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Further Wind Tunnel Tests on a 30 per cent. Symmetrical Suction Aerofoil with a Movable Flap

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Summary.—Reasons for Enquiry.—The present work was undertaken in order to extend the existing experimental information on the 30 per cent. Griffith suction aerofoil obtained by Richards, Walker and Taylor[1] (1945), in particular :

(*a*) to investigate the behaviour of the wing when the flap was deflected,

(*b*) to test a wider slot and improved internal ducting system,

(*c*) to investigate further the variation of suction quantity with speed, and

(*d*) to find the variation of C_D with suction quantity and with different surface conditions.

Range of Investigation.—Tests with zero suction were carried out at a Reynolds number of $2 \cdot 88 \times 10^6$ for a range of incidence of 0–20 deg. and for flap angles of 0–14 deg. With boundary layer suction applied, tests were carried out at this Reynolds number to 6 deg. incidence only, owing to insufficient suction head. At a Reynolds number of $0 \cdot 96 \times 10^6$ the pump power was sufficient to prevent separation up to an incidence of 16 deg. where the maximum C_{NF} recorded was 2·3 with 14 deg. flap angle.

Conclusions.—The flap is effective as a high-lift device. A given C_L can be obtained at a much smaller angle of incidence when there is a positive flap setting than with zero flap angle, and less suction is required to prevent separation. There is considerable scale effect present between the two speeds at which tests were made, and it is desirable to test the wing in the Compressed Air Tunnel in order to estimate flight performance, particularly in the event of suction failure. The suction quantity is high at $R = 0 \cdot 96 \times 10^6$ but now shows a continuous decrease with increase of Reynolds number in contrast to the irregular variation found by Richards. With no suction and with laminar flow to the slot, the C_D has the low value, for the thickness of the aerofoil, of 0·010.

CONTENTS

1. *Introduction.*—Previous tests on the 30 per cent. symmetrical Griffith suction aerofoil in the National Physical Laboratory 13 ft. × 9 ft. wind tunnel were carried out by Richards, Walker and Taylor[1] (1945). The present work was undertaken to test the effect of treating the tail of the aerofoil (from the slot to the trailing edge) as a movable flap, with and without suction. A further investigation into the variation of suction quantity with wind speed was undertaken to provide a check on Richards' results, and observations were made of the changes in profile drag, (*a*) with wind speed, (*b*) with suction quantity and (*c*) with surface conditions for zero suction. Richards had already investigated the effect of transition movements on profile drag and suction quantity.

2. *Description of Model and Experimental Details.*—Suction was applied on both surfaces at 0·8 chord along the central 4 ft. span of the 30 per cent. thick Griffith aerofoil. The part of the aerofoil to the rear of the suction slot was movable as a 20 per cent. flap. The slot, which was backward facing and 0·18 in. wide, was bounded by end fins (*see* Figs. 20 and 21): there was no provision for sucking or for flap deflection on the outer 30 in. sections of the wing. The increase in slot width from the 0·10 in. of Richards' tests considerably reduced the velocity of the air into the slot. It was hoped that energy losses might thus be reduced and that a larger quantity of air would be abstracted by the existing pump.

Improved ducting designed by Rawcliffe[2] (1946) was fitted in the wing as shown in Fig. 1. It gave a nearly uniform flow distribution along the whole length of slot (Fig. 2). Fig. 3 is a diagrammatic representation of the complete ducting system. The air sucked through each slot was passed out of the wing at its lower end into short lengths of calibration piping* where the quantities were measured by means of the difference of the pressures in a total head tube at the centre of the pipe and a static tube at the wall. A preliminary exploration of flow in the pipe was undertaken in order to find the calibration factor.

The two calibration pipes led to two rectangular cross-section diffusers. At the low velocity end of these, baffles were fitted to control the amounts of suction. The air then entered a duct of large cross section, common to both diffusers, which led to the suction pump.

There was insufficient suction for taking readings above 6 deg. incidence at the higher wind speeds. An analysis of energy losses in the ducting system given in Fig. 3 shows that there is room for improvement. It is desirable to expand as soon as possible as the losses are greatest in the suction chamber itself and elsewhere where the velocity remains high, as in the short lengths of calibration piping which must not be omitted.

There was also a considerable loss where the diffuser entered the large ducting, particularly at high incidences when full suction was needed to prevent breakaway on the upper surface of the aerofoil, and only a small quantity was required on the lower surface. Thus only one half of the diffuser was in use, giving a sudden expansion into the common duct. Although the lower surface baffle was then completely closed, some flow was recorded through the lower surface piping owing to a slight leak due to bowing of the partitions down the middle of the diffuser. Hence at high incidences, the suction flow recorded on the lower surface may not be the absolute minimum.

Although it should be possible to reduce the losses still further by more careful design of the internal and external ducting, a more powerful pump will be needed to attain high C_L's at top speed.

The drag of the aerofoil was measured by a pitot-comb placed across the wake at 0·1 chord behind the trailing edge. The velocity distribution over the aerofoil was obtained by pressure plotting over the surface, the pressures on the upper and lower surfaces and in the wake being observed on a multitube manometer. The normal force, pitching moment, and hinge moment were obtained by the appropriate integration of the pressures, due allowance being given to the moments of pressures acting parallel to the chord line. The normal force coefficient, C_{NF}, is

* In order to get a sufficiently even distribution from which the quantity can be obtained by a pitot traverse to an accuracy of ±1 per cent., a length of 10 diameters is necessary for settling behind the point where any major change of section or direction occurs.

very nearly equal to the lift coefficient except at large angles of incidence where the difference may exceed 5 per cent. Future work on thick aerofoils will take chordwise components of pressures into account. This was not done in previous work on the 30 per cent. Griffith aerofoil by Richards, etc.[1] (1945) where the symbol C_L refers to the normal force coefficient.

3. *Zero Suction Tests.*—Tests without suction were carried out at a Reynolds number of $2 \cdot 88 \times 10^6$, corresponding to a tunnel speed of 180 ft. per second. This enabled as much information about scale effect to be gained as was possible in the 13 ft. × 9 ft. tunnel, since Richards' corresponding tests had been carried out at $R = 0 \cdot 96 \times 10^6$. Four positive flap angles (0 deg., 5 deg., 10 deg. and 14 deg.) were taken and observations were made every 4 deg. up to 20 deg. geometric incidence of the wing.* The results are given in Table 1 and plotted in Figs. 4, 5, 6, 7 and 8.

The variation of C_{NF} with incidence and the comparison with Richards' result at a Reynolds number of $0 \cdot 96 \times 10^6$ are shown in Fig. 4. It is seen that considerable scale effect is present in the range of Reynolds number from 1 to 3×10^6.

The variation of transition with incidence, as indicated by the " China Clay " method of Richards and Burstall[3] (1945), is shown in Fig. 5. At small incidences, where there was a considerable region of laminar flow on the upper surface, tests with streamers showed that the china clay recorded the re-adherence of flow to the surface about 0·03 chord behind a laminar separation. Over this range of incidence, the profile drag was small and it was recorded and plotted against incidence in Fig. 6. Separations occurred on both surfaces up to 4 deg. incidence with zero flap setting, though there was considerable scatter of " repeat " measurements, and at least one point in Fig. 6 seems to indicate separation on one surface only. A positive flap setting of 5 deg. cured this double separation. Two observations of drag made at angles above the partial stall, gave values of C_D of 0·069 at 8 deg. incidence and 0·100 at 12 deg. incidence with 14 deg. flap deflection in both cases. This is equivalent to a lift/drag ratio (for infinite aspect ratio) of 10 compared with 60 at the limit of the low drag region. With the wing at zero incidence and transition brought forward to 0·1 chord by means of turbulence wires, the drag of the aerofoil was of the same order as that obtained at high incidences. It was noted that when the pitot comb was in line with the wakes from isolated particles on the wing at 0·1 chord, the drag was even bigger. These increases are discussed more fully in section 5.

Figs. 7 and 8 give the variations of pitching and hinge moment coefficients with C_{NF}. For small angles of incidence, the pitching moment curves agree with the theory and with Richards' result, but the hinge moments differ considerably from both. This may be due to the different Reynolds number. The present results give negative hinge moments as in the theory, and are probably more reliable.

From these graphs, Figs. 4, 7 and 8, it will be seen that C_{NF}, C_m, and C_H change linearly up to between 6 deg. and 7 deg. incidence at which angle the gentle laminar separation near the slot is replaced by a violent turbulent separation which causes a sudden change in the values of the coefficients. With further increase of incidence, the lift again begins to rise and appears to reach a maximum at 20 deg. incidence, which was the greatest angle at which observations were taken.

These results indicate the need for tests at a higher Reynolds number in the C.A.T. There are considerable differences in the hinge moments and in separation and transition movements between the present test at $R = 2 \cdot 88 \times 10^6$ and Richards' results at $R = 0 \cdot 96 \times 10^6$. There may be further changes in the coefficients at higher Reynolds numbers and these can only be explored in a larger tunnel or in the C.A.T.

4. *Non-dimensional Presentation of Suction Flow.*—The choice of a suitable non-dimensional parameter to represent the amount of air sucked away at the point of velocity discontinuity in the aerofoil is a matter of convenience.

* For zero flap setting, the effective incidence can be obtained from Fig. 7 of R. & M. 2149[1]. With the flap set down, it would be very laborious to calculate this. Future tests will be carried out with suction applied along the full span.

The suction quantity coefficient " m " used by Richards, which is the ratio of the quantity of air sucked to the quantity of air in the boundary layer at the slot, assumed laminar, is very unsatisfactory from a practical point of view. In order to estimate the quantity sucked, the quantity in the laminar boundary layer must first be found, and this involves an arbitrary definition of the limit of the boundary layer. Also, when transition occurs in front of the slot, as happens at incidence, the fraction has little physical significance since it is not then the ratio of air sucked to that in the actual boundary layer at the slot.

In this paper, the coefficient " m " has been replaced by the more usual quantity coefficient $C_Q = Q/U_0c$, where Q is the quantity of air removed per foot span per second, U_0 is the stream velocity, and c is the chord of the aerofoil.

With this notation, we find that the power absorbed by the pump, when expressed in the form of a drag coefficient relating to the wing area and speed, bears a simple relation to C_Q:—

C_D pump $= C_Q \times H_1/\eta$, where η is the pump efficiency and H_1 is the loss of head in the boundary layer and in the ducting.

5. *Variation of Wake Drag with Suction Quantity.*—5.1. *Wake Profiles at Zero Lift.*—The distribution of total head across the wake $0 \cdot 1$ chord behind the trailing edge of the aerofoil is shown in Fig. 9 for zero incidence and flap settings at a Reynolds number of $2 \cdot 88 \times 10^6$ for various suction quantities. The area enclosed by each curve, $\int 2\sqrt{g-p}\,(1-\sqrt{g})\,dy/c$ (where g is the total head and p the static pressure in the wake), gives the drag coefficient.

When, without suction, an isolated roughness was placed on each surface at $0 \cdot 1$ chord, in line with the comb, the very large C_D of $0 \cdot 0987$, corresponding to diagram B of Fig. 9, was recorded. The roughness produced a turbulent wedge downstream of itself which was visualised by the china clay technique in Fig. 21. (Fig. 21 was actually taken with suction, but this makes very little difference to the picture.) The picture shows an increasing diffusion of the wedge in a region of severe adverse pressure gradients. This spanwise diffusion causes an extra loss of momentum in the wake directly in line with the roughness and gives rise to the very high local drag coefficient, which is confined to the central core of the wedge. The total drag of a portion of wing completely spanning such a wedge does not exceed the drag with a transition wire spanning the wing at the same place as the roughness. The drag coefficient with transition at $0 \cdot 1$ chord is $0 \cdot 0577$ (diagram A) compared with the peak value of $0 \cdot 0987$.

5.2. *Drag Coefficients at Zero Lift.*—The changes of drag coefficient with suction quantity coefficient for zero flap and incidence settings at three different speeds are plotted in Fig. 10.

With zero suction, laminar separation occurs $0 \cdot 04$ chord in front of the slot. With application of increasing suction, the separation is quickly overcome and the drag falls rapidly to a small value, transition occurring at the slot at $R = 0 \cdot 96 \times 10^6$. At higher speeds, a small adverse pressure gradient due to the approximate method of design of the aerofoil causes transition to move $0 \cdot 04$ chord forward to the laminar separation position. Further increase of suction restores the boundary layer profile to a stable laminar type, and if this persists over the flap, the drag coefficient may be still further reduced. Thus at the highest suctions possible with the present pump, laminar flow can be maintained over the whole aerofoil at $R = 0 \cdot 96 \times 10^6$ and to $0 \cdot 93$ chord at $R = 2 \cdot 88 \times 10^6$ (as illustrated in Fig. 20 and Fig. 9, F) giving a C_D of $0 \cdot 00055$ for the latter. Laminar flow over the flap is not expected to occur at flight Reynolds numbers as the concavity of the flap has a destabilising effect on laminar boundary layers. This has been investigated experimentally by Richards, Walker and Greening[4] (Pt. II, 1944).

