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PART I
Wind-tunnel Technique and Interim Note

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PART II
Effect of Concavity on Drag

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of the Aerodynamics Division, N.P.L.

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By
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Summary.—This report describes tests carried out on a 16 per cent. thick Griffith suction aerofoil in the 13 ft. × 9 ft. wind tunnel. Prior to these tests being carried out, the principle involved in the design of these aerofoils had only been justified experimentally by tests on a very small scale in the National Physical Laboratory 4-ft. wind tunnel[1]; the purpose of the present tests was to verify the feasibility of the Griffith " discontinuity " principle on a satisfactory scale, and to obtain quantitative data on the aerofoil characteristics with and without suction, the amount of suction needed to prevent separation and to develop the optimum slot shape and width for maximum efficiency.

Part I describes the technique used in the experiments, and the method of interpretation of the results to include in the drag a term to account for the power used to develop the necessary suction. The experiments show that separation of the flow on the surface can be fully prevented on this type of aerofoil by sucking less than half the air in the laminar boundary layer at the design position of the slot. If the flow is turbulent from the wing leading edge, the amount of air that must be sucked away is very little greater than that if the flow is laminar to the slot.

In the experiments of Ref. 1, it was found that the flow to the rear of the suction slot remained laminar to the trailing edge of the aerofoil. In the present experiments this was not found to be so, transition to turbulence occurring some distance rear of the slot. Part II (page 7) of this report describes an investigation of this effect and shows that this instability results from the dynamic instability of the boundary layer along a concave surface, and that it is impossible to design any practicable aerofoil shape over which this instability can be prevented at the Reynolds numbers of flight.

Part III (page 11) of the report extends the investigation of slot design to greater slot widths and less extreme shapes and includes the effect on suction mass flow of premature transition to turbulence forward.

In Part IV (page 16) aerofoil characteristics are discussed both with and without suction, including the velocity distribution over the aerofoil, lift coefficient, pitching moments and hinge moment variation with incidence. The effective drag coefficient variation is examined and extrapolation to full-scale Reynolds numbers carried out. It is shown that even with turbulent flow aft of the suction slot, a low-drag coefficient may be anticipated at the Reynolds numbers of flight. The effect of nacelles on suction wings is also examined.

PART I

Wind-tunnel Technique and Interim Note*

By

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Introduction.—A new type of aerofoil profile was described in Ref. 1 over the whole of which it was possible at a Reynolds number of $0 \cdot 37 \times 10^6$ to maintain laminar flow by means of a small amount of boundary layer suction. These preliminary tests indicated that at Reynolds number of $0 \cdot 37 \times 10^6$ the mass flow that it was necessary to remove by suction was less than that in the laminar boundary layer at the slot. The experiments were unsatisfactory in one respect, namely, that it was found necessary to suck away the boundary layer at two positions along the chord whereas the aerofoil had been designed to necessitate suction at only one chordwise position. While it was discovered later that a possible reason for this was that the model had been shaped wrongly near the design slot (*see* Ref. 2) it was decided to carry out further tests on a 6-ft. chord model of the same design as that of Ref. 1 in the 13 ft. × 9 ft. wind tunnel to investigate the principle fully at a more satisfactory Reynolds number and to obtain data on slot design.

* A.R.C. Report No. 7561 (March, 1944).

Design of Model.—A sketch of the model is given in Fig. 1. In view of the difficulty of making a uniform slot of 9 ft. span and consequently the possibility of not obtaining a uniform suction over the whole span of the model the experimental section was made to extend two feet each side of the centre line only, the rest of the span being of normal aerofoil profile. End effects between the two sections were eliminated by fitting end fins of shape shown in Fig. 1. The fins commenced at 0·45 chord in order to prevent the occurrence of too thick a boundary layer at the junction of the test section and the end fins. The pressure at 0·45 chord was designed to be the same on both sides of the fins. The centre section was made in three sections shown in Fig. 1, that from the leading edge to approximately 0·55 chord being of the standard Armstrong Whitworth low-drag wing construction described in Ref. 3, the tail piece from 0·75 chord being made of two metal sheets attached to spacing ribs, and the intermediate section consisting of wooden panels lying on flat metal beds. Each of the four suction boxes, two on each side of the aerofoil consisted of an inner and outer chamber separated by a fine gauze, suction being applied at one spanwise extremity only of the inner chambers. In this way a uniform suction could be obtained over the whole four feet span. Any position of the slots and any slot designs could be obtained by making new wooden panels for the centre section, while the waviness of the model could in this way be kept to a minimum.

Suction in each of the four chambers was controlled by means of throttles on the inlet end of a 50 h.p. centrifugal fan, the amount of air being measured from total head and static tubes placed in the inlet pipe, 75 pipe diameters downstream of the throttle. A traverse across the suction pipe at this point verified that the flow profile was parabolic, and that the mean velocity over the cross section of the pipe was 0·81 times that at the centre of the pipe.

Pressure plotting holes were fitted along the centre section on both sides of the model together with a small number of holes off centre to ascertain that two-dimensional flow was in fact being obtained.

Construction of the Model.—Owing to the many imperfections in the model as received from the maker, the section was measured up accurately. It was found that the profile was $\frac{1}{10}$-in. too thick at the position of maximum thickness, while at midspan this was reduced rapidly to the correct value at the spar, joining the front and centre sections of the test piece. There was, therefore, a spanwise dip in the test section along the junction between the forward and centre sections, which made the construction of new panels for the aerofoil a long and laborious procedure. In addition, the metal beds on which the panels lay were not made flat so that each panel had to be constructed in place on the model. It was impossible, therefore, to obtain a satisfactory profile over the whole chord for all spanwise positions and attention was concentrated on obtaining continuity of curvature at the joints between the metal and wooden sections, together with the correct variation of profile near the slot.

It is evident from the above that while the experiments would be successful if separation was prevented by a small amount of suction, it would be impossible, in the event of a large amount of suction being necessary, to decide whether this was due to approximations in the theory or wrong slot shapes or to inaccuracies of construction.

The surface waviness of the model was satisfactory except on the metal near the joints between the metal and wooden sections. This surface waviness is indicated in Fig. 2 for the centre section. In order to allow extensive laminar flow over the forward part of the aerofoil with this waviness, the tests were limited to a maximum speed of 110 ft. per second which gave an aerofoil Reynolds number of $4 \cdot 24 \times 10^6$. It was verified in the experiments that far back transition did occur at this Reynolds number.

Wind-tunnel Technique.—The aerofoil profile was identical with that of the 4-ft. wind-tunnel model[1] (with the exception of points near the suction slot); the tail of the 13 ft. × 9 ft. wind-tunnel model (which was designed to have a thickness of 0·05 in. on the small model for strength purposes) was of such a thickness (0·02 in.) that comb investigations at the tail suffered from a difficulty in differentiating between the laminar flow drag of the tail and the form drag. It was, therefore, decided to adhere to the procedure found satisfactory in the earlier experiments of indicating transition on the surface and calculating the drag of the aerofoil.

Two methods were employed to indicate transition using, respectively, smoke filaments and very fine silk threads. With the former method, smoke filaments, obtained from paraffin oil by the method described in Ref. 4, were introduced into the stream at 0·587 chord and just behind the slot at 0·706 chord. In this way any transition or separation either forward or to the rear of the slot could be observed. The smoke filaments were illuminated by means of a grazing light but were observed directly by telescope looking normally on to the surface of the aerofoil. Some ejection of paraffin from the smoke holes occurred and formed large drops which tended to run spanwise across the test section. Consequently, it was necessary to wipe the surface continually to prevent any premature transition of flow. It should be made clear that it was the formation of drops that caused transition and not the existence of a thin paraffin film to the rear of the smoke holes.

In view of the above difficulty in the smoke technique, an attempt was made to observe transition by the method evolved by L. F. G. Simmons with very fine silk threads of about half an inch in length attached at one end to the surface. Transition to turbulence is accompanied by fluctuations of the threads.

Early in the experiments it was found that, except at the lowest wind speeds, the laminar smoke filaments to the rear of the slot broke down some distance forward of the trailing edge in spite of the existence of a favourable velocity gradient to the trailing edge; as the threads did not indicate this transition some doubt was expressed as to the validity of the smoke technique. The boundary layer profile was, therefore, measured at 0·9 chord (which was some distance downstream of transition) by means of a small total head tube in conjunction with the surface static tube at that point. In Fig. 3, the velocity profile so observed is compared, firstly, with that estimated on the assumption of laminar flow from the slot, and secondly assuming a turbulent boundary layer from the position of transition indicated by the smoke experiments (calculated by assuming the $\frac{1}{7}$th power law and no velocity gradient). It is seen that in fact the flow has become turbulent as indicated by the smoke filaments and that the silk streamers cannot be relied upon to indicate transition to turbulence.

The breakdown of laminar flow over the tail referred to above has been shown to arise from the instability caused by the concavity of the surface and is discussed fully in Part II.

Separation of flow was indicated satisfactorily by both smoke filaments and silk streamers.

One considerable difficulty occurred in the wind-tunnel technique owing to the difficulty of obtaining a completely uniform slot over the whole 4-ft. span. With very small slot width of the order of 0·040-in. a variation of slot width of 0·002-in. resulted in non-uniformity along the span in the prevention of separation. Consequently great care had to be taken with slots of small widths to give uniform suctions.

Results.—In spite of the considerable inaccuracy of profile at points other than near the suction slot, it was found that separation could be prevented with a small amount of suction air from a single slot at 0·7 chord, and it became apparent at once that there was no need for an auxiliary slot at 0·65 chord as was the case in the earlier experiments. The onset of the non-separated flow as suction was increased, occurred quite suddenly along the whole span, but the mass flow at which this régime commenced could not be repeated accurately from day to day. The criteria obtained if the non-separated régime was first set up and suction then decreased until separation occurred were much more consistent from day to day and this technique has in general been followed. A marked discrepancy occurred between results obtained in these two ways and a discussion of this point follows later.

Design of Slots.—Two slot angles have been investigated so far, the first facing towards the trailing edge and cutting the surface at 15 deg., the other facing forward and cutting the surface at the slot at 45 deg.

The latter slot is similar to that used in the original experiments[1]; the former design arose from work carried out by Dr. A. A. Griffith, and was developed on the argument that since a considerable pressure gradient must occur across the slot from the fore edge to the rear edge of the slot (which was virtually at stagnation point) good flow could only be obtained if this pressure gradient were counteracted by centrifugal forces arising from the large curvature of the stream lines. A detailed investigation of slot design under more favourable conditions has been made by Fage[5]; it is apparent, however, that the width of slot necessary to give an efficient flow is too small to be a practical proposition and these experiments have aimed rather at indicating what losses arise from using under slots rather than on developing the aerodynamically best slot. Diagrams of the slot shapes investigated are given in Figs. 4*a* and 4*b*.

Effect of Slot Thickness.—The fraction m of laminar boundary layer air at 0·7 chord absorbed in each case is plotted against w/δ (where w = slot width and δ = laminar boundary layer thickness at 0·7 chord) in Fig. 5 for the backward-facing slot (15 deg.) and in Fig. 6 for the forward-facing slot. It may be seen that with the backward-facing slot there is a large scale effect on the results, possibly due to the forward lip being of constant radius (0·020 in.) and, therefore, not a constant fraction of δ for varying Reynolds numbers. This lip could not be easily enlarged without moving the slot lip position forward. It is evident, however, that there is no increase in the proportion (0·44) of boundary layer to be removed with increasing slot width, and widths of slot equal at least to the boundary layer thickness may be used without necessitating increased suction mass flow. Slots of greater width could not be investigated in these experiments owing to the small angle which the slot made with the surface. There is nothing to indicate, however, that for this slot direction, slots of width greater than that of the boundary layer necessitate a greater value of mass flow m.

Greater slot widths were investigated in the case of the second slot direction shown in Fig. 4*b*. Fig. 6 shows the variation of m with w/δ for various slot widths up to a maximum of twice the boundary layer thickness. The slot lips in this case were kept to about 0·01 in. radius; an investigation of the effect of slot entry shapes is in hand.

For small slot widths there is little to choose in m between this and the backward-facing slot. If a greater width is used, the value of m increases slightly and 0·6 of the laminar boundary layer air must be absorbed with this direction of slot for a slot width equal to twice that of the laminar boundary layer at 0·7 chord. It is interesting to note that in this case all the curves obtained with different slot widths fall roughly on a general curve which is independent of the slot width and depends only on its ratio to the boundary layer thickness.

Hysteresis Effect.—If m is the fraction of air removed from the laminar boundary layer at 0·7 chord to prevent separation and Δm the difference between the values of m necessary to change the régime with increasing and decreasing suction respectively, it will be seen from Figs. 7*a* and 7*b* that Δm does not in fact depend greatly on the slot width or angle of slot, but varies noticeably with Reynolds number. At high values of R provision for sucking away an additional 0·07 of the air in the boundary layer must be made to overcome this hysteresis effect. The reason for taking the limiting criterion as that obtained with decreasing suction becomes apparent from Fig. 6, which shows the variation of m with w/δ for both the increasing and decreasing suction cases. With increasing suction, the individual observations (obtained from a single slot width with varying wind speeds) do not fall on a single curve and no general relationship suitable for use at much higher Reynolds numbers can be obtained.

Pressure Distribution over the Aerofoil.—Fig. 8*a* shows a typical comparison of the experimental and theoretical velocity distributions over the aerofoil; Fig. 8*b* gives the velocity distribution over part of the aerofoil with varying quantities of air removed from the boundary layer. Comparison of experiment and theory indicates discrepancies which are largely due to errors in the aerofoil profile. The velocity profile without suction is of considerable interest in that it approximates much more closely than would have been anticipated to the theoretical distribution in spite of the existence of a separated region, and the flow in fact re-adheres to the surface at about 0·85 chord. This readherence accounts for the high effectiveness of aileron controls on a Griffith aerofoil[6]. With increasing suction, the velocity approximates more and more to the theoretical value (with no sink effect) and adherence of the flow to the surface near the slot occurs when the experimental velocity distribution approximates closely to the theoretical shape. In Fig. 9 the variation of the velocity at a point just behind the slot is plotted against m for two slot widths at the same Reynolds number. It will be seen that while a definite change in the static pressure occurs with the change of flow pattern, this change is not in all cases sufficiently clear cut to allow of its use as a means of indicating the establishment of a non-separated régime ; (this was suggested as a possibility in flight experiments where direct observation of streamers was impossible).

As stated earlier, once separation was prevented, a laminar layer was observed to the rear of the slot, but in all cases this broke down before reaching the trailing edge, in spite of the existence of a favourable velocity gradient and a good surface. It is shown in Part II that this breakdown of laminar flow is due to the dynamic instability, caused by the concavity of the surface and that no aerofoil of this family can be designed which is likely to give laminar flow to the tail at high Reynolds numbers. Consequently, prevention of separation only has been aimed at in these experiments and minimum suction quantities (n) all refer to this condition.

Suction Head in Slot Chamber.—The effective drag coefficient of an aerofoil of this type does not depend only on the amount of air sucked away, but also on the suction head necessary to perform this removal. The power necessary obviously depends on the suction head necessary at the inlet end of the suction pump and therefore depends considerably on the design of the ducting system. It is impossible in wind-tunnel experiments to simulate such a system and consequently attention has been concentrated on understanding the frictional losses in the slot. In this way it is hoped that the initial flow conditions for which the ducts should be designed can be estimated

In all cases, the static pressure in the suction chamber was recorded ; it became apparent at once that for very thin slots of the widths suggested by Fage[5] as giving the most efficient flow ($w/\delta = 0{\cdot}25$) a very high suction head was necessary to prevent separation, due to the high frictional losses in the short length of slot between the entry and the suction chamber. It was argued in Ref. 1 that an estimate of the effective drag coefficient $C_D{}'$ could be obtained from the formula $C_D{}' = C_D + C_Q\,(1 + C_p)$ with the notation of that report. Fig. 10 shows a sample variation of C_p with w/δ for a wind speed of 100 ft. per second ($R = 3{\cdot}85 \times 10^6$) for both the forward-and backward-facing slots. A direct comparison of the two cannot be made since the lengths of slot differed in the two cases. It is clear however that a slot width of half the boundary layer width is necessary to prevent large frictional losses at the beginning of the slot and a consequently high effective drag coefficient. The value of C_p obviously differs with Reynolds number for a given m and w/δ, and the figures obtained are being analysed with a view to obtaining suitable data for full scale. One further point is worth noting ; with large slot widths and a forward-facing slot it was found that the necessary suction head was less than that occurring at the forward slot lip $0{\cdot}69$ (Fig. 10). This is undoubtedly due to the fact that owing to the large slot width (which had to be cut tailwards from the $0{\cdot}7$ chord position in order to obtain the correct velocity distribution to the rear of the slot) most of the air had already overcome the velocity discontinuity before entering the slot. An investigation of this point and an analysis of the velocity and static pressure pattern along and across the slot has been made and will be reported later. In the meantime, it is advisable that frictional losses in the duct should be calculated assuming a suction equivalent to that at the forward lip of the slot to occur at the slot entry. To prevent large losses the slot width should be made at least as great as one half of the thickness of the laminar boundary layer at $0{\cdot}7$ chord.

Effect of Premature Transition.—The effect of early transition arising from roughness of the surface or from excessive surface waviness has been investigated with the forward-facing slot and a $0{\cdot}08$ in. slot width with transition fixed by means of a thin wire of diameter $0{\cdot}033$ in. at $0{\cdot}1$, $0{\cdot}3$ and $0{\cdot}5$ chord respectively. Further work is to be carried out on this, and only a preliminary analysis is contained in the present paper. Fig. 11 shows the fraction of the calculated *laminar* layer at $0{\cdot}7$ chord which it is necessary to absorb to prevent separation. It is clear that even with transition occurring near the leading edge, the amount of air sucked away is not much greater than that if laminar flow occurs to the slot at $0{\cdot}7$ chord and it appears that a much smaller fraction of a turbulent boundary layer need be absorbed than for a laminar layer. In fact with transition fixed at 0·5 chord the suction mass flow necessary is considerably smaller than that if the flow is laminar to the slot.

Further Developments.—Apart from those developments already referred to, it is proposed to investigate the properties of the aerofoil at incidences other than zero, including measurements of velocity distribution, values of b_1 for various flap arrangements, suction heads and mass flows. The interference at the junction of a Griffith aerofoil and engine nacelle is also to be investigated.

Summary of Conclusions.—(1) Prevention of separation on a Griffith aerofoil may be obtained by suction at a single chordwise position in spite of the poor aerofoil contour at positions other than near the slot.

(2) With a backward-facing slot cutting the surface at 15 deg., this state may be maintained with a mass flow of suction air equivalent to 0·44 of the air in the laminar boundary layer just forward of the slot, this figure being roughly independent of the slot width for slot widths at least as great as the boundary layer thickness.

(3) At the Reynolds number of these tests frictional losses in the ducting system are likely to be large unless a slot width of at least half the boundary layer thickness is used.

(4) With a forward-facing slot, the fraction of boundary layer air to be absorbed lies between 0·4 and 0·5 for slot widths less than the thickness of the boundary layer, but increases to 0·60 for slot width up to twice the thickness of the boundary layer.

(5) In order to set up the non-separated régime, the above figures must be increased by 0·07 of the boundary layer air.

(6) With the boundary layer turbulent from the leading edge, the amount of suction air necessary is not vastly greater than that with the flow laminar to the slot.

The author wishes to acknowledge the help of E. A. Frankland who constructed the centre section panels.

PART II

Effect of Concavity on Drag*

By

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Introduction.—During tests on a Griffith aerofoil in the 13 ft. × 9 ft. wind tunnel at the National Physical Laboratory, it was found that whereas separation could be prevented with a small amount of boundary layer suction at one point on the chord, and whereas a laminar layer could be set up to the rear of the slot, it was impossible, except for the lowest wind-tunnel speeds, to maintain the laminar layer to the trailing edge. It is shown that this instability is due to the concavity of the surface and that no aerofoil of this family can be designed to give laminar flow over the whole chord for Reynolds numbers of 20 millions and over. Assuming a turbulent boundary layer to the rear of the slot, the aerofoil still gives a lower effective drag coefficient than that of a normal low-drag aerofoil at $R = 25 \times 10^6$, particularly if the slot position is moved back along the chord.

Wind-tunnel tests have been carried out in the 13 ft. × 9 ft. wind tunnel at the N.P.L. on the Griffith aerofoil described in Ref. 1. A description of the model and the wind-tunnel technique together with an interim report on the effect of slot design is contained in Part I.

At a very early stage in the experiments it was found that whereas separation could be avoided and laminar flow maintained up to the slot with an amount of suction equivalent to about 0·4 of the quantity of air in the laminar boundary layer at the slot, and whereas it was possible to set up a laminar layer to the rear of the slot, it was impossible, except at low wind-tunnel speeds, to maintain this laminar layer to the trailing edge of the aerofoil. Since, at Reynolds numbers of 25 millions and over this breakdown of the laminar layer approximately doubles the aerofoil drag (0·0022 instead of 0·0012), a thorough investigation of the possible causes of this breakdown has been made.

Description of Investigation.—All the investigations made below were carried out using a backward-facing slot making 15 deg. angle with the surface at the slot. These slots are shown in Fig. 4*a*.

The measured velocity distributions over the aerofoil at 0 deg. incidence with and without suction are given in Fig. 12 together with the theoretical velocity distribution at this incidence. The discrepancy between experiment and theory is largely due to errors in the aerofoil profile and is discussed in Part I. It is evident, however, that with sufficient boundary layer suction to prevent separation, there is a favourable velocity gradient from the slot to the trailing edge, so that the breakdown is not due to an adverse velocity gradient. It was found that, as a result of making the axis of the slot cut the surface at 0·7 chord, the front lip of the slot which was extremely thin was about 0·003 chord ahead of the design position. Consequently a very slight adverse velocity occurred rear of the front slot lip but forward of 0·7 chord which might upset the laminar layer. Observation of smoke filaments indicated, however, that no improvement occurred when the surface was modified to eliminate this slight adverse velocity gradient (shown by a detailed investigation with surface pressure holes). The effect of surface waviness was next investigated, the surface rear of the slot being filled with paint until a considerable degree of smoothness was achieved. In spite of a reduction in waviness from ± 0·007 in. to ± 0·0015 in. on a 3-in. base curvature gauge (Fig. 13), no improvement in the extent of the laminar layer occurred. The Reynolds number of the tests was chosen to be below the critical value for an aerofoil of ± 0·007-in. waviness.

* A.R.C. Report No. 7464 (February, 1944).

The existence of spanwise fluctuations of the laminar layer forward of the slot (as shown by smoke filaments) suggested that some unsteadiness of the suction system might give rise to a fluctuating flow. Although the suction in the suction chamber was made extremely steady by the introduction of gauzes and by arranging the pump to work at its steadiest condition no extension of the laminar layer was observed. Furthermore, it was shown by optical means that the breakdown was not caused by any vibrations of the tail or the extremely thin forward slot lip. An examination of the flow in other parts of the wind stream by means of thin silk threads indicated fluctuations of the same nature as those which occurred in the boundary layer and it was concluded that this was the cause of the fluctuations of the boundary layer upstream of the slot. This conclusion was borne out by the fact that when the aerofoil was reversed later in the experiments, similar fluctuations occurred in the absence of boundary layer suction. The above experiments showed that the breakdown of laminar flow over the tail was not caused by any inadequacies in the wind-tunnel technique, except in so far as the unsteadiness of the wind stream might cause instability of the boundary layer.

The next possibility to be investigated was that as only $0 \cdot 4$ of the boundary layer air was being absorbed, boundary layer oscillations could be carried over from the laminar layer forward of the slot and so cause an early transition to the rear of the slot. This was investigated by observing whether any extension of the length of the laminar layer occurred when the whole boundary layer air was sucked away. The original slot width ($0 \cdot 03$ in.) was chosen as one quarter of the boundary layer thickness for $R = 4 \times 10^6$ and was much too small for lower Reynolds numbers ; consequently it was impossible to remove the whole layer with this slot width with the available suction. Fig. 14*a* gives the position of transition with the maximum amount of air removed that the available plant would allow, for this and other wider slots. For the lower Reynolds numbers this amounted to the whole boundary layer air, while no point is included for which less than $0 \cdot 75$ of the boundary layer air is removed. Fig. 14*b* shows the variation of transition with Reynolds number for the minimum amount of suction necessary to prevent separation of flow from the surface ; this amount was in all cases roughly equal to $0 \cdot 4$ of the amount of air in the boundary layer at the slot (*see* Part I).

It is clear from a comparison of Figs. 14*a* and 14*b* that increasing the proportion of air removed from the boundary layer does not in any way increase the stability of the laminar layer behind the slot.

Effect of Concavity.—The author's attention was drawn to the possibility that concavity might have a very noticeable effect, instability in this case being of a similar nature to that described in Ref. 7, page 86, for the flow in curved channels and of the type considered by G. I. Taylor, also in Ref. 7, page 196, for the case of the flow between two rotating cylinders.

Basing his stability criterion on theoretical work by Görtler, Liepmann has obtained a criterion of stability $R_\theta\sqrt{(\theta/\varrho)} < 7 \cdot 5$ for θ/ϱ above a certain value, where

$$\begin{aligned} R_\theta &= u\theta/\nu, \\ u &= \text{velocity at the point of transition,} \\ \theta &= \text{momentum thickness,} \\ \text{and } \varrho &= \text{radius of curvature.} \end{aligned}$$

While no direct agreement can be expected with Liepmann's experiments owing to the large variation of curvature and the favourable velocity gradient over the tail of the Griffith aerofoil, a comparison is extremely interesting. In Fig. 15 the variation of $R_\theta\sqrt{(\theta/\varrho)}$ obtained using the mean curve of Fig. 14*b* is drawn against Liepmann's criterion. These have the same form and indicate that the breakdown of laminar flow is due to the dynamic instability on the concave surface.

It is interesting to note that the turbulent velocity profile occurring at this concave surface closely resembles that obtained from the $\frac{1}{7}$th power law for a flat plate, the boundary layer being assumed to begin at the observed position of transition. Fig. 17 shows a comparison of the measured and theoretical velocity distribution at $0 \cdot 9$ chord ; it appears that concavity of the surface does not modify the turbulent boundary layer profile greatly from that of a flat surface.

In order to obtain a check of this instability criterion over a concave surface without the complication of any suction mechanism forward of the boundary layer under consideration, the aerofoil was reversed in direction and placed at an angle of -6 deg. incidence. At this incidence, it was estimated that the concave surface should be one of zero velocity gradient while the forward stagnation point was well on the side under observation. The experimental velocity distribution obtained at this incidence is shown in Fig. 16*a*. In this case the constant stability criterion shown in Fig. 16*b* was obtained. Agreement with Fig. 15 cannot be expected as the curved surface is now one of increasing curvature.

Effect of Velocity Gradient.—The present Griffith aerofoil has an unusually large stabilizing velocity gradient over the tail. Since it was feared that removal of this gradient might bring the observed criterion below that obtained by Liepmann an auxiliary aerofoil was introduced to modify the velocity distribution over the tail. With this modified to give the velocity distribution shown in Fig. 12, the mean value of which is zero, the experimental points shown in Fig. 15 were obtained. It is seen that the effect of the velocity gradient is to increase the stability of the layer by only a small amount. Perhaps this difference is shown better in Fig. 18, in which $R_\theta\sqrt{(\theta/\rho)}$ is plotted against the length of the laminar layer.

It thus appears that the experimental curve of Fig. 15 or Fig. 18 gives an experimental criterion for instability, which can be used in estimating whether other less concave aerofoils of the same family can be designed to give laminar flow to the trailing edge.

