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Wind-Tunnel Tests on the 30 per cent Symmetrical Griffith Aerofoil with Distributed Suction over the Nose

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of the Aerodynamics Division, N.P.L.

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Summary.—This report describes tests carried out on the 30 per cent Griffith symmetrical aerofoil with continuous suction applied through a porous capping fitted over the front 15 per cent of the upper surface. Throughout the range of incidence covered in the experiments, distributed suction was found to decrease the slot suction necessary to prevent separation, especially when the distributed suction caused rearward movement of the transition position.

The profile drag of the aerofoil was measured, and estimates were made of the equivalent drag coefficients for the work done by the suction pumps. Assuming no losses additional to those in the boundary layer, it was found that the effect of distributed suction was to reduce slightly the overall drag of the aerofoil.

Measurements of the velocity within the boundary layer were made at various chordwise positions on the porous surface; the profiles recorded were very close to the theoretical. Distributed suction was able to delay transition when this would otherwise be precipitated by a ridge on the surface, or by adverse pressure gradients, but a turbulent boundary layer remained turbulent when suction was applied. The characteristic spread of turbulent flow in the wake of a small particle on the surface was much reduced by distributed suction; under favourable conditions, the wake was entirely eliminated.

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1. *Introduction.*—The principle on which the design of thick Griffith suction wings is based has been substantiated by previous wind-tunnel experiments by some of the present authors[1,2] (1946). For this type of aerofoil, large extents of laminar flow, giving very low drag, are possible because the section is designed to have favourable pressure gradients over the whole surface for a wide range of lift coefficient. This is arranged by replacing the region of pressure recovery by a discontinuous rise in pressure. The flow is induced to adhere to the surface of the aerofoil over this sudden rise in pressure by removing a portion of the boundary layer at a slot at the discontinuity.

A great deal of theoretical work has been done in recent years by Schlichting[3] (1942), Preston[4] (1946) and Thwaites[5,6] (1946) on the effect on the boundary layer of sucking air through a permeable surface. It has been shown that for a flat plate in a uniform stream with constant suction, the boundary-layer thickness does become constant far downstream, as does also the profile shape. The suction also stabilises laminar flow against turbulent disturbances. Similar results are found for different distributions of normal and tangential velocity. In all cases, a reduction in boundary-layer thickness is caused by continuous suction.

The present experiments were devised to test the effect of distributed suction over the leading edge of the 30 per cent Griffith section. Previous experiments by Pankhurst, Raymer and

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Devereux[7] (1948) had shown that distributed suction over the leading edge of a more conventional section 8 per cent thick (H.S.A. V.) had increased the lift coefficient at high angles of attack and delayed the stall. It was hoped that similar effects might be obtained on the 30 per cent Griffith aerofoil, and that by stabilising the boundary layer, the slot suction quantities would be reduced.

2. *Experimental Details.*—The 30 per cent symmetrical aerofoil used in earlier experiments was modified to have a porous surface extending over the upper surface of the profile from the leading edge to 15 per cent of the chord, Fig. 1. The porous surface extended over the central four feet span only, and was formed by sintered bronze sheet rolled to the contour of the aerofoil. The material used was $\frac{1}{16}$-in. thick Grade C 'Porosint'. The suction chamber in the aerofoil was divided into three sections. The aspirated air was removed by two $1\frac{1}{2}$-in. diameter pipes, one of which was connected to the centre foot span and the other to the outer sections, which were linked by an internal duct across the centre section. The flow quantities were measured by means of two 'three-quarter radius pitot tube' calibration pipes as in the previous distributed suction experiments, and by a Rotameter which was fitted in the centre section ducting. Besides providing an immediate indication of the higher rates of flow, the Rotameter gave a check on the calibration of one of the 'three-quarter radius pitot-tube' flow meters. The balance between the quantity of air flowing in each pipe was adjusted by means of a gate valve fitted in each circuit. Immediately beyond these valves, the pipes coalesced to form a common duct leading to the main pump. A third valve situated in this duct regulated the overall suction flow.

The flow was specified by the value of v_0, the mean normal velocity into the porous surface. The valves were adjusted so that the flow into the outer sections was slightly greater than the flow into the centre section. The main suction slots, which were situated at 70 per cent of the chord, were designed to give uniform suction along their whole 4-ft. span. Thus when the flow was adjusted to give minimum suction to prevent separation, the incipient separation tended to occur in the centre of the aerofoil where the distributed suction was least. Profile drag measurements were taken in line with the centre of the span, and the distributed suction quantities plotted in the figures are those for the central portion of the surface.

The local distribution of normal velocity over the porous surface was investigated by means of the hot wire 'stethoscope' described in Appendix I of Ref. 7. Apart from a falling off in velocity at the edges of individual sheets of the bronze where contamination by solder was suspected, the flow appeared to be reasonably uniform, the variations from the mean being about 20 per cent.

The arrangement of the ducting for the slot-suction was as described in a previous report on the 30 per cent Griffith aerofoil in the 13 × 9 ft wind tunnel[1].

The pressure holes in the wooden portions of the wing were retained, and allowed comparisons of the pressure distributions to be made with those of previous experiments ; but as there were no pressure holes in the porous surface it was impossible to find the lift coefficient directly.

The joints between the porous bronze chamber and the wooden part of the surface were made good with wood filler and rubbed down, but at the rear of the porosint surface there was a slight ridge which could not be removed, and which precipitated forward transition at the higher incidences and speeds.

3. *Presentation of Suction Quantities.*—The slot-suction flows are defined, as in previous experiments, by the slot-suction quantity coefficient

$$C_{Q\,s} = \frac{Q_s}{U_0 c}$$

where Q_s quantity flowing into unit length of slot in unit time,

U_0 free-stream velocity,

c aerofoil chord.

An analogous coefficient is used to represent the distributed ('porous') suction flow,

$$C_{Qp} = \frac{Q_p}{U_0 c}$$

where Q_p quantity flowing into unit span of porous surface in unit time,

$= v_0 s$

where v_0 mean normal velocity into the surface,

s chordwise extent of porous material measured along the surface.

4. *Effect of Distributed Suction on Minimum Slot Suction Quantities at Zero Incidence and Various Wind Speeds.*—The effect of distributed suction on the minimum slot suction required to prevent separation was investigated at zero incidence and flap setting over a range of tunnel wind speeds. The results are plotted in Figs. 2, 3 and 4.

Distributed suction achieves little economy of suction quantity when the transition front is back near the slot (0·76 chord) without distributed suction as at low speeds. At the higher speeds, the ridge at 0·15 chord between the porous surface and the rest of the aerofoil causes transition to take place at the ridge. In this case, distributed suction enables the flow to cross the ridge without transition occurring, and substantial reductions in total suction quantity ensue. In assessing the value of distributed suction in these experiments and in those described in the succeeding paragraphs, the influence of the ridge must be borne in mind.

Transition was indicated by the 'china-clay' method. Without distributed suction it moved from 0·76 chord to the 'porosint' edge as the speed increased from 60 to 140 f.p.s. Only at the top speed of 180 f.p.s. was there insufficient distributed suction to delay transition to 0·76 chord. Here the ridge in the surface gave rise to many wakes and the mean transition position was at 0·5 chord so that the full reduction in slot suction was not attained.

