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Introduction.—Tests carried out on a 16 per cent. suction wing[1, 2] have shown that it is impossible to maintain laminar flow aft of the suction slot at high Reynolds numbers, because of the dynamic instability of the laminar layer over the concave surface. As a result of this finding it was concluded that compared with a normal low-drag wing very little was to be gained by this means on wings of normal thickness-chord ratio except at very high Reynolds numbers. Since however the maximum thickness-chord ratio allowable on low-drag wings is of the order of 18 to 20 per cent., it was realised at once that a considerable gain could be obtained from the new designs by virtue of the fact that there appeared to be no limit to the thickness-chord ratios allowable on this type of wing and that wing thickness-chord ratios of 30–40 per cent. could be used which would give low drags and high maximum lifts.

It was further shown in the 16 per cent. tests that the amount of suction necessary if transition could not be delayed to the slot, and the quantity of air that needed removal from the boundary layer were not changed to any great extent ; thus the scheme appeared promising even in the absence of extensive laminar flow because of the structural and storage gains obtained thereby.

The present paper describes tests carried out in the National Physical Laboratory 13 ft. × 9 ft. Wind Tunnel at Reynolds numbers between $0 \cdot 8$ and 3 millions on such a 30 per cent. suction wing to determine whether the suction principle is satisfactory and to investigate the general characteristics of the wing.

Design of Aerofoil.—Since the major part of the external drag of the aerofoil is that arising from the turbulent boundary layer aft of the slot, this region was made as small as possible, subject to the requirement that sufficient control surface area be provided. The slot was therefore fixed at $0 \cdot 8$ chord and the 30 per cent. aerofoil was obtained simply (by the method of Refs. 1 and 2, Part IV) by putting $a = 0 \cdot 26024$, $b = 0 \cdot 42641$, $c = -0 \cdot 32995$ and $d = -0 \cdot 28880$. These values were arrived at from the following four criteria :—

(1) Thickness-chord ratio = 30 per cent.

(2) Favourable C_L range should be the optimum with this family of aerofoils.

(3) Cusped tail to eliminate form drag.

(4) A small favourable velocity gradient over the tail.

The need for criterion (4) is questionable since the boundary layer there is in any case turbulent : some other criterion could as well be used, *e.g.*, the need for a certain control characteristic, say $b_1 = 0$.

Ordinates are given in Table 1, while Fig. 1 gives the aerofoil profile.

The approximate velocity distribution over the aerofoil has been calculated by method III of Dr. Goldstein's approximate theory[4] and the velocities are given in Fig. 2 for an assumed lift slope equal to the theoretical value. It will be seen that owing to the limitations of the simple approximation on which the aerofoil was designed, the favourable velocity gradient disappeared a little distance forward of the slot ; no attempt was made to overcome this on the present model as the adverse gradient was not sufficient to cause separation of the flow, but later designs have all been modified to eliminate as much of this adverse gradient as possible. The greatest doubt in the design work arose from the fact that the accuracy of the mathematical method as a whole was not known for aerofoils of such thickness. In later designs this difficulty has been overcome by the use of an exact theory[5], which holds for any thickness-chord ratio ; it should be stated however that in the present work good agreement is obtained between experiment and the approximate theory at zero incidence and there is therefore no reason to doubt the accuracy of the theoretical velocities at other incidences. How far the thin aerofoil theory can be applied is difficult to tell but it is likely that 30 per cent. is not far from the limit of usefulness of the method particularly with highly cambered aerofoils.

Description of Model and Wind-tunnel Technique.—In view of several practical difficulties which were met with during the tests, it is necessary to give a brief description of the model and the wind-tunnel technique.

The model, of 30 in. chord and 8 ft. 10 in. span, was made of laminated mahogany with independent suction chambers on either surface. Owing to the difficulty which was experienced on earlier models in getting a uniform suction along the whole span, suction was only applied to the centre 4 ft., the ends being shielded by small fins to prevent cross flow into the slots. In order to eliminate thick boundary layers at the fin junctions these end fins did not extend the whole length of the chord but began at about 50 per cent. back, where it was considered that the pressures were not affected by the change of flow occurring when suction was applied. Unfortunately it was found that the wing roots stalled very much earlier than was expected, with the result that at incidences above 6 deg. considerable interference occurred owing to the induced effect of the cast-off vortices. No really satisfactory method was found of overcoming this trouble although it was found that it could be practically eliminated by fitting chord extensions and flaps on the root sections. This technique was very laborious however, and the technique generally adopted in this paper has been to obtain the effective incidence by correlating the experimental and theoretical velocities over the forward part of the airofoil, thereby obtaining the incidence. It is quite clear however, that, since the effective aspect ratio of the model is less than two, such a procedure cannot be considered in any way satisfactory and provision is being made on further models for suction along the whole span.

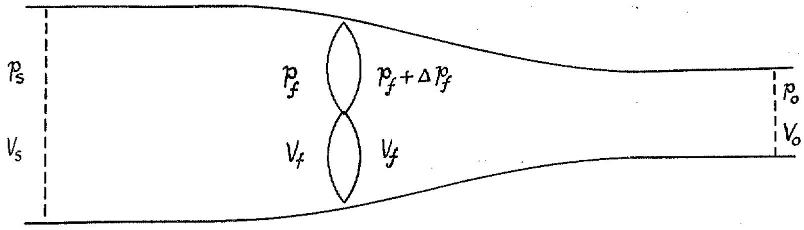
Originally the suction air was drawn off at one end of the model and pumped away via a long length of calibration piping. The pump used in this work was unfortunately not suitable for work at very high incidences where relatively high-suction heads were needed and consequently it was necessary to modify the suction system to eliminate unnecessary losses ; the quantities of air absorbed were then measured by traversing the suction duct inside the model, a procedure which was not so accurate as that of measuring the dynamic head directly in a circular pipe whose velocity distribution was well known and constant.

A diagram of the modified arrangement is shown in Fig. 3a. In addition to the new external ducting system, the earlier arrangement of having an inner settling chamber in which an even suction was built up was abandoned and a ducting system of the type shown in Fig. 3b was used, the tailpieces of the turning vanes being hinged and movable from outside the model. By this means it was possible to obtain a suction arrangement which was uniform along the span for the whole range of suctions.

Method of Interpretation of Results.—Since power has to be used to suck away the air in the boundary layer, it is necessary, in obtaining a comparison of performance with normal aerofoils, to introduce a factor into the drag coefficient to account for the power necessary for the suction. The method of interpretation has been stated in Ref. 1 but as the efficiency of the scheme depends very largely on whether the effective drag coefficient as obtained is optimistic or pessimistic, it is well to repeat it here.

Consider the whole suction installation to be arranged inside the aerofoil, the air being discharged from the pump in the direction of the free stream with a velocity and pressure equal to that of the free stream. The profile drag in this case, being the rate of loss of momentum in the direction of the free stream inside any large contour enveloping the aerofoil and discharge system over which the pressure may be assumed constant, is equal to that measured by pitot traverse across the wake when the air is removed elsewhere, since the sink drag is regained by the jet effect of the discharged air. To this, a term must be added to account for the power H used to drive the pumping mechanism. If D is the drag measured by pitot traverse across the wake, and V_0 is the free stream velocity, the effective drag will be $D + \eta H/V_0$, where η is the efficiency of the propulsive unit of the aircraft.

Without a knowledge of the actual ducting system, it is impossible to make an estimate of the power H, which is expended in overcoming both the skin frictional drag of the aerofoil up to the slots and the internal frictional drag. Simple actuator disc theory is sufficient to give a rough measure of the effective drag in terms of the velocity and pressure inside the slot.



Suppose the velocity and pressure in the free-stream and at some point in the ducting system are (V_0, p_0) and (V_s, p_s) respectively. With the notation of the diagram and neglecting skin frictional losses aft of the measuring point inside the duct,

$$p_s + \tfrac{1}{2}\rho V_s^2 = p_f + \tfrac{1}{2}\rho V_f^2$$

and $$p_0 + \tfrac{1}{2}\rho V_0^2 = p_f + \Delta p_f + \tfrac{1}{2}\rho V_f^2 .$$

Thus the pressure difference across the fan disc is

$$\Delta p_f = (p_0 - p_s) + \tfrac{1}{2}\rho(V_0^2 - V_s^2) .$$

The energy imparted into the air in unit time is

$$\Delta p_f \times Q ,$$

where Q is the volume of air passing the fan in unit time and

$$\frac{H}{V_0} = \frac{Q \,.\, \Delta p_f}{R V_0} ,$$

if R is the efficiency of the pump. If non-dimensional coefficients C_p, C_Q are defined by $C_p = (p_0 - p_s)/\frac{1}{2}\rho V_0^2$ and $C_Q = Q/cV_0$, where c = aerofoil chord, then the effective drag coefficient

$$C_D' = C_D + \sum_{\text{upper and lower surfaces}} \frac{\eta}{R}\left[C_p C_Q + C_Q \left(1 - \frac{V_s^2}{V_0^2}\right)\right] . \quad .. \quad .. \quad .. \quad (1)$$

If it is assumed that the efficiency of the suction pump is equal to that of the main propulsion unit of the aircraft, R should be taken equal to η ; hence

$$C_D' = C_D + \sum_{\text{upper and lower surfaces}} \left[C_Q\left(1 - \frac{V_s^2}{V_0}\right) + C_Q C_p\right] .$$

If it is assumed that the losses in the duct are such as to cause the whole of the air to lose its kinetic energy due to internal frictional losses, the effective drag coefficient becomes

$$C_D' = C_{D\text{pitot traverse}} + [C_Q(1 + C_p)]_{\text{upper}} + [C_Q(1 + C_P)]_{\text{lower}} .$$

It is this expression which has been used in the present analysis, C_p being taken as that suction coefficient obtained at static holes very close to and just forward of the slot inlet. It is clear that it would be purely accidental if the duct losses were such as to give this expression any physical significance, particularly if in practice the air were discharged under other more favourable conditions and if the intaken air were used for some useful purpose such as for cooling or cabin ventilation. There can be no doubt that the usefulness of the scheme can only be considered really satisfactorily if the actual application is defined. It is well worth bearing in mind however that if the boundary layer is laminar to the slot, about half of the above power drag is due to assumed losses in the slot, the other half being due to the frictional losses over that part of the aerofoil forward of the slot.

Results.—*Lift.*—The velocity distribution over the aerofoil was obtained by pressure plotting and the lift obtained by integration of these pressures. Figs. 4a and 4b show the velocity distributions corresponding to the various lift distributions with sufficient suction to prevent separated flow. The establishment of the non-separated flow regime was determined by observation of the change in the pressure just to the rear of the slot in conjunction with the change in the drag diagram as measured on a pitot comb. These changes were not in all cases very clearly defined and as a result it was difficult to eliminate some scatter in the quantity readings and in the pressure readings close to the slot.

Figs. 5a and 5b show the corresponding velocity distributions without suction. Integration of these pressures showed at once that the lift begins to drop off at a very low incidence (Fig. 6) on such a thick suction wing. Fig. 6 shows the variation of lift coefficient with incidence with suction on. In view of the large downwash at the centre of the aerofoil resulting from the loss of lift over the root sections, the incidence given is that for which the experimental velocities near the nose agree with the theoretical values assuming the experimental circulation. Fig. 7 shows the variation of this effective incidence with the geometric incidence together with the estimated incidence obtained from simple vortex theory. The type of agreement reached between the experimental and theoretical velocities is included in Figs. 4a and 4b. In certain cases, the incidence obtained in this way was clearly wrong as seen by the scatter on the lift curve of Fig. 6. The points indicated in the figure by crosses were obtained with the downwash almost eliminated by increasing the root lift by extended chords and by lift flaps. In these cases, it was noticed that no well defined cast off vortex trails occurred at the end fins and the incidences given in these cases are the geometrical values.

It is seen that with suction on a lift coefficient of 2·47 was actually recorded without the aerofoil stalling. It is not considered that this is the maximum lift of the wing; further suction would undoubtedly allow a still higher lift coefficient to be reached.

It will be noticed in the velocity distribution curves of Fig. 4a, that at very high lift coefficients a considerable sink effect occurs on the velocity distributions near the slot. This arises from the much greater quantity of air that must be absorbed at these high lift coefficients through a slot which was designed to give optimum efficiency at low incidences.

