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Summary.—This report describes the two-dimensional wind-tunnel tests carried out in the National Physical Laboratory 13×9 ft wind tunnel on a $31 \cdot 5$ per cent thick suction aerofoil, GLAS II, which has a single slot on the upper surface at 69 per cent chord. Both suction and blowing were used to prevent separation. Lift, drag, pitching moment, and the flow through the slot were measured. Tests without suction were made at Reynolds numbers of 0·96 and 2·88 millions. The results at the two Reynolds numbers were markedly different, and at the higher speed widely varying values of the drag-coefficient were recorded in the same conditions, there apparently being several possible régimes of flow. With suction, the pump power available only enabled tests to be made at the lower Reynolds number, and with the boundary layer on the upper surface laminar to the slot. At low incidences suction quantities agreeing well with theoretical estimates sufficed to maintain unseparated flow, but at higher incidences the flow tended to break down. Three or four times as much suction was required at all incidences to make the separated flow re-adhere. With blowing, still larger quantities were necessary, but the spanwise distribution of the flow from the slot was unsatisfactory.

Two different slot shapes were tested on the model, one with a sharp beak to the front lip, the other with a rounded entry. Intermittent separation of the flow occurred in each case. The phenomena may be of a fundamental character and associated with the profile shape rather than with the shape of the slot entry.

1. *Introduction.*—A full discussion of the ideas behind the design of the aerofoil section GLAS II is given by Glauert[1] (1945). Briefly, thick suction wings enable favourable pressure gradients to be obtained over all or a large part of the aerofoil chord, throughout a wide range of incidence, the extent of which is known as the C_L-range. This is achieved by designing the velocity distribution over the aerofoil surface to have one or more points at which the velocity rises discontinuously or very steeply, and at these points separation is prevented by the use of boundary layer control, usually suction at a slot. Up to the slot, well back on the chord, a thin laminar boundary layer may be obtained owing to the favourable pressure gradient, and the quantity of air to be removed by the slot is small. In spite of the large thickness, the effective drag should be no larger than that of a conventional aerofoil of much smaller thickness.

Most suction aerofoils previously considered have had two slots, one on each surface. The present section has only one, on the upper surface, but is cambered so that the adverse pressure gradients over the rear part of the lower surface are insufficient to produce separation. Details of the aerofoil's shape, velocity distribution, and theoretical characteristics are given in Fig. 1 and Table 1. The C_L-range extends from $C_L = 0$ to $C_L = 2 \cdot 0$, a value more than double that obtainable with a symmetrical suction aerofoil of similar thickness. In spite of the high degree of camber, a C_{M0} of zero is achieved. The single slot simplifies considerably the problems of incorporating the internal ducting in the wing and of controlling the suction distribution.

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The design of the aerofoil was carried out by Lighthill's exact method, as given by Lighthill[2] (1945) and Glauert[3] (1947). In Appendix IV of Ref. 3 the design calculations of this particular section are set out in detail. An intensive comparative study of the theoretical performance with suction of GLAS II and a 30 per cent thick symmetrical section is given by Preston, Gregory and Rawcliffe[6] (1948). Suction quantities, drag coefficients and pump powers are calculated for a wide range of Reynolds number and transition positions.

Extensive wind-tunnel tests have been carried out on the 30 per cent symmetrical section. The results agree well with theory and are reported by Gregory and Walker[7,8] (1946) and elsewhere. Thus the essential soundness of the suction principle is well established. The present tests were intended to confirm the theoretical design and the predictions of R. & M. 2577. The discontinuity of velocity at the slot is larger and the concavity to the rear of it is more acute than for the 30 per cent aerofoil, so greater difficulties might be expected in maintaining unseparated flow.

2. *Description of Model and Experimental Technique.*—The chord of the model was 30 in. and the span 9 ft, so that the aerofoil spanned the tunnel working-section vertically. At each end a turntable was fitted, to enable the incidence to be changed. The model was made up of chordwise mahogany laminations. As a result the waviness and roughness in the chordwise directions were kept to very low values, but the strength of the model for resisting lifting loads was seriously reduced. Appreciable spanwise bowing set in, and when the two halves of the model were taken apart for modifications to the slot, it was found that the thinner upper portion had bowed about half an inch more than the lower, and some difficulty was experienced when bolting the two halves together again. Also considerable warping had set in over the thin section to the rear of the slot. The pointed tip of the original backward facing slot was made of 'Jicwood' impregnated wood. The aerofoil was coated with black 'Phenoglaze' lacquer, which gave an excellent surface finish, and provided a contrasting base for viewing transition indication by the 'china clay' method.

The first slot was of the backward-facing type, so that it could be used for both suction and blowing. As originally constructed it was of width 0·05 in., but it proved impossible to obtain sufficient suction to prevent separation, so the slot was widened to 0·10 in. This slot (original slot shape) is shown in Fig. 2, together with the rounded slot 0·075-in. wide used later (section 5). The internal ducting was designed by Rawcliffe[4] (1947). One duct covered the central 4 ft of the span, and two other ducts each covered the outside 2 ft 6 in. The arrangement is shown in Fig. 3. The air on entering the slot was diffused; then the flow was divided into a number of channels and turned gently. The flow was reunited in the common collector duct. A metal plate was fitted along the span of each duct, to enable the overall spanwise distribution of suction to be adjusted. The arrangement by which the aerofoil was connected up to the pump is shown in Fig. 4. Air from the centre and lower sections of the span was taken out through pipes at the bottom of the aerofoil, and air from the upper section at the top. In each pipe was a baffle plate, to control the suction quantity. In the pipe from the centre section, after a suitable settling length there were fitted two traversing pitot tubes at right angles to each other, and two static holes in the wall, to measure the flow distribution. After calibration, one pitot alone in the centre of the tube and one static hole were used to record the suction quantity.

The pressure distribution over the aerofoil was determined from the readings of a large number of pressure holes. Integration enabled the lift and pitching moment coefficients to be calculated. The components of the pressure both along and perpendicular to the chord line were taken into account in each case. The pitching moments were calculated about 0·3 chord, this being near the theoretical centre of pressure. The drag was measured by a pitot-comb, mounted in the wake at 0·1 chord behind the trailing edge. The position of the transition of the boundary layer from laminar to turbulent flow, or alternatively laminar separation, was measured by the china-clay method developed by Richards and Burstall[5] (1945), using methyl salicylate as the indicator.

3. *Tests without Suction.*—Tests with all sections of the slot sealed off were made at tunnel speeds of 60 ft/sec and 180 ft/sec, corresponding to Reynolds numbers of $0{\cdot}96 \times 10^6$ and $2{\cdot}88 \times 10^6$ respectively. The behaviour in the two cases differed greatly, and furthermore at

180 ft/sec it was found that widely different results were obtainable on different occasions at the same incidence. The variations of lift, drag, and pitching moment with incidence are shown in Figs. 6, 7, 10. In Fig. 8, the variation is shown of transition position, as given by the china-clay method, with incidence. On the upper surface, the position indicated is that at which a laminar separation took place in front of the slot. On the lower surface, at 180 ft/sec there was an ordinary transition to turbulence in the boundary layer, at any rate at low incidences ; but at 60 ft/sec the pressure distribution makes it appear probable that a laminar separation was occurring, followed by transition and the re-adherence to the surface of the turbulent layer, the china-clay indicating the point of re-adherence.

At 60 ft/sec, $R = 0 \cdot 96 \times 10^6$, the lift-coefficient rose steadily with incidence to a maximum value of $1 \cdot 43$ at 18 deg. The readings lay well on a curve and no difficulty was experienced in getting repeats. The wake was wide and the loss of total head was large, so that the drag could only be determined from the pitot-comb readings for a limited range of incidence, and even these values are somewhat suspect. The moment readings are scattered, and the accuracy is probably low.

