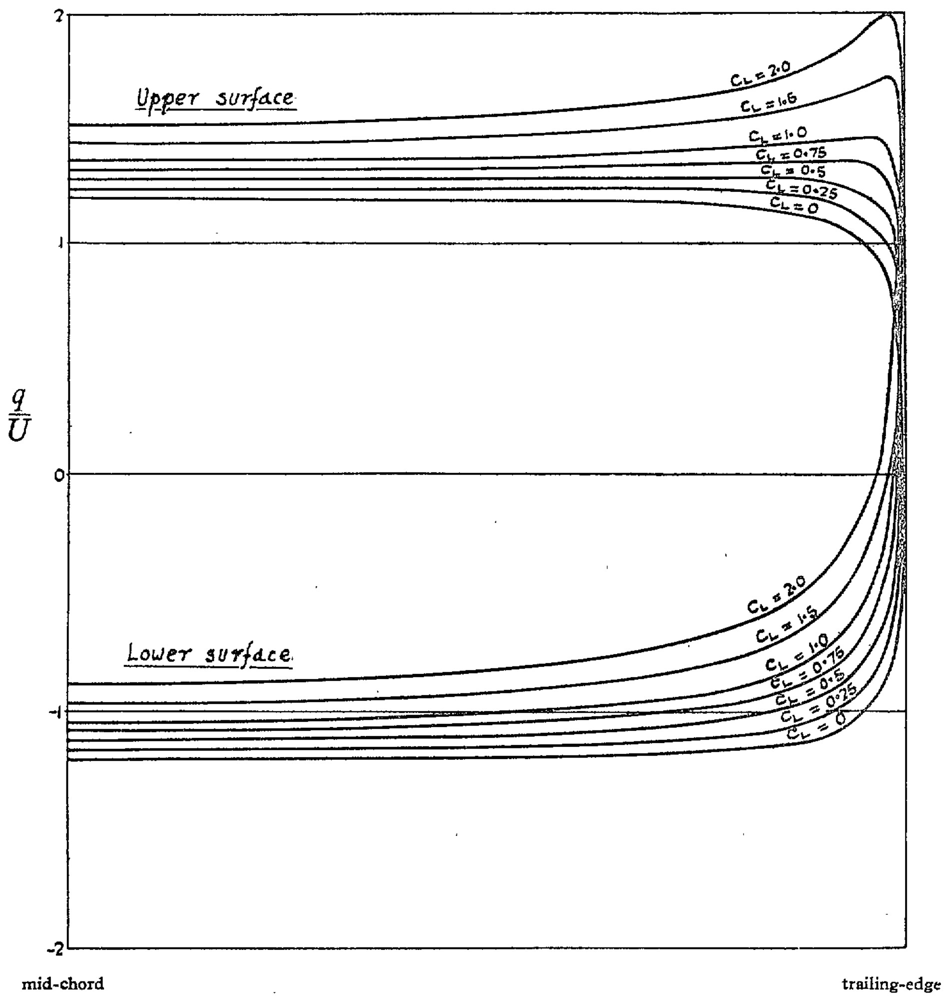

FIG. 2. Velocity distribution over the rear half of an elliptic cylinder, 20 per cent thick, for various C_L's.

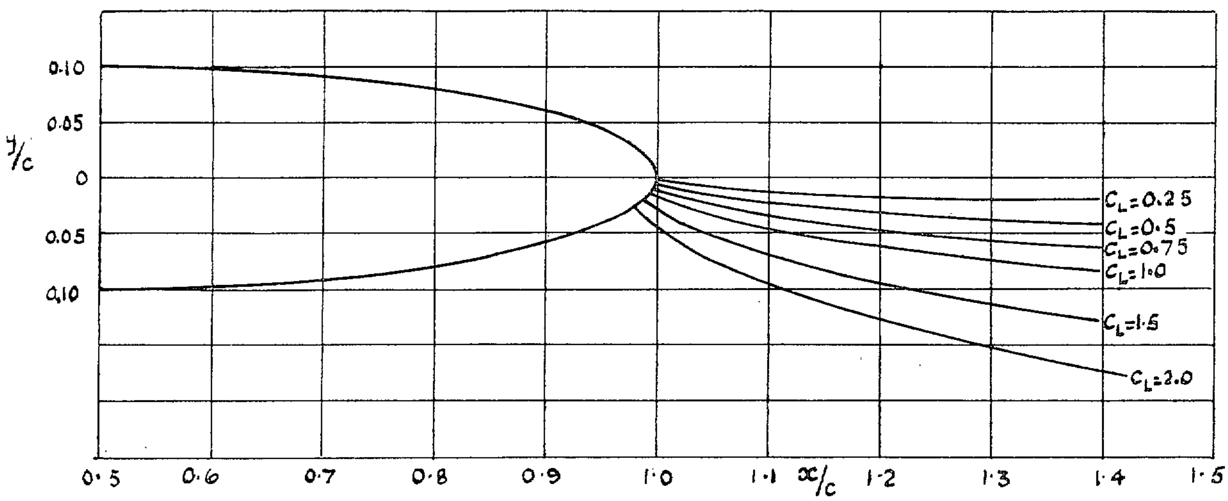

FIG. 3. Dividing streamlines for an ellipse 20 per cent thick at zero incidence and some C_L's.