The quantity of air absorbed at various C_L's is given in Fig. 8 as a fraction "*m*" of the total air in the laminar boundary layer at the slot at 0 deg. incidence. In the favourable C_L range where transition occurs at or near the slot, the quantity of air removed is practically constant, when however transition moves forward, the amount of air absorbed becomes much greater, and in order to remove it, a much greater suction head is needed. The power needed to prevent separation is therefore increased considerably, both because of the extra quantity and also because of the extra head. These figures cannot however be taken as typical for high Reynolds numbers for two reasons. First, the size of slot allowable in the present tests (0·10 in.) is limited to one laminar boundary layer thickness on account of the need to retain surface continuity; at a Reynolds number of 25 millions for instance the same slot width is equivalent to 5 times the laminar boundary layer thickness, so that the quantity shown in Fig. 8 can be absorbed without any danger of choking. Secondly in the present tests, the results are plotted on a constant Reynolds number basis whereas in flight the speed decreases with lift coefficient. Thus if the wing is cambered for a C_L of $0\cdot40$, say, and the same figures hold for $C_L = 0\cdot40$ as do for $C_L = 0$ on the present symmetrical aerofoil, the two conditions $V^2C_L =$ constant and $C_Q \propto mR^{-1/2}$ suggest a variation of the total quantity of air needed for both surfaces as shown below.

C_L	m on upper surface	Total quantity for both surfaces (varies as)
0·4	0·8	1·0
1·0	0·8	0·88
1·5	2·0	0·98
2·0	4·4	2·14
2·5	4·8	2·22

It thus appears that to obtain a lift coefficient of $2\cdot5$ without flaps, twice as much air must be sucked away as is required in the top speed condition with the flow laminar to the slot on both surfaces. It should be pointed out that the above figures were obtained with increasing suction ; the type of difference obtained at high incidences between these figures and those necessary to maintain the non-separated regime only is included in Fig. 8.

At high suctions the aerofoil developed a slight leak between the upper and the lower surface suction chambers. Consequently the figures for the lower surface are pessimistic at large lift coefficients ; the effect of a leak can be seen in Fig. 4b in which at the highest lift coefficient there is a definite sink effect on the velocity distribution on the lower surface near the slot, indicating that there is considerable suction on the lower surface. In general, results have been discarded where this leak is suspected to be large.

Moment Coefficient.—The moment coefficient about the quarter-chord position was obtained from pressure plotting, by integrating the moments of the pressures both normal to and along the chord-line. The results are shown in Fig. 9a plotted against lift coefficient, the suction used being the minimum required to give unseparated flow. The pressure plotting technique is not very satisfactory for this purpose and a fair amount of scatter has occurred. It is seen that the curve is not linear, but no great significance can be paid to this fact with the poor accuracy obtained in the results. It may however be due to the increased sink effect on the upper surface at the higher incidences.

The dotted curve shows the theoretical variation of moment coefficient. This was obtained by direct integration of the pressure differences obtained by approximation III of Ref. 4 with the lift slope assumed to be equal to the theoretical value. Agreement between theory and experiment is as satisfactory as may be expected.

In Fig. 9a the effect of failure of suction on either surface is demonstrated for 3 deg. geometrical incidence. It is seen that quite a considerable change of moment occurs. This is likely to become very much more serious at higher lift coefficients.

Without suction the moment variation with C_L is still in good agreement with the potential flow value for small lift coefficients (Fig. 9b), but when the aerofoil stall is such as to cause a reduction of lift very considerable positive moments occur.

Hinge Moment.—The hinge moment on a flap incorporating the whole of the tail section and with the hinge at $0\cdot8$ chord has been obtained from the observed pressures over the tail of the aerofoil. So far only the case of zero flap incidence has been investigated, but the aerofoil is being modified to have a movable flap and the effect of flap movement is to be investigated. The figures obtained by pressure plotting do not of course include the effects of internal pressures due to the suction system.

Fig. 10 shows the normal force acting on the flap at various incidences with just sufficient suction to maintain unseparated flow. The dotted curve shows the theoretical force that would be expected for a C_L of 1·0 neglecting the effect of the suction on the pressures. It is seen that as the incidence increases, the effect of the high suction on the upper surface is very marked. However, until a high incidence is reached, the hinge-moment coefficient does not appear to be affected greatly by this, and the experimental variation with lift coefficient (Fig. 11) is in quite good agreement with theory. In these hinge moments the effect of the loading along the aerofoil chord has also been considered since on this thickness of aerofoil, chordwise loads have a noticeable effect on the moment characteristics ; thus the forces arising from the suction system have less effect than would be expected from Fig. 10 since the resultant force acts nearly through the hinge point. At high incidences the moment coefficient becomes less negative. Whether this will be so for other slot widths is subject to doubt, since it appears to be largely due to the effect of the suction head.

In Fig. 12 the hinge moment coefficient is given when no suction occurs. The forces normal to the chord are shown in Fig. 13. Even at low incidences the hinge-moment change is considerable, b_1 becoming positive. At the stall a considerable hinge-moment variation takes place.

The worst case of a hinge-moment change occurs when suction fails on one surface only. Fig. 5 shows the velocity distribution with suction having failed on the upper surface and on the lower surface respectively. The hinge-moment change arising from this failure is considerable as is shown in Fig. 11 for 3 deg. incidence. The change in overall moment is not so serious (Fig. 8).

Quantity of Air Absorbed.—The actual quantity of air absorbed was measured by pitot traverse of the parallel portion of the duct inside the model. As it was out of the question to make a very thorough traverse on each occasion, the method actually used was to obtain empirical factors for various amounts of duct flow with the wind tunnel not running and to take readings on three pitot tubes during any particular experiment. With the aid of these three values of $\frac{1}{2}\rho V^2$ and with the empirical factors, fairly satisfactory measurements were obtained. The error likely to occur by this means is about 5 per cent. of the measured value.

These flow quantities have been given here in terms of the quantity of air in the laminar boundary layer at the slot at 0 deg. incidence as calculated by the method of Ref. 6 and shown in Fig. 14. Actually, it was found by both the methods of Refs. 7 and 8 that transition to turbulence occurred at 0·05 chord forward of the slot, owing to the adverse velocity gradient occurring in this region. The boundary layer thickness at the slot is thus greater than shown in Fig. 14 and the ratio m of the quantity of air absorbed to that in the laminar layer at 0·8 chord is pessimistic when applied to the actual air in the boundary layer in these tests. Since, however, the position of transition varies with speed and the amount of suction, it is considered best to relate the quantities measured to a clearly defined datum. It must be mentioned here that the values of m given in the previous interim report[9] were obtained from estimations on flat-plate theory and have been modified in this report to come into line with other new results.

The variation of the quantity m with incidence has already been referred to. A remarkable variation with Reynolds number in the wind tunnel occurred, however, at 0 deg. incidence which cannot be fully explained.* Fig. 15 shows the variation of the quantity m with wind speeds, the figures being obtained by increasing the suction until the flow became non-separated, this regime being recorded by the change in the pressures near the slot and in the change in pitot traverse drag diagram. It is seen that a very considerable variation of m with speed occurs which does not seem to behave in any consistent manner as the speed is increased. The drag coefficients obtained by pitot traversing the tail are included in Fig. 15 and demonstrate that as the suction is increased the profile drag is reduced. Thus the effective drag is brought more nearly constant. It cannot be expected, of course, that if the effective drags were calculated from Fig. 15 a constant value would be obtained, since in this range of Reynolds numbers the power drag is predominant

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* Work carried out subsequent to this report being written and using the " China Clay " technique has shown that most of this variation can be attributed to variations in the position of transition at some point or other along the span.

and the effect of the variation with m of the assumed losses due to the ducts would predominate over any changes in profile drag that are likely to occur. For instance at $R = 1$ million, a change in m from 0·85 to 0·35 causes an alteration of 0·012 in the effective drag coefficient, about half of which is due to the assumed losses in the ducting system. However, the other 0·006 change is very much higher than the increase 0·002 in the pitot traverse drag which results from the change. No satisfactory explanation of these changes has yet been obtained but a thorough investigation will be made later. It should be pointed out that there is always considerable difficulty in determining exactly when the flow has tied on to the surface and there is difficulty, in general, in obtaining consistency of results particularly at the highest speeds in the wind tunnel.

At low speeds, agreement between results obtained with increasing suction are satisfactory and even at very high incidences where large differences would be expected, a difference in m of only 0·6 in 4·0 is obtained (*see* Fig. 7). At the top speed of the wind tunnel, however, this does not seem to be the case and a large difference occurs not only between the results at low incidences with increasing and decreasing suctions, but also between successive runs with increasing suctions. Fig. 16 shows (in full lines) the variation of m with incidence obtained with increasing and with decreasing suction respectively, while the dotted line shows similar results obtained on another occasion. It is seen that with decreasing suction the variation with incidence does not differ radically from that of Fig. 7 obtained with increasing suction at a lower wind speed. The increasing suction curves are, however, badly inconsistent, and in the favourable C_L range, they are very much higher than with decreasing suction. These discrepancies show themselves in the profile drag measurements, (Fig. 17), the increased suctions giving rise to lower profile drag coefficients.

The Effect of Early Transition.—In the 16 per cent. aerofoil tests it was found that the amount of suction needed to prevent separation when transition was far forward along the chord was little if any greater than that with laminar flow to the slot. Since the problem of obtaining a wing construction which is smooth enough to give laminar flow over 0·8 of its chord has not yet been solved, the usefulness of the present thick wings depends largely on their efficiency with forward transition.

In the present tests, transition was simulated at 0·1 and 0·5 chord, respectively, by means of a rough strip. The amount of suction needed to prevent separation is plotted for various wind speeds in Figs. 18 and 19 as fractions of the laminar boundary layer air, while at low speeds the quantity of air needed is only slightly greater than that obtained with the flow laminar to the slot ; this is not so at the highest wind speeds, there being a gradual increase in m with wind speed. In the 16 per cent. wind-tunnel tests a similar increase was obtained in the early transition cases ; it was found that this variation could not be correlated with the amount of air in the actual turbulent layer as would be expected, and it was tentatively concluded that this variation resulted from possible underestimations of the turbulent boundary layer thickness at the higher speeds and the higher tunnel turbulence. In the present work, however, expressing the absorbed air as a fraction h of that in the turbulent layer at the slot does give a reasonably constant value for the varying wind-tunnel speeds.

In Figs. 20 and 21 this variation is shown for both upper and lower surfaces at zero normal incidence, the boundary layer thickness for various positions of transition being indicated in Fig. 14. It is seen that about a quarter of the turbulent boundary layer air must be absorbed with transition in either position. The constancy of this fraction with varying transition points is also shown in Ref. 2, Part III, for the 16 per cent. aerofoil tests, but the actual fraction is considerably higher than that occurring on the 16 per cent. aerofoil. Some increase was to be expected, but the increase of $2\frac{1}{2}$ times occurring here cannot be justified from theoretical reasonings and it is possible that the inefficient slot shape used in these experiments has increased this amount unduly.

Effective Drag Coefficient.—As has been stated previously, the effective drag coefficient obtained at the Reynolds numbers of the present tests has no significance as to the usefulness of the scheme at the Reynolds numbers of flight and in fact the aerofoil is not efficient at these Reynolds numbers. This is shown very clearly in Fig. 22 which shows the variation of pitot traverse drag and effective drag at a Reynolds number of about a million.

The whole efficiency of the scheme apart from structural and other gains to be obtained hinges on the fact that the power drag is considerably reduced at very high Reynolds numbers while the pitot traverse drag is reduced also.

Consider first the case when the flow is laminar to the slot. Fig. 23 shows the calculated effective drag coefficients for aerofoils of 20, 30 and 40 per cent. thickness-chord ratio with either all the boundary layer air (dotted curve) or the theoretical minimum of Ref. 2, Part III (given by the full line) absorbed at the slot. It is seen from Fig. 7 that the actual fraction needed to be absorbed is questionable, but it is clear that at the Reynolds numbers of flight an effective drag coefficient at least as small as that of an extremely good low-drag wing is obtainable in addition to the gain obtained in stowage space and structure. The actual gain to be obtained is of course tied up completely with the question of whether the structural and duct loss penalties that will have to be paid are optimistically or pessimistically covered by the factors included in the power drag coefficient.

