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Wind-Tunnel Tests on the 30 per cent. Symmetrical Griffith Aerofoil with Ejection of Air at the Slots

By

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of the Aerodynamics Division, N.P.L.

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Wind-Tunnel Tests on the 30 per cent. Symmetrical Griffith Aerofoil with Ejection of Air at the Slots

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Summary.—It has been shown by Preston[1] (1946) that ejection of air at the point of velocity discontinuity on a 16·2 per cent. thick Griffith suction aerofoil prevents separation, and that if sufficient air is ejected, the drag is reduced. The present tests were undertaken to apply this principle to the 30 per cent. Griffith aerofoil and to investigate the effect on lift by pressure-plotting the aerofoil.

Ejection of air was found to prevent separation, but about 66 per cent. more air was required than with suction. Three times the suction quantity of air, when ejected, reduced the drag to the low values associated with suction.

At $R = 0 \cdot 96$ millions, the range of the tests was 0–18 deg. incidence and 0–14 deg. flap angle. At 18 deg. incidence and 14 deg. flap angle, a C_{NF} of 2·5 was obtained, giving approximately the same lift-curve slope as with suction. Above this angle of incidence, the pump capacity was not large enough for unseparated flow to be attained. With separation prevented, the pitching moments were the same as with suction, but the hinge moments were sensitive to small changes of blowing quantity.

At $R = 2 \cdot 88$ millions, the pump capacity was insufficient to prevent a partial stall at 6 deg. incidence as occurred with suction.

Curves of C_{NF}, C_Q, C_M, C_H, C_D and velocity distribution when blowing are given, and comparisons are made with corresponding curves obtained with suction and with no suction. The same lift and pitching moments are obtained at any incidence with blowing and with suction, but the suction quantities are about 40 per cent. less than the blowing quantities. The hinge moments are greatly different with blowing, and increase with increase of the normal force.

1. *Introduction.*—It has been shown in earlier reports by Richards[2] (1945) and Gregory[3] (1946) that large increases in lift and large reductions in drag could be obtained on a 30 per cent. thick Griffith type aerofoil when the theoretical velocity distribution was maintained by means of suction at the points of velocity discontinuity. It has been suggested that similar effects would be obtained by ejection of air from the slots instead of by suction. Preliminary tests with blowing were made by Preston, Walker and Taylor[1] (1946) on the 16·2 per cent. Griffith aerofoil. These showed that the quantity of air necessary to prevent separation by blowing was about $2\frac{1}{2}$ times that required with suction, and that to get low values of C_D, seven times the quantity was required for blowing as with suction.

In order to obtain more information, further tests have now been carried out on the 30 per cent. aerofoil used for suction experiments, but with air blown out from the slots.

2. *Experimental Details.*—The section of the 30 per cent. Griffith aerofoil is shown in Fig. 1. The arrangement in the National Physical Laboratory 13 ft. × 9 ft. wind tunnel of the 30-in. chord aerofoil was the same as that described in a previous report by Gregory[3] (1946) with one exception. The calibration ducting previously leading the air away from the aerofoil, was now connected by 9 × 12 in. ducting to the outlet side of the centrifugal blower.

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A traverse was carried out along the slots and the velocity of ejection of air was found to have the saw-tooth distribution shown in Fig. 2. The curves show a local variation of $\pm$ 15 per cent. on the mean, and this is because the passages connecting the collector duct to the slot do not diminish regularly in area, but each has a slight expansion in the middle. This expansion gives a very even distribution of suction flow but leads to a separation when blowing, and the air adheres throughout to one side of each passage. This defect could be remedied by more careful design in future models to make them equally suitable for either suction or blowing. The velocity measurements were made with a probe that fitted 1/16 in. into the slot. The mean flow was very even along the whole span of the slot, and it is probable that the local velocity variations outside the slots were much smaller than was indicated by the figure

The aerofoil was tested at various incidences with the flap set over at angles up to 14 deg. with different amounts of air blown out of the slots. Tests were carried out at three wind speeds, 60, 120 and 180 ft./sec. corresponding to $R = 0{\cdot}96 \times 10^6$, $1{\cdot}92 \times 10^6$ and $2{\cdot}88 \times 10^6$.

The wing was sprayed with china clay which showed up irregularities generating turbulence on the surface, and by removing these a very smooth surface was obtained giving laminar flow over regions of favourable velocity gradient. Measurements of C_{NF}, C_M and C_H were deduced from pressure-plotting the aerofoil and flap. Drag measurements were made by pitot-traversing the wake.

Three sets of experiments were carried out:—

(*a*) Measurement of C_{NF}, C_M and C_H at $a = 4$, 8 and 12 deg. with flap at 14 deg. with varying quantities of air blown out of the upper-surface slot, the quantity blown out of the lower-surface slot being kept constant. The wind speed was 60 ft./sec. (*see* Fig. 5 and section 4).

(*b*) Drag measurements at $a = 0$ deg. $\eta = 0$ deg. on the smooth wing, with wires at $0{\cdot}5$ chord and with wires at $0{\cdot}1$ chord with various quantities of air blown out, equal quantities from the two surfaces, at $V = 60$, 120 and 180 ft./sec. (*see* Figs. 6a, b, c and section 4).

(*c*) Measurements of C_{NF}, C_M and C_H over a range of incidences with the flap set at 0, 5, 10 and 14 deg. with blowing on the two surfaces just sufficient to prevent separation, at $V = 60$ and 180 ft./sec. (*see* Figs. 7–11 and section 5).

3. *Velocity Distribution.*—Two typical velocity distributions obtained on the wing are shown in Figs, 3 and 4, for a low and a high angle of incidence respectively, each with the flap at 14 deg. For purposes of comparison, the velocity distributions obtained on the wing with and without suction are also shown. The suction distribution approximates to the potential flow.

At the lower angle of incidence, $a = 4$ deg., $\eta = 14$ deg., blowing, although preventing the separation observed without suction, does not fully restore the velocity distribution to the theoretical value. On the other hand, at $a = 10$ deg., $\eta = 14$ deg. the effect of the turbulent separation without suction is not only prevented by blowing, but the velocity over the flap is less than the theoretical value. This only appears so because the velocities have been worked out from the experimental pressures assuming the total head to be constant and equal to that of the free stream, and no correction has been made for the total head of the ejected air being greater than that of the free stream. Thus it is only correct to say that the pressures over the flap are greater than the theoretical. This should be noted, as it indicates a reduction in form drag.

4. *The Effect of C_Q' on the Results.*—Fig. 5 shows the effect of varying the upper surface C_Q on the normal-force, pitching-moment and hinge-moment coefficients of the aerofoil for three different incidence positions. Except in the case of zero C_Q, the quantity of air on the lower surface was kept constant ($C_Q = 0{\cdot}011$) and only that on the upper surface was varied.

