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An Investigation of the Use of an Auxiliary Slot to Re-establish Laminar Flow on Low-Drag Aerofoils

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Summary.—The use of an auxiliary slot on a laminar-flow aerofoil has been investigated to check whether laminar flow can be re-established by suction at the rear of the region of deposited dirt, flies, etc.

Results indicate that in the absence of unfavourable pressure gradients, it is possible to re-establish a laminar boundary layer by removing a little more than the whole turbulent layer reaching the slot, and preliminary estimates suggest that with efficient ducting it should be possible to achieve a reduction in overall effective drag coefficient by this means.

1. *Introduction*.—The successful use of all low-drag wings, and of thick suction wings in particular, depends on maintaining a laminar boundary layer over a large proportion of the wing surface. This can be achieved readily in the wind tunnel and in test flights if suitable precautions are taken, but in service the chief difficulty is the tendency of the wing to collect dirt and flies on the nose, thus establishing transition to turbulent flow.

Since flight tests have shown that the affected region of the wing is usually confined to a few per cent of the chord, it was decided at the National Physical Laboratory to investigate whether laminar flow could be re-established behind this region by the use of an auxiliary suction slot.

2. *The Experimental Method*.—The auxiliary slot under investigation was cut in the surface of a symmetrical low-drag aerofoil 13 per cent thick with maximum thickness at 50 per cent chord. The model had a 5-ft chord and was mounted two-dimensionally in the N.P.L. 13 × 9 ft Wind Tunnel. For the tests, transition was effected at 5 per cent chord by means of wires and 'pimples' (conical excrescences), and the slot was situated at 20 per cent of the chord. It should be emphasised that the results would be expected to be applicable in principle to any location of slot in any laminar-flow aerofoil. Sections of the aerofoil, of the forward-facing slot (0·1 in. wide), and of the internal ducting are given in Fig. 1.

Experiments were carried out at incidences from − 8 deg to + 2 deg. At − 8 deg, the velocity gradient at the slot is extremely favourable and so tests at this incidence represent closely the conditions met on thick suction aerofoils at low lift coefficients. At + 2 deg, which is the maximum incidence at which laminar flow could be maintained on the clean wing without a slot, the pressure gradient is zero (Fig. 3).

Boundary-layer traverses were taken by means of a remotely operated traversing head at 19 per cent chord to evaluate the momentum thickness and quantity flow in the boundary layer reaching the slot. The profile-drag coefficient of the upper wing surface was determined by means of a pitot-comb mounted obliquely to the trailing edge to obtain a closer effective tube spacing. Profile-drag coefficients of the whole wing were measured with a standard wake comb.

* An officer of the Department of Supply and Development, Australia, on temporary service at the N.P.L. Published with the permission of the Director, National Physical Laboratory.

A calibrated central pitot-tube in the duct leading to the pump was used to give suction quantities along the central 4 ft of slot. The suction flow in the outer sections of the slot was always maintained at a slightly higher rate to prevent adverse tunnel-wall effects. The position of the transition front on the central portion of the wing was visualised by the china-clay method.

The majority of the tests were carried out at a tunnel speed of 180 ft/sec, giving a wing Reynolds number of $5 \cdot 7 \times 10^6$.

3. *Preliminary Tests.*—The distribution of velocity into the slot along the span was checked with a faired slot entry drawing in static air. It was found that the velocity was within 2 per cent of the mean velocity over the 4-ft long test section in the middle of the wing.

Static pressure distributions were measured over the upper surface of the aerofoil at several incidences within the test range. These are plotted in Fig. 3 as velocity distributions.

To allow comparison of the test results with a smooth wing without a slot, measurements were also made on the lower surface of the aerofoil; Fig. 2 shows the position of natural transition for the two surfaces at various incidences. The disturbance due to the slot gap in the upper surface results in an earlier transition, but it was insufficient to precipitate immediate transition at the slot even at the top speed of the tests (180 ft/sec) at incidences below $+ 2$ deg.

The profile drag of the lower (clean) surface is used later (section 9) as a standard for comparison with estimated effective drag coefficients with suction. It is shown plotted as curve (a) of Fig. 15.

Early experiments with suction showed that it was possible to re-establish a laminar layer as shown in Fig. 4. This can be done even with slight unfavourable velocity gradients; at a wing Reynolds number of $1 \cdot 9 \times 10^6$ laminar flow could be re-established up to an incidence of $+ 5$ deg on a clean wing (Fig. 5), but with a $0 \cdot 1$-in. diameter wire near the leading edge, this was not possible above $+ 2$ deg incidence owing to insufficient suction (Fig. 6). At a Reynolds number of $5 \cdot 7 \times 10^6$, the suction was effective up to $+ 3$ deg on a clean wing (Fig. 7). In all subsequent tests, the trailing-edge comb was fitted and the drag coefficient of the upper surface only was considered.

4. *Tests with Wires at* $0 \cdot 05$ *Chord; Critical Suction Quantity.*—With wires of various diameters fixed at $0 \cdot 05$ chord it was found that the laminar boundary layer could be re-established at the slot, and that in general it was not difficult to decide on a critical value of C_Q by visual observation of the wake manometer as the suction quantity was varied. Fig. 8 shows a plot of surface-drag coefficient against quantity coefficient: in this case the critical C_Q was taken as $0 \cdot 0025$.

Critical quantity coefficients for various incidence and wire diameters are shown in Fig. 9, and in Fig. 10 they are shown expressed in terms of the boundary-layer momentum thickness (θ) and the velocity outside the boundary layer at the slot (U_1). From this it would appear that a value of $Q/U_1\theta = 18$ should always be sufficient to ensure laminar flow behind the slot when transition is caused by a wire.

5. *The Effect of Wire Diameter; Tests with 'Pimples'.*—In an effort to determine the effect of the wire itself, tests were carried out with series of small pimples, spaced $0 \cdot 53$ in. apart replacing the wire. The resulting transition front is shown in Fig. 11. A typical spanwise traverse of the wake at $0 \cdot 19$ chord is shown in Fig. 12 and mean values of the quantity of the boundary layer and of its momentum thickness have been transferred to Fig. 13 where the variation with wire diameter is given. The values for the pimples (spaced as chosen) agree reasonably well with extrapolation to zero wire diameter.

Fig. 14 compares wakes shed by single pimples with those of wires of diameter equal to the height of the pimples. The critical suction quantities, expressed in terms of the momentum thickness at the centre of the wake are plotted in Fig. 10 both for the single pimples and the series. These values are somewhat less than those obtained with wires, and probably represent more closely the practical case of a dirty wing. Thus for design purposes a value of $Q/U_1\theta$ of 14 would appear to be sufficient, except when early transition is caused by ridges, joints or other continuous obstacles when a value of 18 should be taken. These compare with the values for the whole boundary layer of 11 to 12.

6. *Effective Drag Coefficients*.—In the Appendix, an attempt has been made to evaluate the total effective drag coefficient for the upper surface of the wing, with transition at 0·05 chord and slot at 0·2 chord. Corrections have been applied for the effect of the transition wire, and slot and ducting losses have been assumed to be 0·2 of the dynamic head in the slot. The results of this estimate are shown in Fig. 15 as curve (d), compared with drag of the original smooth surface without slot (a), drag of the surface with early transition but without suction (b), and the drag of the surface with suction before including the equivalent pumping power (c).