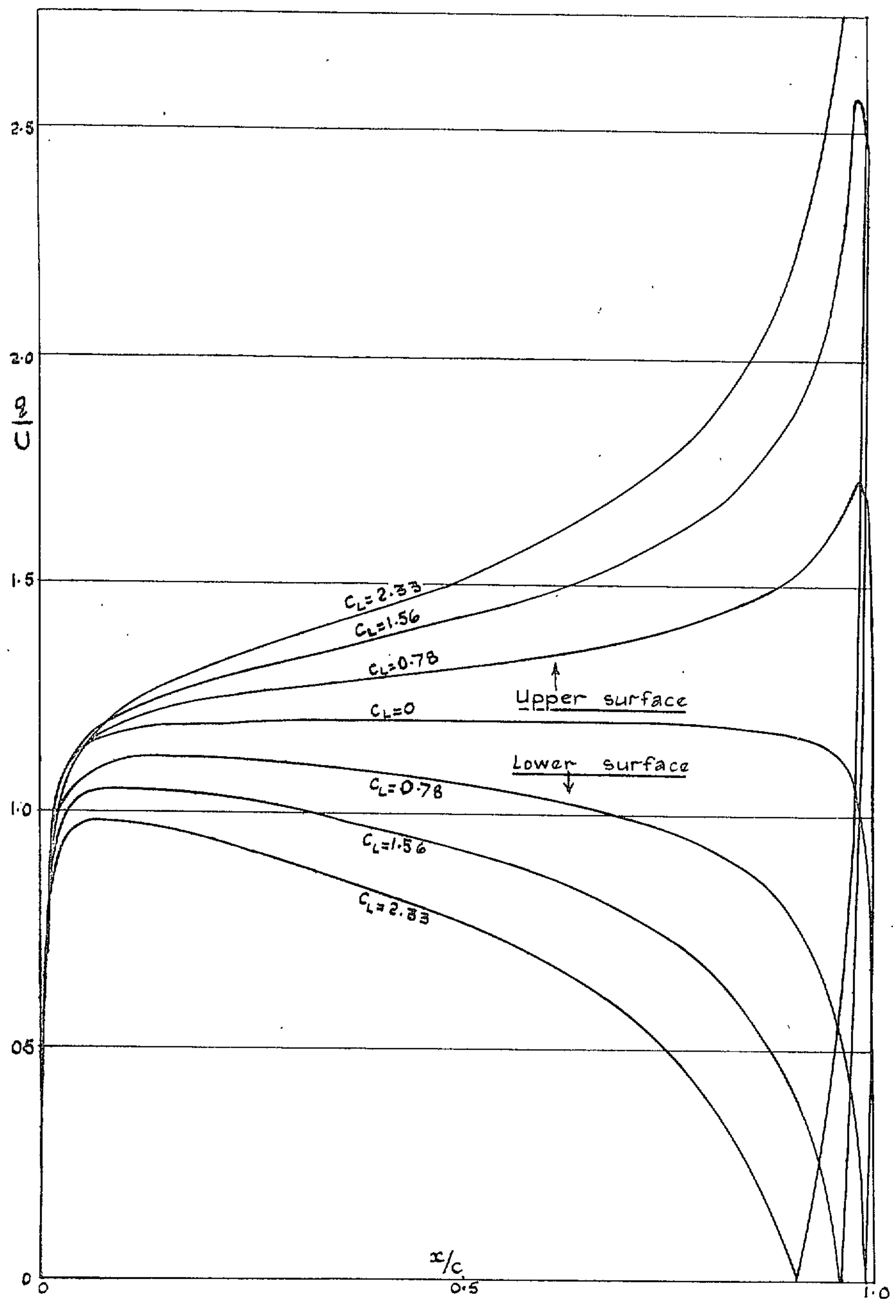

FIG. 4. Ellipse 20 per cent thick.
Velocity distribution for various C_L's when leading edge is a stagnation point.

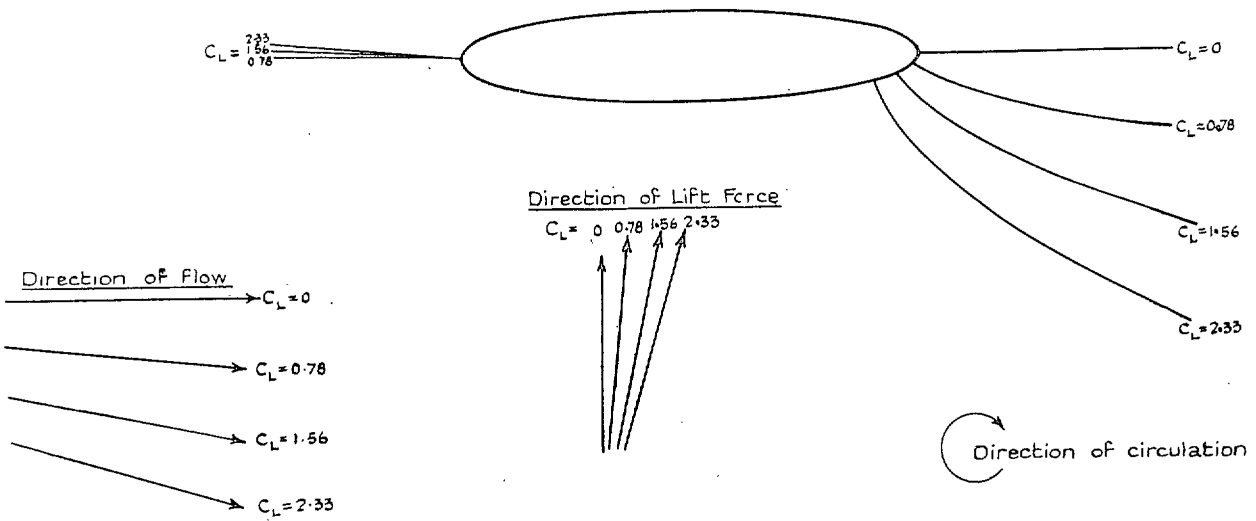

FIG. 5. Ellipse 20 per cent thick.
Dividing streamlines, when leading edge is a stagnation point.

