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AERODYNAMICS NOTE 110

THE USE OF AIR JETS
FOR BOUNDARY LAYER CONTROL

BY R. A. WALLIS

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Aero. Note 110

THE USE OF AIR JETS FOR BOUNDARY LAYER CONTROL

by

R.A. Wallis

SUMMARY

A new method of controlling the boundary layer in regions of severe adverse pressure gradients is proposed. Preliminary experiments with small air jets, suitably located, have shown that

- (a) laminar separation at the leading edge of thin aerofoils can be eliminated, even at small Reynolds numbers, and
- (b) turbulent separation can be delayed.

The method appears to offer considerable improvements in the stalling characteristics of thin swept wings; the principles are equally applicable, however, to any region of adverse pressure gradient.

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NOTATION

| | |
|-------|--|
| C_p | Pressure coefficient $\left(1 - \left(\frac{U}{U_0}\right)^2\right)$ |
| C_Q | Flow coefficient $\left(\frac{Q}{U_0 c}\right)$ |
| U | Local velocity outside boundary layer |
| U_0 | Velocity at infinity |
| Q | Quantity flow/ft. span |
| c | Aerofoil chord |

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1. INTRODUCTION

As the result of a recommendation by the Commonwealth Advisory Aeronautical Research Council, which met in Canada in September 1950, attention in these Laboratories has been focussed on the problem of improving the high lift characteristics of thin swept wings.

2. STALLING CHARACTERISTICS OF THIN WINGS

One of the problems of high speed flight is the achievement of relatively low drag at high Mach number. When a shock wave of sufficient strength is formed, flow separation occurs immediately downstream of the shock. Resulting changes in pressure distribution, and the adverse effect of the wake on the control surfaces, seriously impair the longitudinal and lateral stability of the aircraft. The onset of flow separation can be delayed to higher Mach numbers by the use of a thin symmetrical wing, with or without sweepback, having the point of maximum thickness between 0.4 and 0.5 of the chord (ref.1).

Unfortunately, this type of wing has poor stalling characteristics. At moderate lift coefficients, a large suction peak is present at the leading edge where the radius of curvature is small. The flow is usually laminar at this point of minimum pressure, and hence laminar separation will occur shortly after the flow moves into the region of increasing pressure. Provided the adverse pressure gradient is not too great, transition occurs in the separated laminar layer and the layer rejoins the surface as a turbulent one a small distance downstream. Very thin aerofoils possess a similar stall to that associated with a flat plate. The turbulent layer at a certain incidence fails to re-attach immediately but rejoins the surface some distance from the leading edge. The region of separated flow increases with incidence until it extends over the whole upper surface. Aerofoils possessing thickness/chord ratios of 7% or less are usually affected in this manner. This figure is only approximate, as Reynolds number and aerofoil design will have a large bearing on the precise value. On aerofoils with thickness/chord ratios in excess of those just mentioned, the nose stall is experienced at a lift coefficient greater than the flat plate maximum, namely $C_L = 0.8$ to 0.9 . When this occurs, the flow separates over the whole upper surface of the aerofoil.

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The above considerations apply to the two-dimensional aerofoil. When the wing possesses sweepback, another undesirable feature develops. Owing to strong spanwise pressure gradients, the slow moving boundary layer air is swept towards the wing tips; any laminar separation will only result in an even greater migration. This boundary layer growth at the wing tips induces an early tip stall which impairs the stability of the aircraft and may lead to an unstable stall (ref.2). The tip stall also reduces the maximum lift and the lift curve slope. This latter characteristic means that the maximum lift is reached at higher angles of attack.

Thus it can be seen that an important factor in improving the stalling characteristics of thin swept wings is the prevention of laminar separation.

3. EXISTING METHODS OF LEADING EDGE BOUNDARY LAYER CONTROL

Before embarking on new experimental work, a review of leading edge high lift devices was made (ref.3). This work emphasised the fact that there are a number of ways in which substantial maximum lift increments can be obtained by the use of known devices. Some of these devices are still in the laboratory stage and require considerable development before being used in practice. This is particularly true of continuous boundary layer suction as the porous material used is very susceptible to contamination by dust, ice or water. The removal of the boundary layer through a nose slot on a thin aerofoil would introduce structural problems and in operation would probably require appreciable powers (ref.3). This is due to the low pressures prevailing at the nose, and unless considerable pressure recoveries are made in the slot, very low suction box pressures will be necessary. The surface discontinuity due to the slot may be an undesirable feature at high speed; to avoid drag increases, suction would need to be applied continuously.