7. *Conclusions*.—It would appear that on a suitable wing surface, in the absence of an unfavourable pressure gradient, it is possible to re-establish laminar flow by means of a suction slot behind an area contaminated by insects, dirt, etc. The suction quantities are slightly greater than that in the whole boundary layer (Fig. 10).

It should be possible to economise by using suction, and to obtain effective drag coefficients lower than the drag coefficient associated with a turbulent boundary layer (Fig. 15). In the presence of a very favourable pressure gradient, as on thick suction wings, these economies should be greater.

To realise the maximum improvement in drag coefficient, the auxiliary slot must be placed as near to the leading edge as possible. Before an exact position can be selected, however, it will be necessary to gather statistical evidence of just how much of the chord of the section is likely to be contaminated by deposits in practice.

A series of small pimples appears to be a possible alternative for transition wires for standard model tests, as no correction is needed for the drag of the wire itself. It would be necessary to conduct a preliminary test in each case in order to determine the appropriate pimple spacing.

APPENDIX

Estimation of Total Effective Drag Coefficient.—Estimates of the total effective drag coefficient for the upper surface of the wing for three angles of incidence (— 8, — 4 and 0 deg) at a wing Reynolds number of $5{\cdot}7 \times 10^6$ (corresponding to 180 ft/sec wind speed) are set out in the table and included in Fig. 15. The following ' full-scale ' conditions were postulated:—

(a) Transition takes place at 0·05 chord, and suction restores laminar flow behind the slot, which then persists, as in the experiment, to 65 to 75 per cent chord, depending upon the incidence.

(b) The slot and ducting losses were assumed to be 0·2 of the dynamic head at the slot, which has been designed so that the throat velocity is the same as U_1, the velocity outside the boundary layer at the slot.

The estimates were based on the experimental results of Fig. 13 in which transition was fixed at 0·05 chord by means of a wire. It is necessary to eliminate the interference of the wire on the boundary layer without altering transition. This can be done by extrapolating the curves to zero wire diameter. Fig. 13 shows that this would have the same effect on the boundary layer as the row of pimples, suggesting that the row of pimples closely simulates natural transition at this chordwise station in its effect on profile drag and suction quantity.

The effect on profile drag can be calculated in two ways:—

(i) From the measurements of momentum thickness at 0·19 chord. If we neglect the difference between the rates of growth of the boundary layer aft of 0·19 chord, and ignore the subsequent development of the wake downstream of the trailing edge, then for $\alpha = -4$ deg, a wire diameter of 0·022 in. and with $c = 5$ ft and $U_1/U_0 = 0{\cdot}969$ at 0·19 chord,

Momentum thickness at 0·19 chord, with wire at 0·05 chord = 0·01239 in.

Momentum thickness at 0·19 chord with row of pimples at 0·05 chord = 0·00912 in.

$$\text{Difference } \Delta\theta = 0{\cdot}00327 \text{ in.}$$

$$\text{Therefore } \Delta C_D = 2\,\frac{\Delta\theta}{c}\,(U_1/U_0)^2$$

$$= 2\,\frac{0{\cdot}00327}{60}\,(0{\cdot}969)^2 = 0{\cdot}0001.$$

(ii) From a curve of drag coefficients for transition wires on wings given by Davison[1]. For a wire diameter 0·022 in. and chord 5 ft, the curve gives a drag coefficient for a single wire of 0·0001.

The agreement between these values suggests that despite the crude assumptions, a figure of 0·0001 should be subtracted for the presence of the wire. It is however a very small percentage of the uncorrected drag coefficients, so its accuracy is not important. Curve (b) of Fig. 15 is plotted from experimental results corrected by this amount.

The effect on suction quantity coefficients is more significant. From Fig. 13,

Quantity in the boundary layer, C_{QBL} at 0·19 chord behind wire = 0·00175

Quantity in the boundary layer at 0·19 chord behind row of pimples= 0·00135.

The factor 0·00135/0·00175 has been used to correct the required quantity coefficients (which were measured with a wire in place) in deriving curve (d) of Fig. 15.

The table shows that at 0 deg incidence at the experimental Reynolds number of $5{\cdot}7 \times 10^6$, the ideal effective drag coefficient is 0·00338 compared with a figure of 0·00455 if the turbulent boundary layer is allowed to proceed from 0·05 chord to the trailing edge without suction. This represents a 25 per cent saving in wing drag. Owing to the different scale effect on laminar and turbulent skin friction, the saving would be expected to be greater at the Reynolds number of full-scale flight.

REFERENCE

No.	*Author*	*Title, etc.*
1	B. Davison	Note on the Use of Threads for Ensuring Forward Transition on a Wing. *Wind Tunnel Bulletin No.* 1. R.A.E. January, 1940.

TABLE

Derivation of Total Effective Drag Coefficient for Upper Surface of Aerofoil

Items 1, 2, 4 and 5 are experimental results.

The curves of Fig. 15 are obtained from the table as follows, (a) is item 1, (b) is 3, (c) is 4 and (d) is 12.

Wind speed, $U_0 = 180$ ft per second, $R = 5 \cdot 7 \times 10^6$.

		$\alpha = 0°$	$\alpha = -4°$	$\alpha = -8°$
1	Profile-drag coefficient of clean wing without a slot (far-back transition)	0·00215	0·00165	0·00142
2	Profile-drag coefficient without suction with transition fixed at 0·05 chord by 0·022 in. diameter wire	0·00465	0·00361	0·00314
3	Profile-drag coefficient (2) corrected by 0·0001 to zero wire diameter	0·00455	0·00351	0·00304
4	Profile-drag coefficient with wire at 0·05 chord and sufficient suction to restore laminar flow, in effect, drag coefficient due to boundary layer starting at 0·20 chord	0·00195	0·00159	0·00132
5	Suction quantity coefficient used in obtaining (4)	0·00369	0·00245	0·00150
6	Suction quantity coefficient corrected to zero wire diameter in ratio 0·00135/0·00175	0·00285	0·00189	0·00116
7	Velocity at edge of boundary layer at slot, (U_1/U_0)	1·118	0·970	0·847
8	Mean loss of head due to slot and duct losses of 0·2 dynamic head in slot, where this at velocity $= U_1$	0·25	0·19	0·14
9	Mean loss of head due to boundary layer, if suction quantity is closely equal to the whole boundary layer, $(0 \cdot 2 \times \frac{1}{2}\rho U_1^2)$	0·25	0·19	0·14
10	Total loss of head, C_h equal to (8) + (9)	0·50	0·38	0·28
11	Pump drag coefficient, $C_{Dp} = C_Q \times C_h$, (6) × (10)	0·00143	0·00072	0·00033
12	Total effective drag coefficient, $C_{De} = C_{Dp} + C_{Di}$, (11) + (4) ..	0·00338	0·00231	0·00165

