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Investigation of a Laminar Boundary-Layer Suction Slot

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The flow of a laminar boundary layer into a suction slot has been examined experimentally in a low-turbulence water channel. Dimensional analysis shows that the slot Reynolds number and a parameter that describes the mean velocity gradient in the flow above the slot are the important variables in the problem. Measurements are reported of the length scales of the separation region within the slot and the slot-pressure loss. These data correlate in terms of the similarity variables and may be used as a predictive design tool. The mean-flow profiles above the slot, in both the upstream and downstream directions, were also measured using hot films, and the possibility of a Taylor-Görtler rotational instability occurring just downstream of the slot has been studied.

Nomenclature

a	= width of slot separation bubble
b	= length of slot separation bubble
C_p	= slot pressure drop coefficient, $\Delta p/\frac{1}{2}\rho v_s^2$
Δp	= slot pressure drop
R	= local streamline radius of curvature
Re	= slot Reynolds number $v_s w/\nu$
t	= slot depth
U_s'	= local velocity upstream of slot at $y=y_s$
dU/dy	= velocity gradient upstream of slot
v_s	= bulk slot suction velocity
w	= slot width
x	= streamwise coordinate
x_L	= distance from plate leading edge to slot
y	= cross-stream coordinate
y_s	= height of dividing suction streamline
α	= dimensionless velocity gradient $(dU/dy)(w/v_s)$
ν	= fluid kinematic viscosity
Ω	= local angular velocity
δ_0	= reference boundary-layer thickness
δ^*	= boundary-layer displacement thickness
ω	= vorticity
*	= dimensionless quantities

Introduction

DURING the decade spanning the mid-1950's to mid-1960's a program was undertaken at Northrop to examine the potential of laminar-flow control (LFC) as a means of reducing aircraft drag. The concept, which is now receiving renewed interest as part of the NASA-sponsored Aircraft Energy Efficiency program, is based upon reducing the amplification of the boundary-layer instabilities that lead to turbulent flow over a wing. This is achieved by using controlled wall suction to modify the mean boundary-layer flow, leading to a more stable laminar flow of low skin friction.

The concept can be implemented by a number of different means. Some early British tests,[1] for example, utilized wall suction through an array of small circular holes drilled in the wing surface. However, this can lead to the generation of small three-dimensional disturbances and led Northrop to use instead suction through a number of spanwise running slots to stabilize the laminar boundary layer.[2] This concept is currently being investigated at the Lockheed-Georgia Company and is shown schematically in Fig. 1 along with the definitions that will be used throughout this report.

In the design of these slots there are essentially two flow regimes of different scale and strength that must be considered—the external boundary-layer flow and the suction slot flow—and the proper matching of these two flow regimes presents a significant design challenge. Current designs are guided largely by placement of empirical limits on the various design parameters. For example, Pfenninger, Bacon, and Goldsmith[3] have satisfactorily demonstrated a clear need to maintain the slot Reynolds number $Re = v_s w/\nu$ less than 100 in order to avoid or minimize the outward propagation of slot-induced oscillations into the mainstream. Also, it is known that it is unwise to remove too large a percentage of the boundary layer, since doing this can lead to excessive suction-pressure requirements and boundary layers of high shear stress and greater susceptibility to roughness. For this reason, following the definition of terms in Fig. 1, Goldsmith[4] recommends that the height y_s of the streamline that divides the sucked flow from the main flow should be about 30% of the boundary-layer displacement thickness.

Other design parameters arise from considerations that are less clear. Goldsmith,[4] for example, has argued that a parameter defined by $\beta = t/wRe$ should be greater than about 0.01 in order that the slot flow should have predictable characteristics. This parameter definition arises originally from tests for suction through circular holes with no transverse flow present and, in fact, corresponds to the inlet length of tube required for the sidewall laminar boundary layers to merge. Its relevancy to the slot problem where transverse shear flow is present does seem questionable.

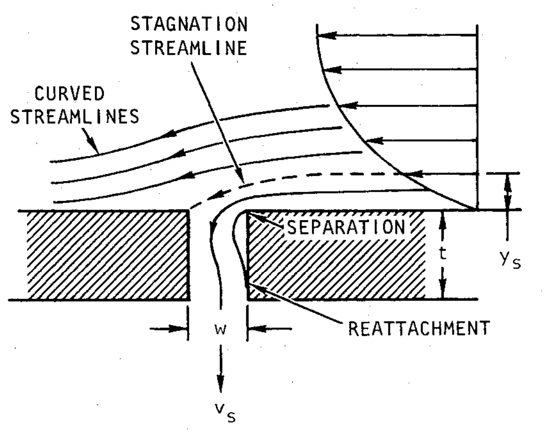

Fig. 1 Configuration of a laminar-flow suction slot.

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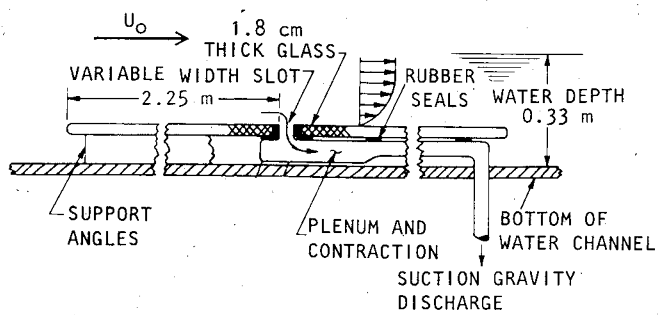

Fig. 2 Suction slot test apparatus.

