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Wind-tunnel Tests on the Prevention of Boundary-layer Separation by Distributed Suction at the Rear of a Thick Aerofoil (NPL 153)

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N. GREGORY, M.A., R. C. PANKHURST, Ph.D., and W. S. WALKER
of the Aerodynamics Division, N.P.L.

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Summary.—Tests of a preliminary nature have been carried out on a 33 per cent thick symmetrical aerofoil (NPL 153) with suction through a porous surface from 0·80 chord to the trailing edge, which was rounded and fitted with a Thwaites flap. The distributed suction was found to prevent separation and to reduce the wake drag to zero. The overall effective drag (including an allowance for the power required for the suction) was reduced slightly, but still remains fairly high. No hysteresis was observed in the change of drag with suction quantity.

The flap was essential to stabilise the flow: without it, the flow with suction was unsteady and the wake drag was appreciable. When the flap was deflected 20 deg there was no increase in the suction quantity required to prevent separation.

1. *Introduction.*—Thwaites (R. & M. 2514[1]. 1946) has shown theoretically that suction through a porous surface should prevent the boundary-layer separation that occurs in flow against an adverse pressure gradient and make possible a close approximation to potential flow. The circulation round an aerofoil with a rounded trailing edge can then be fixed independently of incidence by means of a small flap at the rear.

This idea has been tried out on a wholly porous circular cylinder by Thwaites[2] (1948), and more elaborate tests have recently been concluded in a National Physical Laboratory 4-ft wind tunnel by Pankhurst and Thwaites (R. & M. 2787[3]. 1950). The present tests relate to a body of aerofoil shape with the porous surface confined to the region of adverse pressure gradient.

2. *Experimental Arrangements.*—The aerofoil section, 33 per cent thick, was designed by Thwaites by the approximate methods set out in C.P. 70[4] as a simple roof-top section in which the velocity over the surface at zero incidence (to the first approximation) rises linearly to a maximum value at 0·8 chord and then falls linearly to the trailing edge. The section is illustrated in Fig. 1, and ordinates are given in Table 1.

The model was of 4-ft span and 18-in. chord. The surface to the rear of 0·8 chord was formed from Grade C ' Porosint ' sintered bronze sheet, 1/16 in. thick, soldered in 6-in. wide panels over a series of ribs†. There was a break in continuity of suction at each rib owing to the 0·2-in.

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† The whole of the porous rear part of the aerofoil was constructed by Aero. Department, R.A.E., to whom acknowledgement is due.

width of the rib, but despite this defect no adverse results could be detected. The suction chamber was divided into three by two solid ribs; the outer sections were interconnected and the suction flow removed through two pipes and control valves. The flow in the centre foot of span was measured using a $1 \cdot 125$-in. diameter three-quarter radius pitot-tube type flow-meter[5].

Measurements of wake drag were made from the observations of a comb of pitot-tubes across the wake.

The model had been first tested at zero incidence in the N.P.L. 4-ft No. 2 Wind Tunnel without a trailing-edge flap. A slight reduction in wake drag was observed as suction was applied, but separation could not be entirely prevented, and so the tests were discontinued. Subsequent experiments on a porous circular cylinder (R. & M. 2787[3]) showed, however, that a flap was necessary to stabilise the flow with suction. It was therefore decided to test the aerofoil again with a flap*. As the 4-ft Wind Tunnel was otherwise occupied, these later tests were made in the 13×9 ft Wind Tunnel with the model fitted with end fins and erected at zero incidence between aerofoil-sectioned cantilevers so as to span the tunnel. Two alternative sizes of flap were tested, of 1-in. and $1\frac{1}{2}$-in. chord.

3. *Test Results*.—The experiments were conducted at three wind speeds, 60, 100 and 150 ft/sec, corresponding to Reynolds numbers of $0 \cdot 58$, $0 \cdot 96$ and $1 \cdot 44 \times 10^6$ (based on the aerofoil chord).

The variation of wake drag coefficient with suction quantity coefficient ($C_Q = Q/U_0 c$) was measured with each flap, without a flap, and with a wire in lieu of a flap. The results for the extreme speeds are plotted in Figs. 2 and 3. Points obtained with C_Q both increasing and decreasing lie on single curves: there is no evidence of hysteresis in the movement of the separation points. The wavy form of the curves is due to slight differences in the suction through the porous material such that the prevention of separation occurred on one surface prior to the other. This is shown by the wake traverses given in Fig. 4, in which the ordinate is a measure of the loss of total head, and the area beneath each curve is equal to the wake drag coefficient.