Before considering other such aerofoils, it is of interest to study the effect of Reynolds number on the instability of the boundary layer. Liepmann's work was carried out for the range one to three millions, which is equivalent to an aerofoil Reynolds number of three to ten millions in the present experiments. Since the form of the criterion was derived from Görtler's theoretical work, there is some justification for allowing extrapolation to other Reynolds numbers.

The momentum thickness θ may be estimated to sufficient accuracy from that of a flat plate. Thus we have

where $R_\theta\sqrt{(\theta/\rho)} = 1\cdot36\ (1+e)^{1/4}\ R^{1/4}\ (c/\rho)^{1/2}\ (x/c)^{3/4}$,

$1 + e =$ mean velocity rear of the slot,

$R =$ Reynolds number of the aerofoil

and $x/c =$ length of laminar boundary layer as fraction of chord c.

Thus the effect of concavity becomes increasingly severe as the Reynolds number is increased. A rough estimate suggests that movement of the slot back towards the trailing edge causes no improvement since the decrease in x/c is more than compensated by the decrease of c/ρ. On the other hand forward movement of the slot is impracticable from a structural point of view. The variation of $R_\theta\sqrt{(\theta/\rho)}$ with x/c is shown in Fig. 17 for a range of Reynolds numbers. Comparison with Liepmann's criterion and the experimental criterion obtained in the present tests indicates that laminar flow cannot be maintained to the trailing edge for R greater than about 2 millions. It should be noted that no difficulty occurred in maintaining laminar flow to the tail in the previous small-scale tests[1] for which R was about $0\cdot4\times10^6$. The stability curve would in this case come below Liepmann's stability criterion.

Reduction of Concavity.—Fig. 19 shows a comparison of the profiles of three members of the aerofoil family, the present Griffith aerofoil being denoted by A. Aerofoils B and C are designed to have less concavity than A. The corresponding first approximations to the velocity distributions at zero incidence are included in Fig. 19. It should be pointed out at once that the decrease in concavity is carried out at the expense of an increase in the velocity over the tail and an increase in form drag, and the allowable reduction of concavity is limited to that for which the drag reduction arising from the maintenance of the laminar layer to the tail is not outweighed by the increase in form drag.

Figs. 20*a* and 20*b* show the variation of $R_\theta\sqrt{(\theta/\rho)}$ with x/c for aerofoils B and C for different Reynolds numbers. Neither aerofoil is satisfactory at $R=20\times10^6$. The form drags have been estimated by the formula $C_D=\pi\times$ trailing edge radius of curvature, put forward by Dr. Goldstein for this family of aerofoils, and are included in Figs. 18 and 20. This formula was obtained assuming laminar flow over the tail and is pessimistic if turbulent flow occurs there. The form drag increase is seen to outweigh the reduction due to the laminar flow for both aerofoils B and C. It may be concluded, therefore, that it is impossible to design a practical Griffith aerofoil to give laminar flow to the tail at the Reynolds numbers of flight. It can easily be shown that the optimum aerofoil giving a reduced concavity should have zero velocity gradient over the front and rear segments. An investigation of this case shows that it is still impossible to obtain a satisfactory aerofoil.

Conclusions.—The breakdown of laminar flow over the tail of the Griffith aerofoil in the 13 ft.$\times$9 ft. wind-tunnel tests is due to dynamic instability arising from the concavity of the surface. No aerofoil of this family can be designed to give laminar flow over the whole chord at Reynolds numbers of 20 millions and over. Assuming a turbulent boundary layer to the rear of the slot, the aerofoil still gives a lower effective drag coefficient than that of a normal low-drag aerofoil at $R=25\times10^6$, particularly if the slot position is moved back along the chord.

PART III

The Effects of Wide Slots and of Premature Transition to Turbulence*

By

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Introduction.—Part I gives a description of the tunnel technique used in the experiments on a Griffith aerofoil and an interim note on the amount of boundary layer air that has to be absorbed to prevent separation of flow from the tail of the aerofoil. Two types of slot were tried, one facing backwards at a very acute angle to the surface, the other facing forward at 45 deg. to the surface. Owing to the relatively large boundary layer thickness occurring at the Reynolds numbers of these tests, slot widths up to a single boundary layer thickness only could be investigated for the backward-facing slot. This presented a serious limitation to the usefulness of the tests since, in flight, the thinnest feasible slot is still much wider than the thickness of a single laminar boundary layer. The present paper describes a similar investigation of a less severe backward-facing slot (60 deg. to the surface) for slot widths up to three times the boundary layer thickness. A thorough investigation of the effect of premature transition forward of the slot has been made with this slot direction for various slot widths and positions of transition; the excess suction needed to set up non-separated flow over that needed simply to maintain it has also been determined in a number of cases.

Effect of Slot Thickness.—Fig. 21 shows the widths of slot investigated for backward-facing slots which cut the forward drawn tangent at 60 deg. Fig. 22 shows the variation in m (the amount of air absorbed per second to maintain unseparated flow over the tail, measured as a fraction of the air in the laminar boundary layer at 0·7 chord) with w/δ, the ratio of the width (w) to the boundary layer thickness (δ) at 0·7 chord, each full-line curve being obtained by varying the wind speed. In every case the slot lips were kept unrounded, since otherwise the variation in m would be a function of these radii as well as slot width. A certain amount of rounding was, however, necessary for constructional reasons, and this possibly accounts for the scale effects observed in Fig. 22 for very thin slots. Apart from this variation, however, the quantity of air absorbed remains roughly constant up to $w/\delta = 1 \cdot 0$, after which it increases gradually with slot width at the same rate as for the forward-facing slot. Thus for large slot widths, the quantity to be removed with a backward-facing slot is slightly less than for a forward-facing slot. This does not necessarily mean that this system gives a lower "effective drag", since the power necessary to prevent separation is a function of the suction head as well as the quantity absorbed. Fig. 3 shows, for a definite Reynolds number, the variation of suction head in the suction box, for the three different slot directions. It must be pointed out that the length of the duct into the box and consequently the duct losses varied in each scheme, the slots having all been designed to have a 7 deg. expansion. It appears, however (Fig. 23), that while the suction heads are different for very thin slots, they converge to the same value for slot widths greater than a single boundary layer. Thus at the Reynolds number of the present tests, a slightly greater efficiency will be obtained if a backward-facing slot is used. This will also be true at much higher Reynolds numbers if the ducting losses are the same for all cases.

Extrapolation of the Suction Head to Higher Reynolds Numbers.—While the present arrangement of a suction slot, leading into a large chamber will not be kept in practice, a considerable part of the duct losses will occur near the slot entries where the velocities will be high, and the suction heads shown in Fig. 23 will be the minimum figures for the slot designs considered. Taking the figures as they stand, it is clear that a slot width of more than a single boundary layer thickness should be used. The nature of the curves will, however, vary with Reynolds number and a satisfactory basis for extrapolation to higher R is needed.

* A.R.C. Report No. 8054 (September, 1944).

The velocity pattern across the duct changes from that in the boundary layer to the parabolic type. It is therefore impossible to make an accurate estimate of the variation skin friction along the channel. If, however, the simplest assumption is made that at any point along the duct, the skin friction varies as the mean speed across the duct, it can easily be shown that for a given length of parallel duct, the pressure drop coefficient C_p along this length varies as

$$m \cdot \frac{\delta}{w} \cdot \frac{1}{w} \cdot \frac{1}{U_0} \cdot \propto \frac{m}{r^2} \cdot \frac{1}{R^{1/2}}\,, \text{ since } \delta \propto \frac{\text{chord}}{R^{1/2}}\,,$$

where U_0 is the free stream velocity and r = ratio of slot width (w) to boundary layer thickness (δ) at 0·7 chord. Thus for an arrangement similar to that used in the wind tunnel, it appears that the suction head for a given value of W/δ will decrease with Reynolds number (assuming the same length of duct). If the above assumption is valid the results of the tests will therefore give a conservative estimate of the minimum slot width to be desired to eliminate high frictional losses near the slot entry.

An attempt was made to analyse the pressures in the suction box on the above basis, but it was found that the variation with slot width of the mean pressure at the outside of the slot precluded a satisfactory analysis being made. If, however, for each slot width, a mean value of the outside pressure was guessed, the variation of pressure coefficient C_p did conform with the form given above for variation in W/δ, m and R.

Theoretical Estimate of m.—Sir Geoffrey Taylor has obtained very simply a criterion for the minimum amount of suction air which has to be removed on the assumption that the static pressure does not vary through the boundary layer along the normal to the surface. If (p_1, U_1) are the pressure and velocity outside the boundary layer just forward of the slot and (p_2, U_2) the corresponding values just behind the slot, Bernoulli's equation gives

$$p_1 - p_2 = -\tfrac{1}{2}\rho\,(U_1^2 - U_2^2)$$

and, since these pressures do not differ through the boundary layer,

$$p_1 - p_2 = -\tfrac{1}{2}\rho\,(u_1^2 - u_2^2) = -\tfrac{1}{2}\rho\,(U_1^2 - U_2^2),$$

where u_1, u_2 are the velocities forward and behind the slot along any stream line in the boundary layer.

Thus

$$u_1^2 - u_2^2 = U_1^2 - U_2^2,$$

so that

$$u_1^2\,\cancel{U_1^2} = (U_1^2 - U_2^2) + u_2^2$$
$$\geqslant (U_1^2 - U_2^2),$$

if u_2 is real (u) if the stream line continues past the slot.

Consequently, that part of the boundary layer must be removed for which

$$\left(\frac{u_1}{U_1}\right) < \sqrt{\left\{1 - \left(\frac{u_2}{U_1}\right)^2\right\}} \leqslant \sqrt{\left\{1 - \left(\frac{1+c}{1+b}\right)^2\right\}}$$

with the notation of Reference 1.

Following the method of Reference 7, page 156, the boundary layer profile at the point of maximum velocity may be given by

$$u/U_1 = 2\eta - 2\eta^3 + \eta^4,$$

where

$$\eta = y/\delta.$$

Using this relationship, Fig. 24 shows the variation of m with the velocity parameters b and c. For the present aerofoil the theoretical m is 0·30, which agrees reasonably well with the results obtained in the present experiments. It is seen that a greater proportion of the boundary layer is likely to need removal for high thickness-chord ratios.

Premature Transition to Turbulence Forward of the Slot.—If for some reason transition to turbulence occurs forward of the slot in spite of boundary layer suction, it is essential that the amount of boundary layer air removed to prevent separation should not be prohibitively large. An investigation has been made of the amount of air to be removed for various slot widths and for a range of positions of transition. Fig. 25 shows the variation in m with position of transition (where m is the amount of air absorbed, given as a fraction of the air in the laminar boundary layer at $0 \cdot 7$ chord). For this Reynolds number and for the slot widths shown, the amount of air absorbed does not differ greatly with position of transition ; it decreases slightly as transition moves back to $0 \cdot 5$ chord but increases from there to $0 \cdot 7$ chord. In Part I, it was considered that a reduction in effective drag might be obtained by roughening the surface just forward of the slot. It is seen from Fig. 25, however, that to obtain the best reduction in m, roughening at $0 \cdot 5$ chord would be necessary and this would entail an increase in pitot traverse drag at the tail, since now a much greater proportion of the boundary layer will pass over the slot without being absorbed. The introduction of turbulence has its main effect probably in producing turbulent rather than laminar separation from the surface so that any roughness rear of the point of laminar separation cannot have much effect on the minimum mass flow of air removed from the boundary layer to prevent separation. Fig. 26 shows the fraction of the actual turbulent boundary layer at $0 \cdot 7$ chord (calculated) which is absorbed for various positions of transition. It will be seen that this fraction n remains roughly constant until $0 \cdot 5$ chord after which it increases rapidly to its laminar flow value. The boundary layer and momentum thicknesses were calculated by Squire and Young's method[8] with $H = 1 \cdot 4$, the laminar region being calculated by the simplified method of Reference 9. Curves of θ/c at $0 \cdot 7$ chord against wind-tunnel speed have been calculated for a number of positions of transition and are given in Fig. 27.

Figs. 28, 29 and 30 show the variation of n with w/δ, where n is the fraction of air absorbed from the turbulent boundary layer, and, where w = slot width and δ' the turbulent boundary layer thickness for transition at $0 \cdot 1$, $0 \cdot 3$ and $0 \cdot 5$ chord respectively. Fig. 31 gives a comparison for different positions of transition at one Reynolds number. The points were obtained for four or five slot widths, at each of which a range of wind-tunnel speeds was investigated. Thus each curve refers to a single slot width, the variation in w/δ' arising from the change in tunnel wind speed. For the laminar case (*see* Fig. 22) ; there appeared to be little scale effect ; apart from certain variations which could be put down to inaccuracies in technique, the curves all gave a single variation of m against w/δ which was independent of wind speed. That this is not the case with a turbulent boundary layer is seen in Figs. 28, 29 and 30, where each curve of variation with wind speed is much greater than for the laminar case. This effect has not yet been explained but may be due to a greater growth of turbulent boundary layer as the wind-tunnel turbulence increases with speed.

Since in the laminar case, there appeared to be little scale effect, it was thought that the variation with speed in the tunnel might be eliminated if the quantity absorbed was expressed as a fraction of the air in the viscous layer (that part of the boundary layer for which the viscous forces predominate). Defining the thickness of the viscous layer by the relation

$$y_{\text{visc.}} = 30\, \nu \sqrt{(\varrho/\tau_0)} \quad (\textit{see}\ \text{Reference 7, page 336})$$

and τ_0 as the intensity of the wall friction, and assuming the same relationship to hold between τ_0 and θ (the momentum thickness) as does for a flat plate[8]

$$y_{\text{visc.}} = 30\, \nu\, (\zeta/U_1), \text{ where } \zeta/U_1 = \sqrt{(\varrho/\tau_0)} \text{ and } U_1\theta/\nu = 0 \cdot 2454\, e^{0 \cdot 3914\zeta}$$

Assuming the velocity profile to be given satisfactorily by the $\frac{1}{7}$th power law, the proportion $n_{\text{visc.}}$ of boundary layer air included in the viscous layer is given by

$$n_{\text{visc.}} = \left(\frac{y}{\delta}\right)^{8/7}_{\text{visc.}} \text{ and } \left(\frac{y}{\delta}\right)_{\text{visc.}} = \frac{2 \cdot 26}{R\theta/c} \cdot \zeta \, .$$

Fig. 32 shows the variation of $n_{\text{visc.}}$ with Reynolds number for different positions of transition. The variation with R, seen in Figs. 28, 29 and 30 cannot be accounted for by the variation in $n_{\text{visc.}}$, since the latter decreases with Reynolds number. At $R = 3 \cdot 84 \times 10^6$, except for thin slots (Fig. 31) between 5 and 10 times the quantity of air in the viscous layer must be absorbed to prevent separation of flow over the rear of the aerofoil.

If the $\frac{1}{7}$th power law is assumed to hold for the boundary layer profile, a figure of $0 \cdot 148$ for n is obtained as the theoretical minimum if it is assumed that no pressure gradient can occur normal to the surface through the boundary layer. This figure is greater than those obtained in the present experiments (Figs. 28, 29 and 30). No investigation of the boundary layer profile near the slot has been made, nor has it been established whether or not a gradient does occur across the boundary layer near a place where boundary layer suction is taking place. This apparent discrepancy can, however, be accounted for in another way. It is shown in Part IV that, with a turbulent boundary layer forward of the slot, separation may be prevented (observed visually with silk threads) without the theoretical velocity distribution being attained near the slot. It is likely therefore that a slight separation of flow still occurs (not shown by the silk threads) which alters the velocity pattern near the slot and gives a smaller velocity discontinuity than expected theoretically. Fig. 39 shows the effect of early transition on the velocity distribution with minimum suction for non-separated flow. If the discontinuity over the slot is assumed to cover from $1 \cdot 25$ to $0 \cdot 9$ times the free stream velocity, a theoretical value of $m = 0 \cdot 062$ is obtained as the minimum. This is in keeping with the observed results of Figs. 28, 29 and 30.

Suction Head in Suction Chamber with Turbulent Flow.—Since the energy needed to absorb the boundary layer air is a function of the necessary suction head as well as the quantity, the variation of suction head in the suction chamber with position of transition is of interest. In Fig. 33, this variation is shown for a number of slot widths. Except for very thin slots of less than half the laminar boundary thickness at $0 \cdot 7$ chord, this suction is a minimum when transition is at $0 \cdot 5$ chord. This corresponds (*see* Fig. 25) with a minimum in the quantity absorbed to maintain non-separated flow. It thus appears that quite a considerable reduction in the "suction drag" (given by $2\,C_q\,(1 + C_p)$) can be obtained by inducing transition at $0 \cdot 5$ chord. A rough estimate would indicate this to be about $0 \cdot 0007$. For a normal low-drag wing of the same thickness-chord ratio, and at the same Reynolds number, movement of transition forward by $0 \cdot 2$ chord from the position of maximum velocity increases the drag coefficient by $0 \cdot 0016$[10]. Consequently, since all the extra boundary layer air caused by moving transition from $0 \cdot 7$ to $0 \cdot 5$ chord passes the slot and becomes part of the boundary layer of the tail, the gain obtained in " suction drag " is well outweighed by the increase elsewhere. This is also true for any intermediate position of transition. Thus nothing is to be gained by producing transition slightly forward of the slot. On the other hand, if, due to poor surface finish near the slot, transition occurs slightly forward of the slot, no great losses need be anticipated. Of course, this is not necessarily so if the surface shape (and consequently the pressure distribution) is poor near the slot ; in this case, sufficient suction must be applied to modify the pressure distribution as given by potential flow theory, and this is normally of a much greater order than that necessary simply to remove the boundary layer.

Fig. 34 shows the variation of suction head with slot width (w) as a fraction of the laminar layer thickness (δ) for various positions of transition. For wide slots, the pressure head is less than that at the forward lip of the slot ($-0 \cdot 69$) and differs with position of transition. As explained before, the reduced suction arises from the fact that the slot is working almost entirely in a pressure region when the non-separated regime has been established. This will not be so marked at higher Reynolds number owing to the much smaller slot widths, and it is well to design for a suction head at the slot entry equal to the suction head or the front lip of the slot, as calculated by potential flow theory.

Hysteresis with Turbulent Flow.—It was shown in Part I that with laminar flow up to the slot, an extra quantity of boundary layer air above that needed to maintain the non-separated region, was necessary to establish this regime. Fig. 35a and 35b shows the additional amounts necessary for various positions of transition and for two slot widths. As in the previous case, at the highest Reynolds number of the tests, an additional $0 \cdot 07$ of the quantity of air in the calculated laminar layer at the slot had to be absorbed to establish non-separated flow ; this figure does not vary with position of transition.

Summary of Conclusions.—(1) Backward-facing slots appear to be slightly more efficient than forward-facing slots.

(2) Slot widths up to three boundary layer thicknesses may safely be used, but the proportion of the boundary layer absorbed increases with increase of slot width.

(3) A slot width at least equal to the laminar boundary layer thickness at the slot should be used to prevent high frictional losses at the duct entry.

(4) With laminar flow to the slot the most favourable experiment carried out give values of m in agreement with the theoretical minimum put forward by Sir Geoffrey Taylor.

(5) With transition at any point forward of the slot, between $0 \cdot 05$ and $0 \cdot 10$ of the turbulent boundary layer air at the slot must be absorbed to prevent separation (as indicated by silk threads).

(6) For positions of transition to the rear of $0 \cdot 1$ chord this amount is little if any greater than that necessary with the flow laminar to the slot.

(7) The fraction of air removed in the turbulent case is in agreement with that given theoretically assuming the experimental velocity distributions and is considerably greater than that contained in the " viscous layer " region of the boundary layer.

(8) For slot widths greater than that of a single laminar boundary layer thickness, the suction head with minimum suction is less for forward transition than with laminar flow to the slot.

(9) No improvement in effective drag coefficient can be obtained by causing transition forward of the slot. On the other hand, the effect of forward movements of transition will be no greater than for a normal low-drag wing.

(10) With forward transition, the extra suction needed to establish the non-separated flow régime over that needed simply to maintain it, is no greater than with laminar flow to the slot.

PART IV

Lift, Drag, Pitching Moments and Velocity Distributions*

By

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Introduction.—The variation with incidence of lift, pitching moment and hinge moment about a 30 per cent. flap have been calculated from the measured velocity distributions and the effective drag coefficients calculated from the observed amount of air removed, suction head needed and from comb measurements at the tail. It is shown that while a low effective drag is not possible at $R = 4$ millions, a value equal to about half that of a normal low-drag wing of the same thickness-chord ratio should be obtained at $R = 25$ millions. In view of the likelihood that this type of wing will have its greatest application as a very thick wing (of 30 to 40 per cent. thickness-chord ratio), theoretical curves have been derived for the effective drag coefficients of such sections.

The Griffith aerofoil under test is fitted with pressure holes on both surfaces in order to obtain the velocity distributions at incidences; from these the lift, pitching moment and hinge moment variations with incidence have been obtained. The pitot traverse drag was obtained from measurements on a comb of total head and static tubes placed $0 \cdot 1$ chord behind the trailing edge.

Velocity Distribution With and Without Suction.—The experimental velocity distribution over the aerofoil without suction for a range of wind incidences is given in Figs. 36a and 36b. Some scatter of the experimental points occurs near the slot owing to the necessity for shutting down the wind tunnel after each reading in order to open up a new hole in the surface tubing; some difficulty occurred in repeating exactly the same conditions because of the unsteadiness of the flow in this separated region. The chief point to notice in the velocity distributions without suction is the change in the shape of the velocity curve to the rear of $0 \cdot 6$ chord on the upper surface as the upper extremity of the favourable C_L range is passed. As no such change occurs on the lower surface, it is to be expected that a change in hinge moment will occur at about this incidence; this will be discussed later.

It is stated in Part I that at 0 deg., the unexpectedly high effectiveness of control without suction, arises from the rapidity with which the separated flow readheres to the surface. It now appears from the curves that this is not so on the upper surface for high incidences; poor effectiveness may therefore be obtained for incidences of over 4 deg. and for negative aileron settings (aileron up). Unfortunately negative flap settings were not considered in the balance measurements of Ref. 2 so that no verification of this conclusion is available.

Fig. 37a and Fig. 37b show the velocity distributions over the aerofoil with just sufficient suction on each surface to prevent separation of flow from that surface. The velocity distributions, which are all given for a Reynolds number of $2 \cdot 31 \times 10^6$ do not alter appreciably in the Reynolds number range obtained in the 13-ft. $\times$ 9-ft. wind tunnel.

The quantity of air absorbed to maintain unseparated flow is plotted in Fig. 38 against incidence for three Reynolds numbers. In order to facilitate estimates of amount at other Reynolds numbers, the quantity is given in all cases as a fraction (m) of that in the laminar boundary layer just forward of the slot at zero incidence. This quantity remains practically constant on the lower surface for all the incidences investigated, but a sharp rise is noted on the upper surface as the favourable C_L range is exceeded. This range varies with Reynolds number and accounts for the divergence of the curves above 3 deg. observed in Fig. 38a.

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It will be seen in Fig. 37a that at incidences above the upper extremity of the favourable C_L range (where a peak velocity near the nose brings transition forward), separation is prevented without the velocity distribution over the upper surface approximating to the theoretical figures given by potential flow theory. The dependence of this on the position of transition only and not on incidence is indicated in Fig. 39 which shows that if transition is moved artificially forward to $0 \cdot 1$ chord by means of a surface wire, separation is prevented without the flow becoming sharply discontinuous at the slot, a condition which must be satisfied if the flow is laminar to the slot. Fig 40 also bears this out; an increase in the suction at 6 deg. incidence above the minimum necessary to maintain unseparated flow causes the flow to become more nearly that given by potential flow theory. There was insufficient suction available to cause the velocity distribution to approximate closely to the theoretical.

It should be made clear that in all these experiments, separation was indicated by very fine silk threads and the possibility of the existence of a small region of separated flow near the slot cannot be ruled out.

Comparison of Experimental and Theoretical Velocities.—A comparison of the experimental and theoretical velocity distributions is not of great value since, in the event of any serious discrepancies, it is difficult, without a large amount of computation, to determine whether it arises from the considerable errors in the shape of the model or whether it is a real effect arising, for instance, from the boundary layer or from the sink effect of the suction. The theoretical velocity distribution, calculated by approximation III of Ref. 11, and corrected to wind-tunnel conditions by the method of Ref. 12, gives poor agreement when based on the geometric incidence and the experimental circulation (*i.e.*, if the experimental lift and lift slope are used (Figs. 37a and 37b)). If, however, the experimental lift coefficients are taken and a lift slope of 2π per radian assumed, fair agreement is reached over the front of the aerofoil for the whole incidence range. The plain dotted curve of Figs. 37a and 37b shows the theoretical velocity distribution for $a_0 = 2\pi$.

The lift incidence curve has been obtained by integration of the pressures around the aerofoil and is shown in Fig. 41 both for the separated, and non-separated regime, corrections being applied to give free air conditions. It is seen that the lift slope A_0 is considerably smaller than the value 2π necessary to give agreement between experiment and theory. The simplest explanation of this discrepancy is that the wind incidence has been measured wrongly and it is proposed to check this point before going into the matter further.

With the minimum amount of suction needed to prevent separation of flow, the lift curve does not alter appreciably from that without suction; this will not necessarily be so if suction fails on one surface only. In fact it is possible that a certain amount of aileron control may be obtained by cutting out the suction from one surface only on either wing.

Pitching Moment and Hinge Moment.—The pitching moment coefficients about quarter-chord were obtained by integration of the components of the pressures at right angles to the chord. The error in C_m incurred by neglecting the chordwise components of the pressures is about $0 \cdot 005$ at 6 deg. incidence and has been neglected. Fig. 42 shows the variation with incidence for the separated and unseparated flow condition (suction on), the suction used being the minimum to maintain unseparated flow. In both cases there appears to be a change in slope at the extremity of the low-drag range due to the forward movement of transition. This kink accompanies the change in the characteristics of the velocity curves to the rear of the slot. With suction, the velocity distribution to the rear of the slot at the higher incidences depends considerably on the proportion of boundary layer absorbed and therefore the "suction on" curve of Fig. 42 must not be considered as a unique curve for this aerofoil. The kink will probably vanish if sufficient suction is applied.

The dotted curve shows the results of the N.P.L. 4-ft. wind-tunnel tests. Agreement is not good and there is no evidence in the present tests of the flattening out at 5 deg. which occurs in these earlier balance tests. The kink in the curve is naturally to be expected at a slightly higher incidence in these earlier tests owing to the change with Reynolds number of the incidence at which transition moves forward.

The hinge moment about 0·7 chord of a flap consisting of the whole surface to the rear of the slots is shown in Fig. 43. Here again the change in slope at the low-drag extremity is apparent and a rapid change in b_1 occurs at this incidence both with and without suction. This change in b_1 is large, especially without suction. The " suction on " curve is not unique and the discontinuity in b_1 can probably be eliminated by increasing the suction. The " suction off " discontinuity arises from a change from laminar separation to turbulent separation with a well-developed boundary layer; this will be smaller at high Reynolds numbers where, without suction, transition will occur just before separation and the subsequent turbulent separation will not be modified greatly by transition movement.

The change in pitching moment and hinge moment due to failure of the suction is of considerable importance in flight. It will be seen that for small incidences (up to 3 or 4 degrees) this change is small and will not give rise to large changes of trim and stick force. At higher incidences this is not the case but what will occur at high Reynolds number cannot be foretold. While the change is small at small incidences, failure of the suction on one surface only may give rise to large changes of C_m and C_h. This condition has not been investigated in the present tests but some idea of the changes likely to occur may be obtained if necessary by examining the change in velocity distribution on one surface only, the other being assumed to remain the same. While it is clear that such an investigation is not strictly fair, experience in the present tests has shown that failure of suction on one surface does not alter appreciably the velocity distribution on the other surface.