The parameter $C_{Qp}\sqrt{R_c}$ is chosen from theoretical considerations in an attempt to correlate results obtained for different Reynolds numbers. Unfortunately, owing to the complicated nature of conditions leading to transition behind the ridge, the experiments do not yield a constant minimum value of $C_{Qp}\sqrt{R_c}$, just ensuring laminar flow to the slot, which might be used to estimate the distributed suction quantities at flight Reynolds numbers.

5. *Effect of Distributed Suction at Incidence.*—The wing was tested over a range of incidence and flap settings at a Reynolds number of $0 \cdot 96 \times 10^6$ as in the earlier experiments[1]. As laminar flow was obtained at zero incidence without distributed suction at this Reynolds number, it was hoped that the bad joints in the upper surface would not prove troublesome at the higher angles of incidence, but this unfortunately was not the case. Minimum values of the slot suction necessary to prevent separation were measured for given values of the distributed suction, separation being indicated by the manometer used for measuring the distribution of total head in the wake. The results are illustrated in Figs. 5a, 5b and 6.

The reduction in slot-suction quantities with the increase of distributed suction was due to the rearward movement of transition from the porosint to 0·76 chord near the slot. Owing to the influence of the ridge, the slot-suction quantities needed to prevent separation without distributed suction were larger than in the previous experiments, and at 16 deg incidence, some distributed suction was needed before separation could be prevented with all the available slot suction. Transition at 18 deg and 20 deg was at about 0·5 chord, and numerous wakes appeared from the ridge.

The profile drag coefficients, as measured by loss of total head in the wake, were small (0·0008 to 0·0020) below 16 deg incidence. Above this incidence, they were much larger (0·002 to 0·006), especially when the flap was deflected. At the higher angles of incidence, the minimum slot suction quantity to prevent separation varied with the flap deflection (Fig. 6). This does not agree with the earlier experiments in which the minimum slot suction quantity was the same for all flap deflections.

The pressure measurements taken to the rear of the porous surface agreed with those obtained in previous experiments. The lift curve slope for the range $\alpha =$ 0 deg to 18 deg can therefore be taken to be 7·2 per radian, the value obtained previously. The pressure distribution at 20 deg was the same as at 18 deg, which together with the large drag coefficients of 0·006 to 0·015 leads to the conclusion that a genuine stall was occurring. Examination of the flow with the aid of threads and a chemical indication method showed that at 20 deg incidence and 14 deg flap deflection, turbulent separation occurred from the flap surface, but the flow, which was very unsteady, was crossing the discontinuity. Without distributed suction, the flow separated at 0·57 chord, well in front of the slot.

Thus notwithstanding the adverse effect of the ridge in raising the slot suction quantities without distributed suction, the latter enables laminar flow to be obtained to the slot (in spite of adverse gradients on the porous surface) up to a high angle of incidence. Substantial reductions in slot suction quantity were therefore obtained.

6. *The Total Drag Coefficient of the Aerofoil.*—Since the velocity v, through the porous surface is small, the total head in the suction chamber is closely equal to the static pressure, p_c. Hence the work done by the pump in restoring the total head of the sucked air to that of the free-stream (H_0) is

$$\frac{1}{\eta_P}\int (H_0 - p_c) v \, ds$$

where η_P denotes the efficiency of the pump. If η_P is assumed to be equal to the efficiency of the main propulsive unit, the equivalent aerofoil drag coefficient calculated from the distributed-suction pump work is

$$\int \frac{(H_0 - p_c)}{\frac{1}{2}\rho U_0^2} \frac{v}{U_0} \, d(s/c).$$

This drag coefficient reaches a minimum 'ideal' value C_{Dpi} when the resistance of the porous material to the flow through it is negligible. In these conditions, p_c is equal to the static pressure p_1 at the aerofoil surface and the ideal distributed-suction 'pump-drag' coefficient is given by

$$C_{Dpi} = \int \frac{H_0 - p_1}{\frac{1}{2}\rho U_0^2} \frac{v}{U_0} \, d(s/c) = \int (U_1/U_0)^2 \left(\frac{v}{U_0}\right) d(s/c),$$ where U_1 is the velocity outside the boundary layer.

In the absence of any experimental information about variations in uniformity of the porous material, and of pressure along the surface (owing to the absence of pressure holes), the velocity normal to the surface has been assumed constant (v_0) along the surface. Thus

$$C_{D\,pi} = (U_1/U_0)^2_{\text{mean}} \frac{v_0}{U_0} s/c$$

$$= (U_1/U_0)^2_{\text{mean}} C_{Q\,p} \, .$$

The mean static pressure over the porous surface, and hence $(U_1/U_0)^2_{\text{mean}}$, was taken to be the same as the pressure within the suction chamber, p_c, when there was no suction flow. The velocity distribution over the nose of the aerofoil was assumed not to change when distributed suction was applied.

The ideal slot-suction pump-drag coefficient is

$$C_{D\,si} = C_{Q\,s} \frac{H_1}{\frac{1}{2}\rho U_1^2} (U_1/U_0)^2 ,$$

where $C_{Q\,s}$ is the slot-suction quantity coefficient, (U_1/U_0) is the velocity just in front of the slot, and $H_1/\frac{1}{2}\rho U_1^2$ is the head loss in the boundary layer. The value of $H_1/\frac{1}{2}\rho U_1^2$ was calculated from theoretical velocity profiles (laminar or turbulent as appropriate), the limit of integration of total head loss being that given by Taylor's criterion, for the value of the discontinuity given by the pressure measurements. When the suction quantity was large, the sink effect modified the pressure distribution in the nieghbourhood of the slot, and so the drag coefficients given by the formula must be regarded as tentative figures. A theoretical treatment of the slot-suction pump-drag coefficient is given in a paper by Preston, Rawcliffe and one of the present authors[8] (1947).

The ideal effective drag coefficient may be defined as

$$\begin{aligned} C_{D\,ie} &= C_{D\,0} \quad \text{(profile drag)} \\ &+ C_{D\,si} \quad \text{(ideal slot-suction pump drag) for the lower surface} \\ &+ C_{D\,si} \quad \text{(ideal slot-suction pump drag) for the upper surface} \\ &+ C_{D\,pi} \quad \text{(ideal distributed-suction pump drag).} \end{aligned}$$

This was measured at two Reynolds numbers at 14 deg, 6 deg and 0 deg incidence, and the distribution of the various components of the drag can be seen in Fig. 7.

The application of distributed suction decreased the total drag of the aerofoil by causing rearward movement of transition on the upper surface, except at zero incidence at the lower Reynolds number ($0{\cdot}96 \times 10^6$) when the laminar boundary layer extended to 0·76 chord even without distributed suction. The experimental ideal effective drags are in good agreement with the theoretical drag coefficients given below. They are taken from R. & M. 2577[8] and apply to zero incidence without distributed suction.

Transition, x/c both surfaces	$C_{D\,ie}$	R
0·15	0·015	$0{\cdot}96\times10^6$
0·76	0·007	
0·15	0·014	$1{\cdot}92\times10^6$
0·76	0·006	

7. *Boundary-Layer Profiles with Distributed Suction.*—Total head and static pressure measurements were made through the boundary layer on the porous surface under various conditions. The wing was in all cases at 6 deg incidence as this was the top of the C_L range, and the velocity over the porous surface was then approximately constant and equal to 1·45 times the stream velocity.