With a flap in position, separation was entirely prevented by sufficient suction, and the boundary layer (at $R = 0 \cdot 58 \times 10^6$) was completely absorbed so that the wake drag was reduced to values less than the drag the flap would have experienced alone had it been exposed to the stream. Some form of flap appeared to be necessary to locate the dividing streamline, for without a flap, the flow was slightly unsteady and the pitot-comb registered an appreciable loss of total head, even with full suction†. Even a stout wire, $0 \cdot 095$-in. diameter, fixed along the rear of the aerofoil served to stabilise the flow, and in this case with sufficient suction the wake drag was reduced to zero.

The theory of the laminar boundary layer with distributed suction shows that at different Reynolds numbers, similar flow conditions should obtain for the same value of the parameter $C_Q\sqrt{R}$. Typical curves of the drag coefficient are shown plotted against $C_Q\sqrt{R}$ in Fig. 5 for the three speeds of test. Their wide divergence at low values of $C_Q\sqrt{R}$ suggests that at the higher Reynolds numbers, laminar separation is being replaced by transition followed by turbulent separation further downstream, although in all cases laminar flow persisted to beyond $0 \cdot 8$ chord. At $R = 0 \cdot 58 \times 10^6$, the value of $C_Q\sqrt{R}$ required to prevent separation is about 5, but at higher Reynolds numbers, the critical value is not so well defined. This compares with a very approximate theoretical value of $C_Q\sqrt{R}$ of $2 \cdot 5$ to prevent separation, estimated by the methods of Ref. 6. A precise solution for the present problem has not yet been obtained.

* In the 4-ft Wind Tunnel the aerofoil had also been tested with a 1-in. chord flap, but the flap had been set at an excessive deflection.

† The flow in this case was probably similar to that observed[7] in a smoke tunnel at very low speeds behind a porous circular cylinder without a flap (with suction). There was very little, if any, separation over the rear of the cylinder, and the dividing streamlines left the cylinder in a wavy line. The spanwise distribution of circulation was thus irregular and not very steady with time; its mean spanwise value was probably zero. In consequence, the fluid behind the cylinder was filled with trailing vortices associated with the spanwise distribution of circulation.

Tests with transition wires close to the leading edge were carried out with the small flap in position, at a Reynolds number of $0 \cdot 58 \times 10^6$. The largest suction quantity available, a C_Q of $0 \cdot 02$, reduced the wake drag coefficient from $0 \cdot 13$ without suction to $0 \cdot 010$. The flow was not two-dimensional, as was shown by streamers on a probe; the boundary layer on the end fins thickened and separated owing to the unnatural pressure recovery achieved by distributed suction. There was a strong inflow from the ends of the aerofoil at about the mid-chord position, and an outflow on the trailing-edge flap. This phenomenon was not easily observed, as the presence of the probe resulted in a local separation in its wake. Without transition wires, however, the flow was effectively two-dimensional away from the ends.

The large flap was deflected to 20 deg incidence (rotating about the trailing-edge centre of curvature as indicated in Fig. 1), and the variation of C_D with C_Q was measured (without transition wires) at $R = 0 \cdot 96 \times 10^6$ and compared with values obtained for zero flap deflection, Fig. 6. No increase of suction quantity was necessary to prevent separation. As near-potential flow then existed, it is presumed that the section experienced the appropriate lift coefficient, though it was not possible to measure this because the model was not equipped with pressure holes.

4. *Effective Drag Coefficient.*—The equivalent pump drag has been estimated for the tests with small chord flaps at Reynolds numbers of $0 \cdot 58$ and $1 \cdot 44 \times 10^6$. Fig. 7 shows the wake drag coefficient and curves of the effective drag coefficient for two assumed values of the pump drag.

The lower curve corresponds to an ' ideal ' pump drag which has been shown by Pankhurst and Gregory[8] (1948) to be

$$C_{D\,pi} = \int (U/U_0)^2 (v_0/U_0)\, d(s/c)\,.$$

For the present section, $C_{D\,pi} = 1 \cdot 32 C_Q$. This assumes no porous resistance and a suction chamber pressure varying to match the external pressure.