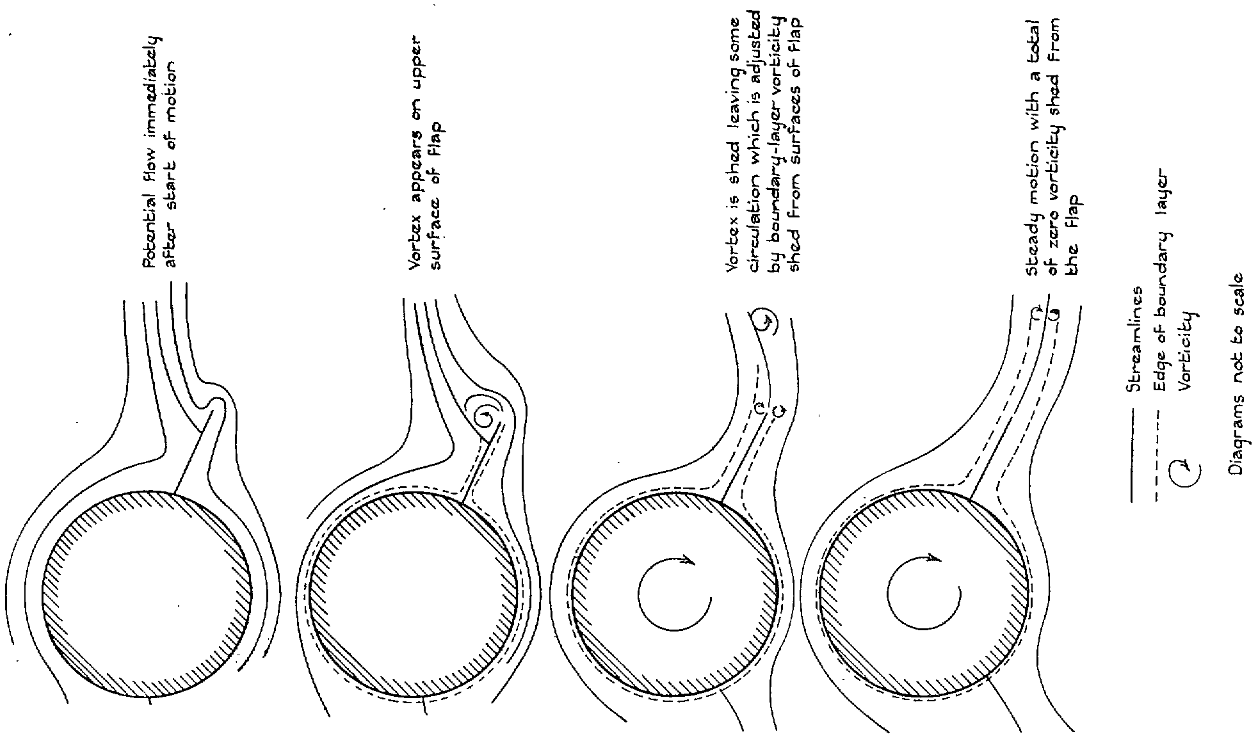

FIG. 6.

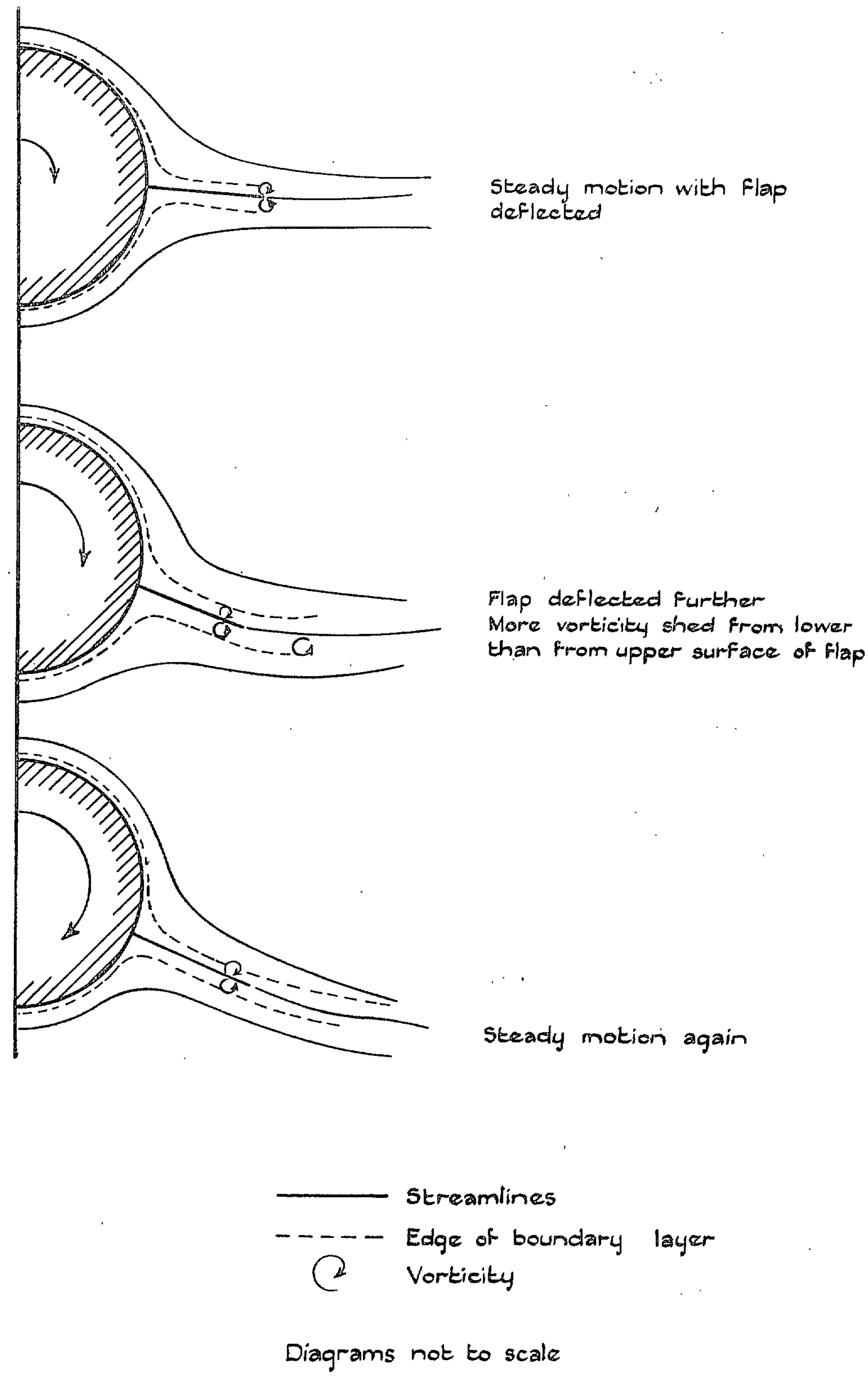
Steady motion with flap deflected
Flap deflected further
More vorticity shed from lower than from upper surface of flap
Steady motion again
Streamlines
Edge of boundary layer
Vorticity
Diagrams not to scale

FIG. 7.