With increasing C_Q there are at first marked changes in the coefficients, but later C_M remains constant and C_{NF} increases very slowly with increase of C_Q, within the range covered. The changes of C_H with C_Q are, however, large. Below a certain value of C_Q, depending on the incidence, $\partial C_H/\partial C_Q$ is negative, above that value of C_Q, it is positive, and there is an abrupt change in the value of C_H at a point wheie good flow conditions are obtained. These changes in C_Q would be an objection to the use of blowing in front of a control surface unless it was arranged for the quantity of air ejected on both surfaces to be equal.

Figs. 6, a, b and c, shows the variation of drag coefficient at $a = 0$ deg., $\eta = 0$ deg., with C_Q at three tunnel speeds, 60, 120 and 180 ft./sec. with three different transition positions in each case. Corresponding curves with suction applied are included for comparison. For small values of C_Q when separation is definitely present, the curves are not very reliable owing to the large fluctuations of pressure recorded in the wake. With transition at 0·5 chord or to the rear, we first obtain an increase of drag as C_Q is increased. This is of the same nature as leakage dıag and is due to the velocity of ejection of the air being less than the minimum velocity of the airflow over the flap outside the boundary layer. The C_Q at which the velocity of the ejected air is equal to the potential velocity just behind the discontinuity is marked on the figures. The scale effect on laminar separation previously noticed in the suction experiments is again present. At low values of C_Q, the C_D curve for the wing with wires at 0·5 chord is below that for the smooth wing at 60 ft./sec., whereas at higher speeds it is above the curve for the smooth wing.

From Figs. 5 and 6, separation seems to be prevented at values of C_Q between once and twice those necessary to prevent separation with suction, and the drag reaches the low values obtained with suction at values of C_Q about three times those necessary with suction. These values are more favourable than those found in the earlier tests with the thinner 16·2 per cent. Griffith aerofoil section.

It must be emphasised that the phrase 'prevention of separation' does not have its usual significance when applied to a wing having air ejected from its surface at a point of discontinuity. It is impossible to tell from observations of pressure in the wake, or from streamers on the surface of the flap, at what value of C_Q separation is overcome. For there is no sudden fall in drag as occurs with suction, and the indications given by the threads of reversed flow on the surface of the flap cease with very small quantities of ejected air, whilst the large amplitude vibrations of the threads are not finally damped out until long after the lift coefficient attains its higher values associated with unseparated flow. The continual variation of the pressures over the rear portion of the aerofoil with increase of C_Q does not give any direct evidence when separation is overcome. The best indication comes from hinge moments. The difficulty arises from the situation of the slot at the point of discontinuity.

It is suggested by Preston[1] (1946) that by ejecting air into the boundary layer (at speeds above the local stream velocity) ahead of the discontinuity, the momentum thickness of the boundary layer could be sufficiently reduced to enable it to cross the discontinuity without separation. On this aerofoil and on the one previously tested, the slots have been at and not ahead of the discontinuity. Therefore, the effect of blowing is to force the old boundary layer off the surface and to form a new layer which remains attached to the flap. Above 8 deg. incidence, a turbulent separation with reversed flow occurs 0·03 chord in front of the slot. This could not be prevented by blowing, although with sufficient quantity the flow was satisfactory behind the slot.

5. *Variation of C_{NF}, C_Q, C_M and C_H with Incidence and Flap Angle.*—Normal-force, pitching-moment and hinge-moment coefficients were measured on the wing flap at 0, 5, 10 and 14 deg. at the minimum values of C_Q necessary to maintain unseparated flow at windspeeds of 60 and 180 ft./sec., corresponding to $R = 0{\cdot}96 \times 10^6$ and $2{\cdot}88 \times 10^6$. Accurate drag measurements were not carried out, but it was noticed that at $R = 0{\cdot}96 \times 10^6$ the pitot-traverse drag was approximately zero throughout the whole incidence range, there being considerable excess momentum in the central core of the wake balancing out the deficiences of momentum in the wake on either side of the centre. This is a low-speed scale effect due to the relatively large C_Qs. At $R = 2{\cdot}88 \times 10^6$ the drag coefficient of the wing varied between 0·005 to 0·010 inside the favourable incidence range and was of the order of 0·050 outside it. This is of the order of the drag of the smooth wing with no blowing or suction, and the effect of blowing was not visible on the multitube manometer recording the total head across the wake.

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5.1. *Normal Force.*—Curves of C_{NF} plotted against incidence for the various flap angles are given in Figs. 7 and 8. Similar curves obtained from the experiments with and without suction are also given. At $R = 0 \cdot 96 \times 10^6$, it was possible to maintain unseparated flow up to 18 deg. incidence, and the normal force coefficient increased linearly with incidence. The highest value of C_{NF} measured was $2 \cdot 5$ at $a = 18$ deg., $\eta = 14$ deg. Beyond this incidence unseparated flow could not be maintained. At $R = 2 \cdot 88 \times 10^6$, the highest angle at which unstalled conditions could be maintained with the pump was again 6 deg. where C_{NF} varied between $0 \cdot 6$ and $1 \cdot 05$ (with flap angles 0 and 15 deg. respectively). The flow was greater than that necessary with suction.

The C_{NF}'s are all slightly greater than those recorded with suction. This might be expected, as blowing is likely to increase the circulation round the aerofoil slightly.

5.2. *Quantity.*—The pump flow coefficients ($C_Q = Q$ per foot run $\div U_0c$) used in obtaining the C_{NF}'s of Fig. 8 ($R = 0 \cdot 96 \times 10^6$) are plotted against C_{NF} in Fig. 9. The suction quantities are also given, which for the same C_{NF}'s are about 40 per cent. less than the blowing quantities. As with suction, to a very rough approximation, the values of C_Q depend only on incidence and not on C_{NF} or flap angle. The values of C_Q are constant between 0 and 6 deg. and increase with incidence above this angle.

5.3. *Pitching Moment.*—The pitching-moment curves are plotted against C_{NF} in Fig. 10, together with those obtained with suction. At $R = 0 \cdot 96 \times 10^6$ the two are in agreement. At $R = 2 \cdot 88 \times 10^6$ the stall occurs at 6 deg. incidence, and above this angle the pitching moments rapidly alter.

5.4. *Hinge Moment.*—As is shown in Fig. 5, the hinge moments are very sensitive to changes of C_Q, so it is difficult to obtain smooth curves by plotting C_H against C_{NF}. This has been attempted for $R = 0 \cdot 96 \times 10^6$ in Fig. 11 at the minimum values of C_Q required to maintain unseparated flow. It should be noticed that there is considerable scatter in repeat readings.

At $R = 2 \cdot 88 \times 10^6$ the observed values of C_Q are even more confused and curves are not reproduced here. Below the stall, the C_H's are of the order of the values obtaining at the lower speed, but at the stall, C_H's fall by about $0 \cdot 8$.

