BOUNDARY LAYER TRANSITION AT THE LEADING EDGE OF THIN WINGS AND ITS EFFECT ON GENERAL NOSE SEPARATION

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1. INTRODUCTION

The design of aircraft to cruise at high subsonic speeds has necessitated the introduction of thin wings, often possessing considerable sweepback. The low speed, high incidence characteristics of such wings, however, leave much to be desired and as a consequence intense research efforts aimed at increasing usable lift are being maintained in many parts of the world.

General separation of the boundary layer from the aerofoil nose at relatively low lifts is the root cause of the flight difficulties encountered. A major factor associated with this phenomenon is transition from laminar to turbulent flow in the affected region. Although the complete answer to this flow problem awaits a fuller understanding of the mechanics of transition, a good working knowledge of the leading edge problem is now available. A theory of general nose separation which does not conflict with available experimental data is propounded.

2. SEPARATION PHENOMENA DEFINITIONS

To avoid possible confusion the phenomena to be discussed will be clearly defined. It is well known that an adverse pressure gradient near the leading edge of an aerofoil will cause separation of the laminar layer from the surface. When this separation first becomes apparent as the incidence is increased, the separating layer re-attaches itself to the surface along a line which is less than 1% chord downstream of the separation line, provided the Reynolds number is not too low.

As incidence is further increased a state is reached where a sudden breakdown in the flow around the aerofoil nose occurs. In the case of thin aerofoils, re-attachment of the flow as a turbulent layer usually occurs at a distance downstream of the leading edge which is ten to one hundred times greater than the length of the separation region referred to in the preceding paragraph.

The first phenomenon is generally referred to as a "laminar separation bubble" or alternatively as a "short bubble." In the second case, Gault(1) calls the separated region a "thin-aerofoil bubble", Küchemann(2) refers to it as a "long bubble".

The terms "laminar separation bubble" and "general nose separation" will, in this paper, be used in reference to the two types of flow separation; the latter term is usually shortened to "nose separation" or "nose stall"(3, 4).

3. TRANSITION THEORIES

Before discussing the leading edge problem the relevant portions of current transition theories will be reviewed.

A dominant feature in any transition mechanism is the creation of relatively large-scale vortices possessing axes parallel to the stream direction. The setting up of these three-dimensional motions is linked with the appearance of turbulent spots in the laminar flow. Of interest in regard to longitudinal vortices is the original work of Townsend(5) in which it was shown experimentally that such vortices exist in a turbulent layer and that these account for the transfer of the bulk of the momentum from the outer to the inner parts of the boundary layer. This vortex structure has now been confirmed in ref. 6; in addition Kline draws attention to the similarity between transition vortices and the formation of vortices in a turbulent layer in a region near the outer edge of the laminar sublayer.

Experiments by Hama *et al.*(7) downstream of a "trip" wire have shown that the amplified two-dimensional Tollmien–Schlichting waves present tend to roll-up the shear layer into a concentrated vortex line. These vortex lines are then distorted into vortex loops by spanwise changes in the rate of amplification. The loops deteriorate downstream into turbulent spots which propagate three-dimensionally until the boundary layer flow is completely turbulent.

Transition investigations by Klebanoff and Tidstrom(8) in which wave-like disturbances were introduced by means of a vibrating ribbon, also established that the Tollmien–Schlichting waves are distorted prior to transition by the transfer of wave energy from one spanwise position to another. These three-dimensional trends lead to the formation of turbulent spots and subsequent transition.

No wavefront vortex loops or irregularities of the Hama type were observed in these tests. Since entirely different experimental techniques were used in refs. 7 and 8 it was suggested(8) that the apparent conflict between the two investigations might be one of interpretation only. However it is suggested by Schubauer(9) that a basic difference may exist between the phenomena. Because of the higher Reynolds numbers used in the vibrating ribbon tests, it was postulated that transition occurred before this relatively weaker wave could concentrate the vorticity into discrete eddies as in the Hama experiments.

Lochtenberg(10) investigated the separated flow due to a step on a flat plate and reported the existence of two distinct transition mechanisms. At low Reynolds numbers a wave-like motion was set up in the separated layer and transition took place gradually without the appearance of turbulent spots. Above a certain critical Reynolds number, transition appeared to follow the creation of turbulent spots or bursts.

Although the available evidence for a change in the transition mechanism is not, as yet, convincing, the possibility of such is worth pursuing in the case of leading edge separations as without such the available experimental data tend to be contradictory.

The above discussion has been centred around the manner in which turbulence arises. Transition is not complete, however, till the boundary layer profile approximates that for a normal turbulent layer. This occurs when the intermittency factor, defined as the fraction of the total time that the flow is turbulent at any point in the transition region, is unity(11).

The intermittency factor is associated with the random appearance and passing of turbulent spots. At the same time as the intermittency factor is increasing, the velocity profile of the layer changes in a continuous manner as the flow passes downstream. Therefore transition needs time and distance for its completion; this includes the case where transition is precipitated by laminar separation.

Most of the transition studies to date have been carried out in regions of zero pressure gradient. The use of wires and steps as a means of precipitating transition in some of the experimental studies has, however, indicated that laminar separation may only have a modifying effect on the main transition mechanism. Extending this argument to the case of a severe adverse pressure gradient at the nose of thin aerofoils at incidence, it is postulated here that the main influence of the gradient is to shorten the distance over which the transition process is occurring without producing a major modification to the basic mechanism. Some justification for this assumption is given in Section 4.3.

4. LEADING EDGE SEPARATION

The remainder of this paper considers the specific problems of leading edge transition and separation. It is propounded that, depending on the Reynolds number, there are two distinct transition mechanisms. This feature results in corresponding detailed changes in the associated laminar separation bubbles. As a consequence there are two fundamentally different mechanisms initiating general nose separation.

4.1 *Flow Upstream of Laminar Separation Bubble*

As aerofoil incidence is increased the forward stagnation point advances down the lower or pressure surface of the wing. Owing to the relatively small distance travelled by the laminar layer from the stagnation point, the Reynolds number, R_{Θ}, at the suction peak is comparatively low. In addition, the highly accelerated flow ensures a relatively large value of $R_{\Theta_{\text{crit.}}}$, the Reynolds number at which the boundary layer becomes unstable. As a consequence, transition is unlikely to occur before the suction peak is reached.

The adverse pressure gradient downstream of the suction peak greatly reduces the boundary layer stability. Nevertheless, there are many reasons why transition may not occur upstream of the normal laminar separation point in the high incidence case. The distance between this point and the stable suction peak region is so small that, for transition to occur, a very rapid mechanism would be essential. Tests at chord Reynolds numbers up to 10 million were carried out by Gault(12) and, with the exception of one or two low incidence cases, transition always occured downstream of separation. Data presented by Crabtree(13) indicate that, for streams of low turbulence level, $R_{\Theta\text{tr.}}$ is approximately 1300 for a boundary layer in a zero pressure gradient and 750 for a laminar layer approaching separation; these values decrease with increasing free stream turbulence. The former quantity relates to conditions at the suction peak.

In view of the above data it is not surprising that, to the author's knowledge, no actual observations of transition upstream of the normal laminar separation point have been made for high incidence cases.

4.2 *Laminar Separation Bubble*

The first theory concerning the laminar separation bubble was propounded by von Doenhoff(14). It was postulated that the separating layer left the surface tangentially (Fig. 1) and continued along a straight line until transition occurred at a Reynolds number, R_L of 50,000. The separated layer then diffused at an angle of 15° and re-attachment took place at the point where the layer met the surface. General separation occurred when this 15° line failed to intersect the surface. Although this concept has in the past proved most helpful, it is now generally regarded as inaccurate.

Many alternative theories based on experimental data have been put forward in an attempt to explain the manner in which transition influences the onset of general nose separation. Unfortunately, the test Reynolds numbers have often been limited to relatively low values in order to obtain laminar separation bubbles of adequate size for detailed investigation.