If now the case of early transition is considered, the aerodynamic efficiency of the scheme is not at all clear, since in this case the power drag coefficient is no longer reduced in the ratio of $R^{-1/2}$ as in the case of the completely laminar flow, but by a factor which varies much more slowly with Reynolds number. For the completely turbulent case, this factor is roughly $R^{-1/5}$. Fig. 24a shows the variation of the momentum thickness of the boundary layer with wind speed in the range of the wind-tunnel work for various positions of transition, while in Fig. 24b, the ratio of the values with forward transition and with flow laminar to the slot are plotted. It is seen that even with the flow laminar to $0 \cdot 5$ chord, there is a considerable increase to be expected in the power drag from that expected in the laminar flow case. In Fig. 25 the effective drags to be expected with the experimental values of m or n are plotted against Reynolds number for leading edge transition, transition at $0 \cdot 5$ chord and with the flow laminar to the slot. On the same figure the equivalent figures for a 20 per cent. low-drag aerofoil are plotted with transition assumed at various positions along the chord.

It is clear that the laminar flow case shows great promise, but the effective drag with transition at the leading edge is somewhat higher than that of a 20 per cent. normal low-drag wing, while that with 50 per cent. transition is also poorer at a Reynolds number of 30 million than that of a normal 20 per cent. aerofoil with similar position of transition. It must be made clear, however, that the extrapolations needed to perform this comparison are extremely hazardous and depend entirely on the constancy of the fraction n with Reynolds number, even though the slot width and shape has been completely altered relative to the boundary layer thickness. Tests at low incidence in the Compressed Air Tunnel at Reynolds numbers of 25 million are urgently needed to eliminate this need for such great extrapolations. Even more hazardous is the method of assessing the duct losses which in fact are assumed to constitute as much as half the difference between the leading-edge transition and laminar flow cases of Fig. 24.

The conclusion to be drawn from the above extrapolation is that with far forward transition an effective drag coefficient of the same order as that of a normal wing with similarly situated transition is obtainable, but that an investigation of the ducting losses which would be incurred, is essential before any more detailed conclusion can be formulated. Against this, there is the gain obtained by the increased stowage, reduced parasite drag and improved structure and aspect ratio.

Discussion.—It is clear throughout the present work that the experimental technique used in the experiments has been sadly lacking and there is practically no aspect of the work which is not subject to doubt on account of these deficiencies in the technique. Consequently it is only possible to draw general conclusions with regard to the usefulness of the scheme and to suggest further experiments that need to be carried out before the aerodynamic efficiency of the scheme can be established.

First of all it is worth mentioning the improvements in technique that are needed in further experiments. They are as follows :—

(1) Uniform lift must be provided over the whole span, either by a single suction system covering the whole span, or by using dummy ends on which full suction is applied throughout the experiments, except when suction off conditions are being investigated. The first needs provision for obtaining uniform suction over quite a considerable span.

(2) A suction pump which gives sufficient suction head and quantity to cover the losses incurred in going through a calibration duct.

(3) A more rapid technique for measuring lift, drag, moment and hinge moment than by pressure plotting and pitot traversing. The tediousness of analysing these results is such that the possibility of a thorough investigation, with varying suction, speeds and slot conditions is out of the question. A fairly simple arrangement which would also simplify the model making, is by using strain-gauges to measure lift, moment and hinge moment, and also possibly drag. The question of interpretation of results would again arise if the last of these were measured by a strain-gauge technique.

Conclusions.—The following general conclusions can be drawn from the above tests :—

(1) With suction at one chordwise station on either surface, a 30 per cent. aerofoil can be designed over which no breakaway of flow will occur for a very large range of incidences.

(2) A maximum lift coefficient of at least 2·5 is obtainable and if sufficient suction is available, this can probably be increased considerably.

(3) As far as the tests go, the experiments show that a very high lift slope is recorded which approaches the theoretical value.

(4) With sufficient suction to prevent separation, the variation of moment coefficient and hinge moment coefficient with incidence is in reasonable agreement with theory, except at high incidences where the increased suction alters the velocity distribution near the slots.

(5) If the flow is laminar to the slot, the amount of suction needed at 0 deg. incidence seems to be a little doubtful, but at all speeds in the wind tunnel it did not exceed 0·9 of the air in the laminar layer at the slot and in certain cases appeared very much lower. Thus the effective drag coefficient at the Reynolds numbers of flight will be less than that of a normal low-drag wing with transition at 0·6 chord.

(6) The amount of suction air needed in flight to give the high maximum lift coefficient is twice as great (on the basis of a given weight of aircraft) as in the low incidence, high speed, condition with laminar flow to the slot. However, it will be considerably less than that needed if the forward transition case has to be covered.

(7) If the flow becomes turbulent at some distance forward of the slot, about a quarter of the turbulent boundary layer air at the slot needs to be absorbed. Owing to the fact that the boundary layer thickness does not decrease with Reynolds number in the same way as in the laminar case, the effective drag with far forward transition is higher than for a normal aerofoil of 20 per cent. thickness chord ratio. This estimate, however, depends entirely on the method of assessing duct losses. A thorough investigation of these ducting losses must be made before the absolute value of the scheme can be assessed.

(8) If suction fails the maximum lift coefficient of the aerofoil is about 0·5.

(9) At incidences below the lift stall without suction, the moment coefficient is in reasonable agreement with the potential flow value and no great change of trim may be expected. Above this incidence, on the other hand, a large change of moment occurs with failing suction.

(10) The hinge moment without suction does not agree with theory at small incidences but does not diverge seriously until the stalling lift has been reached.

(11) The most serious change of hinge moment occurs when suction failure occurs on the surface only.

REFERENCES

No.	*Author*	*Title, etc.*
1	E. J. Richards and C. H. Burge	An Aerofoil Designed to give Laminar Flow over the Whole Surface with Boundary Layer Suction. A.R.C. 6784. June, 1943. (To be published).
2	E. J. Richards, W. S. Walker and J. R. Greening.	Tests of a Griffith Aerofoil in the 13 ft. × 9 ft. Wind Tunnel. Parts I, II, III and IV. R. & M. 2148. July, 1945.
3	S. Goldstein and E. J. Richards	A Theory of Aerofoils of Small Thickness. Part III. Approximate Designs of Symmetrical Aerofoils for Specified Pressure Distributions. A.R.C. 6225. October, 1942. (To be published).
4	S. Goldstein	A Theory of Aerofoils of Small Thickness. Part I. Velocity Distributions for Symmetrical Aerofoils. A.R.C. 5804. May, 1942. (To be published).
5	M. J. Lighthill	A New Method of Two-dimensional Aerodynamic Design. R. & M. 2112. April, 1945.
6	A. D. Young and N. E. Winterbottom	Note on the Effect of Compressibility on the Profile Drag of Aerofoils in the Absence of Shock Waves. R.A.E. Report B.A. 1595. A.R.C. 4667. May, 1940. (To be published).
7	E. J. Richards and F. H. Burstall	The " China Clay " Method of Indicating Transition. R. & M. 2126. August, 1945.
8	J. H. Preston and N. E. Sweeting	Wood Smoke as a Means of Visualising Boundary Layer Flow at High Reynolds Numbers. *J. Roy, Aero. Soc.* Vol. XLVII, No. 387. March, 1943.
9	E. J. Richards	Wind Tunnel Tests on a 30 per cent. Thick Suction Aerofoil. Progress Report and Suggestions for Further Wind Tunnel Work. A.R.C. 8473. February, 1945. (Unpublished).

TABLE 1

Ordinates for 30 per cent. Suction Wing with Cusped Tail

$X_1 = 0\cdot 8,\ a = 0\cdot 260242,\ b = 0\cdot 426414,\ d = -0\cdot 288803,\ (b-c) = 0\cdot 756361$

x	y	x	y	x	y
0	0	0·22	0·1222764	0·78	0·0872383
0·001	0·0089002	0·24	0·1264755	0·79	0·0796780
0·002	0·0125837	0·25	0·1284290	0·795	0·0750649
0·003	0·0154080	0·26	0·1302889	0·80	0·0687860
0·004	0·0177871	0·28	0·1337378	0·805	0·0625086
0·005	0·0198817	0·3	0·1368379	0·81	0·0579016
0·006	0·0217739	0·32	0·1396012	0·82	0·0503633
0·007	0·0235126	0·34	0·1420355	0·83	0·0440945
0·0075	0·0243348	0·35	0·1431311	0·84	0·0386550
0·008	0·0251297	0·36	0·1441461	0·85	0·0338365
0·009	0·0266473	0·38	0·1459353	0·86	0·0295170
0·01	0·0280818	0·40	0·1474032	0·88	0·0220359
0·012	0·0307463	0·42	0·1485475	0·9	0·0159429
0·0125	0·0313763	0·44	0·1493640	0·91	0·0132878
0·014	0·0331929	0·45	0·1496472	0·92	0·0108822
0·016	0·0354664	0·46	0·1498457	0·925	0·0097685
0·018	0·0375982	0·48	0·1499836	0·93	0·0087123
0·02	0·0396114	0·50	0·1497664	0·94	0·0067687
0·025	0·0442285	0·52	0·1491792	0·95	0·0050451
0·03	0·0483851	0·54	0·1482046	0·96	0·0035397
0·035	0·0521908	0·55	0·1475655	0·965	0·0028697
0·04	0·0557172	0·56	0·1468211	0·97	0·0022562
0·05	0·0621178	0·58	0·1450022	0·975	0·0017008
0·06	0·0678483	0·60	0·1427160	0·98	0·0012064
0·07	0·0730642	0·62	0·1399231	0·9825	0·0009832
0·075	0·0755123	0·64	0·1365739	0·985	0·0007771
0·08	0·0778670	0·65	0·1346717	0·9875	0·0005889
0·09	0·0823268	0·66	0·1326056	0·99	0·0004199
0·1	0·0864946	0·68	0·1279358	0·992	0·0002998
0·12	0·0940995	0·70	0·1224530	0·994	0·0001944
0·14	0·1008994	0·72	0·1159991	9·995	0·0001479
0·15	0·1040430	0·74	0·1083318	0·996	0·0001060
0·16	0·1070340	0·75	0·1039254	0·997	0·0000690
0·18	0·1125993	0·76	0·0990374	0·998	0·0000378
0·2	0·1176635	0·77	0·0935446	0·999	0·0000137
—	—	—	—	1·000	0

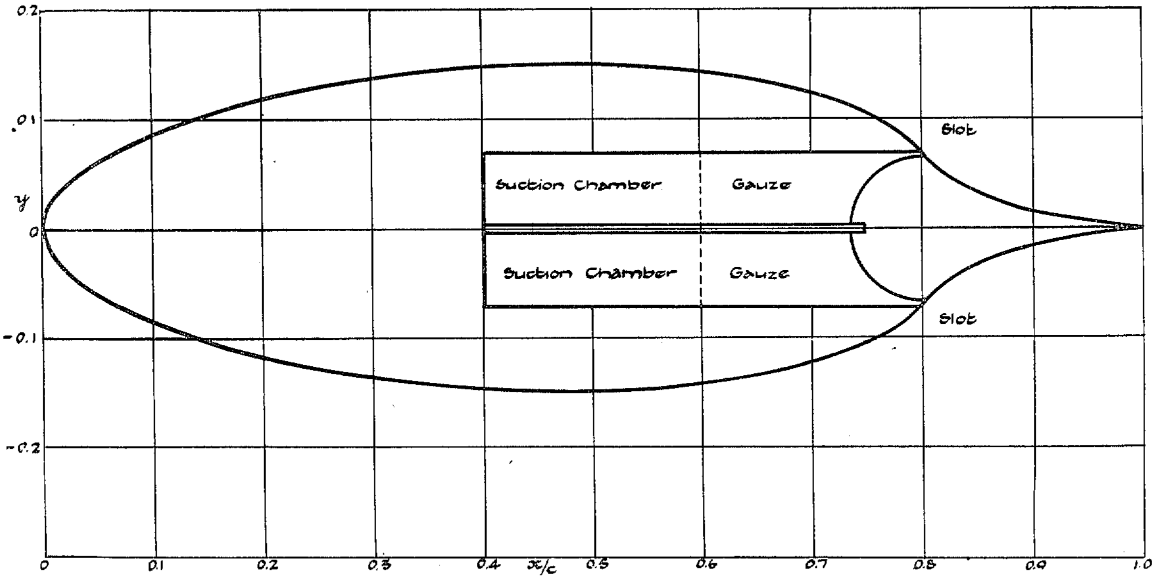

FIG. 1.—30 per cent. Suction Wing with Cusped Tail $X_1 = 0 \cdot 8$, $a = 0 \cdot 260242$, $b = 0 \cdot 426414$, $d = 0 \cdot 288803$ $(b - c) = 0 \cdot 756361$.