Reference 3 suggested that leading edge flaps appeared to be the most promising of the boundary layer control devices, being effective on either straight or swept wings. It would appear that the main function of a flap is to modify the pressure distribution in the vicinity of the leading edge. Flaps, however, have definite disadvantages

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for high speed flight. Even when the flaps are accurately manufactured, some surface discontinuity in the retracted state is certain to be present. This at high speed will almost inevitably lead to transition and a subsequent drag increase. Finally, it is suspected that this device can never be used in high speed manoeuvres, and because of this its high lift applications are limited.

4. USE OF AIR JETS AS METHOD OF BOUNDARY LAYER CONTROL

4.1 General Principles

In the light of the above facts, an endeavour was made to develop a new method of delaying or preventing the onset of separation. It is well known that a turbulent boundary layer is far more capable of overcoming an adverse pressure gradient than a laminar layer. In the former case, momentum is transferred rapidly from the free stream to the slower moving particles near the surface by eddy motion, whilst transfer in a laminar layer is on a molecular scale. With this in mind, we set out (a) to prevent laminar separation by making the flow turbulent, and (b) to delay turbulent separation by increasing the rate of momentum transfer.

Since it is known that the maximum lift of thin aerofoils increases with Reynolds number (ref.3), it seems logical to suppose that this is due to the greater tendency of the boundary layer to become turbulent near the leading edge. This fact would indicate that if a turbulent boundary layer could be produced before the flow turned round the leading edge from the stagnation point, laminar separation would be prevented and the maximum lift be increased.

By providing spanwise rows of small holes suitably located and blowing air jets through the boundary layer, both main objectives have been achieved. Although this use of air jets to produce a turbulent layer is not new, it has not, to the author's knowledge, been used as an effective means of preventing laminar and/or turbulent separation. It is known that blowing through a porous surface will decisively reduce the inherent stability of the laminar layer (refs.4 and 5). In the region of the stagnation point and the leading edge, however, it is doubtful whether porous blowing will produce

a turbulent layer. By using jets to inject very small quantities of air, Fage was able to produce transition downstream of the leading edge in shock wave-boundary layer interaction experiments (ref.6).

When jets are used for the control of separation, the outflow velocities have to be large enough to create turbulence on the jet boundaries. As a product of the jet shear flow, boundary layer air is induced to flow outwards from the surface, and this results in an inward flow midway between the holes. In other words, a secondary flow of scale $P/2$ is created, where P is the pitch of the holes. This has been observed in smoke experiments (ref.6); tuft studies have, in our case, verified the existence of a strong superimposed vortex flow. Hence it is apparent that discreet blowing holes not only produce turbulence, but also provide a means of transporting turbulence and momentum into the boundary layer. It is believed that this method of producing a turbulent layer is fundamentally different to the action of porous blowing. In the latter case, transition is probably caused by the thickening of the boundary layer and a reduction in the stability limit at which small disturbances become amplified.

4.2 Preliminary Experimental Work

Experiments have shown that air jets, suitably located, eliminate laminar separation at the leading edge of thin aerofoils, even at small Reynolds numbers. However, the mechanism by which the air jets induce the laminar boundary layer to become turbulent has not yet been investigated. Nevertheless, it is believed that the secondary flow carries the turbulence created by the jets into the boundary layer.

In this preliminary work, it has been assumed that the nose stall is mainly dependent on the severe local adverse pressure gradients downstream of the leading edge. On thin aerofoils in particular, the minimum local pressure coefficient, $C_{p_{min}}$, can be taken as a measure of the pressure

recovery which has to be effected without separation. In our investigations interest has been centered on the following two aspects:-

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- (1) The elimination of laminar separation;
- (2) A good measure of turbulent boundary layer control as indicated by the minimum pressure peak reached just prior to separation.