Other considerations of suction slot design, besides those already mentioned, are also important. For example, the boundary layer passing over the slot will ultimately relax back to a less stable profile. LFC designers, accustomed to treating the stabilizing effect of suction as if it were uniformly distributed over the wing, must have the proper data available so that they can estimate this effect, ultimately spacing and sizing their array of suction slots accordingly. Finally, there is one other aspect of the problem that has not yet received any treatment in the literature. As can be seen in Fig. 1, just downstream of the slot the boundary-layer streamlines show a strong concave curvature in a region of mean shear. Such a flow is unstable to a centrifugal Taylor-Görtler or rotational instability and can wrap up into fingers of streamwise or longitudinal vorticity. Since these have an adverse effect upon the transitional characteristics of the developing flow, it is crucial that a designer be able to predict whether or not this phenomenon will occur.

Our understanding and ability to predict the behavior of these suction flows is obviously far from complete, and only through a careful series of experiments can the behavior of these flows be determined and the relevant design parameters be identified. Therefore, it was decided to undertake an experimental program at the Lockheed-Georgia Company to examine, in detail, the flow into and within a suction slot. It became apparent that to do this in a wind tunnel would be a difficult task because of the extremely thin boundary layers involved and the very narrow suction slots that would be needed; hence, the tests were conducted in a water channel where the much lower flow velocities allowed thick laminar boundary layers to be developed, permitting the use of wider suction slots while evaluating the same dimensionless parameters. The advantages of flow visualization using dye lines in water are also obvious.

Experimental Considerations

The experiments that are described herein were undertaken in the Lockheed-Georgia Low-Turbulence Water Channel. This is a research-quality open-channel flow facility whose test section is 0.3 m deep, 1.0 m wide, and 5.0 m in length and whose test section turbulence level is only of the order of 0.05%.

For the slot experiments, the arrangement shown in Fig. 2 was placed on the floor of the channel. It consists essentially of two glass plates each 0.6 m wide and 2.25 m long, placed end to end so as to create a uniform suction slot between them; this 0.6-m-long slot is 1.8 cm deep. The downstream plate translates back and forth in the streamwise direction so as to provide a variable width for the suction slot, and a collection plenum beneath the slot discharges, via gravity feed, below the test section. A throttle is used to control the suction flow rate, which is measured by simply recording the time required to fill a known-volume container.

To visualize the flow in the vicinity of the slot and within the slot, Fluorescein fluorescent dye was introduced through 0.2-mm-diam tubes placed far upstream of the slot. When illuminated by black light, the resulting image provided a high-contrast view of the flow. Because the flow is steady, the

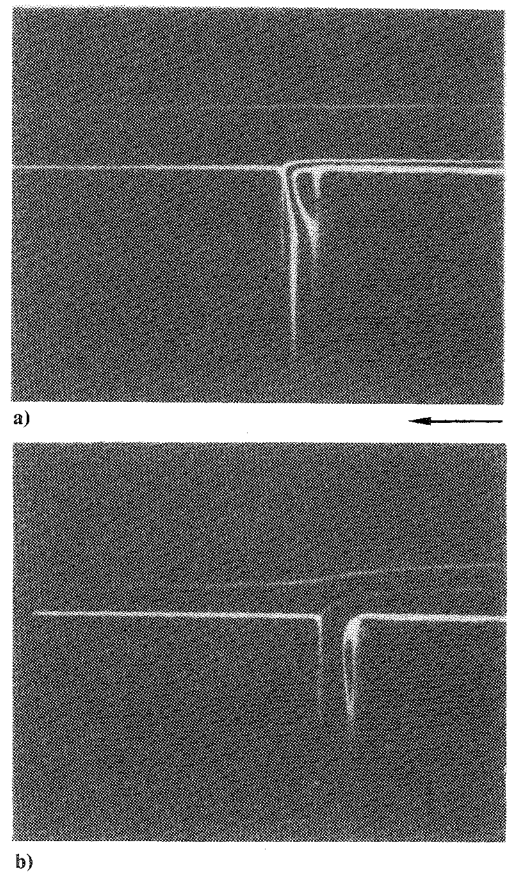

Fig. 3 Fluorescent dye line visualization of the flow into the suction slot. a) $U_0 = 21$ cm/s, $\alpha = 9.0$, $Re = 34$; b) $U_0 = 21$ cm/s, $\alpha = 1.0$, $Re = 301$.

resulting photographs and video pictures of these dye lines represent views of the flow streamlines. Quantitative information was obtained by merely scaling the dimensions and positions of the flow streamlines from the enlarged image on a video screen. The mean profiles and mean velocity gradient existing above the slot were obtained using cylindrical hot film anemometers driven in the constant-temperature mode and calibrated in the freestream of the water channel.