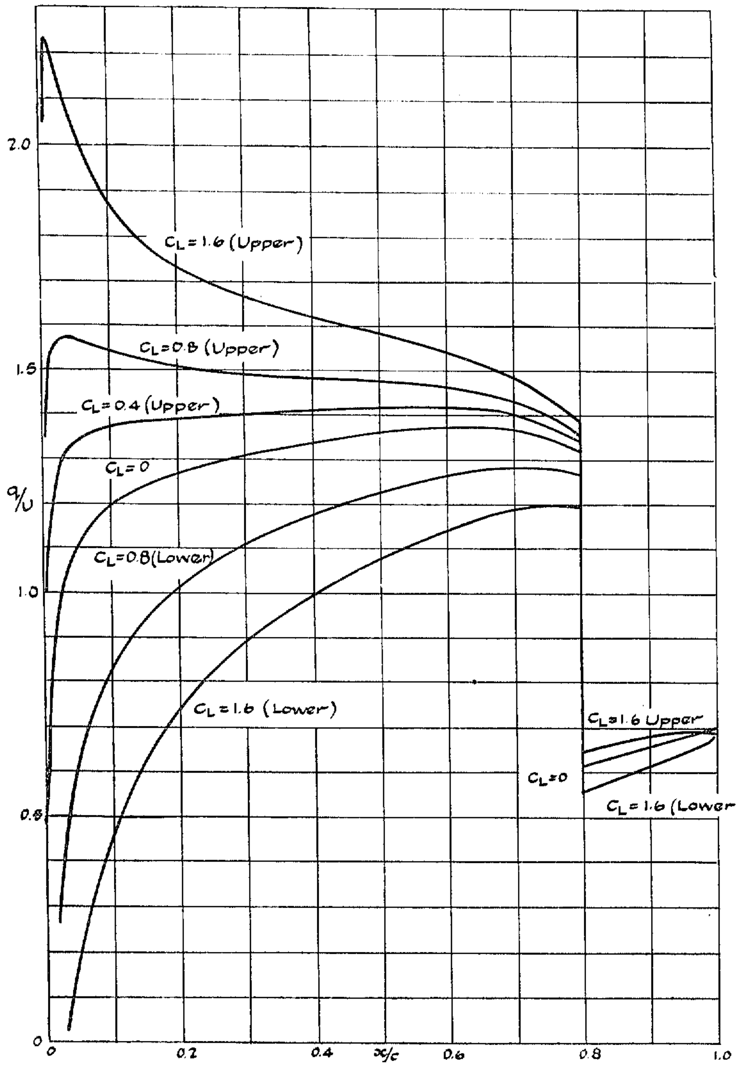

FIG. 2.—Theoretical Velocity Distribution over 30 per cent. Suction Wing $a_0 = 7 \cdot 9$. Approx. III of Reference 4.

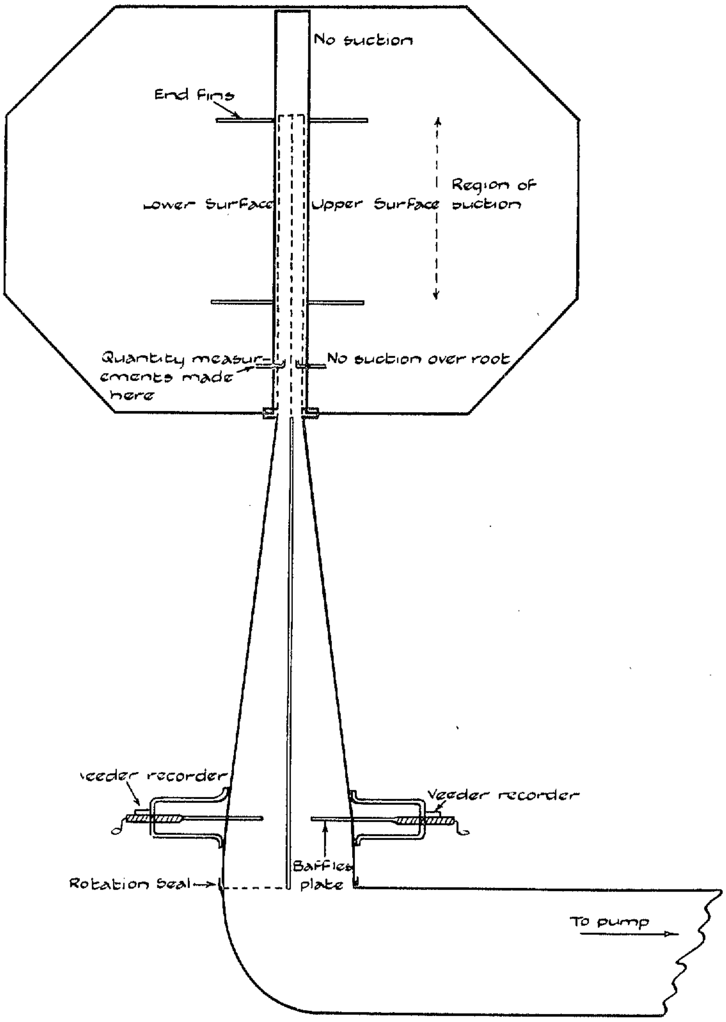

Fig. 3a.—General Rig-Up in Wind Tunnel.

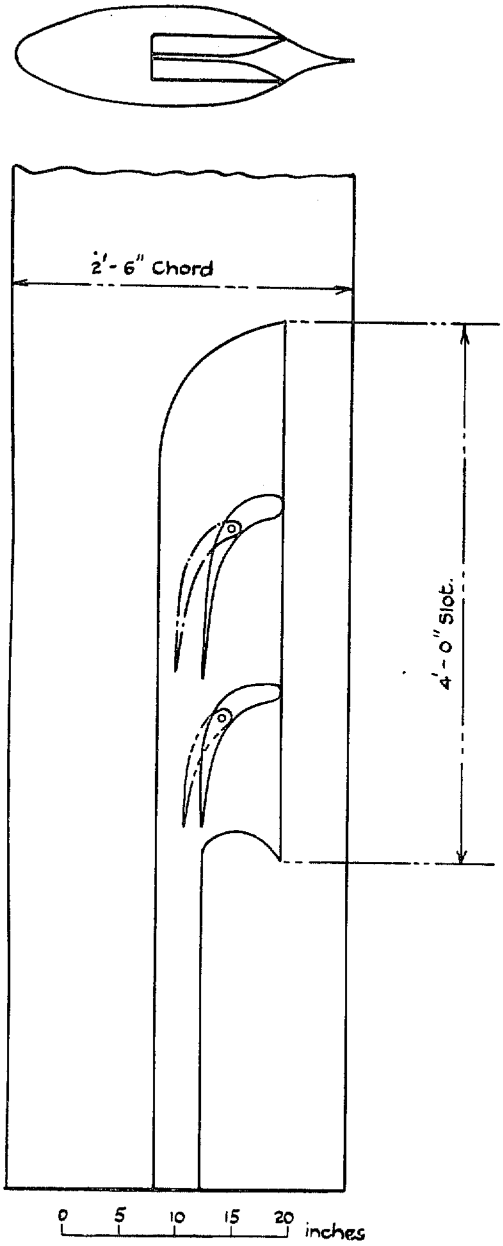

Fig. 3b.—Ducting Arrangement.

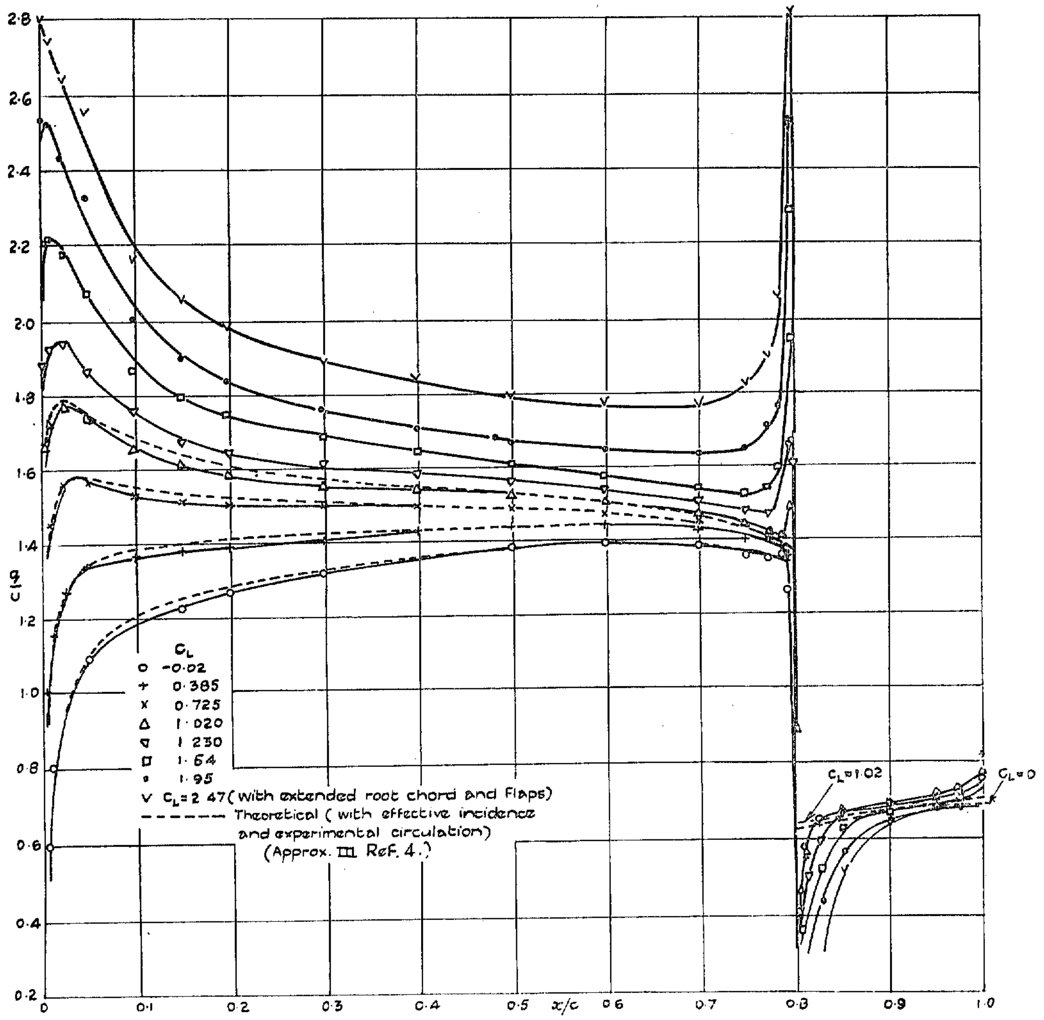

FIG. 4a.—Velocity Distribution with Suction on Upper Surface. $R = 0{\cdot}96 \times 10^6$.