PART II

Introduction.—In Part I, a method is described of obtaining lift on a cylinder in a uniform stream, together with explanations of the mechanism of the fluid flow. There appears generally to be some doubt as to whether in the flow of real fluid, the predicted phenomena will in fact occur, and experiments have been initiated to investigate the working of the device. Part II is to be regarded as an interim report on an experiment designed to show little more than the extent to which the device does in fact work in a particular case.

The requirements of such an experiment were the confirmation, or otherwise, of the postulates made in Part I of this paper, and various considerations had to be taken into account before the decision on the apparatus to be used could be made. First, it was decided that continuous suction would be the best type of boundary-layer control to use, for strong theoretical arguments exist to shew that it is capable of preventing separation under all conditions, even up to a rear stagnation point. This decision was made in spite of the proven effect of suction slots in practice, when no experimental work had been done on continuous suction. Next, if the Flap was to produce lift, then it would be encouraging to obtain, in the first experiment, very high C_L's and this suggested the use of a circular cylinder for which the maximum C_L appears to be 4π.* The circular cylinder possesses the advantage that it is the most ' rounded ' of bodies (*see* Part I, section 3) and that the potential flow velocity gradients are not so great on its surface as on a thinner cylinder whose trailing-edge curvature is much larger. There was the added advantage that porous circular cylinders could be bought in suitable sizes on the commercial market.

1. *Apparatus*.—The general layout of the apparatus is shown in Fig. 1 and a sketch of the cylinder itself in Fig. 2.

The tunnel is an open-circuit type with a working section 4 ft long and 1 ft square in cross-section. No direct estimates of the turbulance of the stream had been made but undoubtedly the scale of turbulence was fairly high—there were no screens in front of the fan and the tunnel itself was situated in a very large room used as a thoroughfare.

The circular cylinder consisted of a centre-section of 6 in. span made of Porosint grade C material with brass end pieces of the same diameter to make the total length about 18 in. The external diameter of the cylinder was $1\frac{1}{2}$ in. The whole cylinder was mounted horizontally in the centre of the working section and false walls were fitted inside the tunnel at either end of the porous centre section extending 9 in. up and down stream. The cylinder was hollow and the two outer ends of the end pieces were connected to a single pipe through a Rotameter flow meter and settling chamber to a Rootes-type pump. The pump was situated far from the tunnel to decrease the effect of its unpleasant noise. A single pressure tube was connected to a hole in the centre-section of the porous part of the cylinder and it was arranged that the cylinder could be rotated as a whole so that the pressure hole could be placed at any angular position around the cylinder with respect to the stream direction. It was assumed that rotation of the cylinder did not affect the flow since the porosity should have been reasonably uniform.

The Flap consisted of a piece of hard steel extending across the whole span of the porous centre section. Its length was equal to a quarter of the cylinder's diameter, *i.e.*, $\frac{3}{8}$ in. and its thickness $\frac{1}{20}$ in. The general mechanism of the flap is shown in Fig. 3. The ends of the flap were attached to two collars which could rotate on the brass end pieces and the rotation was controlled by a linkage. The range of angular movement of the flap was about 40 deg.

2. *Experimental Results and Discussion*.—(i) A considerable disadvantage of the apparatus was the single pressure hole in the surface. To obtain the pressure distribution about the

* For a circular cylinder, the lift is given by $C_L = 4\pi \sin \alpha$, where α is the angular displacement of the flap round the cylinder. When the flap is pointing directly downstream, $\alpha = 0$. 4π may be conveniently called the lift-curve slope.

cylinder for any set of external conditions a set of, say, eighteen or twenty-four distinct readings had to be taken each involving an adjustment of the cylinder. Normally this would be regarded as no more than tedious, but in this case the actual running time was so increased that deterioration in the porous properties of the cylinder was suspected. It has already been pointed out that the tunnel was in a room used as a thoroughfare and the amount of dust and grit passing through the working section was large. It was soon found that the porous surface was being partially blocked up. Continual replacement of a blocked cylinder by a new one was not practicable.

It was evident that to obtain the relations between pressure distributions and drags and suction quantities a different apparatus was necessary. First, the nature of the boundary-layer suction demanded a larger scale so that the building of the model with one or more pressure tubes required a lower degree of precision. On a larger scale it would be possible to incorporate eighteen or twenty-four pressure tubes around the surface thus enabling a complete set of pressure readings to be taken at once and thereby reducing the running time to about a twentieth. Secondly on a larger scale, the boundary layer would be correspondingly thicker and the pores of the surface could be larger. Thus not only is the risk of clogging reduced but also the use of materials other than Porosint, such as very fine gauze becomes possible. It is hoped to carry out tests on such an apparatus in a much larger tunnel. However, the existing apparatus was regarded as sufficient for the verification of the ideas of Part I.

(ii) No attempt was made, for the reasons outlined above, to measure the drag of the cylinder and correlate it with the suction quantity, and therefore it was decided always to use a suction quantity at least sufficient to prevent separation. The suction quantity was increased until a total head tube registered no loss of head when traversed across the stream behind the cylinder. Under these conditions the wake was zero, the total drag was made up of skin-friction and sink drag only, and it was assumed that the flow about the cylinder approximated very closely to potential flow. For this, the total suction flow was given by $Q = 0 \cdot 5$ cu ft/sec. The tunnel was run at a speed of 100 ft/sec. The chord of the cylinder was its diameter — thus $C = 0 \cdot 125$ ft and the span, S, $0 \cdot 5$ ft. Thus $C_Q = Q/UCS = 0 \cdot 08$, and $C_Q R^{1/2} = 62$.

This quantity is, of course, very much larger than is necessary to prevent separation of flow. When the apparatus was first installed, some fairly careful measurements were taken of the suction quantity necessary to prevent separation of flow*, for a wide range of tunnel speeds. On analysis, these results gave a remarkably consistent value for the suction coefficient given by $C_Q R^{1/2} = 13 \cdot 7$. This value compares closely with theoretical estimates which have ranged from $C_Q R^{1/2} = 10 \cdot 1$ to $C_Q R^{1/2} = 13 \cdot 9$ while Watson asserts that for $C_Q R^{1/2} = 22$, separation is very far from taking place. This is a very encouraging result since it gives confidence in theoretical calculations on continuous suction which thereby has been shewn to have considerably advantages over other types of suction.