The first experiments were carried out in the 36" x 20" low speed wind tunnel. Owing to the desirability of testing a model of moderately large dimensions, a nose flap of 15% chord was used, the basic section being a 6% thick, 10 ft. chord ellipse. The nose flap was hinged to a two-dimensional fairing with a tail flap. Most of the experimental work on this model was carried out with holes (0.028" dia.) drilled at a pitch of 1/4" along the span at a surface dimension of 1" from the leading edge. This arrangement is near, but does not necessarily constitute, the optimum. Unless otherwise stated, it can be assumed that all flow conditions were investigated qualitatively with a hot wire. Most of the experiments were carried out at a tunnel speed of 60 f.p.s.

Without blowing, laminar separation was present, and the minimum C_p reached near the leading edge prior to the nose stall was -7.4. By injecting a small amount of air, the boundary layer became turbulent on the lower surface approximately 0.6" along the surface from the leading edge. Laminar separation was thus avoided and before nose separation occurred, a minimum C_p of -20 had been attained. The pressure then increased to $C_p = -3$ in the first 3.5% of chord, which represents a remarkable recovery rate; the local pressure distribution for this condition corresponded to the theoretical distribution for a lift coefficient of 0.85. Very little scale effect was noted within the limited speed range of the experiments (max. speed 80 f.p.s.). The volume flow through the jets to achieve these results was not measured directly, but a conservative estimate would suggest that the flow coefficient, C_Q , was not more than 0.00004.

In order to obtain a quick confirmation of the above promising results on a full chord aerofoil, a 3 ft. chord NACA 64A006 aerofoil of 2 ft. span was fitted to an existing endplate arrangement and mounted on the balance in the 9' x 7' wind tunnel. Supplementary tests on the same aerofoil were carried out in the 36" x 20" wind tunnel, the aerofoil span being 20". The detailed experimental results will be published at an early date.

Laminar separation was eliminated from this aerofoil. Although an appreciable amount of boundary layer control was achieved as a result, the minimum pressure could not be reduced below a C_p of -12 before the nose stalled. This compares with values of from -3 to -6.5 without blowing for the Reynolds number range covered (0.75×10^6 to 3.75×10^6). Very little scale effect was noted for the case of blowing. One row of air jets (0.028" dia. holes) situated approximately $3/8$ " along the surface from the leading edge and at a pitch of $1/8$ " sufficed for the 36" x 20" tunnel experiments. However, an additional row, $1/8$ " closer to the leading edge, was required to prevent laminar separation in the 9' x 7' tunnel tests.

The nose stall, with blowing, was due to a turbulent separation having its origin in the region of the 10% chord position; this separation moved forward very rapidly with increasing incidence. Onset of complete separation over the upper surface then followed a similar pattern to that described previously.

Before analysing these results further, the action of air jets on the turbulent boundary layer will be discussed. As mentioned previously, the air jets produce a secondary flow which transports momentum from the free stream into the boundary layer. A close interaction between this induced flow and a turbulent layer can be expected, as the turbulent boundary layer transports momentum in a similar fashion. This should result in an intense momentum transfer.

Qualitative tests were carried out to check the above theory. For these experiments, a rear stalling aerofoil was chosen in order to ensure that turbulent separation was the only factor involved. An existing model of an NACA 2214 aerofoil with a 17" chord was found to meet the above requirement. Tests on this model in the 36" x 20" wind tunnel with $1/16$ " dia. holes at $3/4$ " pitch drilled on the

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suction surface at the 50% chord position demonstrated the efficacy of air jets in delaying turbulent separation. With a moderate amount of air, trailing edge separation was delayed to an appreciably higher incidence, the stall being reached when turbulent separation moved rapidly from the trailing edge to the nose. Unstalling could only be achieved by substantially reducing the incidence. To ensure that the stall was a turbulent one, in subsequent tests laminar separation was eliminated with small jets situated between the front stagnation point and the leading edge. No substantial change in the stall was noted.