A more practical alternative assumes a single pressure chamber with zero porous resistance at $0 \cdot 8$ chord, but increasing resistance to the rear so as to keep the normal velocity constant. This yields

$$C_{D\,p} = (1 \cdot 39)^2 C_Q \simeq 2C_Q\,.$$

This is the value assumed for the pump drag to give the second curve. There is no necessity for the actual pump drag to be very much greater than this, and if two suction chambers are used, it could be less.

At a Reynolds number of $0 \cdot 58 \times 10^6$ there is considerable reduction in total drag as the suction is applied. The reduction is not so large at the higher Reynolds number, but it is interesting to note that the ratio of the minimum values of total drag at the two Reynolds numbers is approximately equal to the ratio of the square roots of the Reynolds numbers. This suggests that extrapolation to higher Reynolds numbers on a basis of $C_Q\sqrt{R}$ and $C_D\sqrt{R}$ being constant is not unreasonable, but this tentative conclusion needs experimental verification over a wider range of Reynolds numbers before it can be accepted without reserve.

5. *Conclusions.*—The localised application of distributed suction has been shown to provide an effective means of preventing the boundary-layer separation at the rear of a thick aerofoil fitted with Thwaites flap. The wake drag was reduced to very small values associated with the skin friction on the flap, and the total effective drag was shown to be less than without suction but was still fairly high at the Reynolds numbers of the experiment. Without a flap, however, the whole drag remained appreciable and the flow unsteady despite full suction, although a wire $0 \cdot 096$ in. in diameter fixed at the trailing edge restores stable flow with zero wake drag.

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7	W. S. Walker	Smoke Visualisation of Flow Past Circular Cylinder with Thwaites Flap. Appendix II to R. & M. 2787 (Ref. 3).
8	R. C. Pankhurst and N. Gregory ..	Power Requirements for Distributed Suction. C.P. 82. September, 1948.

TABLE 1

The section (NPL 153) is a simple roof-top design with the following constants :

$$X_1 = 0 \cdot 8$$
$$a = 0 \cdot 2777547$$
$$b = 0 \cdot 3889049$$
$$c = -0 \cdot 1111709$$

Ordinates

x	y
0	0
0·0050	0·0215
0·0075	0·0263
0·0125	0·0339
0·025	0·0477
0·050	0·0689
0·075	0·0813
0·10	0·0930
0·15	0·1118
0·20	0·1263
0·25	0·1379
0·30	0·1472
0·35	0·1544
0·40	0·1597
0·45	0·1632
0·50	0·1649

x	y
0·55	0·1648
0·60	0·1627
0·65	0·1583
0·70	0·1513
0·75	0·1414
0·80	0·1268
0·85	0·1049
0·900	0·0787
0·925	0·0644
0·950	0·0492
0·975	0·0322
0·9875	0·0218
1·0000	0·0000

Leading-edge radius of curvature = 0·0462
Trailing-edge radius of curvature = 0·0173