The following calculation gives a rough check on the measured low-drag values. If the whole boundary layer in front of the slot is assumed to be absorbed, then only the flow over the flap need be considered, so that comparing the drag of the wing with the "flat plate" drag of the flap of chord $x/c = 0 \cdot 2$ and velocity $u/U_0 = 0 \cdot 7$, the C_D of the wing is found to fall from $0 \cdot 00072$ to $0 \cdot 00065$ for turbulent boundary layers and from $0 \cdot 00045$ to $0 \cdot 00026$ for laminar boundary layers as the Reynolds number of the wing changes from $0 \cdot 96$ to $2 \cdot 88 \times 10^6$.

As the quantity of suction is decreased, the profile drag rises slightly until separation occurs. This happens at nearly the same values of suction quantity as are needed to prevent separation with increasing suction. At $R = 0{\cdot}96 \times 10^6$ the rise in drag with separation of the flow is sudden, but this is not so at the higher speeds.

5.3. *Incidence Effects.*—Two curves showing the change of C_D with decreasing suction at $\alpha = 14$ deg., $\eta = 10$ deg. and $\alpha = 6$ deg., $\eta = 14$ deg. are included in Fig. 10. These should be interpreted in conjunction with Table 4 which shows how the flow breaks down, as indicated by the wake traverse.

Below 10 deg. incidence, laminar flow persists well back over the surface of the wing and on decreasing suction, the flow breaks down through laminar separation. Above 10 deg., transition is forward and the flow breaks down through turbulent separation. If transition is brought forward at low incidences by means of wires, then violent turbulent separation again occurs. The difference between $R = 0{\cdot}96$ and $2{\cdot}88 \times 10^6$ is that in the latter case, transition is slightly further forward in the favourable incidence range and it moves to the leading edge at an earlier incidence. It is impossible to hold laminar flow to the slot at the higher speed owing to the adverse pressure gradient.

6. *Variation of Minimum Suction Quantity with Speed.*—In the tests in which the minimum suction quantity to prevent separation of the flow was to be determined, the tunnel was run up to speed and the loss of head across the wake observed on the multitube manometer. The suction pump was then started and the baffles opened until separation was overcome and low drag resulted. The baffles were wound out a few extra turns and then closed until separation occurred and the size of the wake increased suddenly. The process was then repeated, the baffles being closed one turn less. If separation had not then occurred the suction quantity was taken to be the minimum and observations were made. This process was satisfactory at high incidences, but between 0 deg. and 4 deg. incidence of the wing it was not always immediately evident when separation had taken place as there was no sudden change of drag.

Fig. 11 gives the variation of C_Q with speed, the wing being set at zero flap and incidence. Experimental points are marked with crosses. Suction quantities obtained by Richards in his various tests have been converted from " m's " to C_Q's and are plotted in the figure. They are also given in tabular form in Table 3. It will be noted that Richards always needed more suction on the upper surface than on the lower. In the present experiments the suction quantities were more nearly equal and as those for one surface were not always larger than those for the other, a mean curve has been drawn through the experimental points. With the smooth wing surface, Richards' quantities are lower than those obtained by us, transition condition being the same. This may be due to the different slot sizes used, but it could have been caused by the more uneven velocity distribution along the slot, obtained in Richards' experiments, if the pressures and wake traverse had been taken at a position of peak velocity. By comparing the two curves, it now appears that Richards' quantities given at speeds of 100, 160 and 180 ft. per sec. are probably incorrect. This is not surprising considering the difficulty of determining when the flow has adhered to the surface. There is no abrupt change in the drag curve for 180 ft. per sec., in Fig. 10, and threads are not very satisfactory for differentiating between laminar separation and transition.

Included on Fig. 11, are theoretical curves of C_Q for different transition positions worked out from Sir Geoffrey Taylor's criterion for sufficient suction[4] (Pt. III). This assumes that there is no loss of head in any streamtube as it crosses the discontinuity. There is, therefore, one particular element of the boundary layer whose dynamic energy is reduced to zero by the pressure discontinuity at the slot. This suggests that only that part of the boundary layer between this element and the aerofoil surface should be withdrawn.

In all the present observations with minimum suction, transition has moved forward to about 1 in. in front of the slot ($0{\cdot}76$ chord). It is seen that at the highest speeds there is good agreement with the theoretical curves, but that at lower speeds the experimental quantities are much greater. This is almost certainly due to the influence of the observed laminar separation. With transition wires at 0·1 and 0·5 chord, Richards obtains quantities which are considerably less than the theoretical. It is found on the other hand that his wake drags are somewhat higher than the theoretical values. Thus the quantities based on Taylor's criterion prove to be pessimistic but will ensure a low drag.

7. *Tests at Minimum Suction: Variation of Velocity Distribution, C_{NF}, C_Q, C_m, C_H, and C_D with Flap and Incidence Positions.*—These tests were carried out at four flap settings. 0 deg., 5 deg., 10 deg. and 14 deg. at 0 deg. incidence and at 2 deg. intervals of incidence as far as the pump could provide sufficient suction to prevent separation. These limits were 16 deg. at $R = 0{\cdot}96 \times 10^6$ and 6 deg. at $R = 2{\cdot}88 \times 10^6$. A complete list of experimental results is given in Tables 1 and 2.

7.1. *Velocity Distribution.*—Velocity distribution is shown in Fig. 12 at 0 deg., 4 deg. and 10 deg. incidences for the range of flap angles. Theoretical curves for zero flap angle are included, and it will be seen that agreement is good. Comparison with Richards shows that the wider slot has reduced the peak velocities just in front of the slot.

7.2. *Normal Force.*—The normal force coefficient is plotted against geometric incidence in Fig. 13. The tailing off of the curves at $R = 2{\cdot}88 \times 10^6$ is due to insufficient suction. The maximum C_{NF} reached at $R = 0{\cdot}96 \times 10^6$ is 2·3, and judging from the behaviour of the curves, it seems probable that they might have been extended to a C_{NF} of 3 had sufficient suction been available. The lift curve slope of 7·2 per radian agrees well with Richards' 7·3 against the theoretical value of 7·9.

7.3. *Suction Quantities.*—Suction quantities are plotted, for the different flap settings and for each surface, against geometric incidence in Fig. 14 and against C_{NF} in Fig. 15. The variations of C_Q with flap angle in the former graph at any given incidence are seen to be small and irregular and so a mean curve is drawn. Thus, at any given incidence, by applying a positive flap setting we can increase the lift of the aerofoil without much affecting either the profile or pump drag, for the power absorbed by the pump may be represented as a drag coefficient which is proportional to the suction quantity coefficient (*see* section 4).

On the upper surface, C_Q remains practically constant below 6 deg. incidence as transition is near the slot. Above this angle transition moves forward, and C_Q rises due to the greater width of the turbulent boundary layer. Owing to the thickening effect of increasingly adverse velocity gradients, C_Q continues to rise throughout the rest of the incidence range.

7.4. *Pitching Moment.*—The pitching moment coefficient C_m about the quarter-chord point is plotted against C_{NF} in Fig. 16. The observed tailing off of these curves at $R = 2{\cdot}88 \times 10^6$ is due to insufficient suction, but at $R = 0{\cdot}96 \times 10^6$ the curves are roughly linear. The gradient of the set of parallel lines giving the closest fit to the experimental points is $dC_m/dC_{NF} = -0{\cdot}0515$. Hence we deduce that the aerodynamic centre of the wing, with zero flap setting, is at 0·3015 chord, with a change of trim on alteration of flap angle given by $dC_m/d\eta = 0{\cdot}0095$.

7.5. *Hinge Moment.*—The hinge moment coefficient is obtained by finding the moments of the loads on the flap. A typical example of such loading is shown in Fig. 17 and this should be compared with Fig. 18 which shows the corresponding loads with zero suction. The moments, with suction, are shown in Fig. 19 where C_H is plotted against C_{NF}.

Agreement with theory, and with Richards' experiments with zero flap setting is good for both pitching and hinge moment curves. It will also be noticed that the curve of C_H agrees closely with the theoretical curve at high C_{NF}'s instead of decreasing as on Richards' graph. This decrease found by Richards is probably due to leakage in the ducting system giving excessive suction on the lower surface.

7.6. *Drag.*—The drag coefficients obtained from pitot-comb exploration of the wake are given in the Tables. With separation prevented, they are all of " low " value between 0·001 and 0·004, but owing to slight departures of C_Q from the minimum, no regular variation of C_D with incidence or flap angle can be found.

8. *Variation of Lift with Suction Quantity.*—Observations made at two different angle settings of the wing, namely $\alpha = 14$ deg., $\eta = 10$ deg. and $\alpha = 6$ deg., $\eta = 14$ deg., which are not recorded in the Tables, showed that when breakaway of the flow from the surface in front of the slot was prevented, further increase in quantity of air sucked at each slot had no effect on the velocity distribution over the aerofoil, except at a very small region near the slot where sink effect predominated. Thus the theoretical value of the lift-curve slope cannot be exceeded by means of suction. This is in contrast to ejection, where, even after separation is prevented increase in C_L would be expected.

9. *Discussion.*—It will be seen from the graphs, that with suction applied, and at the lower Reynolds number $R = 0{\cdot}96 \times 10^6$, a series of mutually consistent results have been collected at incidences up to 16 deg. and 14 deg. flap angle. It must be noted that these results should not be regarded as applying to free air, as firstly, the usual tunnel corrections have not been applied, and secondly, the flow over the section on which the pressures were recorded was by no means two dimensional. With flap setting and suction applied only along the central 4-ft. span of the model there is considerable downwash interference due to the trailing vorticity shed at the " end " fins. Future models will have suction applied over the whole span.

Owing to the approximate design of the aerofoil, it was not possible to maintain laminar flow to the slot in the face of adverse pressure gradients. This reflects in the nature of the breakdown of the flow at low incidences. The new symmetrical and cambered aerofoil designs by Glauert[5], (1945), using the method of Lighthill[6] (1945), will remedy this defect and enable the best results to be obtained from this type of aerofoil.

The effect of a wake arising from an isolated protuberance on the surface of the wing in producing a large local drag coefficient in its path has been noted. This is because the turbulent wedge caused by the particle spreads along the span as well as normal to the surface, particularly in the region of adverse pressure. The high observed value of the drag coefficient, 0·0987, is confined to the central core of the wedge of turbulence, and the mean drag coefficient over a section of wing completely spanning the phenomenon is less than that due to a two-dimensional transition front at the same place, when $C_D = 0{\cdot}0577$.

The wide range of drag coefficients obtainable on the aerofoil gives rise to some interesting problems. For example, a " flying wing " type of aircraft with an aspect ratio of 9, coming in to land with suction on at an incidence of 12 deg. with 14 deg. flap would have a $C_L = 1{\cdot}8$ and hence an induced drag $C_{Di} = 0{\cdot}115$. This is nearly the whole drag, and so the lift/drag ratio = 15. If, however, the suction pumps are cut out and trim can be maintained, the C_L falls to 1·0, $C_{Di} = 0{\cdot}035$, the profile drag becomes $C_{Dp} = 0{\cdot}10$, and hence the lift-drag ratio is halved at 7·4. This is still high, but a more reasonable value for a landing approach. It will be observed that there is little change of pitching moment, or of C_L, if the aircraft had approached with its flaps up, and lowered them to 14 deg. simultaneously as the suction was stopped.

10. *Conclusions.*—A partial stall is present at 6 deg. incidence in the tests without suction at a Reynolds number of $2{\cdot}88 \times 10^6$. Above 6 deg. incidence the drag and hinge moments are large, whilst the pitching moments change irregularly. This stall does not occur in Richards' tests at $0{\cdot}96 \times 10^6$. Thus there seems to be considerable scale effect on C_{NF}, C_m and C_H at zero suction and it would be desirable to test the wing at a much higher Reynolds number in the C.A.T. in order to estimate the flight performance of the wing in the event of suction failure.

Compared with previous tests, a more uniform suction distribution along the slot, and a more accurate measurement of quantity have been attained. The quantity, normal force, and moment coefficients obtained with zero flap angle setting agree approximately with those found by Richards. In particular, the suction quantities now show a smooth variation with speed, and tend to the theoretical values at top speed when transition is near the slot.

The flap has been shown to be a very effective high-lift device as it enables a higher lift to be obtained at any incidence without creating large adverse gradients. Consequently the change of suction quantity with flap angle is small. It is thus desirable to obtain high lifts by the use of maximum available flap angle, as this gives the most economical suction quantity for a given C_L. The flap also exercises good control with linear changes of pitching moment coefficients. An automatic trimmer fitted to a flying wing of this section would cope with the change of trim experienced on changing flap angle.