(iii) Pressure distributions were recorded for four flap angles excluding zero, and the lift coefficient was estimated for a greater range of flap angles. Figs. 3 to 6 show graphically the velocity distributions about the cylinder for $\alpha = 1$, 2, 4, and 10 deg. On each figure is also shown the theoretical velocity distribution for an unlimited stream. Divergence from the theoretical curves increases as the point of maximum thickness is reached, and this is at least partly due to the tunnel interference. Tunnel interference was not calculated for the circular cylinder, since it was felt the labour involved was not justified in view of the nature of the experiment. Nevertheless, the closeness of the experimental and theoretical curves is remarkable, and affords an excellent practical justification of the effect of continuous suction, and it is clear from these figures that separation is quite prevented. The stagnation pressure on the cylinder differed from the total head of the stream by as much as 5 per cent.

* No direct method was available for determining when separation first occurred with suction decreasing. The method employed was to traverse the wake with a total head tube, and when a high maximum in the loss of total head suddenly appeared, separation was assumed to have occurred. This sudden increase of maximum total head loss with decreasing suction was a very noticeable effect.

It is remarkable, however, that the pressure at the flap is always very close to the front stagnation point value, thus showing that if separation is prevented, full pressure recovery in the boundary-layer is possible. Velocity values and lift coefficients were calculated using the value of dynamic pressure as given by a pitot-static tube upstream of the model. However, one could justify the use of the front stagnation point value as the stream's total head, and if this were adopted the C_L's given later in the paper would, of course, be higher. For these four flap angles, the lift-coefficients were computed directly from the integrated pressure from the formula:

$$C_L = - \frac{1}{\rho U^2} \int_0^{2\pi} p \sin\theta \, d\theta$$

in which θ is the angular distance round the cylinder, $\theta = 0$ being the leading edge, and the chord is taken as the diameter. The lift-coefficients for these four flap angles were respectively 0·18, 0·35, 0·7 and 1·75.

For other flap angles, C_L was estimated as follows. Let q_u, q_l be the maximum and minimum velocities respectively on the cylinder and let q_0 be the maximum velocity at $C_L = 0$. Then, exactly for an infinite inviscid stream and otherwise approximately, we have

$$\left. \begin{aligned} q_u &= q_0 + 2U \sin\alpha \\ q_l &= q_0 - 2U \sin\alpha \end{aligned} \right\} \text{ where } C_L = 4\pi \sin\alpha$$

Thus $C_L = \pi\,(q_u - q_l)/U$. It is noticeable that in this formula C_L is independent of q_0 (which for an infinite stream equals $2U$) and it is, therefore, to be expected that it gives tolerable results for a cylinder in a tunnel. In this way, the C_L's corresponding to greater flap angles were estimated. The (C_L, α) curve thus obtained is shown in Fig. 7. It is seen that as α increases, the difference between the observed C_L and the theoretical value increases. To what extent this is attributable to either tunnel interference or the inherent behaviour of the flap must be determined by future experiment. Undoubtedly as the C_L increases the straight flap becomes less effective and a flap curved to the shape of the dividing streamline becomes necessary.

It is a matter of considerable interest whether, in fact, a C_L of 4π is practically obtainable by placing a suitable shaped flap at $\theta = 90$ deg, on the lower surface*. If it is obtainable, then it would appear possible to obtain C_L's of any value by increasing the thickness/chord ratio beyond unity. For example, consider the flow past a circular cylinder when there is no stagnation point on the surface. Then if a body is made to the shape of the closed streamline which passes through the stagnation point and a flap added suitably, a C_L greater than 4π will be obtained. The mathematical theory of the design of cylindrical sections for which the lift is independent of the incidence is given in R. & M. No. 2612.

Further Work.—In (i) of Section 2, various defects in the apparatus were briefly outlined. Whether it will be possible to modify the existing apparatus to enable trustworthy results to be obtained has yet to be decided, but it is the author's opinion that a larger scale model is required. It might be as well to describe below the full programme that it is hoped to complete eventually. Basic principles concerning the effect of continuous suction and the flap have been established.

First, accurate measurements are required of the pressure distribution round the cylinder for large amounts of suction and a range of positions of the flap. Secondly, the relation between the suction coefficient and the rate of momentum loss in the wake is required. Implicit in this investigation would be a determination of the 'hysteresis' effect if there is one. Thirdly, examination of the boundary-layer velocity distribution is required (a) to compare theoretical

* In this case there would be, of course, a single stagnation point on the surface.

results when separation is prevented, (b) to obtain information about the boundary layer when separation and suction both occur. These last two researches are, of course, concerned more with a boundary layer with continuous suction than with a circular cylinder and the requisite information could probably be obtained with greater ease and accuracy with entirely different apparatus.

Further work on the flap is already in hand. A symmetrical aerofoil has been designed according to the methods of Reference I[1] for which the velocity is constant over the whole of the upper surface for a certain C_L at zero incidence, and a model has been made.

Conclusion.—Some preliminary experiments on a wholly porous cylinder fitted with a Thwaites Flap have been described. The experiment has fulfilled its purpose in shewing that the Flap does, in fact, enable lift to be generated under particular conditions. One can be confident, therefore, that under the general conditions laid down in Part I of this paper, it is possible for lift and incidence to be independent, while control on both is fully and effectively maintained. The principles of the Thwaites Flap thus having been firmly established, it remains for refined experiments to be made and development work to proceed.

REFERENCES

No.	*Author*	*Title, etc.*
1	B. Thwaites	On the Design of Aerofoils for which the Lift is Independent of the Incidence. R. & M. No. 2612. January 1947.

Note: At the time of going to press, an experiment has been concluded in a 4-ft wind-tunnel, using a 3-in. diameter porous circular cylinder fitted with a Thwaites flap. Extensive measurements were made of the boundary layer, the wake and the pressure distribution for large ranges of flap deflection, flap size, suction quantity and Reynolds number. The work has been reported in the following two papers:—

(a) R. C. Parkhurst and B. Thwaites — Experiments on the Flow past a Porous Cylinder fitted with a Thwaites Flap. R. & M. No. 2787. October 1950.

(b) D. Hurley and B. Thwaites .. — An Experimental Investigation of the Boundary Layer on a Porous Circular Cylinder. A.R.C. Report 14158. July, 1951. (To be published.)