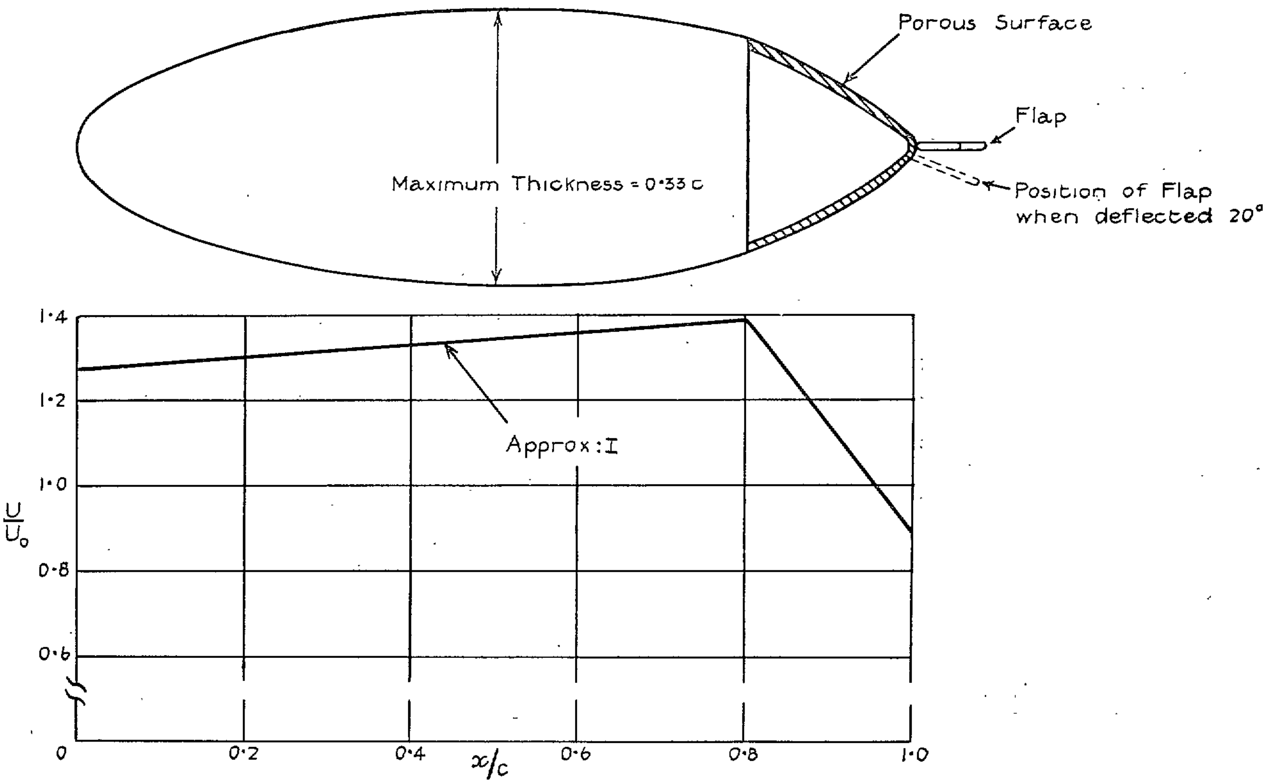

FIG. 1. Aerofoil section (NPL 153) and Approximation I velocity distribution.