At 180 ft/sec, $R = 2 \cdot 88 \times 10^6$, there was a considerable amount of scatter on the lift readings, but the curve rose steadily with a rather smaller slope than at the lower speed, to a maximum C_L of nearly $1 \cdot 2$ at 18 deg. There was an immense variation of the drag readings, vastly different values of the drag-coefficient being recorded at different times in the same conditions. There were apparently at least three possible régimes of flow. At low incidence C_D was either in the neighbourhood of $0 \cdot 02$, or of $0 \cdot 035$. On one or two occasions readings around $0 \cdot 01$ were obtained. The shape of the wake as shown on the pitot-comb manometer was distinctive in each case, and occasionally the drag would switch over from one condition to another in the course of a run. It was noticed that the lower drags tended to be associated with the higher speeds ; as the tunnel was run up the drag would suddenly fall, and sometimes a lower drag could be obtained by increasing the speed well above 180 ft/sec. Often one condition would persist unchanged throughout the day, and next morning a different condition would be equally stable. The transition line obtained by the china-clay method was not noticeably affected by the changes. Threads were glued to the surface behind the slot. They usually indicated a complete separation over the tail region, but with the lowest drags there were signs that the flow was rejoining the surface near the trailing edge. In all cases the pitot-comb showed there was no appreciable dead-air region $0 \cdot 1$ chord behind the trailing edge. No satisfactory explanation of these curious phenomena was arrived at. The moment readings were also considerably scattered, but generally they lay along the same curve as is drawn for the 60 ft/sec case.

4. *Tests with Suction*.—As mentioned earlier, it proved impossible with the original $0 \cdot 05$ in. slot to prevent separation at any reasonable tunnel speed with the pump power available. With the greater slot width of $0 \cdot 1$ in., at low incidence the flow would adhere past the slot at speeds up to about 140 ft/sec. The suction distribution along the span of the slot was measured and, as is seen from Fig. 5, proved to be highly satisfactory. The maximum variation along the 4 ft centre section was about $\pm$ 5 per cent. The suction on the outer sections was adjusted to be slightly greater. Unfortunately, however, it proved impossible to produce unseparated flow on the outer 18 in. of the span, as the boundary layer on the wall of the tunnel gave rise to thick boundary layers on the aerofoil which were beyond the power of the slot to remove. As a result the aerofoil probably had a fairly small effective aspect ratio. The results as given in the figures contain no correction for any form of tunnel interference.

The measurements were all taken at a tunnel speed of 60 ft/sec, corresponding to a Reynolds number of $0 \cdot 96 \times 10^6$. Transition measurements showed that the boundary layer on the upper surface remained laminar right up to the slot. A wire to induce transition was fitted on the upper surface, but it proved impossible to achieve steady unseparated flow with the suction power available. Similarly, once the incidence increased above the top of the C_L-range, so causing adverse pressure gradients and a turbulent boundary layer, it was impossible to maintain unseparated flow. The highest reading obtained was a lift-coefficient of $1 \cdot 94$ at a geometric incidence of 16 deg. A transition wire was fitted in some tests at 55 per cent chord on the lower surface, to avoid the laminar separation occurring at this low Reynolds number, mentioned in the previous section. This was successful in producing a turbulent layer, but the overall effect on the aerofoil proved to be negligible.

The behaviour of the suction quantity to prevent separation, as shown in Fig. 9, was peculiar. At negative incidences the quantity required was only slightly greater than that estimated in the detailed theoretical calculations of R. & M. 2577, and the flow was completely stable. As incidence was increased this suction quantity tended to rise slightly. At a certain incidence the flow, after remaining on the surface for a minute or more, would suddenly flick off. Once separated, the suction had to be increased to three or four times its previous value to make the flow re-adhere to the surface. This hysterersis effect was most marked at all low incidences. As incidence was further increased, the time for which the flow would remain on the surface with the low suction quantity diminished, until an incidence was reached at which the flow broke away almost immediately. With the higher suction quantity, that needed to cause separated flow to re-adhere, the flow was quite stable at all incidences up to about 10 deg after which it tended to kick off occasionally, but would immediately return to the surface. The incidence at which the flow with the low suction quantity became unstable varied considerably from day to day. The results of two widely differing trials are shown in Fig. 9. On the first occasion instability was first noticed at 2 deg and at 4 deg it was impossible to record a low reading. On the second occasion the instability was delayed until 6 deg, and did not become serious until 12 deg was reached. In no case was any difficulty experienced in determining the minimum critical suction quantity, a sudden drag rise to many times its previous value being shown on the pitot-comb as separation occurred.

The experimental lift-curve and no-lift angle agrees well with theory. The value of $2 \cdot 0$ at the top of the C_L-range is closely approached, and the lift-curve slope is $6 \cdot 81$ as against the theoretical value of $7 \cdot 74$, due in part to the separated flow over the outer sections. The drag as measured on the pitot-comb is almost entirely due to the unsucked boundary layer on the lower surface. Neither lift nor drag were at all sensitive to variations of suction quantity. The profile drag agrees well with the theoretical predictions of R. & M. 2577. The pitching moment curve in Fig. 10 shows that $C_{m0} = - 0 \cdot 01$, as against the theoretical value of zero, and the centre of pressure is at about $0 \cdot 31$ chord, agreeing well with the predicted value. Pressure plotting seemed to incur a fair amount of scatter on the readings. The pressure distributions obtained agree well with theory, except near the slot where there is considerable sink effect. The example shown in Fig. 12 is with the larger suction quantity, and for $0 \cdot 05$ chord in front of the slot the velocity commences to rise steeply.

5. *Tests with a Modified Slot.*—It was hoped to improve the stability of the flow by modification of the slot entry shape. The original slot was thought to have a standing vortex over the back of the front lip from which eddies broke away downsteam, so a new slot with a well-rounded upper lip and a different direction of entry was chosen, this being the best of a series of four designs tested in the 1-ft wind tunnel by Mr. A. G. Rawcliffe. The floor of the tunnel was built up into a symmetrical bulge, shaped so as to produce discontinuities in velocity (at each end) equal to that of GLAS II. As the minimum suction quantity required to prevent separation was not appreciably affected by changes in slot shape, the slot design finally selected was that which gave the smallest pressure drop to the collector duct. Intermittent separation still occurred, but only occasionally; it was attributed to poor spanwise distribution of the suction flow, because increasing the uniformity resulted in reductions in minimum suction quantity. The slot finally chosen was made $0 \cdot 075$ in. wide, and is compared in Fig. 2 with the original shape.

With the new slot incorporated in the GLAS II model, no improvement was observed with regard to intermittent separation, and no reduction was obtained in minimum suction quantity for preventing separation.

The new slot was used with a more efficient ducting system. The spanwise distribution of suction flow could not be checked as the slot did not run full during exploration (at zero tunnel speed). The resultant variation in velocity across the slot, coupled with slight variations in the contour of the slot, made it impossible to take steady readings. Such measurements as were obtained, however, did not indicate the existence of any marked irregularities in the spanwise distribution of suction flow.

The reason for the intermittent separation phenomena remains a matter of speculation. The effect has now been observed with two widely differing slot entry shapes on the GLAS II in this country, and also with a GLAS II model tested in Australia [9, 10]. It thus appears to be associated with the aerofoil profile rather than with the slot design. This observation is supported by the fact that the Australians surmounted the difficulty by rather drastic modifications to the aerofoil shape near the discontinuity. They pared away the shoulder and inserted two additional slots (Fig. 1). They thus spread the fall in velocity over an appreciable distance along the surface without causing separation, and eventually obtained stable flow with a low total suction quantity.

Other evidence on slot suction towards the rear of a thick aerofoil is provided by the tests on the 30 per cent Griffith aerofoil[7]. In this case no intermittent separation was experienced. The aerofoil differed from the GLAS II in that the velocity discontinuity was only 2·16 instead of 3·08 and was effectively spread over a small chordwise extent of the surface* owing to the approximate method by which the profile was designed. The GLAS II was designed by an exact method, with the result that the velocity drop should theoretically be discontinuous. More recent technique with the exact method enables the velocity fall to be spread over any short distance.