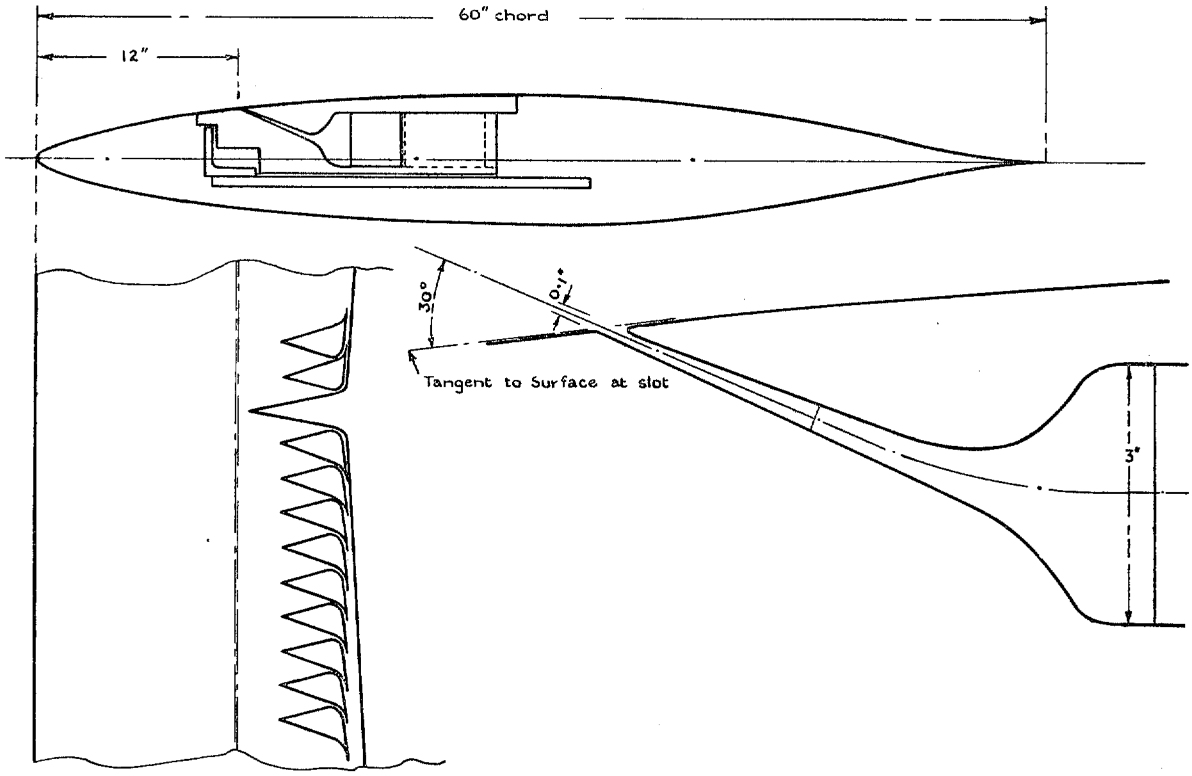

FIG. 1. 13 per cent low-drag aerofoil section, slot, and internal ducting.

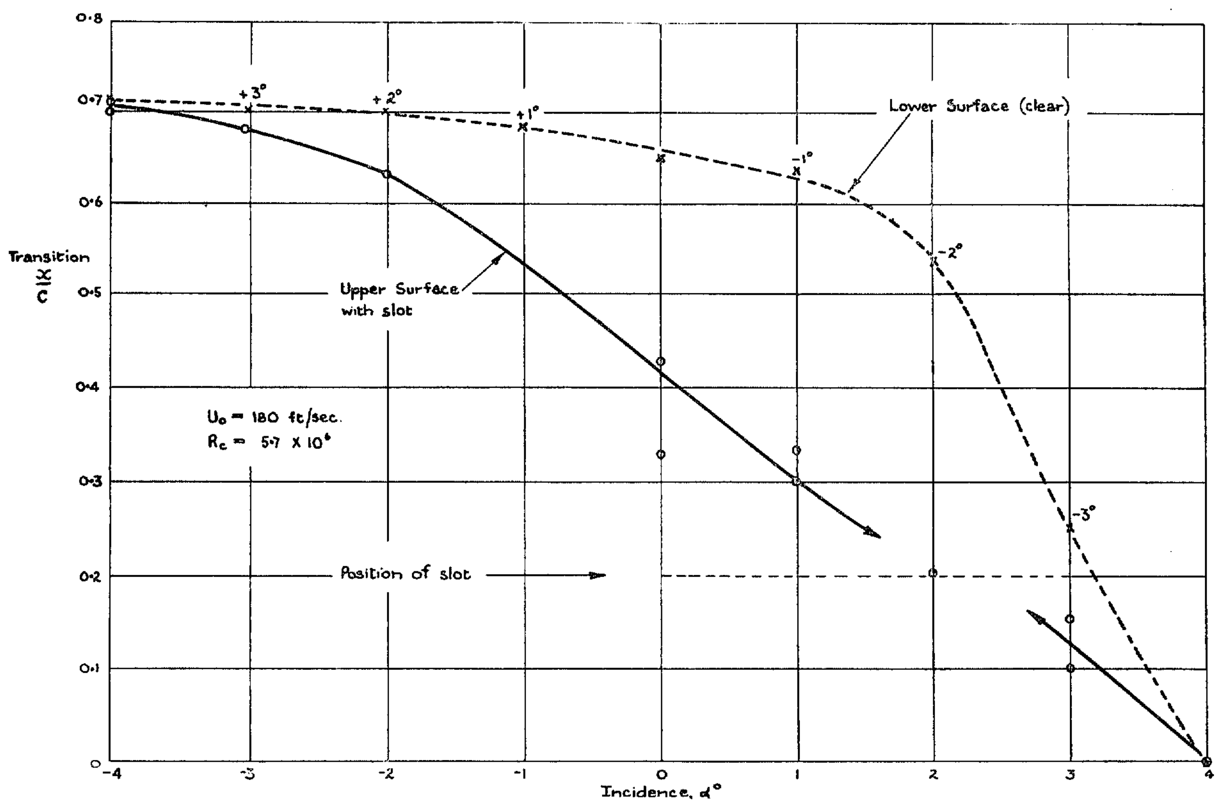

FIG. 2. Variation of transition position with incidence.

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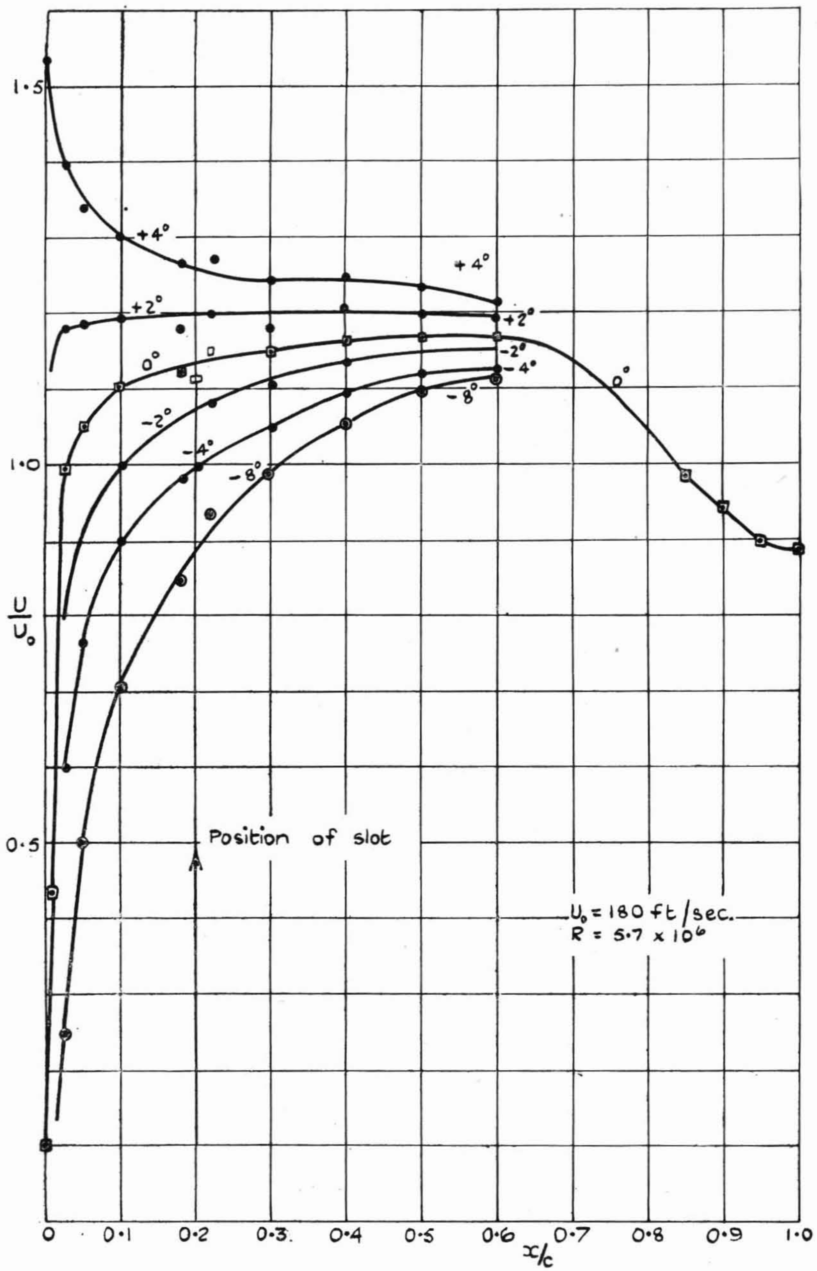