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TABLE 1

Experimental Results

No Suction

$R = 2{\cdot}88 \times 10^6$

Incd. α deg.	Flap η deg.	C_L	C_m	$-C_H$	C_D	Laminar Separation or Transition	
						Upper	Lower
20	14	1·320	−0·0700	1·228			
	10	1·232	−0·0214	1·038			
	5	1·098	+0·0006	0·938			
	0	1·030	+0·0183	0·848			
18	14	1·265	−0·0660	1·085			
	10	1·212	−0·0406	1·013			
	5	1·15	−0·0341	1·093			
	0	0·977	+0·0115	0·945			
16	14	1·200	−0·0746	1·298			
	10	1·123	−0·0518	1·200			
	5	1·085	−0·0282	1·063			
	0	0·863	+0·0170	0·928			
14	14	1·095	−0·0722	1·240			
	10	1·007	−0·0532	1·133			
	5	0·890	−0·0222	0·973			
	0	0·749	+0·0230	0·878			
12	14	0·999	−0·0777	1·160	0·100		
	10	0·900	−0·0457	1·108			
	5	0·742	−0·0153	1·008			
	0	0·652	+0·0135	0·853			
10	14	0·855	−0·0684	1·125			
	10	0·752	−0·0487	1·050			
	5	0·583	−0·0097	0·850			
	0	0·437	+0·0287	0·803		0·167	0·777
8	14	0·722	−0·0802	1·088	0·069		
	10	0·664	−0·0305	0·995			
	5	0·524	−0·0164	0·880		0·27	
	0	0·435	−0·0100	0·763		0·33	0·758
6	14	0·876	−0·1144	1·240			
	10	0·738	−0·0458	1·093			
	5	0·624	−0·0719	0·748	0·02015	0·675	0·742
	0	0·459	−0·0384	0·685	0·01669	0·634	0·758
4	14	0·809	−0·1423	0·490	0·01524	0·767	0·700
	10	0·731	−0·1245	0·310	0·01162	0·767	0·725
	5	0·474	−0·0582	0·278	0·01110	0·735	0·735
	0	0·301	−0·0198	0·225	0·01323	0·717	0·742
2	14	0·652	−0·1351	0·415	0·01396	0·767	0·692
	10	0·493	−0·0986	0·185	0·01121	0·767	0·717
	5	0·323	−0·0522	0·110	0·01044	0·754	0·735
	0	0·167	−0·0131	0·165	0·01136	0·726	0·742
0	14	0·447	−0·1186	0·293	0·01398	0·774	0·683
	10	0·318	−0·0871	0·163	0·01082	0·767	0·692
	5	+0·129	−0·0400	0·025	0·00987	0·754	0·704
	0	−0·037	+0·0001	0·035	0·00948	0·74	0·74

TABLE 1—*Continued*

Experimental Results

Minimum Suction

$R = 0{\cdot}96 \times 10^6$

Incd. α deg.	Flap η deg.	C_L	C_D	C_Q Upper	C_Q Lower	$-C_m$	$-C_H$
16	14	2·300	0·00302	0·01444	0·00542	0·2576	0·425
	10	2·043	0·00108	0·01830	0·00672	0·1982	0·285
	5	1·754	0·00162	0·01533	0·00589	0·1348	0·173
	0	1·532	0·00177	0·01544	0·00598	0·0365	0·030
14	14	2·095	0·00319	0·01285	0·00523	0·2745	0·430
	10	1·815	0·00170	0·01585	0·00615	0·1825	0·265
	5	1·595	0·00156	0·01495	0·00598	0·1279	0·163
	0	1·422	0·00167	0·01305	0·00492	0·0792	0·045
12	14	1·811	0·00373	0·01035	0·00580	0·2243	0·408
	10	1·595	0·00254	0·01093	0·00523	0·1741	0·278
	5	1·375	0·00215	0·01201	0·00458	0·1045	0·165
	0	1·143	0·00178	0·01112	0·00447	0·0626	0·028
10	14	1·570	0·00339	0·00872	0·00732	0·2038	0·383
	10	1·321	0·00285	0·00836	0·00542	0·1456	0·320
	5	1·133	0·00214	0·00812	0·00458	0·0826	0·175
	0	0·883	0·00136	0·00923	0·00523	0·0249	0·018
8	14	1·288	0·00418	0·00415	0·00634	0·1807	0·400
	10	1·135	0·00224	0·00513	0·00514	0·1534	0·283
	5	0·924	0·00196	0·00349	0·00486	0·0912	0·170
	0	0·743	0·00133	0·00486	0·00486	0·0407	0·040
6	14	1·168	0·00149	0·00523	0·00600	0·1868	0·360
	10	1·000	0·00104	0·00482	0·00504	0·1406	0·268
	5	0·756	0·00080	0·00402	0·00436	0·0739	0·158
	0	0·537	0·00124	0·00560	0·00492	0·0198	0·033
4	14	0·977	0·00168	0·00513	0·00582	0·1747	0·343
	10	0·810	0·00074	0·00551	0·00582	0·1284	0·265
	5	0·574	0·00078	0·00472	0·00493	0·0691	0·145
	0	0·330	0·00113	0·00503	0·00504	0·0404	0·015
2	14	0·796	0·00184	0·00493	0·00582	0·1643	0·343
	10	0·622	0·00098	0·00551	0·00650	0·1244	0·248
	5	0·390	0·00065	0·00461	0·00494	+0·0625	+0·148
	0	0·130	0·00088	0·00513	0·00504	−0·0026	−0·018
0	14	0·619	0·00232	0·00523	0·00524	+0·1671	+0·313
	10	0·436	0·00051	0·00532	0·00514	0·1161	0·230
	5	+0·208	0·00106	0·00472	0·00502	+0·0584	+0·118
	0	−0·019	0·00133	0·00474	0·00455	−0·0018	−0·020

TABLE 2

Experimental Results

Minimum Suction

$R = 2 \cdot 88 \times 10^6$

Incd. α deg.	Flap η deg.	C_L	C_D	C_P Upper	C_Q Lower	$-C_m$	$-C_H$	Remarks
8	0	—	0·00114	0·00673	0·00622	—	—	Separation Intermittent
6	14	0·980	0·00284	0·00380	0·00267	0·1511	0·395	A
			0·00289	0·00414	0·00193			B
	10	0·860	0·00196	0·00322	0·00153	0·1174	0·288	
	5	0·671	0·00203	0·00262	0·00137	0·0727	0·155	
	0	0·463	0·00110	0·00308	0·00331	0·0049	0·033	A Very unsteady.
			0·00187	0·00312	0·00123			B
4	14	0·885	0·00116	0·00293	0·00251	0·1569	0·350	A
			0·00319	0·00268	0·00199			B
	10	0·709	0·00099	0·00253	0·00296	0·1184	0·285	A
			0·00183	0·00220	0·00260			B
			0·00316	0·00240	0·00153			C
	5	0·503	0·00157	0·00196	0·00164	0·0627	0·195	A
			0·00686	0·00134	0·00123			B
	0	0·297	0·00266	0·00200	0·00164	0·0024	0·025	A
			0·00152	0·00187	0·00132			B
2	14	0·766	0·00106	0·00287	0·00380	0·1752	0·340	
	10	0·557	0·00092	0·00204	0·00282	0·1159	0·248	
	5	0·365	0·00143	0·00164	0·00181	0·0616	0·135	
	0	0·143	0·00126	0·00232	0·00211	0·0043	0·013	
0	14	0·579	0·00122	0·00277	0·00338	0·1679	0·363	
	10	0·343	0·00093	0·00212	0·00256	0·0989	0·233	
	5	+0·177	0·00105	0·00232	0·00237	+0·0521	0·123	
	0	−0·003	0·00109	0·00222	0·00294	−0·0034	0·035	

TABLE 3

Richards' Experimental Drag and Quantity Coefficients

Zero Flap Throughout. Minimum Suction

At 180 f.p.s. $R = 2 \cdot 88 \times 10^6$

Incd. α deg.	Smooth Wing			Transition Wire at 0·5c			Transition Wire at 0·1c		
	C_D	C_Q Upper	C_Q Lower	C_D	C_Q Upper	C_Q Lower	C_D	C_Q Upper	C_Q Lower
0	0·00144	0·00181	0·00224	0·0028	0·00309	0·00275	Not recorded	0·00454	0·00381
2	0·0011	0·00378	0·00218	0·00257	0·00574	0·00222		0·00564	0·00324
3	—	—	—	—	—	—		0·00636	0·00296
4	0·00131	0·00580	0·00270	0·00237	0·00568	0·00211		—	—
5	—	—	—	0·00232	0·00602	0·00199			
6	0·00079	Not taken		—	—	—			

At 60 f.p.s. $R = 0 \cdot 96 \times 10^6$

Incd. α deg.	Smooth Wing		
	C_D	C_Q Upper	C_Q Lower
0	0·00068	0·00380	0·00402
4	—	0·00391	0·00357
8	0·00162	0·00385	0·00357
12	0·00135	0·0112	0·0033
13	0·00138	0·0124	0·00362
14	0·00133	0·0134	0·00397
16	0·0008	0·0179	*

* Large because of Leak.

Scale Effect at 0 deg. Incd.

Speed f.p.s.	Smooth Wing			Transition Wire at 0·5c			Transition Wire at 0·1c		
	C_D	C_Q Upper	C_Q Lower	C_D	C_Q Upper	C_Q Lower	C_D	C_Q Upper	C_Q Lower
60	0·00068	0·00402	0·00380	0·0031	0·00385	0·00295	0·00402	0·00562	0·00477
80	0·00086	—	0·00250	0·00284	0·00383	0·00323	0·00374	0·00527	0·00446
90	0·00176	0·00215	0·00174	—	—	—	—	—	—
100	0·00108	0·00279	0·00218	0·0033	0·00317	0·00248	0·00371	0·00465	0·00425
110	0·0022	0·00145	0·00118	—	—	—	—	—	—
120	0·00232	0·00147	0·00102	0·00318	0·00326	0·00258	0·00350	0·00460	0·00410
130	0·00193	0·00131	0·00102	—	—	—	—	—	—
140	0·00206	0·00116	0·00075	0·00303	0·00321	0·00267	0·00372	0·00462	0·00387
160	0·00118	0·00162	0·00156	0·00287	0·00317	0·00272	0·00344	0·00479	0·00387
180	0·00100	0·00224	0·00183	0·00280	0·00310	0·00275	0·00338	0·00455	0·00381

TABLE 4

Effect of Decreasing Suction on Flow Over the Wing

$R = 0{\cdot}96 \times 10^6$

incd.	C_Q Upper	C_Q Lower	China Clay indications on Upper Surface	Drag Diagram Upper Side	Drag Diagram Lower Side	Remarks
$\alpha = 6°$ $\eta = 0°$ and less.	0.00561	0.00491	Transition 0.767c Upper 0.80c (Slot) Lower			C_Q's above this value, Flow Laminar to slot on both surfaces. No separation
	0.00349	0.00481	Tr. Upper 0.758c			
	0.00246	0.00580	Laminar separation 0.75c			Flow on Flap very rough and intermittent
	0.00201 and	0.00324 less	Lam: seps at 0.64c (No suction)			Reversed Flow on Flap
$\alpha = 8°$ $\eta = 0°$	Similar breakdown of flow, quantities higher,					
$\alpha = 10°$ $\eta = 0°$	0.01192	Minimum throughout	Transition very ragged mean at 0.37 chord (const.)			
	0.00900					Flow smooth on Flap. Disturbance at slot lip (on cotton thread).
	0.00493 and less					Turbulent separation at 0.667 chord.
$\alpha = 14°$ $\eta = 0°$	0.02070	0.00754	Transition at 0.10 chord			Note: Transition at slot (lower). China Clay indicates white portion 0.10 → 0.50 chord and line at 0.79c on slot lip. Also laminar flow on Flap to 0.95c (Excess suction + Good profile)
	0.07474	0.00544				
	0.01233 and	0.00458 less				Turbulent sep. at 0.58 c. reversed flow on Flap
$\alpha = 6°$ $\eta = 0°$	0.00924	0.00598	Transition wire Upper Surface at 0.10 c.			
	0.00712	0.00562				Turbulent separation at 0.667c. Reversed flow behind and also on Flap
	No	suction		Ditto		Turb. sep. at 0.667c Reversed flow only on Flap
$\alpha = 8°$ $\eta = 0°$	0.01130	0.01045	Transition wire Upper Surface 0.10 c.			
	0.00912	0.00972				Turbulent separation at 0.70c. Reversed Flow on Flap.
	0.00866 and decreasing	0.00807				Ditto, note holding down of drag diagram
	0.00472 and	0.00400 less				Ditto, sep moving Forward to 0.63 chord.

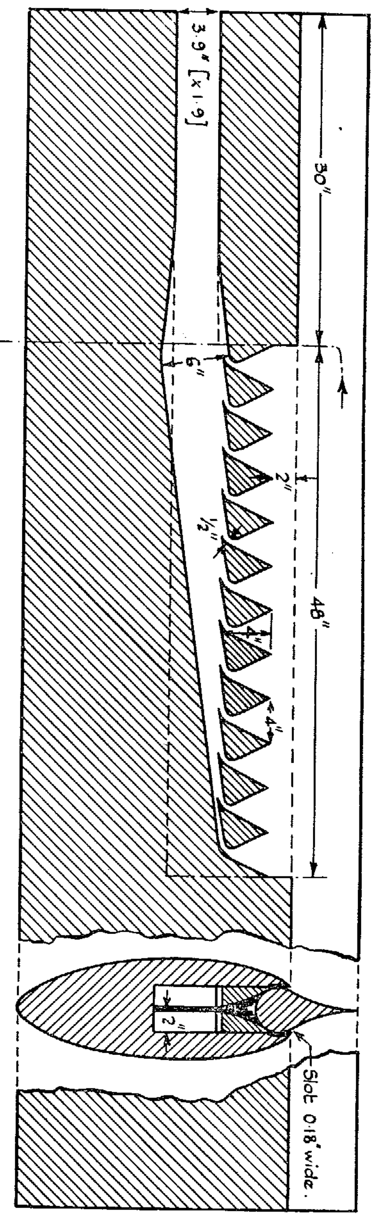

Fig. 1. Internal Suction Ducting of 30 per cent. Griffith Wing.