It seems probable, therefore, that the intermittent separation phenomena is either due to the magnitude of the velocity ratio at the slot (3·08), or to its being localised at a point instead of being spread over a small chordwise extent of the aerofoil surface, or to the associated abrupt changes of surface curvature.

6. *Tests with Blowing.*—For blowing the same ducting was used as for suction, but connected up to the outlet instead of the inlet of the pump. It was necessary to modify the calibration pipes so that the measuring pitot-tubes were not in the immediate wake of the baffle plates. Calibrations were made for various settings of the plate but, except with the plate almost closed, the calibration factor remained very nearly constant. The tests were carried out with the original slot shape. The distribution of blowing quantity along the span of the aerofoil involved some most curious phenomena. As measured by a total head tube in the slot mouth, the variations along the span seemed small, and this was confirmed by pitot traverses across the jet. However, at about $0 \cdot 15c$ behind the slot, pitot-traverses showed a much greater flow at some points than at others. The variations were periodic along the span with period 3 in., corresponding to the spacing of the partitions inside the slot, the flow maxima being approximately in the wake of the partitions. The flow was separating from the surface immediately behind the slot owing to the large concavity, and was rejoining the surface shortly afterwards, but the separation was occurring later and the return taking place earlier in the wake of the partitions than elsewhere possibly owing to a turbulent boundary layer from the partitions. The asymmetry was resulting in the jet concentrating behind the partitions. By the time the jet reached the pitot-comb behind the trailing edge of the aerofoil, the flow had largely evened itself out again. In spite of this peculiar behaviour, the tests were proceeded with.

The quantities of air necessary to prevent separation proved to be far larger and less well defined than with suction. For quantity coefficients less than those shown in Fig. 9, the pitot-comb behind the trailing edge recorded a wake from the upper surface of a width as much as 0·15 chord. As the blowing was increased, the loss of total head in the wake diminished, but its width remained sensibly unchanged, until with a sufficient quantity the wake disappeared altogether. In this condition the readings were taken. So much air was being ejected that the

* Yet the velocity fall was localised in practice by the sink effect to lie between the front lip of the slot and the stagnation point to the rear of the slot.

pitot-comb in the wake recorded a thrust instead of a drag. This behaviour was presumably due to the asymmetry of the jet from the slot, and with more suitable ducting or a differently shaped slot the ejection quantity required might be considerably reduced.

The blowing quantities used were limited by the pump power available, but were generally just sufficient. Transition was found to occur about 0·1 chord in front of the slot. The lift-curve, as shown in Fig. 6, had the same slope as with suction, but the value of the lift-coefficient was about 0·25 less than that with suction at the same incidence. A maximum lift-coefficient of 1·9 was recorded. At higher incidences the lift dropped, though the blowing power available was enough to prevent any serious separation over the tail. The blowing quantities used are those shown in Fig. 9.

The moment coefficients were sensitive to changes in blowing quantity, and do not lie at all well on a curve. The values are about 0·07 higher than with suction. Several of the pressure holes on the upper surface behind the slot gave curious readings. Immediately in rear of the slot one or two holes recorded very high pressures, which were ignored in the integrations to find the lift and pitching moment. As is seen, for example in Fig. 12, the pressures over the extreme tail ended to rise above the total pressure in the main stream. It will also be seen that a definite falling-off of velocity is recorded just in front of the slot.

It may be, that for preventing separation the velocity of ejection is as important as the quantity ejected. With the present slot, the velocity of ejection V_e is given by $V_e = 300\ C_Q U$*. Thus is the present tests V_e was in the neighbourhood of $6U$. To maintain a high value of V_e while reducing C_Q a narrower slot would be necessary.

7. *Conclusions and Future Developments.*—Without suction there is still need for considerable clarification. The lift-curve is free from kinks and rises to a value of well over unity, more than double that at which a partial stall was recorded on the 30 per cent symmetrical section, so that on an aeroplane the stalling speed without suction should not be too dangerously high. The behaviour of the drag at the higher Reynolds number is perplexing. Variations of the flow in the tunnel may account for the difficulty of repeating readings, but clearly the aerofoil is inherently capable of producing various flow patterns. The extent of the separation over the rear of the aerofoil definitely tends to decrease with increase of Reynolds number, and some of the drag-coefficients recorded at the higher speed are very small indeed. Tests carried out in the Compressed Air Tunnel by Salter[11] (1948) at higher Reynolds numbers have revealed stable flow conditions, but with considerable scale effect present.

Of the performance with suction, once separation is overcome, the aerofoil behaves as theoretically predicted within the C_L-range, no difficulty was experienced in getting laminar flow right up to the slot, indeed a rapid velocity rise took place immediately before it, but this was mainly due to the large suction quantities which had to be used.

The intermittent separation observed with the GLAS II section is a new and unexpected phenomenon which is probably of a fundamental character. Although the practical difficulties may be overcome by suitably modifying the aerofoil contour, the phenomenon does not appear to recur in aerofoil designs with sharper and greater drops in velocity

The quantity of air required to prevent separation, when blowing, was large. The jet left the surface for a small distance before rejoining it, encouraging irregularities in the flow to develop. It is difficult to see how to avoid the trouble in view of the large concavity behind the slot; this is another reason for preferring suction to blowing on thick suction aerofoils. The mechanism by which blowing overcomes separation is not fully understood. Probably the jet forces the boundary layer off the surface, while the outer portions of the jet swiftly mix with the inner and slowest moving part of the boundary layer, raising its energy and enabling it to cross the discontinuity. If this is the case the velocity of the jet may be the significant parameter, and a narrower slot might permit smaller quantities to be used.

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*$C_Q = Q/Uc$, where Q is the quantity per sec per unit span, U the stream velocity and c the chord. This is the expression given in Fig. 9.

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TABLE 1

Details of GLAS II

Ordinates	Lower Surface		Upper Surface	
	x	y	x	y
	0	0	0	0
	0·00007	–0·00229	0·00017	0·00290
	0·00118	–0·00680	0·00119	0·00861
	0·00394	–0·01096	0·00307	0·01475
	0·00803	–0·01519	0·00578	0·02123
	0·01327	–0·01947	0·02438	0·04954
	0·01957	–0·02376	0·05460	0·07988
	0·02688	–0·02805	0·09540	0·11036
	0·03515	–0·03231	0·14550	0·13935
	0·04434	–0·03654	0·20344	0·16546
	0·08973	–0·05272	0·26745	0·18749
	0·14737	–0·06720	0·33564	0·20427
	0·21516	–0·07930	0·40591	0·21523
	0·29079	–0·08846	0·47604	0·21929
	0·37179	–0·09422	0·54363	0·21589
	0·45550	–0·09612	0·60606	0·20421
	0·53921	–0·09372	0·65963	0·18276
	0·61999	–0·08588	0·67089	0·17549
	0·69844	–0·07080	0·68088	0·16719
	0·77532	–0·05251	0·68878	0·15755
	0·84703	–0·03484	0·69196	0·15225
	0·87964	–0·02701	0·69248	0·14920
	0·90937	–0·02012	0·69109 –Slot–	0·14684
	0·93562	–0·01427	0·68681	0·13957
	0·95792	–0·00949	0·68840	0·13018
	0·97574	–0·00571	0·69819	0·11385
	0·98881	–0·00279	0·71954	0·08773
	0·99705	–0·00071	0·74436	0·06715
	1·00000	0	0·77000	0·05065
			0·82047	0·02677
			0·86681	0·01176
			0·90727	+0·00298
			0·94091	–0·00135
			0·96723	–0·00268
			0·98591	–0·00205
			0·99669	–0·00061
			1·00000	0