Measurement of the slot-pressure drop was more difficult because of the very low pressure differences that were encountered. Typically, only a few thousandths of an inch of water were recorded using two inclined manometers. One of these was connected to the suction plenum, and the other was connected to a static port above the slot. A microscope with a filar optical eyepiece was used to read the change in the pressure of the two manometers as the suction was applied.

During the test program the freestream velocity was typically between 0.1 and 0.25 m/s. This flow provided a constant-pressure laminar boundary layer whose total thickness was of the order of 1.8 cm at the suction slot. The bulk suction velocity v_s was between 0.03 and 0.1 m/s, and the aspect ratio of the slot was varied by changing the slot width (typically between 2 and 7 mm). Aspect ratio and slot depth did not influence such things as the dimensionless characteristics of the flow within the slot, provided, of course, the slot remained fully attached. Obviously, this could not be the case for global quantities such as the slot-pressure drop, and these data are presented accordingly.

Some Observations of the Slot Flow

As a first experiment, lines of fluorescent dye were introduced into the flow upstream of the slot in order to visualize the flow within the slot itself. Typical photographs of the resulting dye lines are shown in Fig. 3 for test con-

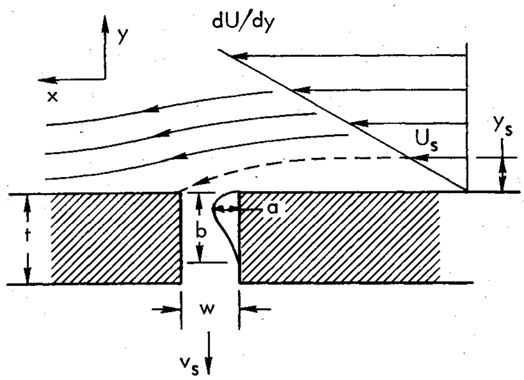

Fig. 4 Idealization of the flow into a small suction slot.

ditions corresponding to two different values of slot Reynolds number and mean shear above the slot. An examination of these and other photographs taken as different test conditions that typify LFC applications leads to the following observations:

1) The streamline that separates the fluid flowing into the suction slot from the flow in the outer part of the boundary layer is always observed to stagnate on the downstream corner of the suction slot.

2) Within the slot a separation bubble is always observed to form on the upstream face of the slot. (Depending upon the depth of the slot, the bubble may or may not reattach, and it is crucial that a designer be able to predict whether or not this is the case.)

These findings, depicted also in Fig. 1, may seem trivial, but it is by no means obvious that the flow should always behave in this manner. This behavior has been consistently observed, however, and the flows at widely different test conditions all exhibit this similarity.

These findings suggest that the nondimensional relationships defining the present problem may not be very complex. In principle, it is therefore possible to apply similarity reasoning to define the form of these dimensionless parameters and then, by experimentation, to determine the functional relationships between them. Such a correlation of experimental data could then be used as a basis for the design of suction slots in LFC and other applications.

Dimensional Analysis of the Problem

To invoke similarity or dimensional reasoning, essentially two flow regimes must be considered. First, there is the incoming boundary-layer flow itself. This flow can adopt a wide variety of speeds, profiles, and thicknesses, all of which might have a bearing on the problem. Second, there is the flow within the slot. These two different regimes have been depicted in Fig. 1 previously, and many variables would need to be specified in order to completely define the flow.

It is possible, however, to make certain assumptions that greatly simplify the problem. It is important for LFC applications, for example, that only a small percentage of the boundary-layer mass flow actually enter into the slot, and it may be assumed that slot flow will depend not so much on the freestream conditions or the freestream velocity and pressure gradient but rather on the flow immediately adjacent to the surface. The flow in the outermost part of the boundary layer and in the freestream may be thought of as being decoupled from the slot flow and need not be considered. Therefore, without loss of validity the problem depicted in Fig. 1 can then be redefined and presented in the way depicted in Fig. 4.

In this presentation of the problem, the flow in the boundary layer has now been replaced by a uniform shear flow of the same wall velocity gradient, and it is the strength of this gradient that is a necessary and sufficient characteristic to uniquely define the flow in the vicinity of the slot. The problem is now one of determining, by dimensional reasoning, the dimensionless parameters that are relevant to this simplified flowfield.

Referring then to Fig. 4, it can be seen that the only imposed velocity and length scales in the problem are now the bulk suction velocity v_s and the slot width w. Therefore, the flow in the slot can be characterized by its Reynolds number $v_s w/\nu$ and the slot itself by its aspect ratio t/w. Since the velocity gradient dU/dy is now the only external-flow parameter, then the dimensionless term $\alpha = (dU/dy)\ (w/v_s)$ provides a means of tying the strength of the outer flow to the strength of the suction flow. Alternatively, the parameter $\chi = (dU/dy)\ (w^2/\nu) = \alpha\, Re$, which does not depend upon the suction rate, could be used with equal validity, and the final choice is merely one of convenience.

Referring to Fig. 4, the following dimensionless terms have been identified: slot Reynolds number $Re = v_s w/\nu$; dimensionless wall gradient $\alpha = (dU/dy)\ (w/v_s)$; slot aspect ratio t/w; separation-bubble scales a/w, b/w, etc. Since no other terms exist, then it also follows that the characteristics of the flow within the slot, such as the size of the separation bubble (a/w, b/w) as well as the characteristics of the flow above the slot (streamline curvature, mean profiles, etc.), are functions of α and Re alone. An experiment covering a sufficient range of α and Re will then allow these functional relationships to be determined.