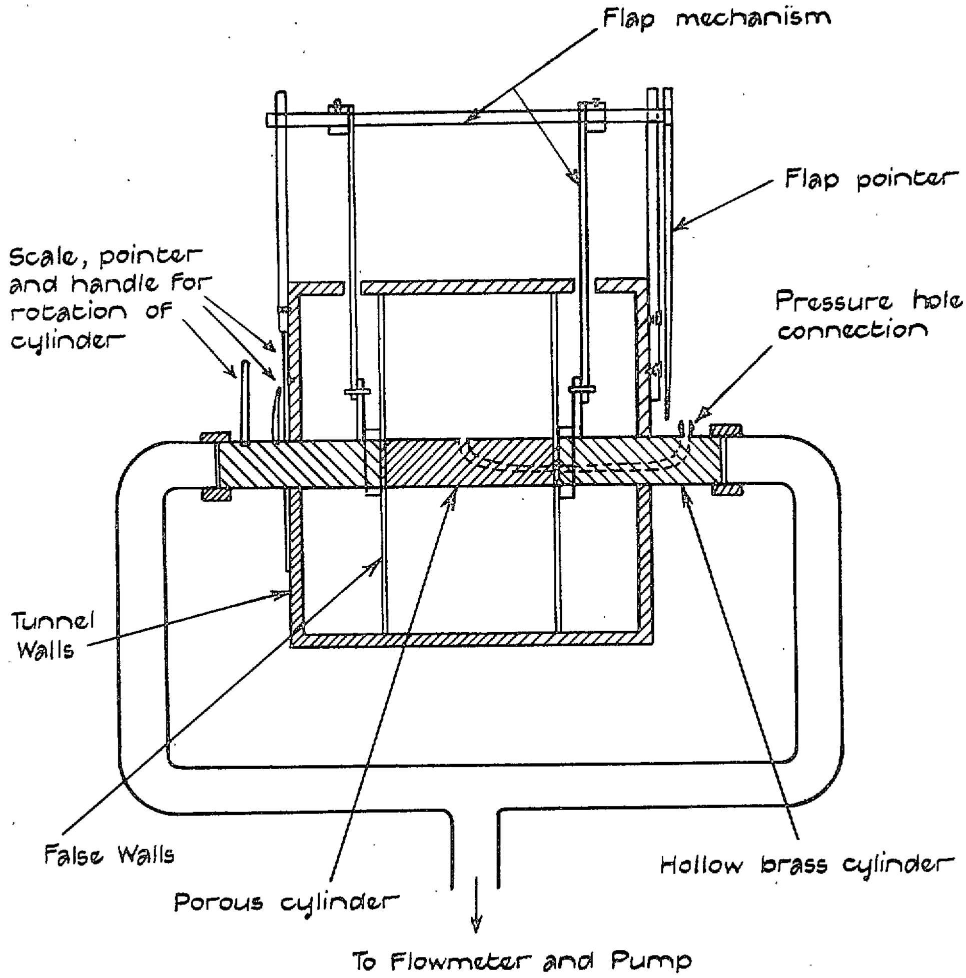
Flap mechanism
Flap pointer
Scale, pointer and handle for rotation of cylinder
Pressure hole connection
Tunnel Walls
False Walls
Porous cylinder
Hollow brass cylinder
To Flowmeter and Pump

FIG. 1.

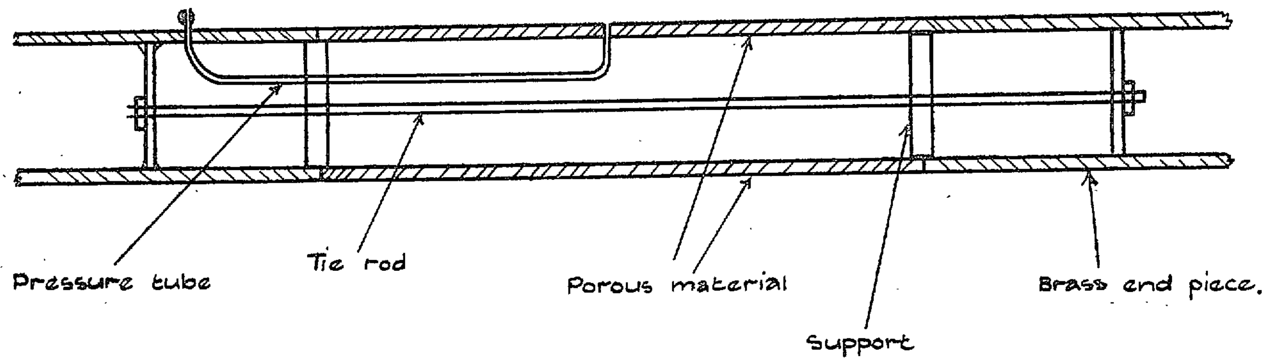
Pressure tube
Tie rod
Porous material
Support
Brass end piece.

FIG. 2.