Dr. Goldstein[13] has derived two theoretical expressions for the hinge moment on an aerofoil flap, the first being based on approximation I of Ref. 11, the second on approximation III (and therefore more accurate). The first of these gives $b_1 = -0 \cdot 57$ for this aerofoil; while the actual calculation for the more accurate approximation has not been made on this aerofoil, comparison with a somewhat similar aerofoil suggests that $b_1 = -0 \cdot 38$ is a better theoretical figure for the aerofoil under test. This is in rough agreement with the experimental value at 0 deg. incidence.

Drag.—In these experiments the properties of the aerofoil have hitherto been assessed by investigations of the nature of the boundary layer both forward and to the rear of the slot, the drag being estimated theoretically with the observed types of boundary layer. The reason for this was that the trailing edge of the model was ¼-in. thick and consequently the form drag arising from this tail would be of the same order as the laminar skin friction drag of the tail itself (to the rear of the slot). Part II shows, however, that it is impossible to maintain laminar flow over the tail of a Griffith aerofoil at high Reynolds numbers owing to the instability caused by the concavity of the surface; the form drag thus becomes a smaller proportion of the drag of the tail and pitot traverse measurements have now been made. Fig. 45 shows the variation with Reynolds number of drag coefficient measured by pitot traverse behind the tail both without suction and with sufficient suction to maintain unseparated flow over the tail.

Without suction the flow breaks down with laminar separation from the surface up to $R = 4 \times 10^6$, transition moving forward at this stage owing to the excessive waviness of the model and turbulence of the wind stream. It is not expected that the flow will break away by laminar separation at high Reynolds numbers, and transition to turbulence just forward of the separation point will decrease the drag coefficient (*see* Fig. 48); thus at high Reynolds numbers and at 0 deg. incidence drag coefficients of less than 0·014 should be recorded without suction if the wing smoothness is sufficient to allow extensive laminar flow at this Reynolds number.

The observed drag coefficients in the unseparated flow case (suction on) are shown in Fig. 45, and are compared with those of a flat plate of the same chord as the tail of the aerofoil with transition at its leading edge. The experimental figures have not been corrected for the form drag of the tail and the discrepancy between experiment and that of the flat plate is shown later to be roughly the same as that of the form drag due to the thick tail. The gradual rise in the drag coefficient is due to the forward movement of transition and the greater proportion of the boundary layer forward of the slot which is carried over and included in the pitot traverse drag.

Fig. 46 shows the variation of pitot traverse drag coefficient at a Reynolds number of $2 \cdot 31 \times 10^6$ for a range of incidences. With suction, the drag coefficient remains practically constant except at the extreme incidence tested. Without suction, however, the drag variation is unusual and needs a more detailed investigation. Fig. 47 gives the wake profile from which these figures were calculated. Whereas at 2 deg. a large separation occurs on the upper surface, this becomes less severe at 4 deg. and appears to be very small at 6 deg. incidence. An investigation of the boundary layer profile at the trailing edge of the upper surface was made at 2 deg. incidence, the position of transition being fixed by means of wires. It is seen (Fig. 48) that transition to turbulence about $0 \cdot 1$ chord forward of the laminar separation point, decreases the drag considerably and alters the profile in the manner occurring in Fig. 47. Further forward movement of transition increases the drag. Thus the decrease in drag arises from a change from laminar to turbulent separation at the tail at the extremity of the favourable C_L range. These observations and those of the " suction on " curve indicate that transition has just begun to move forward at 6 deg. incidence. This is difficult to understand, as there are indications in the velocity curves that forward movement of transition has commenced at 4 deg. incidence. It is clear, however, that at large Reynolds numbers where the flow breaks down by transition followed closely by turbulent separation this unusual peak in the (C_D, α) curve will not appear and that no very rapid increase in drag with incidence is likely to occur.

Effective Drag Coefficient.—In considering the drag coefficient of this type of aerofoil, account must be taken of the power necessary to absorb the requisite amount of air and overcome the duct friction. It was concluded in Ref. 1 that a suitable measure of the effective drag coefficient C_D' (which included these losses) was given by

$$C_D' = C_D + [C_Q (1 + C_p)]_{\text{upper}} + [C_Q (1 + C_p)]_{\text{lower}},$$

where C_D = drag coefficient measured by pitot traverse at the tail,

$C_Q = Q/cU_0$, where Q = quantity of air absorbed from each surface (unit span) per second and c = chord, U_0 = free stream velocity

and $C_p = (p_0 - p_s)/\frac{1}{2}\varrho U_0^2$, where p_0 = free stream pressure and p_s = pressure inside suction chamber.

For this aerofoil $C_Q = 3 \cdot 85 m/R^{1/2}$ for each surface,

where R = Reynolds number of the aerofoil and m = fraction of laminar boundary layer at $0 \cdot 7$ chord at 0 deg. incidence absorbed per unit span.

As stated previously, the test model was constructed with a thick trailing edge (0·25-in.) and the form drag arising from this tail was appreciable. A conservative estimate of this drag may be obtained by assuming that no mixing has occurred in the distance between the trailing edge and the pitot traverse comb and that the centre 0·25-in. of the wake arises from the thick tail. At 0 deg. incidence, this correction on C_D amounts to about $0 \cdot 0012$.

Fig. 49 shows the variation of effective drag coefficient and pitot drag coefficient with incidence after the above correction has been applied. A few check points, made at a higher Reynolds number are included in the figure. The values of C_p used are shown in Fig. 50 ; m is given in Fig. 38.

It is clear that no reduction in drag coefficient below that of a normal low-drag wing is possible at the Reynolds numbers of the present tests, and in order to anticipate the drag coefficients likely to occur at very high Reynolds numbers, a comparison must be made with theory. Apart from that part of the laminar boundary layer carried over the slot (in which the air will be only very slightly retarded), the drag measured by pitot traverse consists entirely of the drag arising from the aerofoil to the rear of the tail. It was shown in Part II that the boundary layer here was laminar for a short distance, transition to turbulence occurring as a result of instability caused by the concavity of the surface ; at high Reynolds numbers this laminar region is likely to be negligible, and a good estimate of the pitot traverse drag can be obtained from that of a flat plate with transition at the leading edge. Neglecting that part of the laminar boundary layer not absorbed at the slot this portion of the drag is given by

$$C_D = 0\cdot91\left(\frac{U_1}{U_0}\right)^2 [1 - X_1]\left[\log_{10}(1 - X_1)\, R\frac{U_1}{U_0}\right]^{-2\cdot58},$$

where X_1 = chordwise position of suction slot and U_1/U_0 is the mean velocity over the tail as a fraction of the free stream value. Thus

$$C_D = 0\cdot91\left(\frac{U_1}{U_0}\right)^2 [1 - X_1]\left[\log_{10}\frac{U_1}{U_0}(1 - X_1)\, R\right]^{-2\cdot58} + \sum C_Q(1 + C_p)\,.$$

At $R = 2\cdot3 \times 10^6$, $C_D = 0\cdot0027$, which, is in agreement with that measured after it has been corrected for tail thickness ($0\cdot0028$). This agreement and the fact that boundary layer measurements at the tail (*see* Part I) agree with theory indicate that pitot traverse drag can be estimated satisfactorily at higher Reynolds numbers from that of a flat plate.

The above formula gives us a satisfactory basis for extrapolating the results of the present tests to much higher R. The proportion m of the boundary layer which must be absorbed, should not alter with R and it has been shown in Part III, that, for a given ratio of slot width to boundary layer thickness, C_p should tend to decrease with R. Hence Fig. 51, which has been derived with constant m and C_p (the values obtained in the tests) shows the expected variation of C_D' with Reynolds number at 0 deg. incidence. The following table gives the variation of C_D' and C_D with R.

$R \times 10^6$	C_D	$\Sigma C_Q(1 + C_p)$	C_D'
1	$0\cdot0026_5$	$0\cdot0053$	$0\cdot0079_5$
5	$0\cdot0019_5$	$0\cdot0024$	$0\cdot0043$
10	$0\cdot0017$	$0\cdot0017$	$0\cdot0034$
50	$0\cdot0013$	$0\cdot0007_5$	$0\cdot0020_5$
100	$0\cdot0012$	$0\cdot0005_5$	$0\cdot0017$

Reproduced in Fig. 51 is the curve obtained by extrapolating the results of the 4-ft. wind-tunnel tests[1]. In this case it was assumed that laminar flow occurred over the whole chord. The increase in drag arising from the turbulent flow at the tail is about $0\cdot0011$ at $R = 10^8$ for this position of slot. It will be seen that at R = 25 millions, a drag coefficient of $0\cdot0025$ is recorded whereas the estimated drag coefficient of a normal low-drag wing is about $0\cdot0037$. Thus at the Reynolds numbers of high-speed flight, even with a turbulent boundary layer to the rear of the slot at $0\cdot7$ chord, a reduction over that of a low-drag wing is to be expected. If the slot is moved to $0\cdot85$ chord, the drag coefficient at $R = 25 \times 10^6$ should be about $0\cdot0018$, which is half that of a normal low-drag wing.

Since approximately the same quantity of air must be absorbed when forward transition occurs, some idea of the increase in drag resulting from early transition can be obtained by adding to these values the extra drag forward of the slot, arising from the turbulent flow there.

Effective Drag Coefficients for High Thickness-Chord Ratios.—It can be argued from the above estimations of the optimum drag coefficient likely to be attained in flight, that the drag reduction obtainable for normal thickness-chord ratios below that of an equally well finished normal low-drag wing, while being appreciable (a reduction of wing drag to half that of a normal low-drag wing is possible), is not very large in view of the extra complication arising from the installation and may not justify the extra cost and labour. It should be pointed out, however, that the advantages of the scheme should be considered, in conjunction with other gains arising from changes in aircraft design and weight. Chief of these is that, as far as can be anticipated, there is no limitation on the allowable thickness-chord ratio of those wings except in so far as shock waves may have to be prevented. Thus, if the slot is designed to operate further back than at 0·7 chord, a thickness-chord ratio may be chosen such as to allow a much more efficient structure with high aspect ratio, and possibly completely buried engine installations. An all-wing machine would therefore gain in every way; first the wing drag would be halved, and improved structure could be used and a much smaller machine could be designed to give the requisite storage space and headroom. Even if laminar flow cannot be maintained to the slot, a normal drag coefficient would still be recorded.

In view of the likelihood of this Griffith principle being used in conjunction with very thick wings, theoretical curves have been produced (Figs. 52 and 53) showing the variation with Reynolds number of effective drag coefficients for different thickness-chord ratios and positions of slot. The proportion of boundary layer absorbed has been determined from Prof. G. I. Taylor's criterion (which agreed fairly well with the present tests where the flow was laminar up to the slot), C_p is taken as that at the forward end of the discontinuity in velocity, and all the wings have been designed to have cusped trailing edges, and the best possible C_L range to give far back transition. It should be made quite clear that these curves have not been derived from experiment and give the minimum effective drag to be expected. The dotted curves show the variations if the whole boundary layer air is absorbed. Tests on a 30 per cent. aerofoil with the suction slot at 0·8 chord are shortly to be carried out.

Wing-Nacelle Interference.—At the junction between a plane wall and a Griffith aerofoil there is some danger that the discontinuity in pressure, arising from the shape of the wing and the presence of boundary layer suction there, will extend some distance outwards along the plane wall and a breakaway of the boundary layer of the wall will take place. This condition has been investigated at the junction between the aerofoil and an engine nacelle similar to that to be fitted to a flight project incorporating this type of wing. Unfortunately this nacelle is known to be poor and an extended version has been proposed. Fig. 55 gives a diagram of the nacelle-wing junction. A total head traverse carried out at the trailing edge of the wing is shown in Fig. 56, the scale being ten times that of Fig. 55. While the interference is appreciable, it is difficult to determine how much of this arises from the poor flow over the nacelle itself. Streamers in the wing nacelle junction indicated a separated flow.

Methods of Determining Separation in Flight.—In the experiments here described, separation has been determined visually, either by observation of smoke filaments or of silk threads. In some flight experiments which are proposed, the test panels are outboard of the engine nacelles, and consequently visual methods are ruled out. Other methods of determining separation have therefore been investigated with a view to indicating separation from pressure measurements only.

The first of these and the most successful consisted of measuring the static pressure just behind the slot by means of a surface tube. If the correct position of hole is chosen, separation of flow from the surface is accompanied by a relatively large pressure difference. In all cases this change was found to occur when the visual method indicated separation. Fig. 57 shows the variation in static pressure with suction at various chordwise positions near the stagnation point at the rear lip of the slot. As the amount of air is increased the static pressure remains practically constant until the change in flow régime occurs, when a very sharp change occurs, the nature of this change depending on the position of the pressure hole. If the pressure hole is forward of the stagnation point, the change is not instantaneous (*see* hole No. 6 of Fig. 57) and as would be expected from a hole which is virtually in the duct, the suction increases indefinitely. If the hole is just to the rear of the stagnation point (*e.g.*, No. 7) the pressure remains constant after the discontinuity. The range investigated after the discontinuity was however not sufficiently large to indicate whether movement of the stagnation point with increasing suction is likely to cause alteration of pressure after the non-separated régime has been established. Further movement of the pressure holes away from the slot (*e.g.*, hole No. 8 and those given in Part I) causes the discontinuity to become less pronounced.

From the above investigation it is probable that two or three pressure holes placed near the estimated stagnation point with suction on, will be sufficient to indicate whether or not the non-separated régime has been established.

Two other methods were investigated, the first consisting of measuring the total head just to the rear of the slot at a distance from the surface equivalent to the thickness of the boundary layer in the non-separated régime. Thus if the flow has separated, a decreased total head should occur whereas the full total head should be obtained as soon as adherence of the flow takes place. Fig. 58 shows the variation of total head with suction for various positions of the total head tube, the range in suction being the same as that of Fig. 57. It is seen that the discontinuity is small in all cases and the method is not satisfactory.

The last method investigated consisted simply of plotting the static pressure in the suction chamber against the amount of suction ; here again the discontinuity is small and the method is unsatisfactory.

Hysteresis Effects at Incidences.—The additional amount of suction air over that required to maintain unseparated flow necessary to establish the unseparated régime for different incidences is plotted in Fig. 60. It will be seen that as incidence increases, the additional amount decreases both on the upper and on the lower surface.

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13	Goldstein, S.	Pressure Distribution over an Aerofoil with a Flap. (Unpublished.)

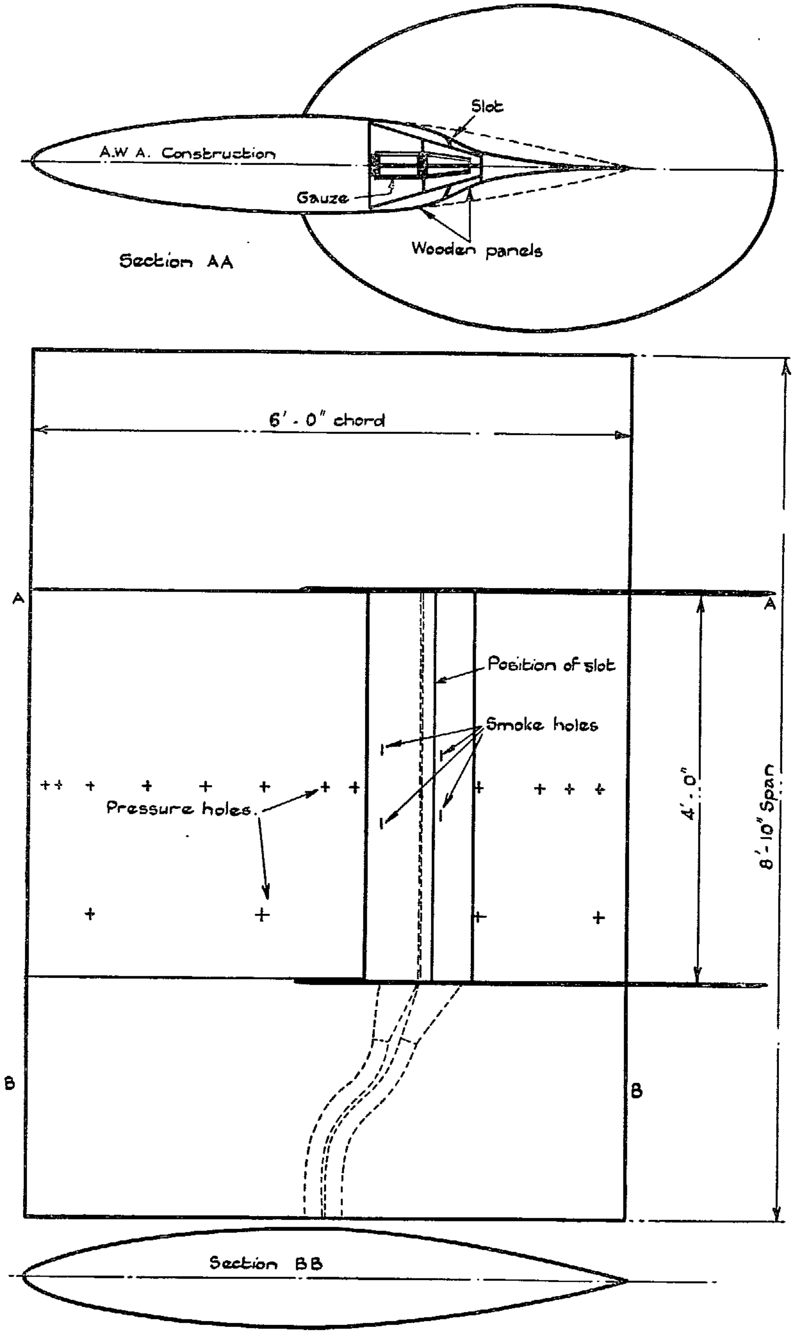


FIG. 1.

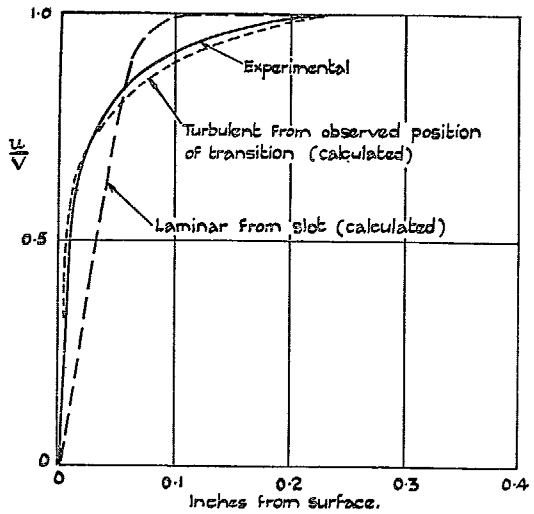


FIG. 3. Boundary Layer Profile at 0·9 chord.

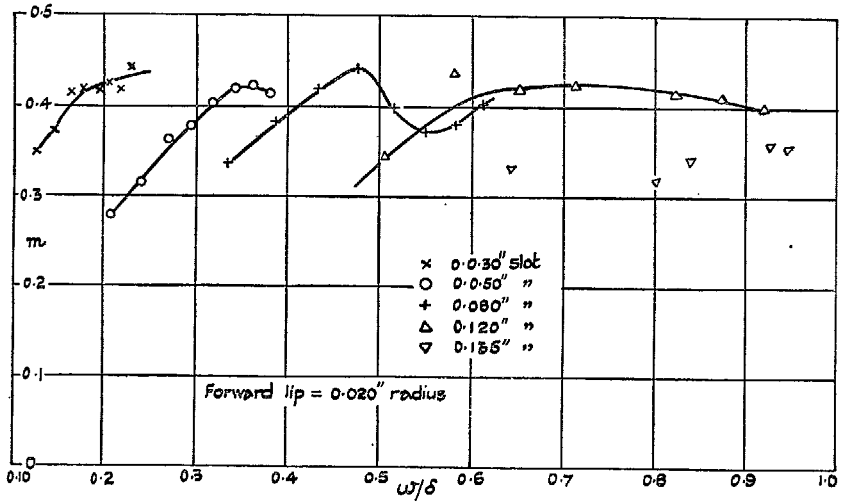


FIG. 5. Proportion (m) of Air in Boundary Layer Removed to Prevent Separation Backward-facing Slot, 15 deg. to Surface.

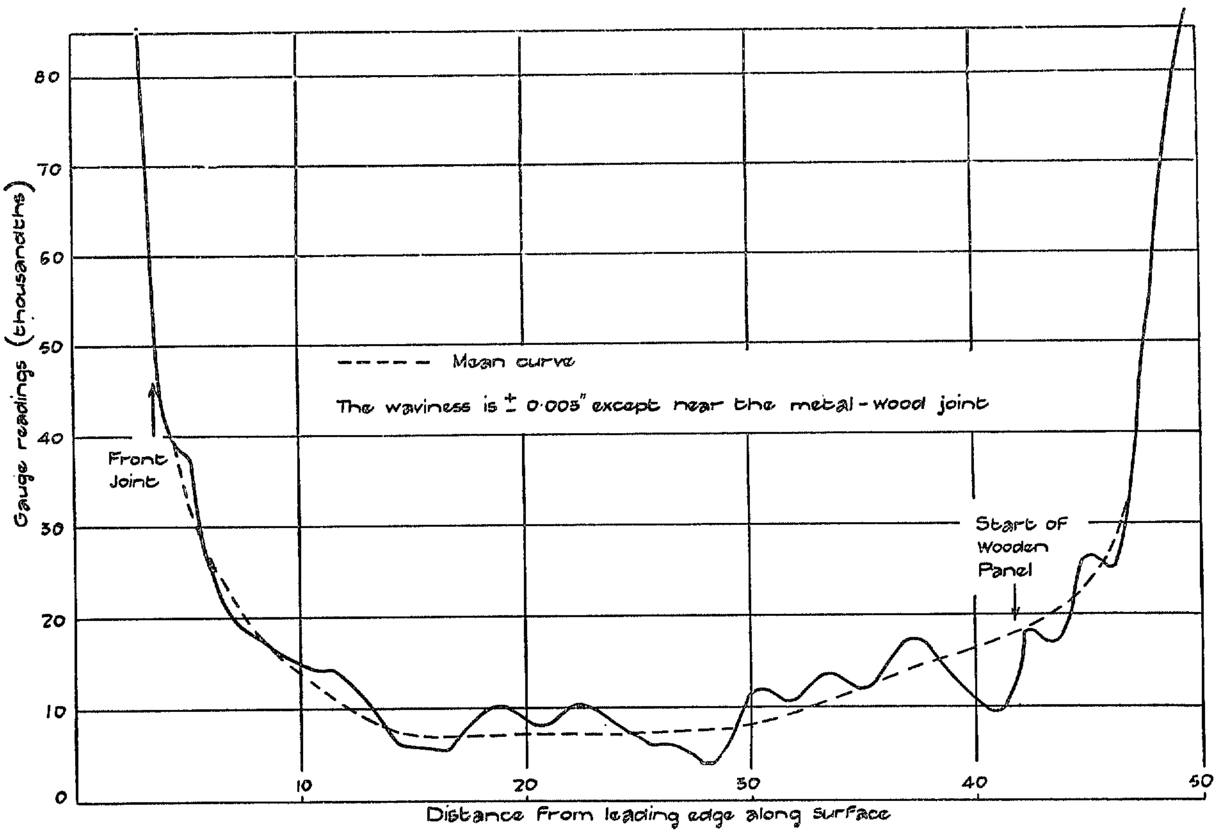


FIG. 2a. Waviness of Griffith Aerofoil (Front Metal Section) (Mid-span Position).

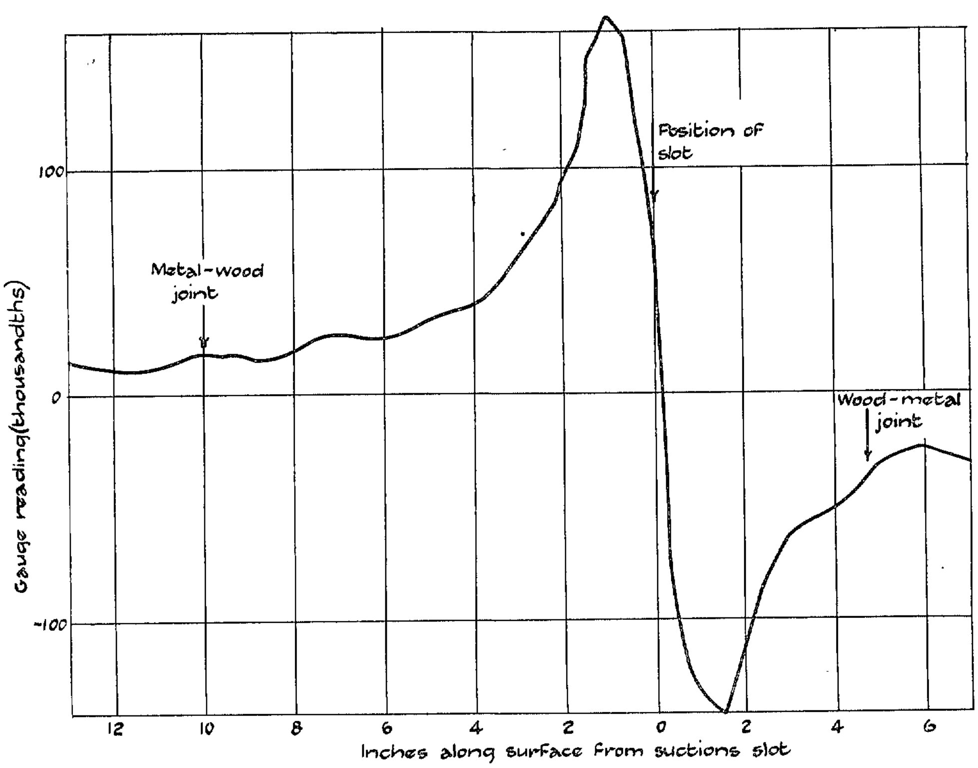


FIG. 2b. Waviness of Griffith Aerofoil (Centre Wooden Section) (Mid-span Position).

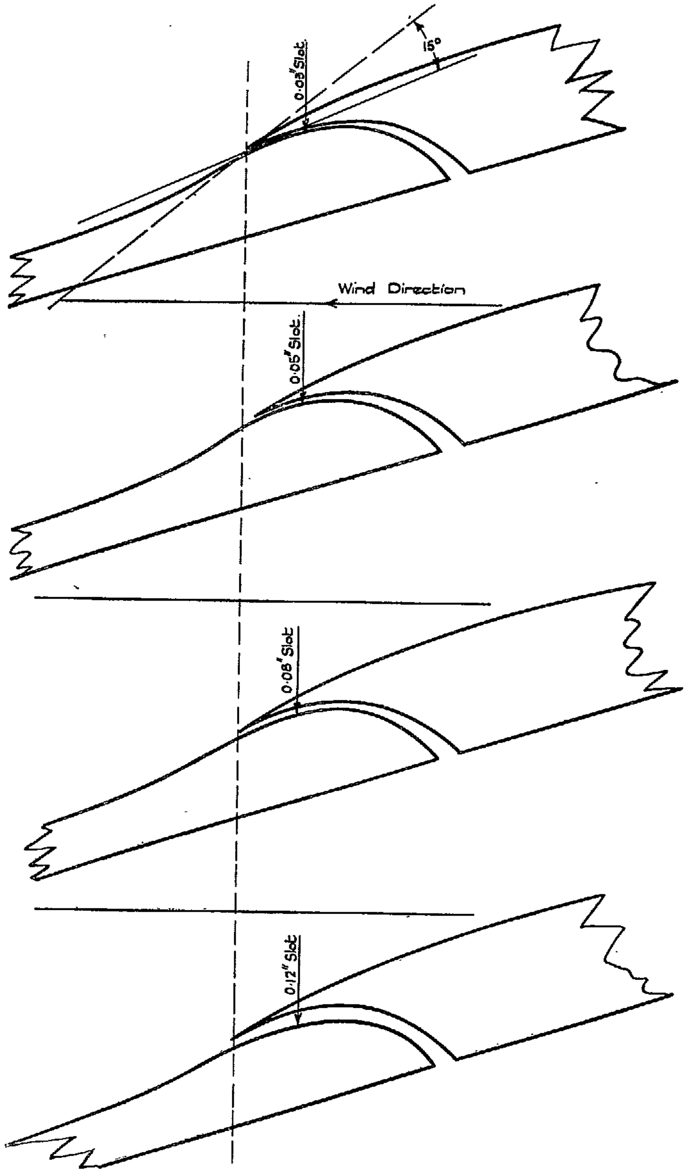


FIG. 4a. Diagram of Backward-facing Slots.