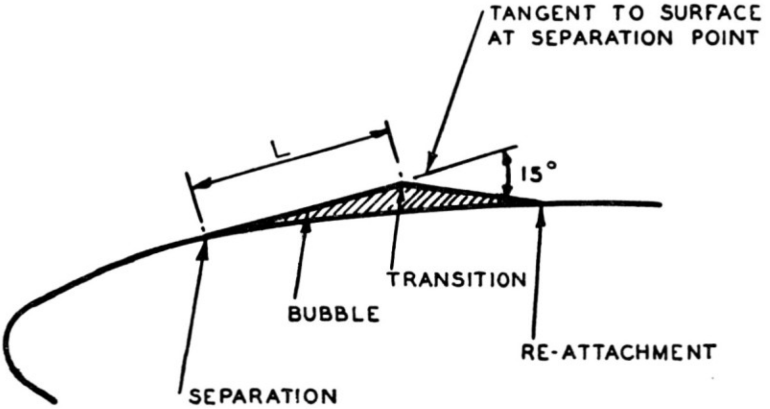

FIG. 1. Von Doenhoff bubble concept.

Recent experimental work, however, has indicated the existence of two possible types of laminar separation bubble which will be referred to as the low and high Reynolds number cases.

The low Reynolds number type of bubble has been extensively investigated, particularly by McGregor[15]. From measurements of mean and fluctuating velocities he postulated the existence of a bubble which consists of a "stagnant" zone and a vortex, as illustrated in Fig. 2. Efforts

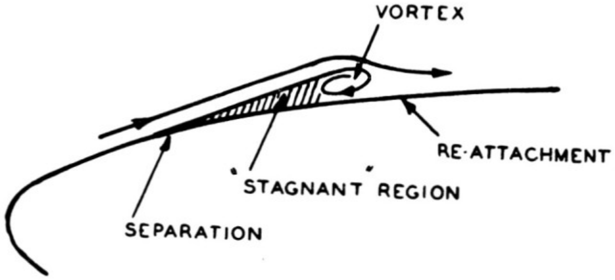

FIG. 2. McGregor bubble concept.

to obtain direct evidence of a vortex core failed and hence the above diagram may be over-simplified. It is clear, however, that concentrated vorticity does exist just upstream of flow re-attachment.

The lower pressure distribution curve in Fig. 3 illustrates the above two regions. The flat part of the curve corresponds to the stagnant zone which is bounded on the stream side by the separated laminar layer. The development of transition commences at the downstream edge of this

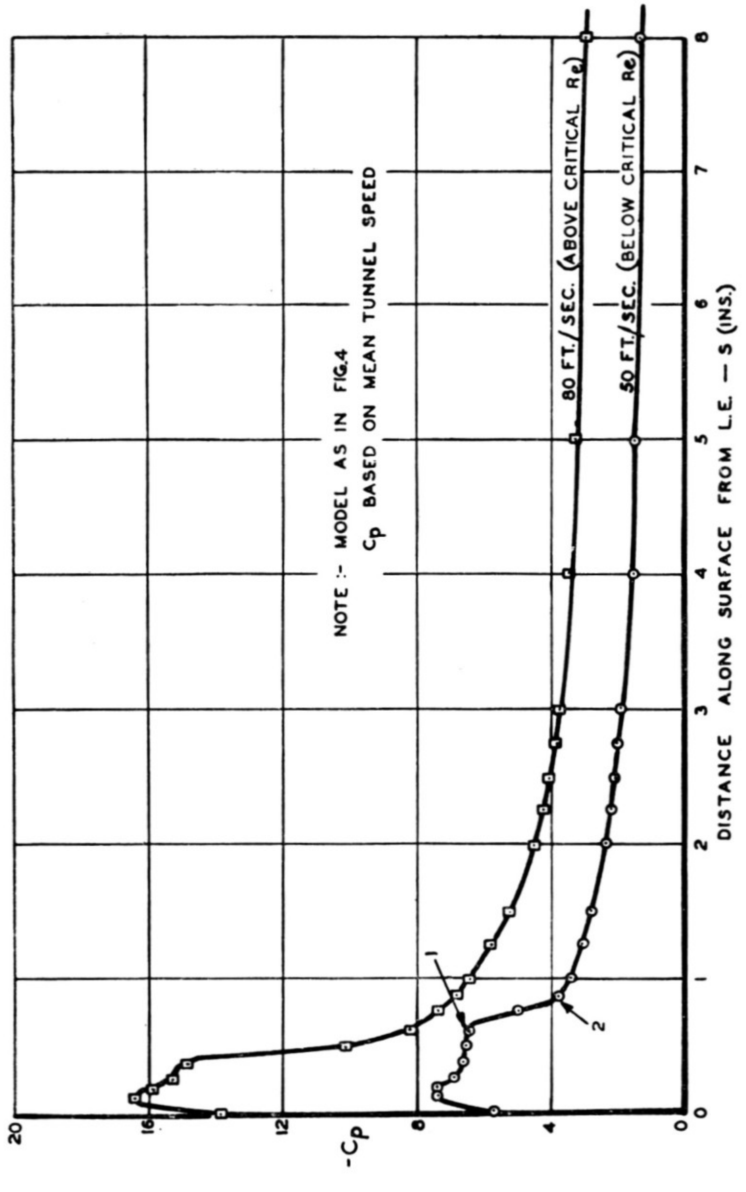

FIG. 3. Pressure distributions just prior to nose stall-clean aerofoil effect of Reynolds number.

region and is accompanied by a steep increase in the surface static pressure as the flow moves downstream. The concentrated vorticity associated with this pressure rise is an integral part of the transition mechanism.

It is well-known that the length of the laminar separation bubble decreases with increasing Reynolds number(16) due to a speeding-up of transition in the separated layer. Less well-known, however, is the fact that over a narrow Reynolds number range the rate of decrease is higher than elsewhere. It is this Reynolds number range which divides the two types of bubble referred to previously.

For a high Reynolds number type of laminar separation bubble, the region of approximately constant surface static pressure is replaced by one in which a significant amount of pressure recovery takes place (Fig. 3); a similar result was obtained by Gault(12). In this type of bubble the transition mechanism is apparently initiated immediately downstream of the separation point. At high enough Reynolds numbers the laminar separation bubble will be so small that, for all practical purposes, its existence may be ignored.

There are no detailed data of laminar separation bubbles at chord Reynolds numbers greater than 10 million(12). It is known, however, that increased turbulence and suitable surface roughness have a similar effect to that exercised by increasing Reynolds number. McGregor records that increased turbulence greatly modified the bubble, halved the bubble length, reduced the strength of the reverse flow and to some extent destroyed the region of constant pressure.

By using suitable surface roughness, Hurley(17) was able to simulate high Reynolds number conditions at a test Reynolds number of approximately 4 million. The optimum roughness was located between the 0·42 and 0·52% *c* positions around the surface from the leading edge on the under-surface and consisted of 0·025% *c* diameter carborundum grains. This arrangement facilitated transition in the separating layer without increasing the boundary layer thickness above that of the normal laminar layer at separation. Similar quantitative results were obtained on the same model with discrete air jets in the same general region(17, 18), suggesting that the main effect of these is the precipitation of transition. The results with air jets should therefore be representative of high Reynolds number cases.

4.3 *Experimental Data Relating to Transition in the Laminar Separation Bubble*

Before tentatively suggesting the manner in which transition is initiated and developed within the bubble, some boundary layer work carried out at A.R.L., and other external experimental work, will be discussed.

