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R. C. PANKHURST, D.I.C., Ph.D., A.F.R.Ae.S.,
of the Aerodynamics Division, N.P.L.
and
B. THWAITES, M.A., Ph.D., A.F.R.Ae.S.,
Department of Aeronautics, Imperial College of Science

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W. S. WALKER,
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*Summary.*—This paper describes wind-tunnel experiments on a porous circular cylinder of 3 in. diameter fitted with a Thwaites Flap. Measurements were made of the pressure distribution at mid-span, together with a number of wake traverses, over a range of suction quantity, flap size, wind speed and flap setting.

The distributed suction effectively prevented boundary-layer separation and enabled a close approximation to potential flow to be achieved. The flap was essential to the attainment of steady flow conditions with suction; without a flap the pressure recovery at the rear of the cylinder was incomplete and the pressure distribution fluctuated. In view of this unsteadiness in the flow without a flap, the circulation could scarcely be expected to remain, as had previously been conjectured, when the flap was withdrawn.

Over the limited Reynolds number range of the tests, the minimum suction quantity needed to prevent separation ($C_{Q\,\min}$) appeared to be proportional to $R^{-n}$ with $n$ rather greater than the theoretical value of $\frac{1}{2}$ for a laminar boundary-layer. For a given Reynolds number, $C_{Q\,\min}$ decreased with increasing flap size.

At small flap deflections the wake could be completely suppressed. The suction quantities required increased with flap deflection, owing to the increased severity of the adverse pressure gradient over the rear of the cylinder. With the available pump the maximum lift coefficient attained was about 9, but there is no reason to doubt that still higher values would have been reached with greater suction.

The wake traverse measurements indicated only slight hysteresis according as the suction was increasing or decreasing.

1. *Introduction.*—The possibility of reducing the adverse effects of viscosity in applied aerodynamics by withdrawing boundary-layer air through slots or porous surfaces is widely appreciated. Further, such control of the boundary layer can result in the setting-up of real fluid flows which previously had not been possible. In particular, boundary-layer control can theoretically prevent separation† and enable near-potential flows to be achieved.

Previous experimental work concentrated on slot suction and showed that, in suitable circumstances, this method of boundary-layer control could delay or prevent both transition and separation. In some applications it has been found that the amount of air withdrawn must exceed the whole of that in the boundary layer—for example, in re-establishing a laminar layer downstream of a turbulent one (R. & M. 2742[1]). This is understandable. It is not so easy to understand the necessity (R. & M. 2646[2 and 3]) of sucking more than the boundary layer at a

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† For instance, in the case of the steady flow of a laminar boundary layer over a porous surface through which the normal inward velocity $v_0$ is sufficiently large, the theoretical velocity distribution is (in the usual notation)

$$\frac{u}{U} = 1 - e^{-v_0 y/\nu},$$

which is far from a separation profile.



(26373)

place of large and sudden pressure-rise in order to prevent intermittent separation and ensure steadiness: this suggests (apart from some possibility of adverse effects arising from the slot design) that conditions of stability may have to be considered over and above the requirements indicated by the theory of the steady boundary layer.

Suction through porous surfaces has not received so much attention experimentally, but it has been verified[4–11] that it can, again in suitable circumstances, produce similar effects to slot suction as far as transition and separation are concerned, and no considerations of steadiness have had to be made.

The physical possibility of maintaining a thin boundary layer over the whole of a body of any shape led to the idea of the Thwaites Flap[4, 12], a device for obtaining any circulation about any body with a rounded rear and set at any incidence to the stream. The Flap is essentially a thin piece of material running spanwise along the rounded trailing edge of a wing on which slots or porous surfaces are used at least to prevent separation. The flap, normal to the surface and in contact with it, fixes the position of the rear dividing streamline and so determines the circulation about the body. In the absence of a sharp edge, the circulation can presumably take any steady value according to the method of its generation. Certain limits to circulation, shape and incidence are set by other aerodynamic considerations, but are probably beyond those dictated by ordinary practical considerations.

In the original paper (R. & M. 2611[12]) the following proposition was made: if, after establishing steady motion with circulation, the flap is suddenly withdrawn into or away from the surface, then the boundary-layer suction will prevent the escape of any vorticity generated at the boundary and the circulation will remain constant*. A similar statement is made in Ref. 13.

The tests described in this paper were undertaken in order to check experimentally, as far as possible, theoretical predictions concerning the flap and its withdrawal. A circular cylinder was chosen because (i) the potential flow patterns about it are easily calculable, (ii) it presents a severe test for distributed suction, owing to the large pressure rise to the rear stagnation point, (iii) the mechanism for moving the flap round the surface is particularly simple, and (iv) porous circular cylinders are obtainable commercially from stock. The theoretical predictions which it was hoped in particular to verify were those concerning

(a) The question of flap withdrawal

(b) The variation of $C_L$ with flap deflection ($\alpha$); the theoretical relation is

$$C_L = 4\pi \sin \alpha$$

and a previous rough experiment[4] in a small tunnel gave a lift-curve slope, at low incidence, of $0{\cdot}85 \times 4\pi$.

(c) The development of the boundary layer with continuous suction. This is most conveniently considered separately and will accordingly be described in a later report[17].

In addition, information was sought on the following points which it is not yet possible to predict theoretically:—

(d) The dependence of the pressure distribution on suction quantity, and hence the variation of $C_L$ with $C_Q$ for fixed $\alpha$.

(e) The progressive development of the wake as the suction is reduced.

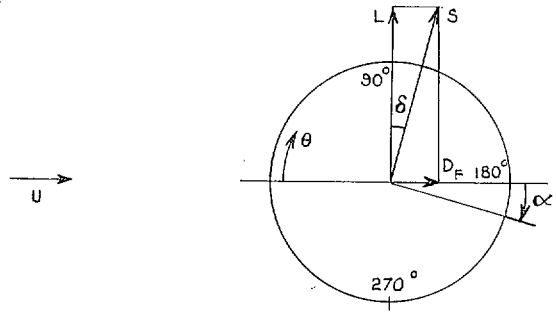
(f) Scale effect, as far as this could be investigated over the limited range of tunnel speed.

(g) The effect of flap size.—Theory gives no indication of the minimum length of flap, except that this should presumably be greater than the boundary-layer thickness if near-potential flow is to be obtained. Another result which cannot be predicted theoretically is whether, for values of $\alpha$ greater than say 60 deg, the flap needs to be curved to follow the dividing streamline of potential flow.

(h) The possible occurrence of hysteresis according as the suction quantity is being increased or reduced.

* If confirmed by experiment, this phenomenon would assume practical importance. For example, the effects of gusts in the atmosphere could be lessened.

*List of Symbols*




| | |
|---|---|
| $c$ | Cylinder diameter |
| $D_F$ | Form drag (at mid-span) |
| $C_{DF}$ | Form drag coefficient, based on cylinder diameter:— $$C_{DF} = (1/\rho U^2) \oint P \cos\theta \, d\theta$$ |
| $C_D{}'_F$ | Form-drag coefficient referred to apparent wind axis (sect. 11):— $$C_D{}'_F = C_{DF} - C_L \sin\delta'$$ |
| $C_{DW}$ | Wake-drag coefficient, based on cylinder diameter:— $$C_{DW} = 2\int(1 - \sqrt{g})\sqrt{(g - p_w)}\, d(y/c)$$ |
| $C_L$ | Lift coefficient, based on cylinder diameter:— $$C_L = -(1/\rho U^2) \oint P \sin\theta \, d\theta$$ |
| $C_p$ | Pressure coefficient:— $$C_p = (P - P_0)\tfrac{1}{2}\rho U^2$$ |
| $C_Q$ | Suction quantity coefficient:— $$C_Q = Q/Uc$$ |
| $g$ | $(H - P_0)/\tfrac{1}{2}\rho U^2$ |
| $H$ | Total head at point $y$ in wake |
| $L$ | Lift (at mid-span) |
| $P$ | Static pressure at point $\theta$ on surface of cylinder |
| $P_0$ | Static pressure in undisturbed stream |
| $P_w$ | Static pressure at point $y$ in wake |
| $p_w$ | $(P_w - P_0)/\tfrac{1}{2}\rho U^2$ |
| $Q$ | Suction quantity flow per unit span of cylinder (centre section) |
| $R$ | Reynolds number, $Uc/\nu$ |
| $S$ | Resultant of lift and form drag |
| $U$ | Wind speed as measured at position of model with model removed |
| $y$ | Distance across wake, measured normal to the flap |
| $\alpha$ | Flap setting |

*List of Symbols—continued*

| | |
|---|---|
| $\delta$ | Inclination of force $S$, *i.e.*, arc tan $(D_F/L)$ |
| $\delta'$ | Inclination of apparent wind direction deduced from pressure distribution (*see* sect. 11) |
| $\theta$ | Angular position round circumference of cylinder |
| $\nu$ | Kinematic viscosity of fluid |
| $\rho$ | Density of fluid |

2. *Apparatus.*—The porous cylinder was 3 in. in diameter and was made of sintered bronze (' Porosint ', grade C) $\frac{1}{4}$ in. thick. Its resistance to normal flow was such that in the experiments the pressure drop across the porous material, while within the range of the pump, was much greater than the variations in static pressure over the external surface of the model, thereby ensuring uniformity of suction velocity*. The overall span was restricted to 15 in. because of the limited volume capacity of the pump. The model was mounted horizontally between false walls, extending 2 ft upstream and 2 ft downstream, in the N.P.L. 4 ft No. 2 Wind Tunnel. As the porous material was not available in a 15 in. length, the model was constructed in three sections. The lengths supplied were found to differ in porosity by 12 per cent; the more porous material was used for the outer sections (each of 3·75 in. span) in the hope of minimizing end effects. The model (Fig. 1) was provided with 36 pressure holes, equally spaced in two rows $\frac{1}{2}$ in. on either side of mid-span, by inserting short lengths of hypodermic tubing as force fits into holes drilled (slightly undersize) in the porous material. The Flap was carried from side-plates attached to circular flanges concentric with the cylinder. Flap sizes of $\frac{3}{4}$ in., $\frac{1}{2}$ in., $\frac{3}{8}$ in., $\frac{1}{4}$ in. and $\frac{1}{8}$ in. were tested.

For the flap-withdrawal experiment the flap was carried from arms attached to its ends and rotating about an axis parallel to that of the cylinder and located (near the tunnel ceiling) so that the initial path of the flap followed approximately the calculated dividing streamline for a setting of about 8 deg. The withdrawal gear was spring-loaded and was operated by means of a cable release.

A pitot-comb was mounted behind the cylinder from the same side-plates as carried the flap. The total-head tubes were therefore parallel to the flap with their open ends along a line at a perpendicular distance of $1\frac{1}{2}$ in. $(0{\cdot}5c)$ from the surface of the cylinder. Static tubes were provided at the extremes of the comb and, slightly off-centre, at the middle.

Suction quantity was measured by means of a pitot-tube set centrally in a calibration pipe.

The datum tunnel speed was measured (between the false walls) with the model removed. The static-pressure gradient in the tunnel was measured at the same time.

3. *Reduction of Observations.*—The mid-span pressure distribution was recorded over a range of suction quantity, Flap size, tunnel speed (25 to 70 ft/sec nominal) and flap setting. The wake traverses were restricted to small flap deflections (0 and 20 deg).

The tunnel interference due to lift constraint was negligible, as was also that due to solid blockage. No correction was applied for wake blockage because this did not reach 1 per cent until the wake-drag coefficient ($C_{D\,W}$) exceeded 0·64, where little interest attaches to the results. A correction was applied to the form-drag coefficient ($C_{D\,F}$) to allow for the measured static-pressure gradient with the model removed.

* There was some evidence, however, of non-uniformity in the porous material itself.

The values of $C_{D\,W}$ are of rather limited absolute accuracy, especially with the flap deflected, the probable error in some cases being as much as 5 to 10 per cent. This inaccuracy arose partly from the considerable cross-stream variation in static pressure and partly from the curvature of the streamlines behind the cylinder when the suction prevented boundary-layer separation. Had time permitted, the pitot-comb would have been provided with additional static-pressure tubes and mounted further downstream. In any event the results are adequate for the determination of the suction quantities required for complete suppression of the wake (zero $C_{D\,W}$), and the relative values are reliable for comparisons at different experimental conditions with flap fixed.

No estimates have been made of the pump power requirements, as these would have little significance in this investigation. Moreover, the porous resistance of the material of the cylinder had deliberately been chosen to be high in order to even out variations in suction velocity over the surface. The practical significance of the various drag forces is discussed in general terms in Appendix I.

The general scheme of the test programme is set out below:—

(a) *Pressure plotting*

(i) Scale effect for various flap sizes at zero flap setting

(ii) Scale effect for $\frac{1}{2}$ in. flap at 10 deg deflection

(iii) Variation of lift with suction quantity* (at upper end of the $C_Q$-range) for flap settings of 10 deg, 20 deg and 30 deg and (nominal) tunnel speeds of 25 and 60 ft/sec.