A series of laminar boundary-layer velocity profiles obtained at a position near the rear of the porous surface is shown in Fig. 8. The profile without suction closely resembles the Blasius flat-plate profile, while the profiles with suction agree well with the theoretical asymptotic-suction profile. The momentum thickness of the boundary layer is less than the theoretical asymptotic value, but approaches most closely to it with the highest value of distributed suction where the value of the parameter $(v_0/U)^2\ (Us/\nu)$ is greatest.

The velocity profiles measured with a constant value of v_0/U at various positions along the surface are illustrated in Fig. 9. The profiles are again laminar, and the momentum thickness rises along the surface towards its theoretical asymptotic value. A close approach to the theoretical value could not be obtained owing to the limited extent of porous surface, but in the region of the experimental traverses, the rate of increase of momentum thickness is of the same order as that expected by the theory.

A transition wire was fitted near the nose, and velocity profiles in the turbulent boundary layer were measured (Fig. 10) for different values of distributed suction. The profiles do not agree with the form derived from mixture-length theory by Kay[9], neither does the momentum thickness satisfy the asymptotic momentum thickness equation given by Schlichting (1942)[3].

Thus although the laminar boundary-layer velocity profiles measured on the porous surface fully substantiate the existing theory, further fundamental work, both theoretical and experimental, is clearly needed for the case of turbulent flow.

8. *The Effect of Distributed Suction on Wakes created by Surface Excrescences.*—Small pimples, which consisted of lead shot or steel spheres ranging from 0·03 to 0·156 in. in diameter, were successively affixed to the porous surface at various distances from the leading edge and the flow near the surface was examined by the china-clay technique. Without distributed suction, at a tunnel speed of 60 feet per second, even the smallest pimple gave rise to a well-defined wake on the surface of the wing to the rear of the Porosint.

The first effect of distributed suction was to decrease the width of the wake everywhere. When the suction quantity was sufficiently great, the width of the wake was reduced to a very small amount at the rear edge of the porous surface so that the wake appeared to emanate from that point. For a large pimple, twin streaks half an inch apart appeared at the edge of the porous surface, probably due to the formation of a Bénard vortex pair. Overlapping wedges of turbulence then began to spread from points 10 to 12 in. (0·3 chord) behind the pimple. Finally, with more suction, no wake appeared at all. These features are illustrated in the photographs of Fig. 12.

The quantitative results are given in Fig. 11. The tests were performed at three wing incidence positions ranging from +1 deg with the pimples situated in a very favourable gradient, to + 6 deg with the velocity nearly constant over most of the porous surface. The suction velocity needed to suppress the turbulent wakes was found to vary with the pressure gradient, the wind speed, the size of pimple and with the distance between the pimple and the rear edge of the porous surface.

It is difficult to foresee from these tests how porous suction would work in suppressing turbulent wakes at flight Reynolds numbers. Full-scale experiment appears to be necessary. It would also be necessary to investigate the economy of the process, and to include the 'extra' pump drag due to the porous resistivity of the surface.

9. *Conclusions.*—(1) Distributed suction decreases the ideal drag coefficient of the aerofoil and also the slot suction quantity necessary to prevent separation of the flow, especially when the distributed suction delays transition.

(2) Distributed suction delays transition when this would otherwise be precipitated by a ridge on the surface or by adverse pressure gradients.

(3) Distributed suction much reduces the spread of turbulent flow in the wake of a small particle on the surface. Under favourable conditions the wake can be prevented from occurring The suction cannot re-establish laminar flow if the boundary layer is already turbulent.

(4) There is no experimental indication how the quantitative results obtained with distributed suction on the 30 per cent Griffith aerofoil can be extrapolated to higher Reynolds numbers.

(5) Boundary-layer velocity profile measurements over the porous surface agree with the theory when the flow is laminar, but indicate the need for further research when the flow is turbulent.

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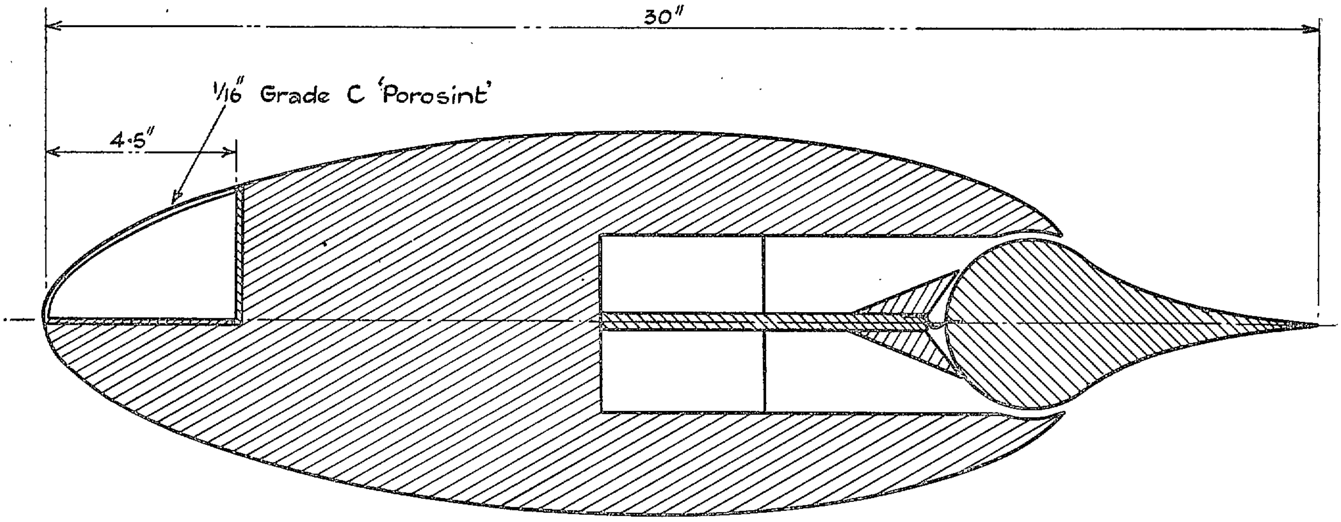


FIG. 1. 30 per cent Griffith aerofoil with porous nose capping on the upper surface.