Owing to these promising results, it was decided to apply this knowledge to the nose of the 64A006 aerofoil in order to control the turbulent separation encountered. The most effective arrangement tried consisted of two rows of holes (0.028" dia.) at 1/4" pitch situated 1/4" and 3/8" along the upper surface from the leading edge, in addition to the row of lower surface holes. With the optimum amount of blowing, a C_p of -17.5 was achieved at 40 f.p.s.; at the higher speed of 80 f.p.s. the pressure coefficient was -15.5 and still falling with increasing box pressure. The maximum mean jet velocities were of the order of 350 - 400 ft/sec. As before, the nose stall, which occurred at a higher incidence, resulted from a turbulent separation moving forward from the 10% chord position. However, the difference between the nose stall incidence and the complete stall had been reduced owing to the extension of unseparated flow conditions. These tests were carried out in the 36" x 20" wind tunnel.

Experiments have shown that laminar separation can be eliminated, thereby delaying the nose stall which is then influenced by turbulent separation moving from a region just downstream of the leading edge. As a result of this control, one would expect appreciable improvements in the stalling characteristics of thin wings. From the balance readings in the 9' x 7' wind tunnel the following points of interest were noted:-

- (a) Maximum lift increased by 10% ;
- (b) Maximum usable lift coefficient increased by approx. 0.2 ;

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- (c) Drag greatly reduced at high incidence;
- (d) Pitching moment virtually constant until nose stalled.

These results were obtained with two rows of air jets on the lower surface, the flow coefficient, C_Q , being 0.00043 at a chord Reynolds number of 3.8×10^6 . The flow coefficient is higher than the value used in the nose flap experiments; this is due to difficulties in implementing the device on a smaller chord aerofoil and the use of a jet flow in excess of the minimum requirement.

Much remains to be done in exploring the potentialities of the device, particularly on thin swept wings. Here one may expect outstanding improvements when laminar separation is eliminated; encouragement in this respect is obtained from the large scale effect which has been found on thin swept wings.

Discussion so far has centered on the low speed landing case. High lift, however, is also required for high speed manoeuvres. It can be assumed tentatively that at high speed the turbulent boundary layer produced by air jets will be far more effective in resisting separation than a laminar layer or the normal turbulent one. Actual flight tests may be necessary to confirm or disprove the above assumption.

4.3 Maximum Lift Considerations

The foregoing experimental work has been centered on wings of 6% thickness. On such aerofoils large increments in maximum lift cannot be expected by this blowing technique alone. To illustrate this point, the local minimum pressure coefficients near the leading edge of the 64A006 are -22 and -32 for lift coefficients of 1.0 and 1.2 respectively; unless means of dealing with the subsequent pressure rises are found, the lift of this type of unflapped aerofoil will be severely limited. If, however, we consider that the usable lift is limited by the point at which nose separation occurs on a two-dimensional wing, or the tips stall on a swept wing, then the use of the above form of boundary layer control will give an appreciable increase. An attempt has been made to estimate the probable maximum lift increments on aerofoils with a thickness greater than 6%. Assuming, as before, that the severe local pressure gradients at the leading edge are the governing factors in nose

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stall and that the minimum pressure near the leading edge is a measure of the gradient, $C_{p_{min}}$ has been presented as a

simple function of C_L in Fig.1. The data are taken from the systematic tests reported in references 7. to 9 and illustrate very clearly the two types of nose stall. By extending these curves, it will be seen that considerable maximum lift increments are possible on the NACA 63009 and 64A010 when it is assumed that C_p values of -20 are obtainable with this device.

It is conceivable that the complete stall will be a more gradual one with turbulent separation from the rear being the basic cause. Hence the application of the principle to the thicker aerofoils also appears warranted.

Whilst the above gains appear attractive, the desired increase in lift may not, in all cases, be obtainable with air jets alone. Therefore it may be necessary to use this method of control in combination with other high lift devices. Since, however, the flow is controlled in the region which normally presents great difficulties, other known devices such as suction slots and trailing edge flaps will be more effective due to the absence of separated flow. The flow over the ailerons will also be improved, thus giving greater lateral control on the thin swept wing in the high lift condition.

4.4 Laminar Flow Considerations

With increasing aircraft speeds, the maintenance of laminar flow on the upper surface of thin swept wings is becoming difficult. For instance, the lift coefficient beyond which adverse gradients appear on the NACA 64A006 is only 0.02; this is less than the usual flight values. Hence in flight, adverse gradients may occur over most of the upper surface, thus making laminar flow impossible. On the lower surface, however, care must be taken to preserve the laminar flow as long as possible.