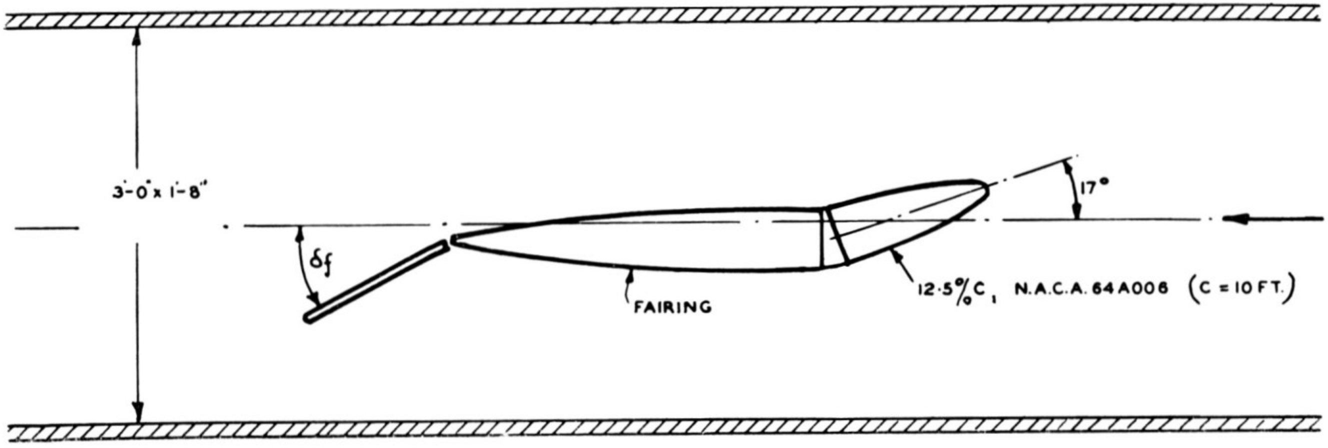

FIG. 4. Plan view of A.R.L. nose flap model in tunnel.

Most of the A.R.L. work was carried out on the model shown in Fig. 4. By increasing the deflexion of the trailing edge flap, suction peaks and steep adverse pressure gradients similar to those experienced on thin wings at incidence were reproduced. The model was designed with the aim of obtaining relatively large boundary layer phenomena for investigation in a wind tunnel of moderate dimensions.

The test cases chosen from refs. 17 and 18 for discussion in this paper are listed in the following table:

Case	P. D.	Test condition	Flow condition	Remarks
1.	Fig. 5	Plain wing	Flow approaching nose stall	Low R_e type of bubble.
2.	Fig. 5	Air jets operative	Very stable boundary layer	Representative of high R_e for same incidence as case 1.
3.	Fig. 6	Air jets operative	Intermediate between cases 2 and 4	Representative of high R_e
4.	Fig. 6	Air jets operative	Flow approaching nose stall	Ditto
5.	Fig. 6	Roughness as in Sect. 4.2	Ditto	Ditto

The discrete air jets with a spanwise pitch of $0{\cdot}2\%\ c$ were located at a distance of $0{\cdot}8\%\ c$ around the undersurface from the leading edge. The amount of air used in the above test cases is expressed by:

$$C_Q = \frac{\text{cusecs/ft span}}{U_0 c} \approx 0{\cdot}0001$$

The hot-wire anemometer employed in obtaining the boundary layer measurements of Figs. 7 to 12 tended to precipitate a premature nose stall and hence the results for cases 1, 4 and 5 correspond to flow conditions less severe than those which exist just prior to general nose separation.

For air jets to give results which are truly representative of high Reynolds numbers it is desirable that they should neither produce transition nor thicken the laminar layer upstream of the normal separation point. Proof that this desired condition is attained in the present case can be obtained from Fig. 7 and ref. 17.

At the Reynolds number of these tests, air jets reduced the size of the laminar separation bubble greatly, as illustrated in Figs. 5, 6 and 13.

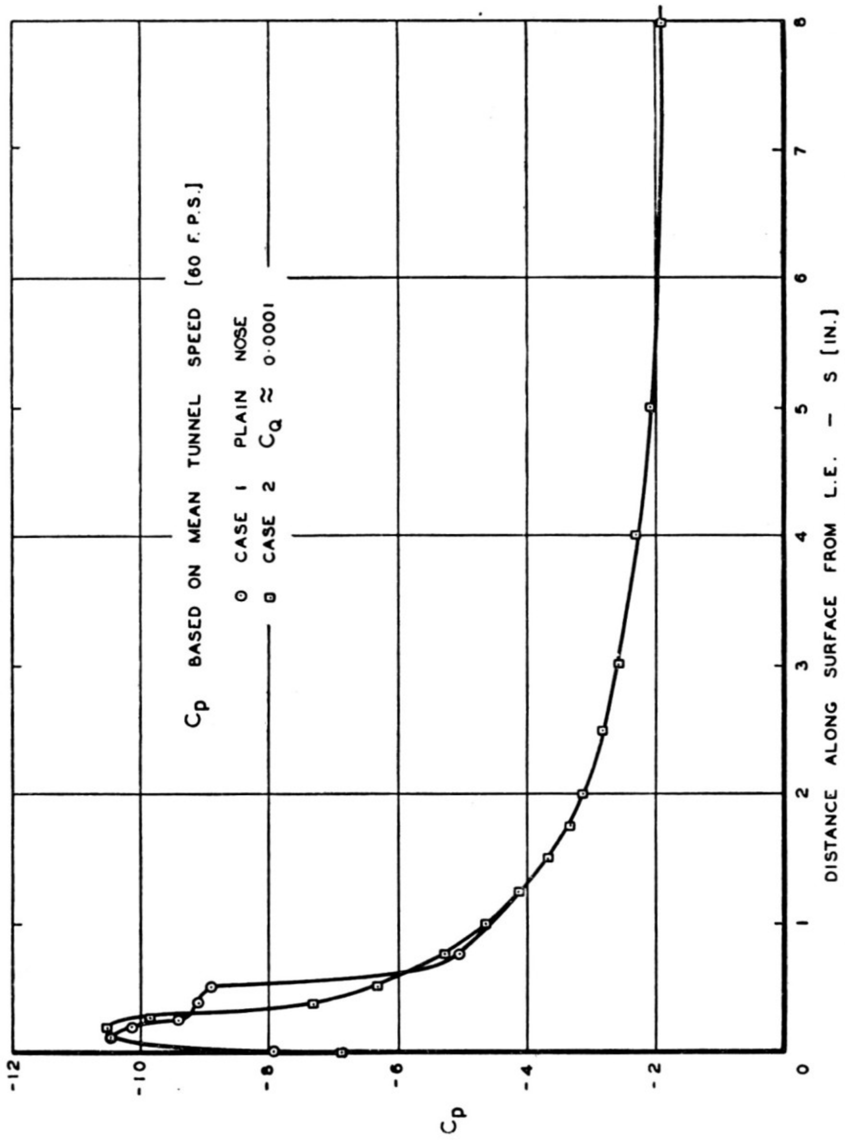

FIG. 5. Pressure gradient conditions for which boundary layer measurements were made.