Before closing this section, it is noted that alternative and more rigorous derivation of the dimensionless terms in the problem can be found by considering the two-dimensional vorticity equation,

$$u\frac{\partial \omega}{\partial x} + v\frac{\partial \omega}{\partial y} = \nu\left(\frac{\partial^2 \omega}{\partial x^2} + \frac{\partial^2 \omega}{\partial y^2}\right) \tag{1}$$

where the coordinate axes are as depicted in Fig. 4. The following dimensionless terms arise logically:

$$x^* \sim x/w \qquad u^* \sim u/U_s \sim u y_s / v_s w$$
$$y^* \sim y/y_s \qquad v^* \sim v/v_s \tag{2}$$

Here the scales for x and v are set by geometry but the length scale for y is set by the suction. The appropriate choice is y_s. The scale for u then immediately follows from continuity, and substitution in Eq. (1) with some dimensionless vorticity term ω^* yields:

$$\frac{v_s}{y_s}u^*\frac{\partial \omega^*}{\partial x^*} + \frac{x_s}{y_s}v^*\frac{\partial \omega^*}{\partial y^*} = \frac{\nu}{w^2}\left[\frac{\partial^2 \omega}{\partial x^{*2}} + \left(\frac{w}{y_s}\right)^2\frac{\partial^2 \omega}{\partial y^{*2}}\right] \tag{3}$$

Furthermore, continuity of mass flow into the slot requires that

$$\alpha = 2(w/y_s)^2 \tag{4}$$

which after substitution in Eq. (3) yields the dimensionless equation

$$u^*\frac{\partial \omega^*}{\partial x^*} + v^*\frac{\partial \omega^*}{\partial y^*} = \frac{1}{Re}\sqrt{\frac{2}{\alpha}}\left(\frac{\partial^2 \omega^*}{\partial x^{*2}} + \frac{\alpha}{2}\frac{\partial^2 \omega^*}{\partial y^{*2}}\right) \tag{5}$$

Under the definitions of dimensionless variables used to develop this equation, the slot is now normalized to unity width and unit suction velocity independent of the external flow. The upstream velocity gradient dU/dy is nondimensionalized as unity, and this represents a boundary condition to the solution of Eq. (5) Therefore, the solution to Eq. (5), which depends only on the coefficients in the equation and the boundary conditions, is a function only of α and Re. This result supports the current similarity arguments and shows that the flowfield in the vicinity of the slot can be uniquely determined from α and Re alone.

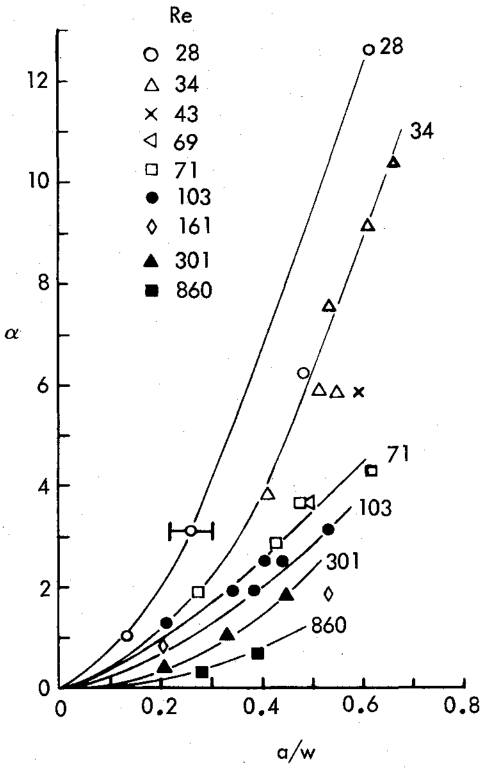

Fig. 5a Width of the slot separation bubble as a function of *Re* and α.

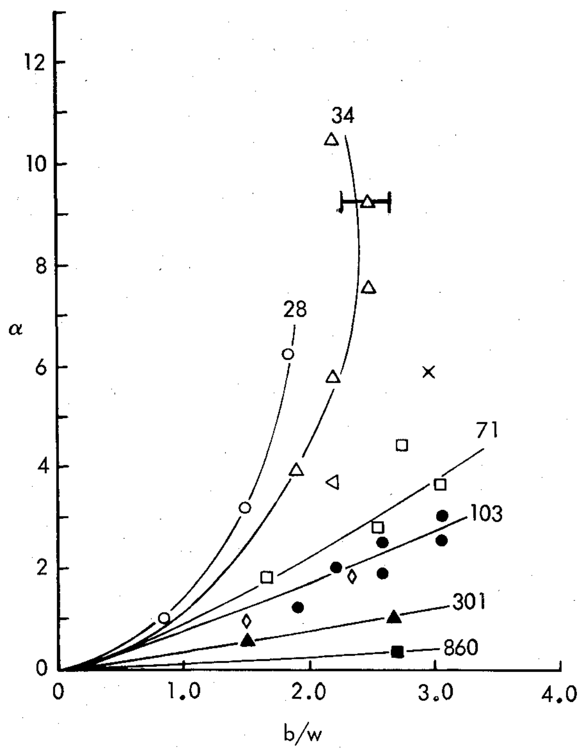

Fig. 5b Length of the slot separation bubble as a function of α and *Re*. Symbols correspond to those in Fig. 5a.