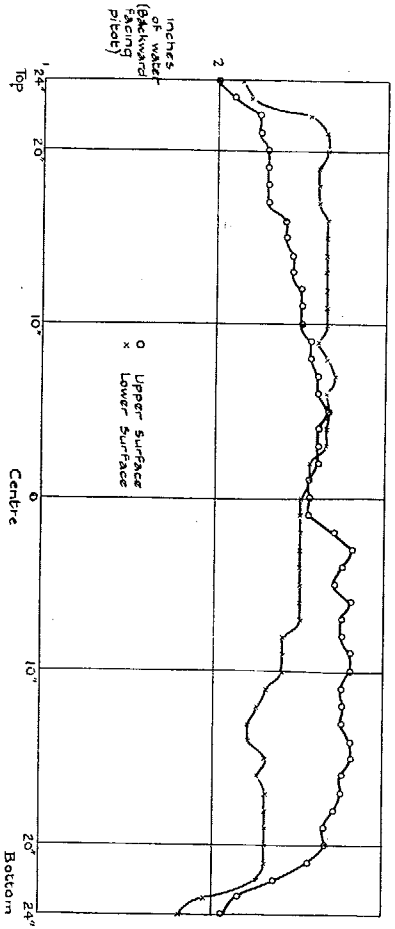

Fig. 2. Calibration of Flow along Length of Slot.
Suction quantities are the minimum to prevent separation
$\alpha = 0$ deg., $\eta = 0$ deg., $U = 60$ f.p.s.

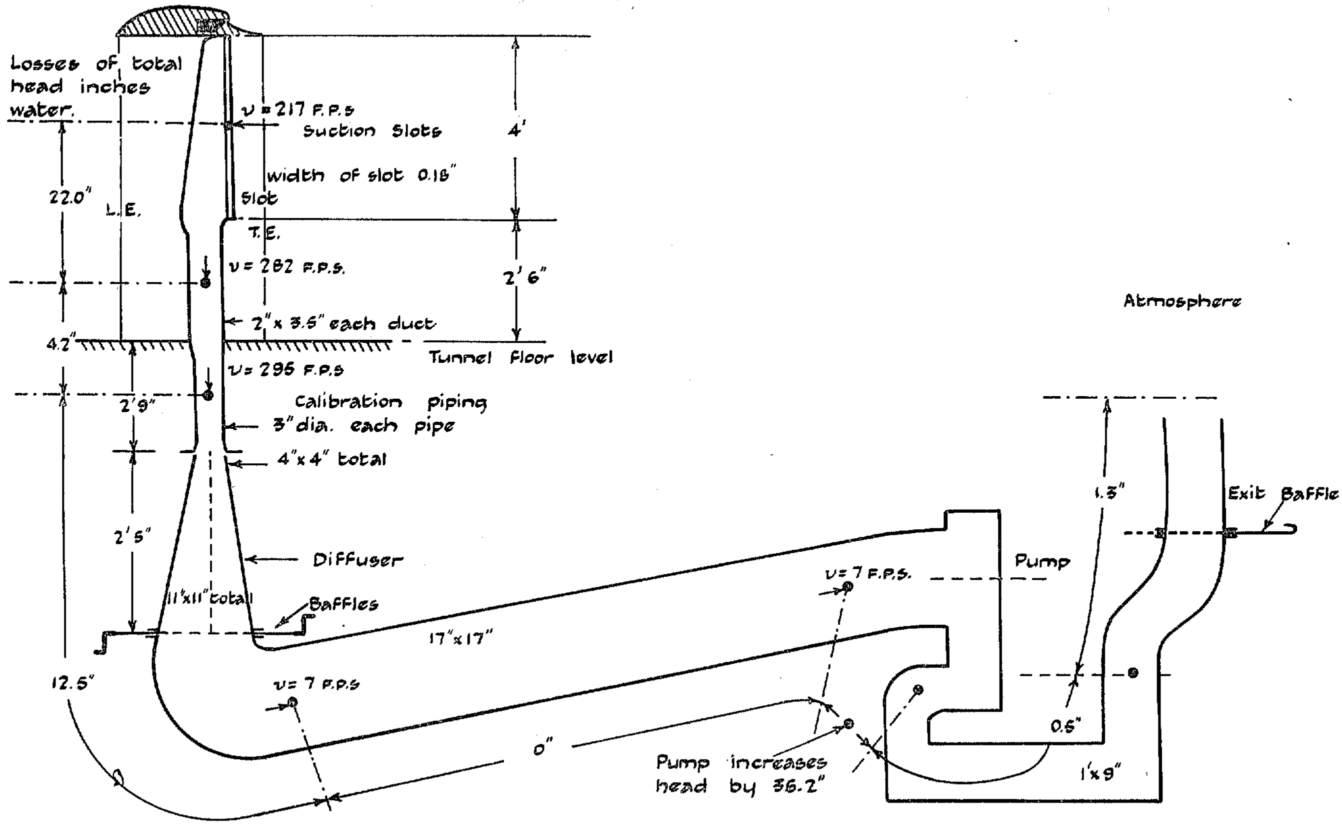

FIG. 3. Diagrammatic Representation of Velocities and Losses in Suction Ducting.

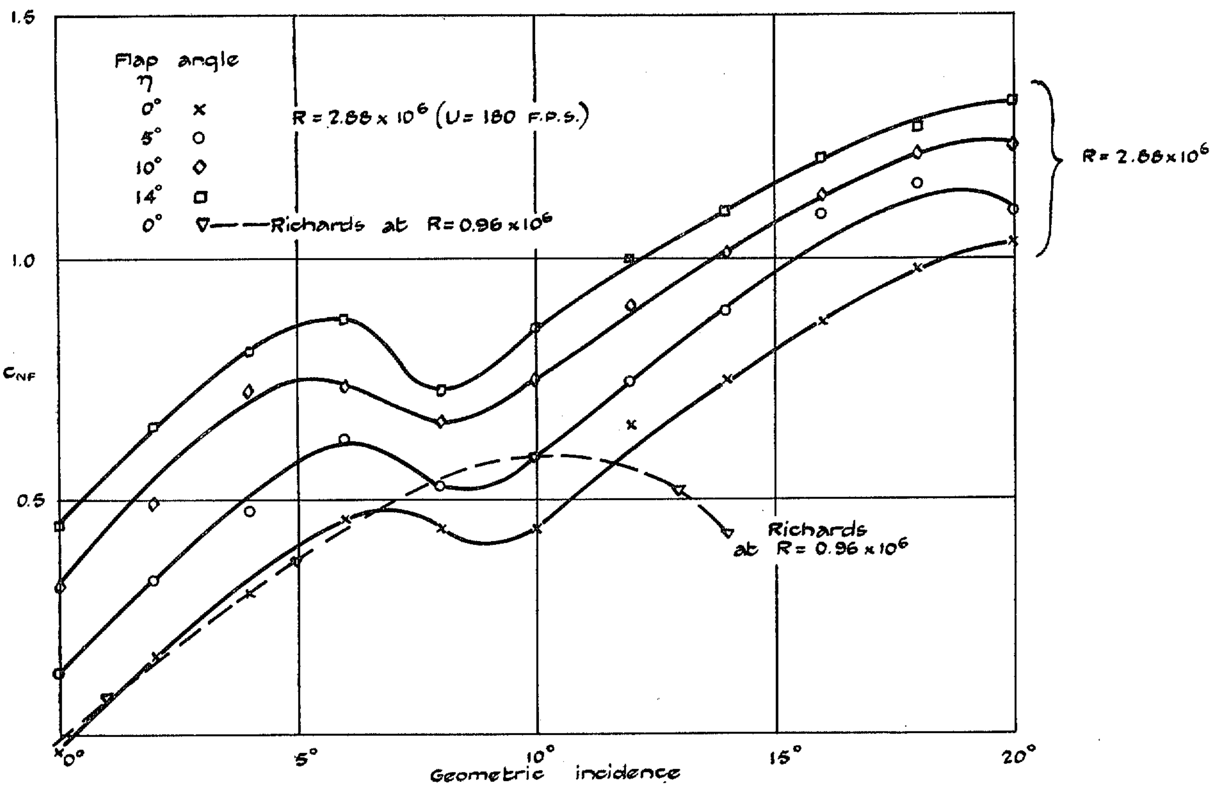

FIG. 4. Variation of Normal Force Coefficient with Geometric Incidence, Various Flap Angles—Suction Off. $R = 2 \cdot 88 \times 10^6$.

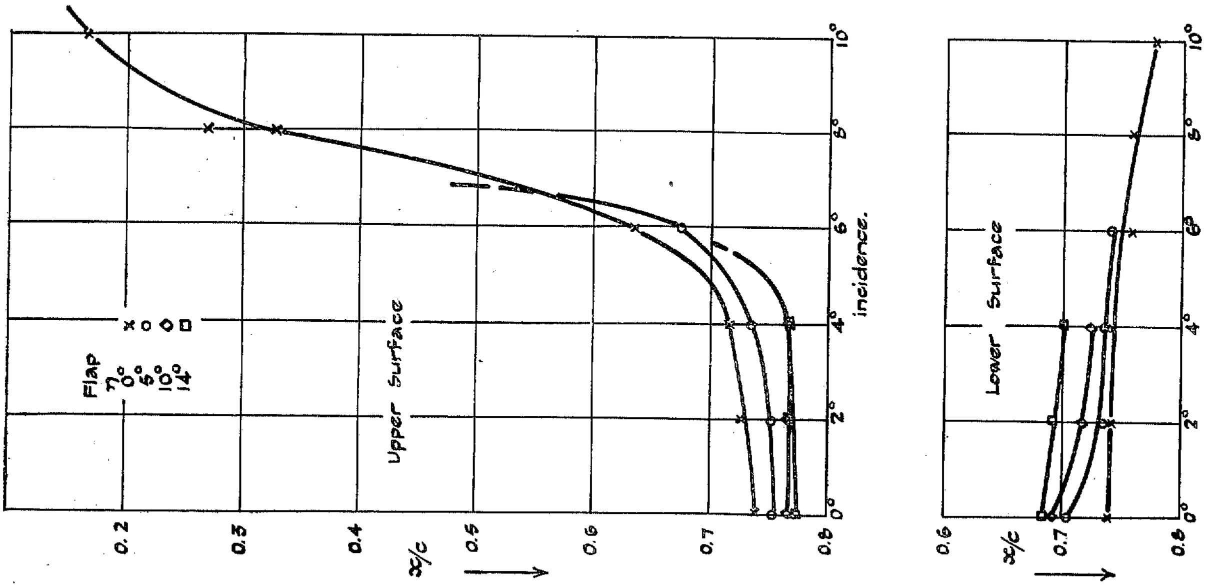

FIG. 5. Laminar Separation or Transition Position with Flap and Incidence. $R = 2{\cdot}88 \times 10^6$. No Suction.

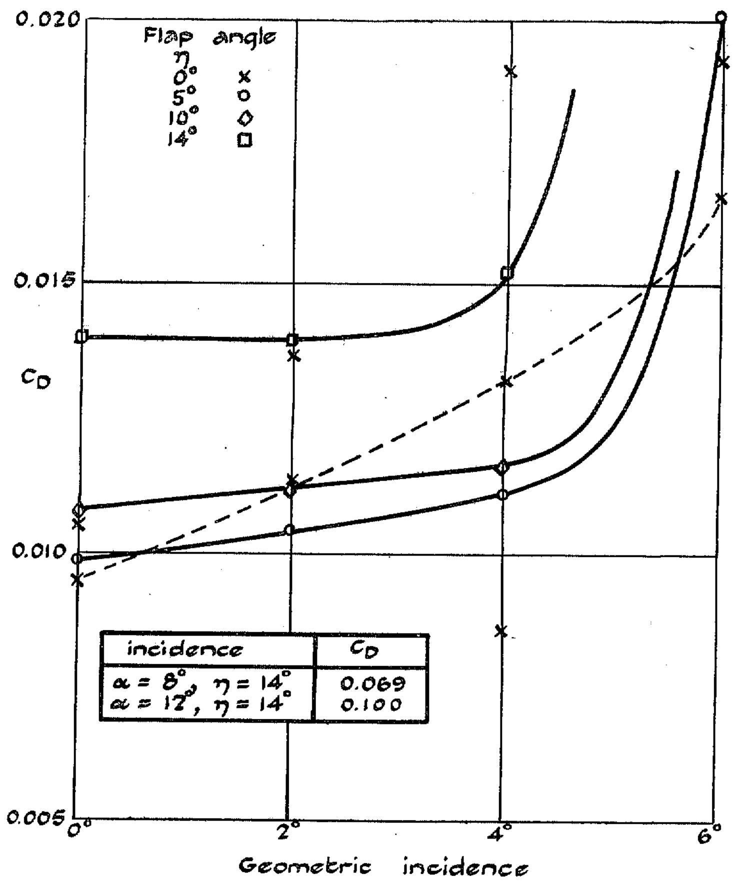

FIG. 6. Variation of C_D with α. No Suction. $R = 2{\cdot}88 \times 10^6$.