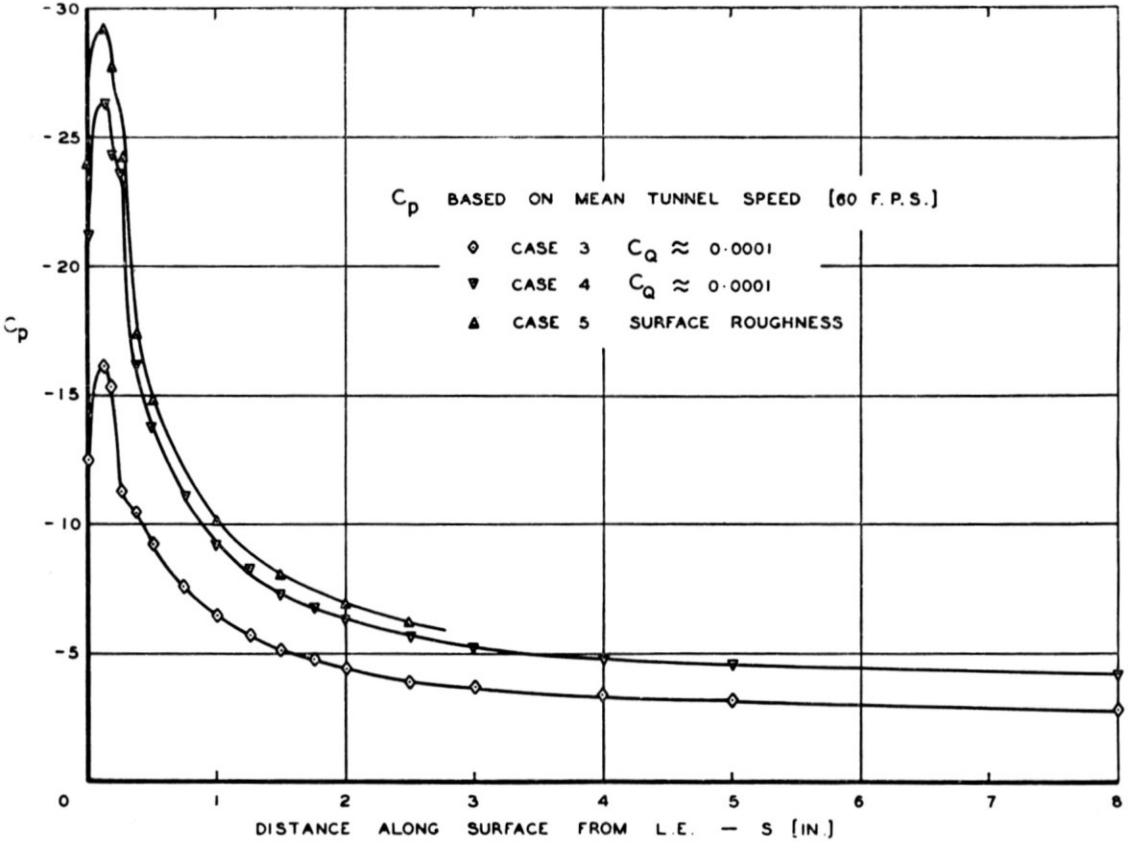

FIG. 6. Pressure gradient conditions for which boundary layer measurements were made.

The possible elimination of laminar separation at certain spanwise positions for case 2 will be discussed later.

Transition in the separated layer for the plain nose case does not occur readily, as illustrated in Figs. 8 and 9. In contrast to this, air jets facilitate the establishment of a fully developed turbulent layer. For case 4, transition is complete when the flow reaches $S = 0{\cdot}50$ in. after travelling a distance of only 0·2% c from the separation point. The magnitude of the adverse pressure gradient is obviously a very important transition factor as will be seen in Fig. 8 for cases 2, 3 and 4, which correspond to different pressure gradients.

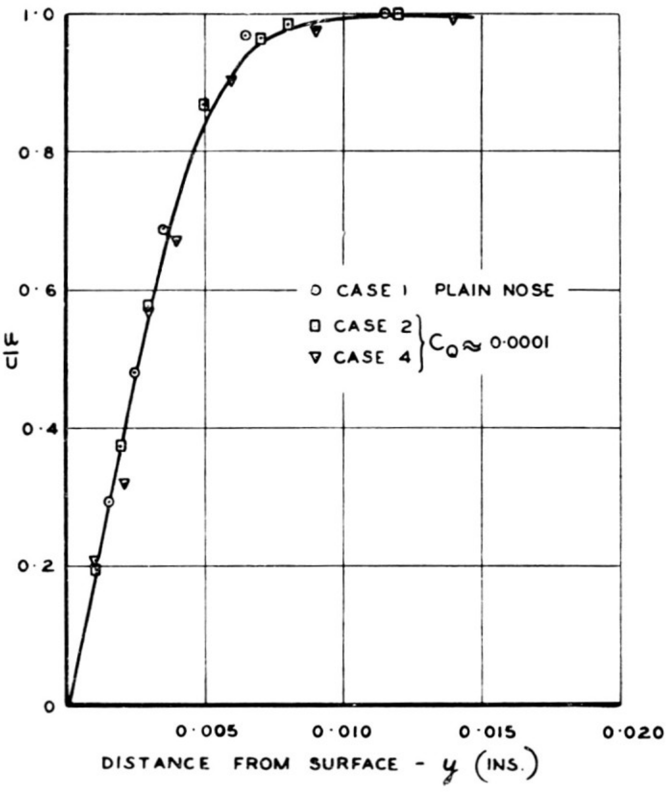

FIG. 7. Boundary layer profiles at $S = 0{\cdot}25$ in.

Transition is not complete until the boundary layer profile is of the normal turbulent type discussed in Section 3. When the shape parameter, H, is plotted against distance along the surface, as in Fig. 12, transition can be assumed to be complete at the chord location where H has fallen from a laminar value or, alternatively, a high value at the re-attachment point to that representative of turbulent layers. Unfortunately, the re-attachment profile for the plain nose condition was not obtained. However, some boundary layer profiles from ref. 12 have been reproduced in Fig. 14, the marked similarity between the curves upstream of re-attachment with those of Figs. 7–9 for case 1 suggests that the two bubbles are of an identical type.

McGregor⁽¹⁵⁾ quotes a value of 2·75 for *H* at re-attachment, Bursnall and Loftin⁽¹⁶⁾ a value of 2·6, while Moore⁽¹⁹⁾ has recorded a figure of 2·5 immediately downstream of re-attachment. All experimental results available show an extremely sharp reduction in *H* after re-attachment, of which Fig. 12 is an illustration. Transition is therefore complete shortly after the flow has re-attached.

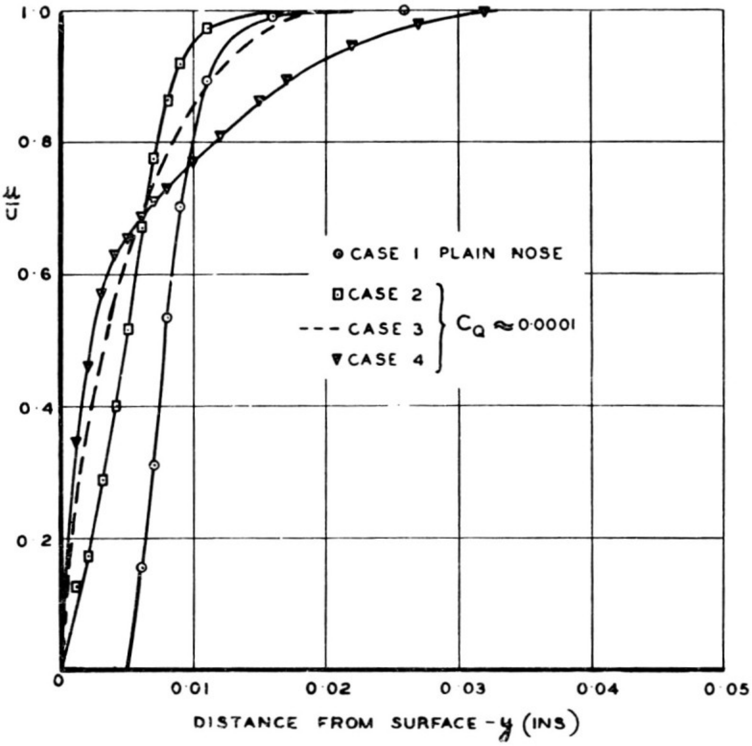

FIG. 8. Boundary layer profiles at $S = 0·38$ in.