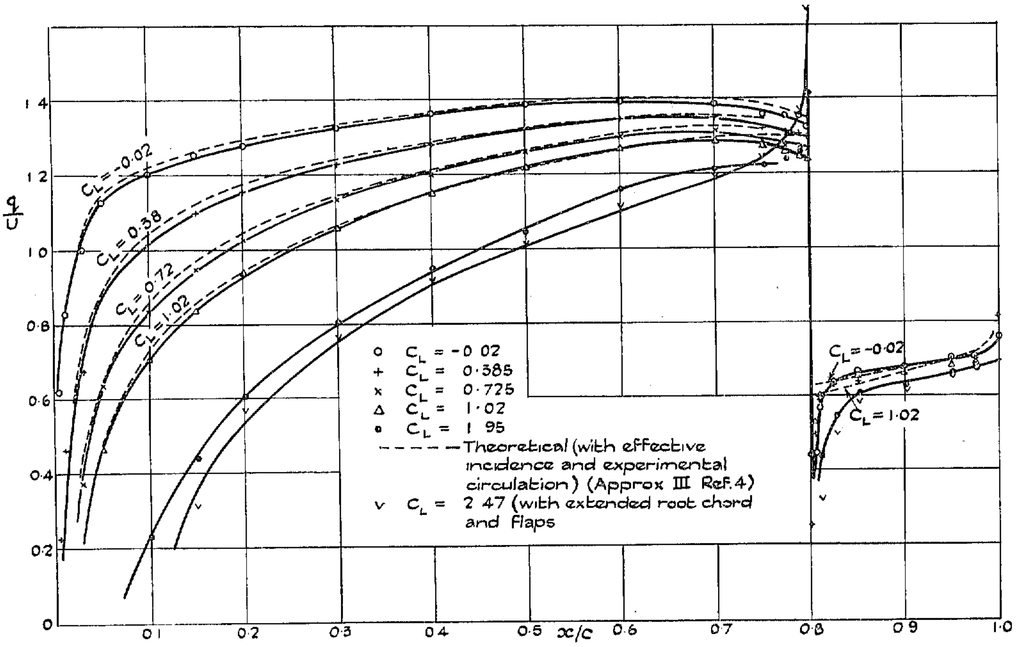

FIG. 4b.—Velocity Distribution over Lower Surface Minimum Suction. $R = 0{\cdot}96 \times 10^6$.

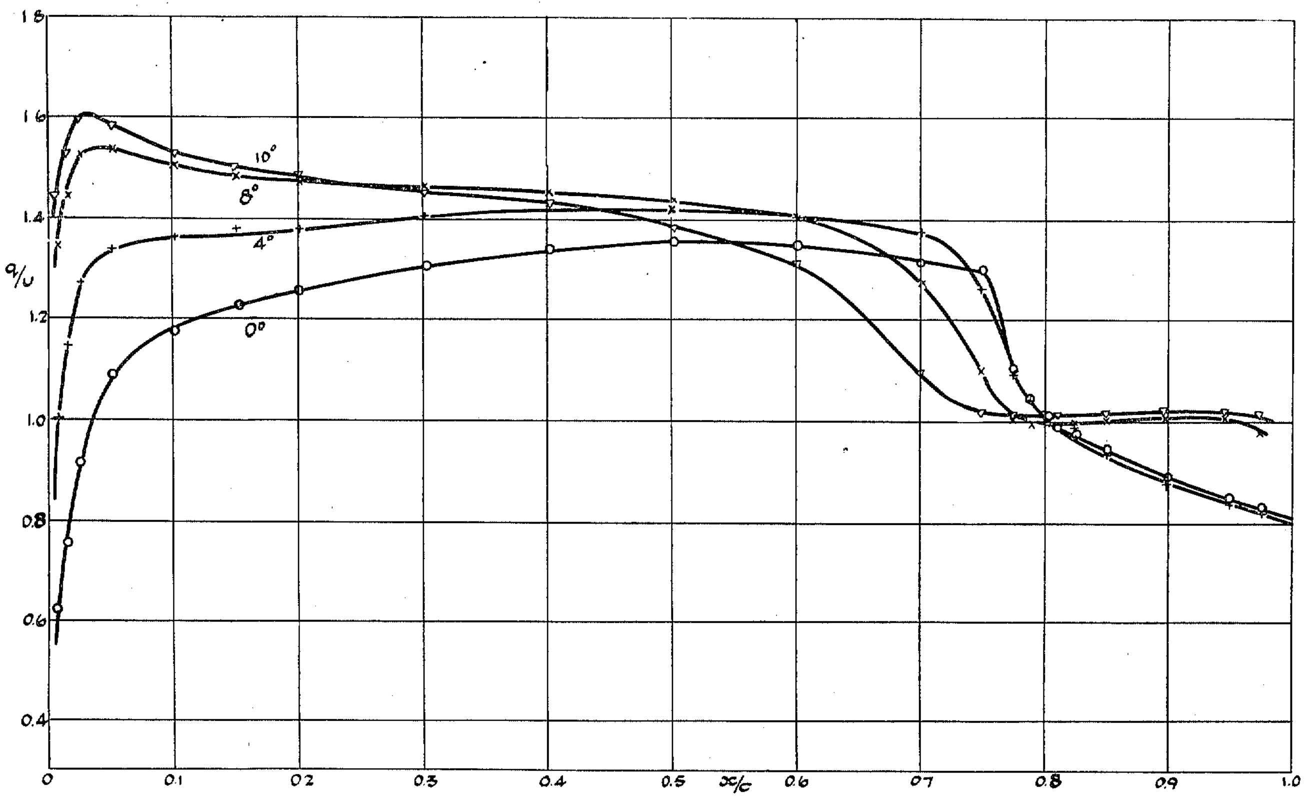

FIG. 5a.—Velocity Distribution over Upper Surface Zero Suction. $R = 0{\cdot}96 \times 10^6$.

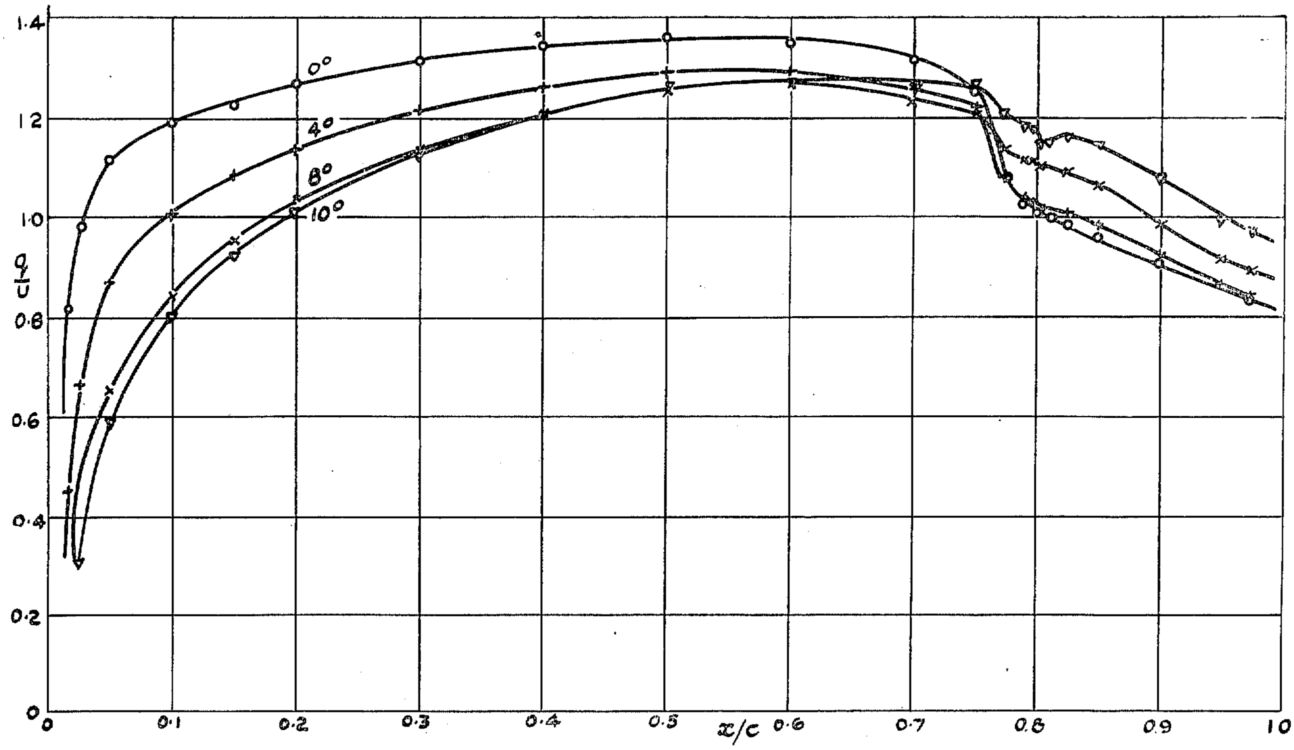

FIG. 5b.—Velocity Distribution over Lower Surface Zero Suction. $R = 0{\cdot}96 \times 10^6$.

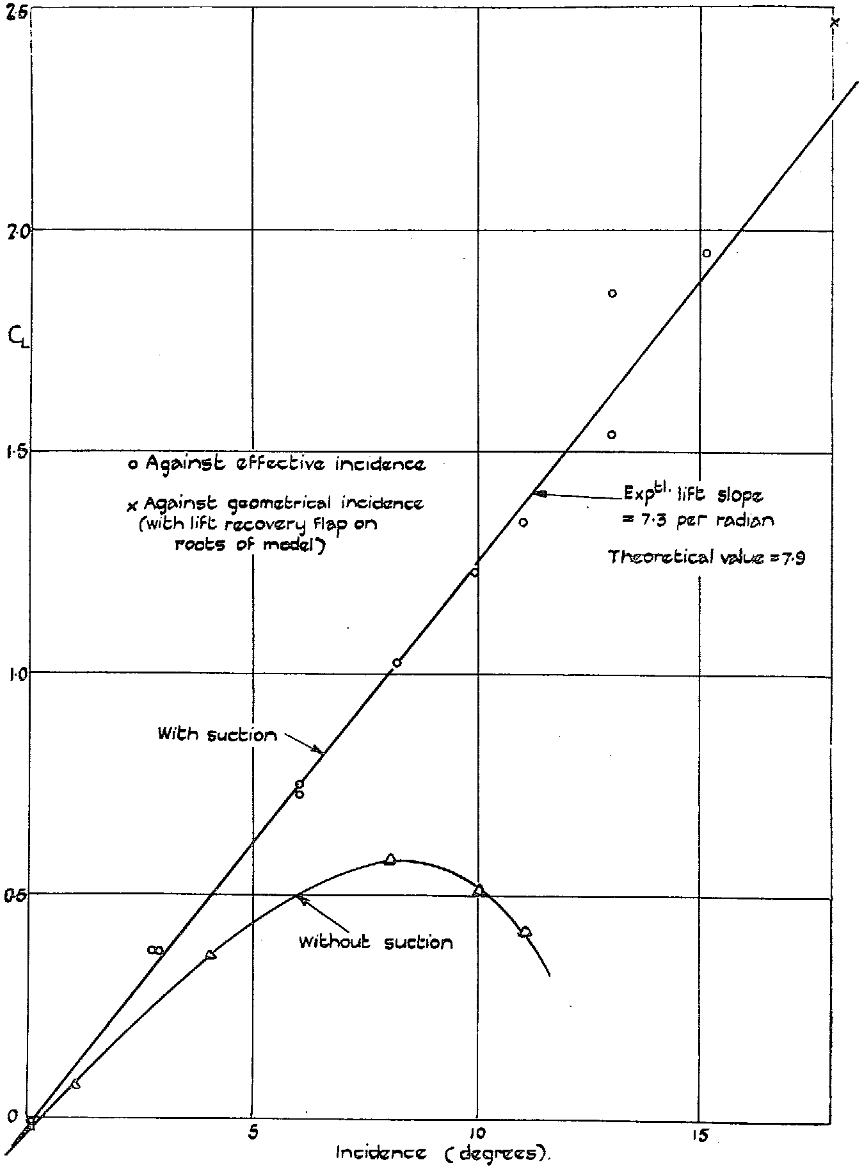

FIG. 6.—Variation of C_L with Effective Incidence. $R = 0 \cdot 96 \times 10^6$.