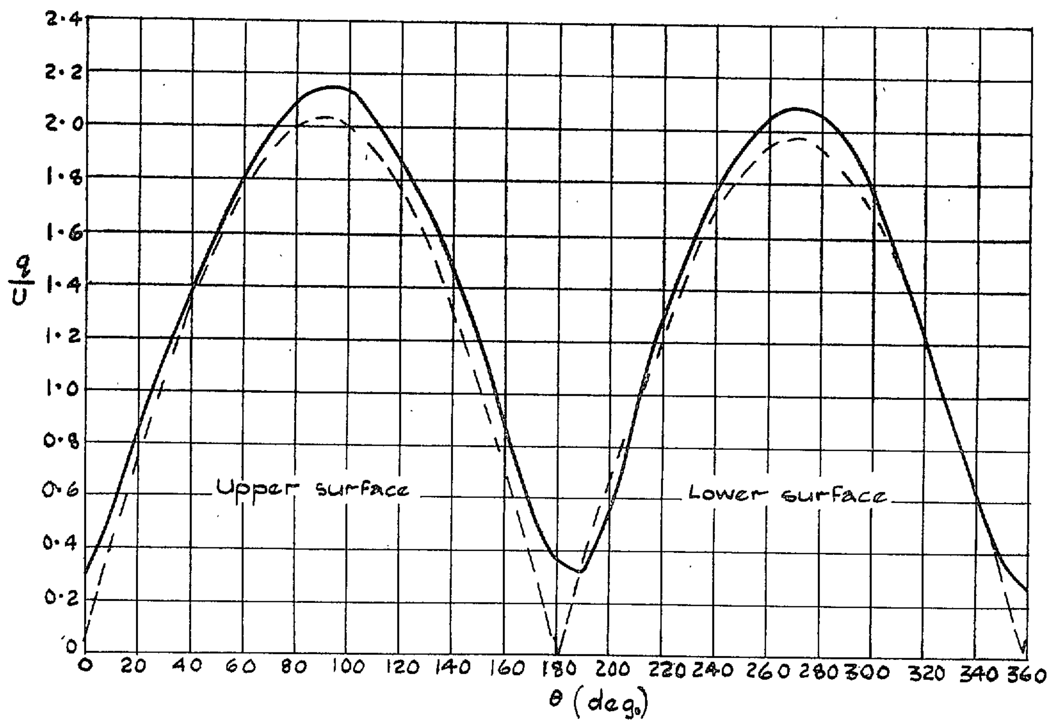

Fig. 3 Flap at 1 deg. Incidence

——— Experimental velocity distribution
– – – Theoretical curve for infinite stream

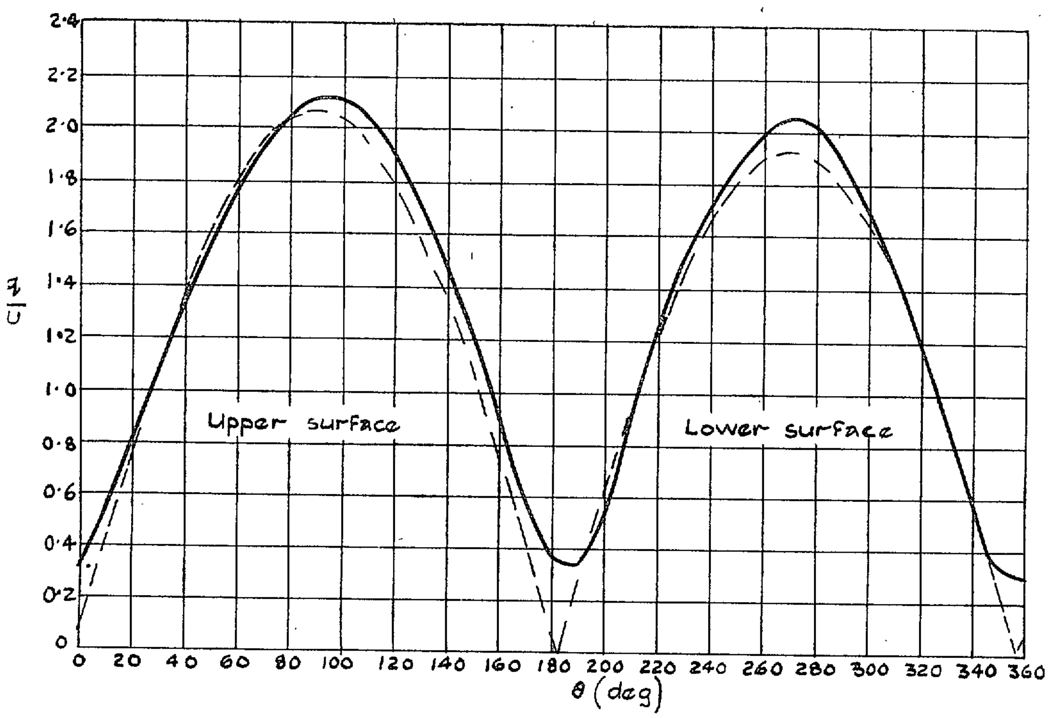

Fig. 4 Flap at 2 deg. Incidence

——— Experimental velocity distribution
– – – Theoretical curve for infinite stream