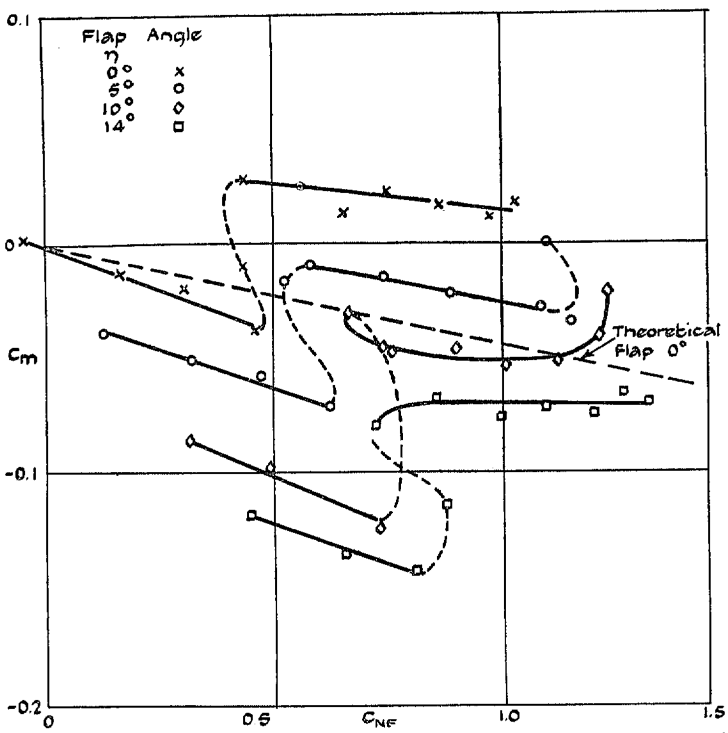

FIG. 7. Variation of C_m with C_{NF}. No Suction. $R = 2\cdot88 \times 10^6$.

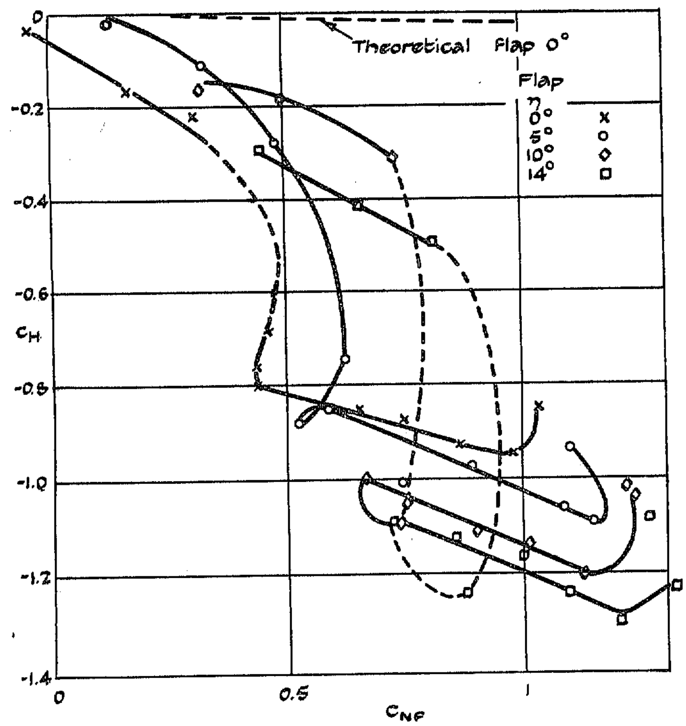

FIG. 8. Variation of C_H with C_{NF}. No Suction.

Letter	Condition	Transition	C_D	Total C_Q
A	Wires at 0.1c	0.1c. Turb: sep. in front of slot	0.0577	No Suction
B	Wakes at 0.1c in line with comb	Turb: sep. in front of slot	0.0987	No Suction
C	Smooth wing	Lam: sep. at 0.74 c	0.0106	No Suction
D	Smooth wing	Lam: on Upper Surface only. Tr. lower 0.76c	0.0032_1	0.00238
E	Smooth wing	Tr: at 0.76 c	0.0015_6	0.00345
F	Smooth wing	Tr: at 0.76c Laminar flow on Flap to 0.930c	0.0008_5	0.01414

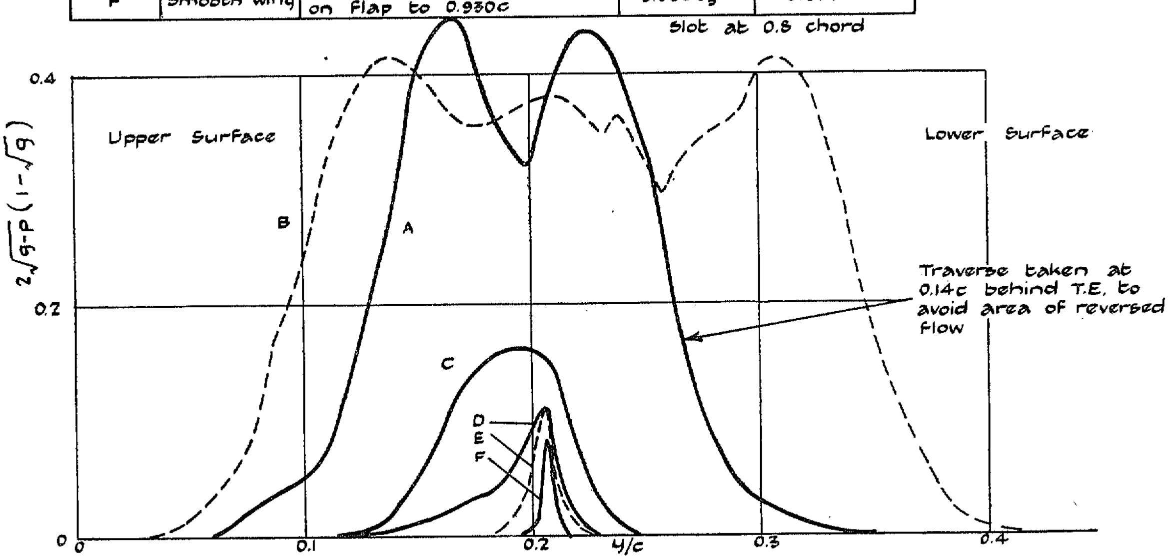

FIG. 9. Wake Profiles at 0·1 Chord behind Trailing Edge. Incd. 0 deg. Flap 0 deg. $R = 2\cdot88 \times 10^6$.

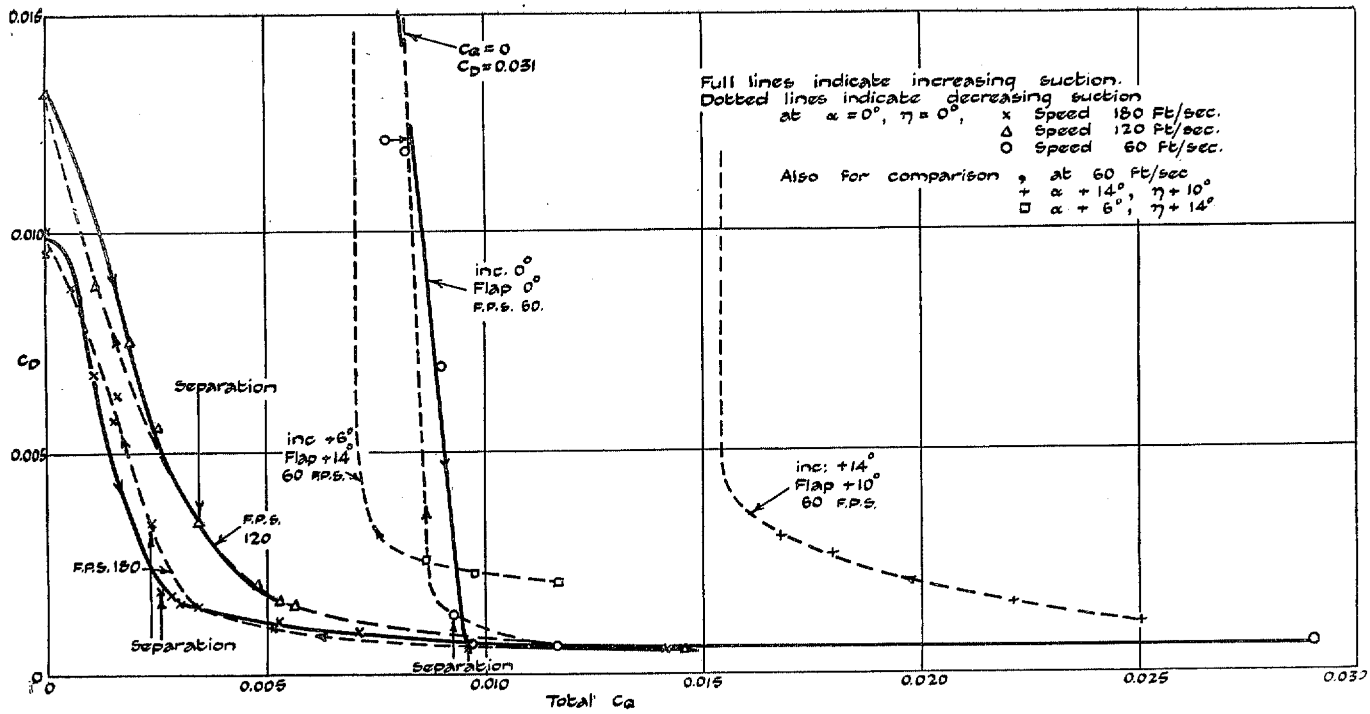

FIG. 10. Variation of Profile Drag Coefficient with Quantity Sucked from Both Surfaces.

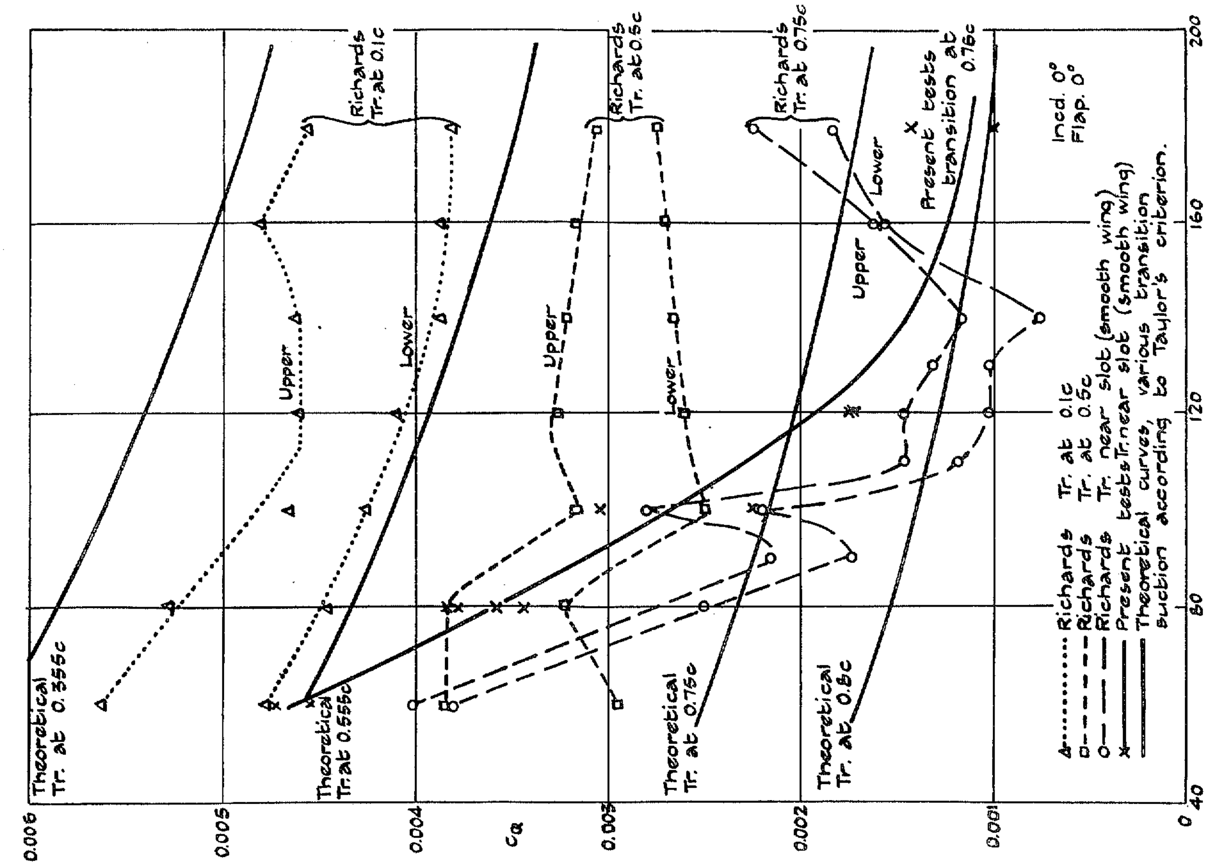

FIG. 11. Scale Effect. Variation of C_Q (Just giving low C_D) with Tunnel Speed for Various Tests. Also Theoretical Curves Based on Taylor's Criterion.