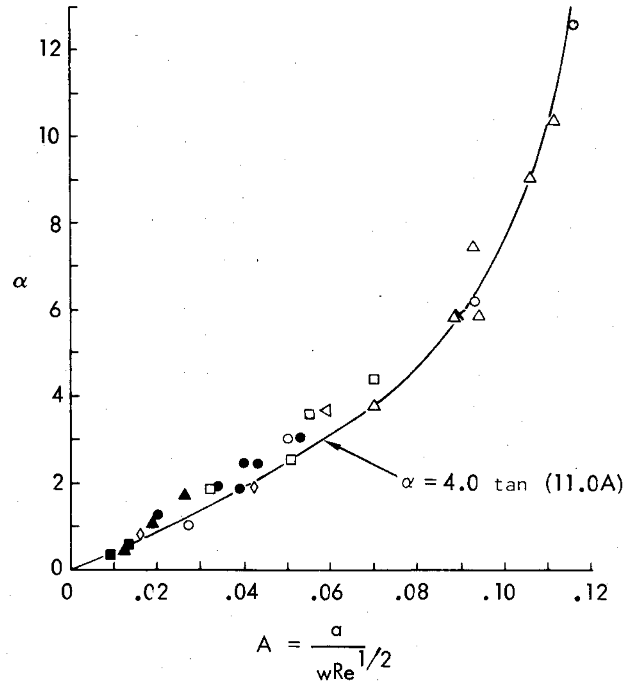

Fig. 6a Dimensionless width of the slot separation bubble. Symbols correspond to those in Fig. 5a.

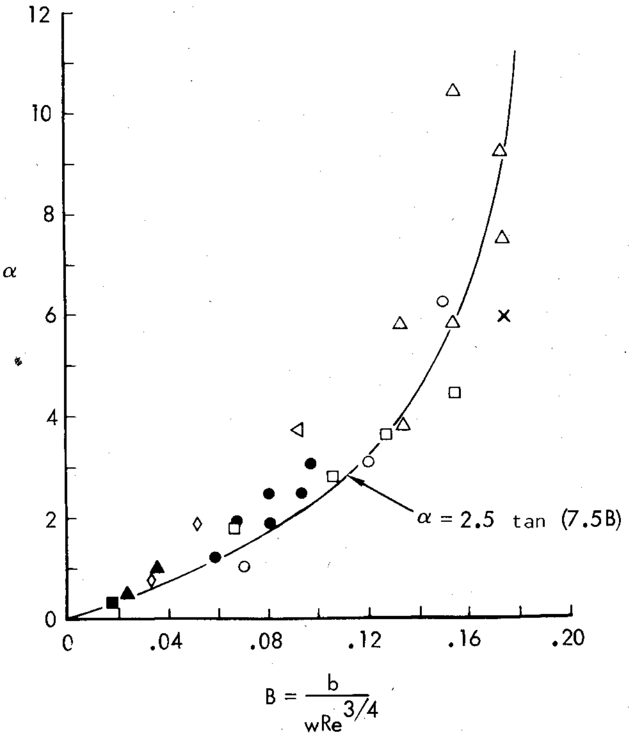

Fig. 6b Dimensionless length of the slot separation bubble. Symbols correspond to those in Fig. 5a.

Measurements of the Flow within the Slot

Having defined the external flow in terms of its wall gradient, it now remains to determine the characteristics of the flow in the slot as a function of this external shear flow and of the suction. Measurements were made of the dimensions a/w and b/w of the separation bubble within the slot for a number of different test conditions. These data are presented in Figs. 5a and 5b in terms of the suction Reynolds number *Re* and dimensionless wall gradient α where α has been measured from the video pictures using Eq. (4). As the previous discussions would imply, there is an obvious tendency for the data to group themselves in terms of the slot Reynolds number. Furthermore, it is apparent that steep incoming velocity gradients can lead to quite large separation bubbles and a considerable constriction of the flow in the slot. For example, Figs. 5a and 5b show that as much as 60% of the slot width may be consumed by the separation bubble, which itself may be up to three slot widths in length.