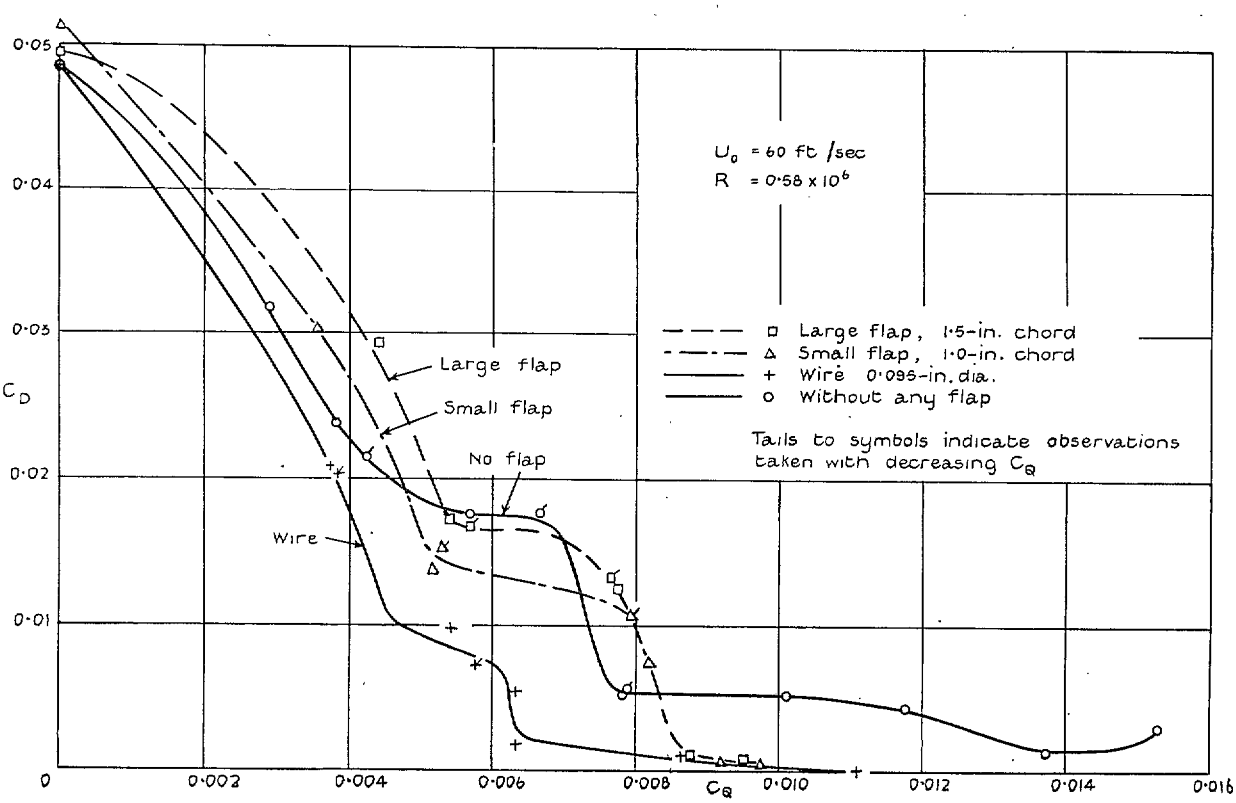

FIG. 2. Variation of wake drag coefficient with suction quantity coefficient. $R = 0{\cdot}58 \times 10^6$.

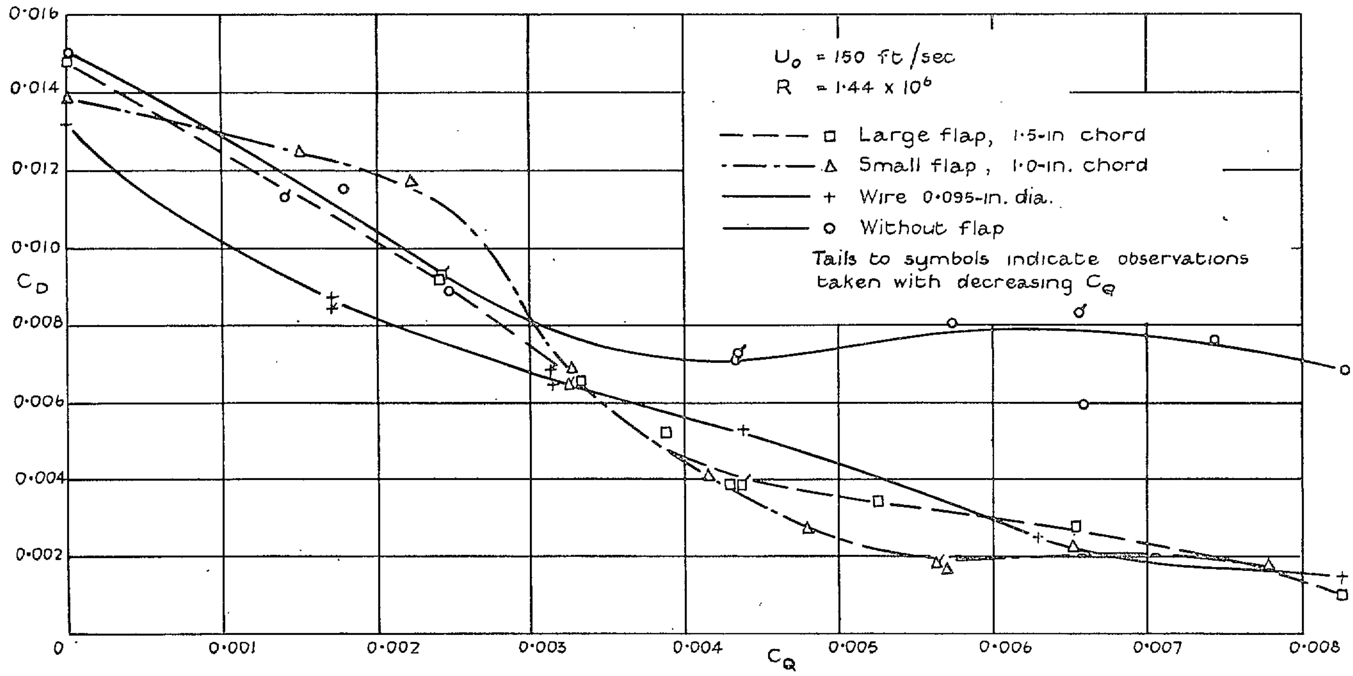

FIG. 3. Variation of wake drag coefficient with suction quantity coefficient. $R = 1 \cdot 44 \times 10^6$.