Theoretical Characteristics

Thickness = 31·5 per cent
C_L-range $C_L = 0$ to $C_L = 2 \cdot 004$
(corresponding to an incidence range of 15 deg)

$C_{M0} = 0$

Theoretical lift-curve slope 7·743
No-lift angle –1 deg 49 min
Aerodynamic centre $x = 0 \cdot 3077$
Maximum velocity at $C_L = 2 \cdot 004$, $q = 1 \cdot 901$
Maximum velocity at $C_L = 0$, $q = 1 \cdot 750$
Position of suction slot $x = 0 \cdot 6911$
Ratio of velocities at slot 3·081 : 1
Critical Mach number = 0·458

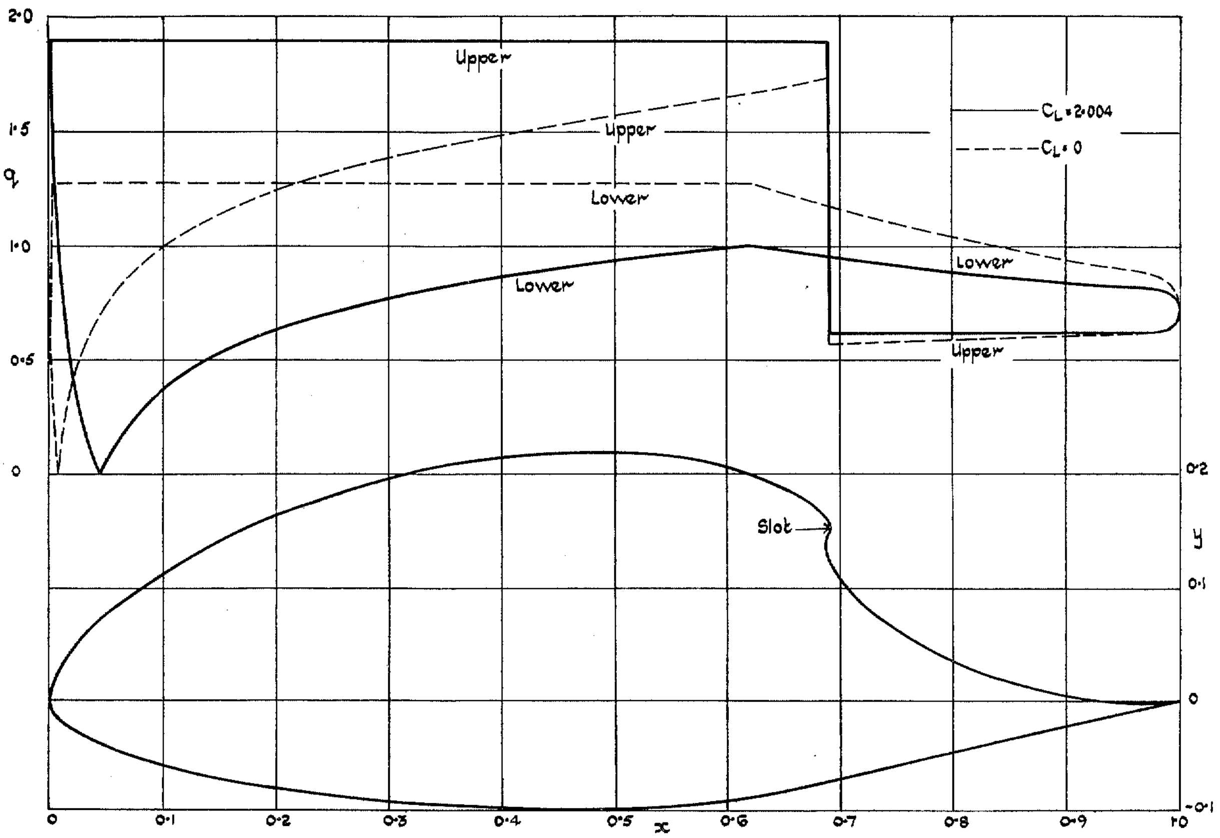

FIG. 1. Suction aerofoil with a single slot. 31·5 per cent thick.

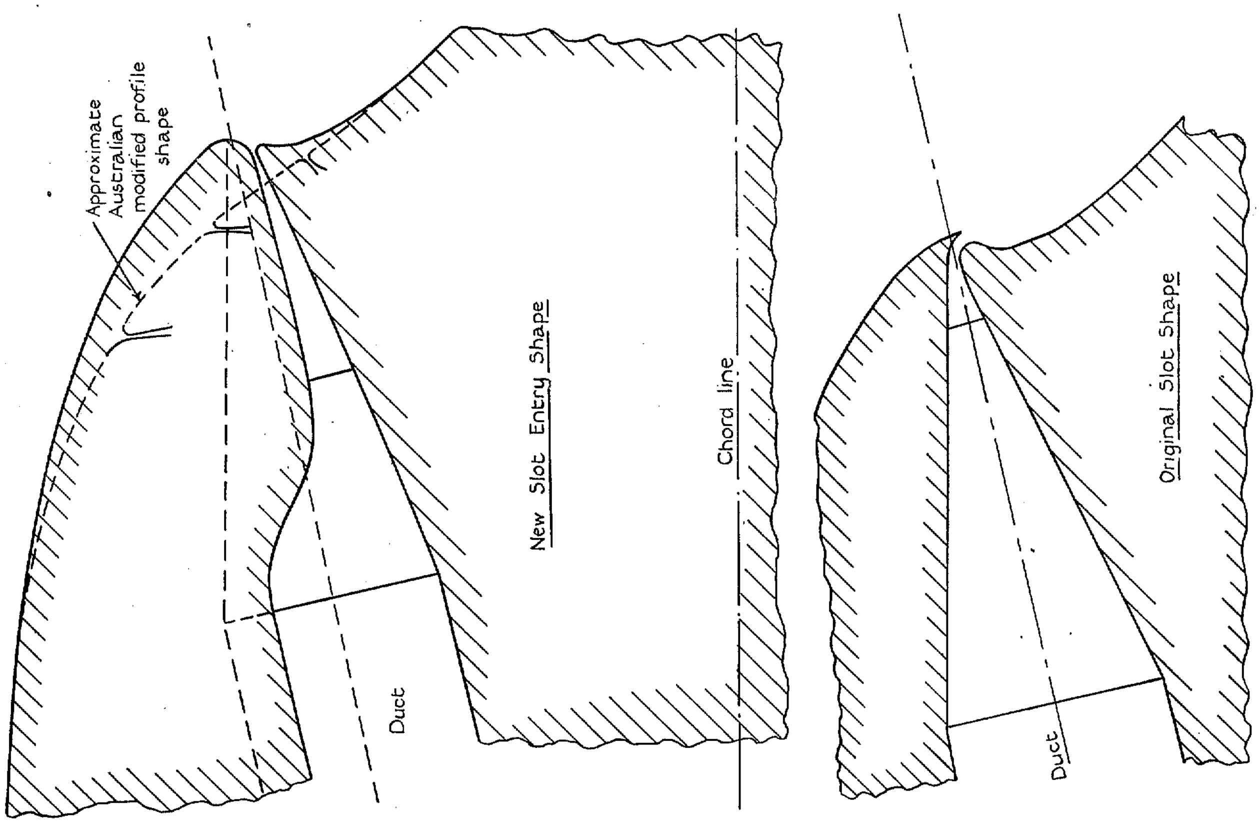

FIG. 2. GLAS II profile and slots.