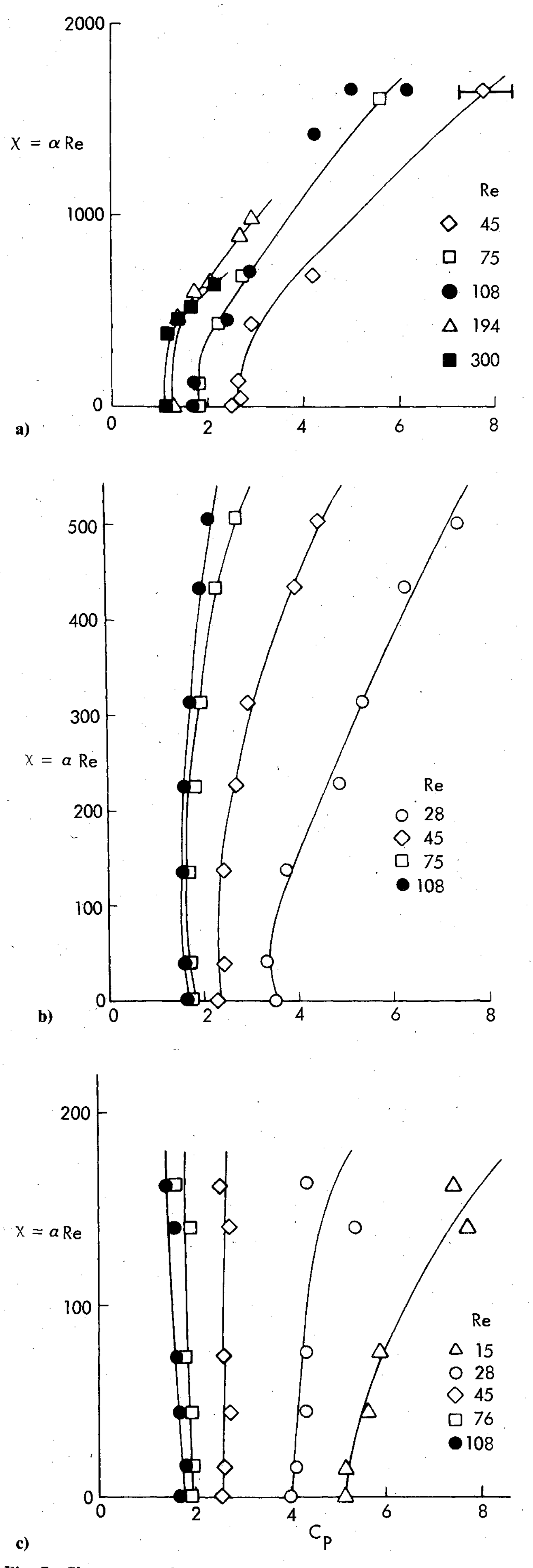

Fig. 7 Slot pressure loss coefficient for a) $t/w = 2.1$ (fully separated condition); b) $t/w = 3.8$; c) $t/w = 6.6$.

The data in Fig. 5 may be useful as design charts; however, the obvious grouping of the data with Reynolds number does suggest that a simpler correlation might be possible. As depicted in Figs. 6a and 6b, this is indeed the case. When the data are presented in terms of $a/w\sqrt{Re}$ and $b/(wRe^{3/4})$, essentially a single curve is obtained in each case. (Any residual scatter in the data can be attributed to the difficulty of accurately measuring the very small distances involved. This is particularly true for the ill-defined distance to the point of reattachment b/w in Fig. 6b.)

These data represent one of the main conclusions of this work and provide a unique definition of the flow into the suction slot. For example, as a design criterion, fully attached flow within the slot will occur when the dimensionless slot depth $t/(wRe^{3/4})$ lies to the right of the curve in Fig. 6b. Note that a threshold on the parameter $\beta = t/wRe$ has been used in the past to characterize the predictability of the flow into the slot,[4] and this now seems an inadequate description of the phenomenon.

The following curve fits to the data are provided:

$$\alpha = 4.0\tan(11.0A) \qquad A = a/(wRe^{1/2}) \tag{6}$$

$$\alpha = 2.5\tan(7.5B) \qquad B = b/(wRe^{3/4}) \tag{7}$$

These functions are also depicted in Fig. 6 and enable a/w and b/w to be computed from the known suction flow and transverse shear flow.

Pressure Drop Across the Slot

Before describing the experimental study of the pressure drop across the slot, it is first necessary to discuss the definition of "pressure drop." There is, for example, a difference in pressure between the top lip of the slot and its lower discharge lip. Likewise, as the flow turns into the slot, there will be a pressure difference generated between a point far from the slot and a point near the lip of the slot. The possibility also exists for some pressure recovery to occur in the plenum beneath the slot. Clearly, from a practical design point of view, it is necessary to consider all these effects together because LFC suction slots would be designed on a basis of the wing pressure coefficient, existing in the absence of the slot and the plenum pressure. Therefore, in the present study the term "pressure drop" will refer to the difference in pressure between a point in the freestream above the slot and the plenum pressure; is it this pressure differential that essentially drives the slot flow.

Following the assumptions under which the slot flow has been modeled, this pressure drop can be expressed as a dimensionless coefficient $C_p = \Delta p/\frac{1}{2}\rho v_s^2$ and will depend upon α and Re. Also, because of viscous losses occurring in the slot itself, it will depend upon the slot depth-to-width ratio t/w. This coefficient has been measured over a range of operating conditions and for values of $t/w = 2.1$, 3.8, and 6.6. These data are displayed in Figs. 7a, 7b, and 7c, respectively. The data in Fig. 7a correspond to cases where the flow in the suction slot is fully separated and does not reattach to the sidewall, whereas the other two cases (Figs. 7b and 7c) correspond to reattached flow.

As the slot Reynolds number is increased, the pressure coefficients become smaller and approach unity for small values of α. This is to be expected in view of the fact that such a flow resembles the case of an inviscid sink flow for which $C_p = 1.0$ precisely. It is noteworthy, however, that for the lower Reynolds number flows more typical of LFC applications, large pressure coefficients occur, probably due no doubt to the high viscous losses within the slot. It is further apparent that, for the cases of attached flow, the pressure-loss coefficient is very sensitive to slot Reynolds number. This is much less true for the case of separated flow (Fig. 7a), where the Reynolds number sensitivity is weaker.