(iv) Variation of lift and form drag with flap setting for several flap sizes at 40 ft/sec.

In (i) to (iii) a range of suction quantity* was covered for all conditions; in (iv) the suction was reduced until inspection of the manometer showed separation to be imminent at the rear of the cylinder.

(b) *Wake traverses*

Variation with suction quantity* and flap size at zero flap deflection and 60 ft/sec. *See* also (c).

(c) *Hysteresis*

Pressure-plotting and wake-traverse measurements at zero flap setting for the $\frac{3}{8}$ in. flap, and at 20 deg flap setting for two flap sizes ($\frac{1}{8}$ in. and $\frac{3}{4}$ in.). Tunnel speed 60 ft/sec.

Porosity measurements before and after the above extensive programme of tests showed that no serious clogging of the porous material had occurred during this period.

4. *General Results.*—With the Flap in position, the application of sufficient suction enabled complete pressure recovery to be obtained at the rear of the cylinder, with a close approximation to potential flow, up to quite large flap deflections. Without the flap, however, full pressure recovery was never recorded on the pressure-plotting manometer, even with the maximum available suction quantity (which in one instance at least was more than twice that which ensured full pressure recovery with a flap present at zero deflection). Fig. 2a shows typical pressure distributions, with full suction, both without a flap and with the smallest flap ($\frac{1}{8}$ in.). The corresponding results with zero suction are included for comparison.

The wake-traverse measurements (at $\alpha = 0$ and $\alpha = 20$ deg) showed that, with the flap present, the suction was able to suppress the wake completely. Without flap, however, the pitot-comb always indicated some loss of total head (Fig. 2b). The smoke visualization experiments described in Appendix II showed that, without a flap, the spanwise distribution of circulation was irregular, as vorticity was continually being shed by the cylinder all along the span. There was, however, little or no separation in the smoke experiments.

* Unless otherwise indicated, all measurements were made with suction decreasing and wind speed held constant (*see* section 9).

Further, without a flap the pressure distribution with suction fluctuated markedly, particularly over the rear of the cylinder. So also did the wake pattern, although not to such a great extent*. Without suction the pressure-distribution and wake-traverse measurements were completely steady although the boundary layer had separated over the rear of the cylinder.

In these circumstances, the circulation could not be expected to remain when the flap was withdrawn, as the final state postulated (that of unseparated steady flow without flap) appears to be physically impossible. What in fact happened when the flap was withdrawn suddenly, after steady conditions with circulation had been established, was as follows. After one or two seconds (part of which may have been due to lag in the pressure leads) the pressure at the rear stagnation point decreased from the full total head of the free stream; within a few more seconds there was a general decrease of pressure over the rear of the cylinder, although there was no marked unsteadiness in these pressures. During this time, vorticity must have been shed into the wake, for the minimum pressures on upper and lower surfaces began to approach each other, indicating a loss of circulation. Subsequently the pressures over an arc of, say, 60 deg† at the rear of the cylinder slowly decreased and fluctuated more and more, while the pressures elsewhere decreased slightly and the circulation fell to zero. After about a minute, a new quasi-steady state had been reached, with zero circulation.

Thus, in addition to its function as a means of generating lift, the flap is essential for the establishment of steady unseparated flow on a body with a rounded rear. Two questions immediately arise: what size of flap is necessary, and why is the flow oscillatory even with a large suction quantity? A theoretical answer to the first question would probably follow from that to the second. Experimentally it was found that flaps of $0{\cdot}25$, $0{\cdot}16$, $0{\cdot}08$ and $0{\cdot}04$ of the cylinder diameter ($c$) all produced the necessary stabilising effect, although the minimum suction quantity to prevent separation increased slightly as the flap size was reduced. Even a wire of diameter $0{\cdot}028$ in. ($0{\cdot}009\ c$) was effective in stabilising the flow‡§.

In the absence of further knowledge it is not possible to say whether this instability phenomenon is a two- or a three-dimensional effect. In the former case the loss of total head in the wake is to be ascribed to boundary-layer separation; in the latter case, to the effects of spanwise variations of circulation. Both possibilities are examined more fully below.

(a) The inability of the suction to prevent separation in the absence of the flap suggests that in these circumstances some type of boundary-layer oscillation occurs which, if not itself unstable, at least results in a separation velocity profile. The problem is essentially a boundary-layer one: there appear to be disturbances which under conditions of large suction velocity can produce separation. Such disturbances could originate from spanwise variations or from variations in the flow at any cross-section. Spanwise disturbances may well be generated at the false walls, on which there is almost certainly separation near the rear of the cylinder because of the large pressure rise made possible by the prevention of separation on the cylinder itself. When the flap is withdrawn, this separation might result in an unstable spanwise distribution of circulation. As regards disturbances in two-dimensional flow, it is possible that the suction does not prevent *any* vorticity at all being shed into the wake but that there is a *continual* shedding of vorticity alternately from upper and lower surfaces of the cylinder, resulting in a rapidly oscillating small-amplitude disturbance to the circulation. The effect

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* The curves shown for this case in Figs. 2a and 2b were obtained from instantaneous photographs of the recording manometer.

† This extent depends on the suction quantity. The figure quoted corresponds to the maximum $C_Q$; for the minimum quantity necessary to prevent separation with the flap, the extent of arc is more like 120 deg.

‡ The wire was placed at about 8 deg deflection together with the $0{\cdot}25c$ flap. When the latter was suddenly withdrawn, no change occurred in the pressure distribution, and the circulation remained.

§ The absolute minimum is probably determined by the boundary-layer thickness, which is inversely proportional to the suction velocity when this is large. This suggests that the minimum flap length may also be inversely proportional to $v_0$.

on the boundary-layer could be restricted by the flap and the flow could be unstable without this constraint. Alternatively, oscillations might be started within the boundary layer by variations in suction velocity, by irregularities in the surface, or by vibration, again producing unstable disturbances without the constraint imposed by the flap.

In view of the intuitive feeling that a stagnation point away from a surface (as the rear stagnation point in this experiment) may be unstable, together with the known tendency for disturbances to be amplified in a region of rising pressure, it was decided to place the flap at the front of the cylinder, as a strong inducement to instability. The result, however, was unexpected: the flow was considerably less unsteady than without flap, although not completely steady as it was with flap at the rear. With the forward flap approximately central, the pressure recovery over the rear of the cylinder was not far from complete*, although there was a small local separation from the leading edge of the flap. With the forward flap deflected to 30 deg ($\alpha = 210$ deg), the pressure distribution showed that separation became marked at the rear of the cylinder* and also locally at the flap, but a lift coefficient of $-1{\cdot}23$ was obtained nevertheless.

(b) On the other hand, the smoke experiments indicated little or no separation over the rear of the cylinder, the downstream dividing streamlines leaving the cylinder in an unsteady wavy line. Certainly the same suction quantity is adequate for the prevention of separation when the flap is present (with pressure gradients which are not greatly different from those without the flap, and which moreover are less severe than those which the boundary layer surmounts when the flap is present and deflected). If the flow conditions are similar at the higher Reynolds numbers of the main experiments, the loss of total head recorded behind the cylinder corresponds to the induced drag associated with the trailing vortices. In normal applications the pitot-traverse method does not register induced drag because its effects are spread over a much wider area than the wake. In our case, however, the measured loss of total head (without flap, with full suction) extends over a distance greater than one cylinder diameter despite the nearness of the pitot-comb to the cylinder. If the trailing vorticity does in fact account for the observed loss of head, the incomplete pressure recovery recorded over the rear of the cylinder is to be ascribed to the fact that (with the whole flow pattern unsteady) the manometer records some sort of mean, which necessarily falls short of stagnation conditions.

Clearly this new instability problem needs further elucidation, and theoretical investigations should be made into its mechanism so that its future occurrence will be predictable in advance, especially as several recent experimental researches have also disclosed peculiar unsteadiness phenomena which may well be of a related character.

## EFFECT OF SUCTION VARIATION

5. *Pressure Distributions.*—Examples of the progressive development of the pressure distribution with suction are shown in Fig. 3. With sufficient suction, separation is entirely prevented. A close approximation to potential flow is then achieved, with complete pressure recovery at the rear of the cylinder.

6. *Form Drag.*—With zero suction the form drag increased with Reynolds number and decreased with flap size (Figs. 4a and 4b). Typical curves of form drag against suction quantity are shown in Fig. 5. These suggest that separation was prevented at values of $C_Q\sqrt{R}$ greater than about 30. To obtain a more definite value, the upper part of each curve could be continued linearly to give an extrapolated value corresponding to zero $C_{DF}$. Although such a procedure is quite arbitrary, it would be expected to give reasonable rough estimates of the required suction quantity and enable comparisons to be made; the values thus obtained are included in Figs. 6 and 7, although a more accurate estimation of the suction needed to suppress the

* The suction was sufficient to ensure full pressure recovery with flap in the corresponding positions at the rear of the cylinder.

wake can be obtained from the wake-drag measurements (*see* section 7). The fact that the measured value of $C_{DF}$ did not reach zero even when separation was known to have been prevented is not significant (*see* Appendix I), but its low value (of the order of one hundredth its value without suction) indicates a close approximation to potential flow. This is confirmed by the corresponding pressure distributions.

According to the theory of the laminar boundary layer with distributed suction, scale effect can be wholly taken into account by the parameter $C_Q\sqrt{R}$. The experimental results show. however, that the curves obtained for various Reynolds numbers do not coincide exactly (*cf.* Fig. 5), but that over the speed range of the tests the values of $C_Q\sqrt{R}$ for chosen values of $C_{DF}$ fall slightly with increase of Reynolds number (Figs. 6a and 6b). For given $C_{DF}$ the values of $C_Q\sqrt{R}$ also fall slightly with increas eof flap size (Fig. 7b), particularly at the lowest values of $C_{DF}$. The rough values for zero $C_{DF}$ obtained by linear extrapolation of the curves of $C_{DF}$ against $C_Q\sqrt{R}$, however, show no systematic variation (Fig. 7c); but the (more precise) values for zero *wake* drag do fall as the flap size increases (section 7 and Fig. 9b).

7. *Wake Drag.*—Results for zero flap deflection are shown in Figs. 8 and 9. The values of $C_Q\sqrt{R}$ for given $C_{DW}$ decrease as the flap size is increased; values for zero $C_{DW}$ (complete suppression of the wake) are plotted in Fig. 9b. Comparison with Fig. 7c shows that, for all flap sizes, separation had certainly been prevented with suction quantities considerably smaller than those obtained by linear extrapolation of the curves of $C_{DF}$ against $C_Q\sqrt{R}$ (section 6).

The wake traverses themselves (Fig. 8) show that at low values of $C_{DW}$ the main contribution to the drag came from the top surface of the cylinder, suggesting non-uniformity of porosity. (This observation also applies to the form drag, as was shown by a comparison of theoretical and experimental curves of $C_p \cos\theta$ plotted against $\theta$.)

For a given flap size, the suction quantity for a chosen value of $C_{DW}$ increases with flap deflection. Results for 20 deg flap deflection and two flap sizes are shown in Fig. 11 and discussed in section 9.

8. *Lift.*—The variation of lift coefficient with suction quantity is shown in Fig. 10a for flap deflections of 10 deg, 20 deg and 30 deg for the lowest and highest wind speeds. The lift increases less rapidly at the highest suction quantities, but does not appear to have reached asymptotic values. The highest lift coefficient recorded was less for the highest Reynolds number than for the lowest, although at smaller values of $C_Q\sqrt{R}$ the largest Reynolds number gave the highest lift for a given value of $C_Q\sqrt{R}$. As in current R.A.E. tests on an application of distributed nose suction to increase the maximum lift of a swept-back wing, the falling off at high wind speeds may be due to an appreciable departure from uniformity of suction velocity over the circumference of the cylinder.

With very small suction quantities the lift varies erratically (Fig. 10b). Inspection of the pressure distribution recorded on the manometer suggested that as the area of separated flow extended with decreasing suction, vorticity of one sign or the other was shed unpredictably from the cylinder. In view of this, the variation of $C_L$ with $C_Q$ at low suction quantities is not surprising, and could be due to non-uniformity of porosity.

With zero suction a small deflection of the flap has little influence on the lift, although a small positive value was observed at the lowest Reynolds number (Fig. 4c).

9. *Hysteresis.*—For a given suction quantity the measured wake drag tended to be slightly less when approached from higher values of $C_Q$ than when approached from lower. This is exemplified by Fig. 11. No definite trend was observed for lift and form drag.

Unless otherwise stated, all the results in this report were obtained with suction decreasing (wind speed held constant). The maximum values of $C_Q\sqrt{R}$ obtainable were approximately 46, 42, 37, 32, 29 and 27 at the Reynolds numbers of $4{\cdot}23$, $5{\cdot}07$, $6{\cdot}76$, $8{\cdot}44$, $10{\cdot}14$ and $11{\cdot}83 \times 10^4$ respectively, corresponding to tunnel speeds of 25, 30, 40, 50, 60 and 70 ft/sec.