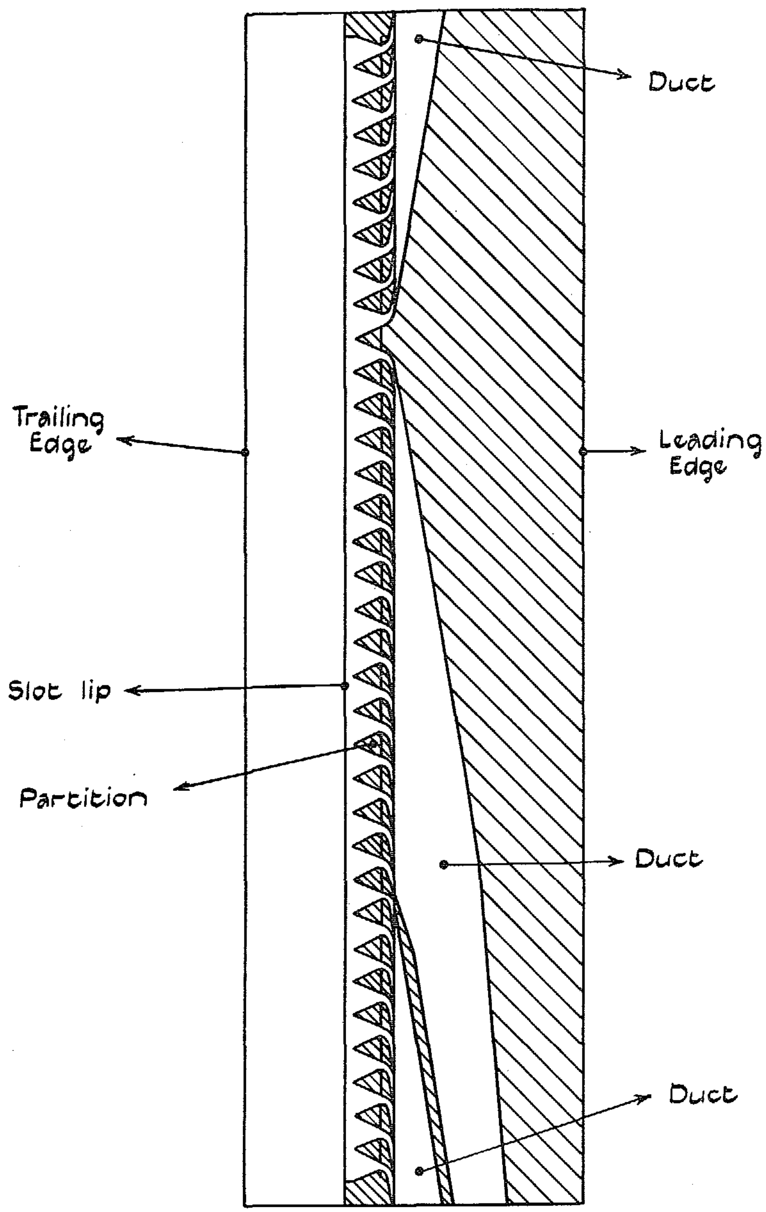

Fig. 3. Internal ducting in wing.

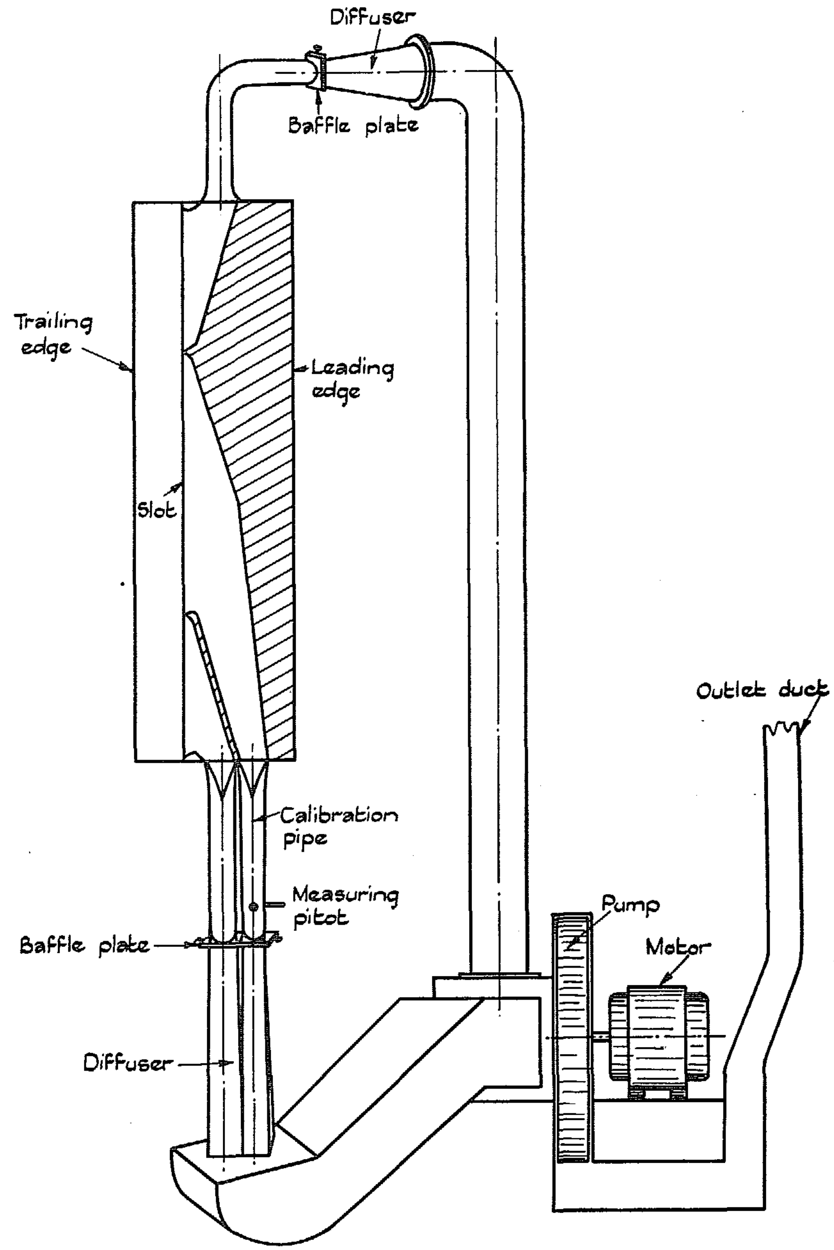

Fig. 4. General layout of ducting.