It is obvious that at high speed, i.e. low incidence, the holes may influence flow conditions over the lower surface as the stagnation point is ahead of the holes. Any small outflow will probably produce early transition, and hence safeguards should be taken to ensure this does not occur. As the holes are in a region of high pressure, the pressure box could

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be vented to a region of low pressure* when the device is not required, in order to counter small leaks which may develop in the shut-off valves from the compressor. Another possible effect of small outflows is discussed in section 5.

The size of hole visualised is too small to constitute a surface irregularity likely to cause transition in this very stable flow region. If this assumption proved to be wrong, a small amount of suction as suggested above would stabilise the flow. Hence it appears that this device, when inoperative, does not adversely affect the laminar boundary layer and in this respect differs from most of the other leading edge high lift devices known.

4.5 Installation and Power Considerations

One main application of this device is to high speed aircraft. Such aircraft will normally be powered with either a jet or gas turbine engine, and hence the engine compressor is the natural choice for an air supply. A preliminary investigation on its suitability disclosed that the bleed quantities only amount to a few per cent even under idling conditions. The box pressures, which at the moment appear to be of the order of 0.5 to 1.0 lb/in.² relative to atmospheric pressure, may be difficult to obtain when idling, although sufficient pressure will probably be available for normal engine speeds at landing. Alternative power supplies would be an auxiliary compressor, or an ejector system powered by either high pressure air or a liquid fuel rocket. Studies on the latter system have been carried out at N.P.L. by Williams (ref.10).

Owing to the intermittent use of the device, it is envisaged that operation will be on a fully automatic basis. A suitable controlling instrument for landing and take-off would be the A.S.I. When the more general application of high speed manoeuvres is considered, either an incidence meter or a ratio meter to measure C_p would be required. Actuation of a switch would then provide power to open or close the necessary valves; quick acting valves would ensure a rapid application or removal.

* Reference 6 suggests a similar scheme for the whole aircraft wing as a means of minimising the effect of inadvertent leaks.

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Insufficient data are available to make an accurate estimate of the power requirements. From the assumptions that $C_Q = 0.00004$, $U_0 = 150$ ft./sec., $c = 8$ ft., and the box pressure relative to surface static = 1 lb/in.², the air power per foot span lost across the aerofoil skin is approximately

$$\begin{aligned} \text{Power/ft. span} &= p C_Q U_0 c / 550 \\ &= 0.013 \text{ H.P.} \end{aligned}$$

Even when liberal allowances are made for losses in the tube from the compressor, the power required is likely to be low and of no importance. This calculation applies, of course, only to the case of one row of holes on the lower surface as used on the nose flap model. If blowing were applied to the upper surface, power considerations would be of greater importance.

Fundamentally, this form of boundary layer control differs from most other methods. The air jets can be considered as activators which accelerate the transfer of momentum. This in fact corresponds to an increase in the skin friction drag, which means that the engine power has been used in a simple, indirect way to provide a measure of boundary layer control. Alternatively, use has been made of the known advantages of a turbulent boundary layer, and an attempt has been made to increase its effectiveness.

With increasing Reynolds number it is expected that the flow coefficient, C_Q , will decrease sharply owing to the greater ease with which turbulence can be produced. The above considerations promote optimism concerning the power requirements likely to be encountered in flight.

5. OTHER APPLICATIONS

Air jets have been considered as a means of boundary layer control on thin swept wings. It is obvious, however, that the principles involved are applicable to many other fluid flow problems. For instance, the air inlets and ducting of jet engines may benefit appreciably from either the prevention of laminar separation or the control of the turbulent layer. In fact, the above principles warrant investigation, wherever rapid diffusions occur e.g. in wide angle diffusers.

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As a wind tunnel tool, the blow principle offers a means of eliminating large scale effects; this may increase the usefulness of low speed wind tunnels in testing high speed aircraft. The high speed tunnel application has been mentioned before (ref.6).