## EFFECT OF FLAP DEFLECTION

10. *Pressure Distributions.*—The pressure distribution was measured over a wide range of flap deflection (0 to 90 deg) with the suction quantity adjusted in each case until local separation was imminent at the rear of the cylinder (as indicated by inspection of the manometer). Although this is a rather indefinite criterion for suction quantity, the lift does not vary rapidly with $C_Q$ in this region.

Typical pressure distributions are shown in Fig. 12. The lift coefficient increased steadily with flap setting (Fig. 13) until the available suction was insufficient to maintain full control of the boundary layer in the presence of the severe adverse gradients over the rear part of the upper surface at the higher flap deflections. The maximum $C_L$ obtained was about 9. Even the extreme flap deflection of 90 deg (which theoretically corresponds to a single stagnation point, with a lift coefficient of $4\pi$) did not result, as had been expected, in violent separation, despite the use of a straight flap of length $0{\cdot}12c$.

At fixed flap angle, $C_L$ increased somewhat with flap size (Figs. 13 and 14).

With the suction quantities employed* in this series of tests, $C_{DF}$ was about $0{\cdot}1$ at zero flap deflection ($\alpha$) and increased with $\alpha$ (Fig. 15a). Like $C_L$, it also tended to increase with flap size. When plotted against $C_L$ (Fig. 15b) the results for all flap sizes lay close to a single curve as long as the lift curves of Fig. 13 had not stalled.

11. *Apparent Wind Direction.*—Even the best lift curve obtained lay considerably below the theoretical, despite full pressure recovery at the rear of the cylinder (Fig. 12) and, at least at small flap settings, complete suppression of the wake. This suggests that the model, although spanning the tunnel, behaved as if it were of finite aspect ratio, with an induced downwash at mid-span. Wool tufts confirmed that conditions were unexpectedly far from two-dimensional near the false walls. The severe adverse pressure gradients achieved on the cylinder tend to cause separation of the boundary layers of the false walls, with a resulting loss of circulation towards the ends of the cylinder, and trailing vorticity.

Although an effective aspect ratio of this sort would presumably involve a marked spanwise gradient of static pressure, the suggested explanation is strongly supported by the results of an experiment† on a small porous cylinder (1 in. diameter) in a 9 in. × 5 in. smoke tunnel. Besides confirming that conditions varied across the span, this small-scale experiment showed that the front stagnation point was nearer the horizontal (*i.e.*, at a larger value of $\theta$) than symmetrically opposite the flap.

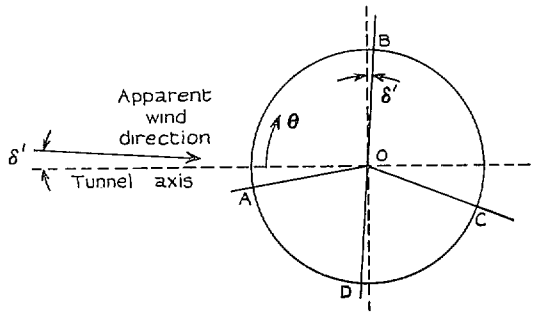
A Front stagnation point

B Position of maximum velocity on top surface of cylinder

C Position of flap

D Position of maximum velocity on bottom surface

O Axis of cylinder




* Fig. 18.

† Described in Appendix II.

Such an effect is normally associated with downwash, which would decrease the effective flap deflection and thus reduce the measured lift-curve slope below its true value. Moreover, the backwards tilt of the lift vector would give rise to an induced drag of considerable magnitude, especially as the lift coefficients are unusually high.

A quantitative estimate of this effect can be made from a comparison between the observed pressure distributions and the theoretical curves at the same $C_L$. A typical example is shown in Fig. 16. This suggests that, with the rear stagnation point ($C$) at the flap, the front stagnation point ($A$) was about 10 deg nearer the horizontal than symmetrically opposite the flap. Further, the positions of maximum velocity ($B$ and $D$) were likewise displaced by about 3 deg or 4 deg in the direction of increasing $\theta$, so that $OB$ and $OD$ were roughly in the same straight line, with $BD$ bisecting the angle $AOC$. By forming a mean* between the angular displacements of the points $A$, $B$ and $D$ as estimated from the experimental pressure distribution, the inclination $\delta'$ of the apparent wind direction in this case is seen to be about 4 deg.

If the effective wind direction is in fact inclined downwards at this angle $\delta'$, the lift coefficient should be plotted against $(\alpha - \delta')$ instead of $\alpha$. The resulting curves (Fig. 17) are much closer to the theoretical than are the uncorrected curves of Fig. 13. This analysis has also been applied to the highest lift coefficients shown in Fig. 10a, as these were obtained using the maximum available suction and were closer to the asymptotic values. The result (Fig. 19a) shows an initial lift-curve slope equal to the theoretical. The low values of the drag when referred to the apparent wind axes (Fig. 19b) also suggest that in these cases the residual boundary-layer effects were small.

To sum up, the evidence from the pressure distributions and the smoke experiments strongly supports the suggestion of downwash at the model, causing a reduction of effective incidence and an induced drag. It probably arises from separation of the wall boundary layers. A similar effect may well have been the cause of the observation reported in Ref. 14 in which the maximum lift attainable was stated to have been limited by the boundary layers of the tunnel walls ' bleeding into ' that of the model and causing a variation of circulation across the span. As in the present experiments, the pressure recovery over the rear of the model was assisted by boundary-layer suction. Thus end effects of this type may become serious whenever an abnormally strong pressure recovery is established by artificial means.

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*Concluding Remarks.*—Besides the systematic investigation of the effects of variation of suction quantity, Flap size and Flap deflection, these experiments have revealed two unexpected phenomena. One of these—the flow instability in the absence of a Flap—is believed to be of a fundamental character and of sufficient importance to warrant further research both experimental and theoretical. The other—the spanwise non-uniformity and large apparent downwash at the model—also needs further elucidation and may find practical application in relation to the design of wind tunnels for tests of two-dimensional aerofoils, particularly if the model span is little greater than the chord.

*Acknowledgement.*—The apparatus was designed by Mr. P. H. Allwork and was constructed by Mr. W. W. Smith in the Aerodynamics Division Workshop, N.P.L.

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* The expression used was

$$\delta' = \tfrac{1}{3}[(\theta_B - 90 \text{ deg}) + (\theta_D - 270 \text{ deg}) + \tfrac{1}{2}(\theta_A + \theta_C) - 270 \text{ deg}]$$

Note that the apparent wind direction is not necessarily normal to the resultant of the lift and the form drag, which is usually inclined at a greater angle ($\delta$) to the vertical.

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## APPENDIX I

*Drag Analysis for a Suction Aerofoil*

In the past a variety of terms have been used to describe the various components of drag, energy losses and power requirements for a suction aerofoil system. These are summarised in the accompanying Table and are discussed below in an attempt to avoid future misunderstanding. Only two-dimensional flow is considered.

The equation of momentum for the fluid within a circuit enclosing the aerofoil gives (using the notation set out in the Table on the next page):—

$$D_w + D_s - T_e - D = 0 \quad \ldots \quad (1)$$

and the total force on the body is

$$D = D_F + D_f + D_d. \quad \ldots \quad (2)$$

Thus

$$D_F + D_f + D_d = D = D_w + D_s - T_e. \quad \ldots \quad (3)$$

In wind-tunnel experiments it is usual to withdraw the sucked air perpendicularly to the stream, so that $T_e = 0$ and

$$D = D_w + D = D_F + D_f + D_d. \quad \ldots \quad (4)$$

For solid-surfaced bodies with no slot, (4) reduces to

$$D = D_w = D_F + D_f.$$

In the general case of bodies with slots or porous surfaces, the relative magnitudes of $D_F$, $D_f$ and $D_d$ can vary within wide limits according to the particular arrangements of the suction. As a simple example of this, consider the potential flow about a circular cylinder (perfect fluid),

(a) with concentrated sink at the rear (point sink, zero slot width)

and

(b) with uniform inward velocity over the whole surface,

the total suction quantity $Q$ being the same in both cases. Assuming $T_e = 0$, we have

$$D = \rho UQ = D_s, \quad D_w = 0, \quad D_f = 0$$

for both cases. If the contour for the evaluation of the form drag is the circumference of the cylinder, then for (a), $D_F = \rho UQ$ (provided the force on the sink is included), and $D_d = 0$; and for (b), $D_F = 0$ and $D_d = \rho UQ$. Equation (3) is satisfied in both cases. These examples show that for a suction aerofoil the form drag may have little significance as far as the total drag or the power requirements are concerned, although in some circumstances it may be used as a measure of the closeness of the real flow pattern to that of potential flow.

*Terminology*

| Term | Symbol | Definition | Comment |
|---|---|---|---|
| Total drag .. | $D$ | Force on body, as measured by a supporting balance, in direction of stream velocity*. | In flight, this is equal to the thrust force required to maintain steady motion. |
| Wake drag .. | $D_w$ | The drag force represented by the loss of pressure and momentum of the fluid downstream of the model (measured in such a way as to exclude the effects of the ejected air)*. | This can be deduced from total-head measurements in the wake. |
| Form drag .. | $D_F$ | The integral, over the surface of the body, of the drag components of the normal pressures. | Its value depends on the line of integration. The most suitable line in the case of aerofoils with slots is not obvious. |
| Friction drag .. | $D_f$ | The integral, over the surface of the body, of the drag components of the shear stresses. | Ditto |
| Sink drag .. | $D_s$ | $\rho UQ$* .. .. .. .. .. | Due to the complete destruction of the momentum of the sucked air. |
| Suction exhaust thrust | $T_e$ | Thrust component of the force (reaction on the body) due to the pressure and momentum of the ejected air*. | In tunnel experiments the air is usually ejected perpendicularly to the stream, so that $T_e = 0$. In flight the air will probably be pumped to its original pressure and velocity, so that $T_e = D_s$. |
| Duct drag .. | $D_d$ | The drag force due to the pressures and shear stresses on the body surfaces which are excluded in the evaluation of $D_F$ and $D_f$. | |

It should be noted at this stage that although the drag has been determined, the power requirements have not been considered.

To maintain steady motion the drag force given by equation (3) must be balanced by an equal thrust, and it is now necessary to consider the method of producing this thrust, the important practical criterion being minimum power. Now the efficiency of a thrust-producing system increases as the total kinetic energy gain of the fluid decreases. To avoid any kinetic energy gain at all, there would have to be no wake from the wing and no slipstream from the propulsive element, while the sucked air would have to be expelled at its original pressure and velocity by means of a suitable pump. The first two of these conditions cannot be satisfied in practice, but it can be arranged for the sucked air to be discharged as stipulated. Then $T_e = D_s$ and $D = D_w$. Let $P_p$ denote the power output of the suction pump and $P_v$ that of the propulsive element used to overcome the residual drag $D_w$. Then the total effective drag coefficient $C_{De}$ is given (R. & M. 2577[15]) by

$$\tfrac{1}{2}\rho U^3 c C_{De} = P_p + P_v = \tfrac{1}{2}\rho U^3 c(C_{Dp} + C_{Dw}) \quad .. \quad .. \quad .. \quad .. \quad .. \quad (5)$$

Since the evaluation of $C_{Dp}$ involves the energy losses in the suction ducts, which depend on the particular aircraft considered, it is convenient in experimental work to define an 'ideal' pump power $P_{pi}$ (and associated drag coefficient $C_{Dpi}$) as that corresponding to zero losses both in the ducting and at entry (in the case of slots) (R. & M. 2577[15]) or across the porous material[16]

* If the drag $D$ is evaluated by integrating the pressures and the momentum flux over a simple closed curve $C$ enclosing the system, then $D_w$, $-T_e$ and $D_s$ correspond to the separate contributions from the parts of $C$ bounded respectively by the aerofoil wake, the air discharged and the air withdrawn into the aerofoil.

(in distributed suction*). Duct losses can be minimised by good internal design, and so for suction slot aerofoils $P_p$ should not be much greater than $P_{pi}$. For aerofoils with distributed suction, $P_p$ will be considerably greater than $P_{pi}$ if the porous material offers a high resistance to the suction flow.

For practical applications and performance predictions, the over-riding considerations are power requirements (equation 5), the evaluation of the drag itself (equation 3) being relatively unimportant. It is in comparisons with theoretical flow patterns that the significance of the various components of the drag assumes importance, quite distinct considerations being involved.

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* In this case $P_{pi}$ becomes the power required to pump the sucked air from zero velocity and the local external surface pressure to the original values.