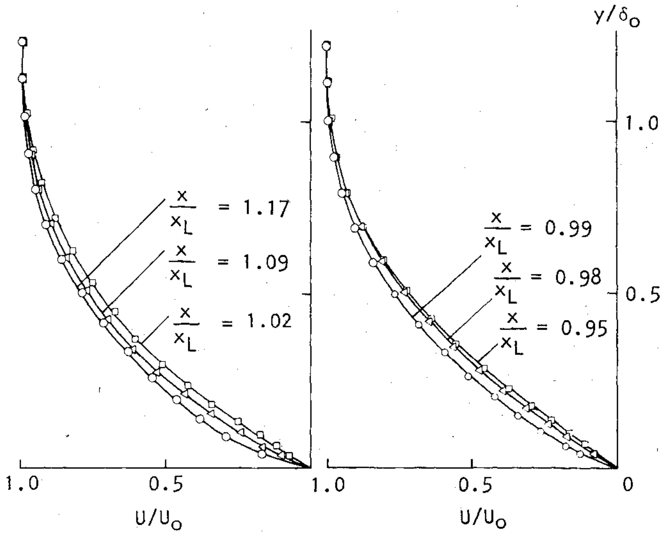

Fig. 8 Mean boundary-layer profiles existing upstream and downstream of the slot; $Re=110$, $Re_{\delta_0^*}=1300$, $w=6.4$ mm, $U_0=21$ cm/s.

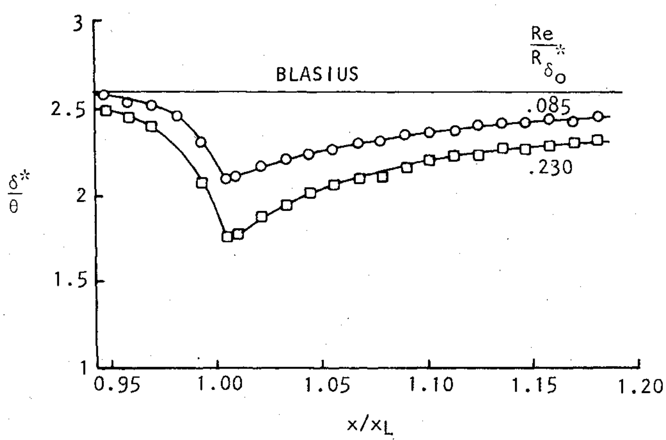

Fig. 9 Shape factor distribution for flow over a suction slot; $Re_{\delta_0^*}=1300$, $U_0=21$ cm/s, $w=6.4$ mm.

Perhaps one of the more interesting aspects of these data is the finding that the minimum pressure-loss coefficient does not correspond to the case of zero flow above the slot ($\alpha=0$). Apparently, there is some nonzero external velocity gradient that minimizes the pressure drop across the slot. This arises because, unlike the case of zero shear flow, the external flow now has some average momentum that actually aids in driving the fluid into the slot, with minimal acceleration or viscous losses being associated with the downward turning of the flow. On the other hand, as the shear is further increased, the suction flow comes from a region closer to the wall and must be turned more suddenly and sharply so as to be able to enter the slot. The penalty for this acceleration is the observed rise in pressure-loss coefficient at the higher values of α.

Character of the Boundary-Layer Flow

Since the discussion to this point has been concerned with the slot flow itself, it has not yet been necessary to consider the detailed character of the flow in the outer part of the boundary layer. However, this region is important, too, and has an influence on the design spacing of the suction slots.

This flow region was studied by recording the mean velocity profiles both upstream and downstream of the suction slot. These data are quite extensive, and although not included herein, a few representative cases are shown in Fig. 8. The data show that the slot has a considerable upstream influence as the flow accelerates, under the induced favorable gradient,