In the literature dealing with laminar separation bubbles, transition is assumed to occur at the point where the steep increase in static pressure commences (see Fig. 3). It would appear to the author, however, that this flow feature marks the point at which the turbulence associated with transition is first established. Transition apparently commences in the inner part of the separated layer. The boundary layer profile of Fig. 14

shows a composite layer at re-attachment with a turbulent inner layer and an essentially laminar outer flow, thus suggesting that the mechanism by which turbulence is rapidly diffused through the layer is probably dependent on an attached flow possessing the appropriate characteristics in the inner region. Of interest in this respect is the paper by Kline(6) which outlined both the origin and development of longitudinal vortices in turbulent flow.

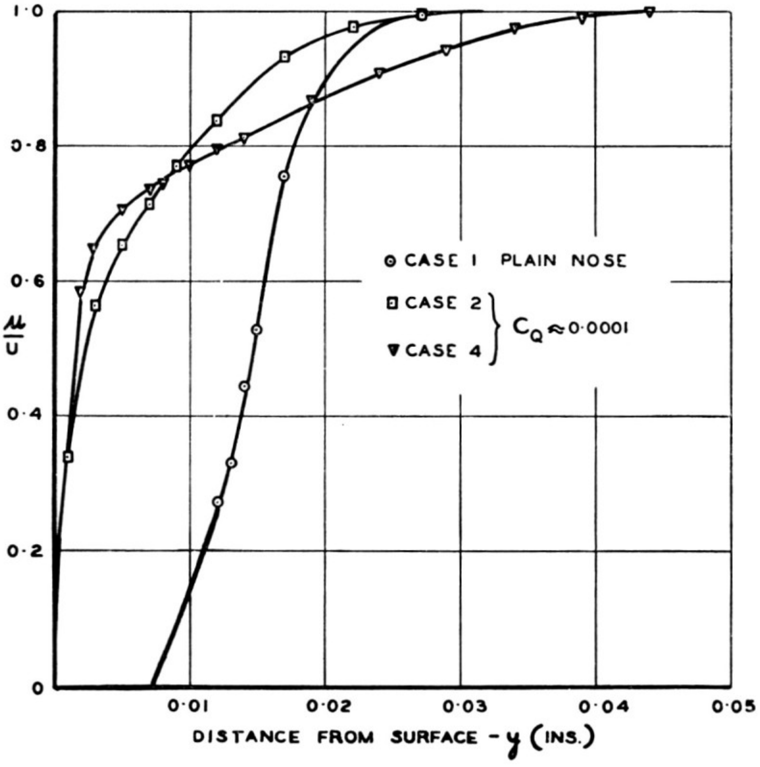

FIG. 9. Boundary layer profiles at $S = 0{\cdot}50$ in.

According to Kline(6) the three-dimensional vortex flows have their origin very close to the surface and have axes which are inclined away from the surface. The angle of inclination increases with the severity of the adverse pressure gradient. In the case of flow re-attachment, therefore, the influence of the inner turbulent layer on the outer flow will be more quickly established in the case of the largest adverse gradient. A comparison of the results for cases 2 and 4 in Fig. 12 is of interest in this respect as in the latter case transition occurs sooner.

The importance of the inner region of the turbulent boundary layer was also emphasized by the present author(20) concerning experiments

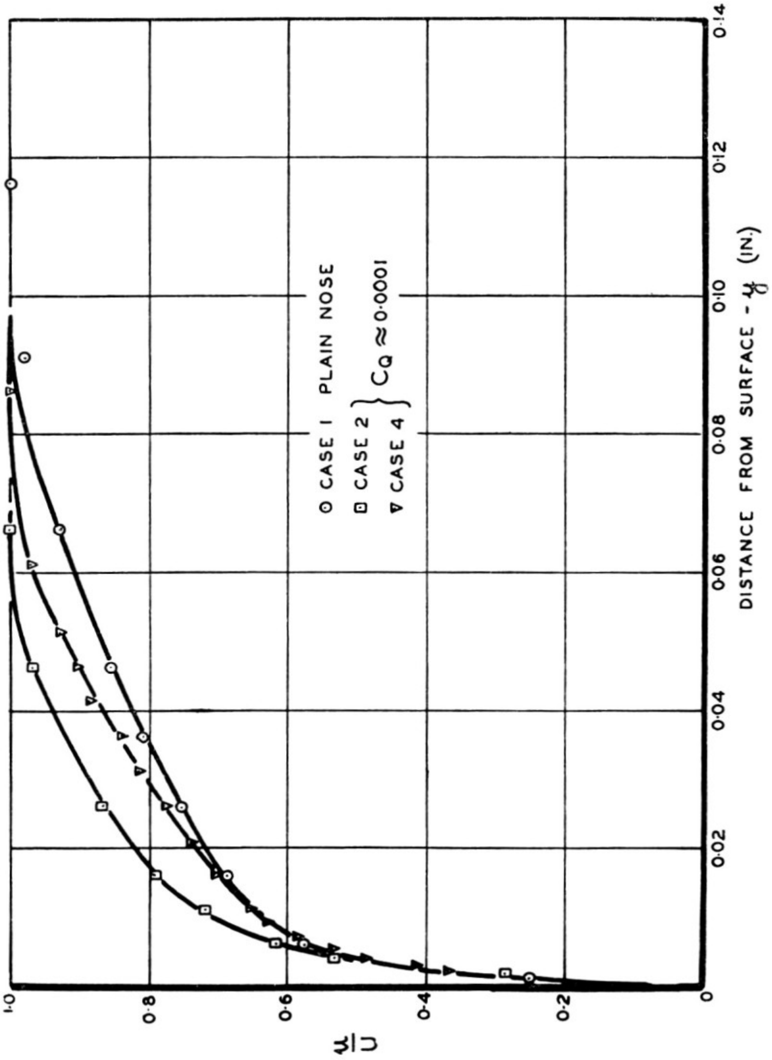

FIG. 10. Boundary layer profiles at $S = 1$ in.

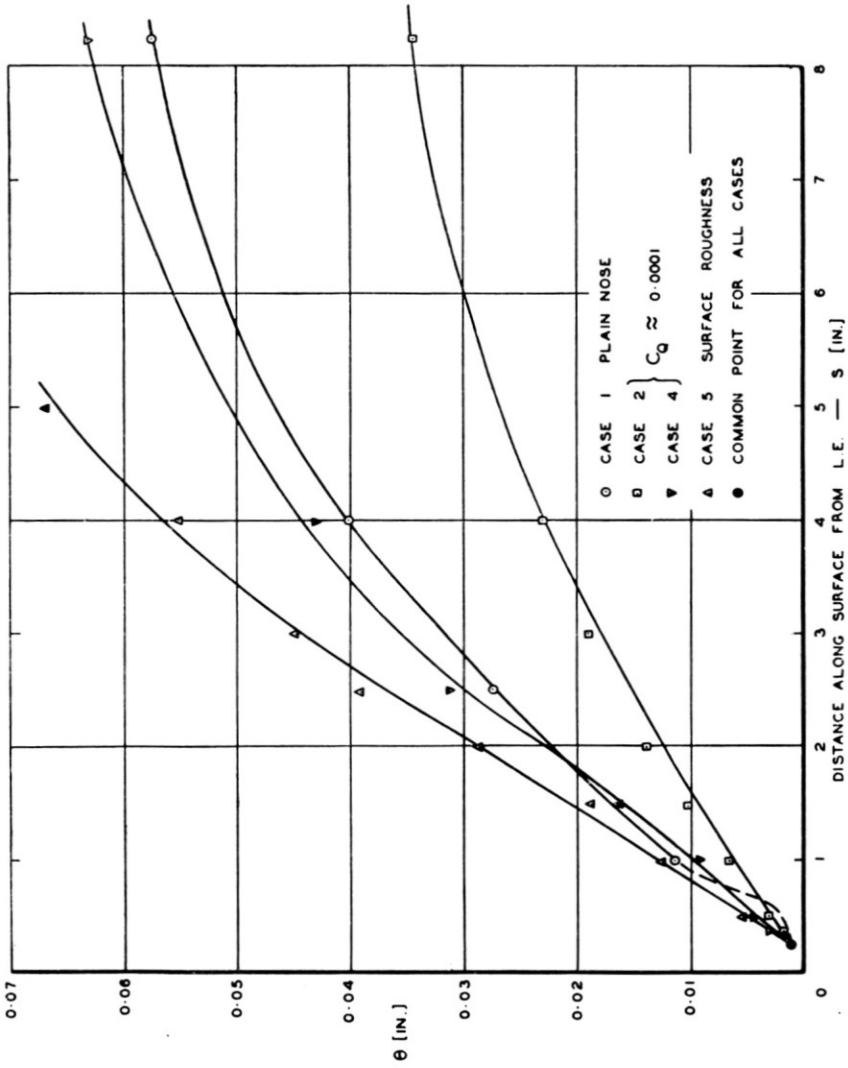

FIG. 11. Growth of boundary layer momentum thickness.