FIG. 3. Velocity distribution on upper surface of aerofoil.

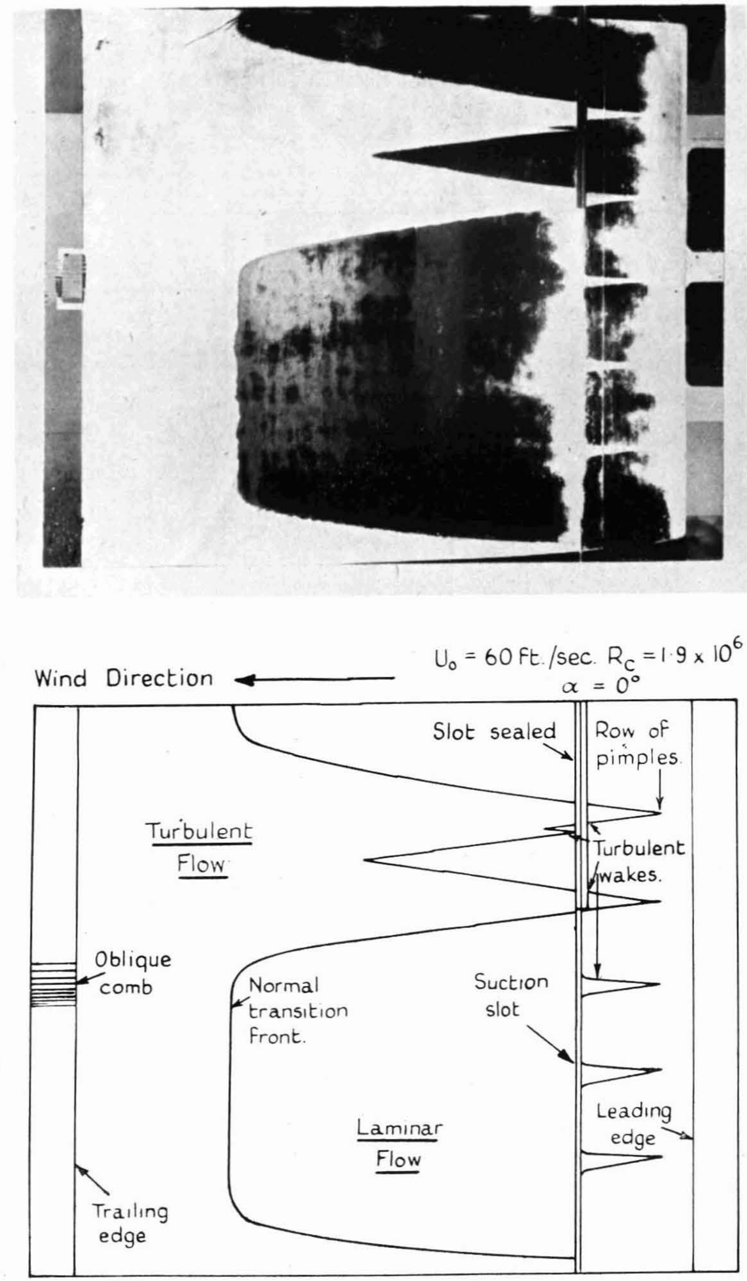

FIG. 4. Re-establishment of laminar flow by boundary-layer suction at a slot, visualised by the china-clay technique.

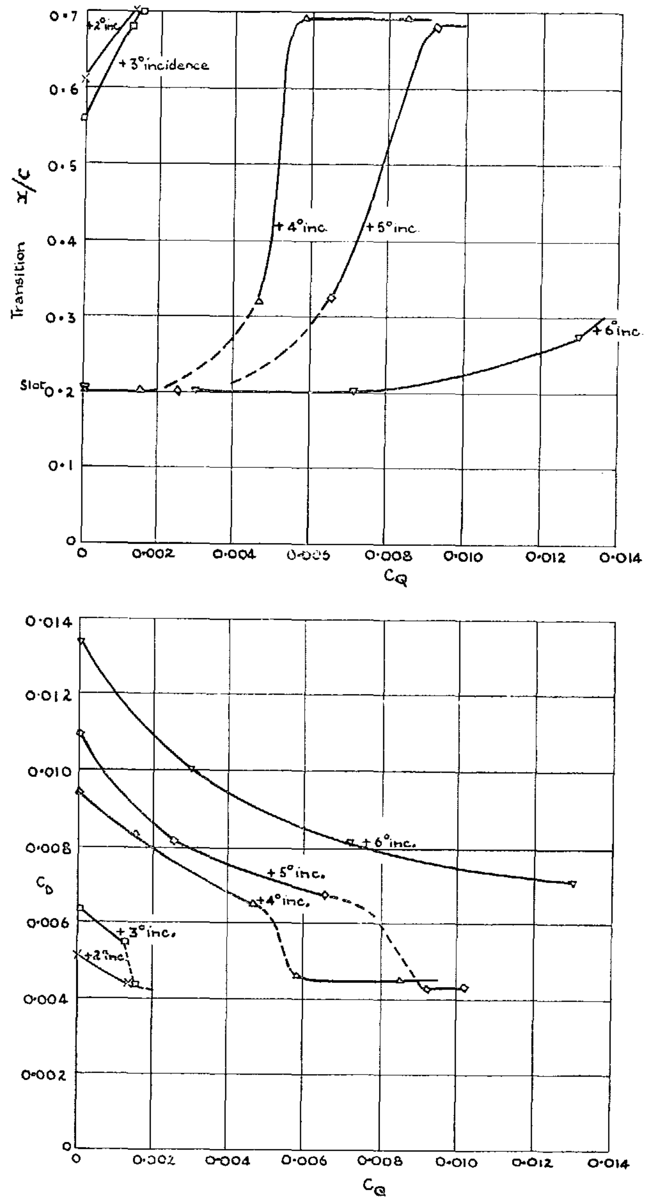

FIG. 5. Variation of upper surface transition and wing profile drag with suction. No transition wire. $U_0 = 60$ ft/sec, $R = 1 \cdot 9 + 10^6$.