6. *Discussion of Results and Comparison with Suction.*—The comparison shown in the C_{NF} curves of Fig. 8 for suction and blowing shows that blowing is as effective as suction in preventing separation and obtaining the high lift coefficients for which the Griffith type aerofoils are designed. Theoretically, higher C_{NF}'s may be obtained by extra blowing on the upper surface, but in the present experiments, the increase of C_{NF} with increase of C_Q, after separation is prevented, is small compared with the rise of C_{NF} as the non-separated flow régime is attained.

The quantity of air used in obtaining unseparated flow is larger than that needed with suction. For small incidences, on each surface, $C_Q = 0 \cdot 008$ for blowing compared with $0 \cdot 005$ for suction. This is offset by advantages pointed out by Preston[1] (1946) that much of the air ejected needs little expenditure of power, that large heads in the pump are more easily obtainable when blowing than with suction, and that the ducting losses should be less.

No definite conclusions can be drawn on the basis of total drag of the wing. The negative pitot-traverse drag recorded at $R = 0 \cdot 96 \times 10^6$ is a low-speed scale effect and disappears at the higher speeds where no reduction in profile drag is to be found. On the other hand, the power required to eject the air is less, and low-loss ducting will be easier to design.

It was discovered during the tests that a serious objection to blowing over a control surface of a Griffith aerofoil is the sensitiveness of the hinge-moment coefficient to changes in blowing quantity. This indicates that if blowing is adapted as a means of boundary-layer control on a thick Griffith aerofoil in flight, it would be desirable to place all control surfaces outboard of parts of the wing where blowing is applied. There might, however, be cases where moments are unimportant and suction inconvenient, for example, as suggested by A. D. Young of the Royal Aircraft Establishment, in turbine blades, where a Griffith section with blowing would give high lift associated with low drag. The ejected air would serve to cool the blades and so the mainstream temperature could be raised with consequent gain in efficiency.

7. *Conclusions.*—Ejection of air at the discontinuity of the 30 per cent. symmetrical Griffith aerofoil is shown to be effective in preventing separation of the airflow and obtaining high lifts. About 66 per cent. more air is needed than with suction, and there is no big drop in drag except at small Reynolds numbers.

It should be emphasised that the effect of blowing depends not only on the quantity of air ejected but also on the pressure and velocity with which the air leaves the slot, and these depend not only on the rate of mass flow but also on the total head in the slot and the width of the slot. Variations of these parameters have not been investigated in the present tests.

The highest C_{NF} obtained was 2·5 at 18 deg. incidence and 14 deg. flap angle, giving the same lift-curve slope as with suction. The pitching moments were the same as with suction, but the hinge moments were found to be very sensitive to changes of blowing quantity.

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No.	*Author*	*Title, etc.*
1	J. H. Preston, W. S. Walker and C. R. Taylor	The Effect on Drag of Ejection of Air from a Backward Facing Slot on a 16·2 per cent. Griffith Aerofoil. R. & M. 2108 (Jan., 1946).
2	E. J. Richards, W. S. Walker and C. R. Taylor	Wind Tunnel Tests on a 30 per cent. Suction Wing. R. & M. 2149 (July, 1945).
3	N. Gregory and W. S. Walker ..	Further Wind Tunnel Tests on a 30 per cent. Symmetrical Griffith Aerofoil with Flap. R. & M. 2287 (July, 1946).

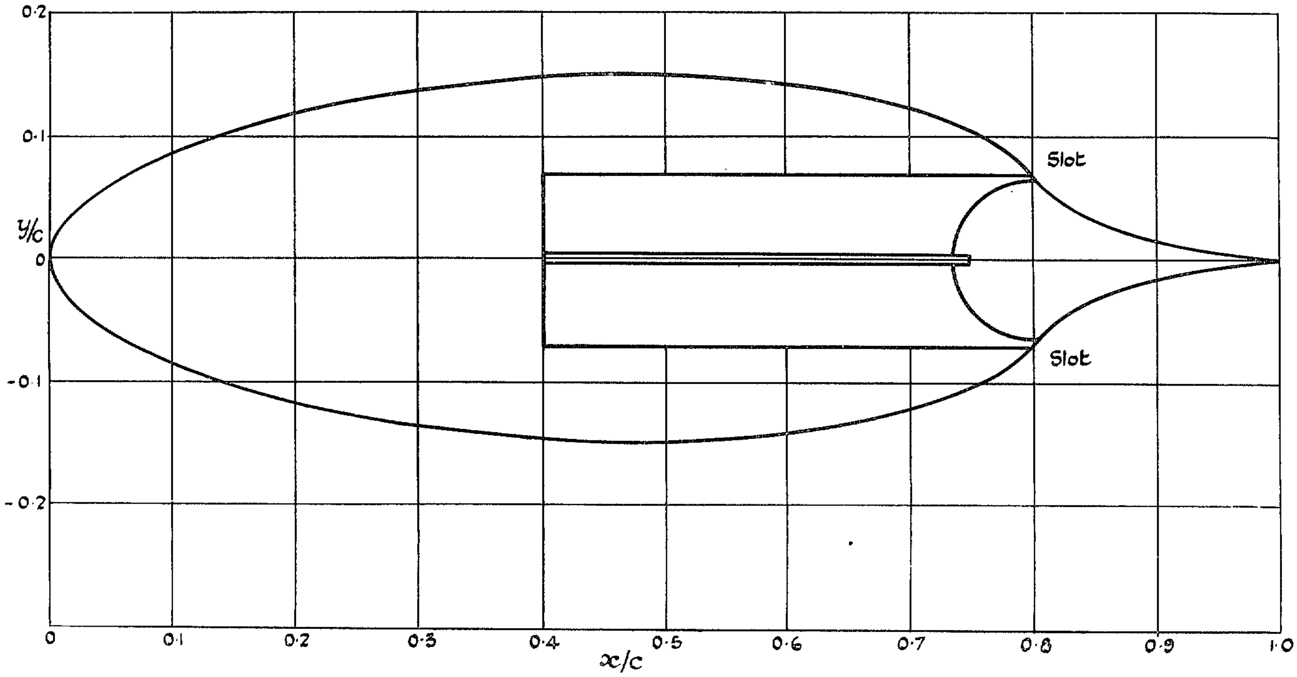

FIG. 1. 30 per cent. suction wing with cusped tail, chord 30 in.