Finally, it has been noticed that blowing with air jets can spoil the flow over the leading edge. Although this does not appear to present a hazard, it is worth mentioning as it could form a very effective form of air brake at high speed where flutter and compressibility effects are dangerous. This spoiling effect was noted on the nose flap model when a minute outflow was permitted. The reason for this behaviour is not at all clear, but it appears to be related to the stability of the stagnation point as this moved from the surface into the free stream. This phenomenon was absent during all the tests on the 64A006, and hence cannot be considered as a normal feature of this device. However, owing to the speed with which a brake of this type could be applied, the original phenomenon may warrant investigation as speed of operation is essential where flutter and compressibility troubles call for a sudden reduction in aircraft speed. If this were a practical proposition, it might mean a separate system with a different arrangement of holes from those used at high lift.

6. EXPERIMENTAL WORK IN HAND

In addition to the work which has previously been outlined, plans are well advanced for flight testing the device on a Vampire fighter. Another flight project is an application to a high speed target aircraft now in production, where increased maximum lift is very desirable. A model of this aircraft will soon be tested in the wind tunnel.

Wind tunnel experiments have either begun or are projected in the near future on (a) a swept wing (North American Sabre aircraft); (b) high speed tests on a small chord model; (c) use of jets to delay trailing edge separation on an NACA 23012 aerofoil; and (d) fundamental studies.

7. CONCLUSIONS

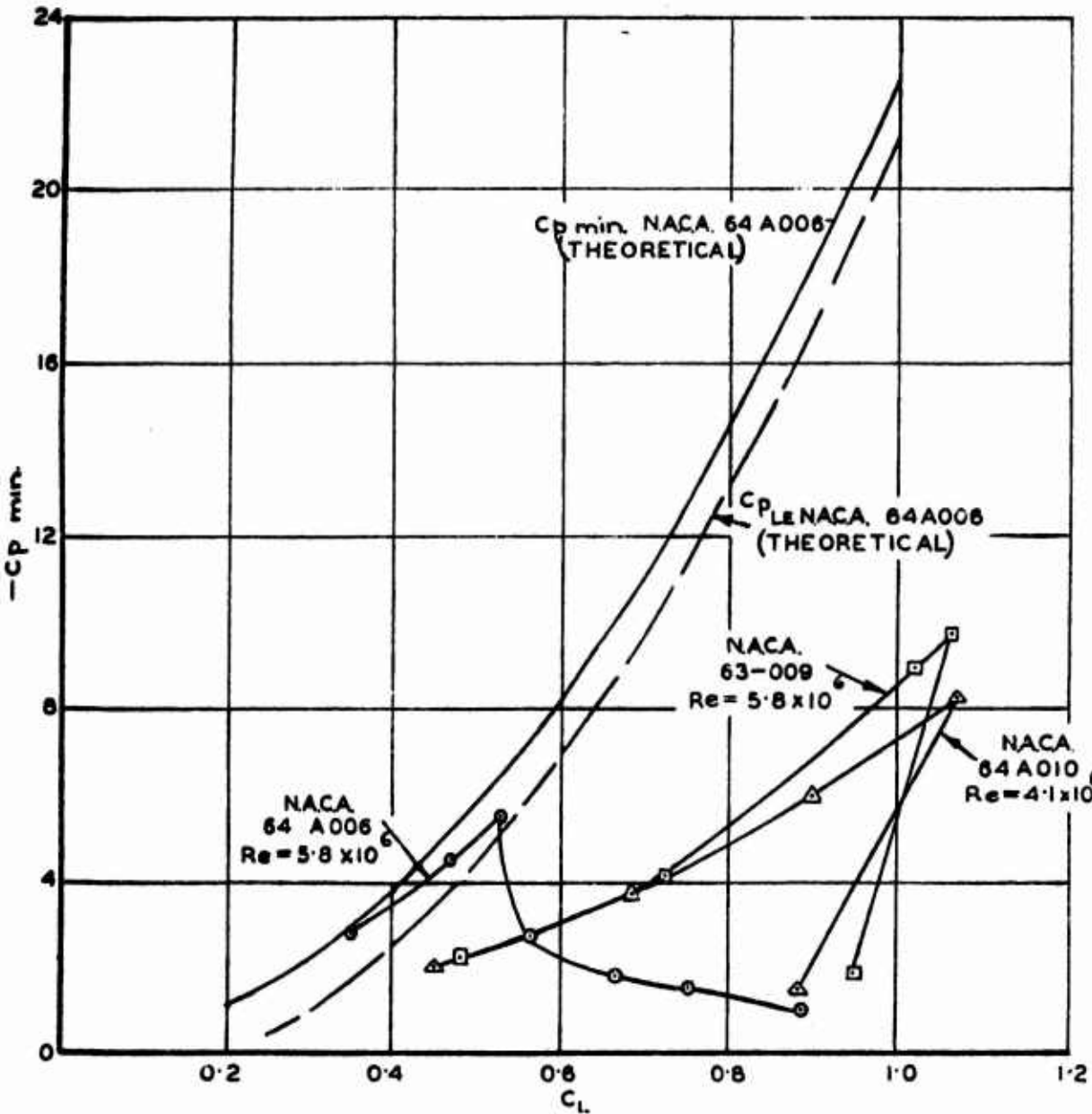
In conclusion, it may be said that the use of air jets to control flow separation appears very promising.