# APPENDIX II

*Smoke Visualization of Flow Past Circular Cylinder with Thwaites Flap*

*By*

W. S. WALKER, of the Aerodynamics Division, N.P.L.

In the preceding experiments, measurements of the pressure distribution suggested that (with the Flap deflected and boundary-layer separation prevented by suction) there was a marked downwash at mid-span. This downwash was assumed to have been due to spanwise variations of circulation, with their accompanying trailing vortex system. Further experiments were therefore made on a porous circular cylinder* of 1 in. diameter fitted with a $\frac{3}{8}$-in. flap and spanning a 9 in. $\times$ 5 in. tunnel horizontally. The wind speed was low, in order to facilitate the use of smoke for visualizing the flow patterns. Observations were also made on the unsteady flow in the absence of the Flap (with suction still applied). Photographs of the flow patterns were taken with the advice and co-operation of Mr. C. A. Guthrie, Head of the Photographic Section, N.P.L., using a telephoto lens.

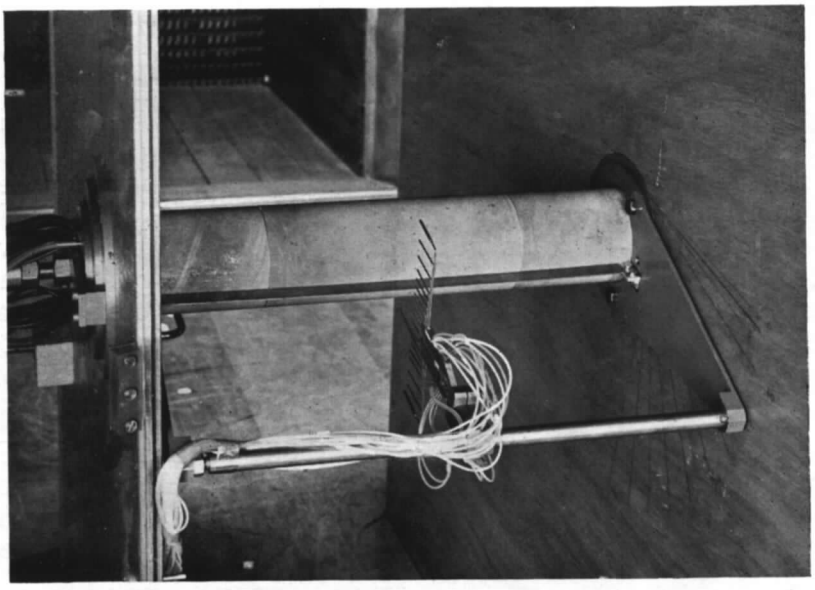
Fig. 20 shows the usual extensive separation without suction, while Fig. 21a shows the orderly flow with sufficient suction to prevent separation with flap symmetrical. The suction quantity was large because of the very low Reynolds number. With flap deflected, and again with sufficient suction to prevent separation, trailing vorticity was observed on either side of mid-span as sketched in Fig. 22a. The associated spanwise variation of circulation almost certainly arises from local separation of the boundary layers of the tunnel walls in the presence of the abnormally large pressure recovery achieved over the rear of the cylinder by means of the suction. The magnitude of the effect is much greater than in the previous experiments because the Reynolds number of the present experiments is much lower and the wall boundary layers correspondingly thicker.

A photograph of the trailing vorticity is shown in Fig. 22c, in which the plane of the smoke was nearer the camera than the mid-span section (as at AA in Fig. 22b, viewed from the left): downstream of the model the smoke filaments from below the cylinder came nearer the camera than those from above. In the photographs of Fig. 21 the smoke was in the mid-span plane, where there was no trailing vorticity.

The trailing vortex system induces a marked downwash at mid-span, as is shown in Figs. 21b and c for Flap deflections of about 30 deg and 70 deg respectively. The resulting clockwise displacement of the front stagnation point in these two photographs was of the same order as would be expected if the circulation fell to zero near the tunnel walls.

Without flap (still with suction) conditions behind the cylinder were no longer steady. There appeared to be little, if any, separation over the rear of the cylinder, but the downstream dividing streamlines left the surface in an unsteady wavy line. Associated with this irregular and fluctuating spanwise distribution of circulation, vorticity was observed to be shed continually by the cylinder, with an irregular spanwise distribution and at each section varying from moment to moment both in magnitude and sign. This is a further manifestation of the flow instability discussed in section 4. A typical instantaneous photograph of the unsteady flow pattern is shown in Fig. 23, for which the suction quantity was much the same as gave unseparated flow with flap at zero deflection in Fig. 21.

* Constructed by winding several layers of brass-wire cloth (140 mesh/in.) on a former of perforated brass.



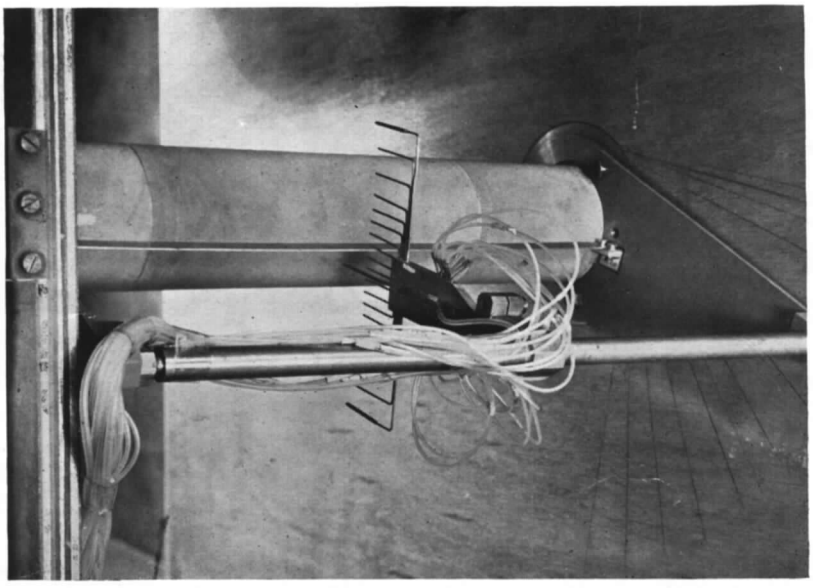


FIG. 1. Photographs of model.

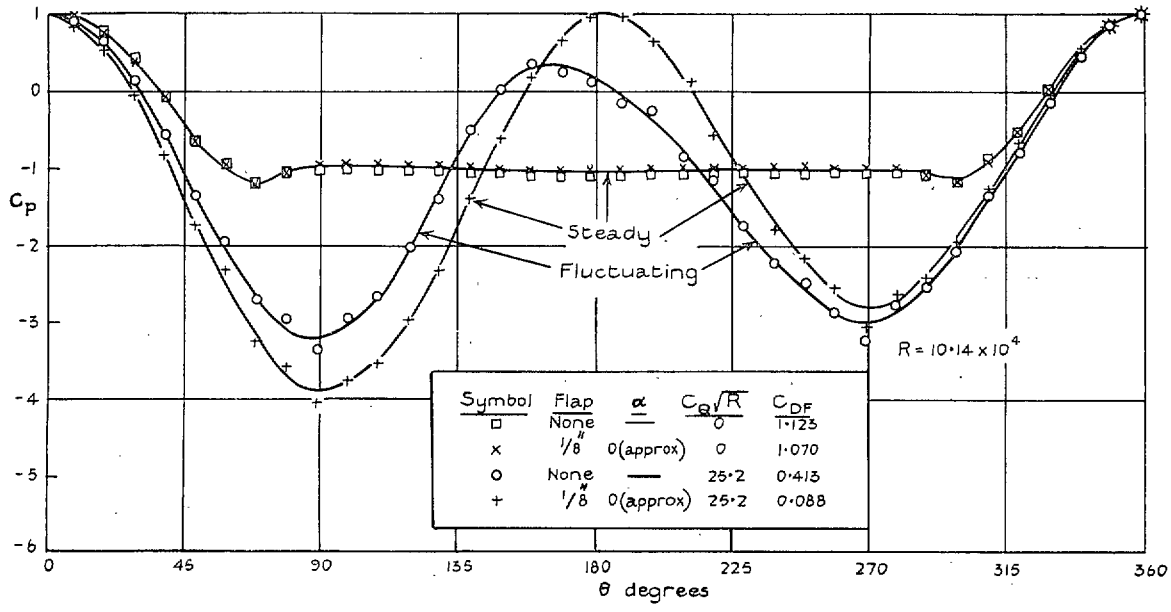



FIG. 2a. Pressure distributions with and without flap.

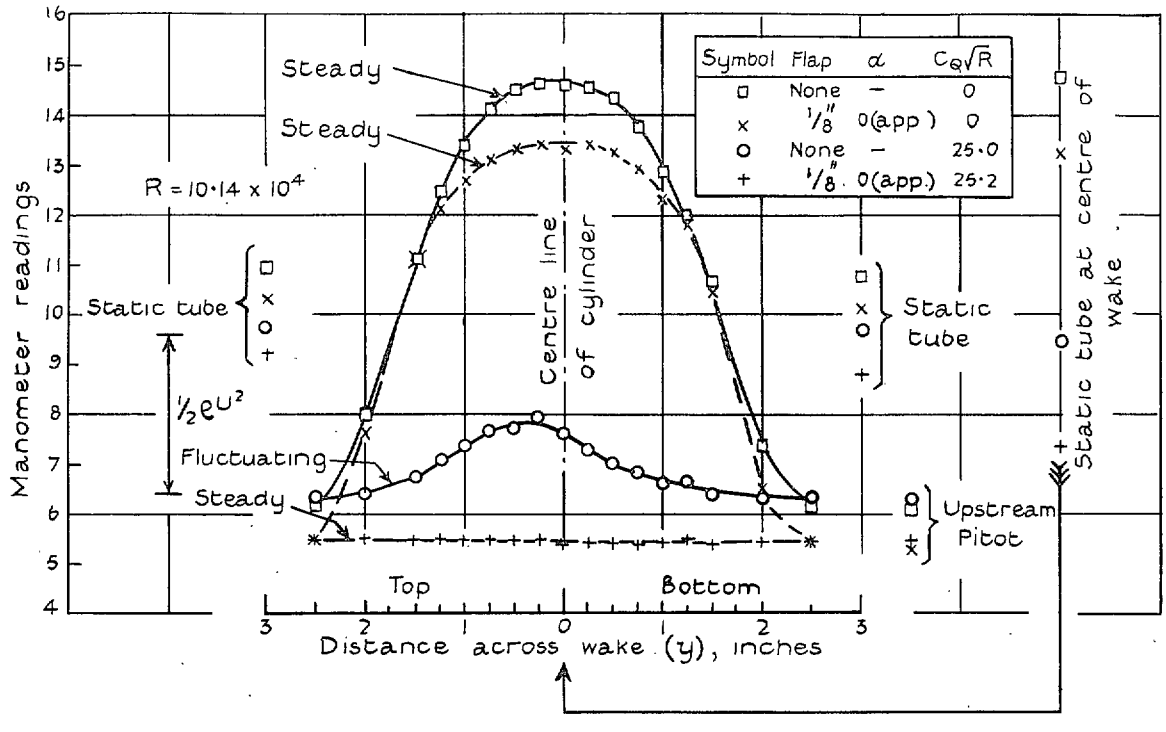
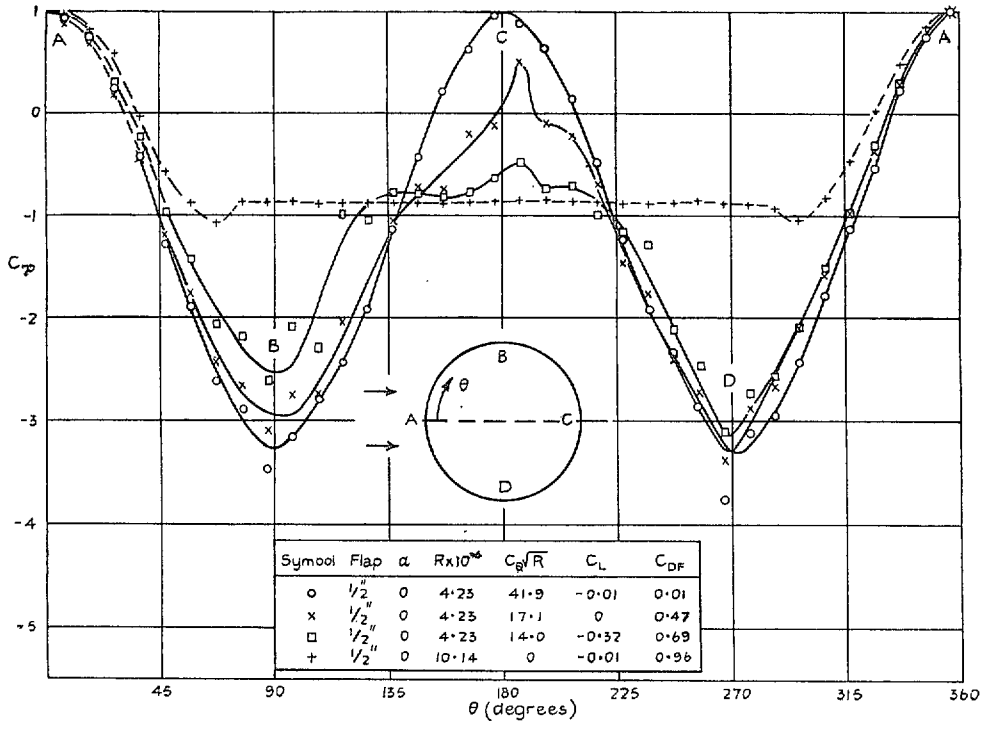
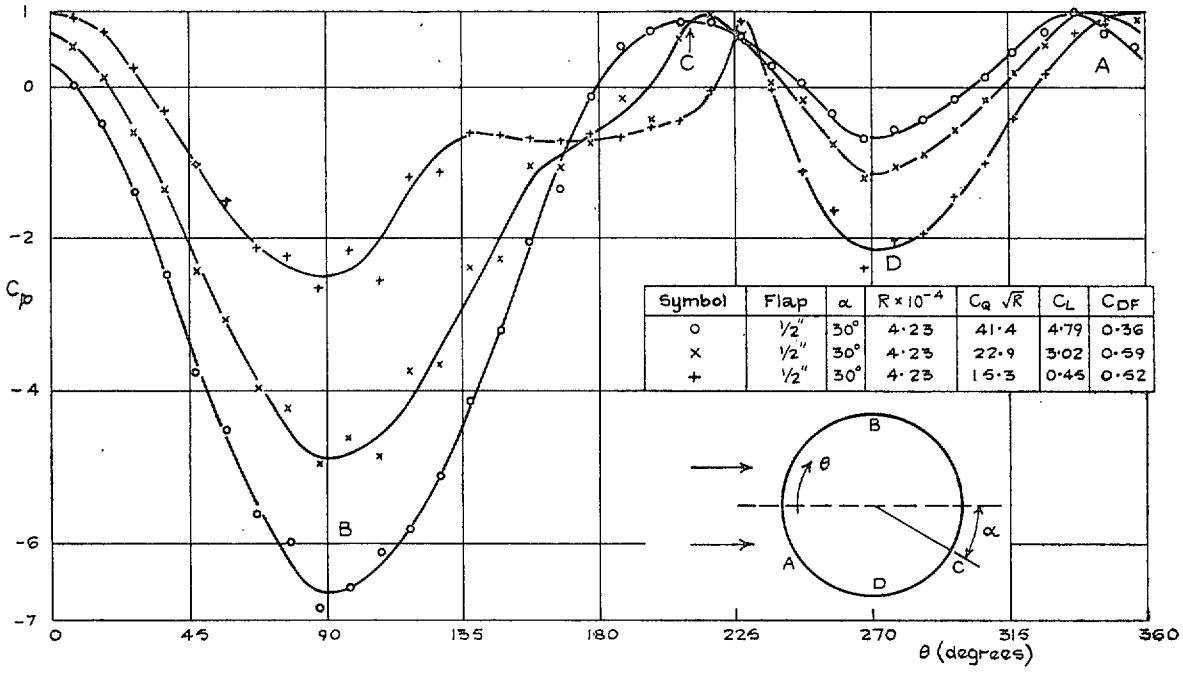