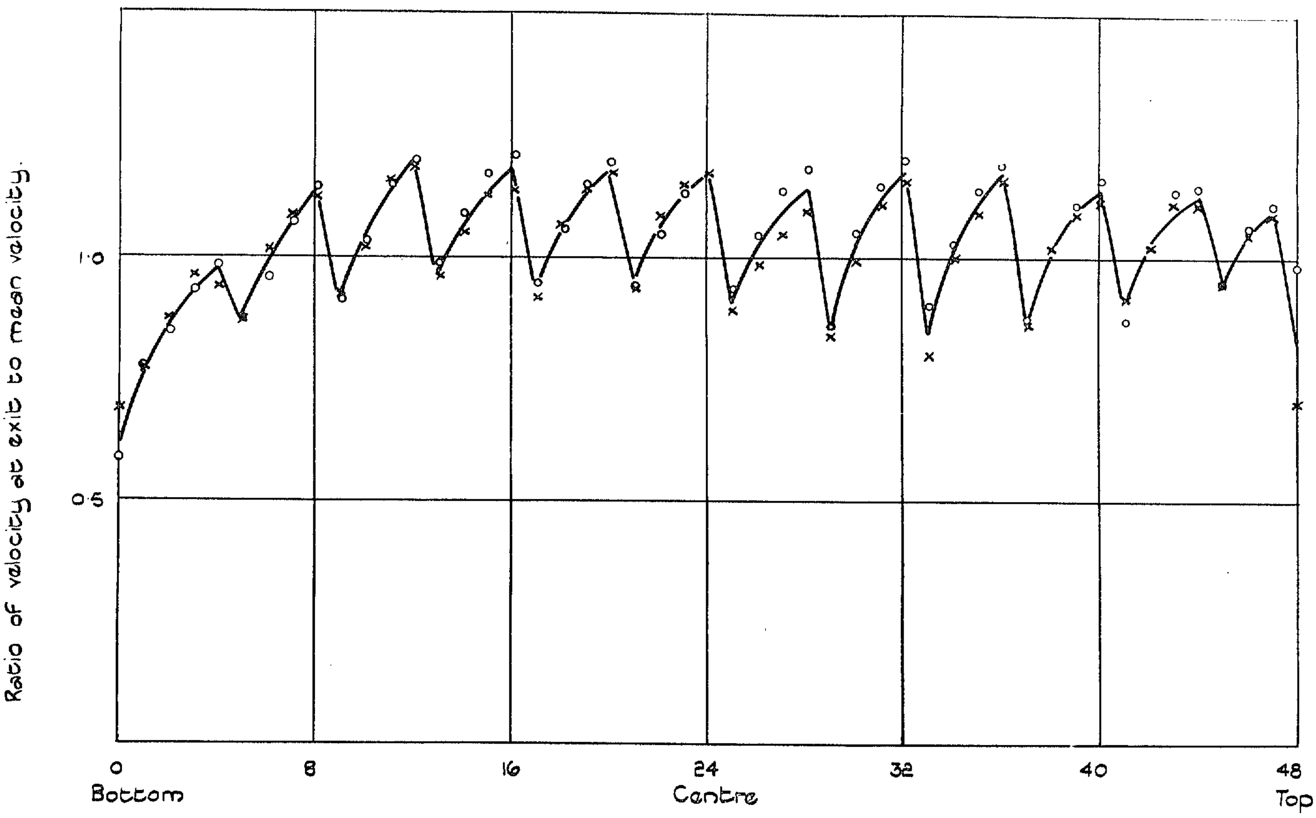

FIG. 2. Velocity distribution along slot (blowing).

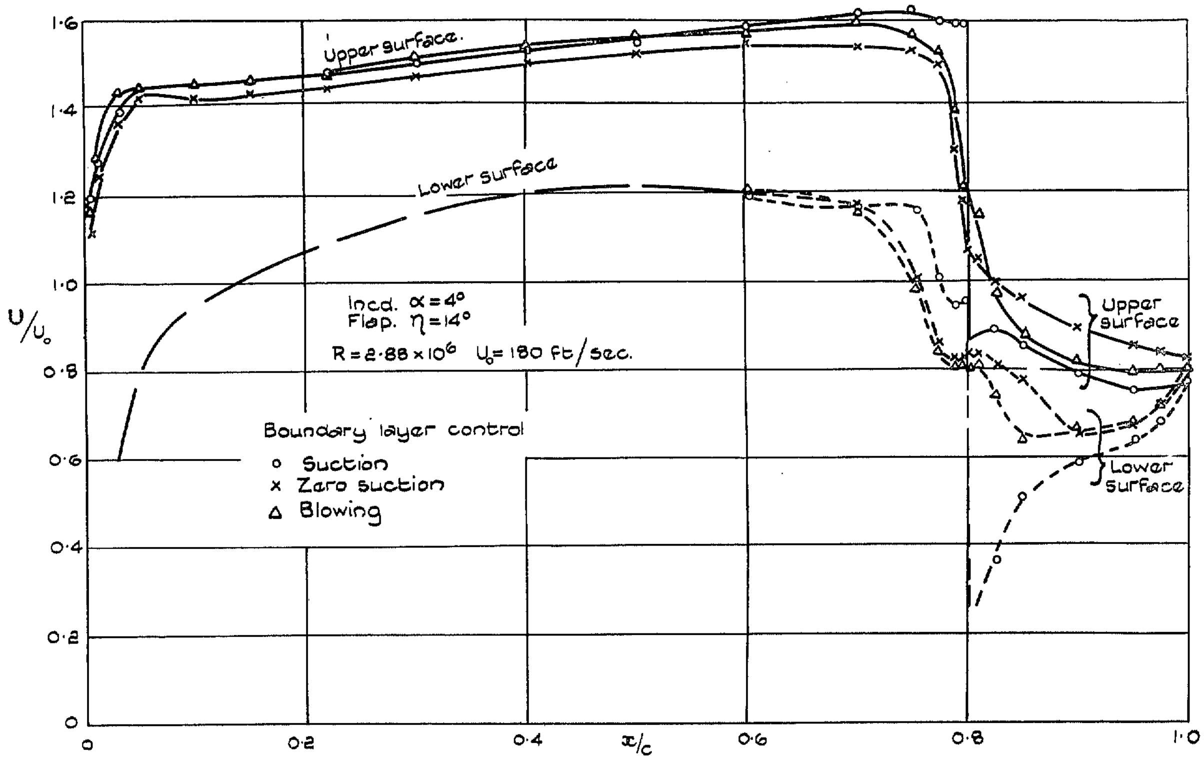

FIG. 3. Velocity distribution over aerofoil—comparison between methods of boundary-layer control.