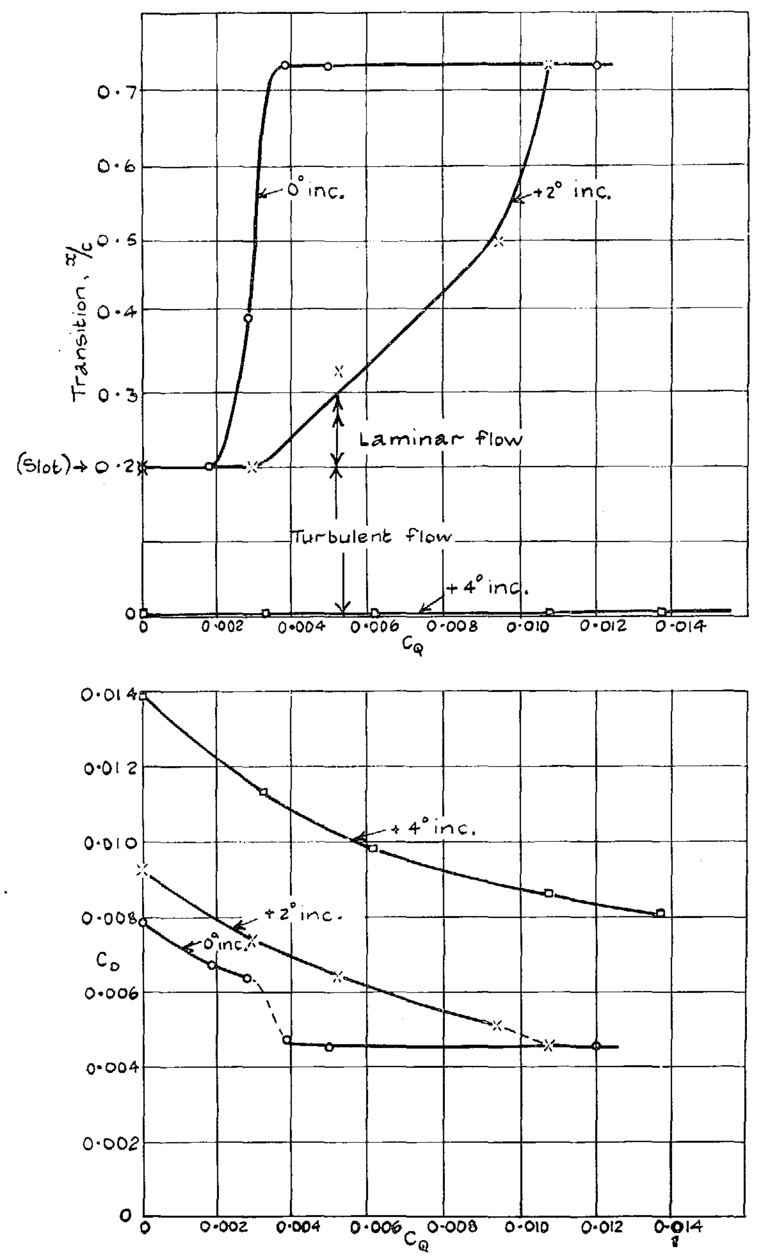

FIG. 6. Variation of upper surface transition and wing profile drag with suction. 0·1-in. dia. wire $\frac{1}{4}$ in. behind leading edge. $U_0 = 60$ ft/sec, $R = 1 \cdot 9 \times 10^6$.

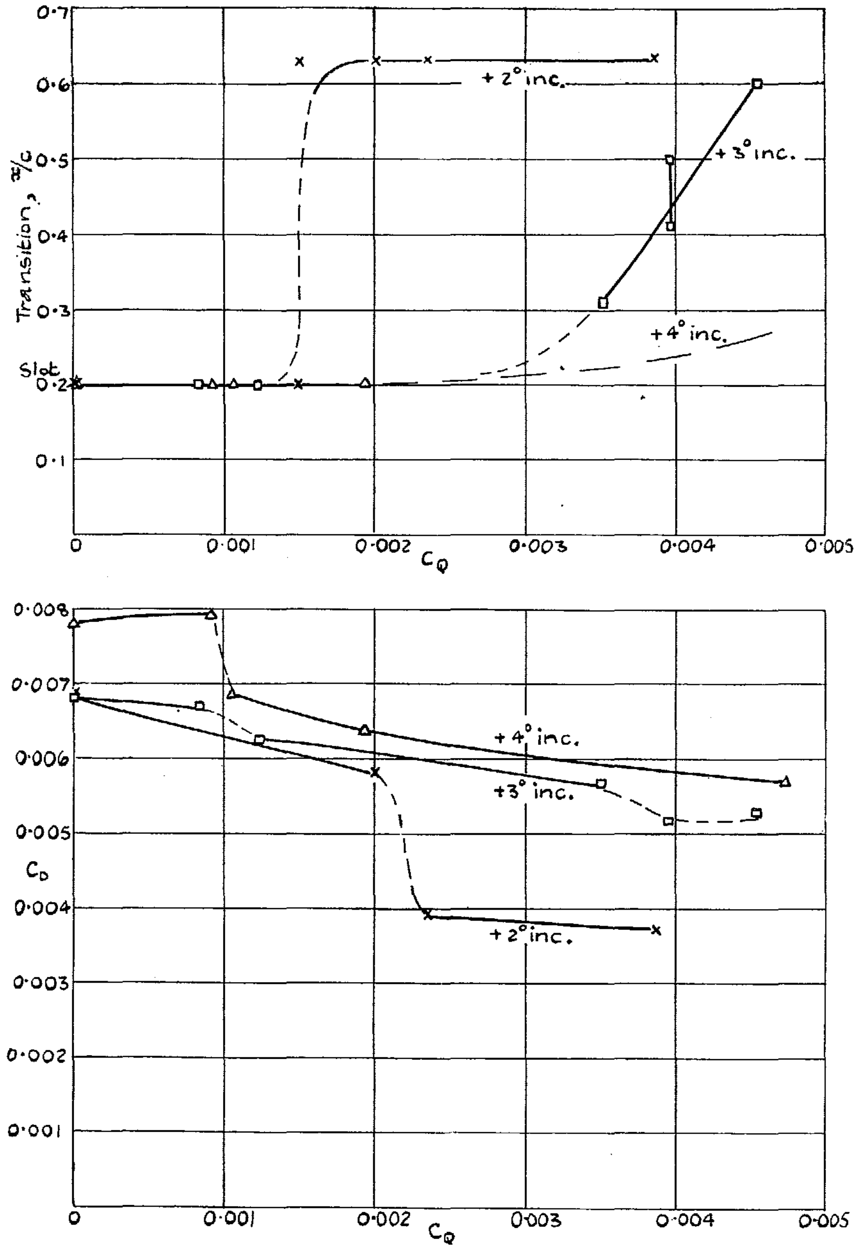

FIG. 7. Variation of upper-surface transition and wing profile drag with suction. No transition wire. $U_0 = 180$ ft/sec, $R = 5 \cdot 7 \times 10^6$.