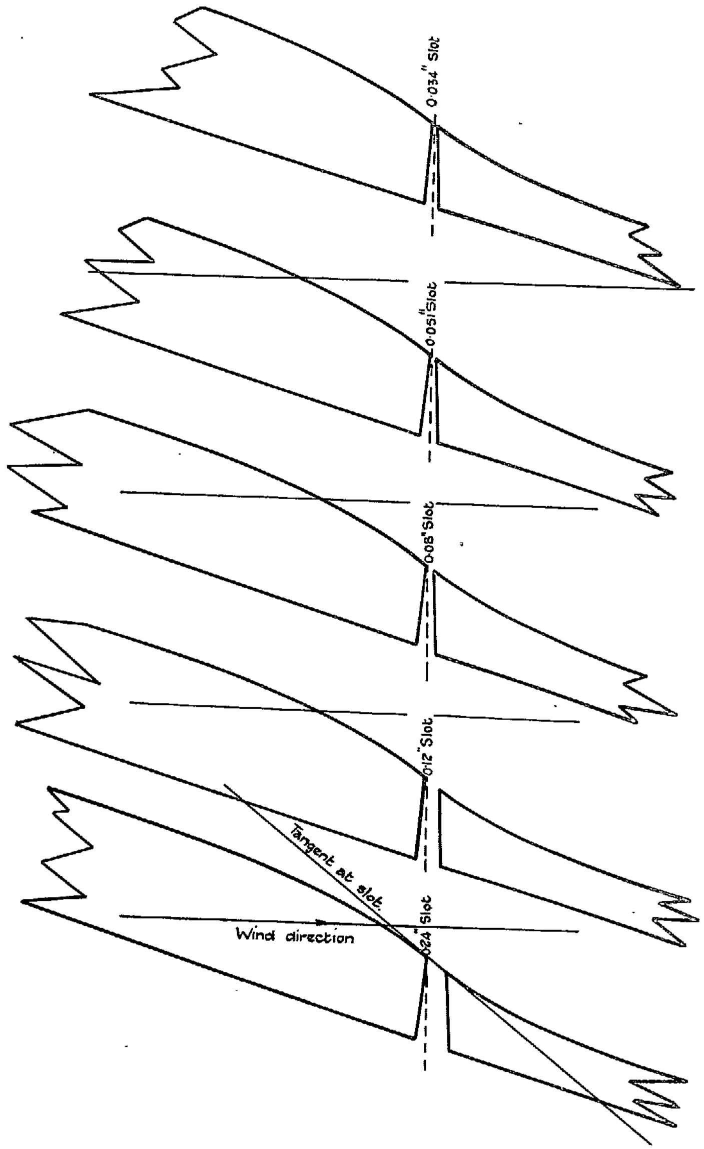


FIG. 4b. Forward-facing Slots.

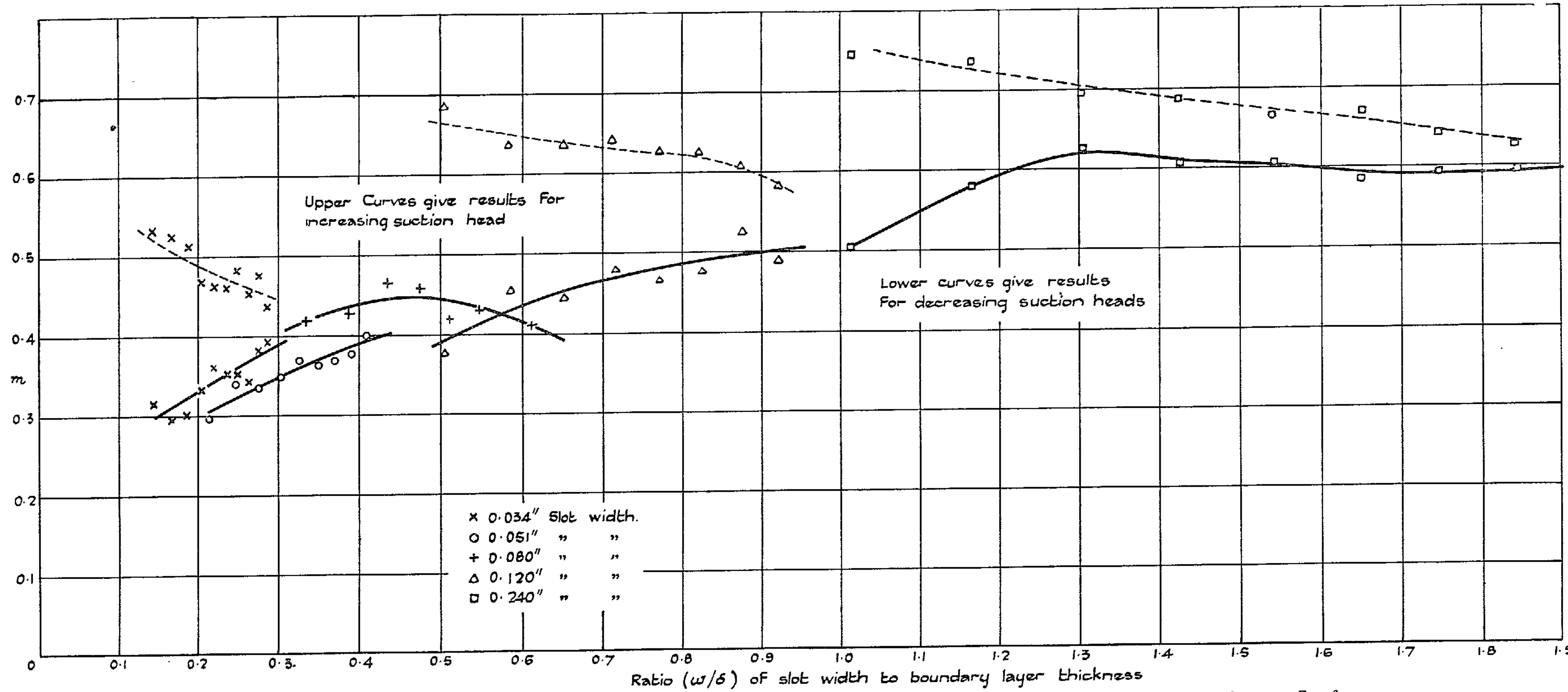


FIG. 6. Proportion (m) Air in Boundary Layer Removed to Prevent Separation Forward-facing Slot 45 deg. to Surface.

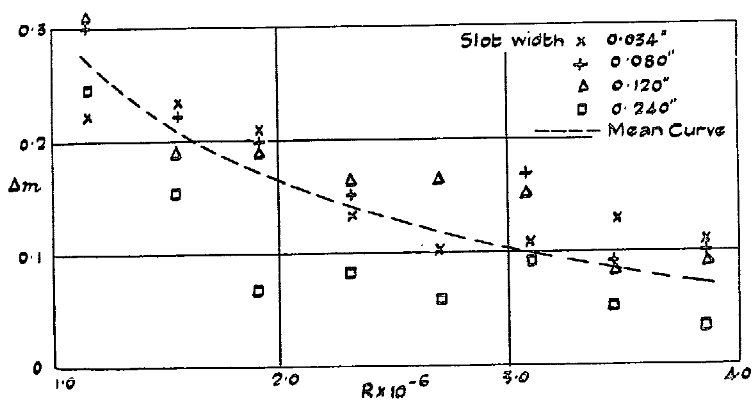


FIG. 7a. Forward-facing Slot.

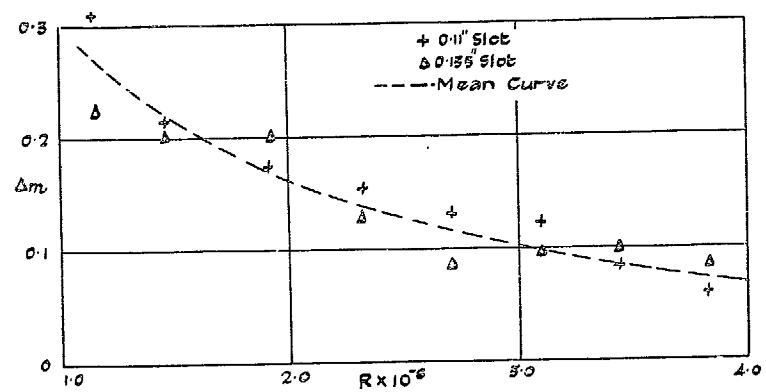


FIG. 7b. Backward-facing Slot.

Extra Suction Needed to Establish Non-separating Flow.

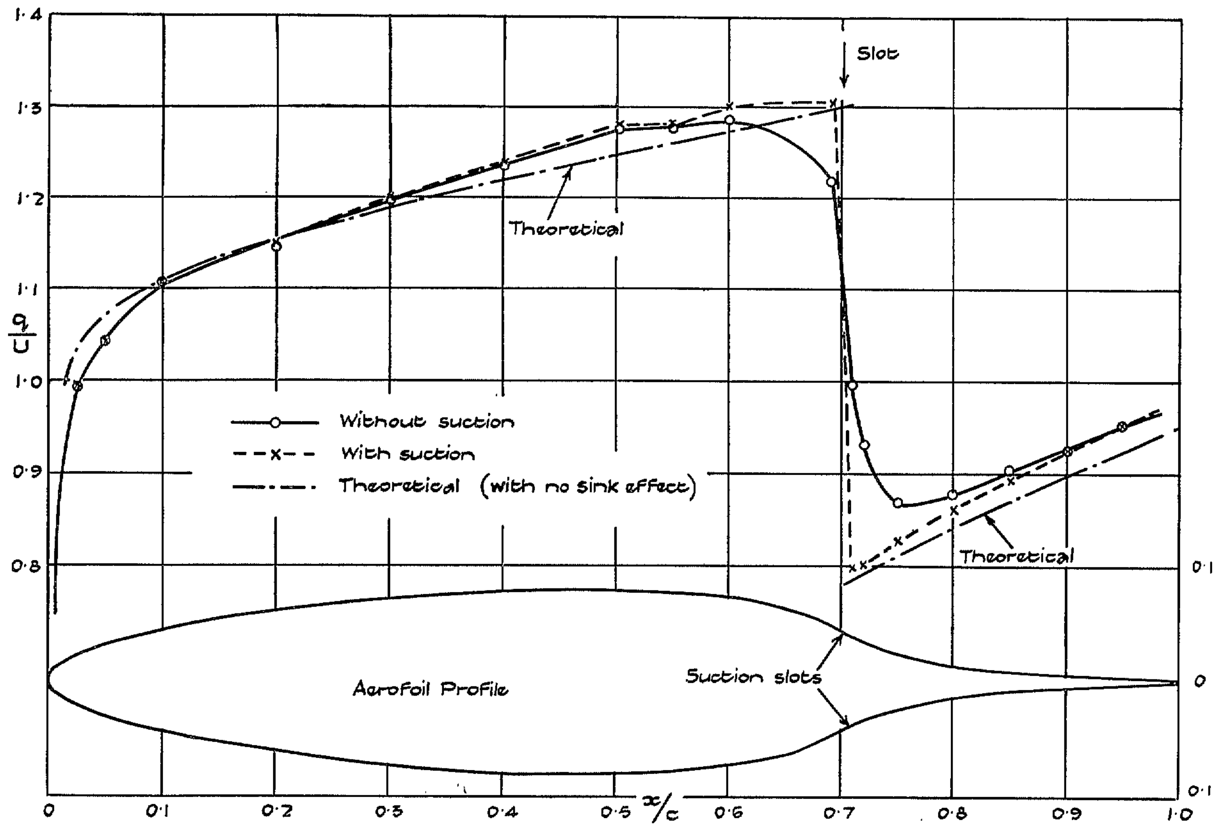


FIG. 8a.—Velocity Distribution over Griffith Aerofoil with and without Suction. 0 deg. Incidence. Slot width 0·039 in.

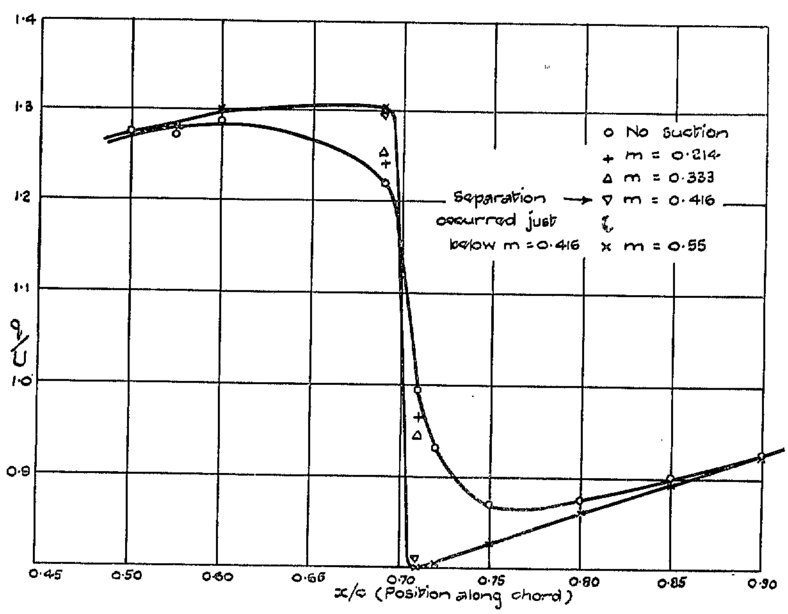


FIG. 8b.—Velocity Distribution with Varying Suction. $R = 3 \cdot 85 \times 10^6$ New Slot.

Slot Width = 0·089 in.

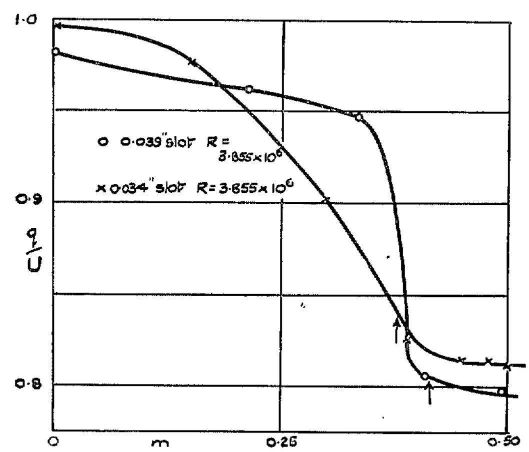


FIG. 9.—Variation of Velocity with Suction at 0·71 chord.

Arrows indicate Value of m at which Flow separated from Surface.

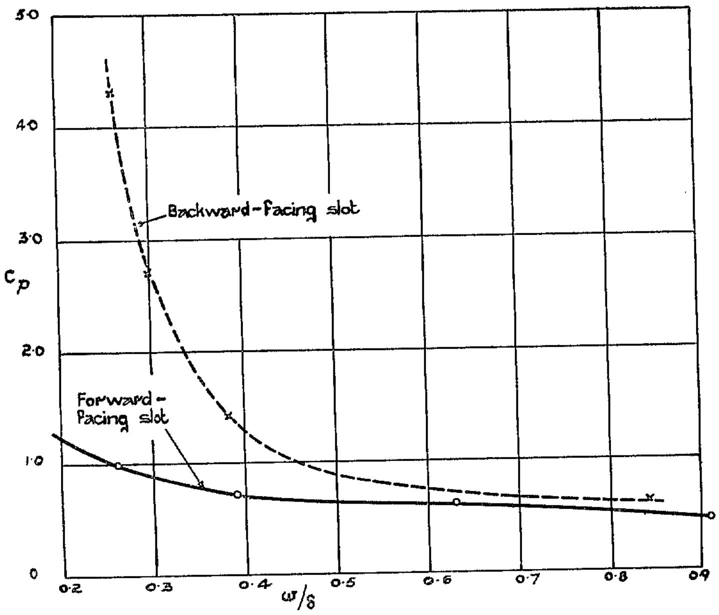


FIG. 10.—Comparison of Box Suction Needed to Prevent Separation. $R = 3{\cdot}85 \times 10^6$.

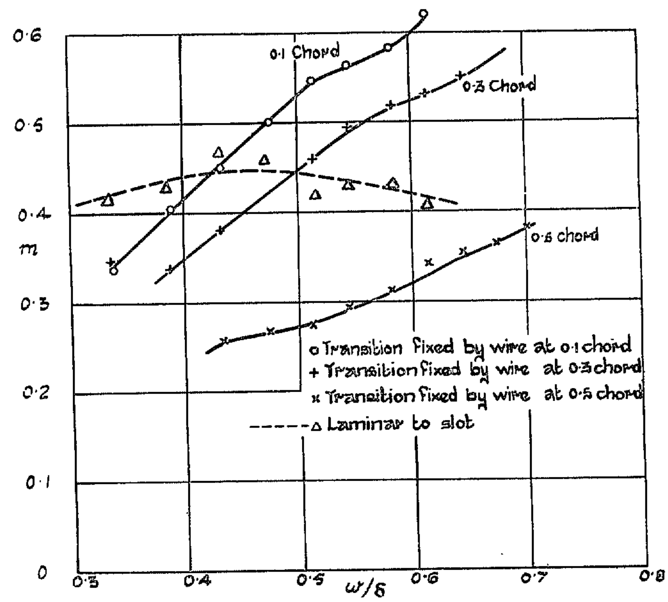


FIG. 11.—Amount of Air Removed to Prevent Separation if Flow is Turbulent Forward of the Slot.

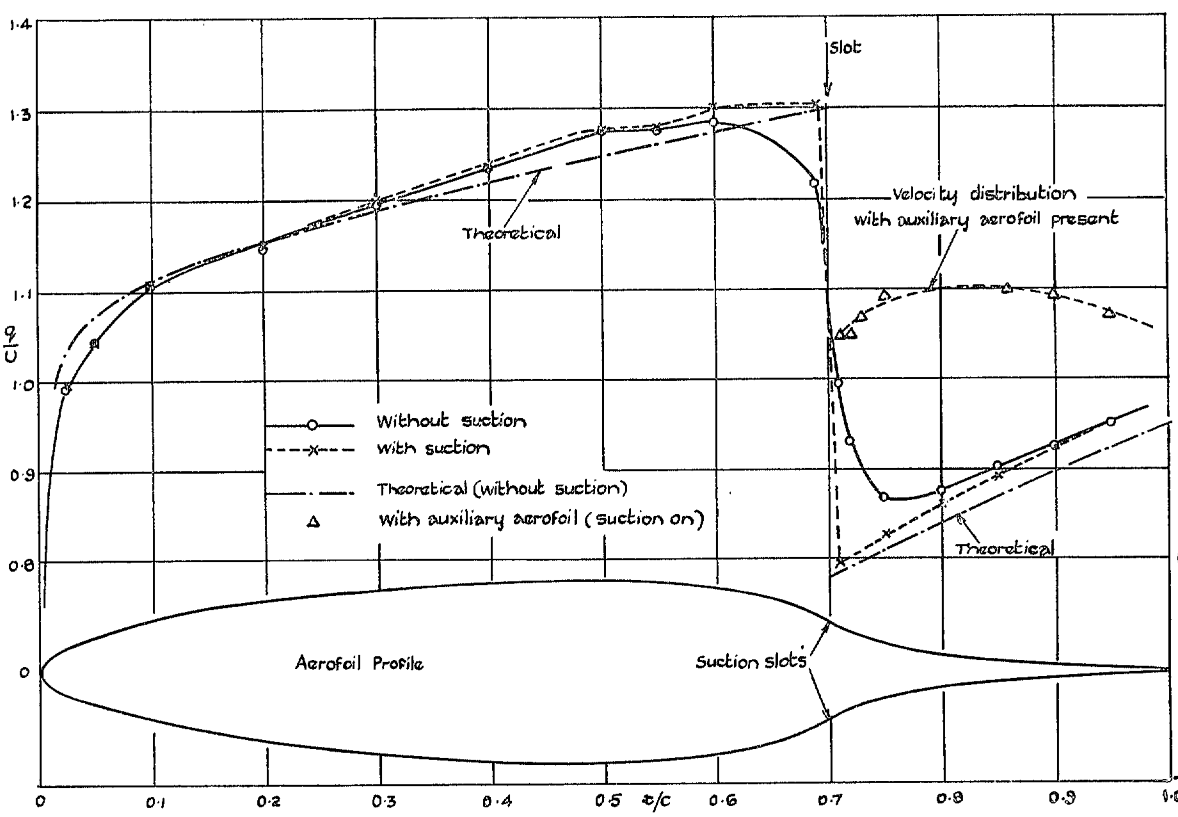


FIG. 12.—Velocity Distribution over Griffith Aerofoil with and without Suction. 0 deg. Incidence.

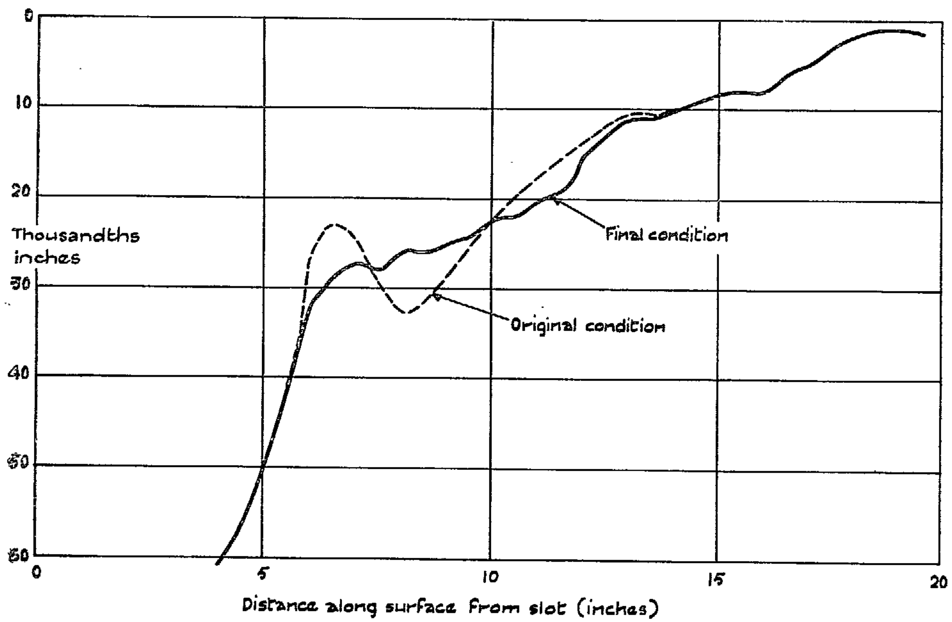
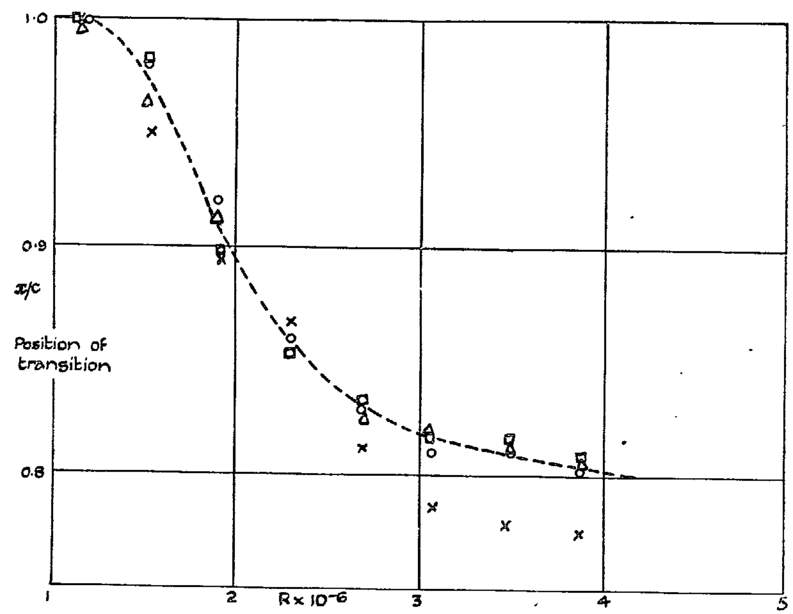


FIG. 13.—Curvature of Surface Rear of Slot measured on 3 in. Gauge.



Movement of Transition on Concave Tail.

FIG. 14b.—Minimum Suction Necessary to Prevent Separation.

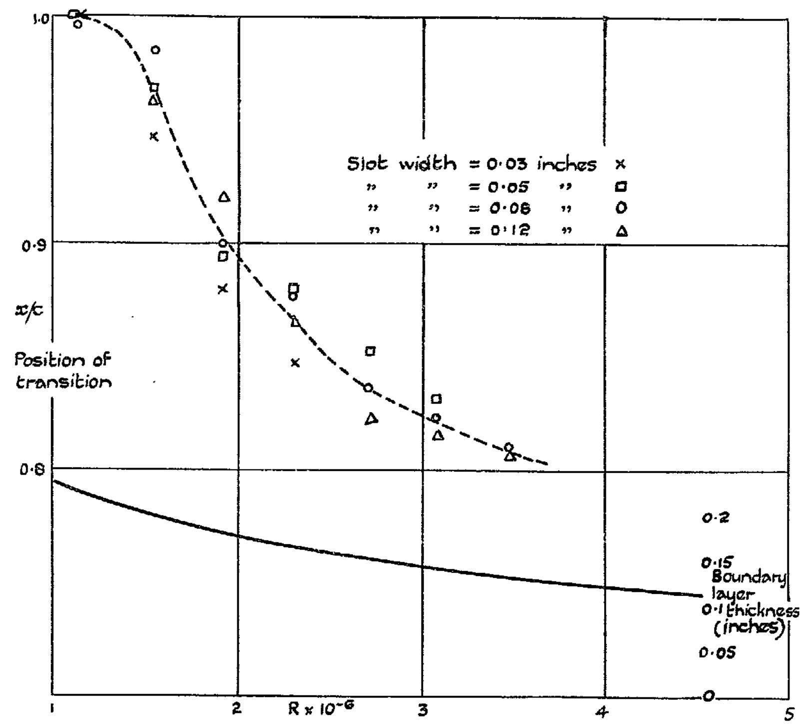


FIG. 14a.—Maximum Suction Available (approximately sucking away whole boundary layer).