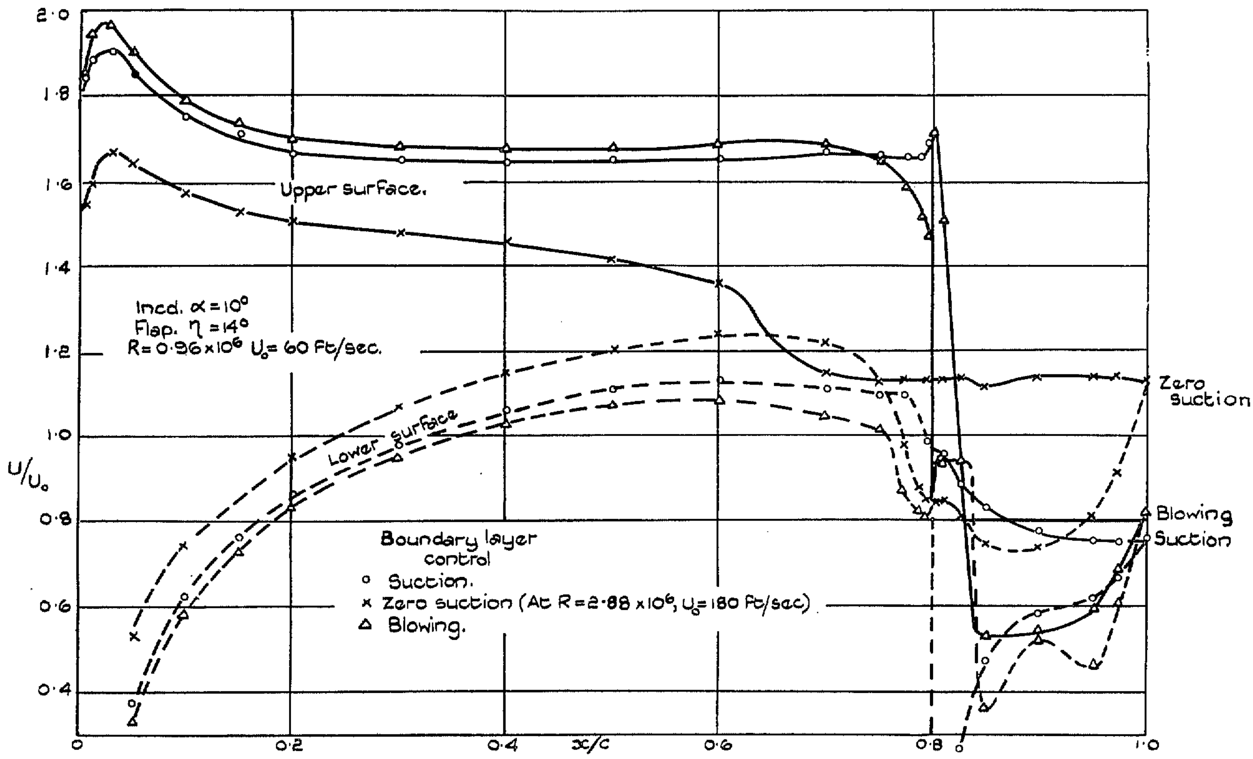

FIG. 4. Velocity distribution over aerofoil—comparison between methods of boundary-layer control.

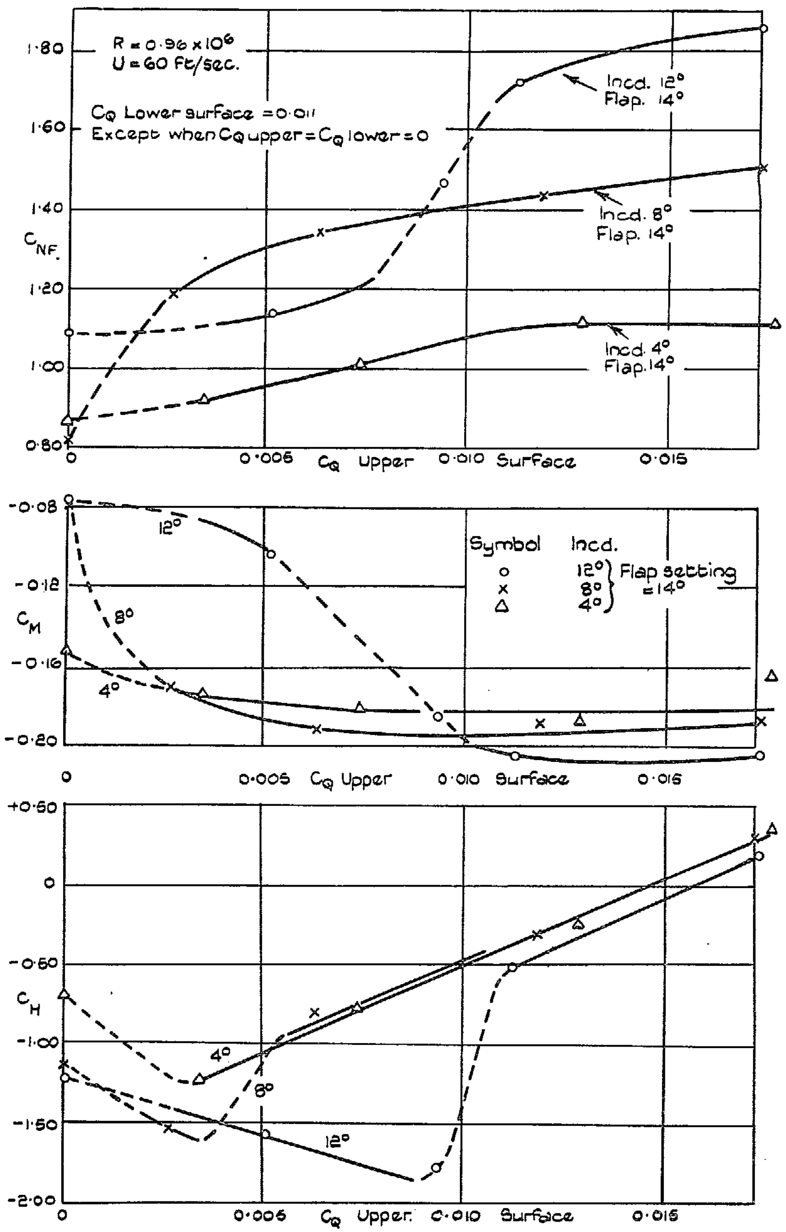

FIG. 5. Variation of C_{NF}, C_M and C_H with C_Q at three different wing incidence positions.