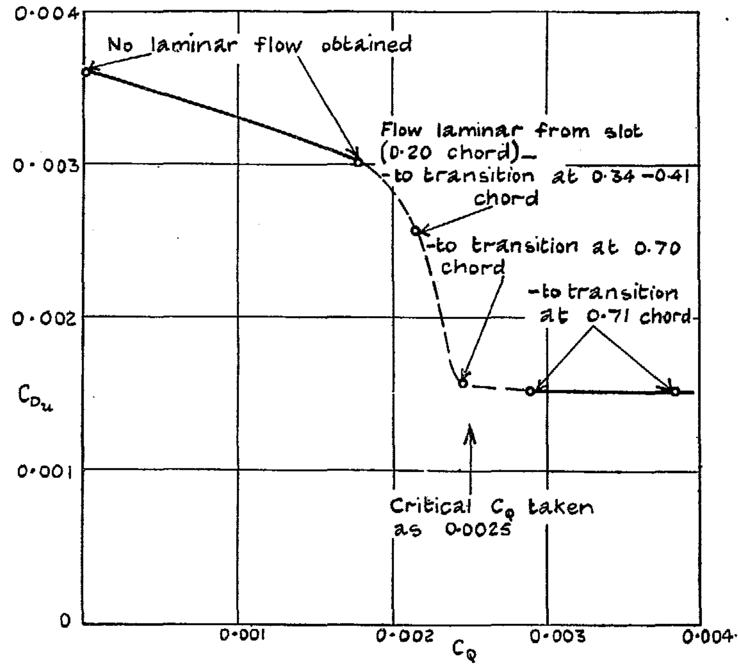

FIG. 8. Variation of upper-surface drag coefficient with suction quantity. 0·022-in. dia. wire at 0·05 chord. $\alpha = -4$ deg, $U_0 = 180$ ft/sec, $R = 5 \cdot 7 \times 10^6$.

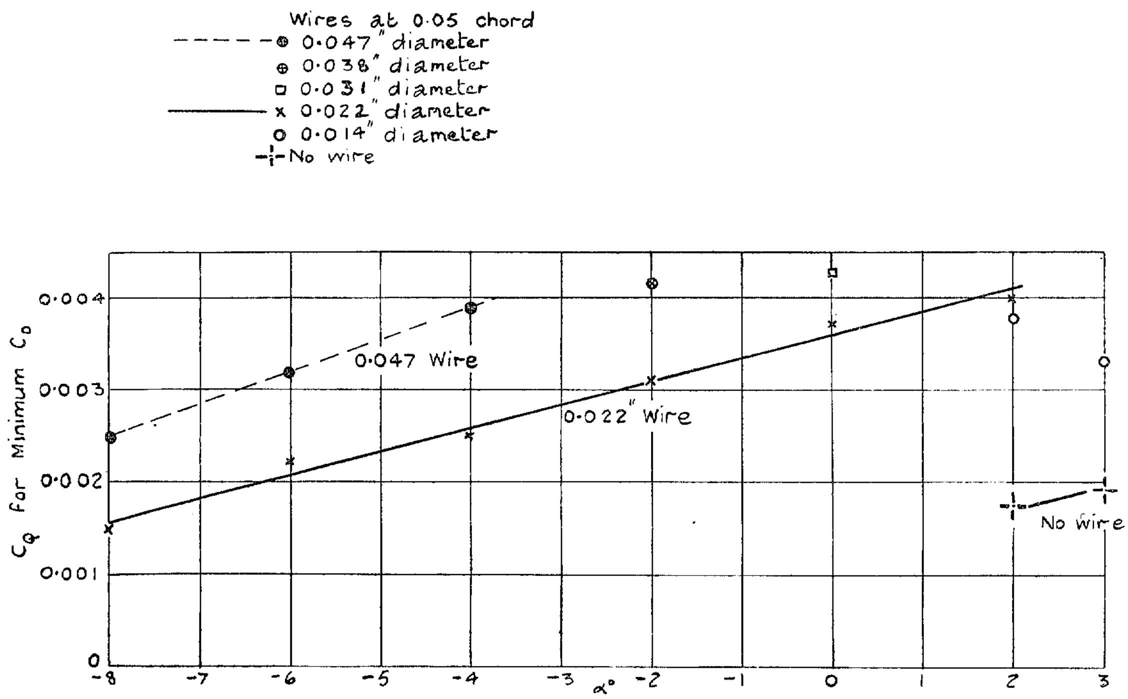

FIG. 9. Variation of critical quantity coefficient with incidence.

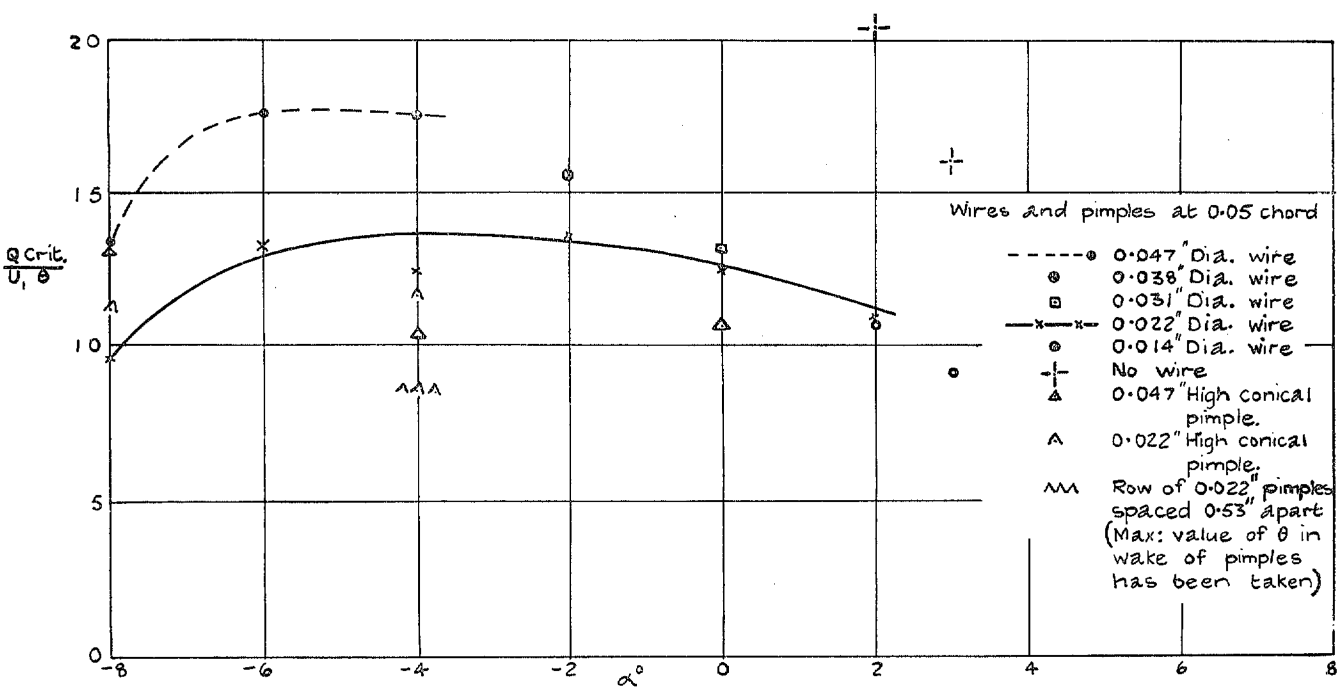

FIG. 10. Variation of critical $Q/U_1\theta$ with incidence.