(88537)

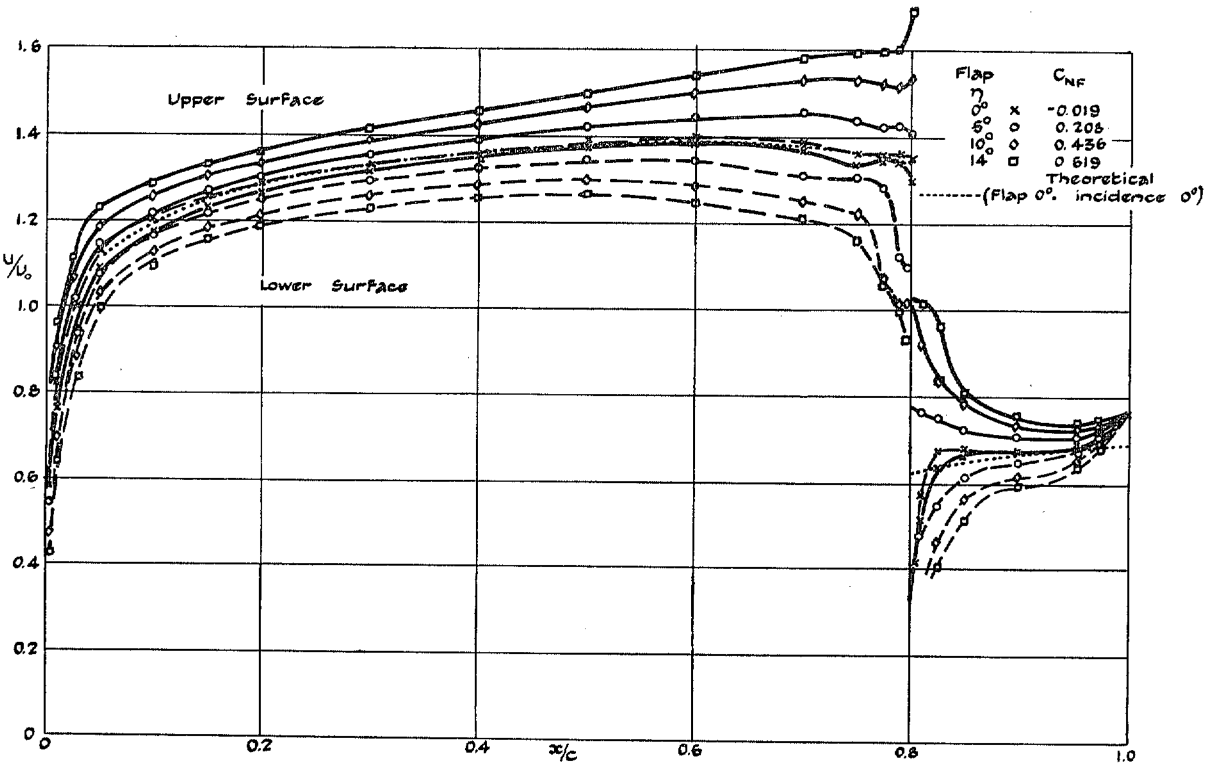

FIG. 12. (*a*) Variation of Velocity Distribution with Flap Angle. Incidence 0 deg. $R = 0 \cdot 96 \times 10^6$. Suction On.

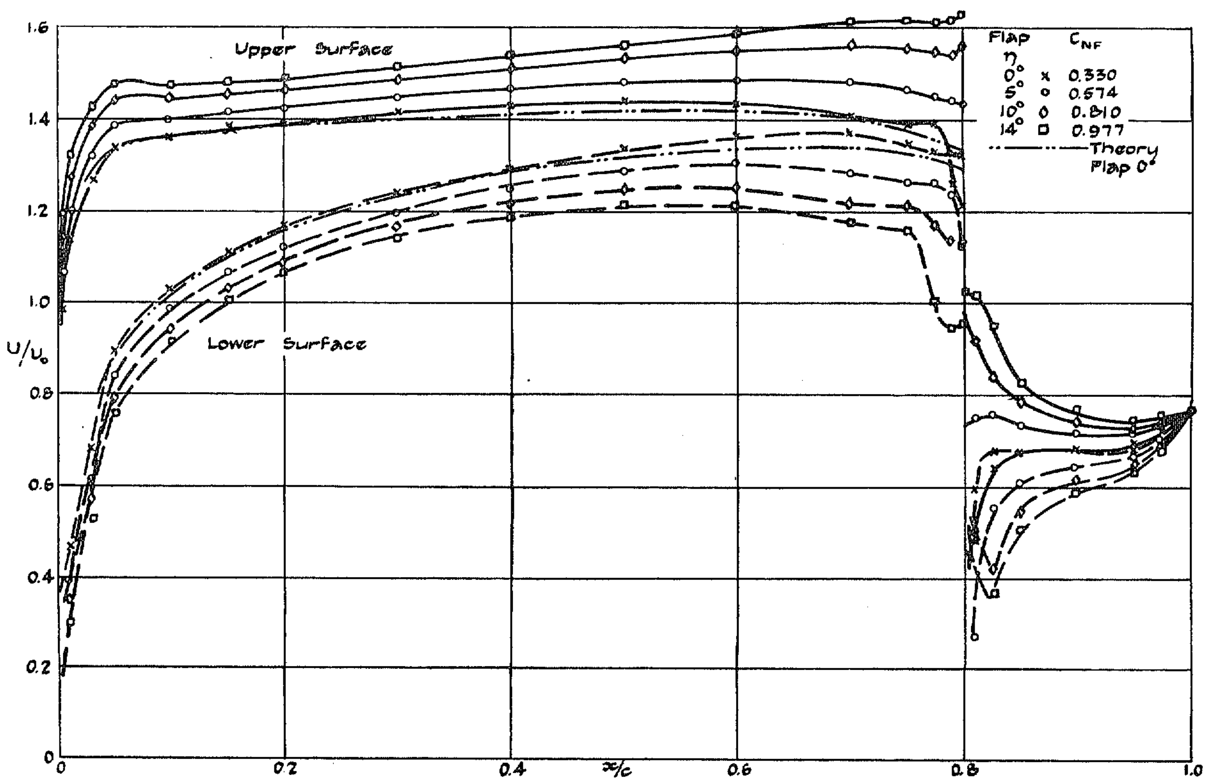

FIG. 12. (*b*) Incidence 4 deg. $R = 0 \cdot 96 \times 10^6$. Suction On.

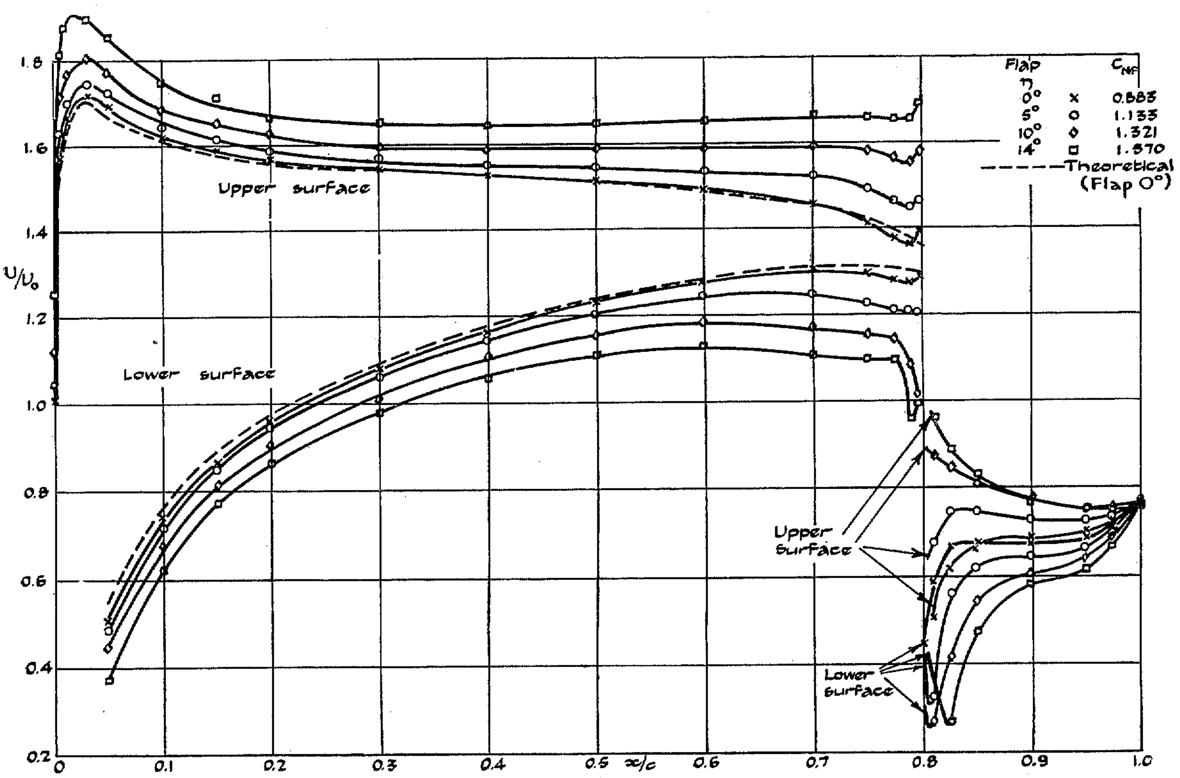

FIG. 12. (*c*) Incidence 10 deg. $R = 0{\cdot}96 \times 10^6$. Suction On.

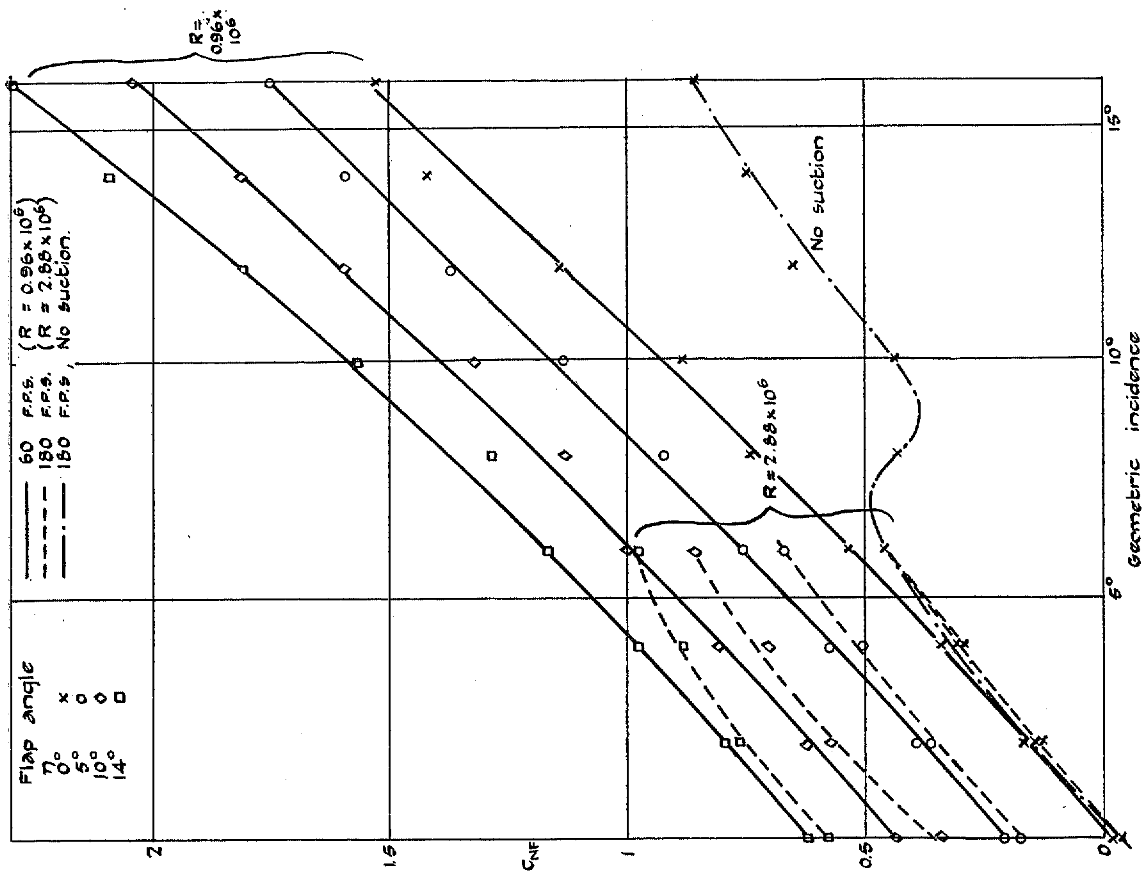

FIG. 13. Variation of Normal Force Coefficient with Geometric Incidence, Various Flap Angles, Reynolds No. $0{\cdot}96$ and $2{\cdot}88 \times 10^6$. Suction On (Minimum to prevent separation).