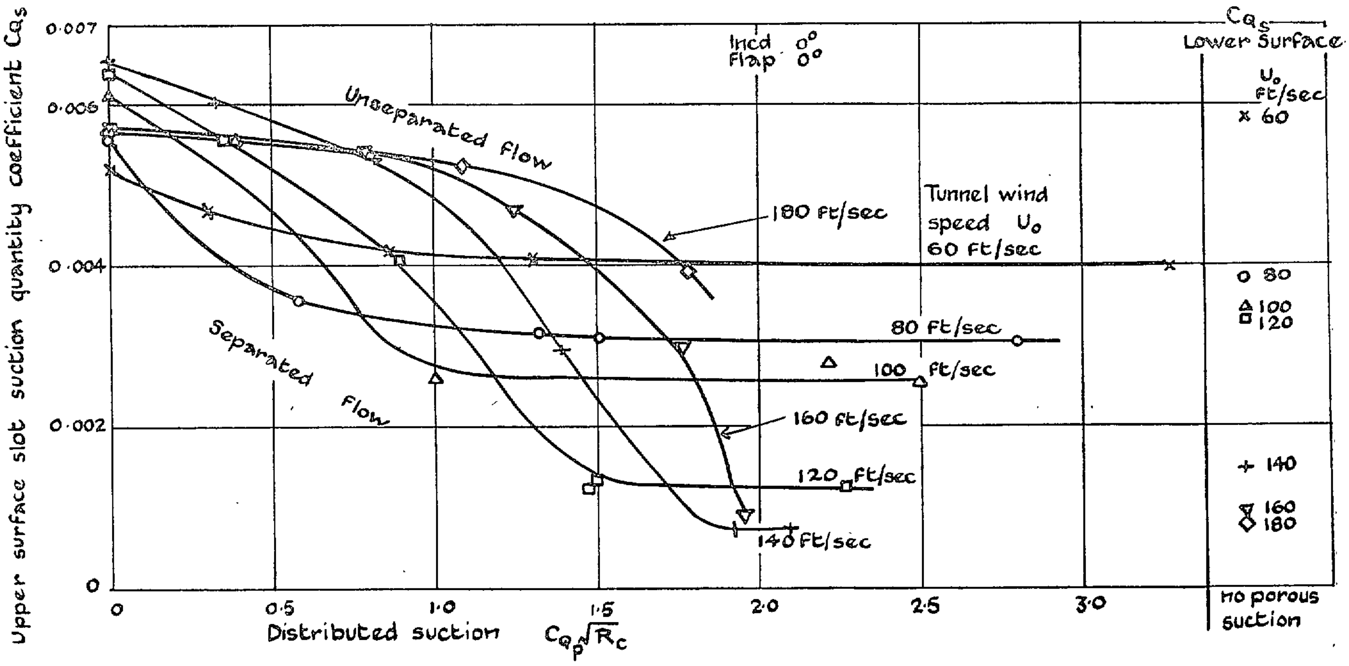


FIG. 2. Variation of slot and distributed suction quantities just giving low drag with tunnel-wind speed.

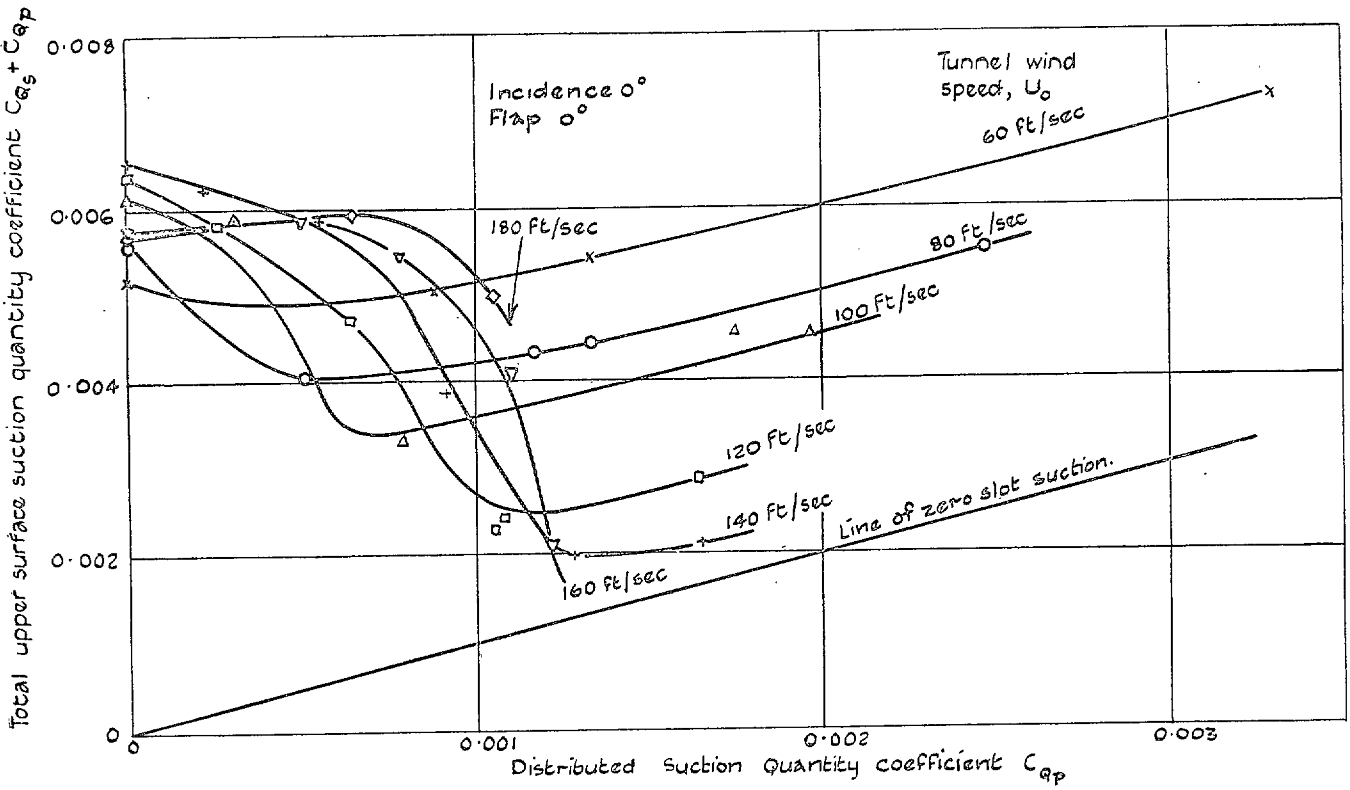


FIG. 3. Variation of total suction quantity with the distributed suction quantity and wind speed.