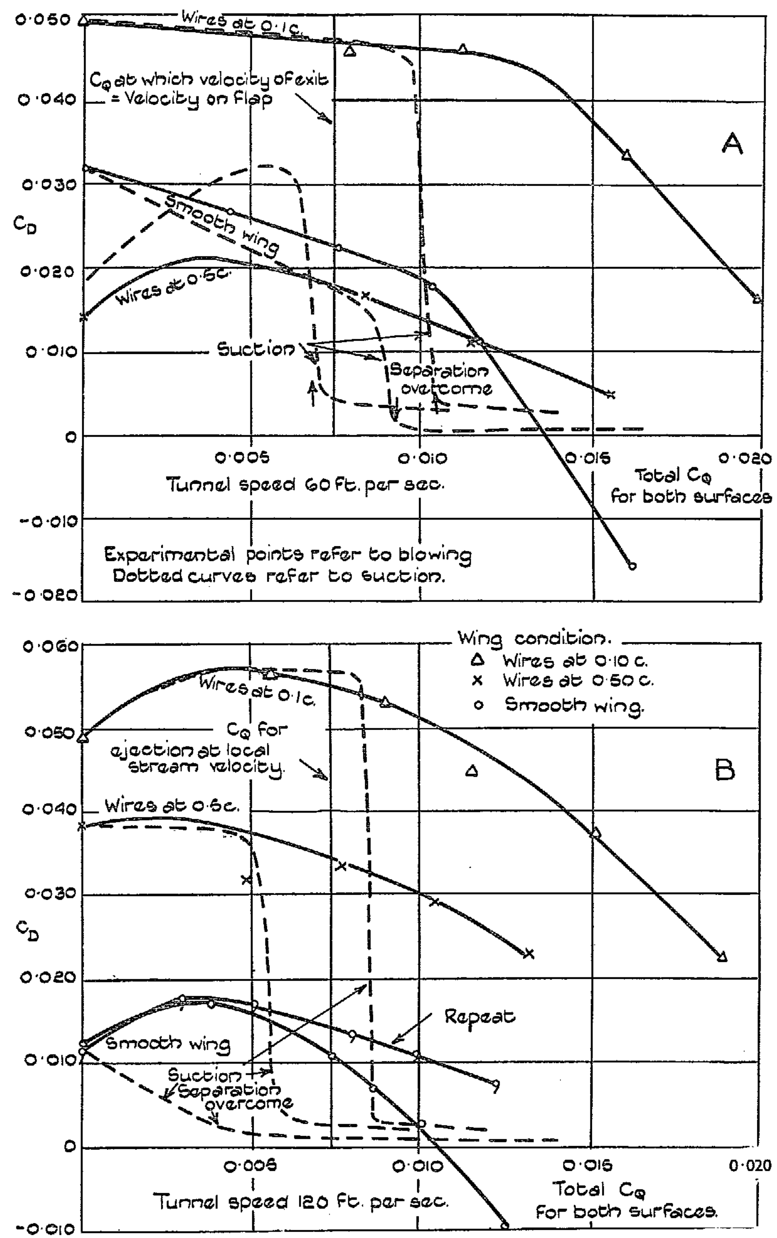

FIG. 6 a and b. Variation of C_D with suction or blowing quantity for different surface conditions, at zero incidence and flap angle.

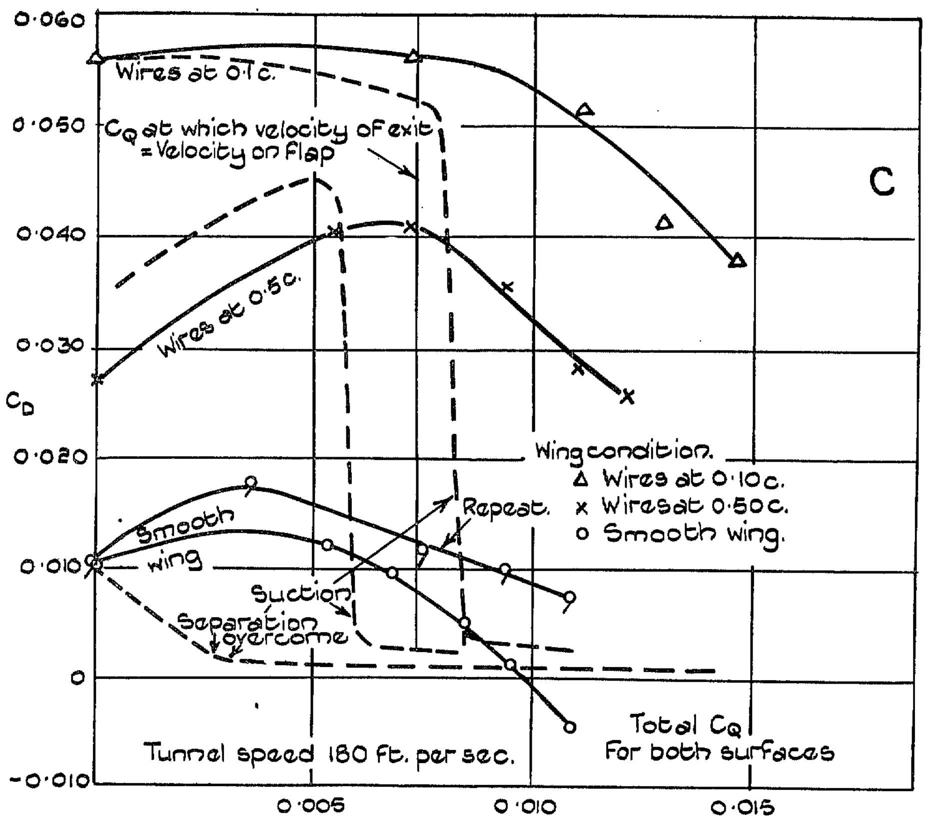

FIG. 6 c. Variation of C_D with suction or blowing quantity for different surface conditions, at zero incidence and flap angle.

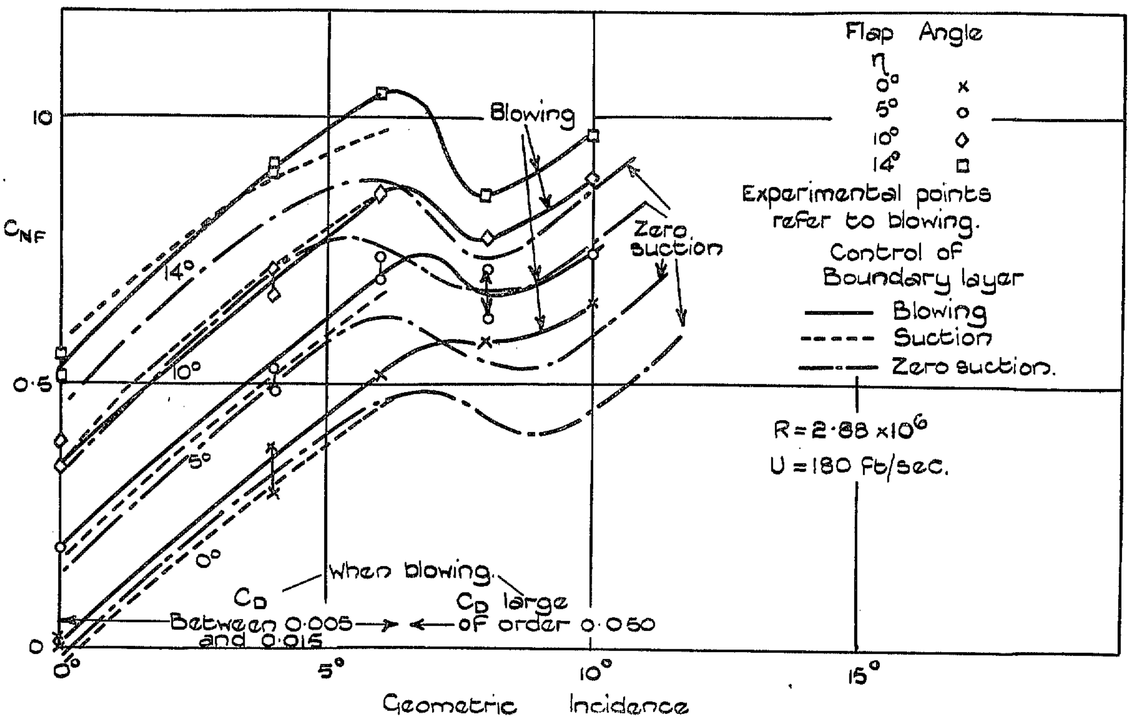

FIG. 7. Comparison of the variation of C_{NF} with incidence and flap angle between different systems of boundary layer control. $R = 2{\cdot}88 \times 10^6$, $U = 180$ ft/sec.