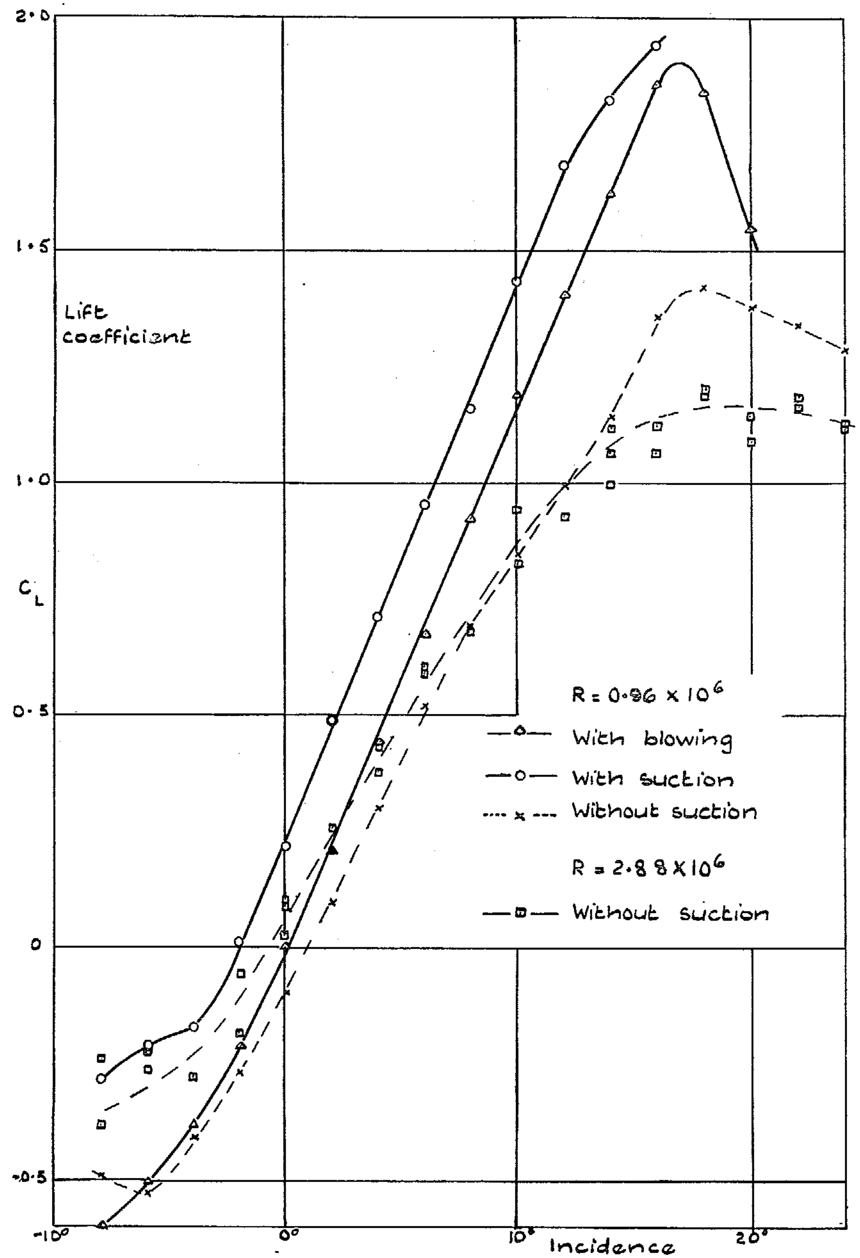

FIG. 6. Variation of lift with incidence, with and without suction and with blowing.

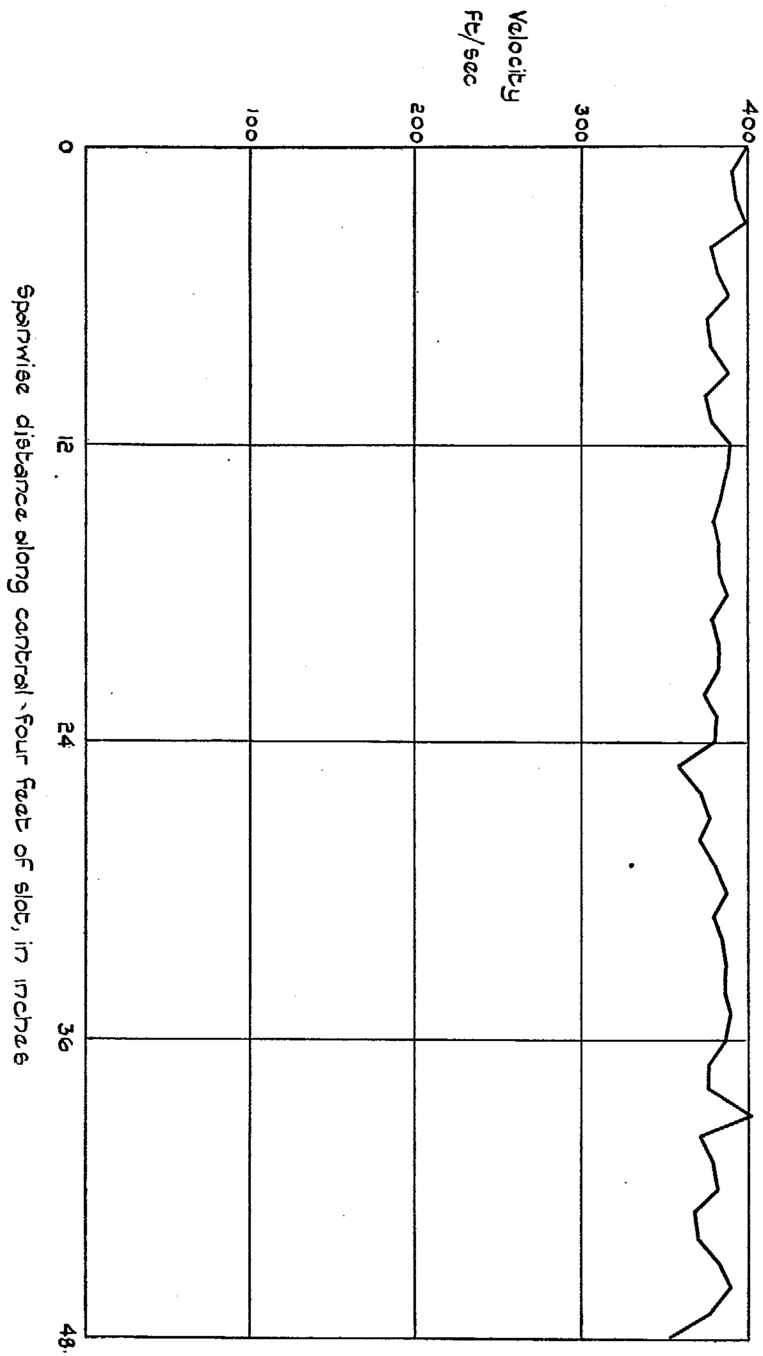

FIG. 5. Distribution along span of velocity into slot. Slot width 0·1 in.

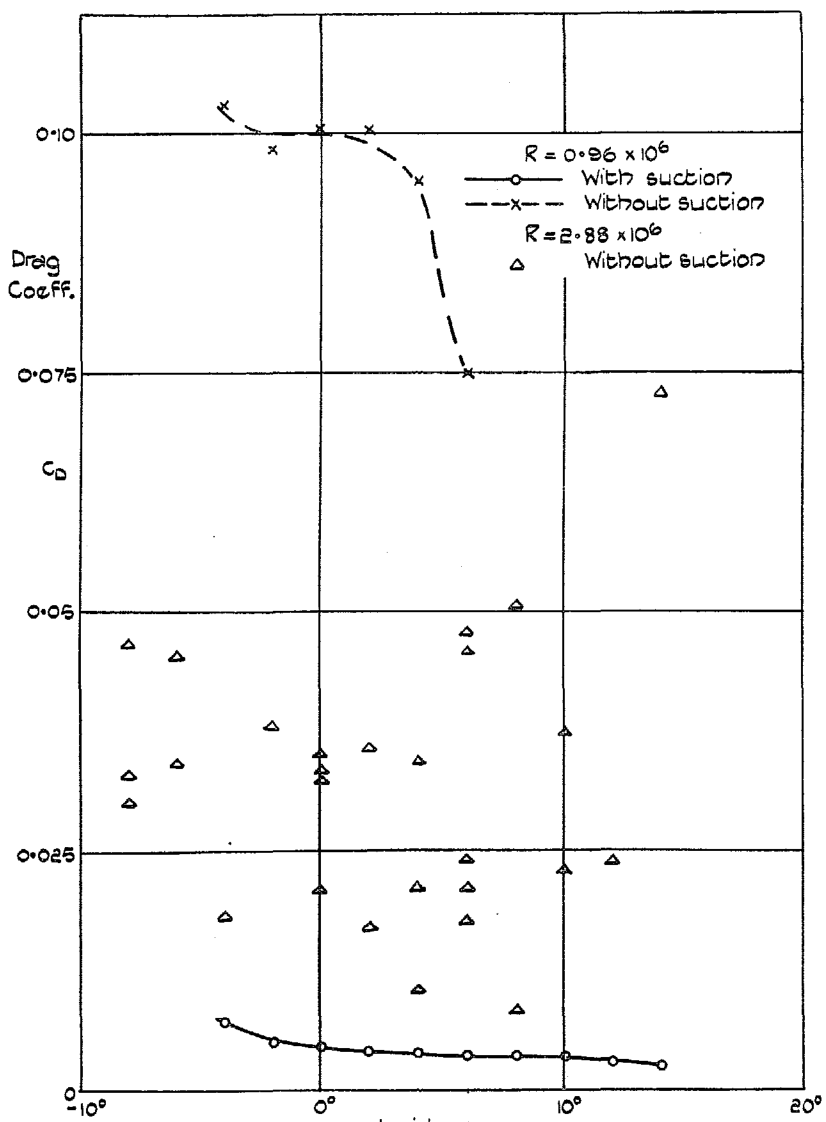

FIG. 7. Profile drag coefficient, with and without suction.