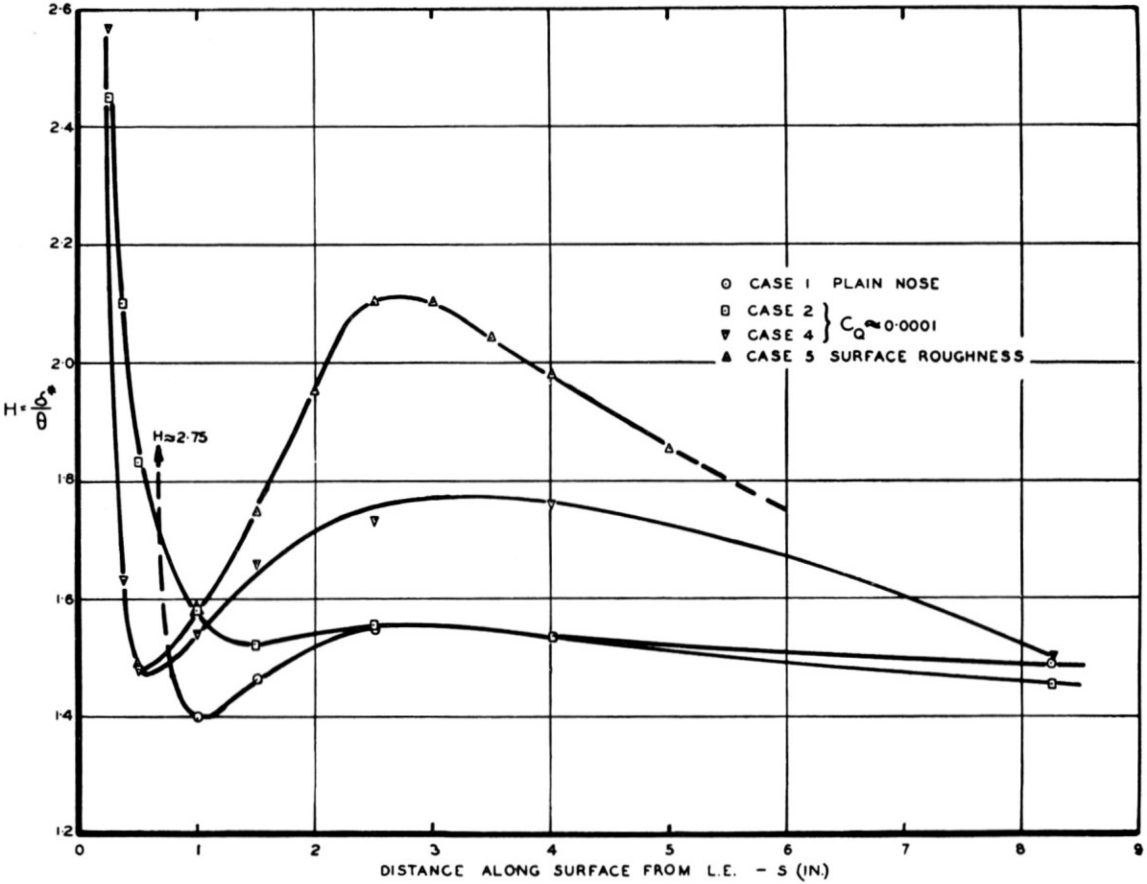

FIG. 12. Variation of boundary layer parameter with S.

in which the inner portion of a turbulent layer was removed by a suction slot. A composite layer of inner "laminar" flow and outer turbulent flow was reported downstream of the slot. Until "transition" occurred in the inner layer there was no diffusion of turbulence in the 'y' direction; in fact the level of turbulence in the outer layer fell during this period.

For a low Reynolds number type of laminar separation bubble there is virtually no growth in the separated layer during the period of constant surface pressure; this is confirmed from many sources(15,16). There is, however, a rapid increase in momentum thickness, Θ, during the transition period after which the rate of growth is markedly reduced. Detailed experimental data relating to this are available in ref. 16. A study of Figs. 9, 10 and 11 for case 1 in the A.R.L. experiments shows a similar feature. On comparing cases 1 and 2 in Fig. 11 it is clear that higher fluid losses, as expressed by increased Θ, are associated with the low Reynolds number type of laminar separation bubble and transition.

If the air jet cases are accepted as representative of high Reynolds numbers then, from the available data (Figs. 8 to 10), it appears that transition commences immediately following laminar separation. Case 2 is of particular interest because of the possibility that, at various spanwise positions, the transfer mechanism of the transition flow has been able to cope with the modest adverse pressure gradient, thus avoiding local separation (Fig. 13).

Experiments on leading edge flow conducted by Gault(12) at Reynolds numbers up to 10 million are relevant in this respect. For modest adverse gradients, i. e. low incidences, the commencement of transition occurs close to the normal separation point for the higher Reynolds numbers. The evidence available does not suggest that transition commences upstream of this separation point although under certain conditions such a possibility cannot be overlooked.

4.4 *Suggestion Concerning Initiation of Transition*

The above data show a marked change in the transition phenomena as the effective Reynolds number is sharply increased.

Suggestions concerning the onset of transition in the two cases under consideration are now presented.

(i) For the low Reynolds number case there is strong evidence of a wave motion in the separated layer prior to transition. Experimental data supporting this are available from refs. 10 and 14 and also ref. 4 from which Fig. 15 is taken. This wave motion is terminated by the concentrated vortex line immediately upstream of re-attachment. Provided the aerofoil incidence is significantly less than the nose stalling one, the flow in the laminar separation bubble is a steady one. This implies that the three-dimensional