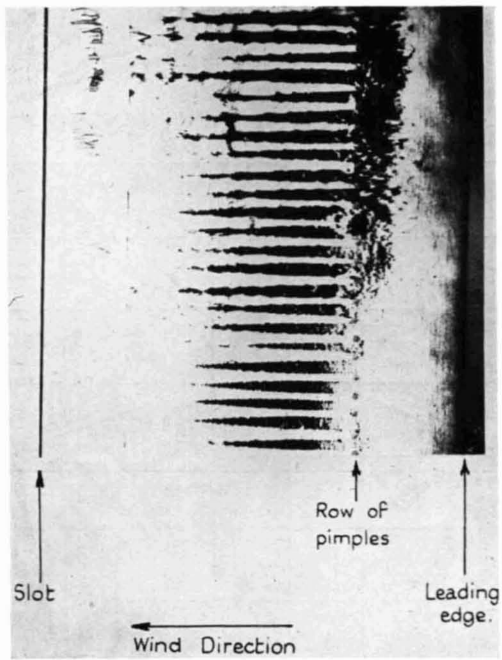

FIG. 11. Row of 0·022-in. high conical pimples spaced 0·53 in. apart causing transition.

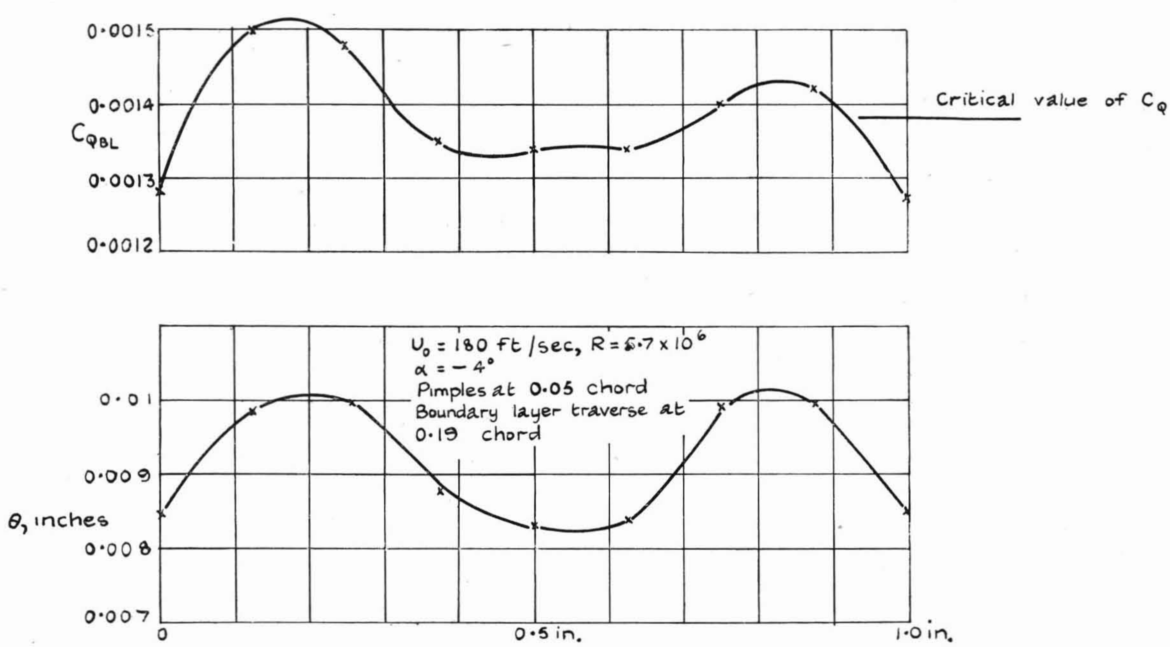

FIG. 12. Spanwise variation in wake behind row of pimples 0·53 in. apart and 0·022 in. high.

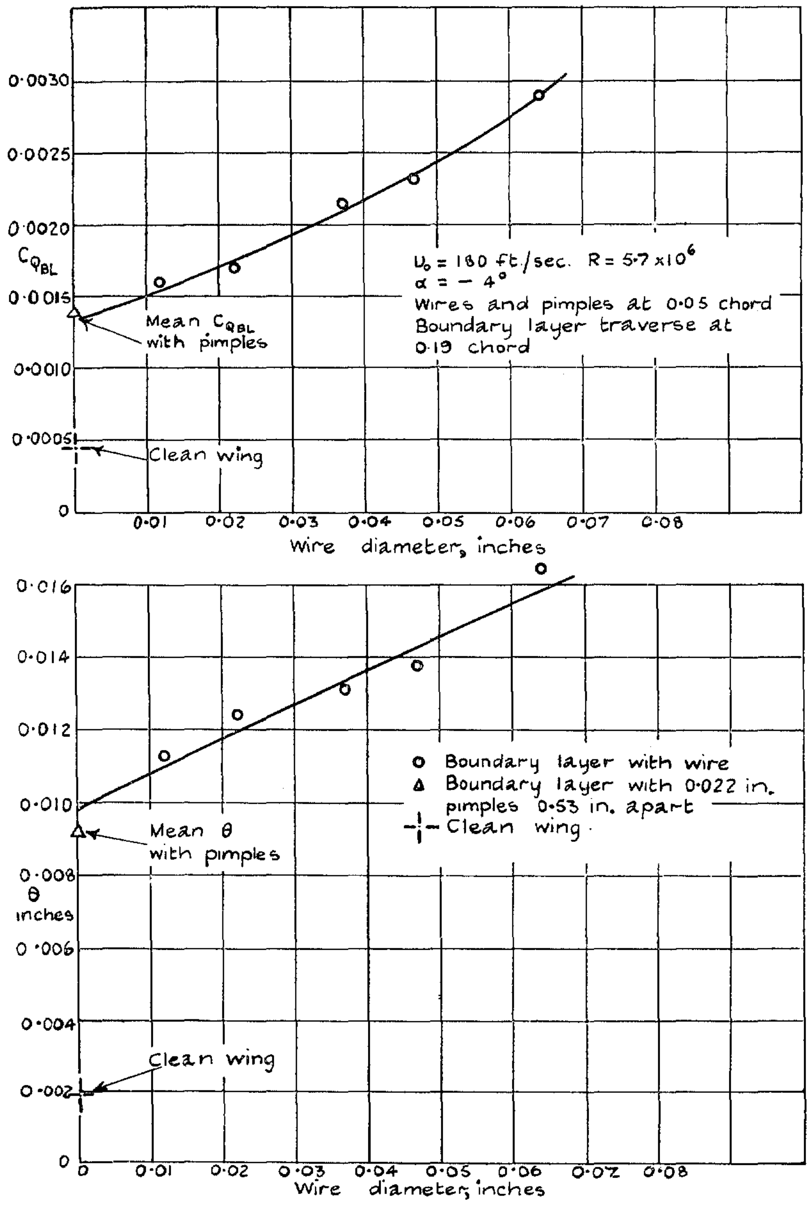

FIG. 13. Variation of quantity and momentum thickness of boundary layer at 0·19 chord with diameter of transition wire.