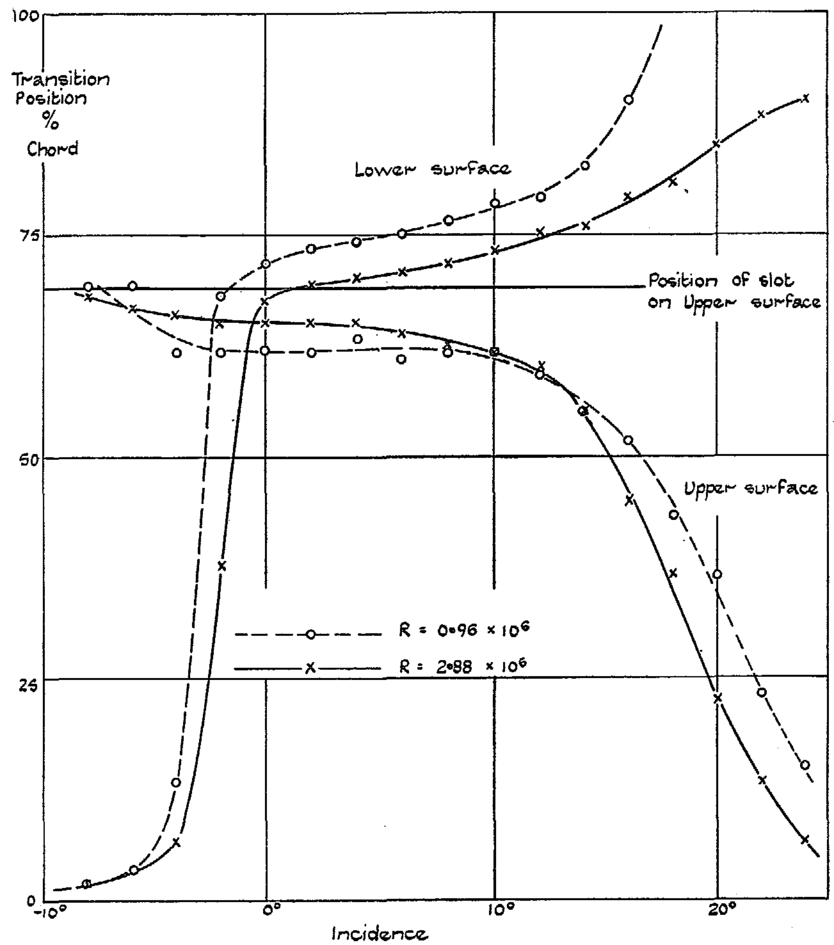

FIG. 8. Transition as recorded by the china-clay method. No suction.

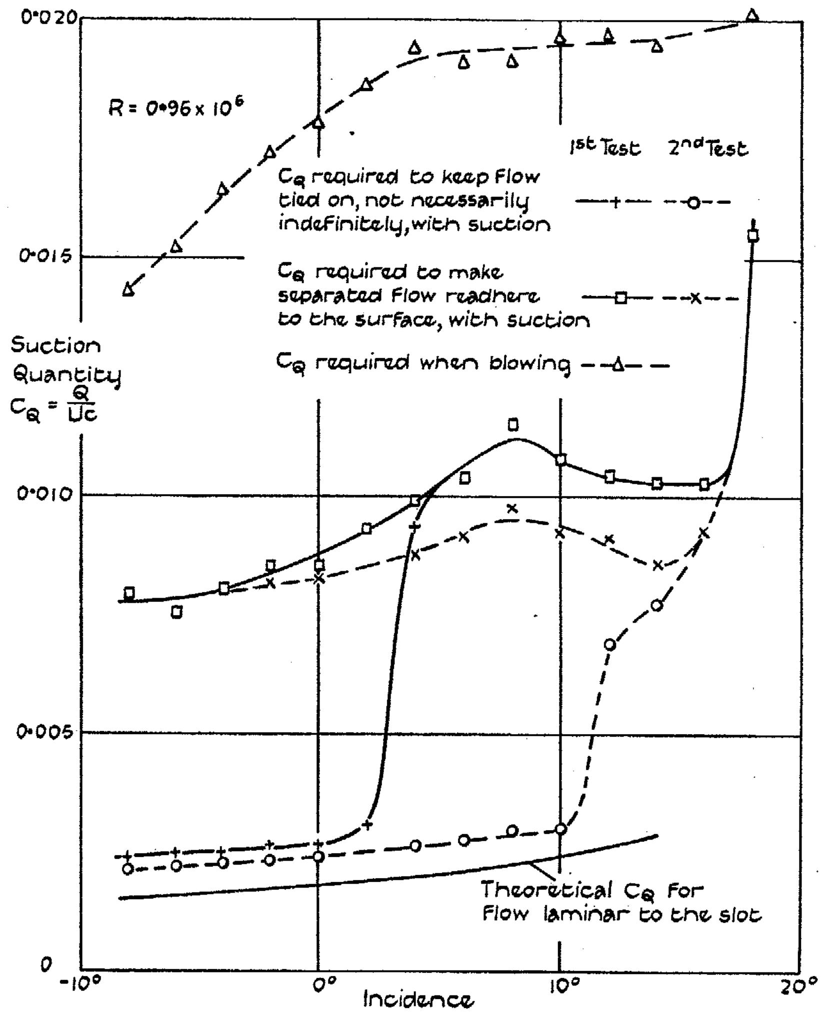

FIG. 9. Suction quantity to prevent separation.