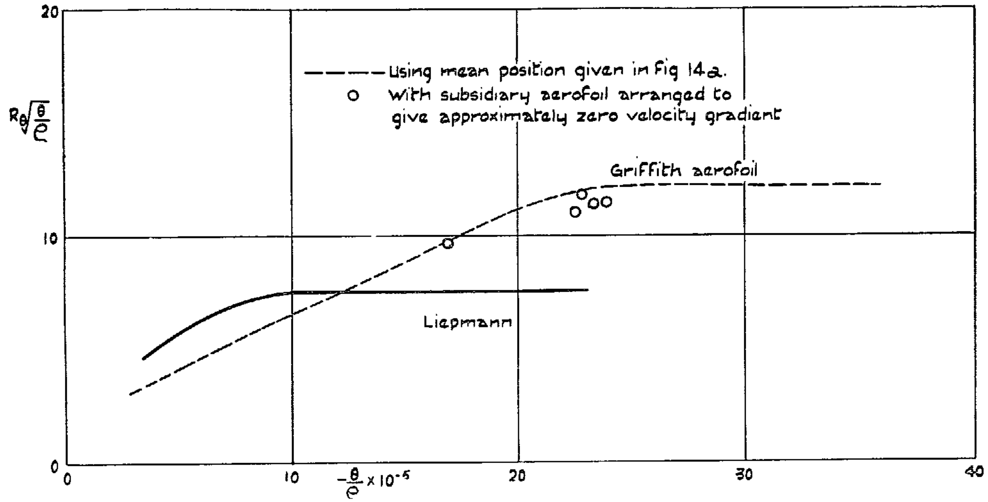


FIG. 15.—Stability Criterion of Boundary Layer on Concave Surface. Griffith Aerofoil 0 deg. Incidence.

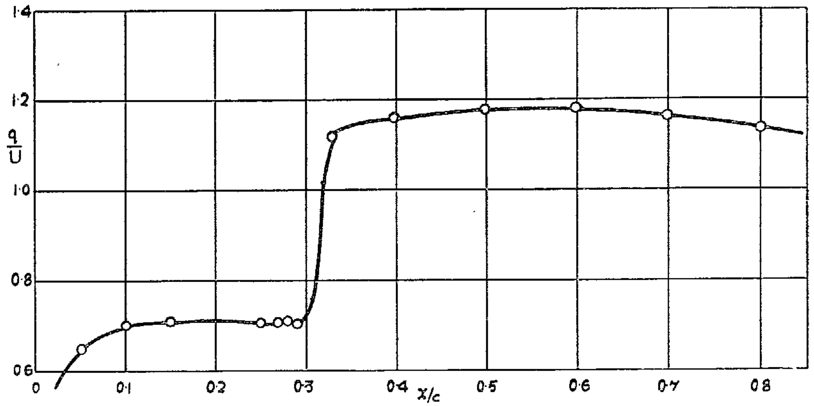


FIG. 16a.—Velocity Distribution with Tail Foremost. Incidence —6 deg.

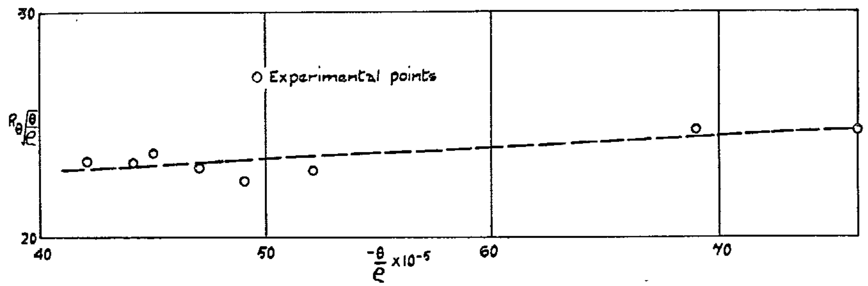


FIG. 16b.—Griffith Aerofoil with Tail Foremost. Incidence —6 deg.

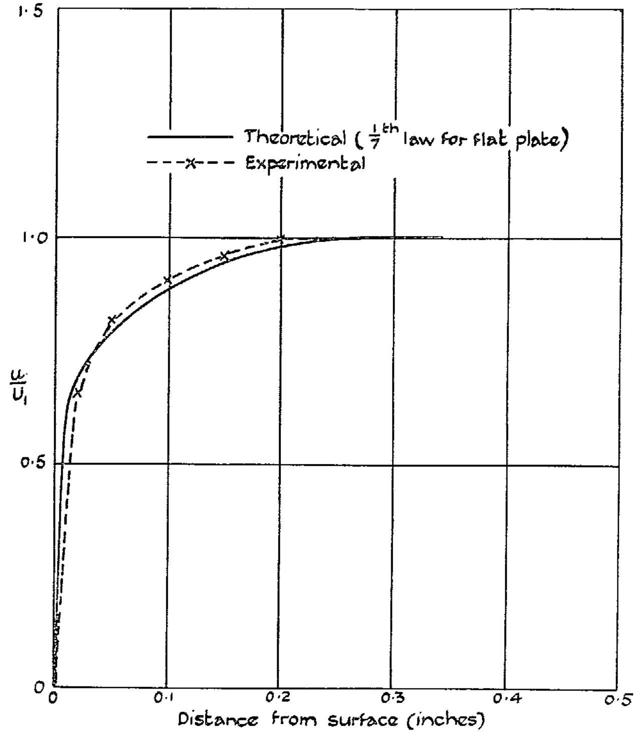


FIG. 17. Velocity Profile at 0·9 chord.

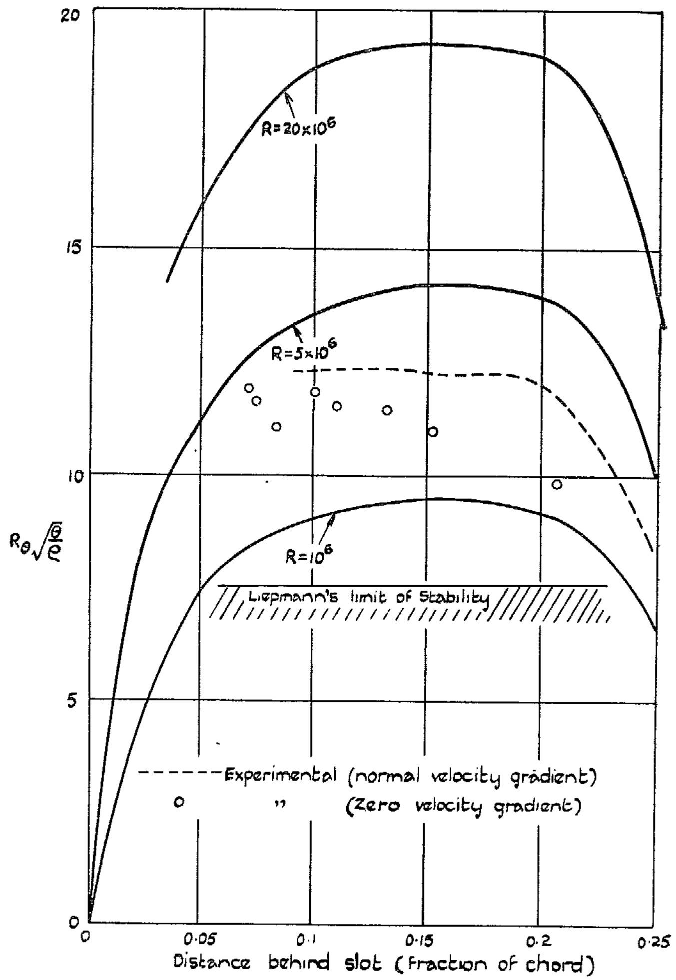


FIG. 18. Aerofoil A. Estimated Form Drag $C_D = 0 \cdot 00026$.

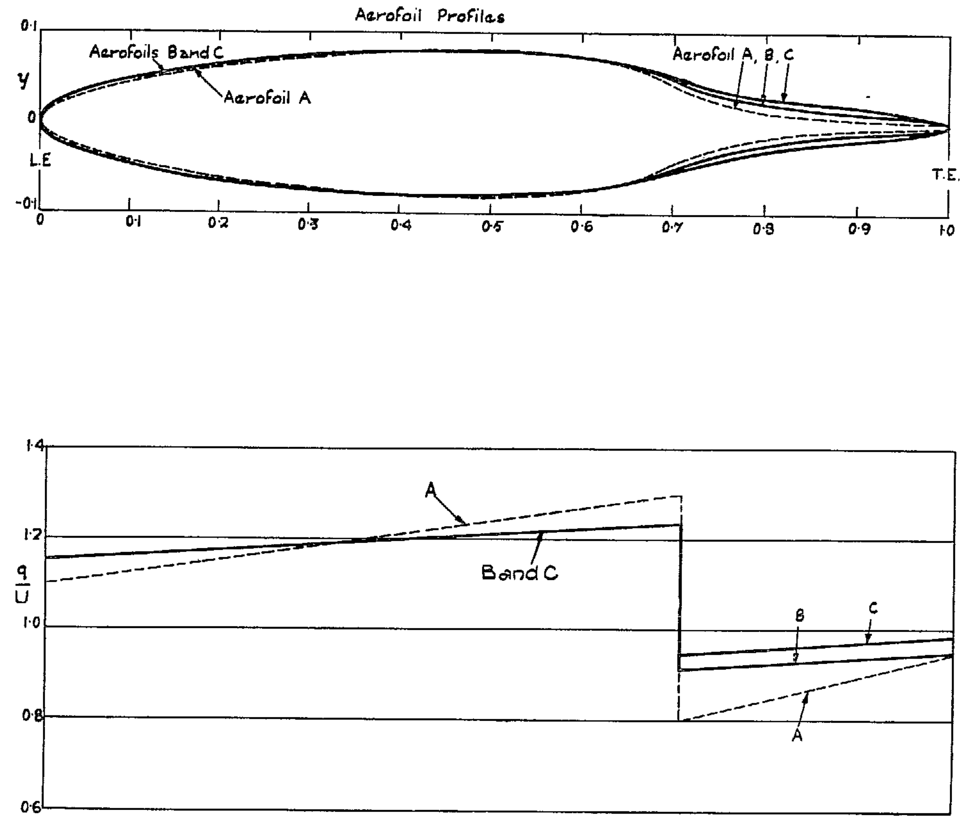


FIG. 19.—1st Approximation to Velocity Distribution for Aerofoils of Varying Concavity.

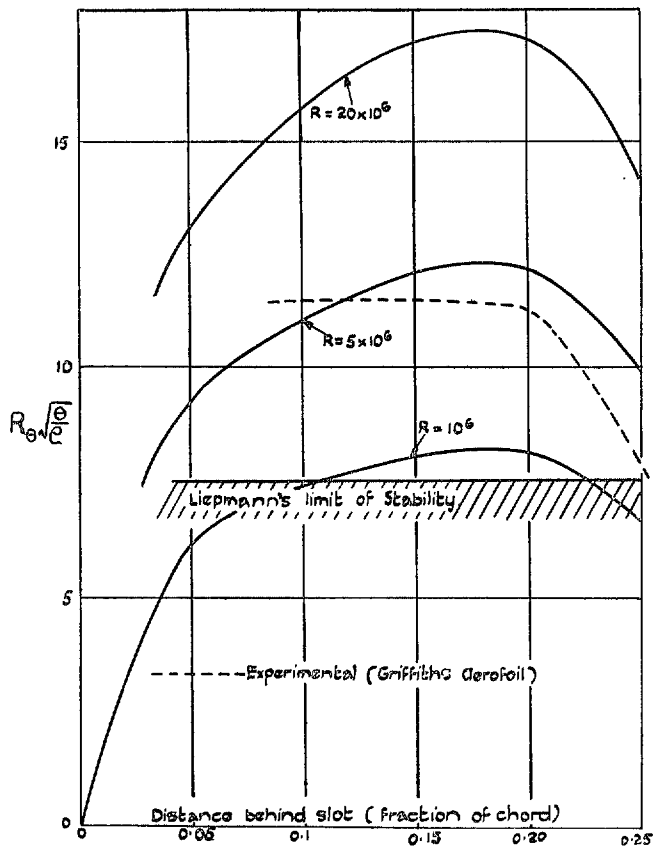


FIG. 20a.—Aerofoil B. Estimated Form Drag $C_D = 0 \cdot 00137$.

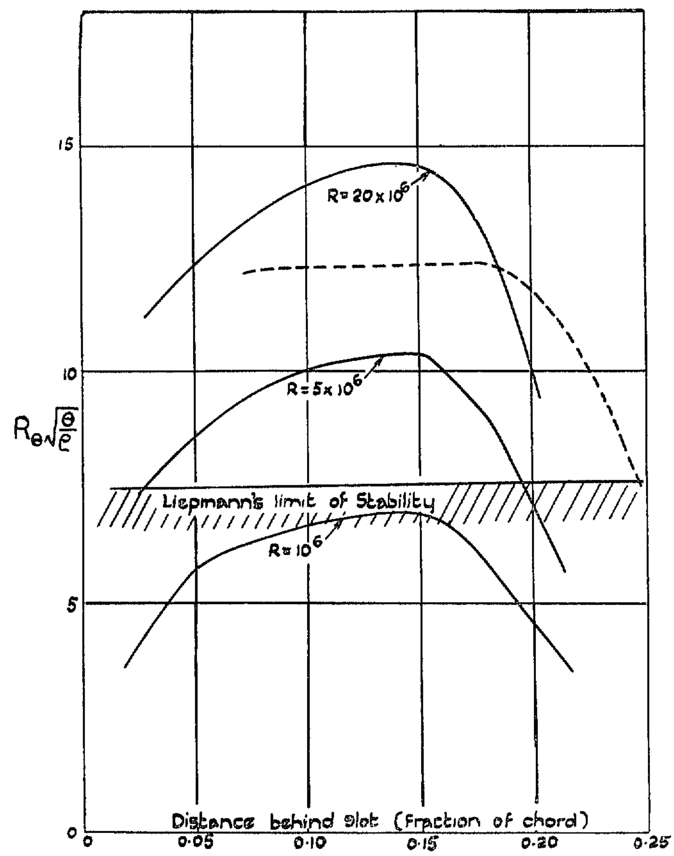


FIG. 20b.—Aerofoil C. Estimated Form Drag Drag $C_D = 0 \cdot 00245$.

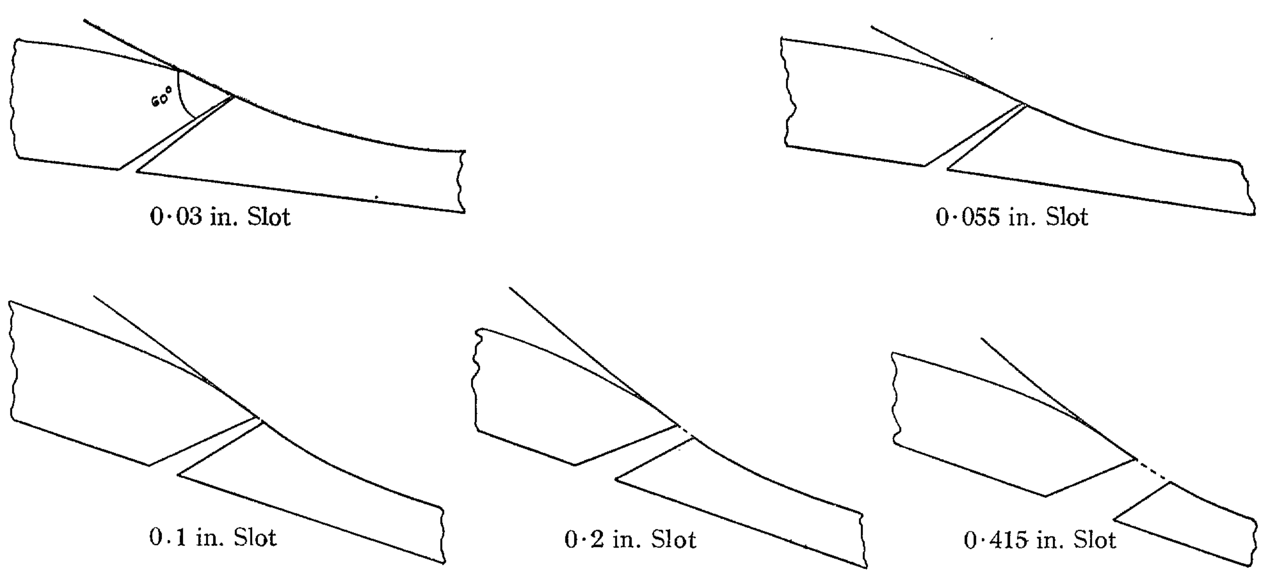


FIG. 21.—Diagrams of Slots investigated (60 deg. to Forward-facing Tangent).

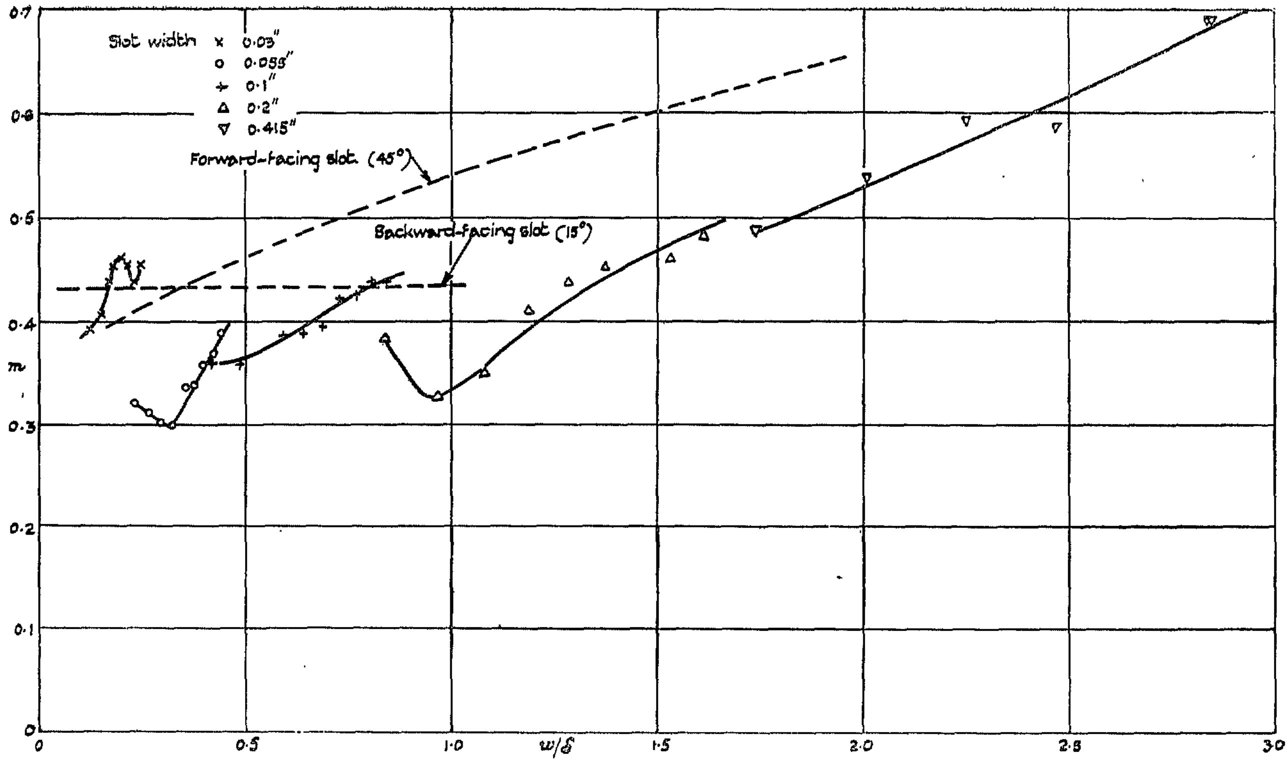


FIG. 22. Variation of m with w/δ for 60 deg. Backward-facing Slot. Flow Laminar to the Slot.

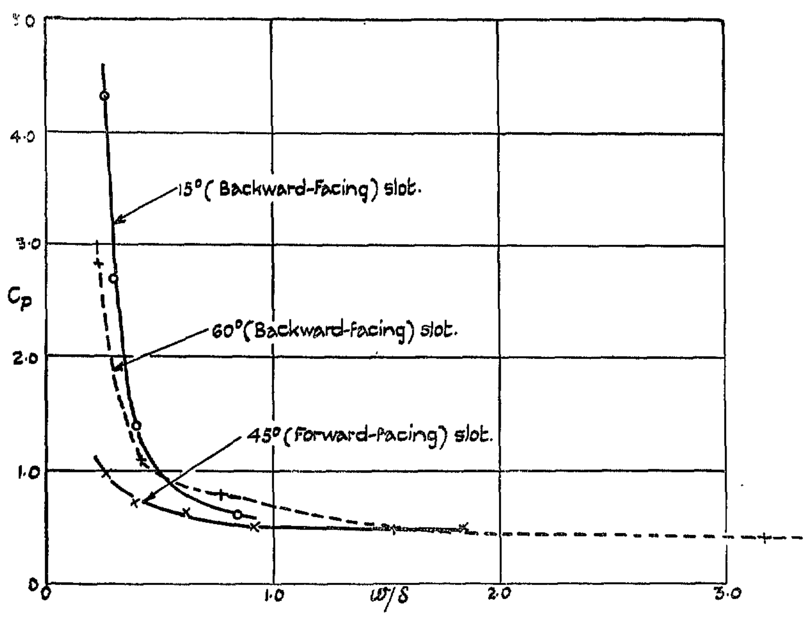


FIG. 23. Variation of Suction in Suction Chamber.
$R = 3{\cdot}85 \times 10^6$.

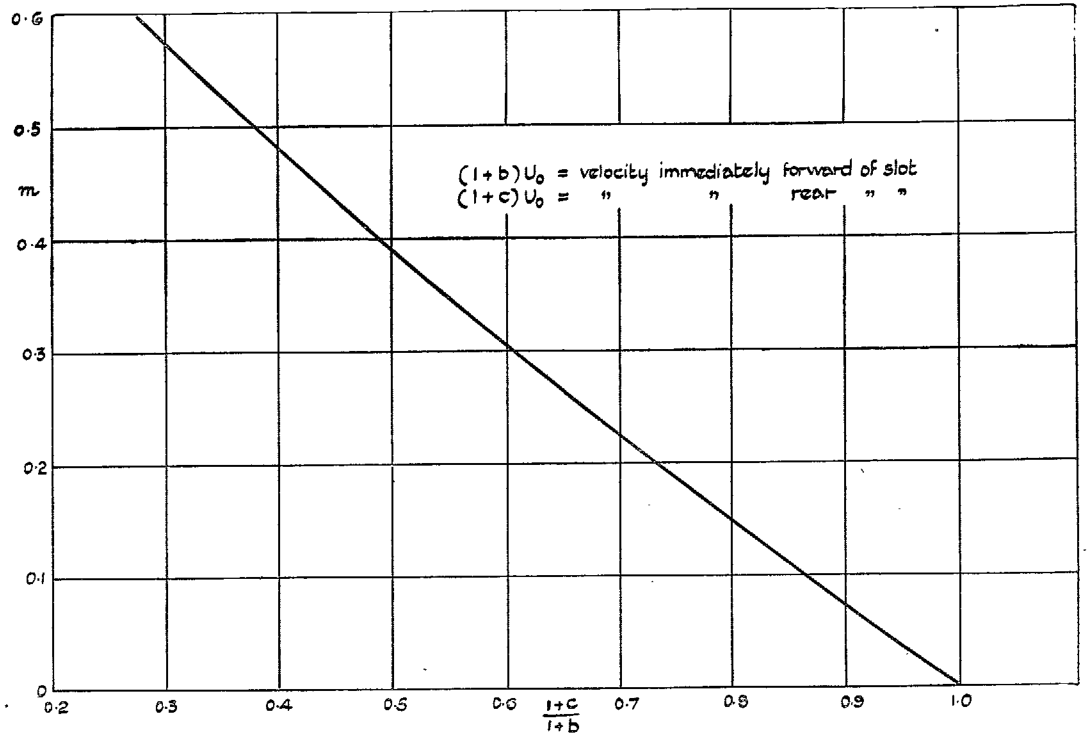


FIG. 24. Variation of m with Aerofoil Characteristics. (Theoretical Minimum.)

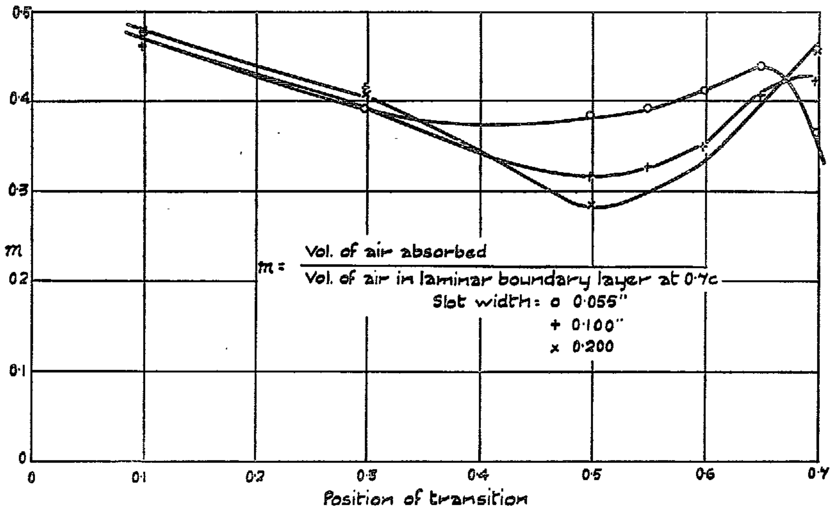


FIG. 25. Proportion of Air (as fraction of laminar boundary layer) Absorbed from the Turbulent Boundary Layer to Maintain Unseparated Flow. $R = 3{\cdot}85 \times 10^6$

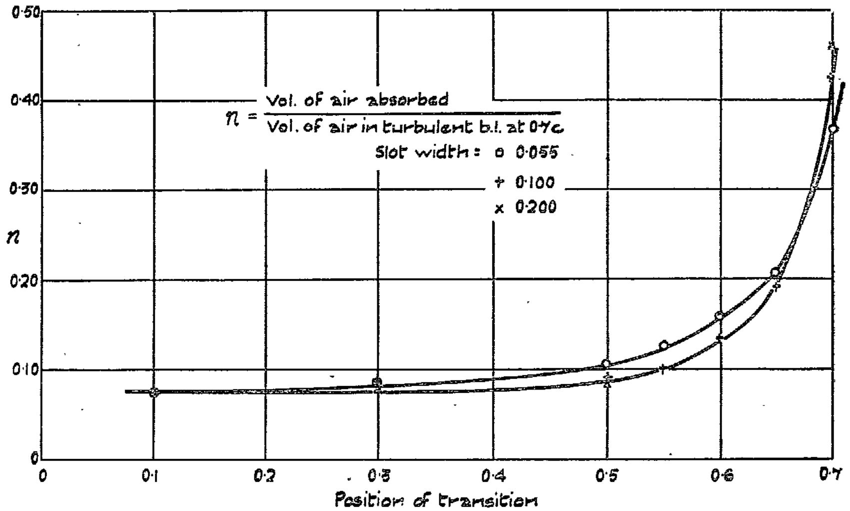


FIG. 26. The Proportion n of Air Absorbed from the Turbulent Boundary Layer to Maintain Unseparated Flow. $R = 3{\cdot}85 \times 10^6$.