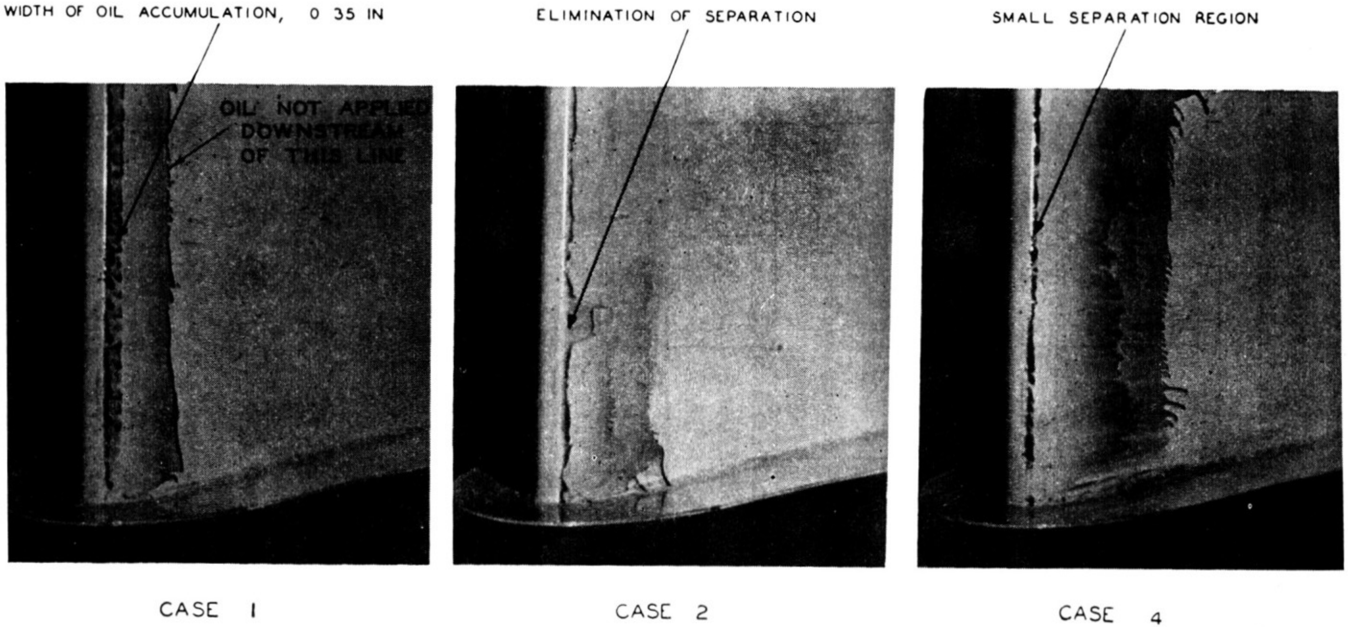

FIG. 13. Oil flow patterns on model of Fig. 4 for various conditions.

flows required for transition are supplied at a steady rate from the concentrated vortex line. The manner in which this occurs is not clear. Since it appears from the data just presented that transition is initiated in the inner layer, it is logical to assume that the reverse flow along the surface just upstream of re-attachment is of importance. The air particles in this turbulent reverse flow will eventually be turned downstream to pass along the free boundary of the shear layer and thus play a role in the transition process.

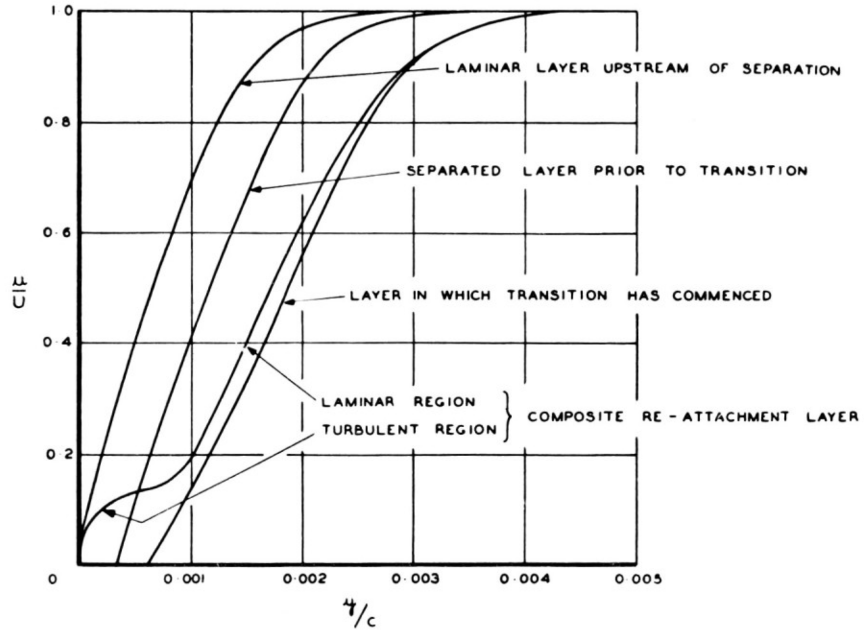

Fig. 14. Boundary layer profiles of ref. 11 illustrating transition and re-attachment.

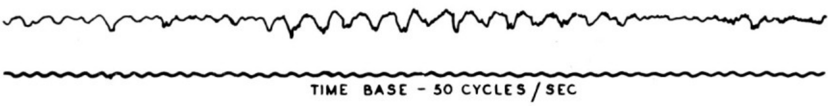

Fig. 15. Oscillations in. separated layer at $S = \frac{5}{16}$ in. and $y = 0{\cdot}015$ in. for 50 F.P.S. case of Fig. 3.

(ii) At high Reynolds number there is no evidence from either the general transition studies(8, 10) or the A.R.L. experiments with leading edge separations to suggest the existence of a concentrated vortex. For the high Reynolds number case it can therefore be assumed from data presented that the transition process is initiated in the separated shear layer thus eliminating the concentrated transverse vortex observed at low Reynolds numbers.

4.5 *Flow Downstream of Transition*

In the foregoing the details of the flow up to the point at which transition is complete have been discussed. If the aerofoil is at a sufficiently high incidence, the adverse pressure gradient will cause the turbulent layer to deteriorate, that is, the value of the shape parameter, H, will increase with S. On thin wings, however, the pressure gradient moderates quickly and this feature leads to a decrease in H downstream of a peak value. This signifies a subsequent turbulent boundary layer recovery.

These features of boundary layer flow, which are illustrated in Fig. 12, have been verified experimentally by Moore(19) while calculations of boundary layer properties by accepted methods also predict the above trends(18, 19). In particular, Moore has investigated the effect of increases in momentum thickness and shape parameter at the point where transition is assumed to be complete; both result in a marked increase in H_{max}. It should be noted that, on thin wings, these high values of H_{max} are reached at relatively moderate lifts.

4.6 *Onset of Nose Separation*

If there are two distinct types of laminar separation bubble, then it might be expected that the mechanism precipitating nose separation will also change with Reynolds number.

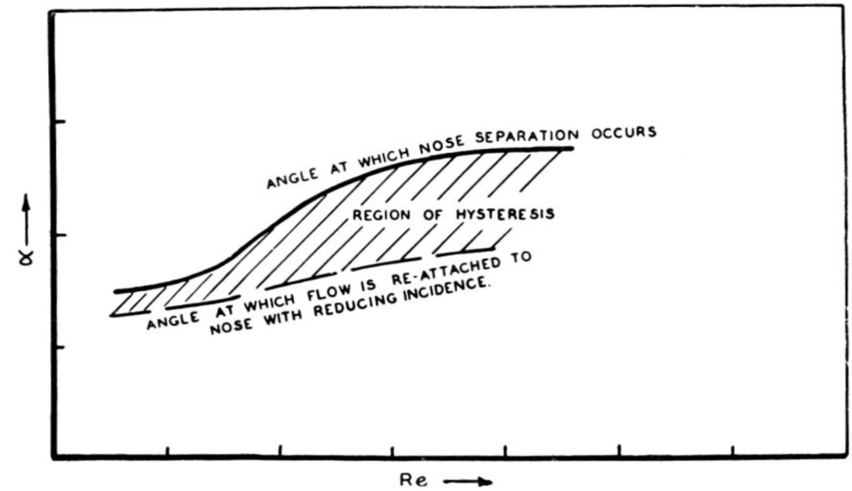

FIG. 16. Effect of Reynolds number on nose-stalling incidence—diagrammatic.

A convenient method of presenting Reynolds number effects is that illustrated diagrammatically in Fig. 16 for a typical thin, nose-stalling aerofoil. Over a Reynolds number band of approximately 1 to 2 million the angle of incidence at which nose stalling occurs is sharply increased.

The author has, from experiments reported in refs. 4 and 21 and other unpublished work, established that marked differences in nose-stalling phenomena occur over this range.