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The Air-Injection Method of Fixing Transition for Laminar to Turbulent Flow in a Boundary Layer.
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1944
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NACA T.N.1923
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NACA T.N.1894
June 1949
9. Peterson
The Boundary Layer and Stalling Characteristics of the NACA 64A010 Airfoil Section
NACA T.N. 2235
Nov. 1950
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Note on the Use of Hydrogen Peroxide Rockets for Boundary Layer Control on Sweptback Wings
N.P.L./Aero/210
June 1951

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MINIMUM SURFACE PRESSURE VERSUS LIFT COEFFICIENT

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DEPARTMENT OF SUPPLYAERONAUTICAL RESEARCH LABORATORIESADDENDUM TO AERO. NOTE 110"THE USE OF AIR JETS FOR
BOUNDARY LAYER CONTROL"

by

R.A. Wallis

It has been suggested that we might enlarge on one or two of the points mentioned in Aero. Note 110. As the application of air jets to the problem of producing transition in the region of the stagnation point is new, a brief discussion of the flow stability based on experimental data and observations might prove useful.

In a favourable gradient on a smooth surface, there are three ways in which transition may occur.

- (i) Two-dimensional instability (Tollmien-Schlichting)
- (ii) Dynamic instability due to inflexion point velocity profiles (Rayleigh)
- (iii) Three-dimensional instability on curved surfaces (Görtler-Taylor)

Calculations show that in the region of the jets, the critical R_{δ^*} above which small two-dimensional disturbances become δ^* amplified is approximately 12,000. Hence the first type of instability can be ruled out as the Reynolds number based on the displacement thickness of the boundary layer, R_{δ^*} , at the jets is of the order of 70 for a chord Reynolds number of 4×10^6 .

The second type of instability could very easily have a bearing on the question of transition as the jet flow will almost certainly produce inflexion point profiles close to the jets. Due to the marked convexity of the surface it is not expected that the Görtler-Taylor type will have any effect other than to possibly damp out some of the component frequencies of the turbulent flow.