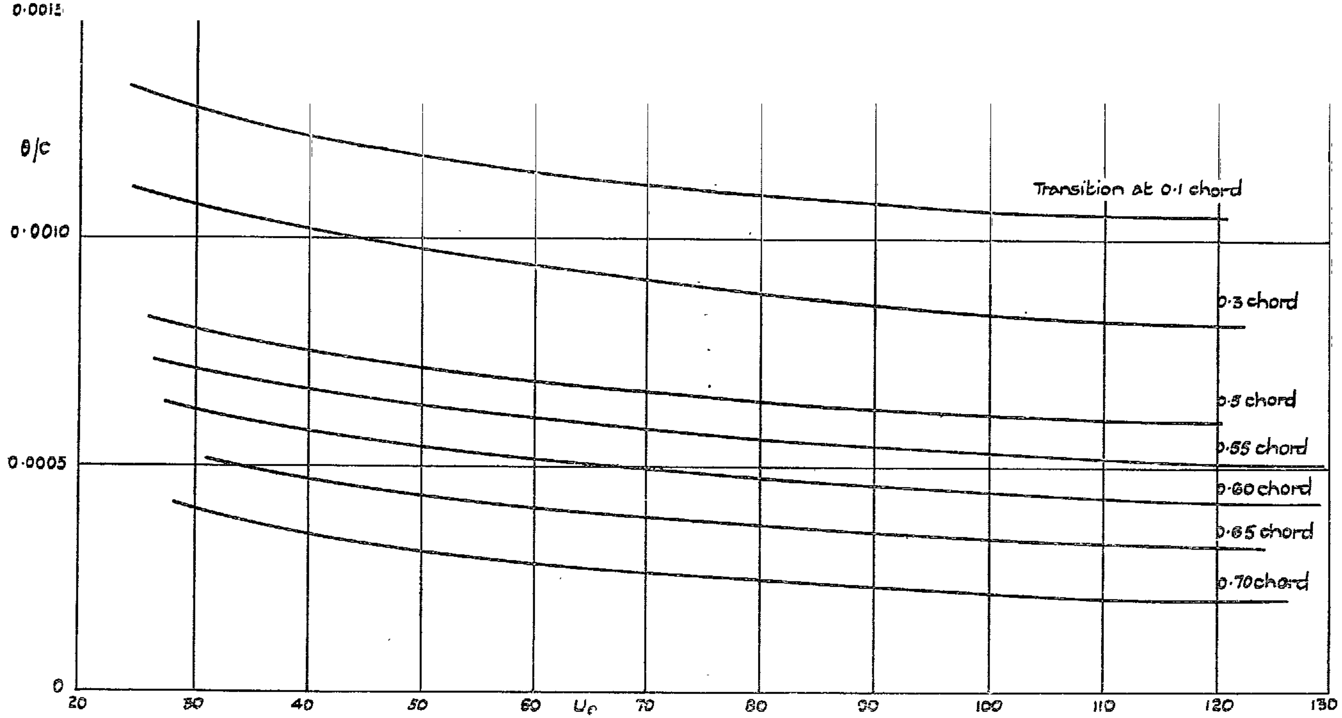


FIG. 27. θ/c against U_0 (Griffith Wing in Tunnel).

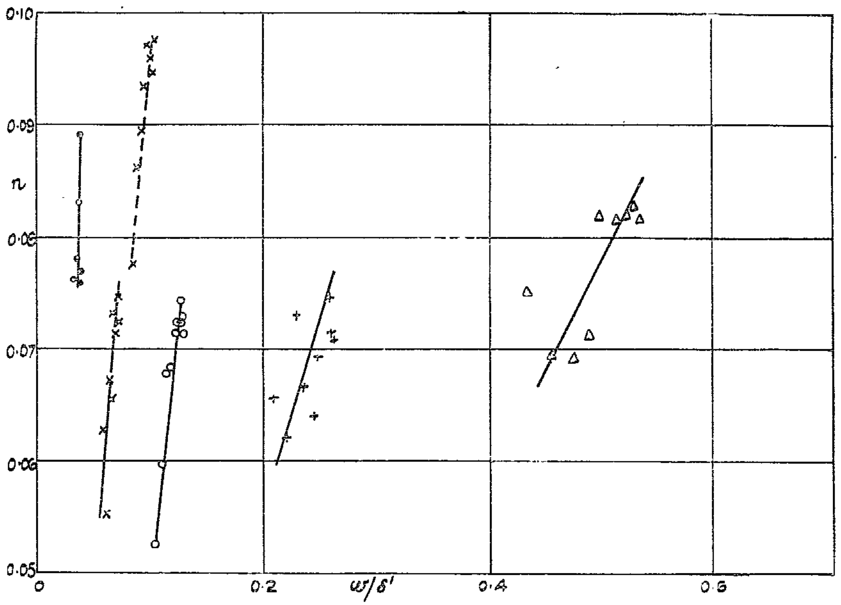


FIG. 28. Proportion (n) of Air Absorbed from Turbulent Boundary Layer. Transition at 0·1 chord. (60 deg. slot).

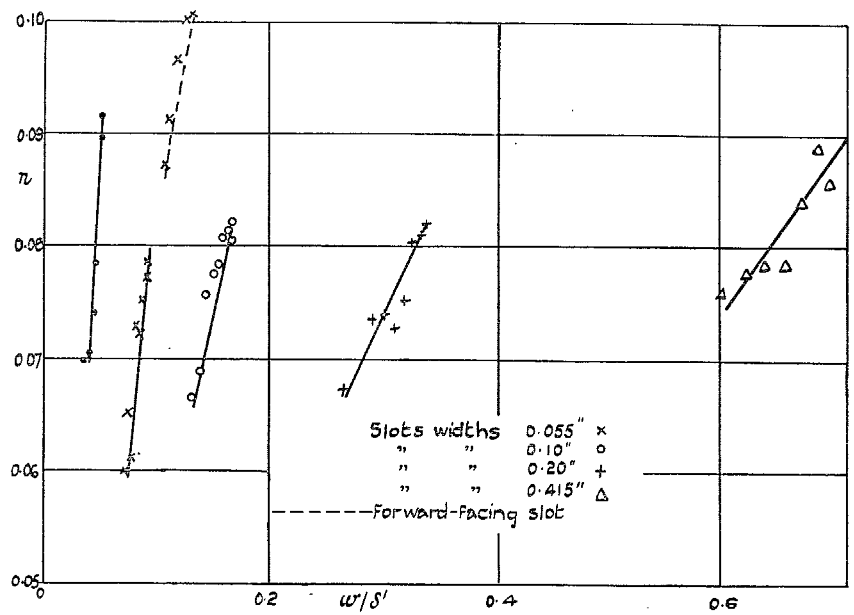


FIG. 29. Proportion (n) of Air Absorbed from Turbulent Boundary Layer. Transition at 0·3 chord (60 deg. slot).

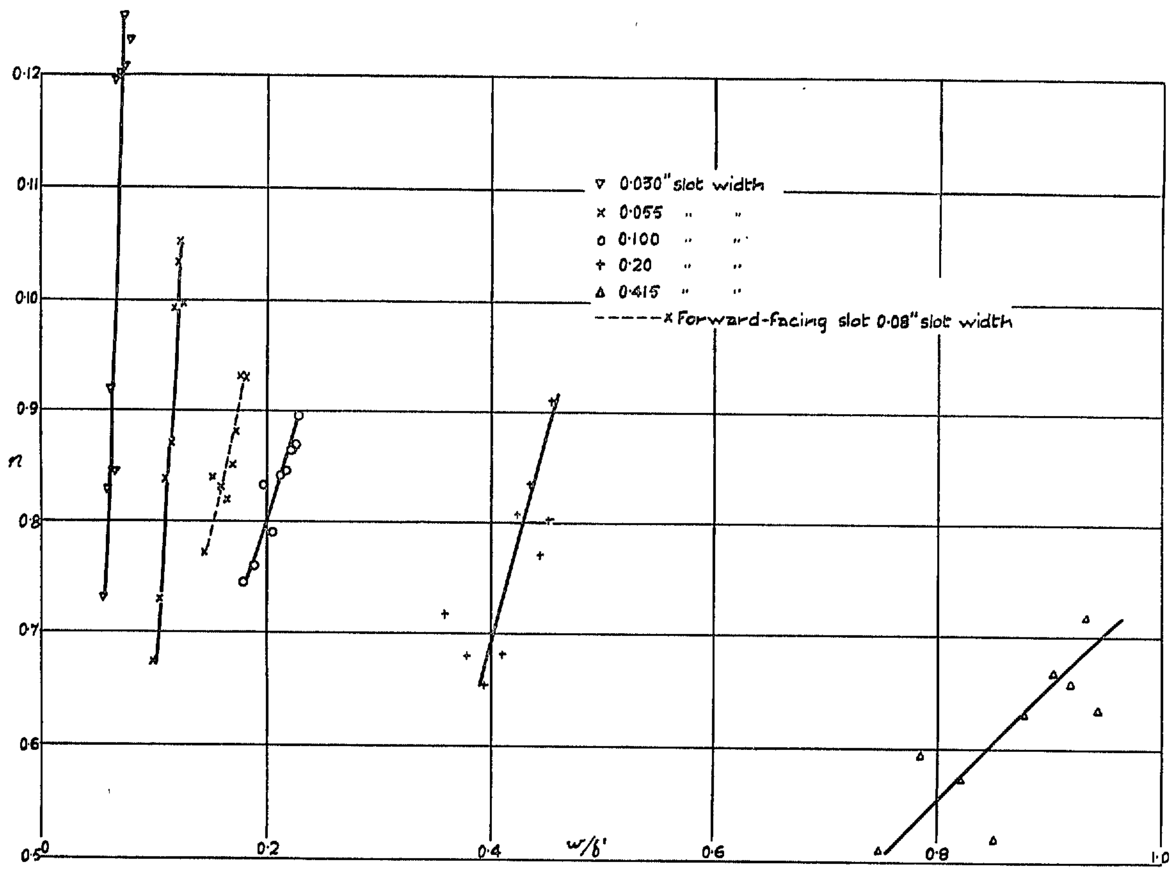


FIG. 30. Proportion (n) of Air Absorbed from Turbulent Boundary Layer. Transition at 0·5 chord.

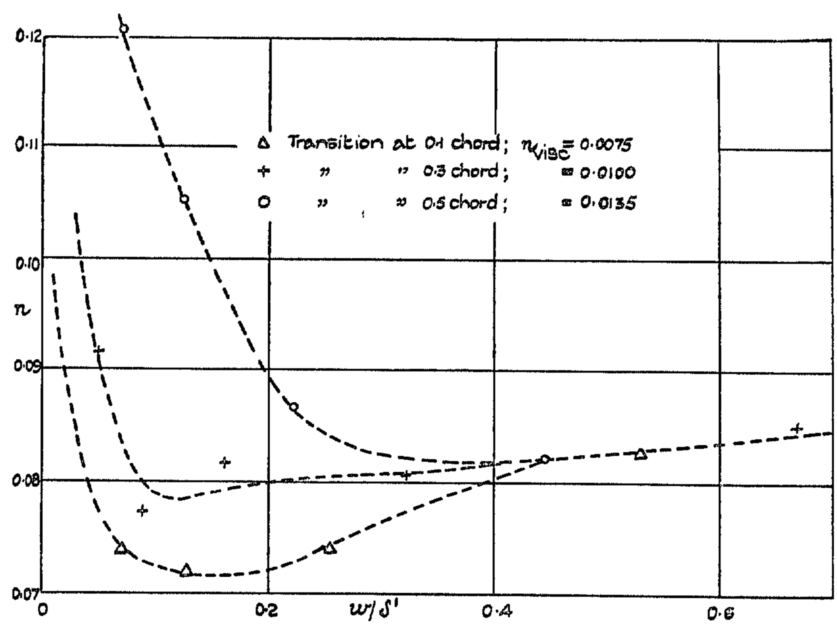


FIG. 31. Variation of n with w/δ'. $R = 3{\cdot}84 \times 10^6$.

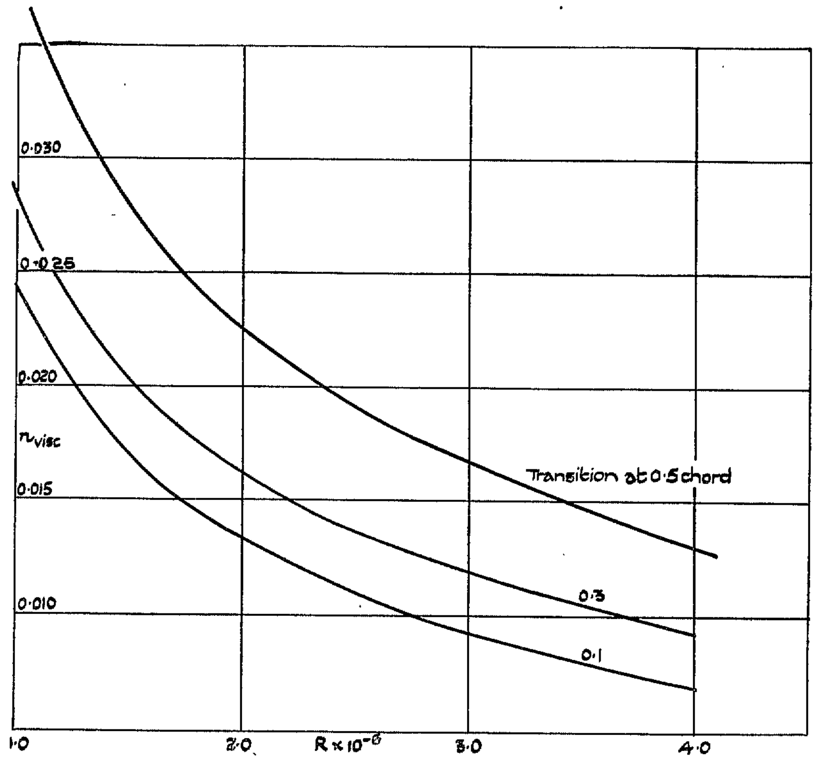


FIG. 32. Quantity of Air in Viscous Layer as Fraction (n) of that in Whole Turbulent Boundary.

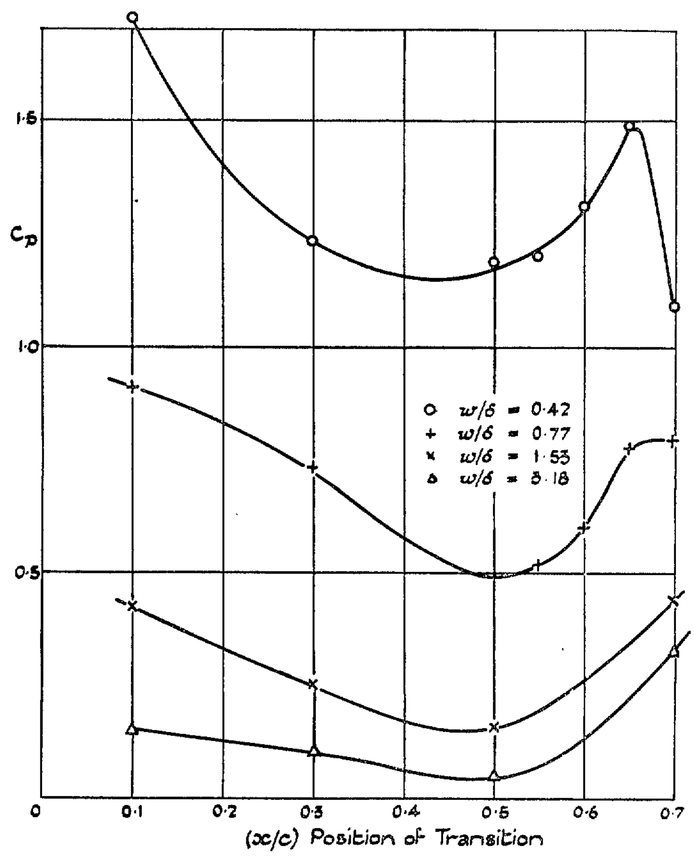


FIG. 33. Variation of Suction Head Necessary to Maintain Non-separated Flow. $R = 3 \cdot 85 \times 10^6$.

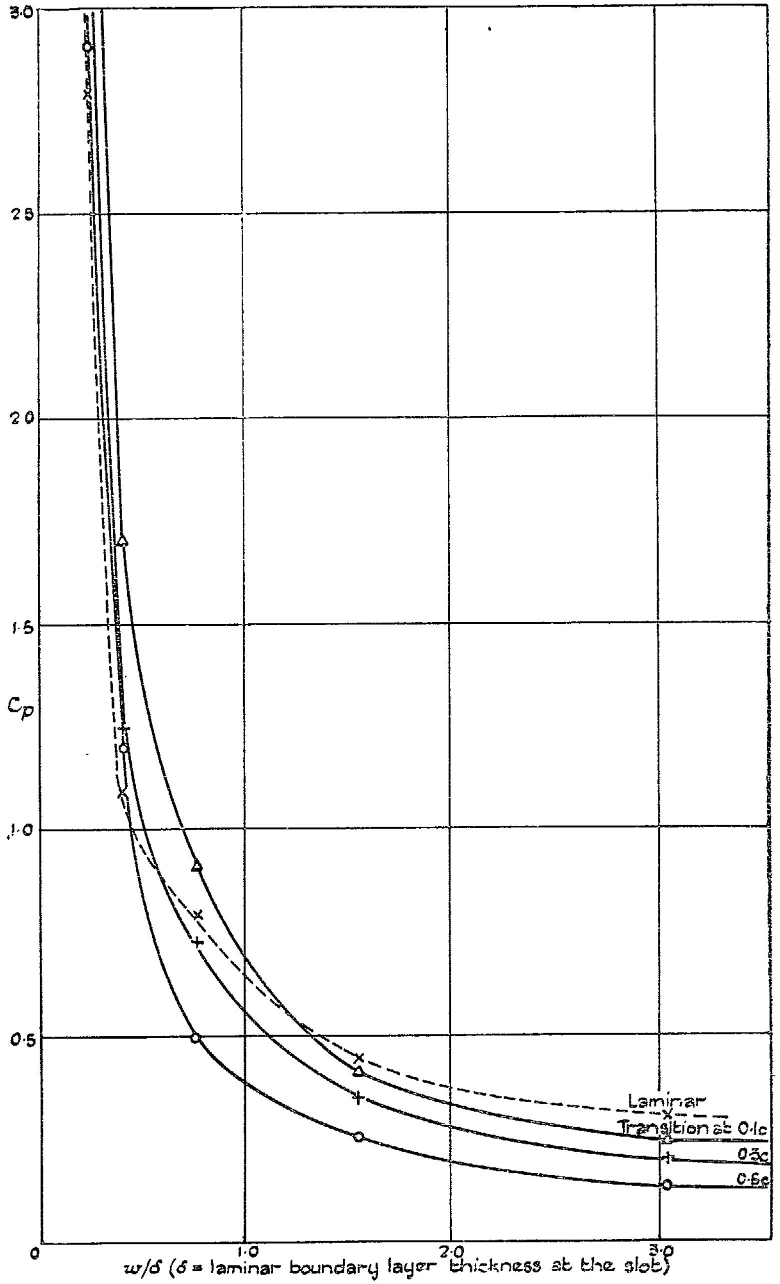


FIG. 34. Variation of Minimum Suction Head with Slot Width. $R = 3{\cdot}85 \times 10^6$.

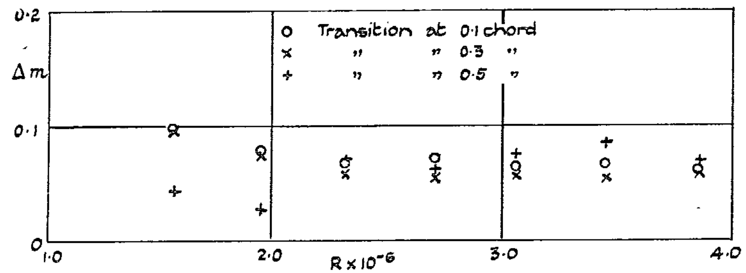


FIG. 35a. Slot Width $= 0{\cdot}20$ inch.

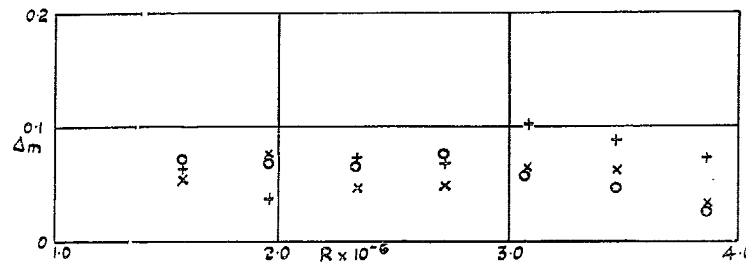


FIG. 35b. Extra Suction needed to Establish Non-separated Flow. (60 deg. Slot.) Slot Width $= 0{\cdot}10$ inch.

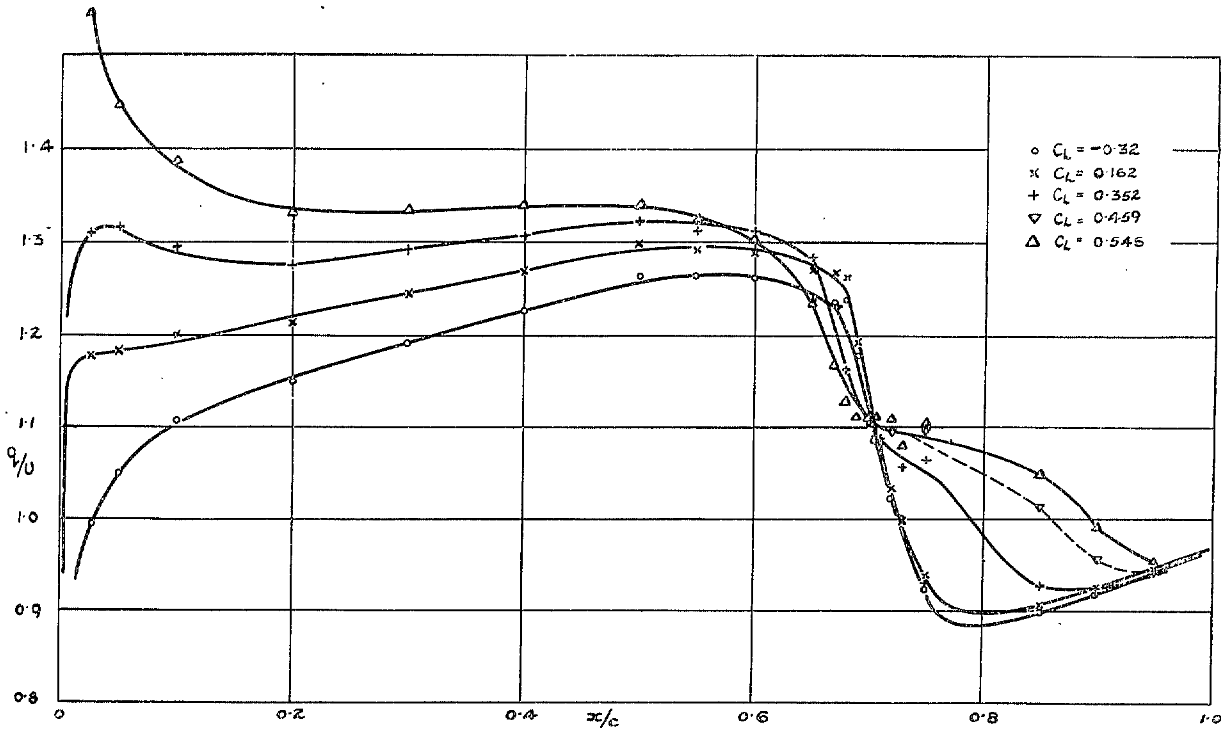


FIG. 36a. Velocity Distribution on Griffith Aerofoil without Suction (Wind-tunnel Conditions). Upper Surface. $R = 2 \cdot 31 \times 10^6$.

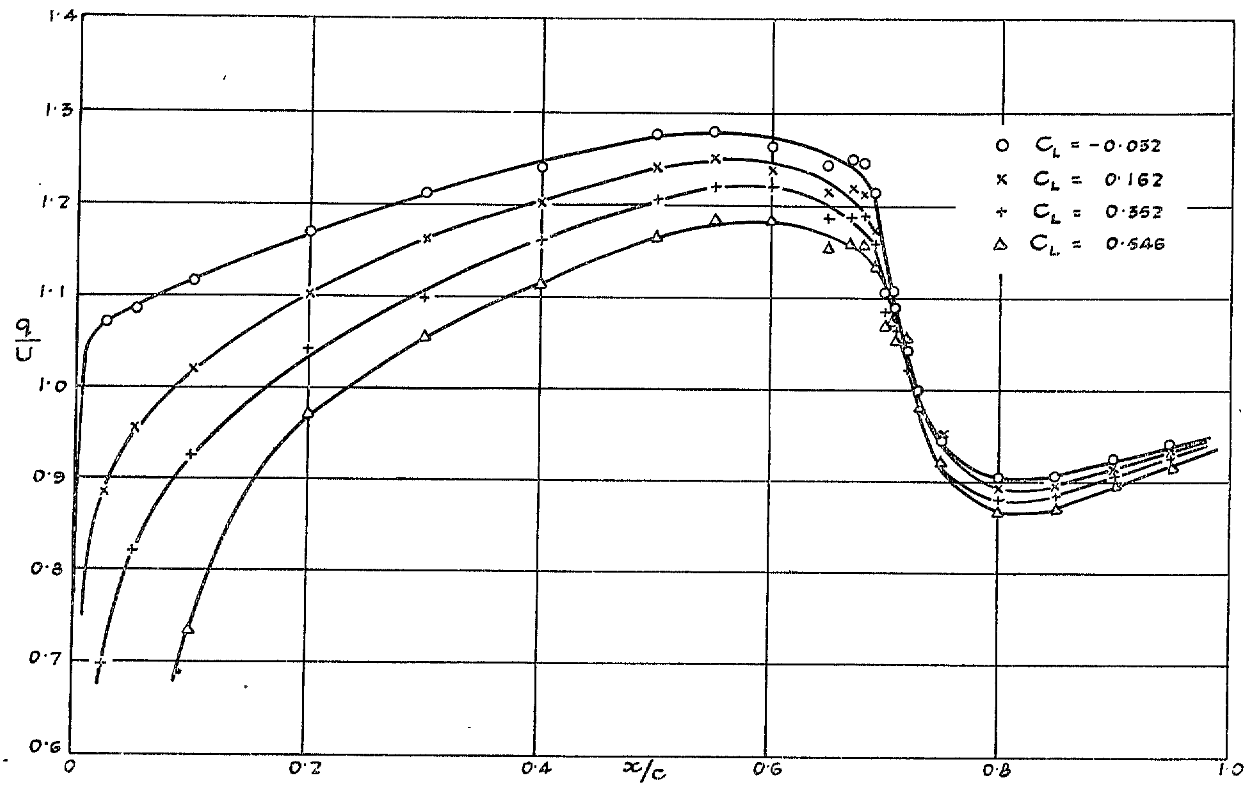


FIG. 36b. Velocity Distribution over Griffith Aerofoil without Suction (Wind-tunnel Conditions). Lower Surface. $R = 2 \cdot 31 \times 10^6$.