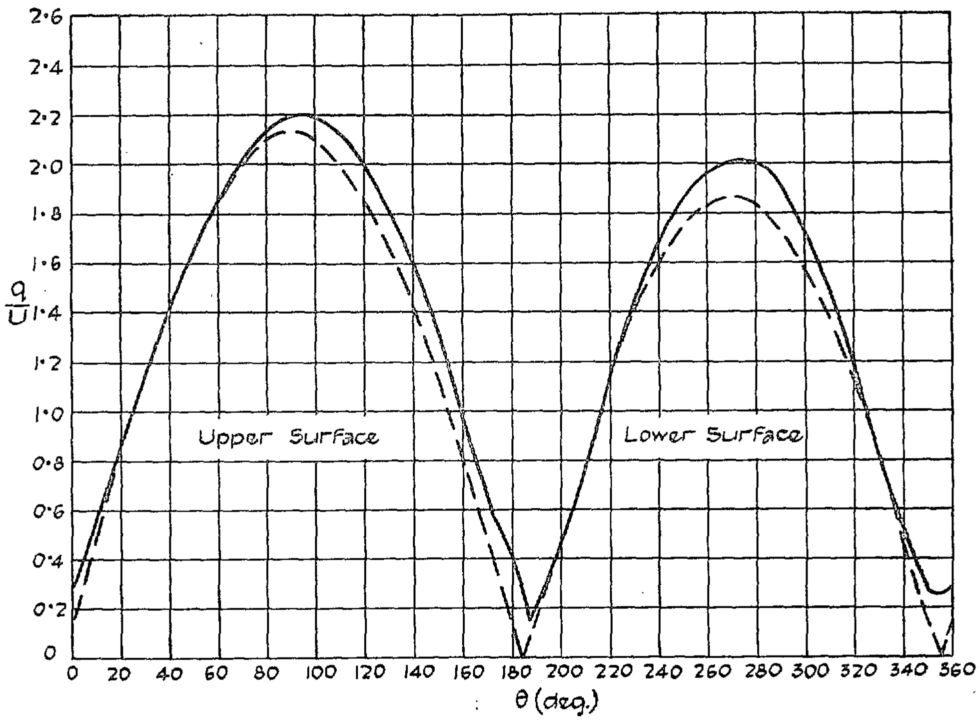

Fig. 5 Flap at 4 deg. Incidence

——— Experimental Velocity Distribution

– – – – Theoretical Curve for Infinite Stream

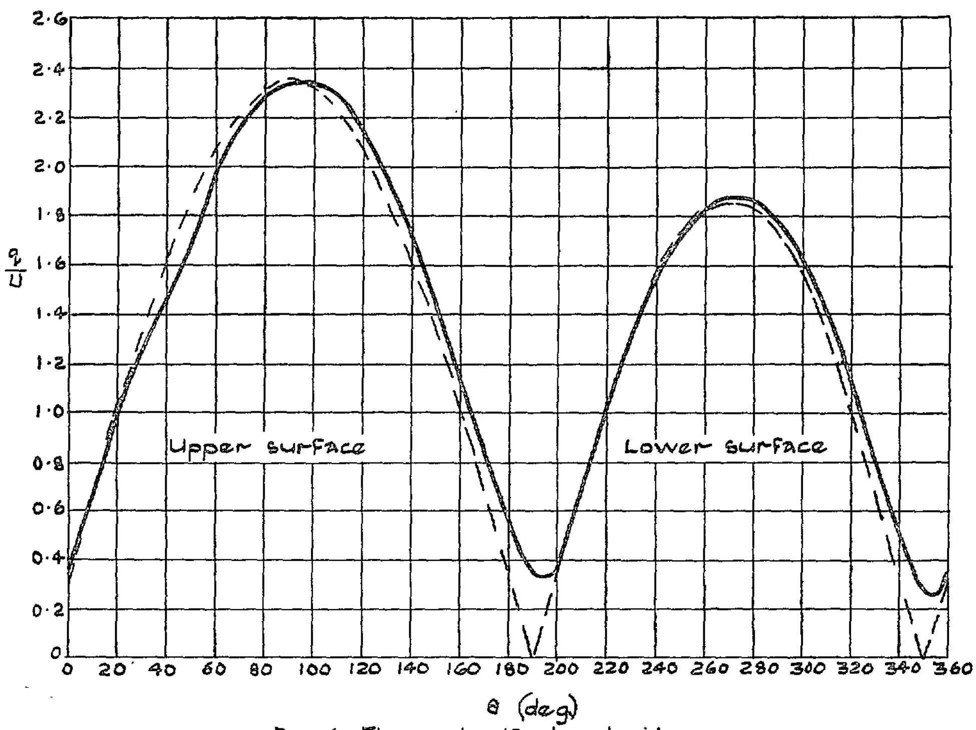

FIG. 6 Flap at 10 deg. Incidence

——— Experimental velocity distribution

– – – – Theoretical curve for infinite stream

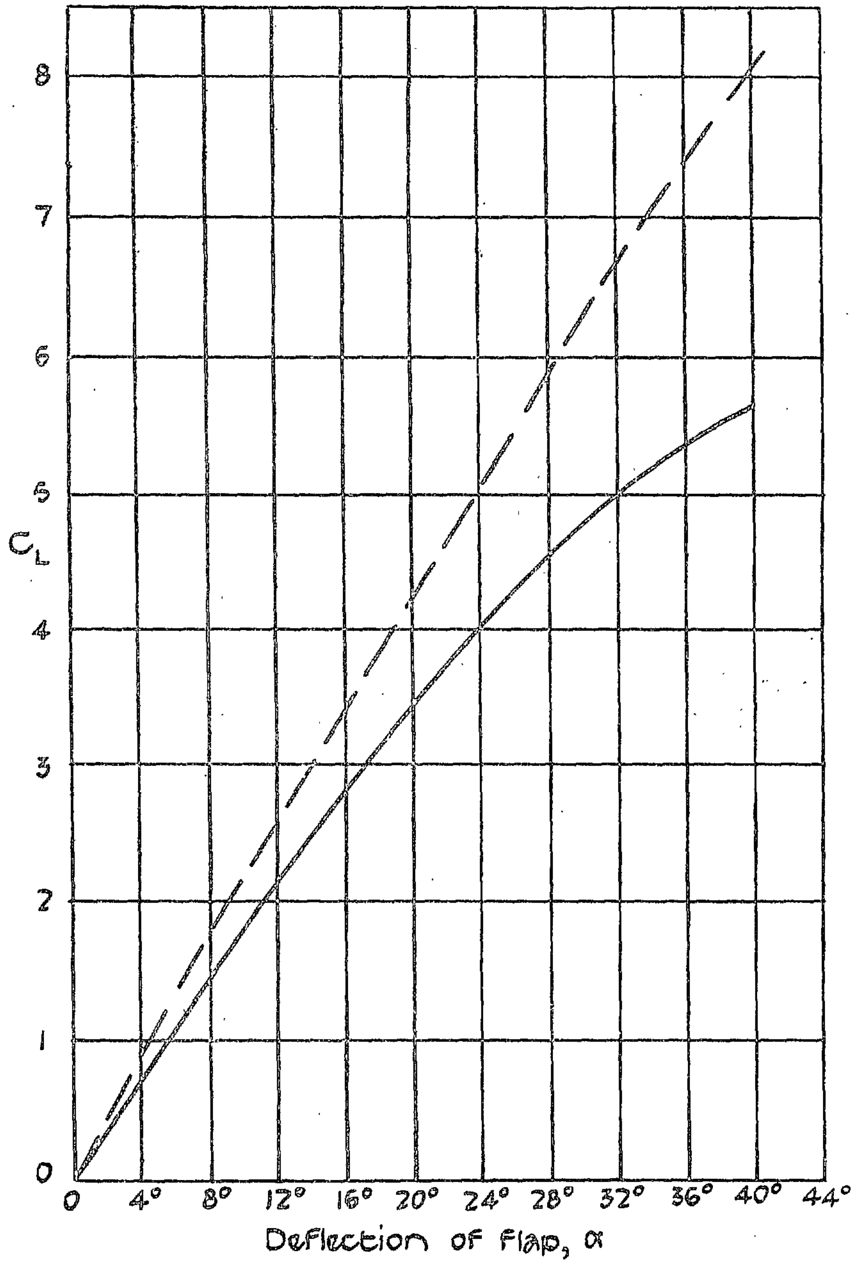

Fig. 7.

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