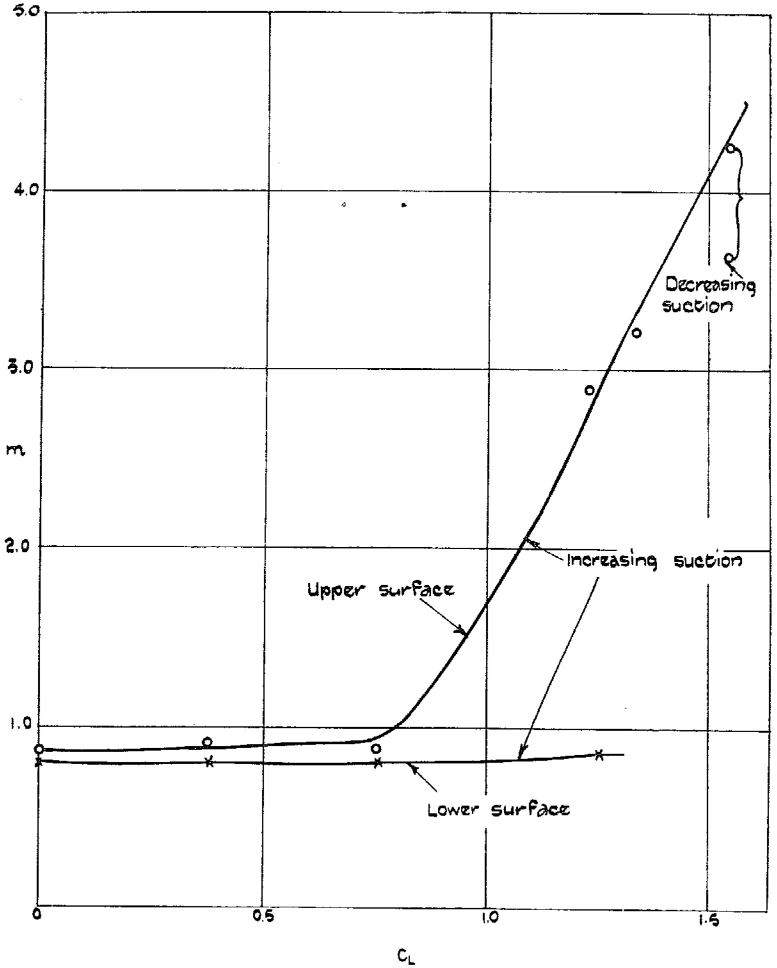

FIG. 8.—Quantity of Air Sucked Away to Set Up Non-separated Flow Region. $R = 0 \cdot 96 \times 10^6$.

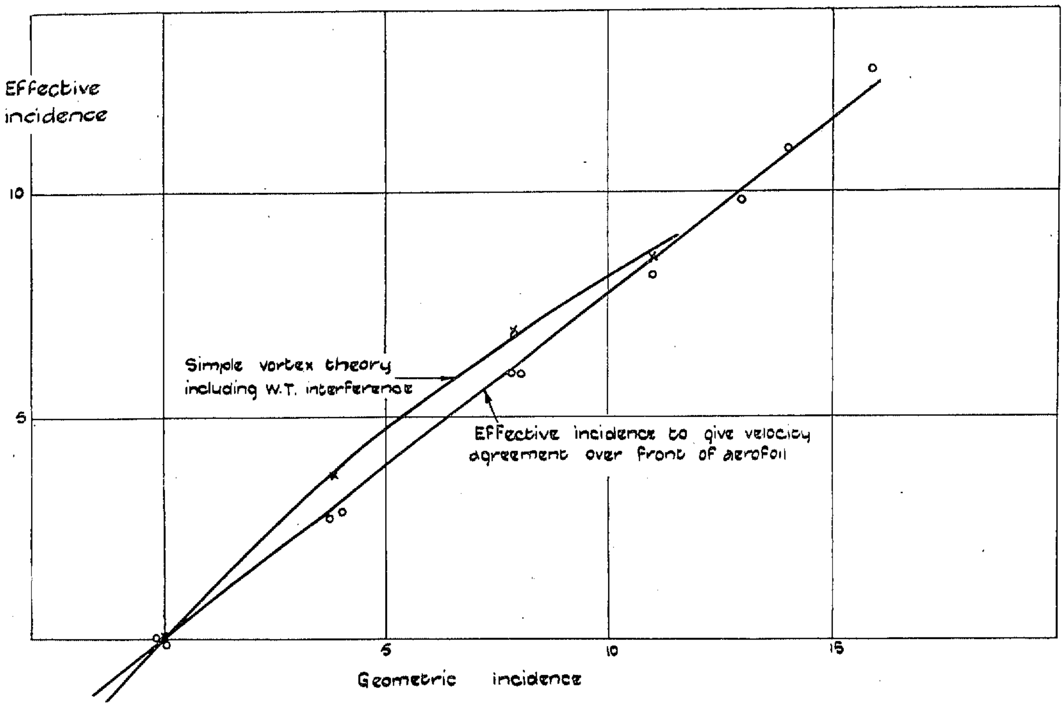

Fig. 7.—Effective Incidence Due to Interference.

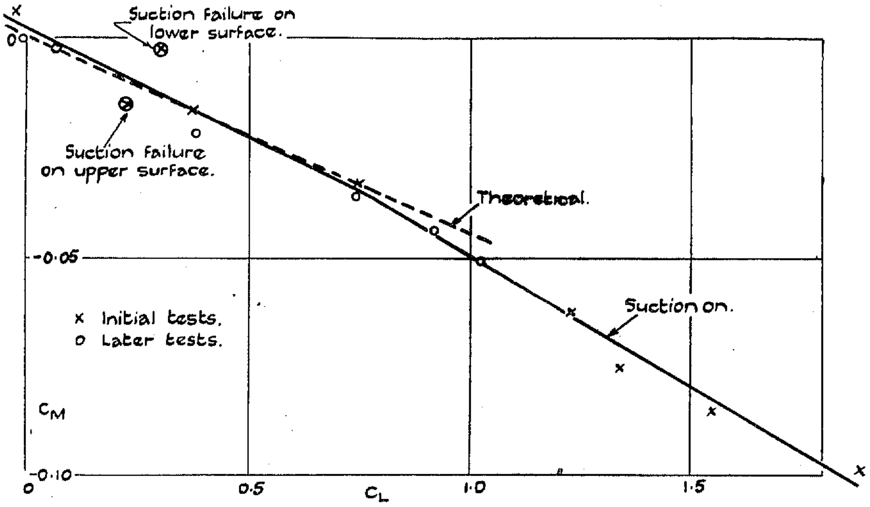

Fig. 9a.—Variation of Moment Coefficient with Suction on. $R = 0{\cdot}96 \times 10^6$.

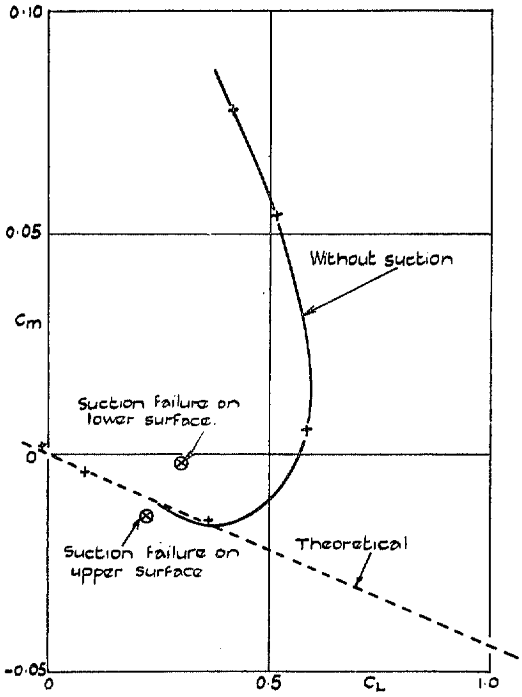

Fig. 9b.—Variation of Moment Coefficient without Suction. $R = 0{\cdot}96 \times 10^6$.

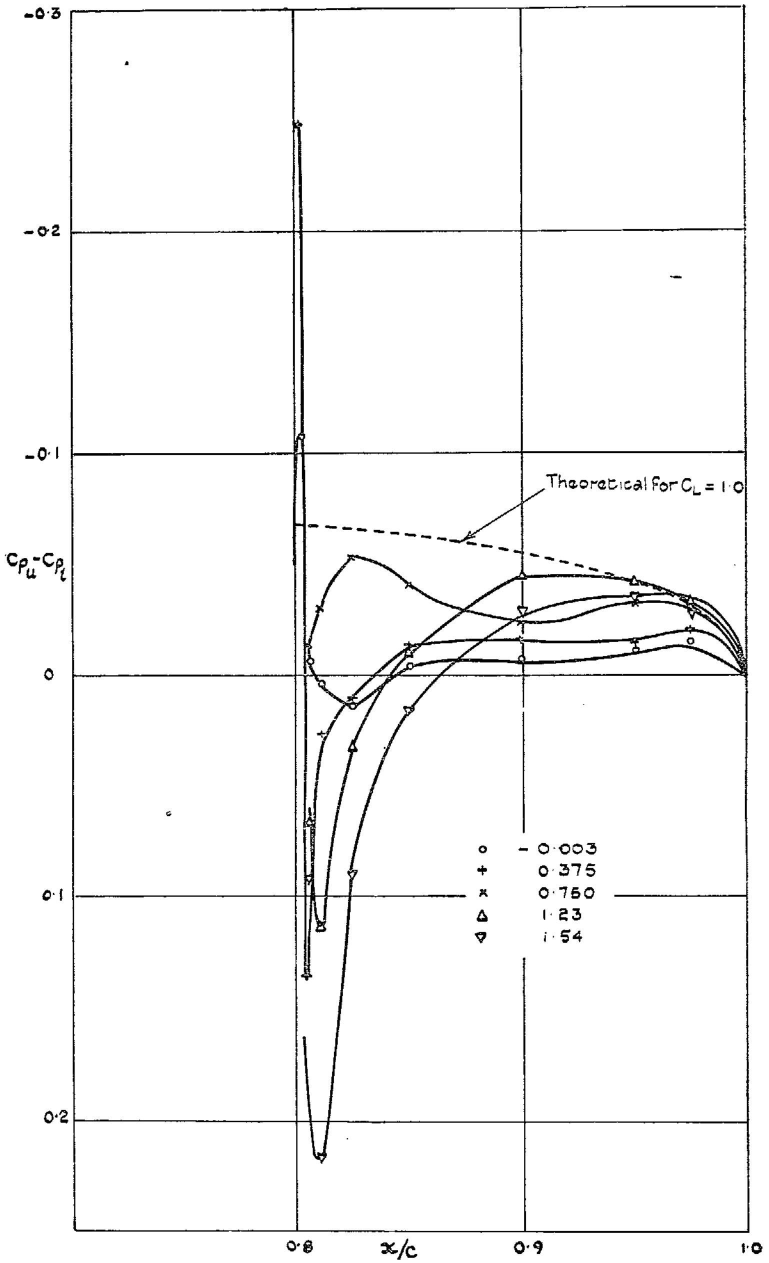

FIG. 10.—The Variation of Normal Loads on the Tail with Incidence. $R = 0·96 \times 10^6$. Minimum Suction.

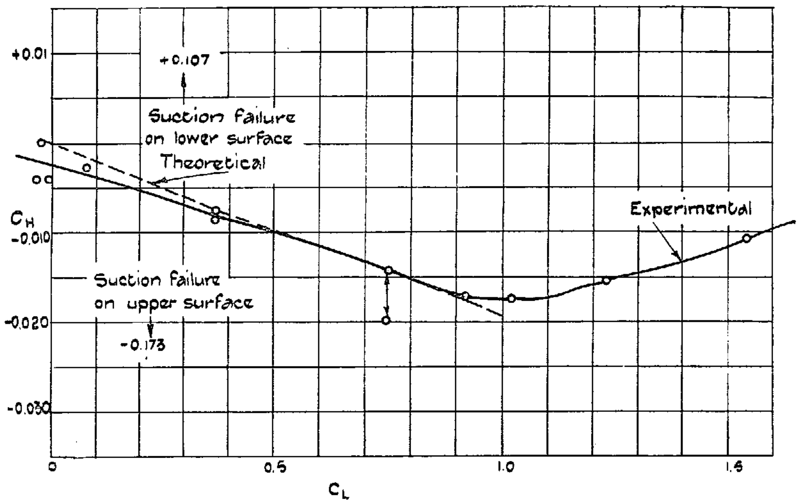

FIG. 11.—Variation of Hinge Moment Coefficient with C_L. $\eta = 0$ deg. $R = 0·96 \times 10^6$. Suction On.