FIG. 2b. Wake traverses with and without flap.




| Symbol | Flap | α | $R \times 10^{-6}$ | $C_Q\sqrt{R}$ | $C_L$ | $C_{DF}$ |
|---|---|---|---|---|---|---|
| o | 1/2" | 0 | 4·23 | 41·9 | -0·01 | 0·01 |
| × | 1/2" | 0 | 4·23 | 17·1 | 0 | 0·47 |
| □ | 1/2" | 0 | 4·23 | 14·0 | -0·32 | 0·69 |
| + | 1/2" | 0 | 10·14 | 0 | -0·01 | 0·96 |

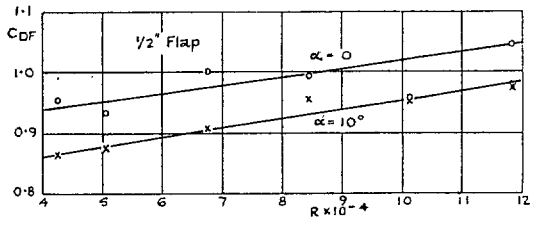
(a) Zero flap deflection



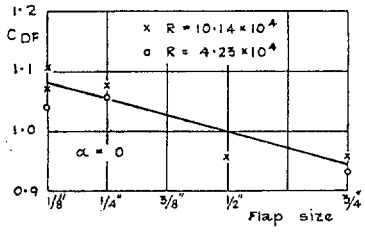

| Symbol | Flap | α | $R \times 10^{-4}$ | $C_Q\sqrt{R}$ | $C_L$ | $C_{DF}$ |
|---|---|---|---|---|---|---|
| o | 1/2" | 30° | 4·23 | 41·4 | 4·79 | 0·36 |
| × | 1/2" | 30° | 4·23 | 22·9 | 3·02 | 0·59 |
| + | 1/2" | 30° | 4·23 | 15·3 | 0·45 | 0·62 |

(b) 30 deg flap deflection

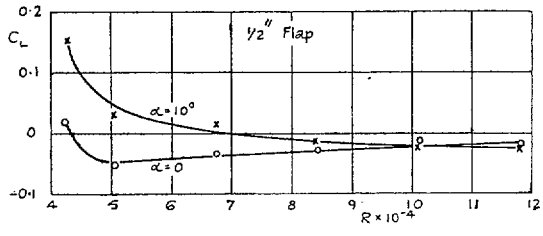
FIG. 3. Variation of pressure distribution with suction quantity.




(a) Variation of form drag with Reynolds number




(b) Variation of form drag with Flap size




(c) Variation of lift with Reynolds number

FIG. 4. Data with zero suction.

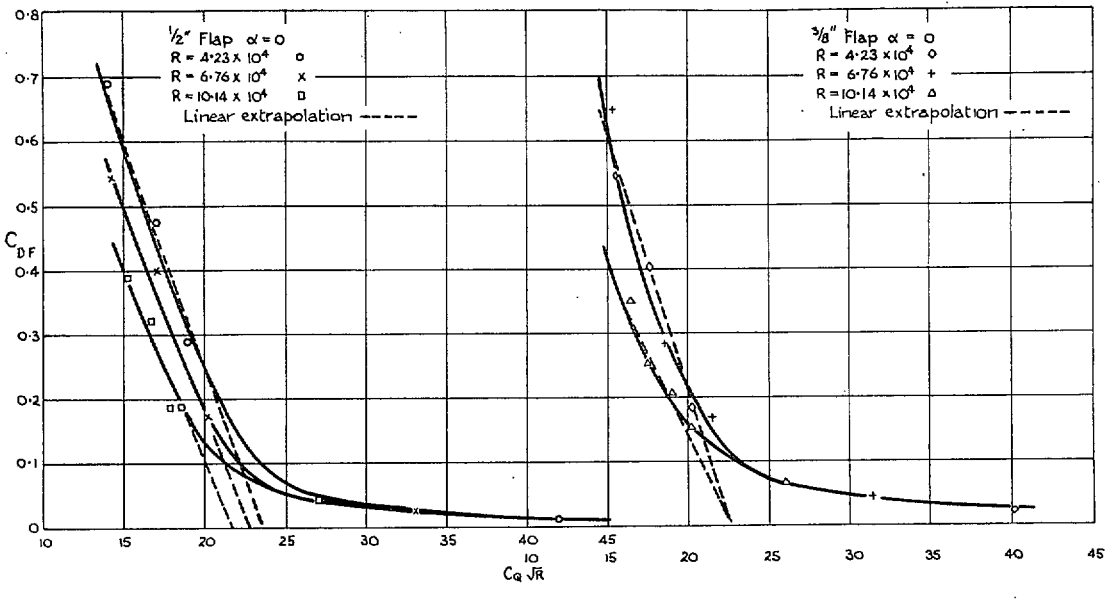



FIG. 5. Typical curves showing variation of form drag with suction quantity.

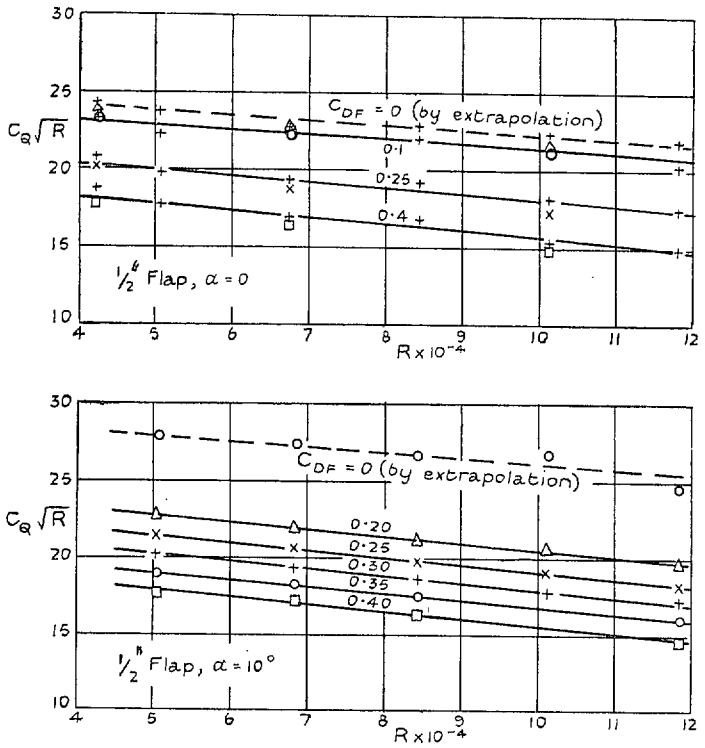



FIG. 6. Scale effect.
Suction requirements for given values of form-drag coefficient.

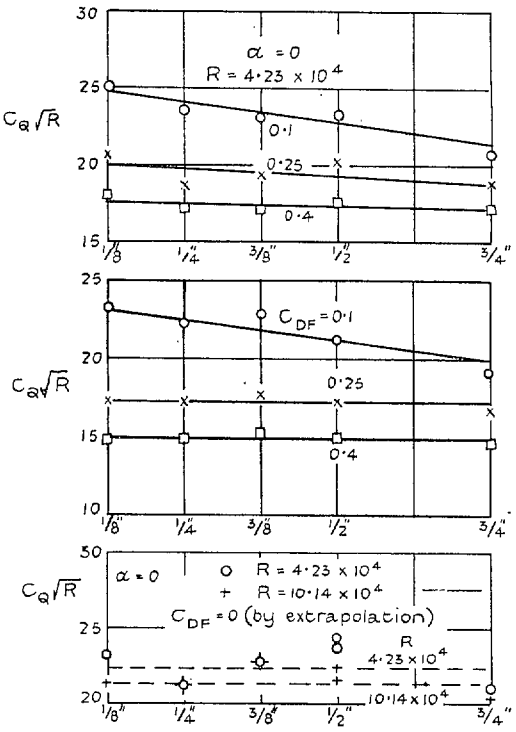



FIG. 7. Effect of flap size.