(88537)

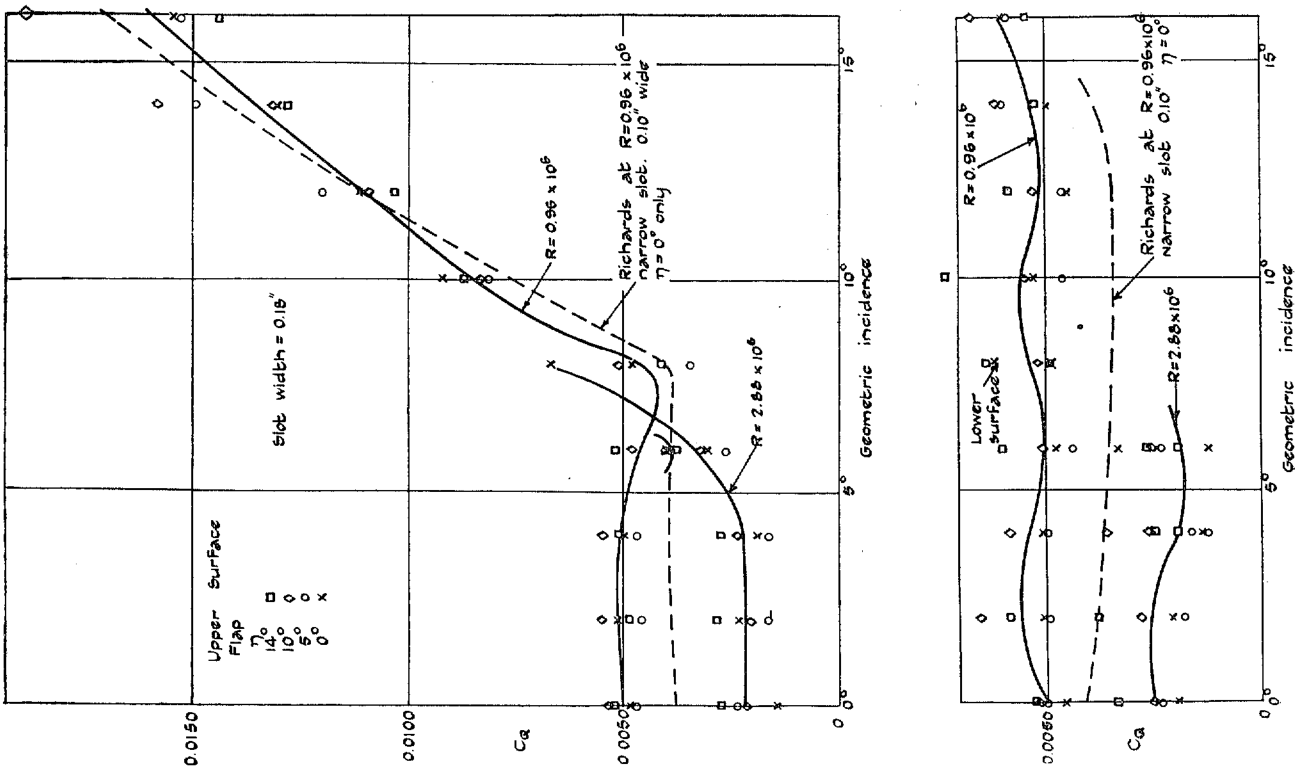

FIG. 14. Variation of C_Q to Prevent Separation with Incidence for Upper and Lower Surfaces.

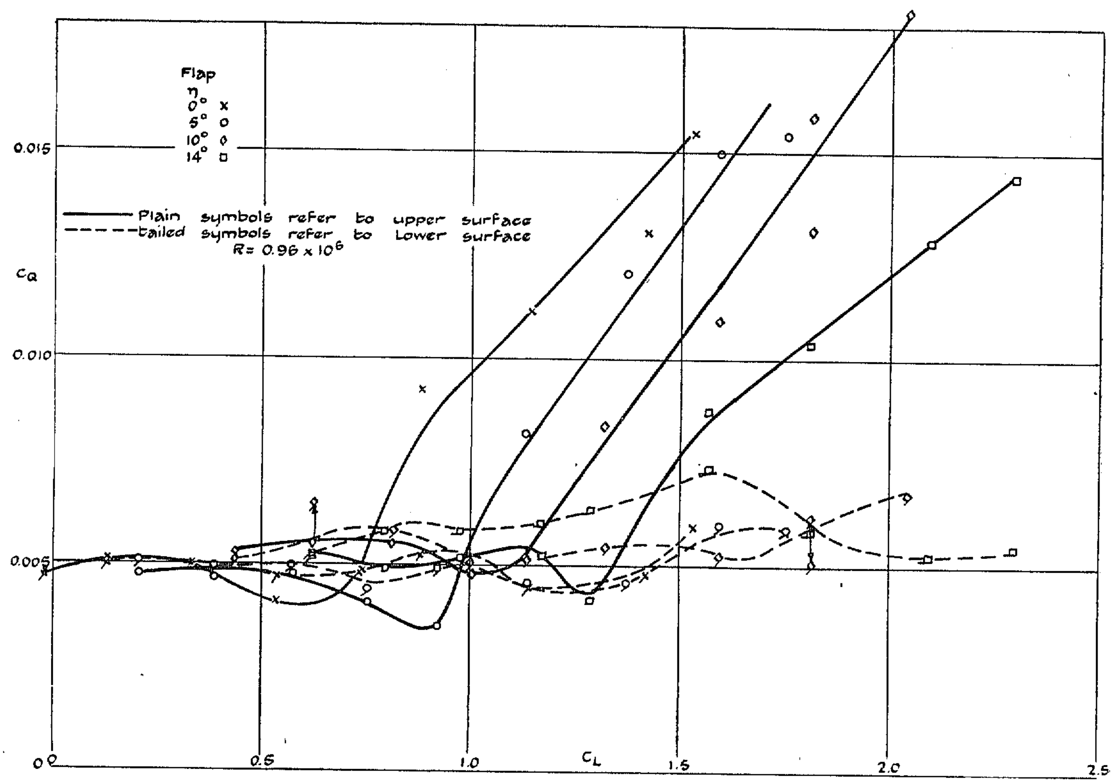

FIG. 15. Variation of C_Q for Each Surface with C^{x}_{NF}, at 4 Flap Angles.

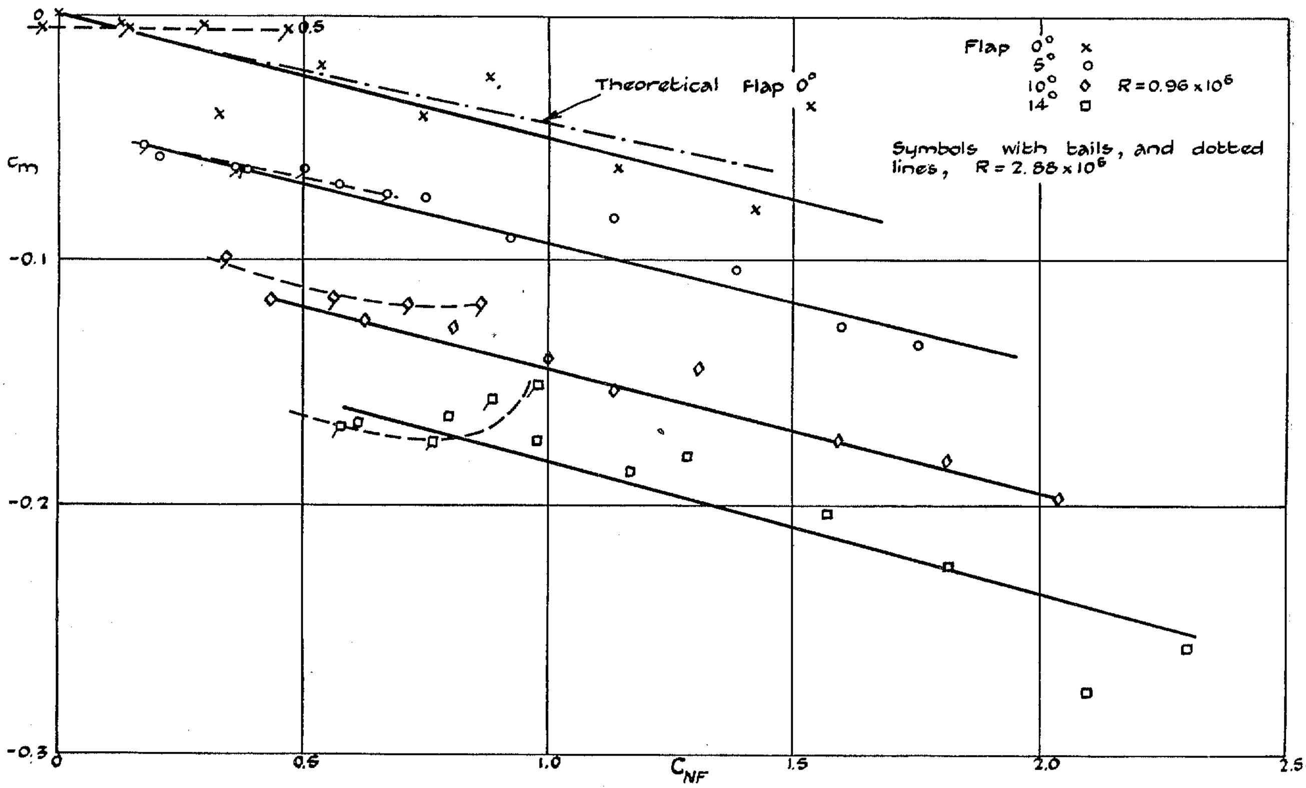

FIG. 16. Variation of C_m with C_{NF}. Suction On (Minimum to prevent separation). $R = 0{\cdot}96 \times 10^6$.

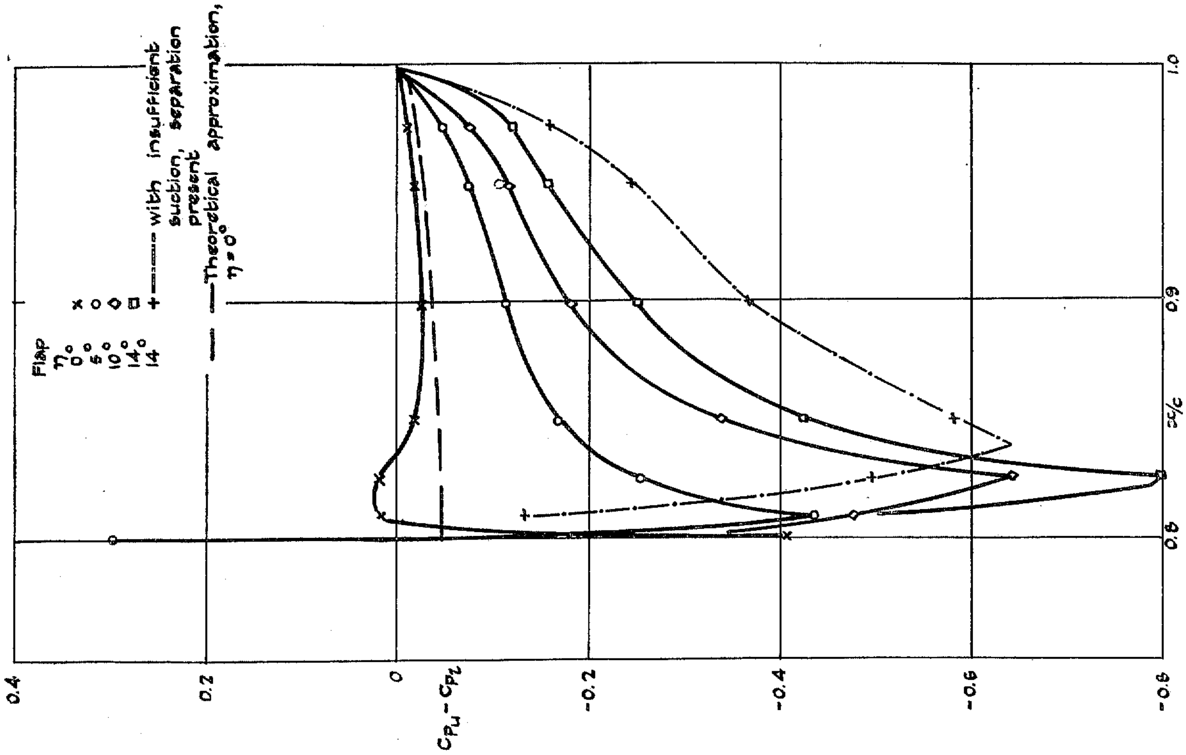

FIG. 17. Variation of Normal Loads on Tail with Flap Angle. Incidence 6 deg., $R = 0{\cdot}96 \times 10^6$, Minimum Suction. The pressures at $R = 2{\cdot}88 \times 10^6$ are nearly the same, and the diagrams at different α's aresimilar.