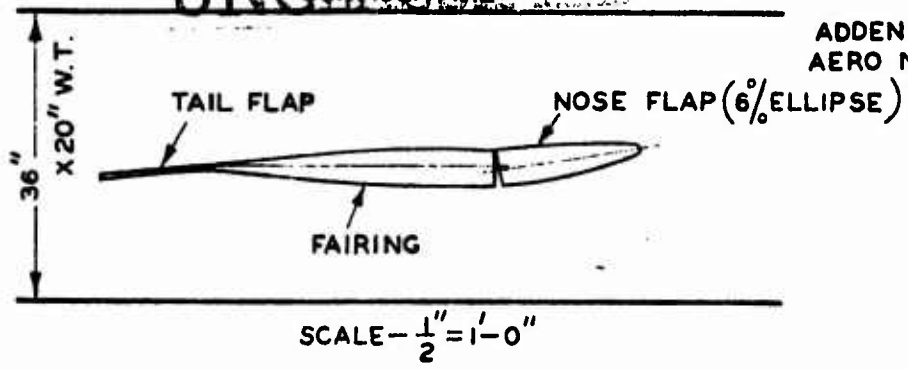


FIG. 1 DIAGRAM OF MODEL

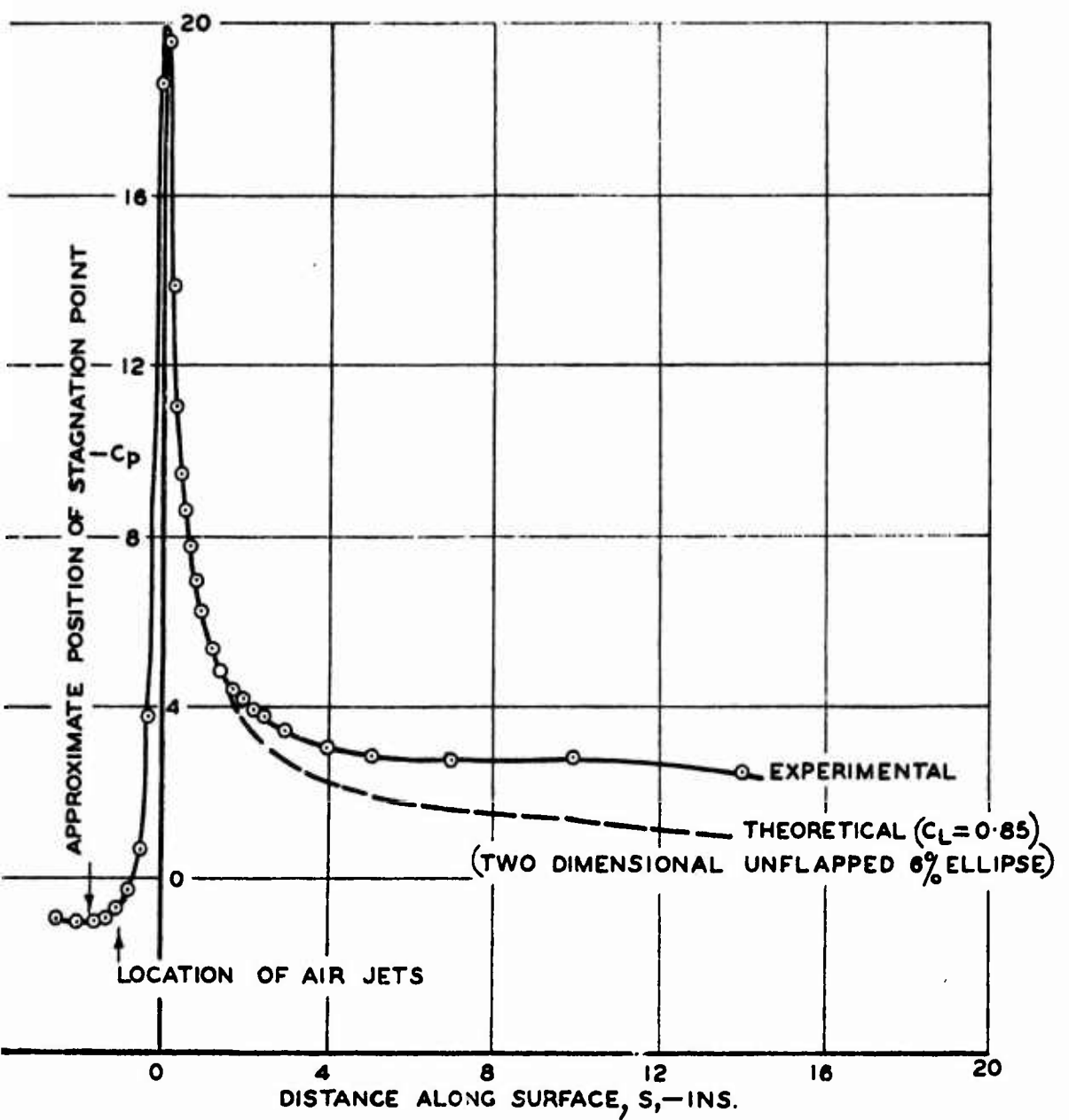


FIG. 2 PRESSURE DISTRIBUTION