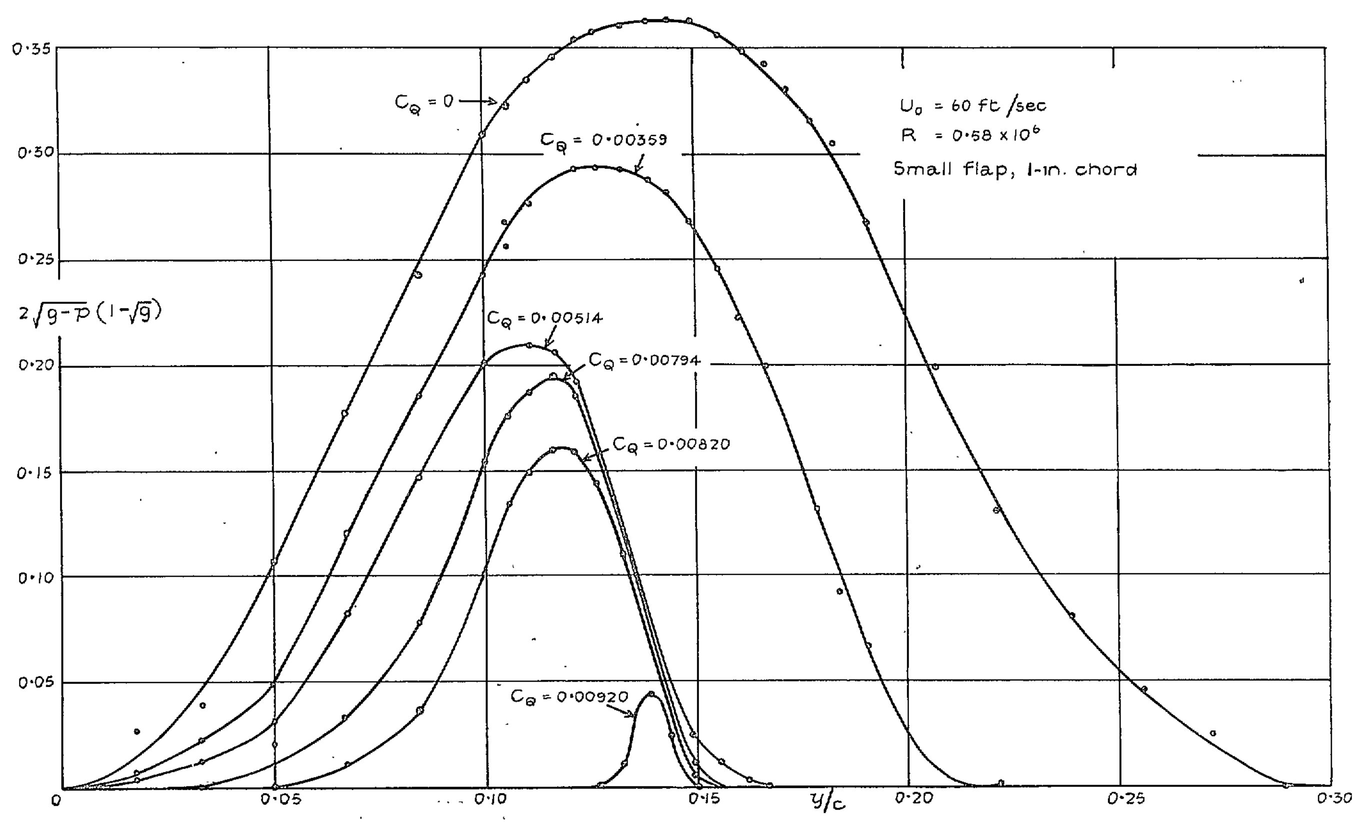

FIG. 4. Variation of wake profile with suction quantity coefficient.

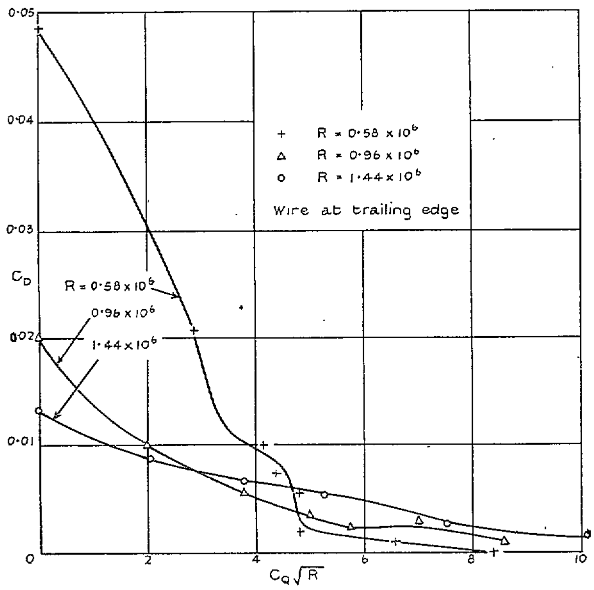

FIG. 5. Scale effect on the variation of wake drag coefficient with suction quantity.