The value of $H_{\max}$ will, prior to the onset of general nose separation, increase with incidence. References 4 and 22 reason that, if turbulent separation occurs when $H_{\max}$ approaches a critical value, surface roughness upstream of the critical region will precipitate such stalling while porous suction will delay it. Experiments with such devices on the model of Fig. 4 supported the theory for the high Reynolds number case and confirmed the location of the critical chord region. Additional evidence supporting the turbulent separation theory for the high Reynolds number case is available in refs. 3 and 23 and unpublished work.

When turbulent separation initiates nose stalling, there are strong reasons for believing that the separation point will move forward immediately in order to establish equilibrium. There are then two possibilities, namely the separation point will move into the laminar separation bubble region and cause it to "burst" or else the boundary layer flow will be stabilized with regions of both laminar and turbulent separations. The first possibility is the one usually experienced but examples of the second exist particularly when the critical region is in the vicinity of 15% *c* rather than 5% *c*.

In the lowest Reynolds number case of ref. 4 it was noted that an instability appeared to arise in the bubble just prior to nose separation. This is in qualitative agreement with McGregor who measured an increased growth and unsteadiness in the re-attaching layer just prior to nose-stalling. Additional evidence of a similar nature was obtained in ref. 23 where the large increase in drag associated with nose stalling was preceded by a sudden significant small increase in profile drag; in this instance the laminar separation bubble contained a region of constant static pressure thus suggesting it was of the low Reynolds number type. A sudden increase in boundary layer thickness at re-attachment will produce a corresponding increase in $H_{\max}$ and thus make the flow more susceptible to turbulent separation.

The lowest Reynolds number at which turbulent separation may be a relevant factor in nose separation is not known(4). However, since the stability of the bubble is by far the greatest single factor it might be useful to look at the problem from this angle. As suggested previously, there is a stability problem at the downstream edge of the bubble where the concentrated vortex line supplies energy for the three-dimensional flows associated with transition. Unsteadiness will arise when the wave motion feeding the vortex line is supplying energy at a greater rate than it can be absorbed into such flows.

Of interest in this respect are the experimental data of refs. 19 and 24. It is suggested that a measure of the turbulent mixing associated with flow re-attachment can be obtained from the pressure recovery achieved. The coefficient of pressure recovery, σ, is defined as $(Cp_2 - Cp_1)/(1 - Cp_1)$ where the subscripts refer to conditions at the points indicated in Fig. 3. Experiments show that σ increases with increasing incidence until just prior to nose stalling when the value of σ levels off at approximately 0·36. This suggests that there is a limit to the amount of mixing which can be produced by the fluid mechanism present. This conclusion does not differ greatly in essence from that just implied using transition arguments. McGregor also expressed the opinion that nose stalling is the result of an adverse balance of vortex or mixing energy(15).

The hot-wire experiments of ref. 4 showed a growth in amplitude of the wave motion in the constant pressure region of the bubble as nose stall conditions were closely approached. Downchord of re-attachment near-stall conditions were announced by intermittent high amplitude bursts of turbulence being convected downstream. It is possible that this excess turbulent energy represents that part of the wave energy not absorbed into the normal transition re-attaching mechanism at Reynolds numbers below the critical.

A full solution of the manner in which the low Reynolds number type of laminar separation bubble gives way to general nose separation must await a more detailed study of the transition mechanism within the bubble.

5. CONCLUDING REMARKS

In the interests of clarity the foregoing discussion has avoided a study of the phenomena present in the Reynolds number range dividing the two distinct cases propounded. The experimental data available show a smooth changeover from one to the other and suggest a blending of the mechanisms involved. This suggestion presents no physical difficulties in relation to the theory of this paper.

ACKNOWLEDGEMENT

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REFERENCES

1. Gault, D. E., An Investigation at Low Speed of the Flow over a Simulated Flat Plate at Small Angles of attack Using Pitotstatic and Hot-wire Probes. NACA TN 3876, March 1957

2. KUCHEMANN, D., Types of Flow on Swept Wings with Special Reference to Free Boundaries and Vortex Sheets, *J. Roy. Aero. Soc.*, Nov. 1953
3. WALLIS, R. A., Experiments with Air Jets to Control the Nose Stall on a 3 ft Chord NACA 64A006 Aerofoil, A.R.L. Aero. Note 139, Sept. 1954
4. WALLIS, R. A. and RUGLEN, N., A. Note on the Cause of the Nose Stall of Thin Wings, A.R.L. Aero. Note. 161, May 1957
5. TOWNSEND, A. A., The Structure of the Turbulent Boundary Layer, *Proc. Camb. Phil. Soc.*, Vol. 47, Pt. 2, 1951
6. KLINE, S. J. and RUNSTADLER, P. W., Some Preliminary Results of Visual Studies of the Flow Model of the Wall Layers of the Turbulent Boundary Layer, A.S.M.E. Preprint No. 58–A64
7. HAMA, F. R., LONG, J. D. and HEGARTY, J. C., On Transition from Laminar to Turbulent Flow, *J. Appl. Phys.*, April 1957
8. KLEBANOFF, P. S. and TIDSTROM, K. D., Evolution of Amplified Waves Leading to Transition in a Boundary Layer with Zero Pressure Gradient, NASA TN D–195, Sept. 1959
9. SCHUBAUER, G. B., see ref. 8
10. LOCHTENBERG, B. H., Transition in a Separated Laminar Boundary Layer, A.R.C. Unpublished Report 19007, Jan. 1957
11. SCHUBAUER, G. B. and KLEBANOFF, P. S., Contributions on the Mechanics of Boundary Layer Transition, NACA TN 3489 Sept. 1955
12. GAULT, D. E., An Experimental Investigation of Regions of Separated Laminar Flow, NACA TN 3505, Sept. 1955
13. CRABTREE, L. F., Prediction of Transition in the Boundary Layer of an Aerofoil, *J. Roy. Aero. Soc.*, July 1958
14. VON DOENHOFF, A. E., A Preliminary Investigation of Boundary Layer Transition along a Flat Plate with Adverse Pressure Gradient, NACA TN 639, March 1938
15 MCGREGOR, I., Regions of Localized Boundary Layer Separation and their Role in the Nose-Stalling of Aerofoils, Ph. D. Thesis, Queen Mary College, London, June 1954
16 BURSNALL, W. J. and LOFTIN, L K., Experimental Investigation of Localized Regions of Laminar Boundary Layer Separation, NACA TN 2338, April 1951
17. HURLEY, D. G. and WARD, G. F., Experiments on the Effects of Air Jets and Surface Roughness on the Boundary Layer near the Nose of an NACA 64A006 Aerofoil, A.R.L. Aero. Note 128, Sept. 1953
18. WALLIS, R. A., The Turbulent Boundary Layer on the Articulated Nose of a Thin Wing Provided with Air Jets, A.R.L. Aero. Note 141, Oct. 1954
19. MOORE, T. W. F., A Note on the Causes of Thin Aerofoil Stall, *J. Roy. Aero Soc.*, Dec. 1959
20. WALLIS, R. A., Some Characteristics of a Turbulent Boundary Layer in the Vicinity of a Suction Slot, A.R.L. Aero. Note 87, May 1950
21. WALLIS, R. A. and RUGLEN, N., Experiments with and without Air jets on a NACA 64A006 Semi-wing having 50° Sweepback on the Leading Edge, A.R.L. Report A113, July 1959
22. HURLEY, D. G. and RUGLEN, N., A Note on the Cause of the Nose Stall of Thin Wings, A.R.L. Aero. Note 162, May 1957
23. HURLEY, D. G., WALLIS, R. A. and CALAME, M., Experiments on the Effects of Air Jets and Surface Roughness on the Stalling Characteristics of a 5 ft chord NACA 64A006 Aerofoil, A.R.L. Report A 107, Dec. 1957
24. CRABTREE, L. F., Effects of Leading Edge Separation on Thin Wings in Two-dimensional Incompressible Flow, *J. Aero. Sc.*, Vol. 24, Aug. 1958