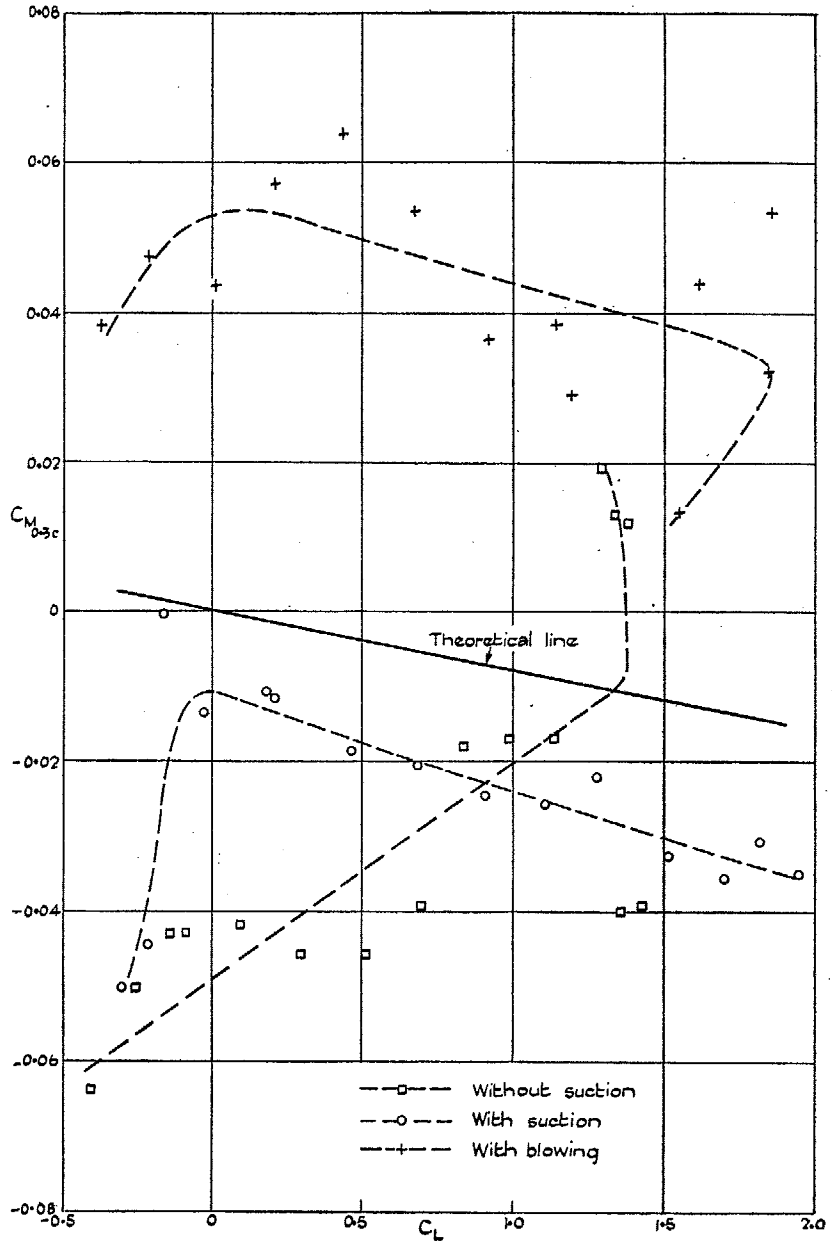

FIG. 10. Pitching moment, with and without suction and with blowing.

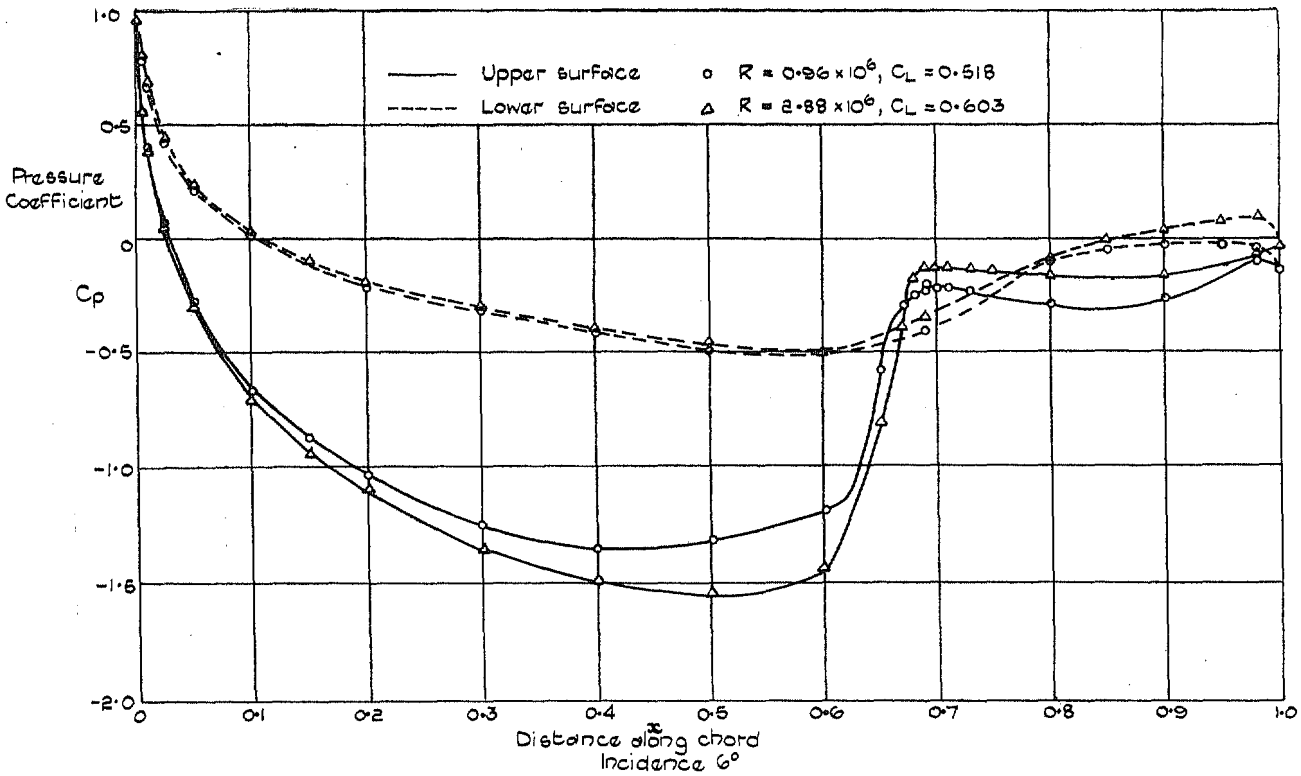

FIG. 11. Typical pressure distributions without suction.

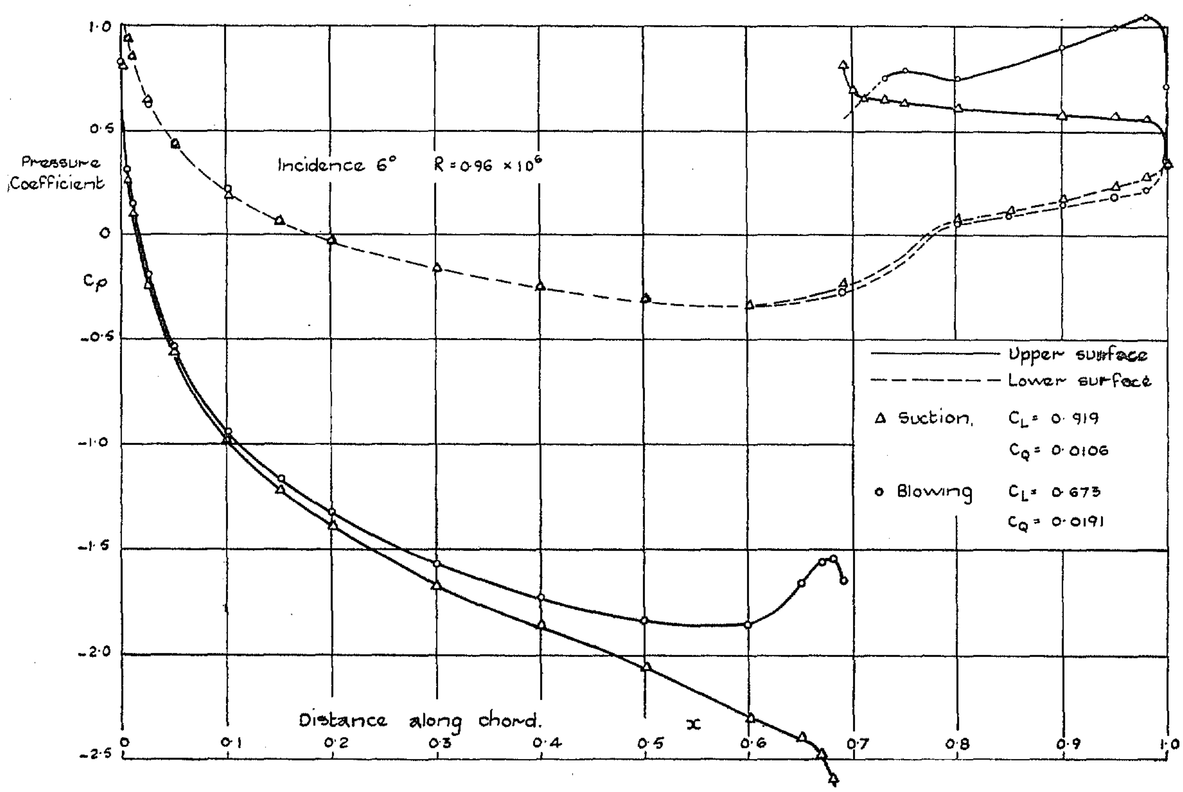

FIG. 12. Typical pressure distributions with suction and blowing.

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