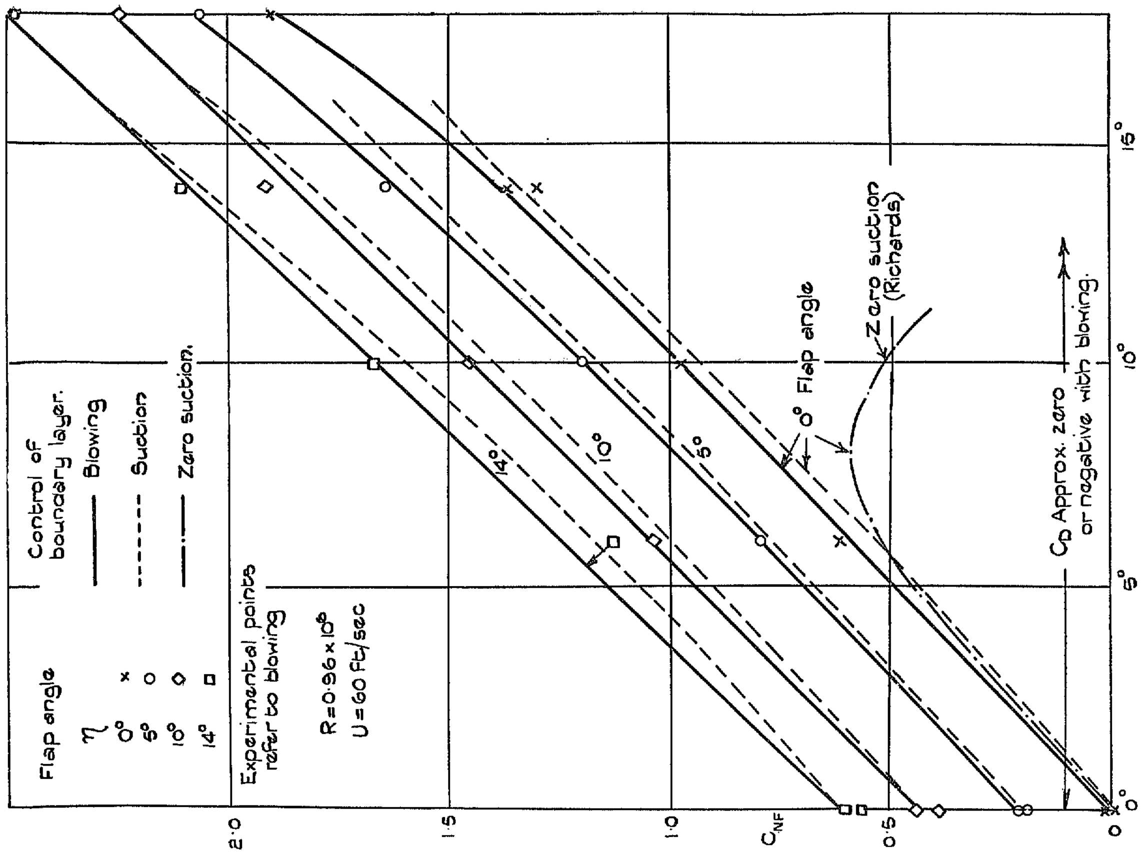

FIG. 8. Comparison of the variation of C_{NF} with incidence and flap angle between different systems of boundary-layer control. $R = 0{\cdot}96 \times 10^6$, $U = 60$ ft/sec.

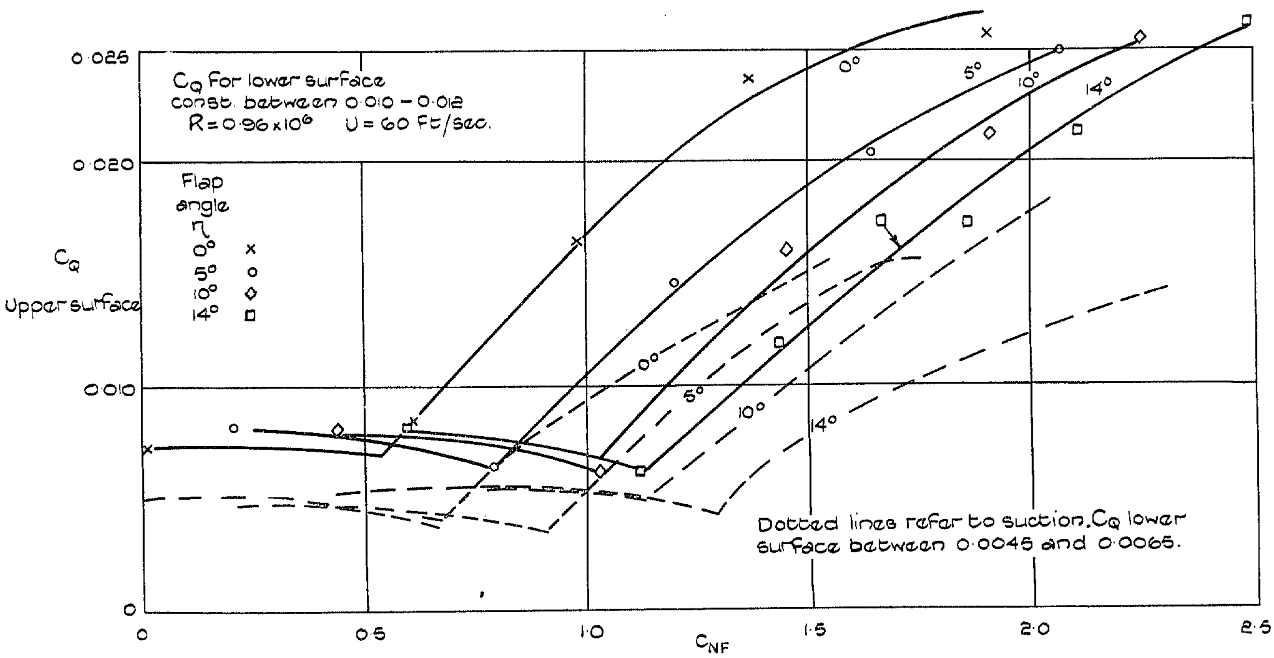

FIG. 9. Variation of C_Q with C_{NF} for various flap settings. C_Q sufficient to prevent separation.