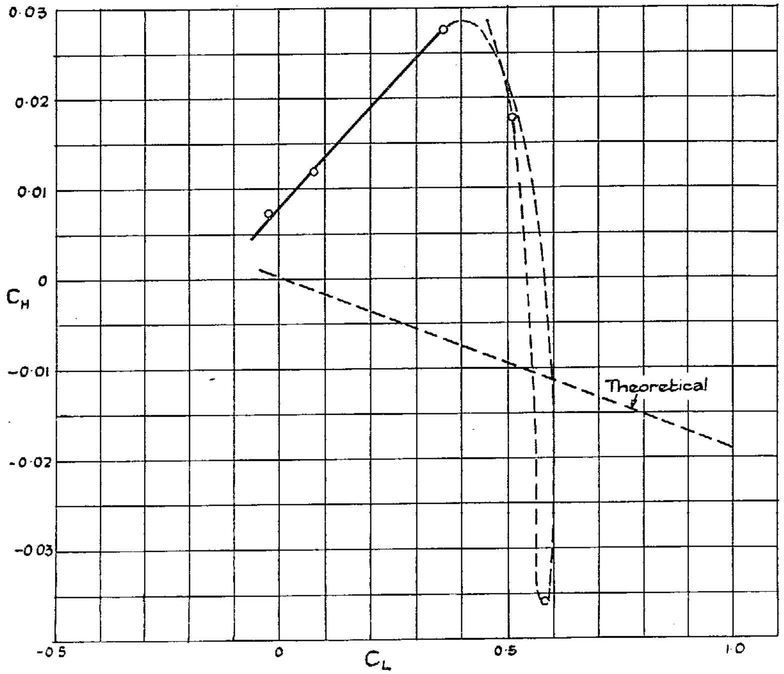

FIG. 12.—Variation of Hinge Moment Coefficient with C_L. $R = 0·96 \times 10^6$. No Suction.

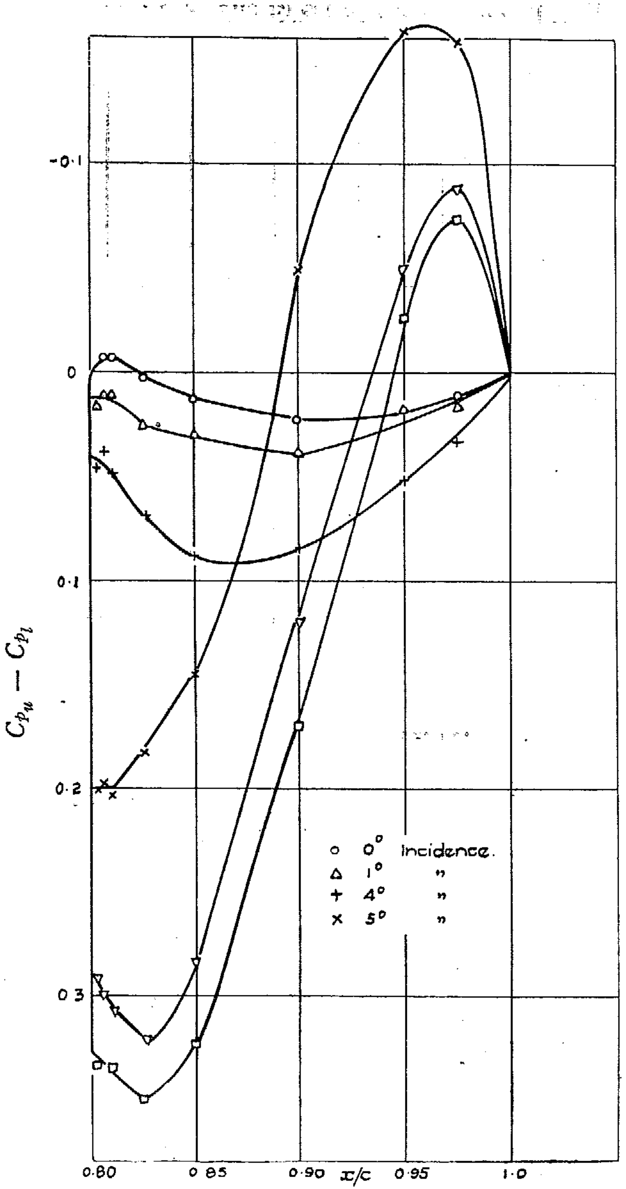

FIG. 13.—Variation of Normal Load on Tail with Incidence. No Suction.

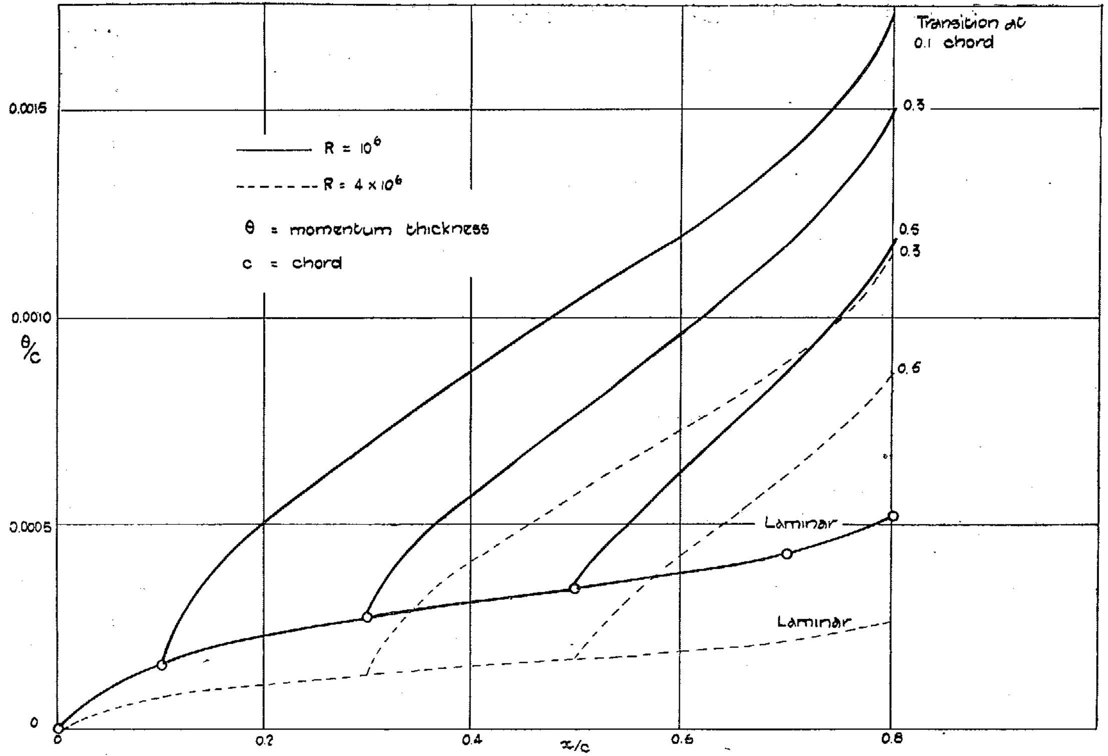

FIG. 14.—Variation of Boundary Layer Thickness Along Chord.

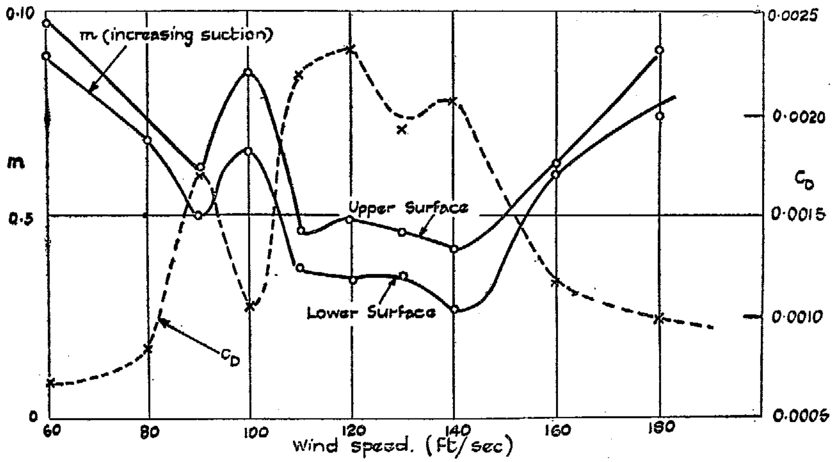

FIG. 15.—Variation of m (increasing) and C_D with Wind Speed Laminar to Slot.

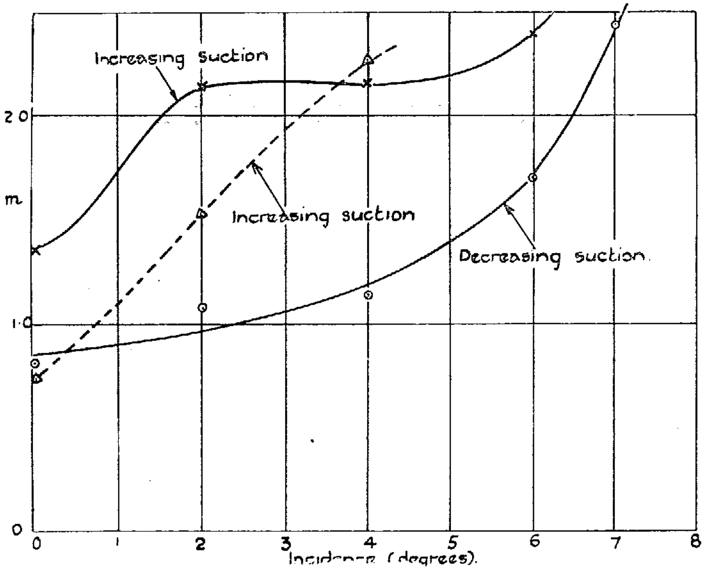

FIG. 16.

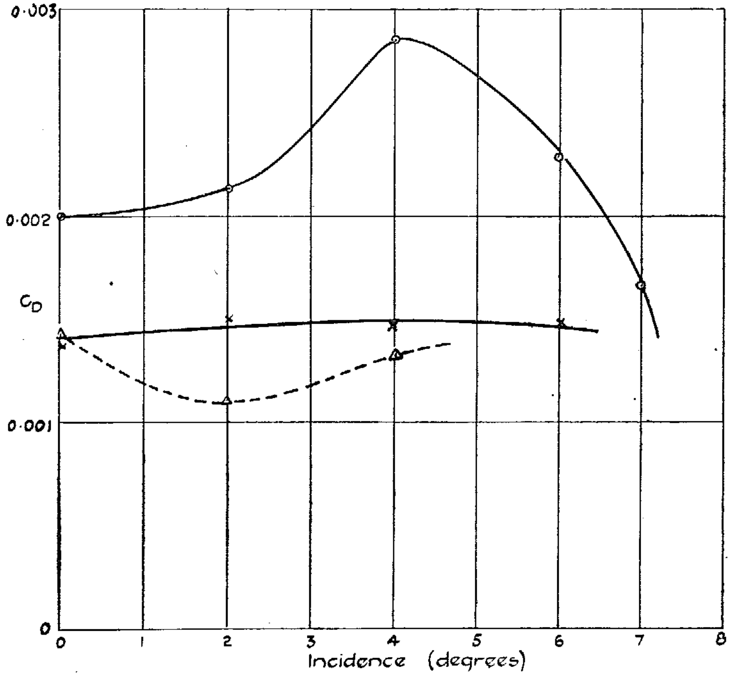

FIG. 17.—The Effect of Increasing and Decreasing Suction. $R = 2{\cdot}9 \times 10^6$.