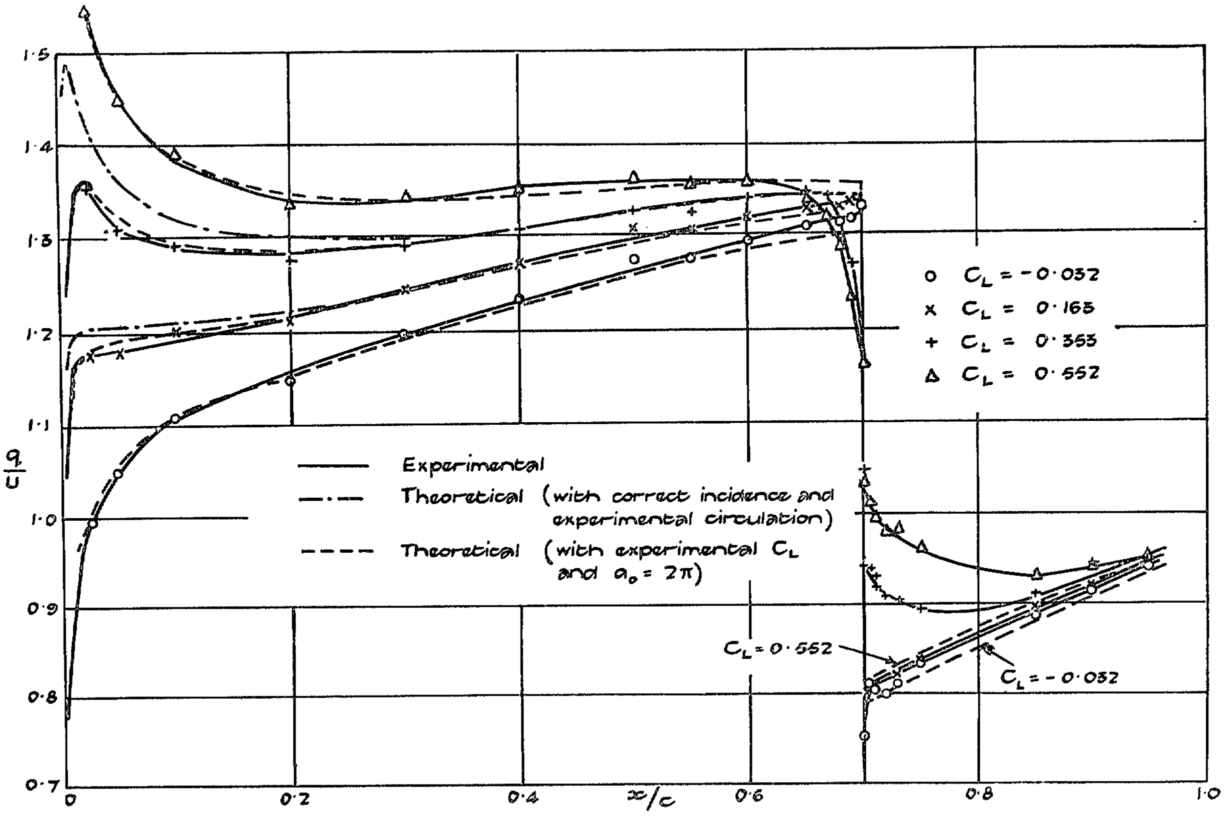


FIG. 37a. Velocity Distribution over Griffith Aerofoil with Suction (Wind-tunnel Conditions). Upper Surface. $R = 2{\cdot}31 \times 10^6$.

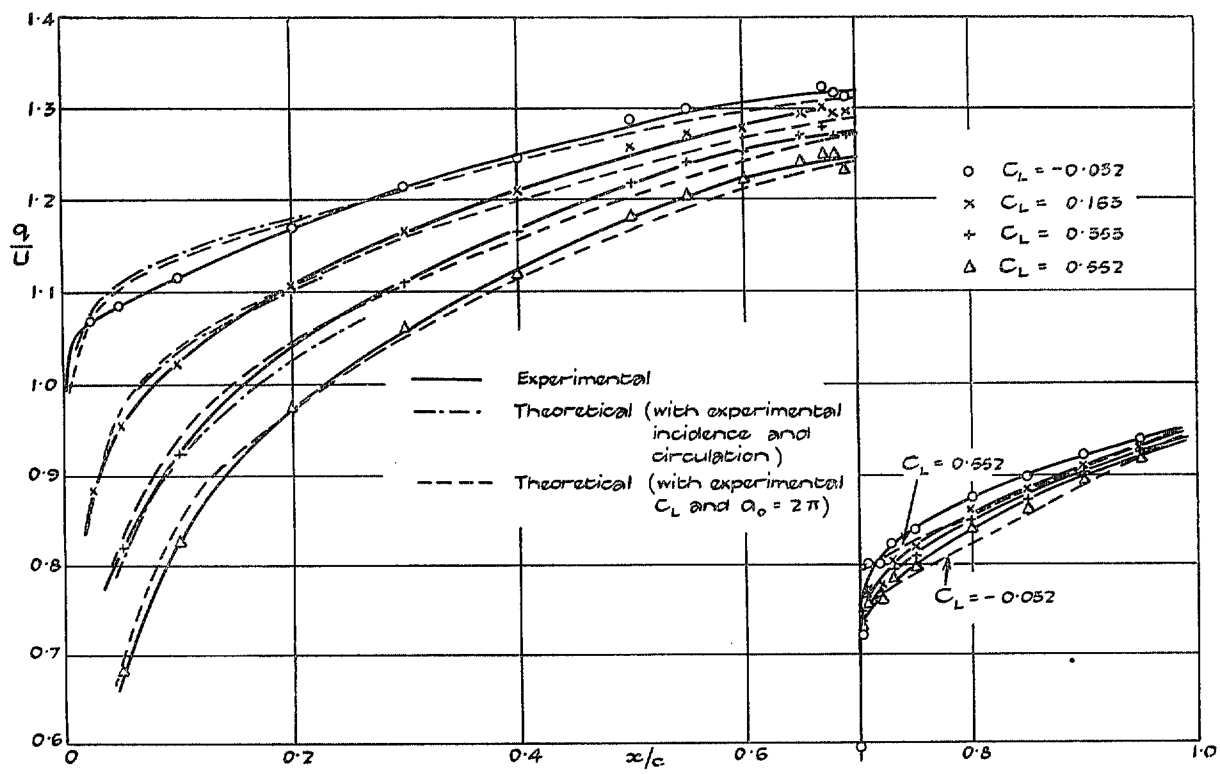


FIG. 37b. Velocity Distribution over Griffith Aerofoil with Suction (Wind-tunnel Conditions). Lower Surface. $R = 2{\cdot}31 \times 10^6$.

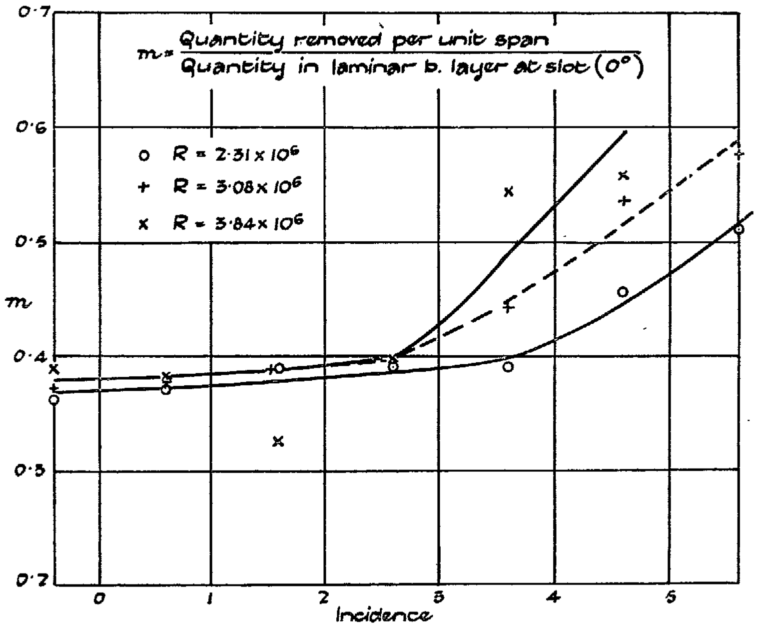


FIG. 38a. Upper Surface.

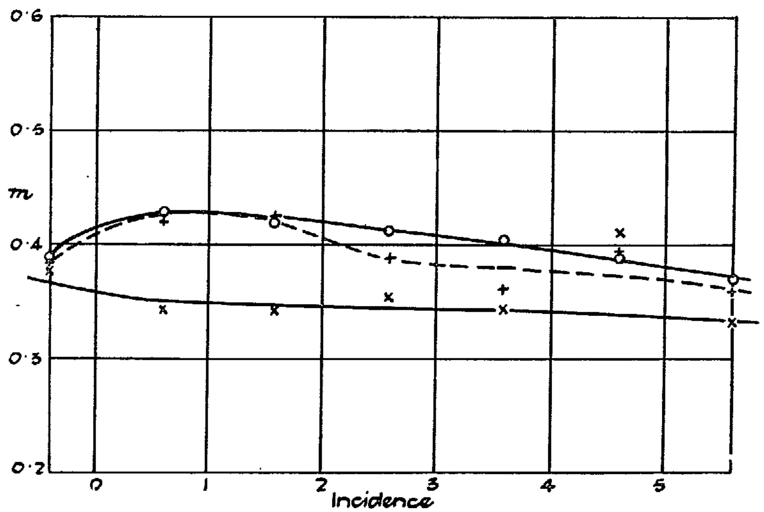


FIG. 38b. Lower Surface.

Quantity of Air to be removed to Maintain Unseparated Flow at Incidences.

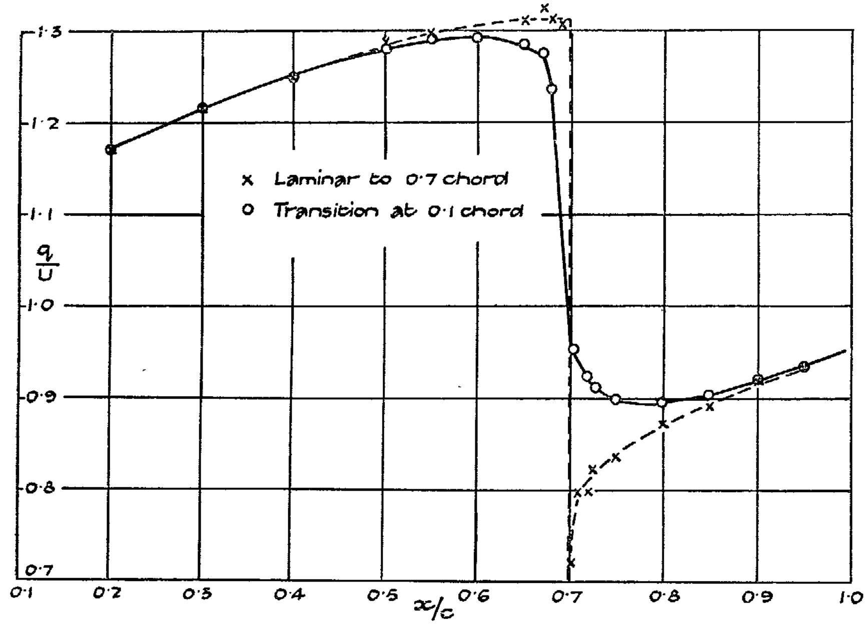


FIG. 39. Velocity Distribution with Minimum Suction necessary to Maintain Unseparated Flow. 0 deg. Incidence. $R = 2{\cdot}31 \times 10^6$.

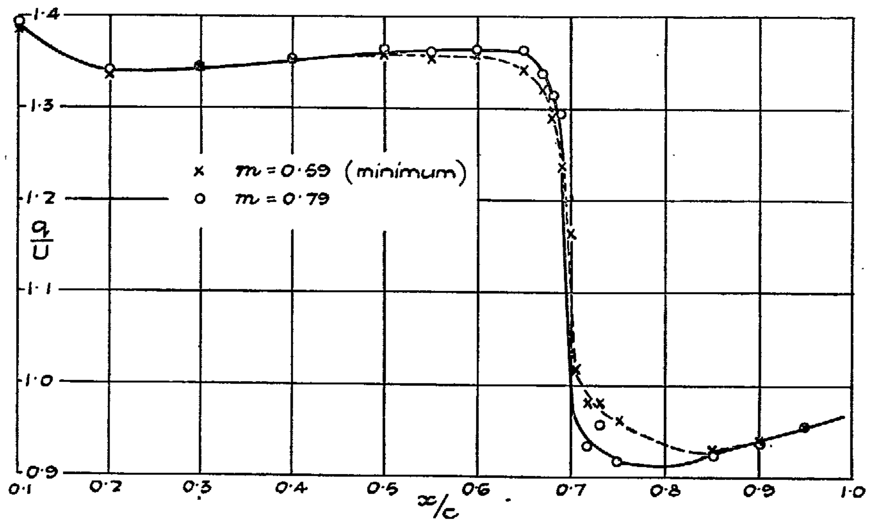


FIG. 40. Velocity Distribution at 6 deg. Incidence; Effect of Varying Suction. Upper Surface.

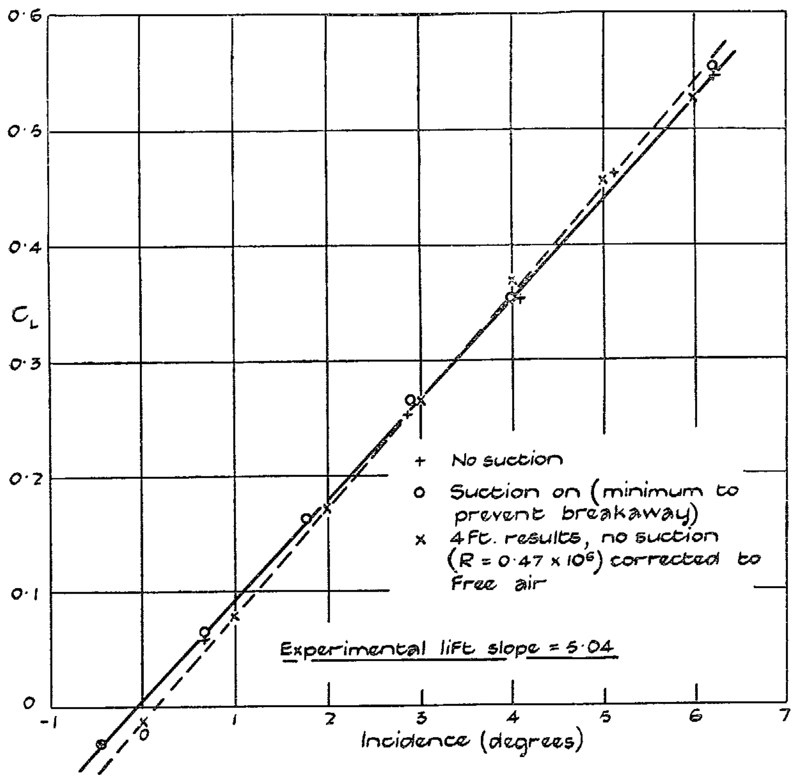


FIG. 41. (C_L, α) Variation with Suction on and Suction off. (Corrected to Free Air.) $R = 2{\cdot}31 \times 10^6$.

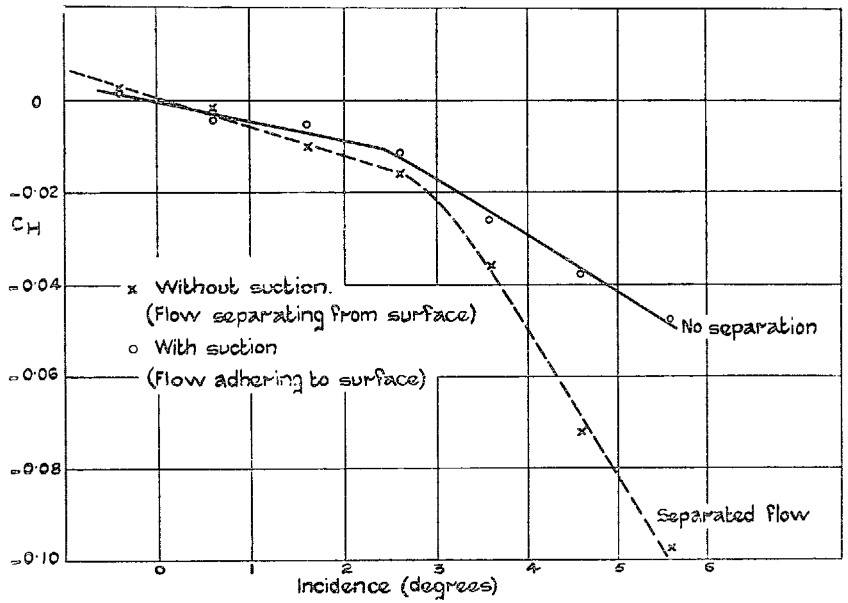


FIG. 43. Hinge Moment about 0·7 chord. (Zero Angle of Flap.) $R = 2{\cdot}31 \times 10^6$.

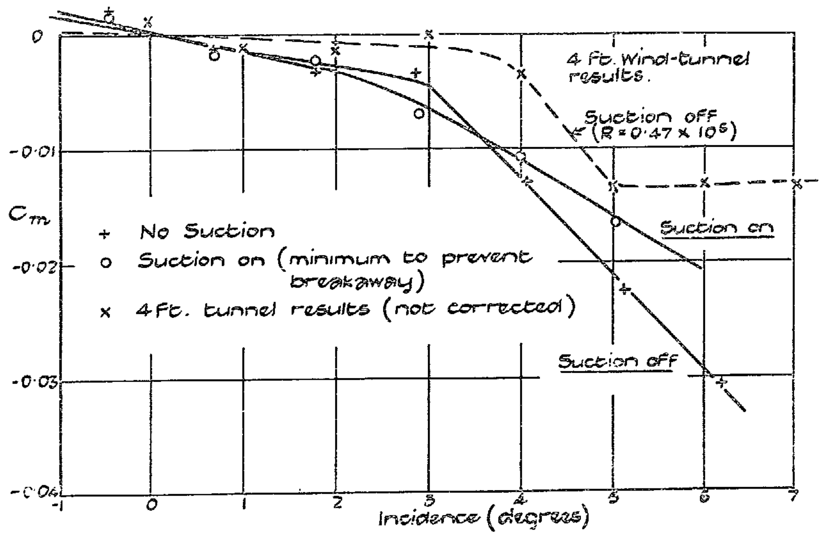


FIG. 42 (C_m, α). Results with and without Suction (Corrected to Free Air). $R = 2{\cdot}31 \times 10^6$.

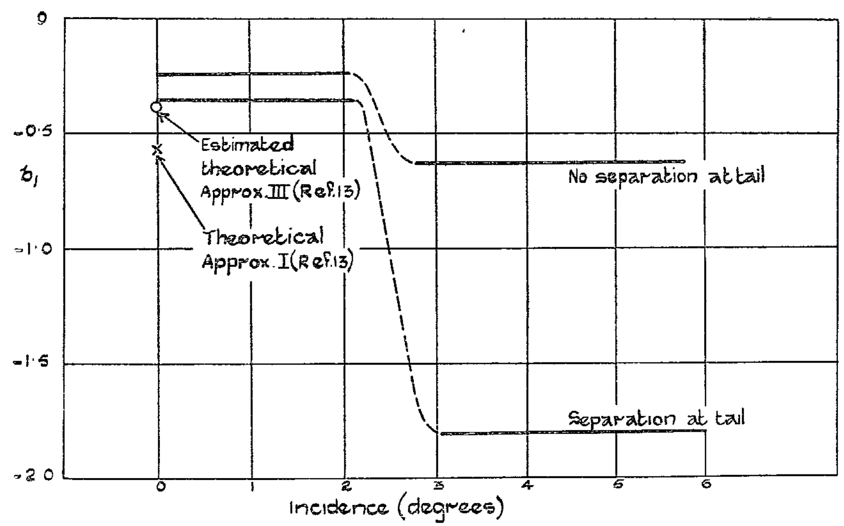


FIG. 44. Variation of b_1 with Incidence. $R = 2{\cdot}31 \times 10^6$).

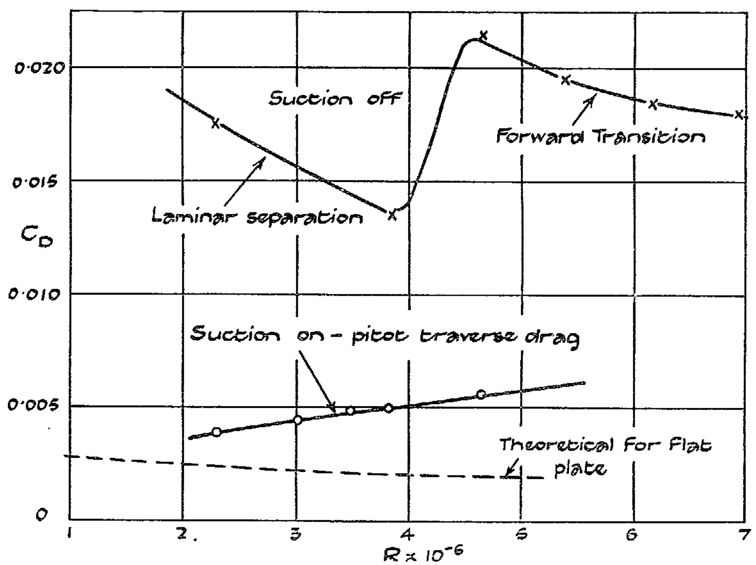


FIG. 45. Variation of Profile Drag with Reynolds number in Wind Tunnel.

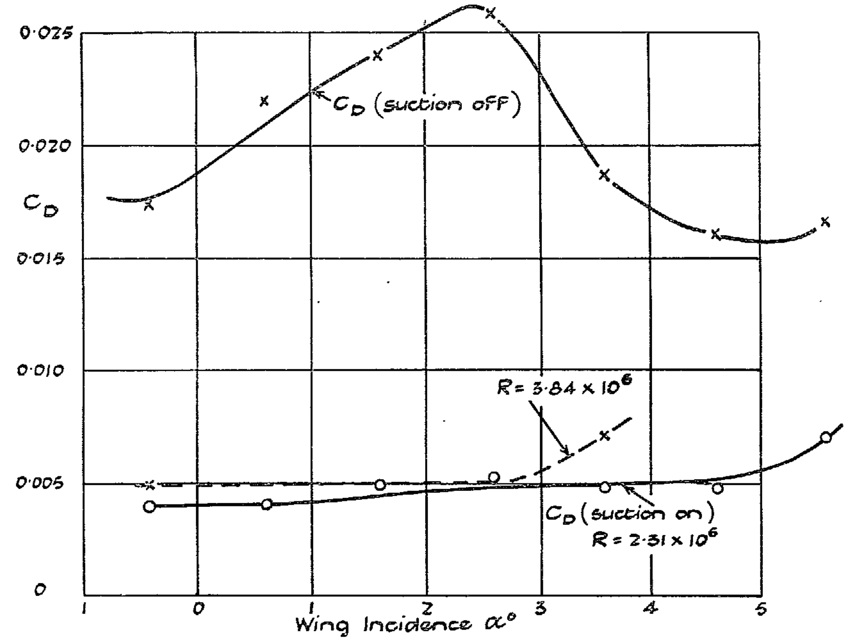


FIG. 46. Variation of Drag Coefficient (Pitot Traverse) with Incidence. $R = 2{\cdot}31 \times 10^6$.)

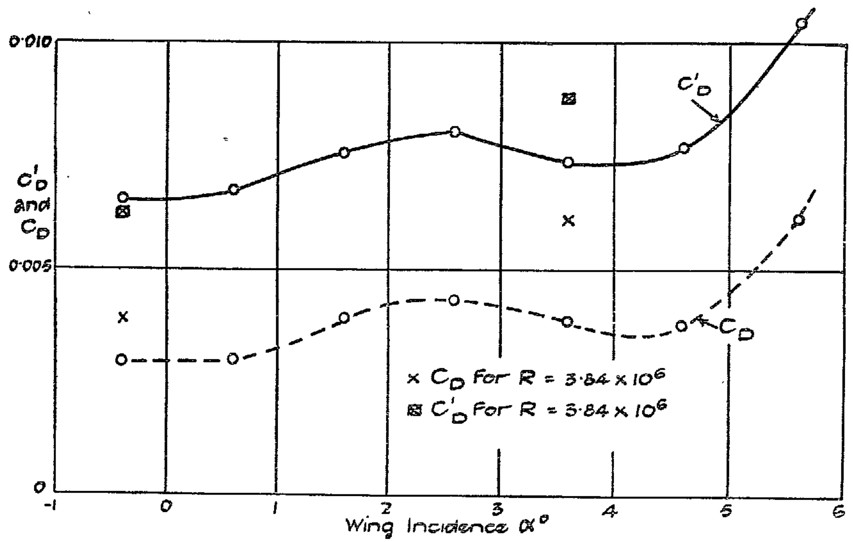


FIG. 49. Effective Drag Coefficient against Incidence. $R = 2{\cdot}31 \times 10^6$.

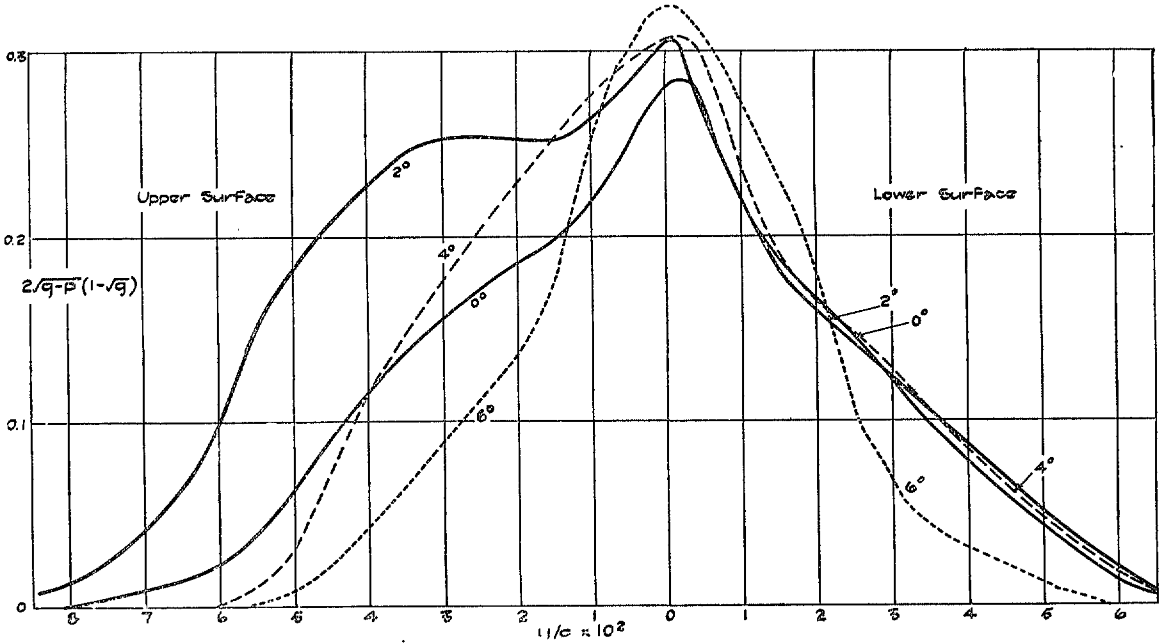


FIG. 47. Wake Profile at 0·1 chord behind T.E. Without Suction.