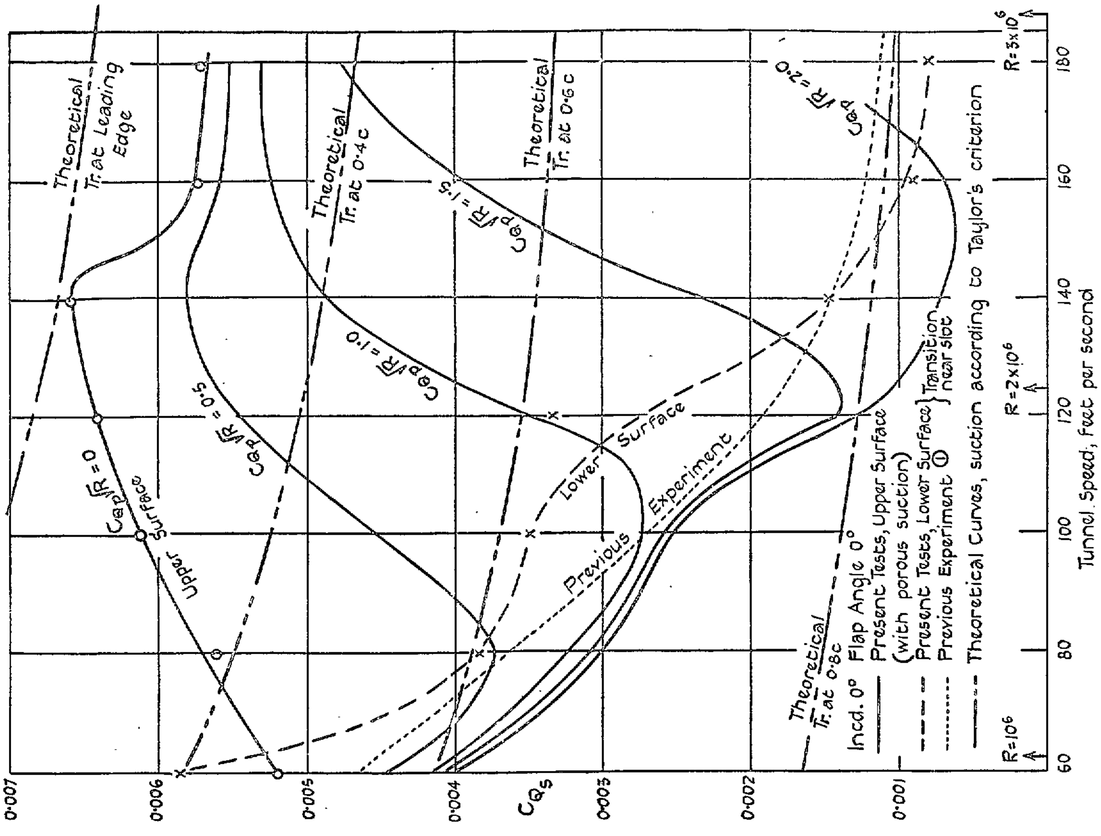


FIG. 4. Variation of slot-suction quantity (minimum to prevent separation) with porous suction and wind speed.

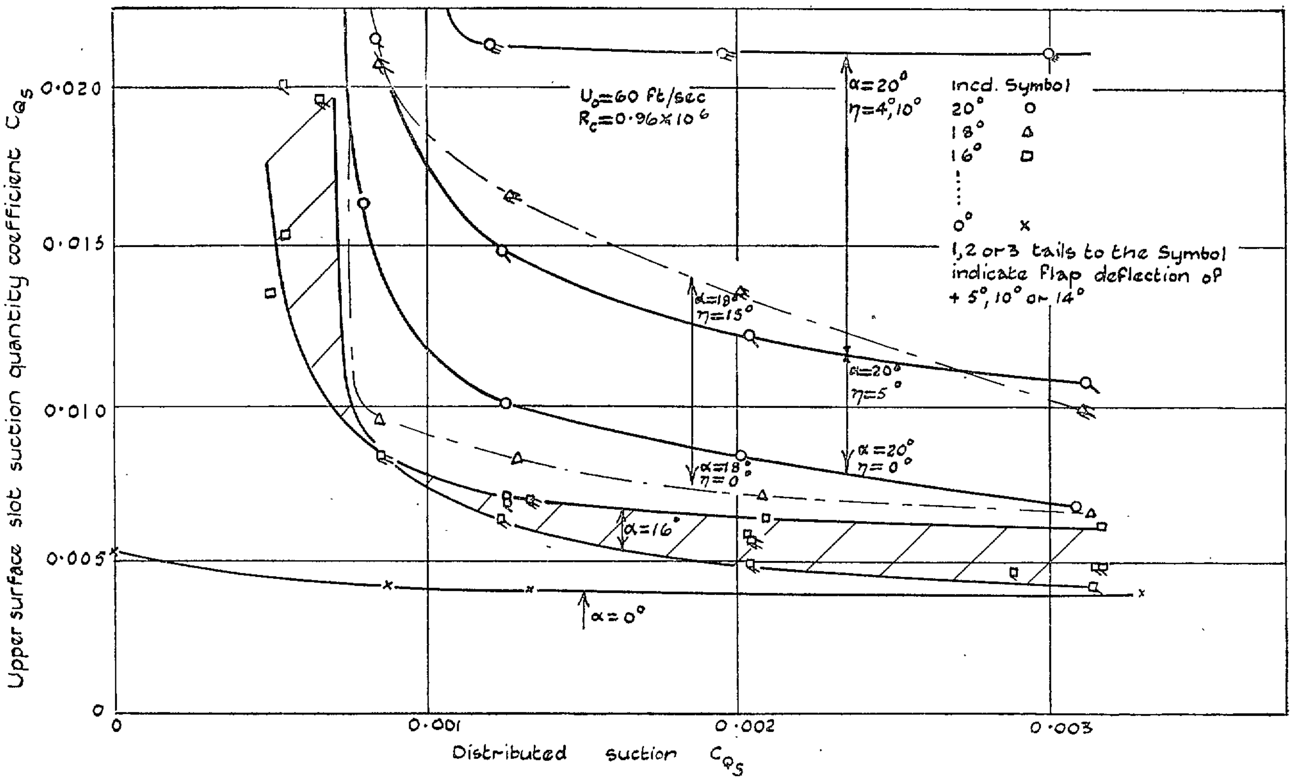


FIG. 5a. Variation of distributed and slot-suction quantity with incidence.

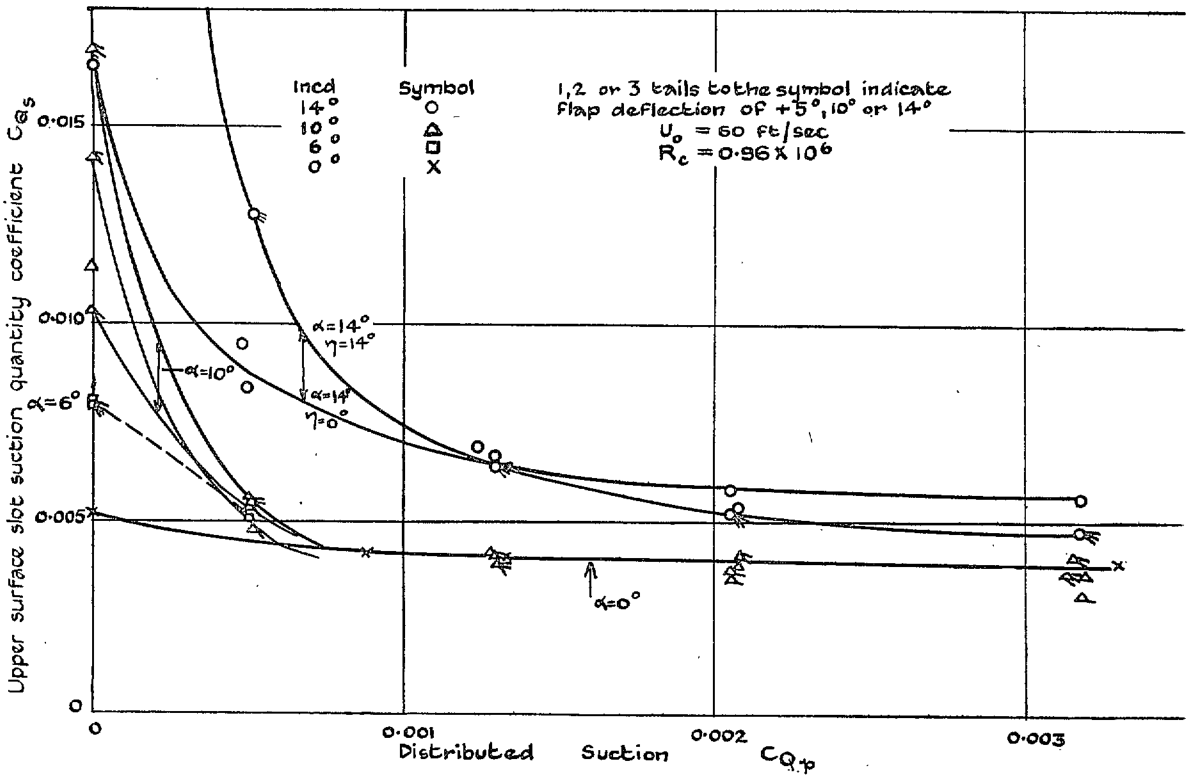


FIG. 5b. Variation of distributed and slot suction quantity with incidence.