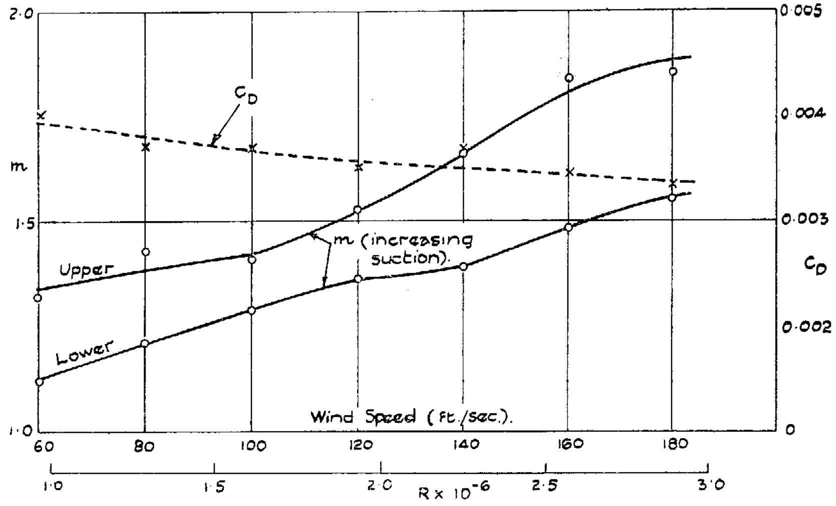

FIG. 18.—Transition at 0·1 Chord.

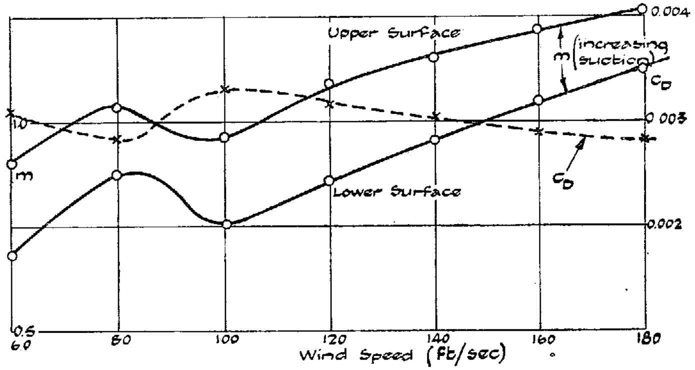

FIG. 19.

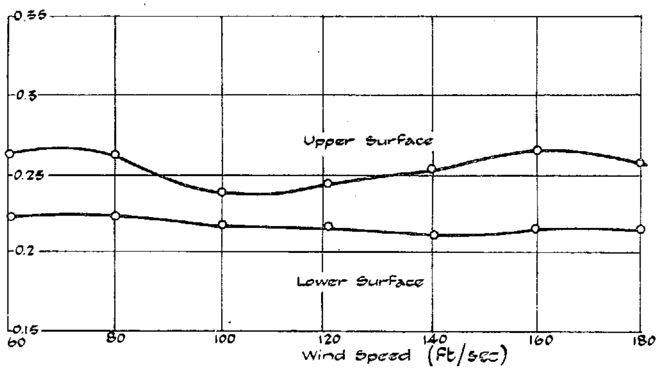

FIG. 20.—Variation of "n" with Wind Speed.

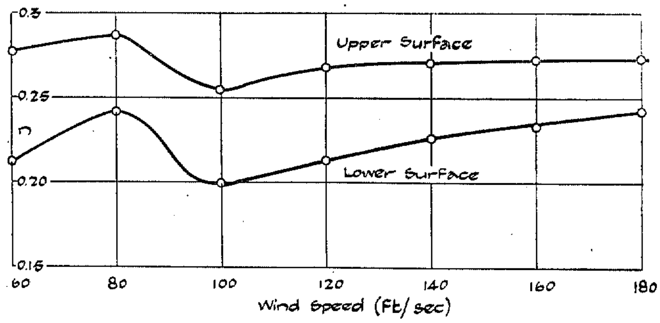

FIG. 21.

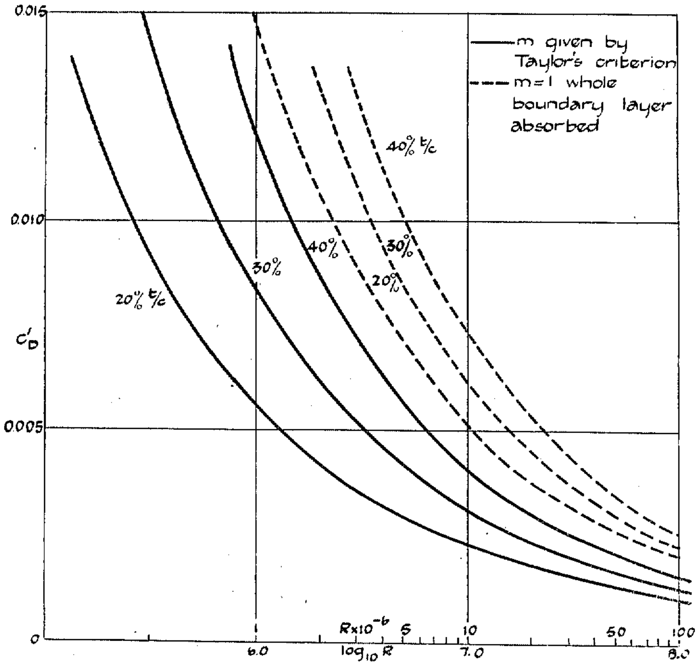

FIG. 23.—Theoretical C_D' for Different Thickness Chord Ratios Slot at 0·8 Chord.

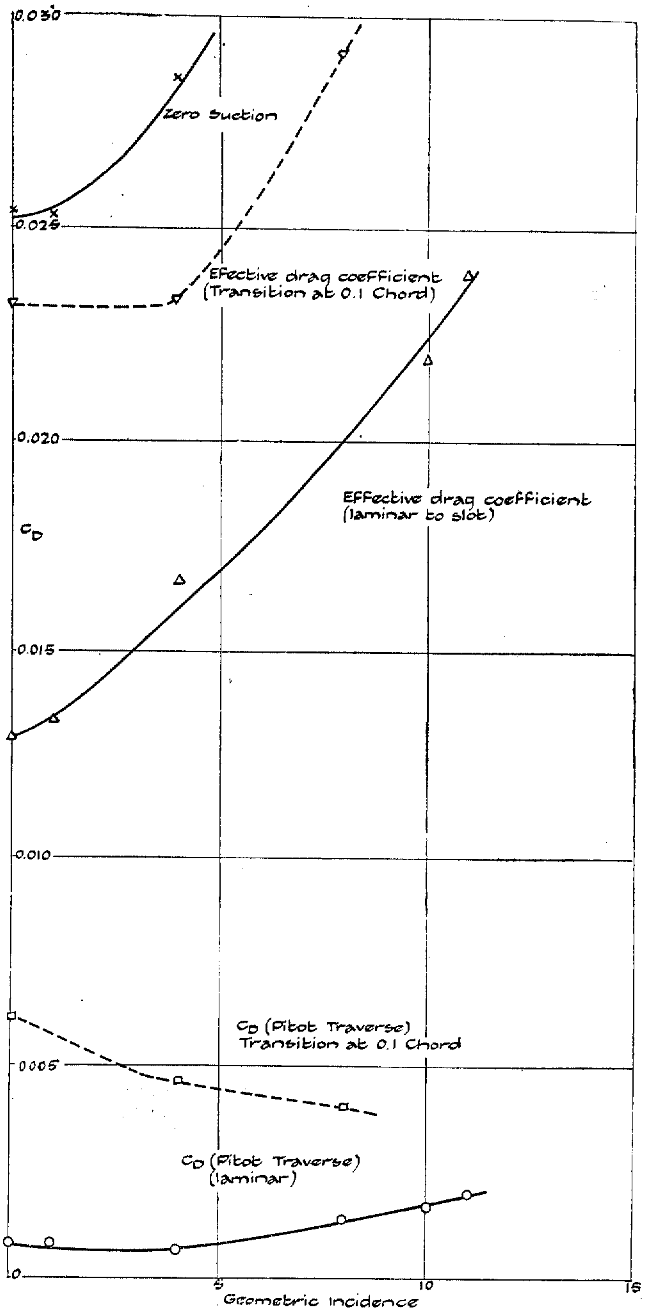

FIG. 22.—Drag of Suction Aerofoil, $R = 0{\cdot}96 \times 10^6$.

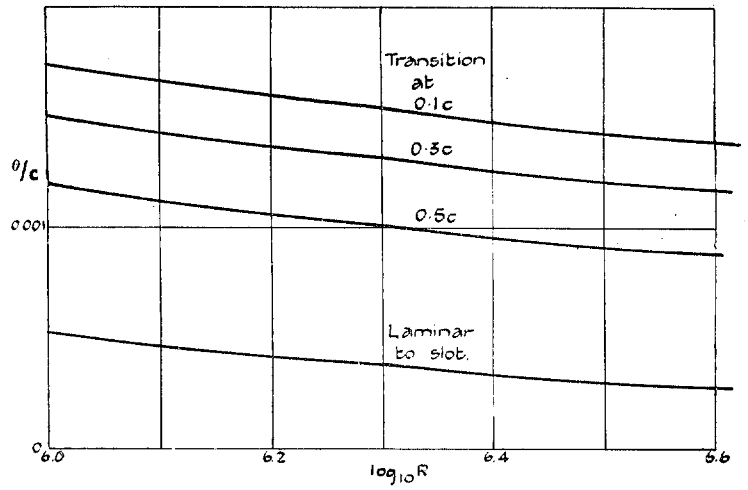

FIG. 24a.—Variation of Momentum Thickness with *R*.

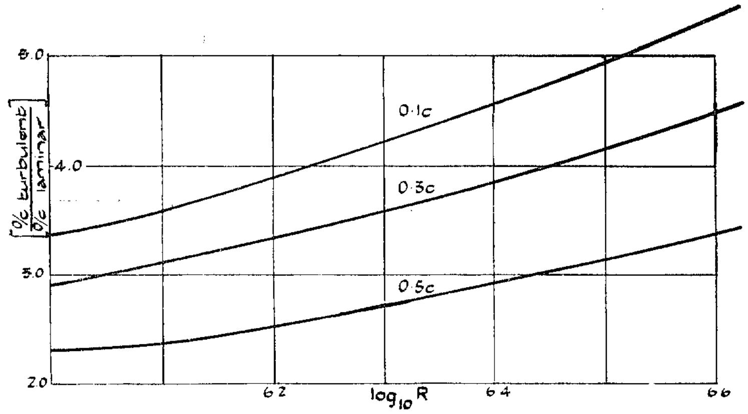

FIG. 24b.—Ratio of Momentum Thickness to that with Laminar Flow to the Slot.

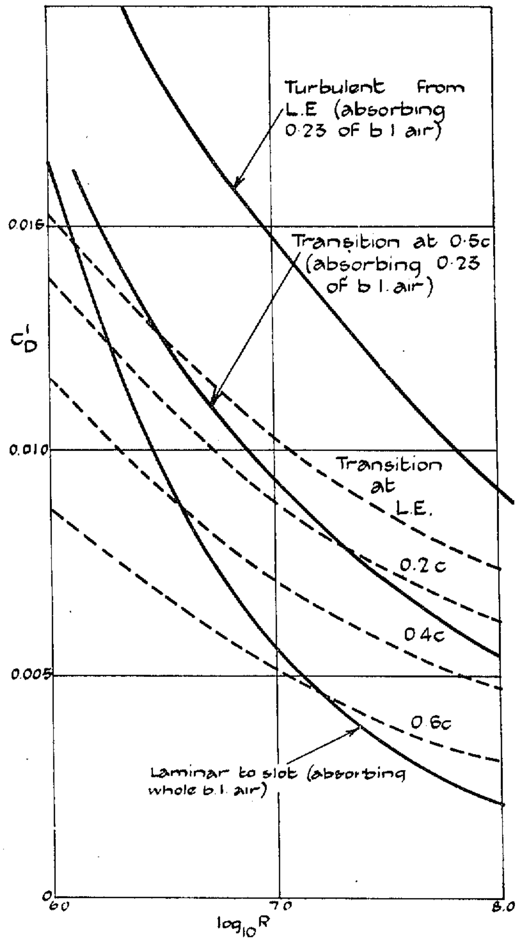

FIG. 25.

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