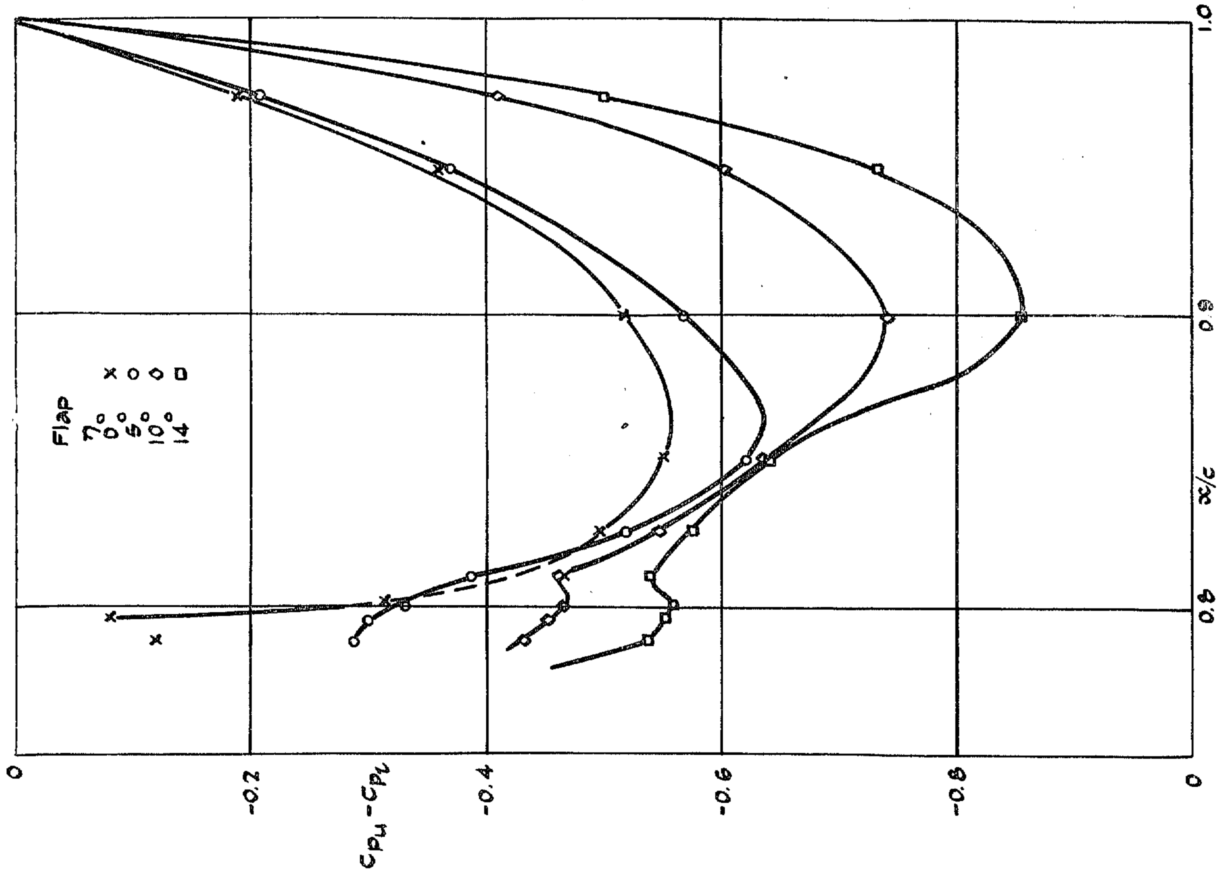

FIG. 18. Variation of Normal Loads on Tail with Flap Angle. Incidence 6 deg., $R = 2 \cdot 88 \times 10^6$. No Suction.

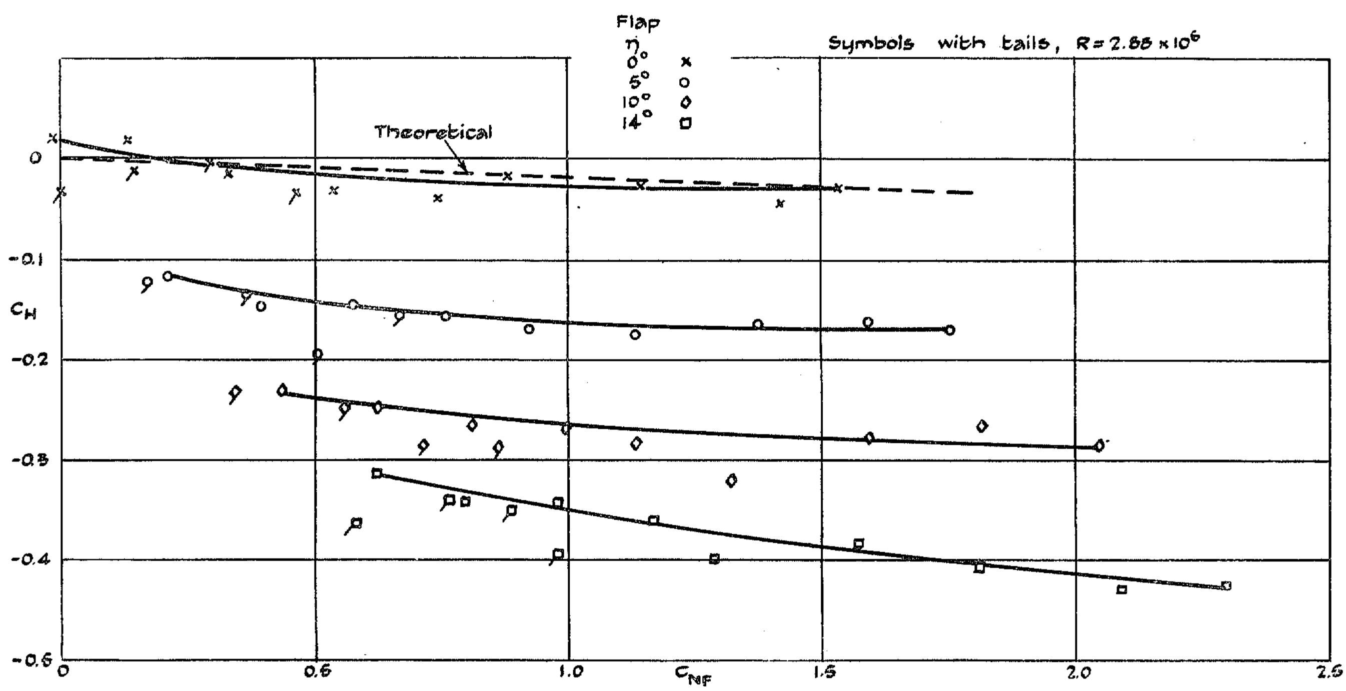

FIG. 19. Variation of C_H with C_{NF}. Suction On (Minimum to prevent separation). $R = 0 \cdot 96 \times 10^6$.

(88537) Wt. 12/818 K5 2/50 Hw.

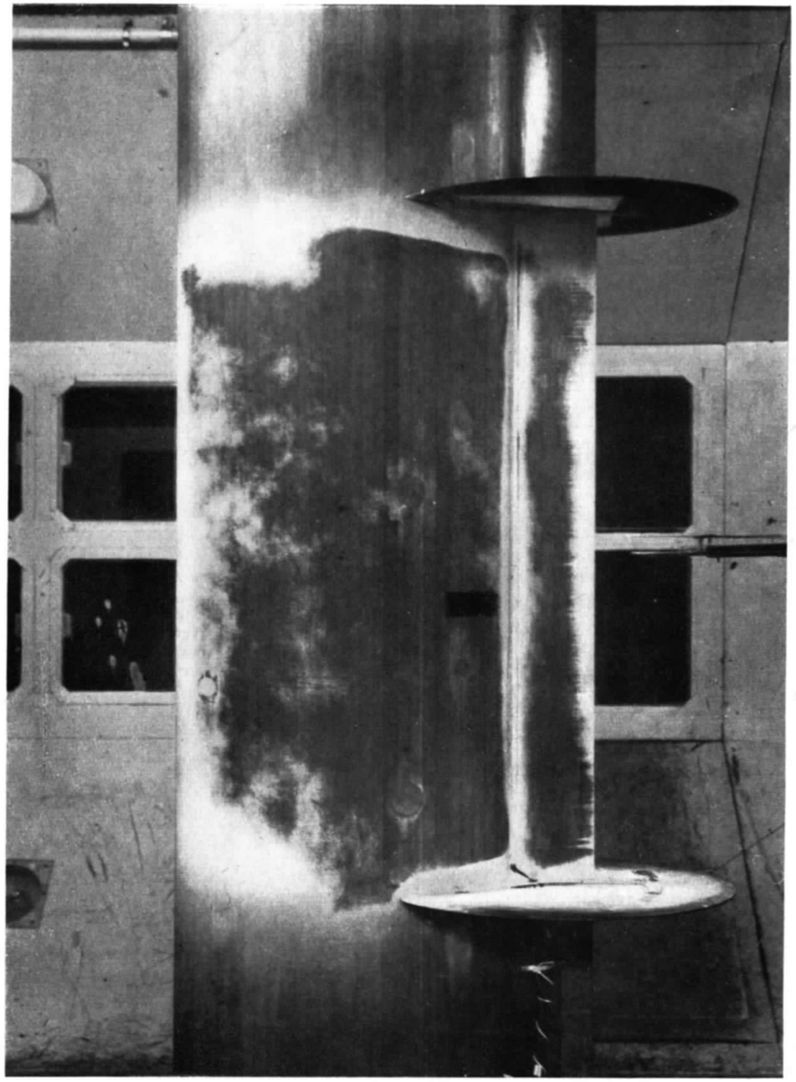

FIG. 20. Laminar Flow on Flap to 0·94c. $R = 2{\cdot}88 \times 10^6$. Incidence 0 deg. Flap 0 deg. C_Q each surface 0·007.

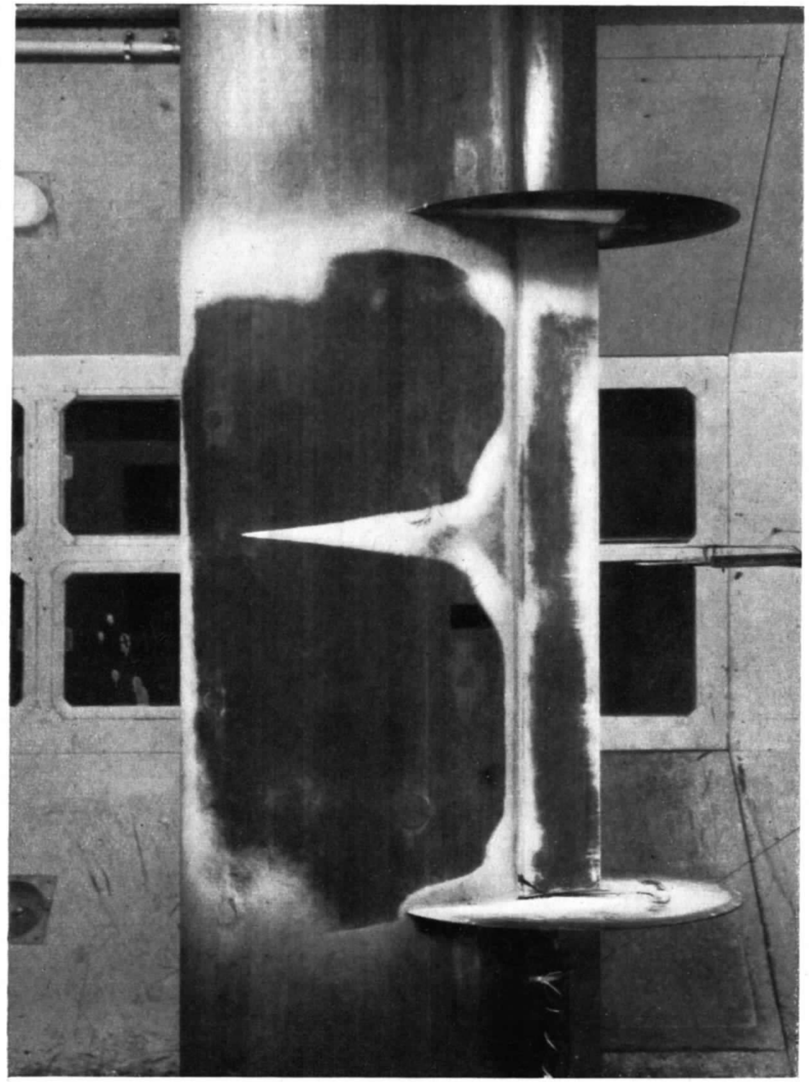

FIG. 21. Wake, with Turbulent Separation. Flow on flap was *not* laminar but appears so owing to short exposure and velocity discontinuity. $R = 2{\cdot}88 \times 10^6$. Incidence 0 deg. Flap 0 deg. Minimum suction.

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