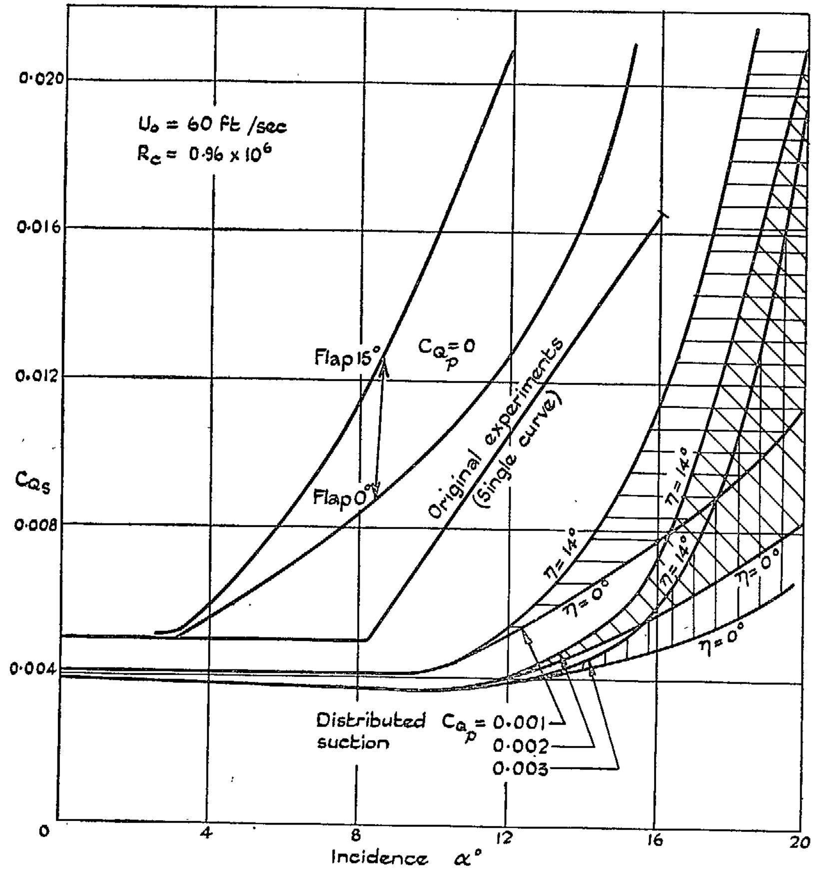


FIG. 6. Variation of slot suction (upper surface) with incidence for given distributed suction.

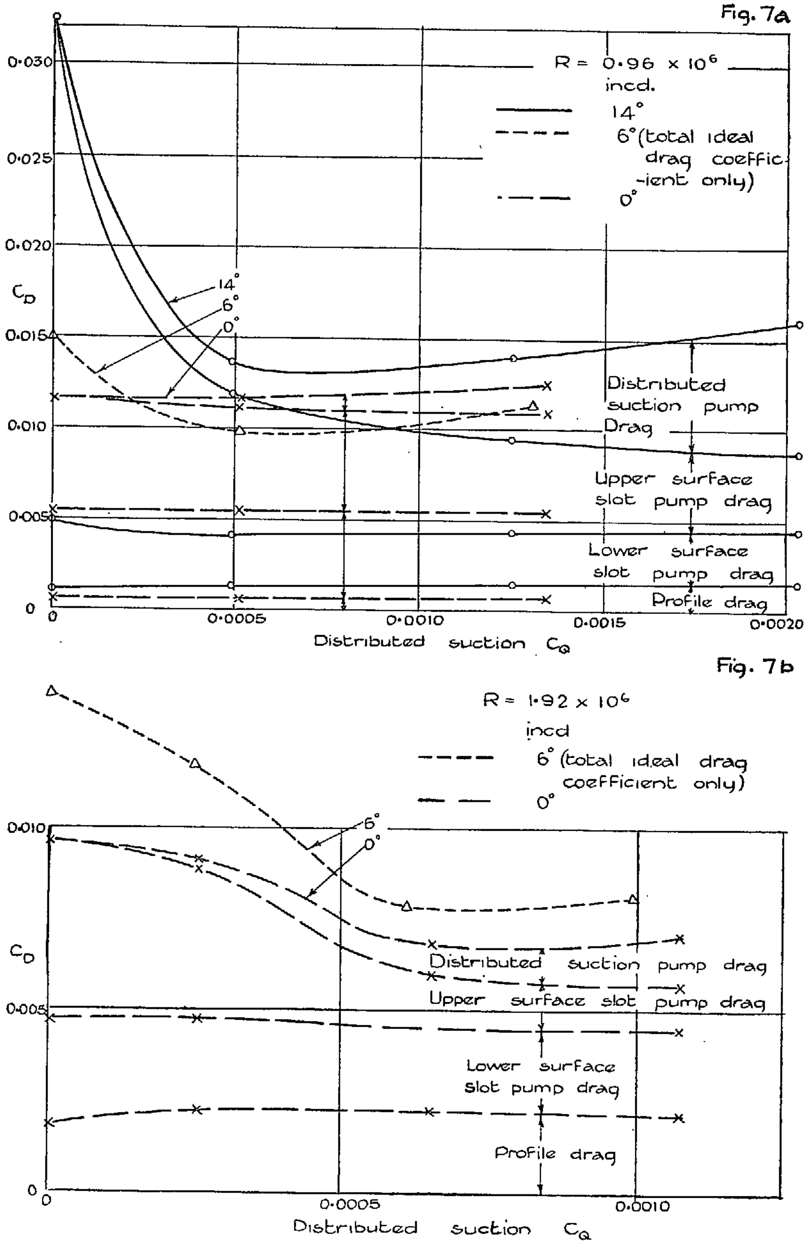
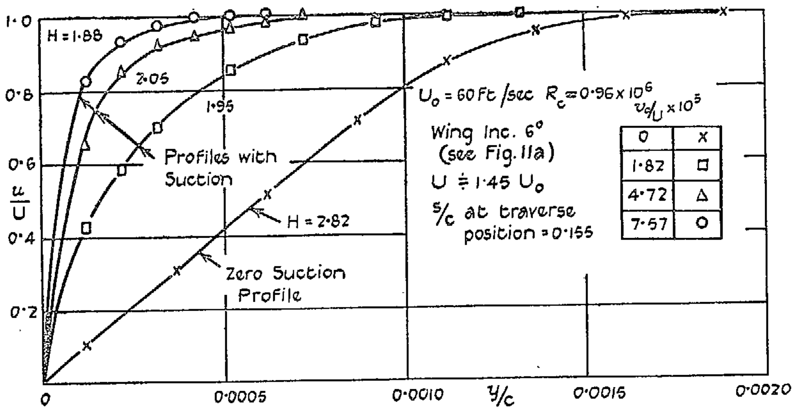
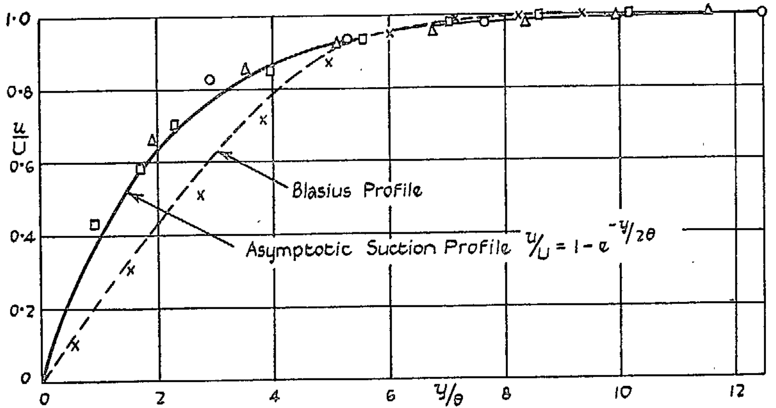