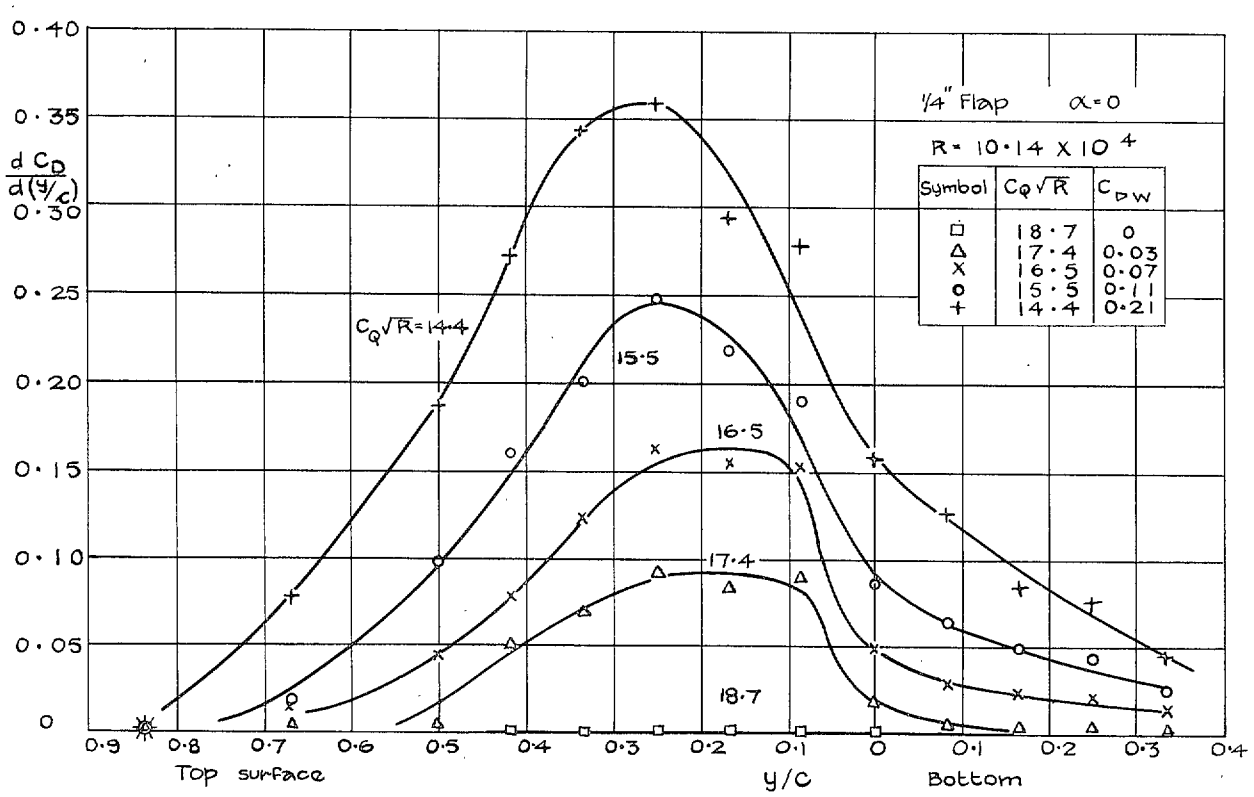
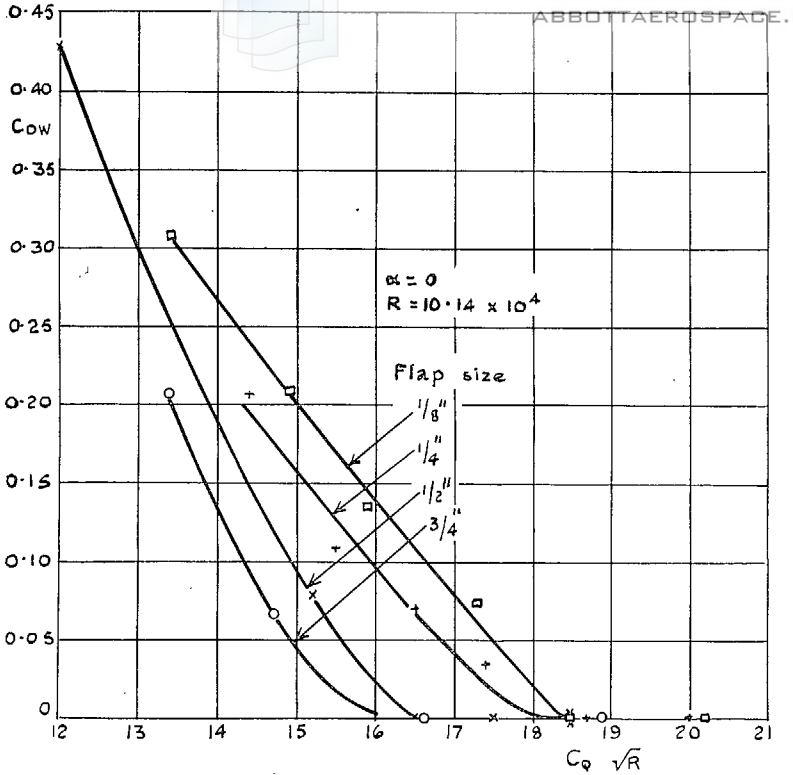
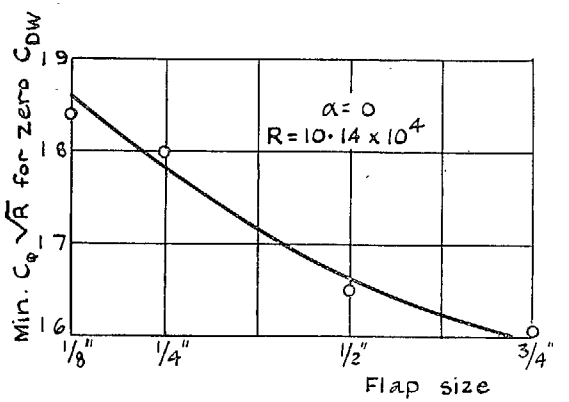



FIG. 8. Progressive development of wake as suction quantity is reduced.




(a) Variation of wake drag with suction quantities and flap size.




(b) Minimum suction for complete suppression of wake.

FIGS. 9a, 9b.

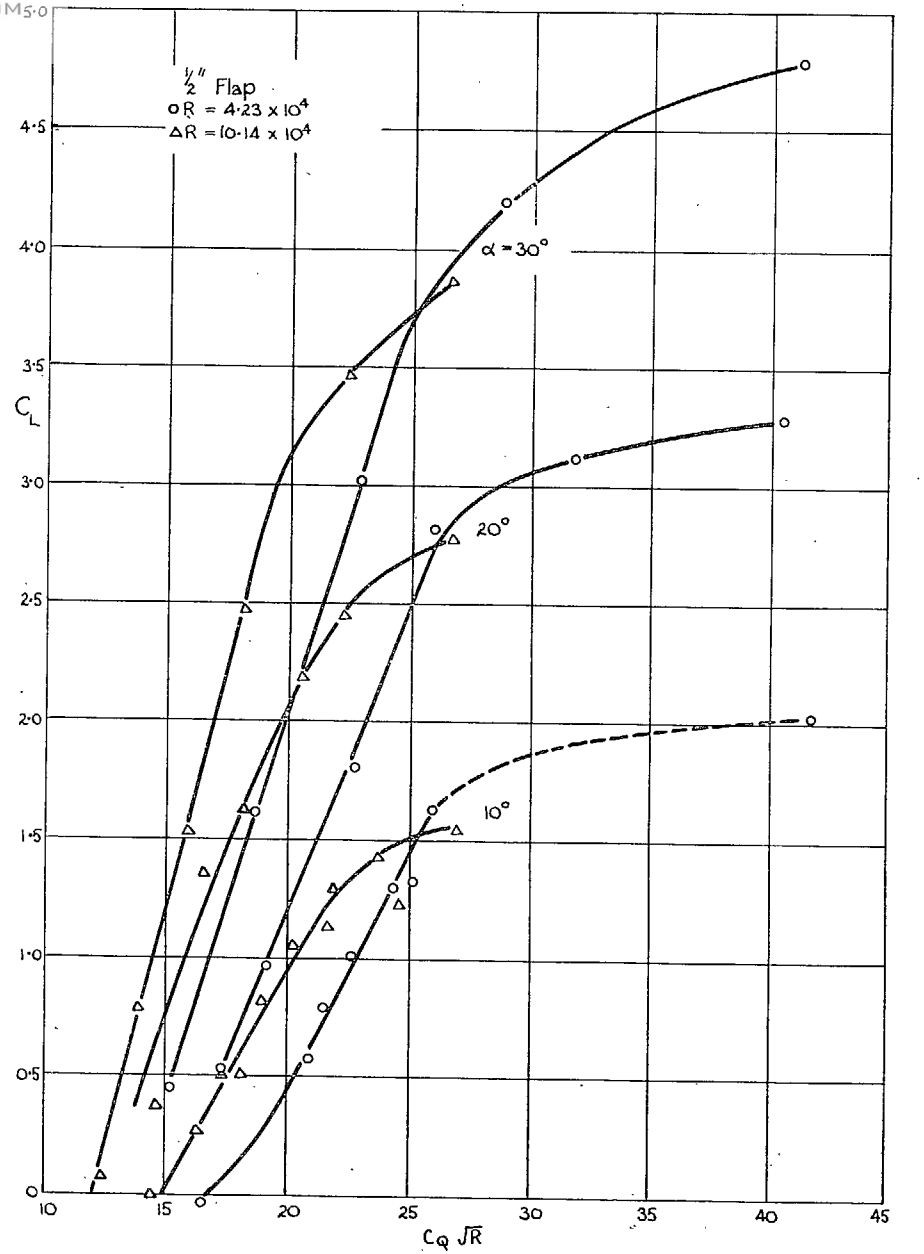



FIG. 10a.

Variation of lift with suction quantity, Reynolds number and flap setting.

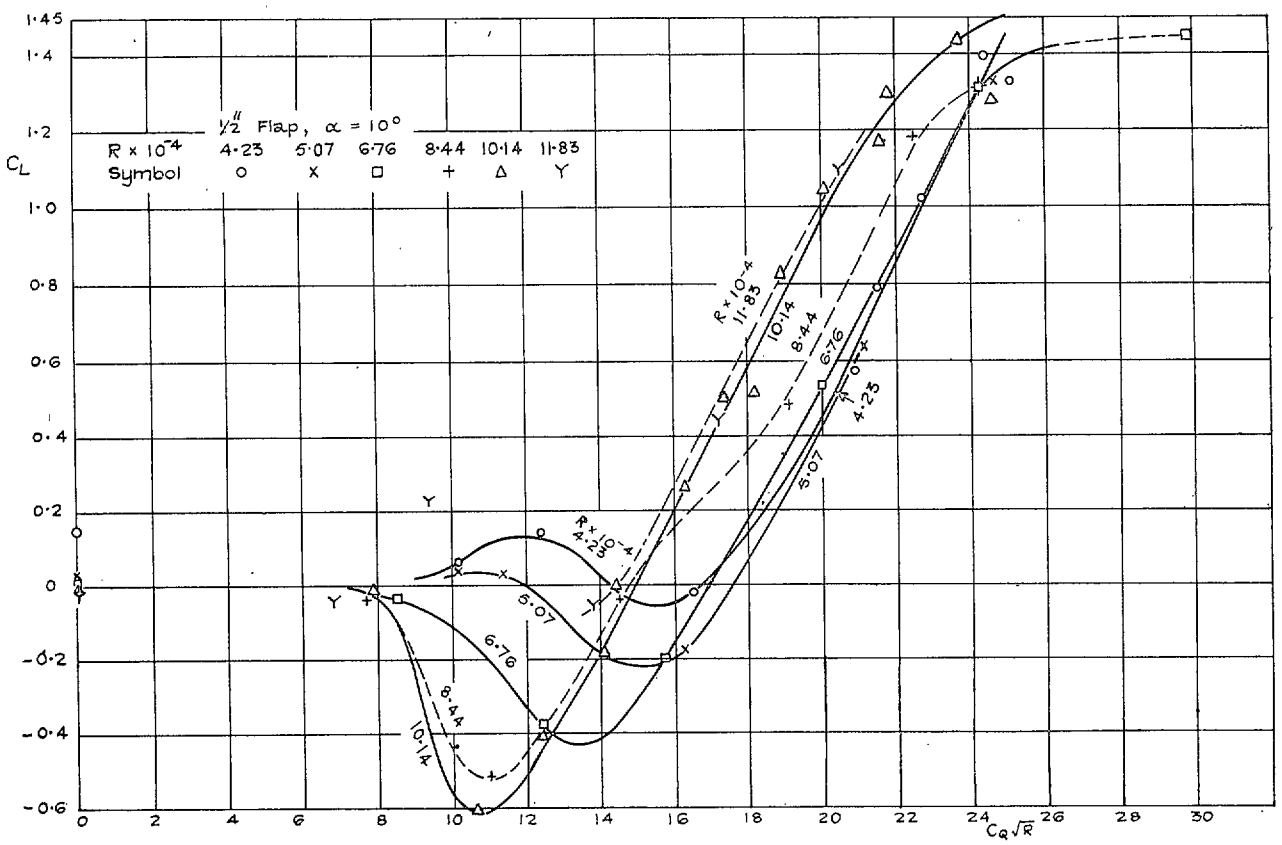



FIG. 10b. Variation of lift with suction quantity and Reynolds number: $\alpha = 10$ deg.

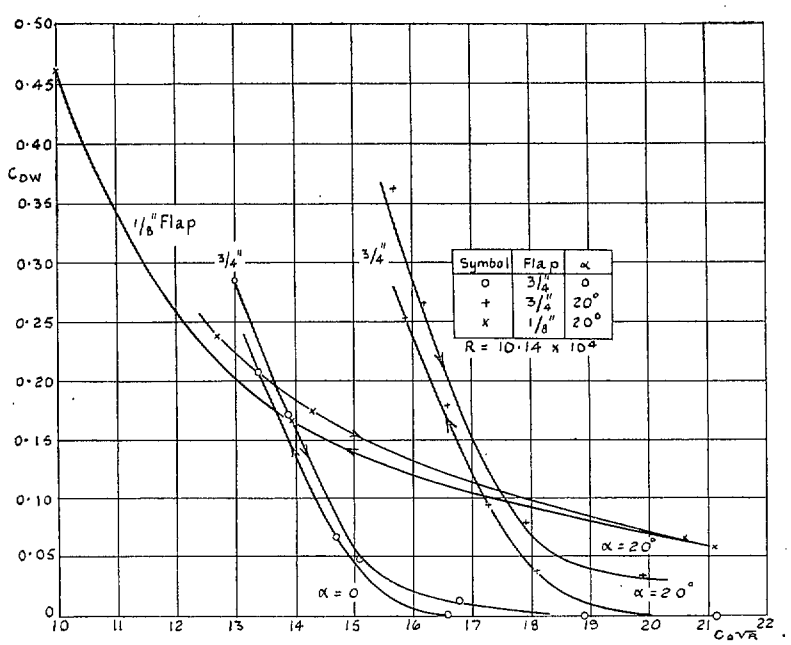



FIG. 11. Hysteresis effects on wake drag, for two flap sizes and two flap settings.