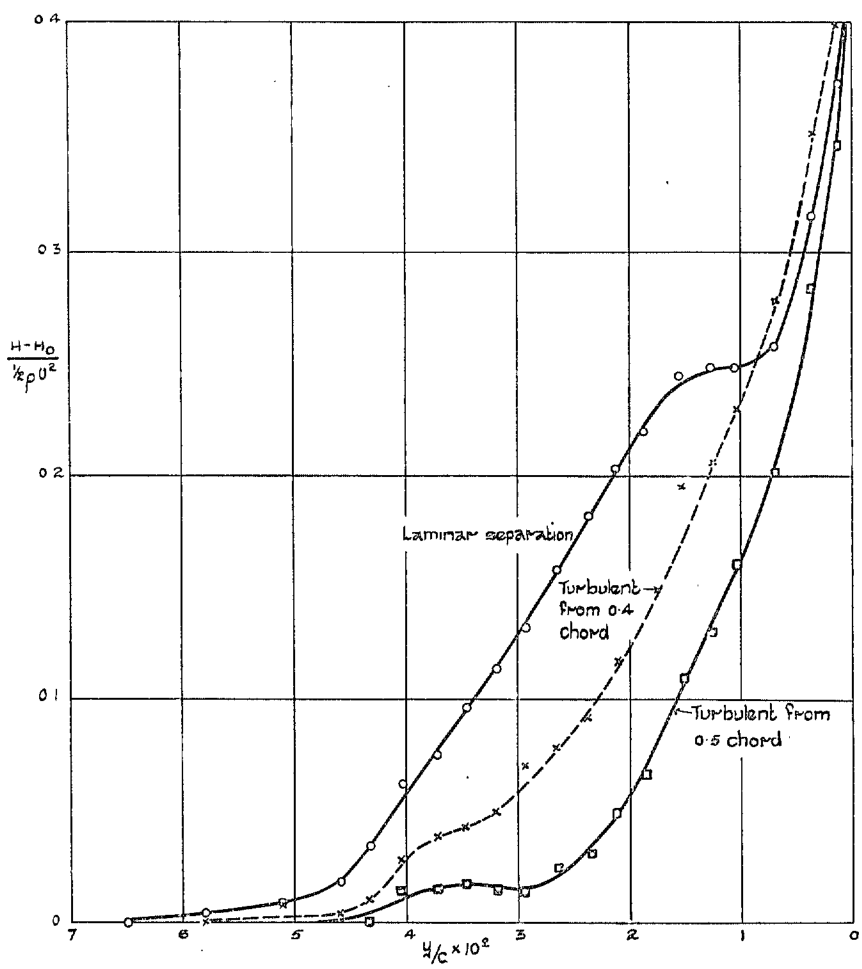


FIG. 48. Wake Traverse at T.E. (Upper Surface 2 deg.) Showing Reduction in Drag Obtained when Transition Occurs before Separation.

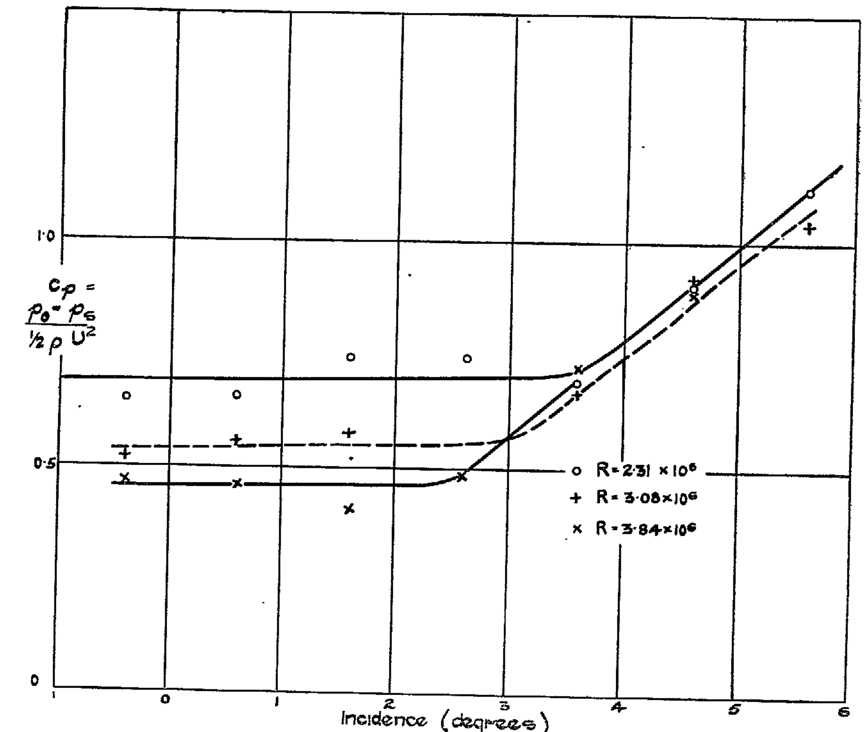


FIG. 50a. Variation of Suction Head in Box with Incidence. Upper Surface. Slot Width = 0·14 in.

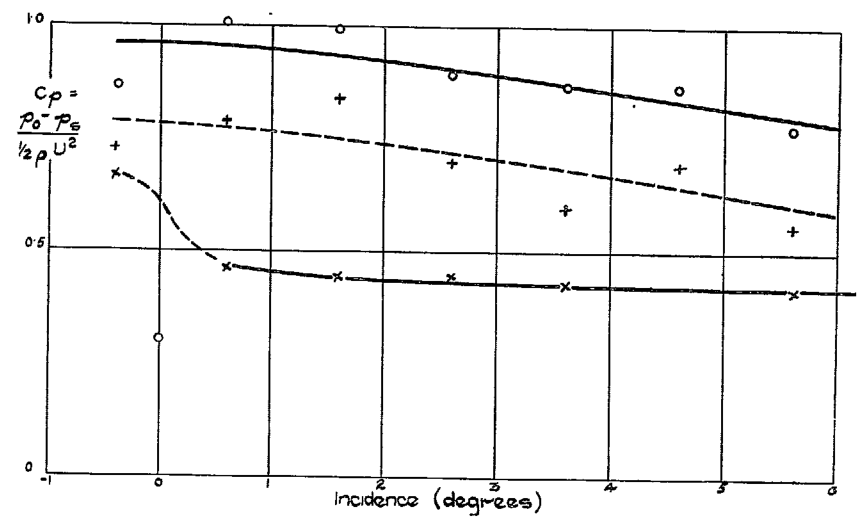


FIG. 50b. Variation of Suction Head in Box with Incidence. Lower Surface. Slot Width = 0·14 in.

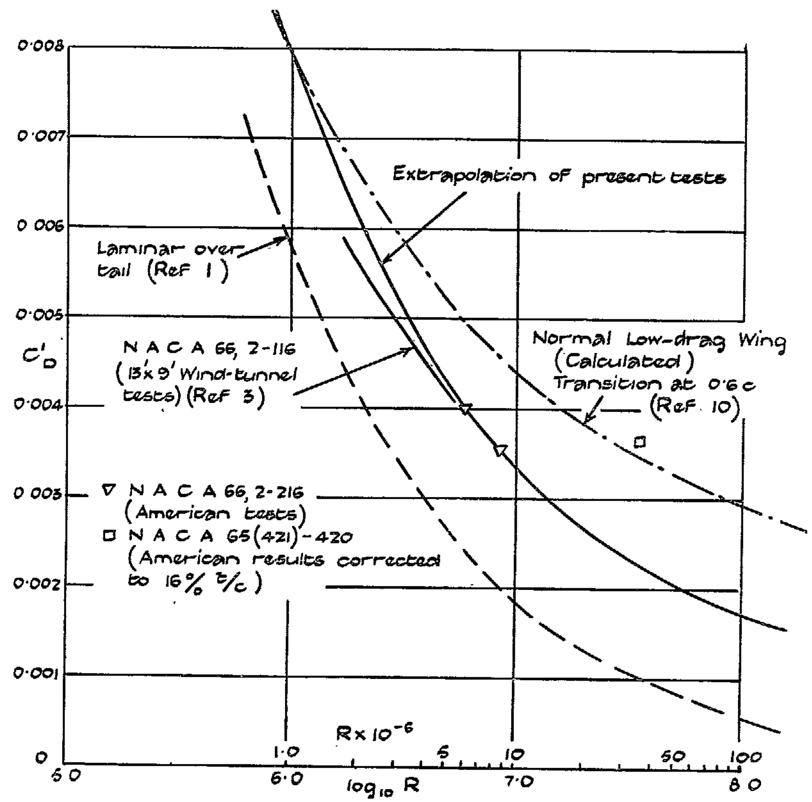


FIG. 51. Variation of Effective Drag Coefficient with Reynolds number.

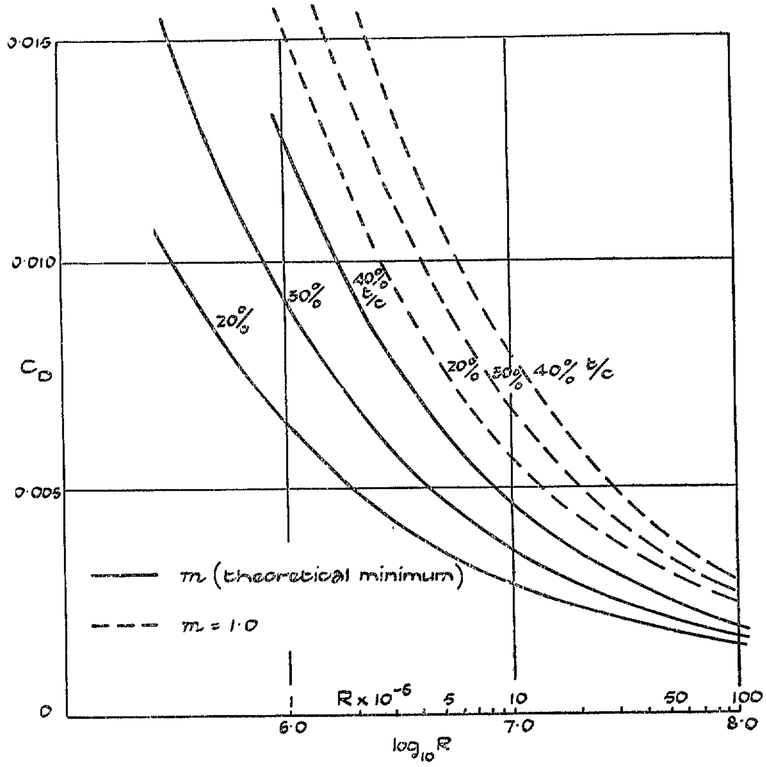


FIG. 52. Theoretical C_D' for Different Thickness-Chord Ratios. Slot at 0·7 chord.

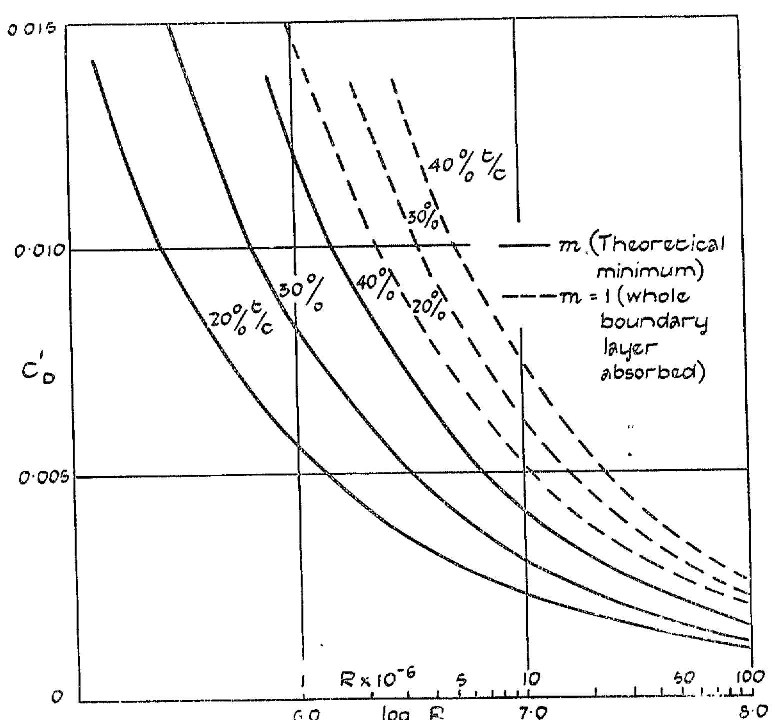


FIG. 53. Theoretical C_D' for Different Thickness-Chord Ratios. Slot at 0·8 chord.

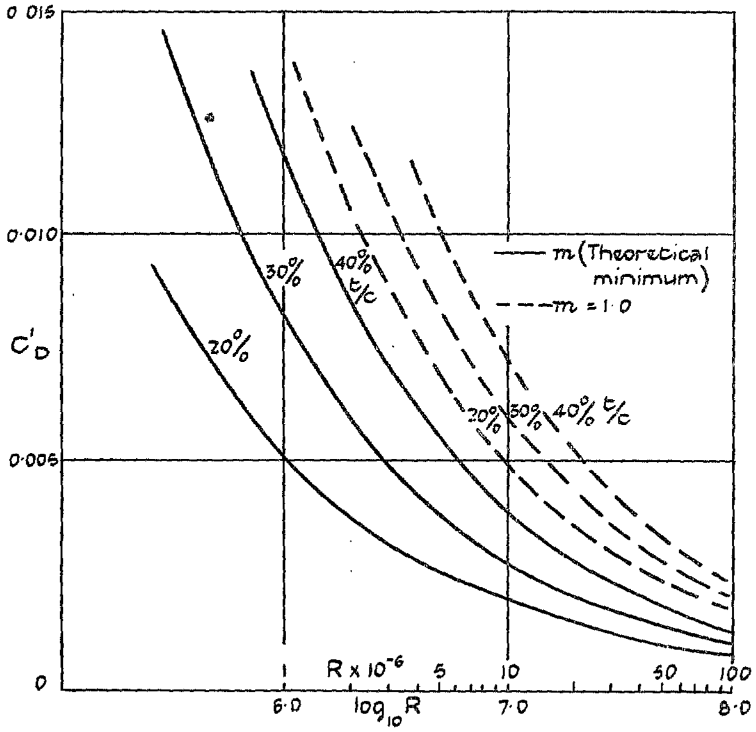


FIG. 54. Theoretical C_D' for Different Thickness-Chord Ratios. Slot at 0·9 chord.

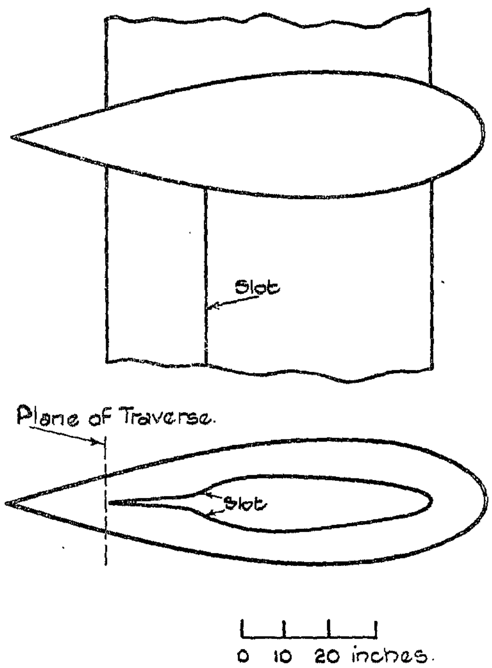


FIG. 55.

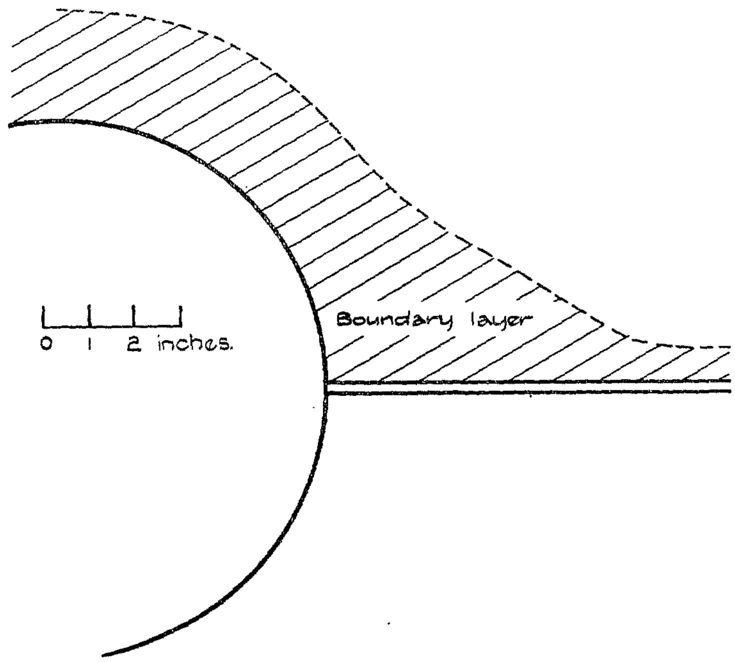


FIG. 56. Thickness of Boundary Layer at Wing-Nacelle Junctions (at T.E. of Wing).

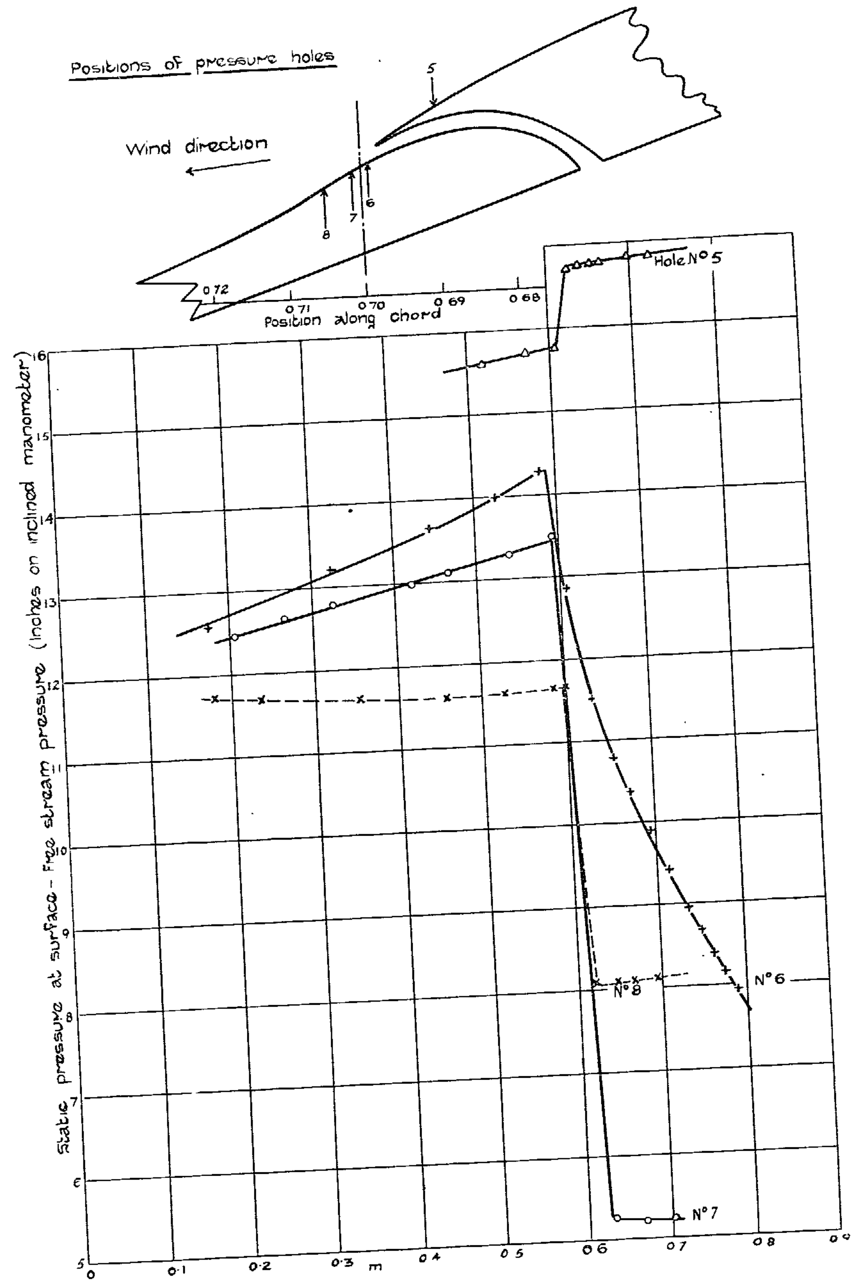


FIG. 57.

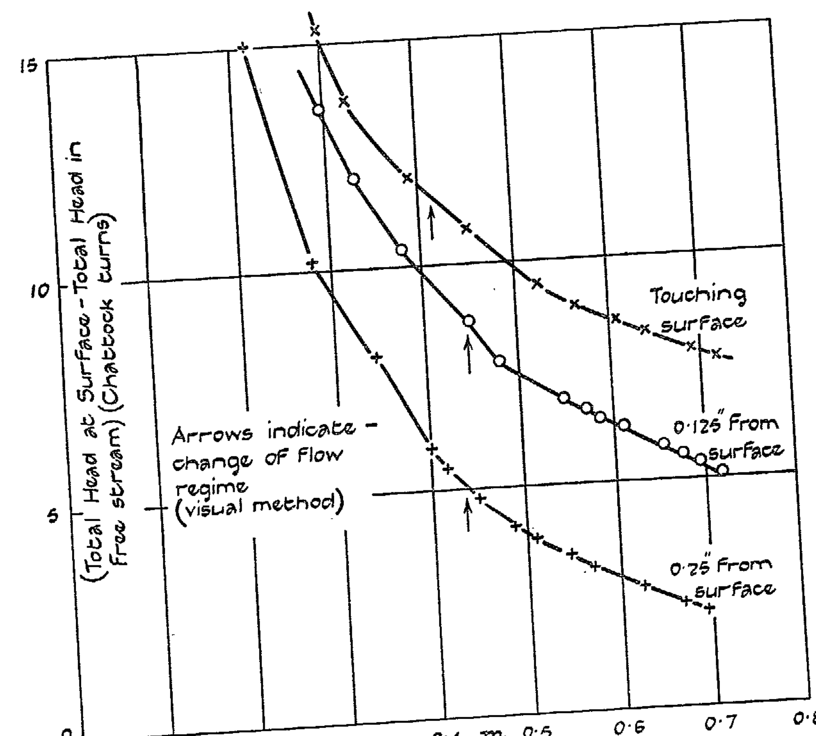


FIG. 58a. Variation of Total Head near Surface with Suction (60 deg. Panel) 3 in. rear of Slot. $R = 3{\cdot}84 \times 10^6$.

(78303) Wt. 10/7116 11/47 Hw. G377/1

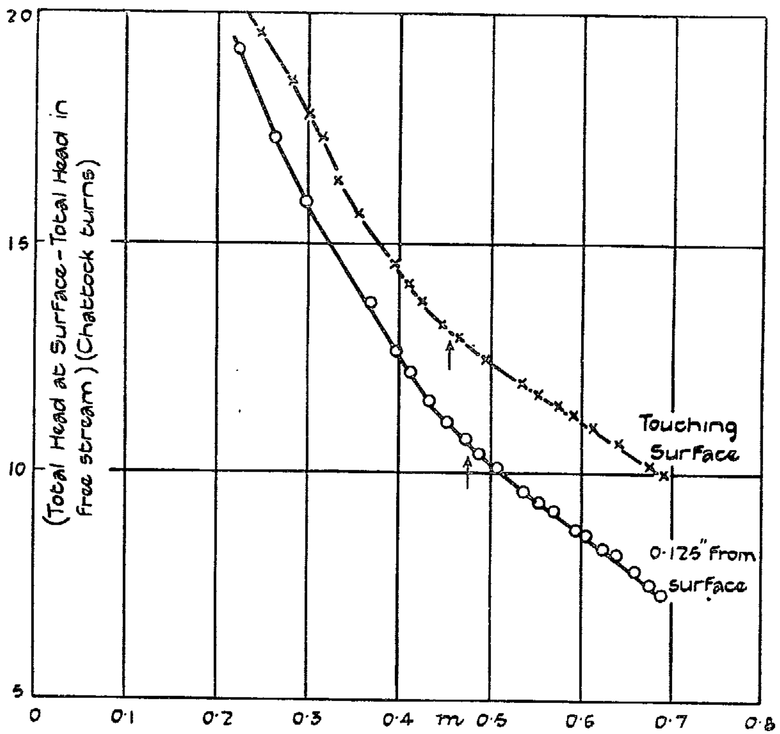


FIG. 58b. Variation of Total Head near Surface with Suction (60 deg. Panel) 0·5 in. behind Slot. $R = 3{\cdot}84 \times 10^6$.

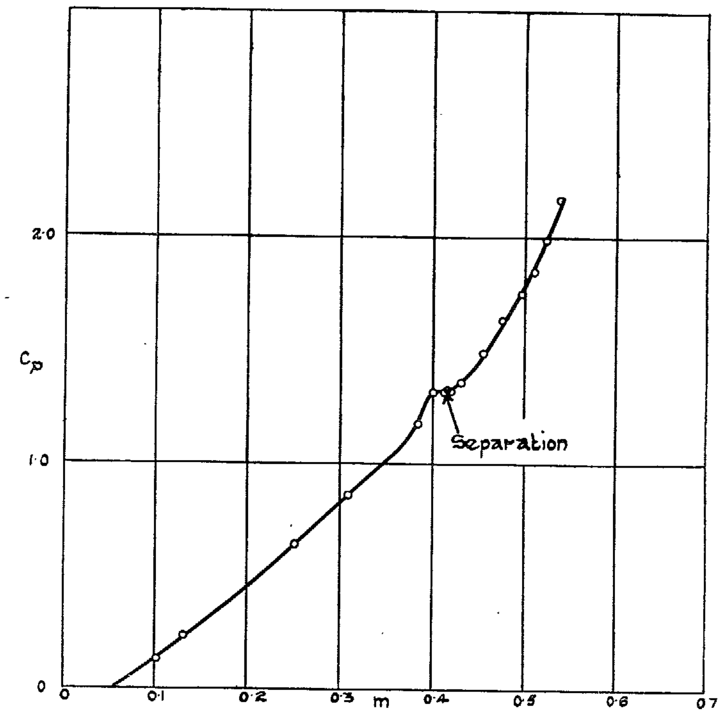


FIG. 59. Variation of Suction (60 deg. Panel) in Chamber with Amount of Air Absorbed. $R = 3{\cdot}84 \times 10^6$. Curve obtained with Decreasing Suction.

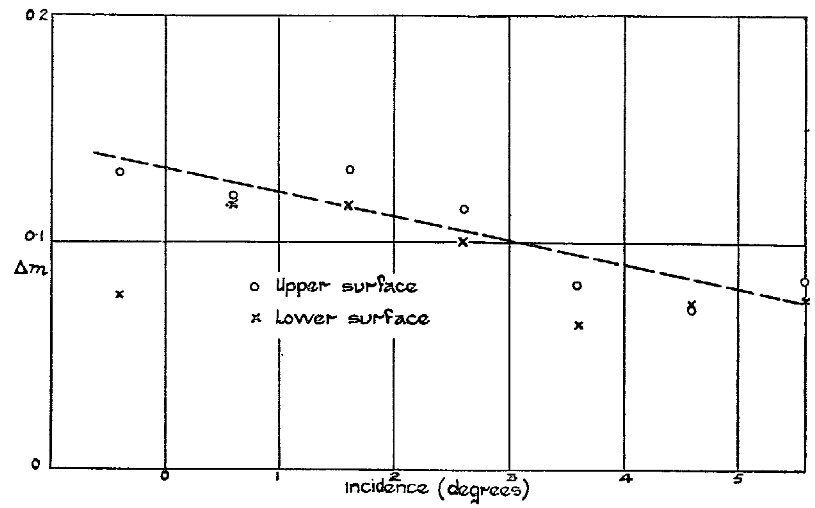


FIG. 60. Extra Suction Necessary to Establish Non-separated Flow (Variation with Incidence). $R = 2{\cdot}31 \times 10^6$.

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