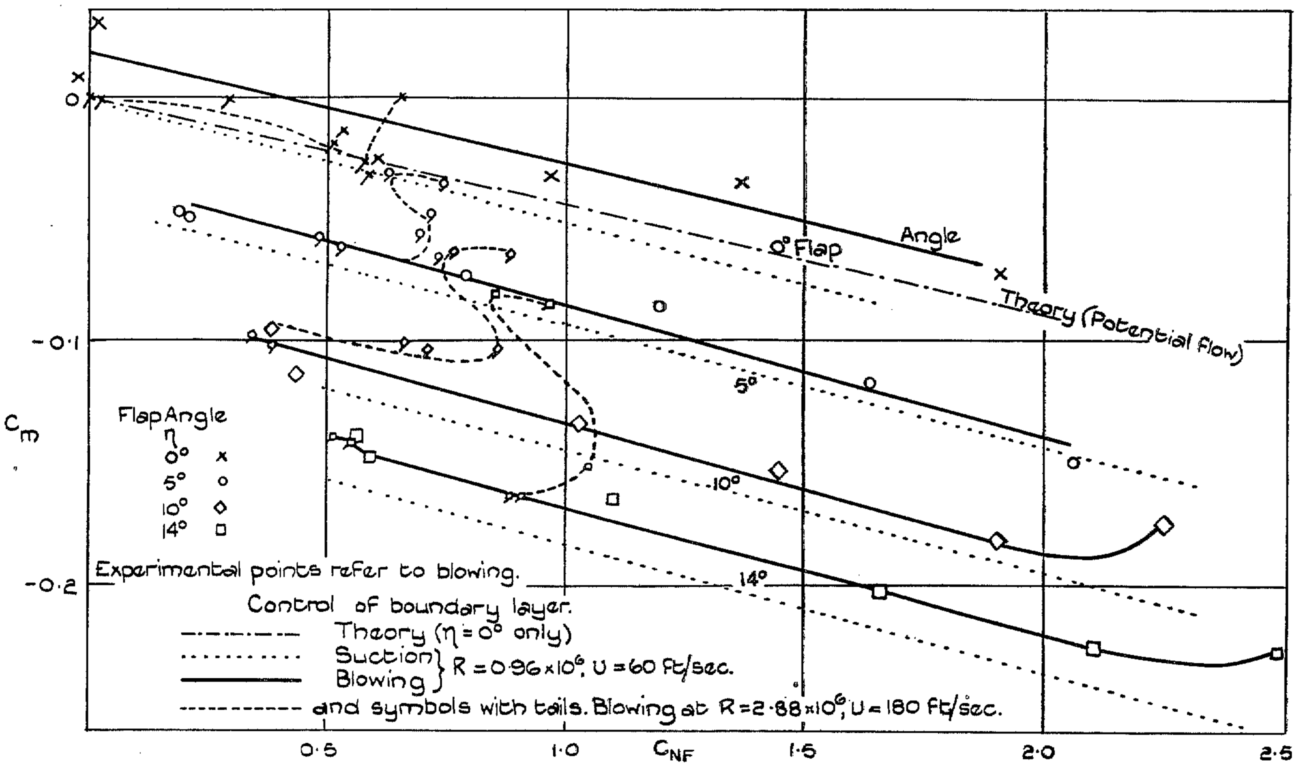

FIG. 10. Comparison of the variation of C_M with C_{NF}, for various flap angles, between different systems of boundary-layer control.

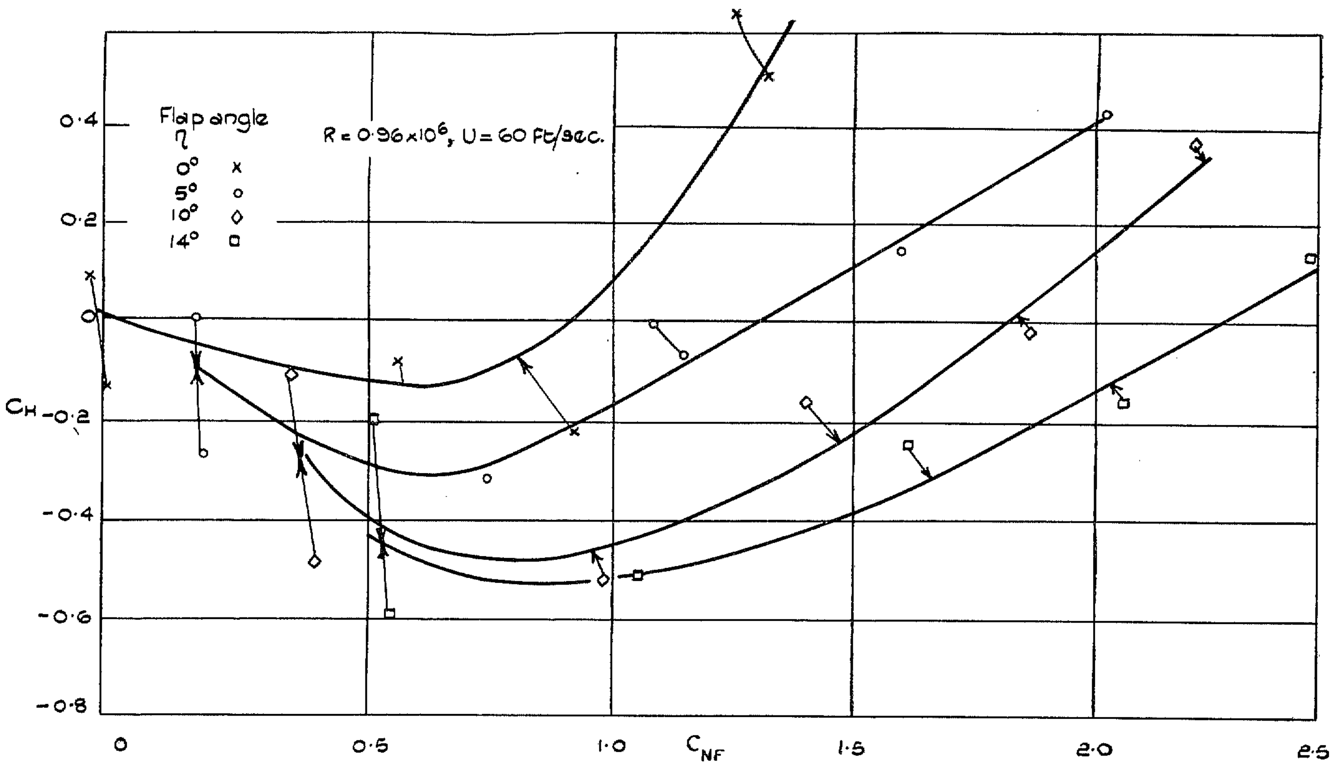

FIG. 11. Variation of hinge-moment coefficient with C_{NF} for various flap angles.

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