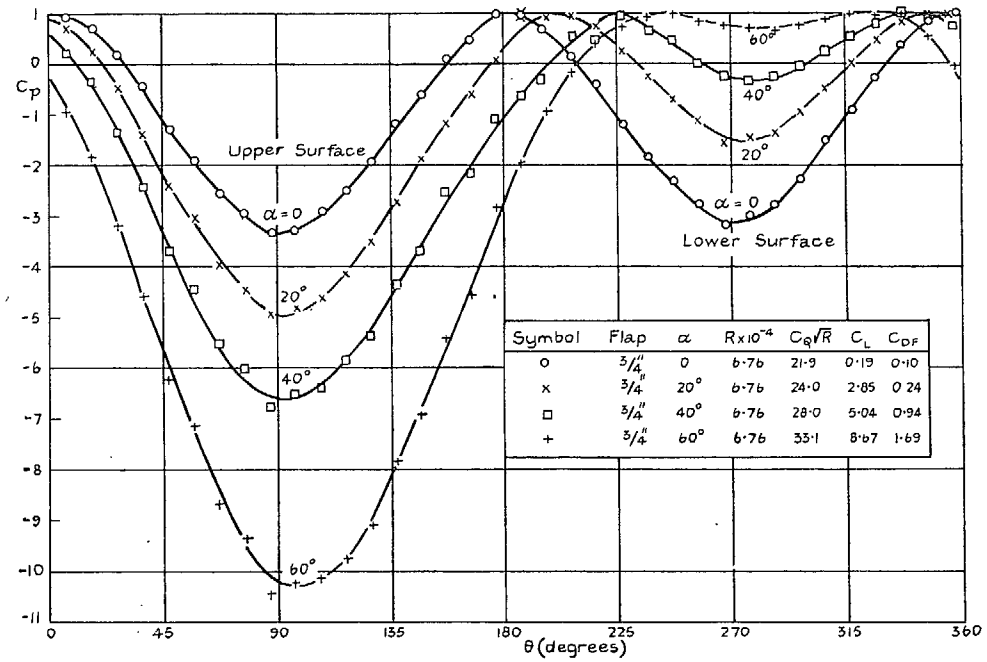



FIG. 12. Pressure distributions for various flap settings.

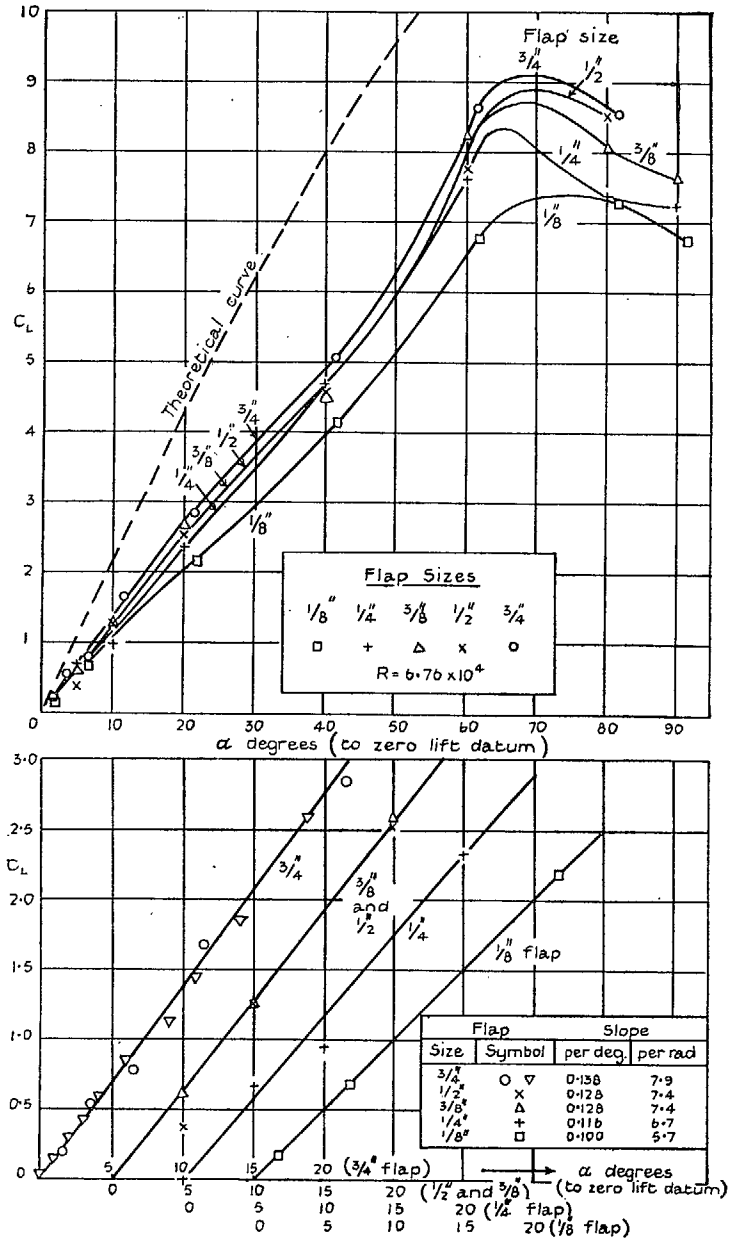



FIG. 13. Lift curves for various flap sizes.
Incidence not corrected for mid-span downwash.

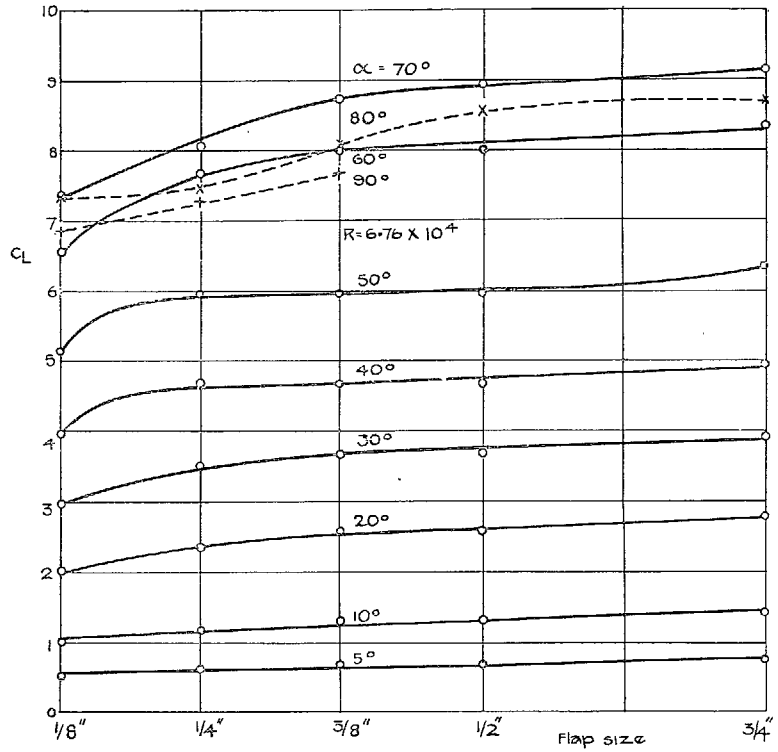
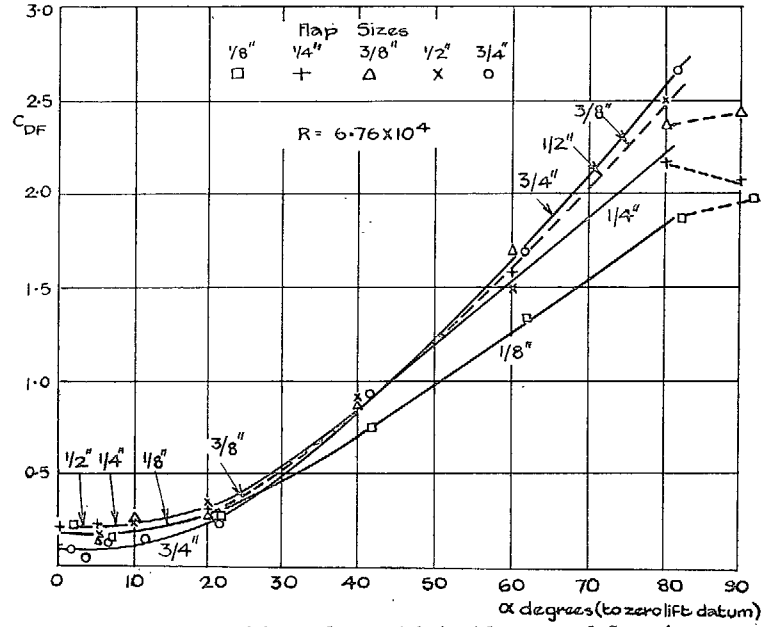
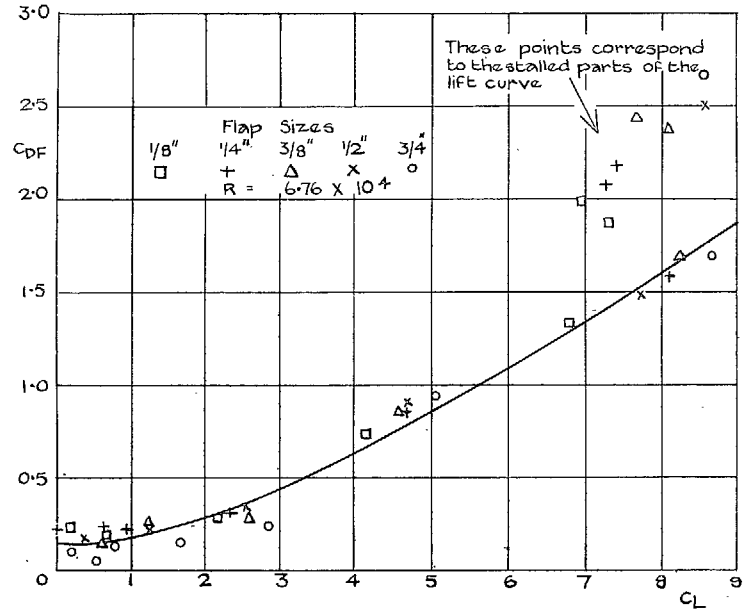



FIG. 14. Variation of lift with flap size.
(Cross-plotted from curves of Fig. 13).




(a) Variation of form drag with incidence and flap size.




(b) Variation of form drag with lift.
FIGS. 15a, 15b.

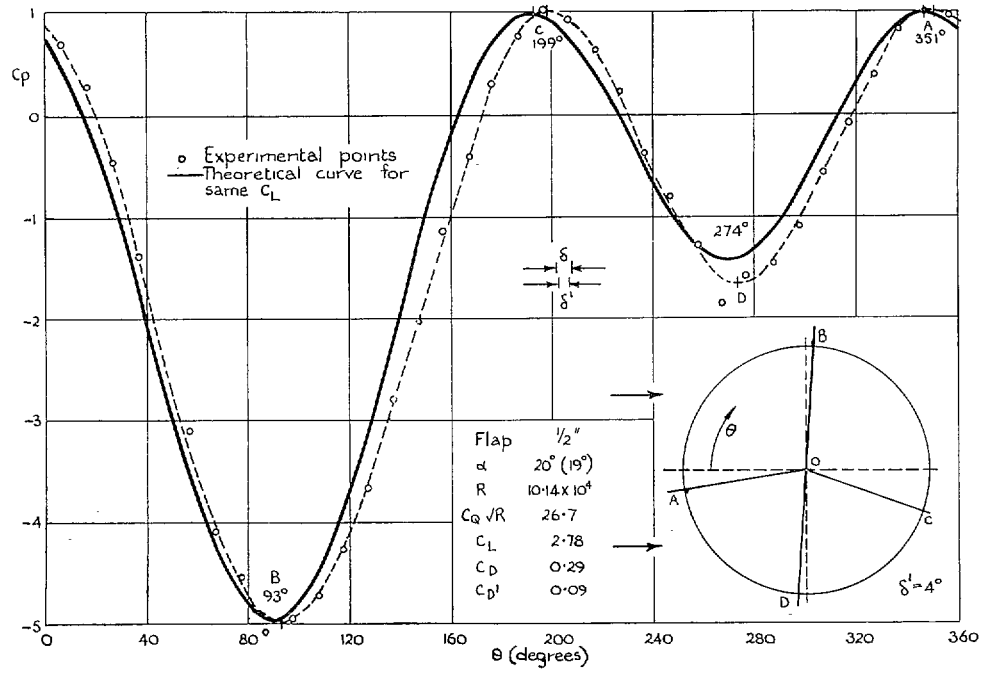



FIG. 16. Determination of apparent wind direction from pressure distributions.