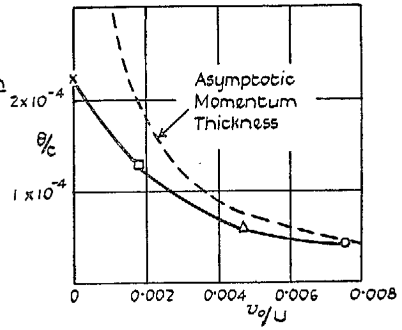
FIG. 7. Composition of ideal drag coefficient and its variation with C_Q.



(a) Experimental Laminar Boundary Layer Profiles

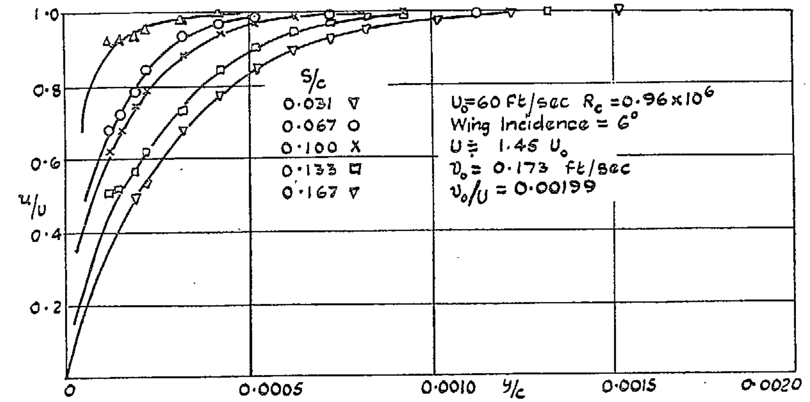


(b) Boundary Layer Profiles plotted non-dimensionally

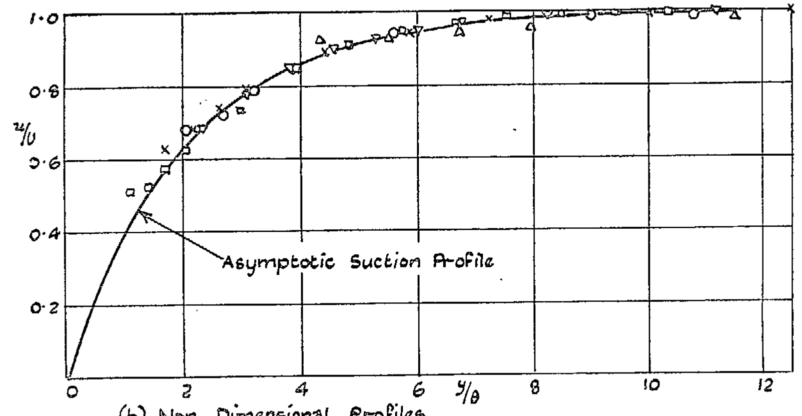


(c) Variation of Momentum Thickness of Boundary Layer at the Traverse position with the Suction Velocity

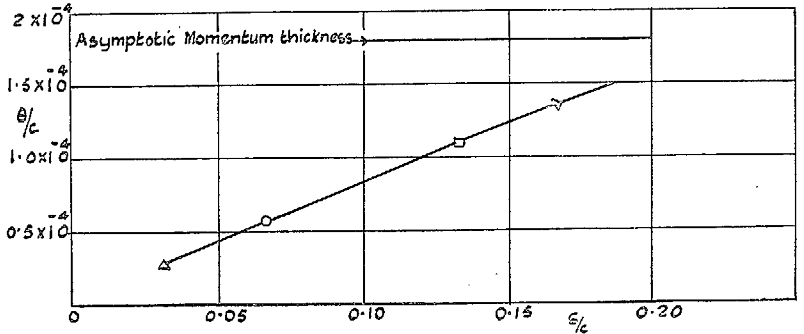
FIG. 8. Effect of distributed suction on laminar boundary-layer profiles.



(a) Experimental Laminar Boundary Layer Profiles along Surface

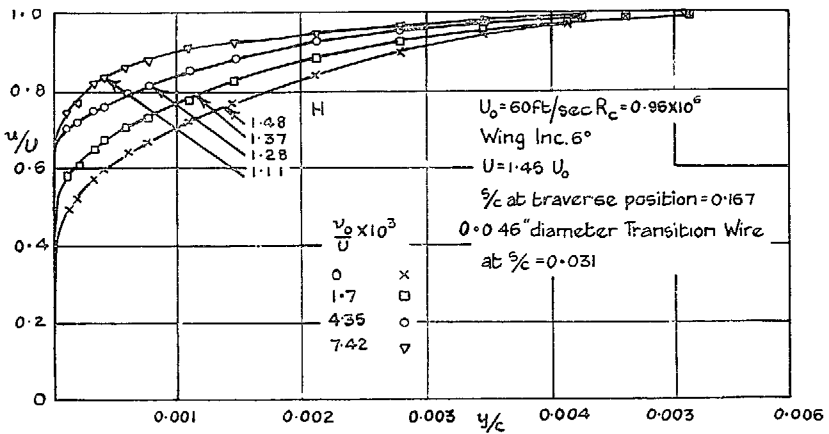


(b) Non Dimensional Profiles

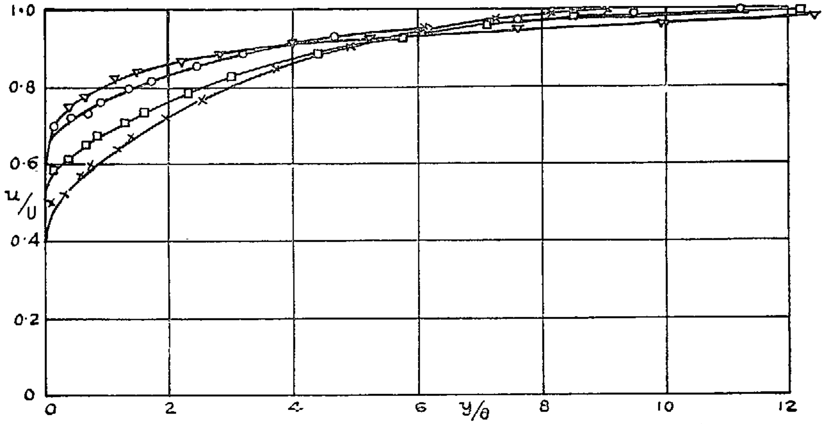


(c) Growth of Momentum Thickness along Surface

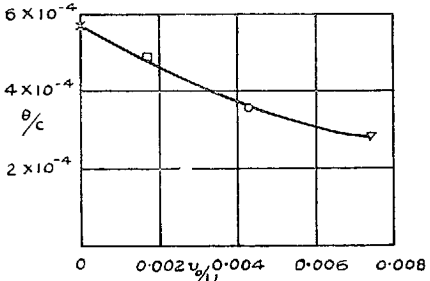
FIG. 9. Boundary layer traverse along porous surface.