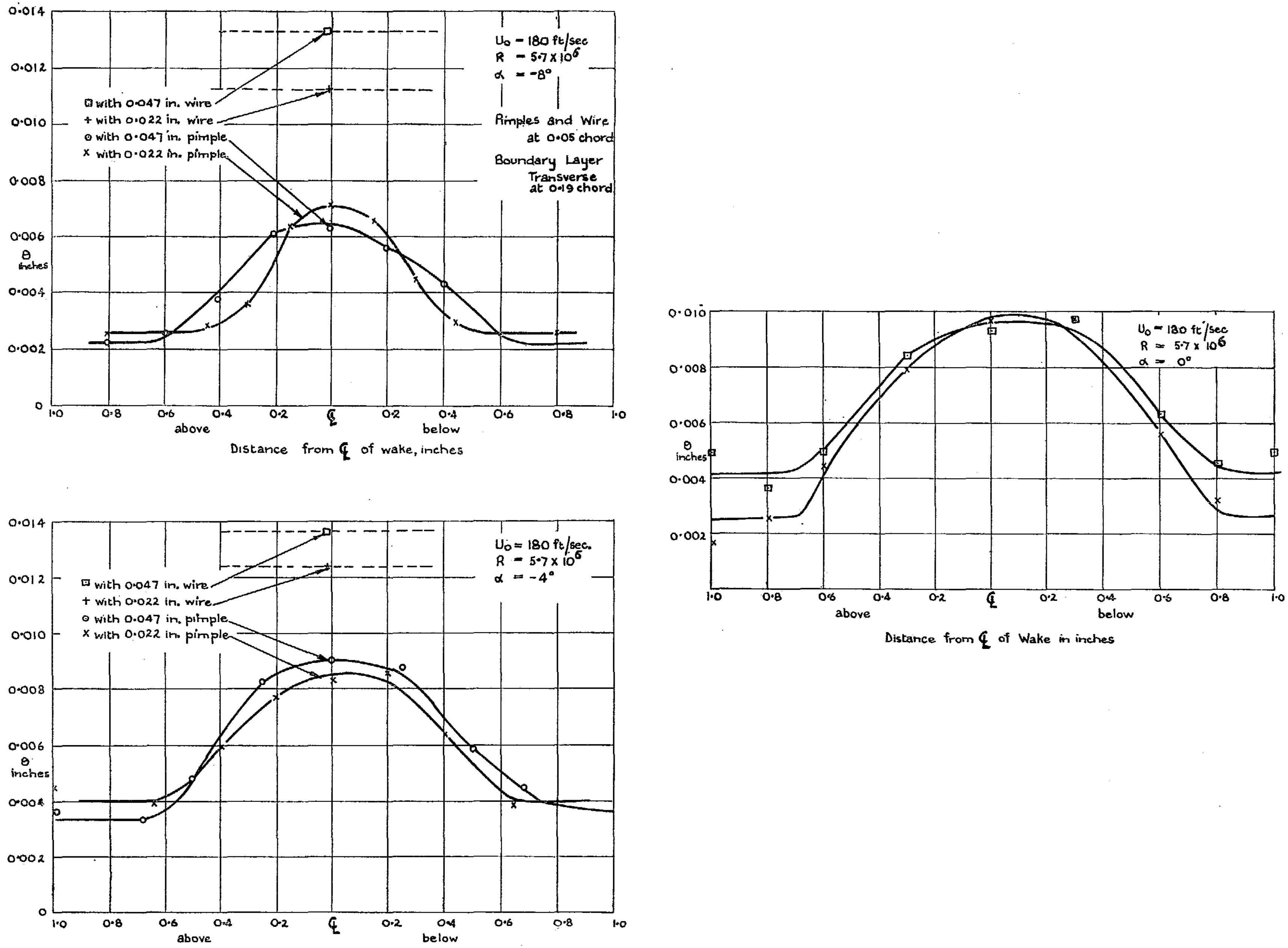

FIG. 14. Variation of boundary-layer momentum thickness across wake of single pimple.

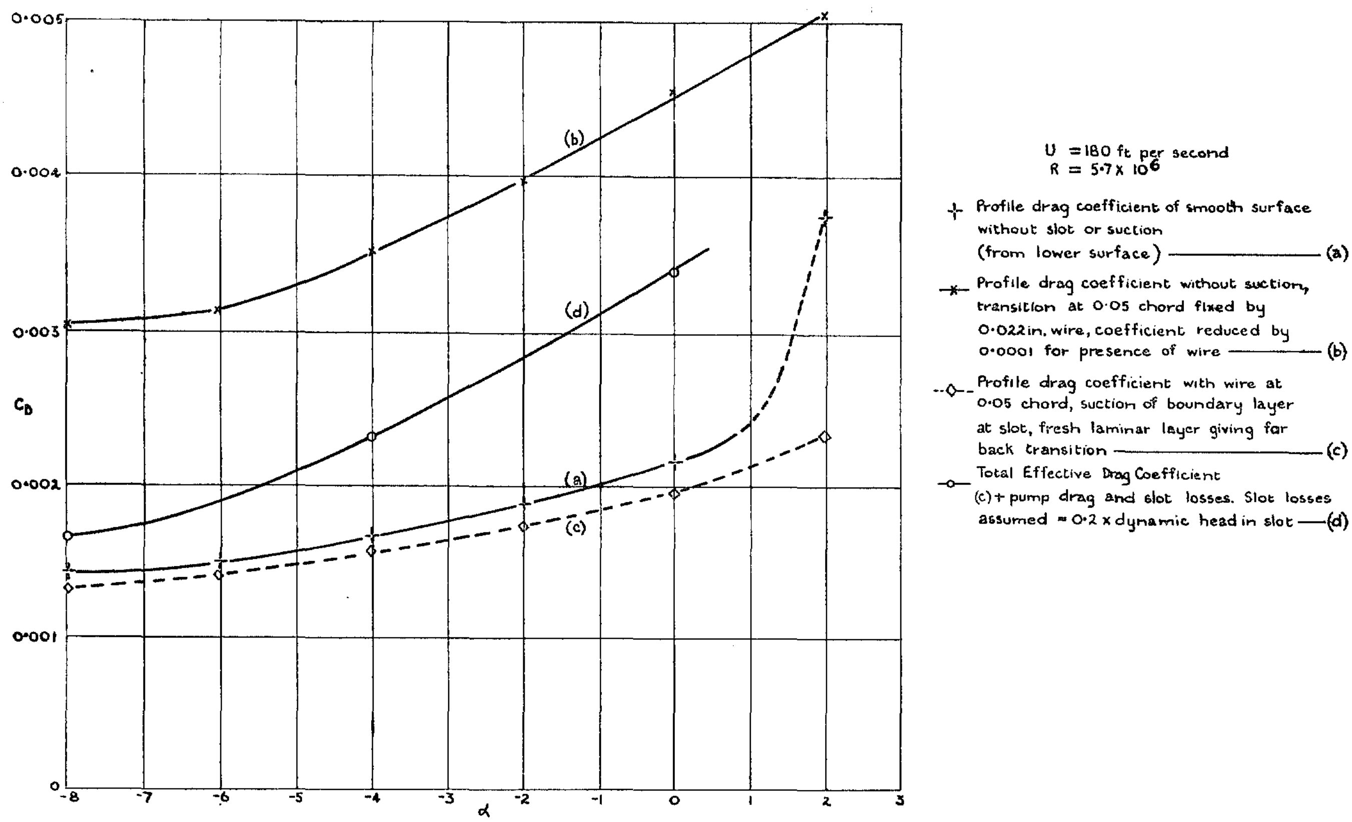

FIG. 15. Variation of upper-surface drag coefficient with incidence.

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