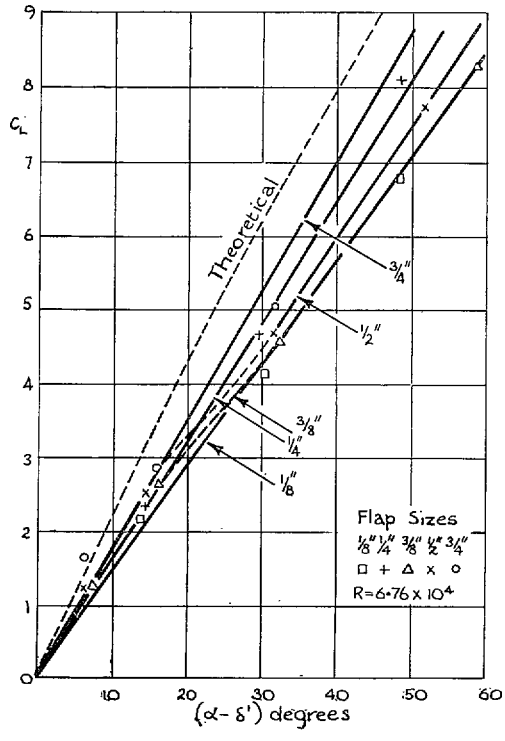



FIG. 17.
Lift curves of Fig. 13 referred to apparent wind directions deduced from pressure distributions.

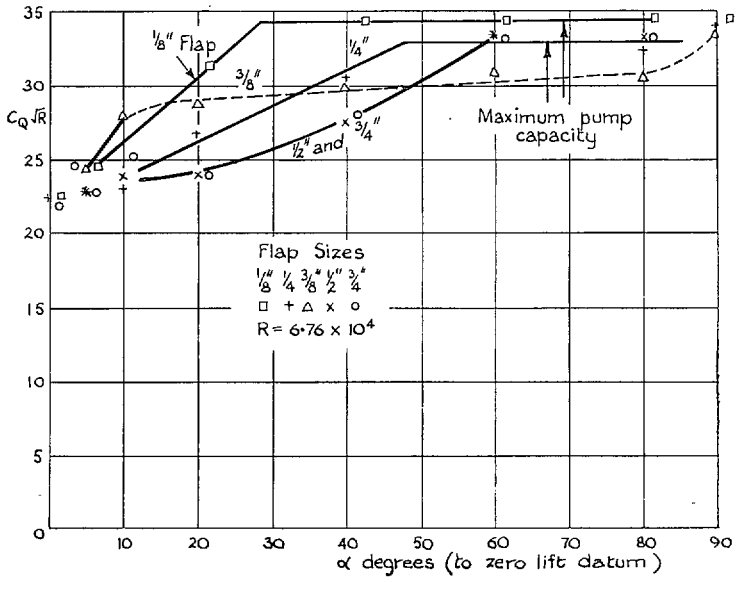
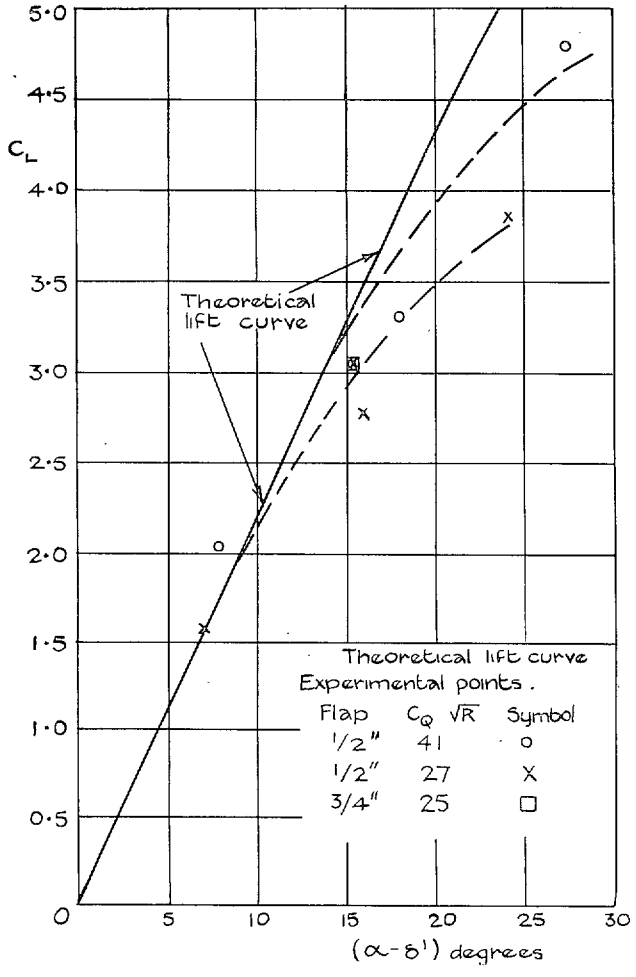
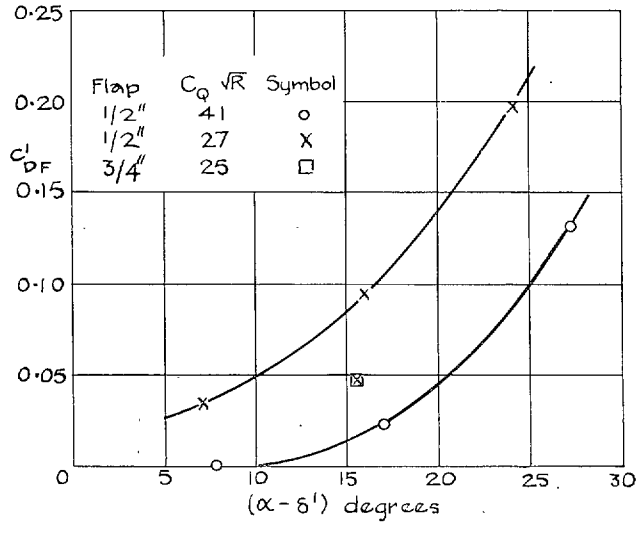



FIG. 18. Suction quantity relevant to Figs. 12 to 15 and 17.




(a) Lift.




(b) Drag.

FIG. 19. Lift and drag curves with full suction, referred to apparent wind directions.

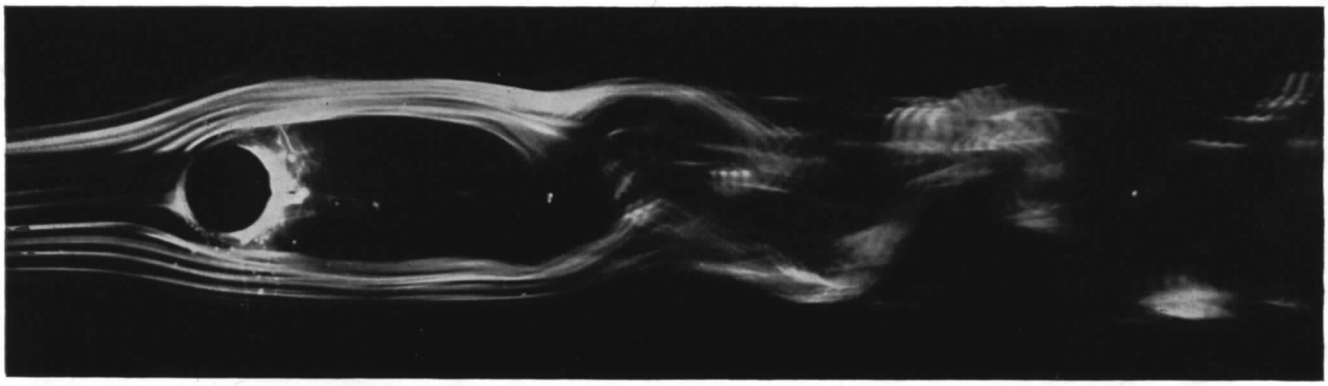
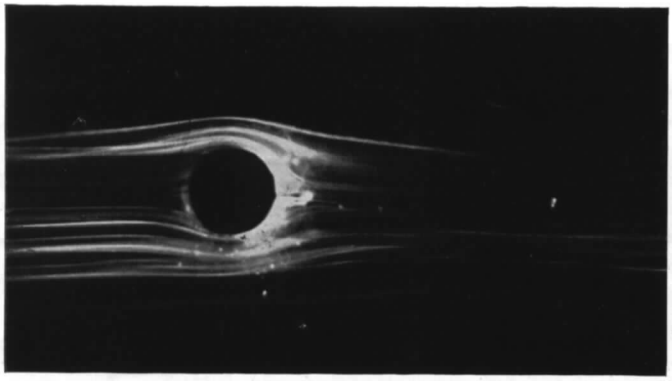
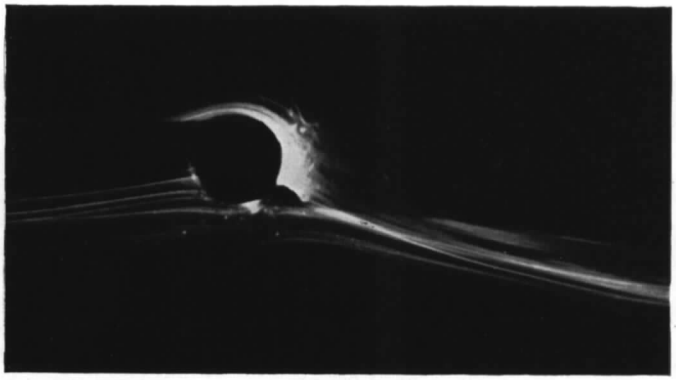


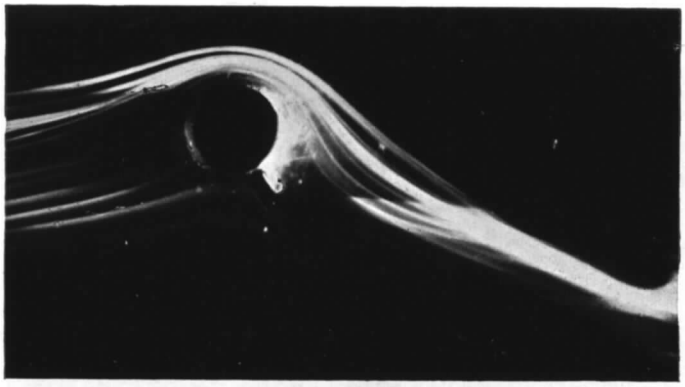
FIG. 20. Flow pattern with zero suction.



(a) $\alpha = 0°$.

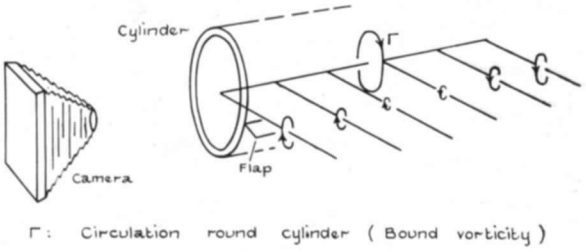


(b) $\alpha = 30°$.

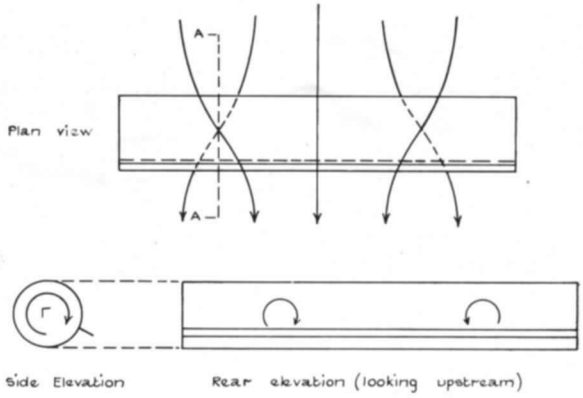


(c) $\alpha = 60°$.

FIGS. 21a, 21b and 21c. With sufficient suction to prevent separation.




(a) Perspective sketch of trailing vortex system.




(b) Sketches showing the sign of the trailing vorticity shed at any spanwise station.

(c) Photograph of the trailing vorticity with flap deflected about 40 deg (off-centre position, side nearest camera).

FIGS. 22a, 22b and 22c. Trailing vorticity with suction, with flap deflected.

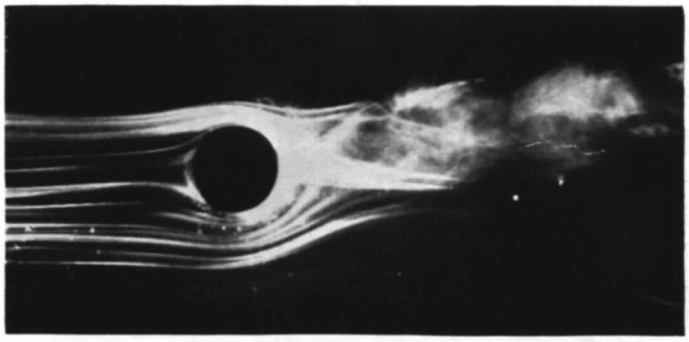


FIG. 23. Typical flow patterns without flap, with suction.

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