(a) Experimental Turbulent Boundary Layer Profiles

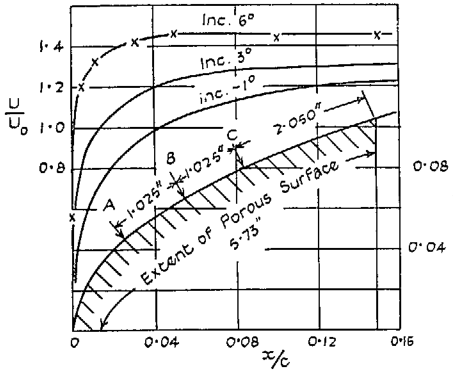


(b) Boundary Layer Profiles Plotted Non Dimensionally

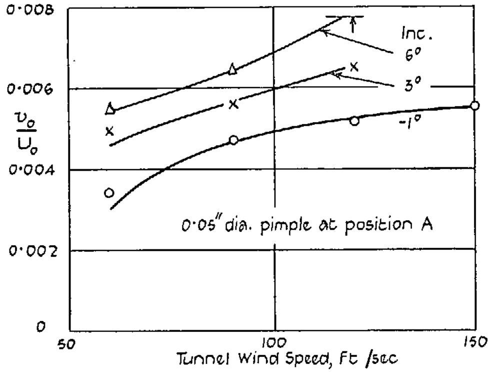


(c) Variation of momentum thickness at traverse position with distributed suction velocity

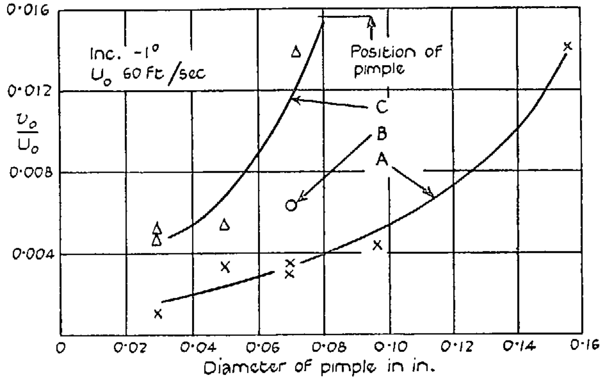
FIG. 10. Effect of distributed suction on turbulent boundary-layer profiles.



(a) Profile and Velocity Distribution of Porous Nose of 30% Griffith Aerofoil



(b) Variation of distributed suction to suppress wakes with incidence and tunnel speed



(c) Variation of distributed suction to suppress wakes with position and diameter of pimple

FIG. 11.

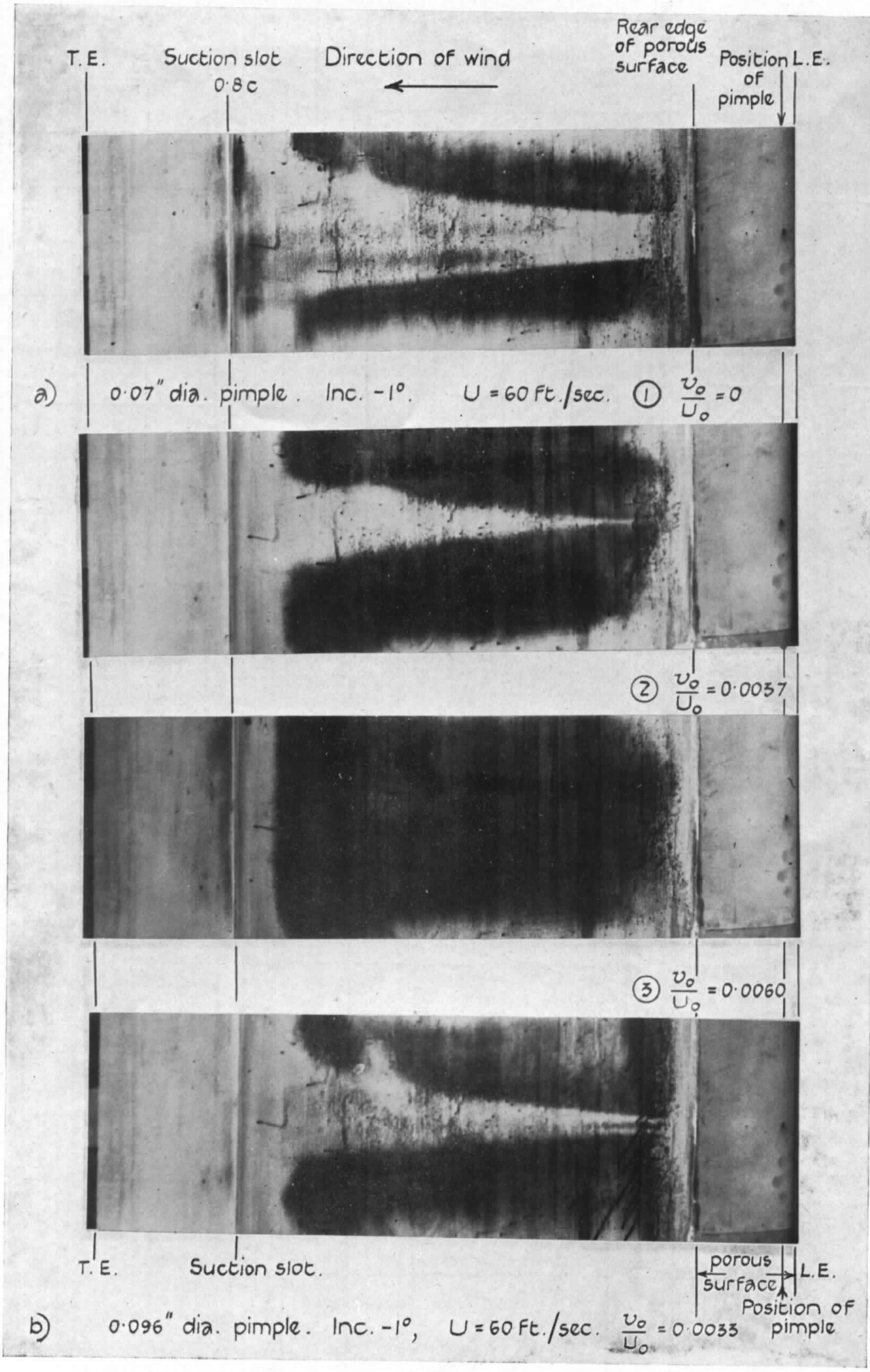


FIG. 12. Effect of distributed suction on wakes produced by excrescences on a porous surface.

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