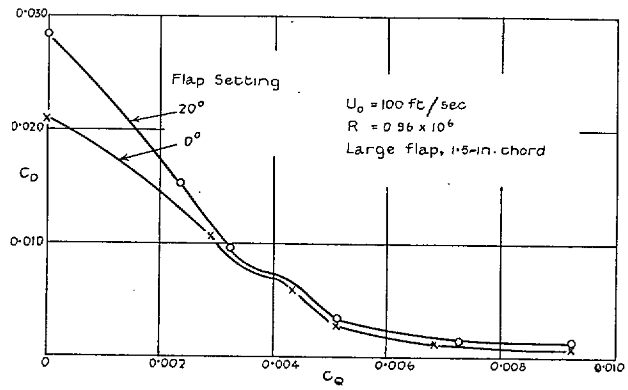

FIG. 6. Effect of flap deflection on drag and suction quantity relation.

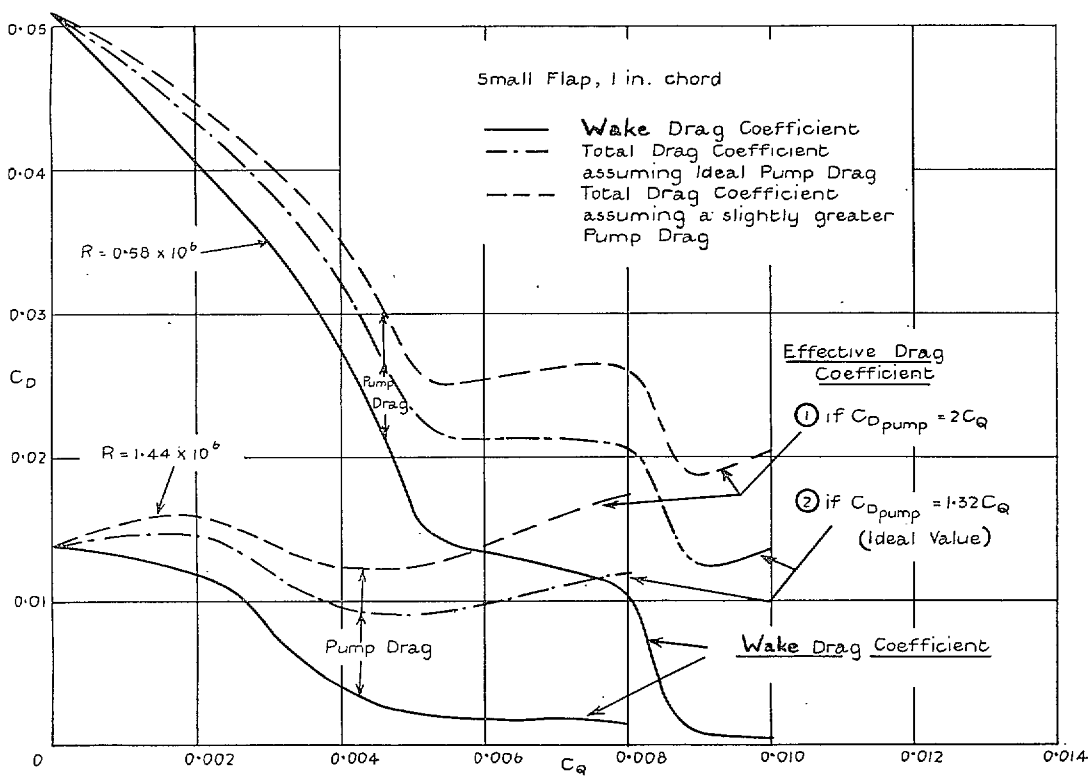

FIG. 7. Variation of total drag coefficient with suction quantity coefficient.

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