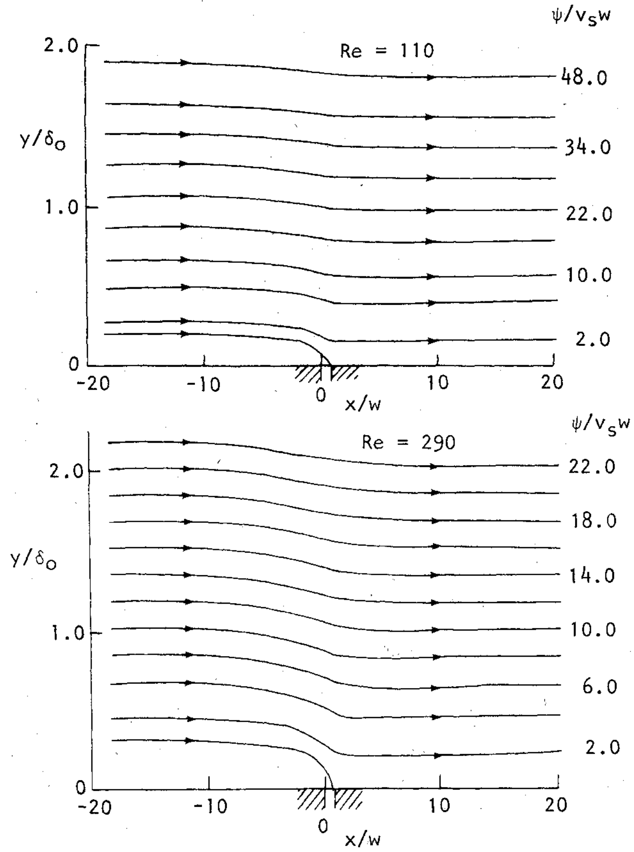

Fig. 10 Streamline pattern of flow over the slot as determined from the boundary-layer profiles; $Re_{\delta_0^*}=1300$, $U_0=21$ cm/s, $w=6.4$ mm.

toward the slot. After passing over the slot, the profiles are fuller (and more hydrodynamically stable) and slowly relax back to the more conventional profile shape.

This phenomenon can be more easily demonstrated by considering the variation in the boundary-layer shape parameter δ^*/θ with streamwise distance shown in Fig. 9. Here the suction strength has been characterized in terms of the boundary-layer mass flux, which, for the Blasius flow of the present tests, is equivalent to the ratio of Reynolds numbers Re and $R_{\delta_0^*}$. Also, the streamwise distance has been nondimensionalized by the distance to the slot from the leading edge since it is this distance that determines the character of the boundary layer developing over the slot. It is clear from the figure that the slot has a considerable upstream influence (equivalent to about 15 slot widths) and the shape factor reduces steadily as the flow approaches the slot. As shown in Fig. 8, this is because the mean-flow profile tends to fill out as the flow accelerates into the slot. It is of some surprise to see that because of this the minimum shape factor does in fact occur slightly after the slot. Further downstream the mean boundary-layer flow slowly relaxes back to the Blasius condition, with the suction rate determining how far the flow travels before this is complete. For the configurations shown in the figure, this distance is in excess of 20% of the distance from the leading edge to the slot.

Streamline Pattern of the Slot Flow

Streamlines are defined by lines of constant streamfunction ψ, where ψ is defined by

$$u=\partial\psi/\partial y \tag{8}$$

integrating with respect to y leads to a definition of ψ at some position above the wall $y=y'$,

$$\psi(y=y')=\int_0^{y'} u(y)\,\mathrm{d}y \tag{9}$$

Using this equation, lines of constant ψ may be determined from the mean velocity data. These are shown for two test conditions in Fig. 10. For clarity the vertical scale has been stretched so that the picture is somewhat distorted; however, the similarity with the dye line pictures in Fig. 3 is clear.

The strong upstream influence and the turning of the flow down toward the slot are both visible. Furthermore, the range of this influence can now be seen to be quite significant and to extend for a considerable distance away from the wall into the main flow. For example, the outer flow is still markedly influenced at distances as much as 2½ boundary-layer thicknesses or about 20 slot widths above the wall. This large extent of influence may seem to be in conflict with the previous assumptions about the nature of the near wall and slot flow. This is not the case, however, since the data in Fig. 10 also clearly show that only a small part of the boundary layer does in fact enter the slot and that the remainder of the boundary-layer flow is simply a response to the change in wall flow conditions. The main feature of this is shown to be a region of convex streamline curvature followed by a region of concave curvature. The latter can be quite high, particularly near the wall, and the potential destabilizing effect of this flow will be discussed in the next section.

Possibility of a Taylor-Görtler Instability Downstream of the Slot

Any flowfield exhibiting streamline curvature is rotationally unstable if the sense of the local vorticity is in opposition to the local curvature. This condition can lead to the downstream formation of a series of contrarotating streamwise vortices.

In a study of circular Couette flow, Coles[5] has determined a criterion for this instability that can be expressed as

$$\Omega\omega \leq -\nu^2/2\ell^4 \tag{10}$$

Here Ω is some characteristic angular velocity, ω is the local vorticity, and ℓ is a characteristic scale for the instability motion. This definition follows from order-of-magnitude estimates in the vorticity equation and is essentially equivalent to the concept of Taylor number used by others.[6] For the present configuration, defining the streamline radius of curvature as R, the following estimates may be made for each term in Eq. (10):

$$\begin{aligned} \Omega &\sim U_s/R & \omega &\sim U_s/y_s \\ &= (U_s/y_s)(y_s/R) & &= \alpha v_s/w \\ &= \sqrt{2\alpha}v_s/R \end{aligned} \tag{11}$$

where α is given in Eq. (4). It is further assumed that the order of magnitude of the scale ℓ of the secondary motion is also y_s. Hence, the right-hand side of Eq. (10) becomes

$$-\nu^2/2\ell^4 = -\nu^2/2y_s^4 = \nu^2\alpha^2/8w^4 \tag{12}$$

Using these definitions in Eq. (10) leads, after some reduction, to the following definition of the threshold of curvature, above which the instability can be expected:

$$R/w \leq -8Re^2\sqrt{2/\alpha} \tag{13}$$

The minus sign is merely a need for the rotation to be in opposition to the vorticity. In view of the dimensionless result expressed previously in Eq. (5), it is no surprise to see that R/w depends on α and Re only.

For typical values of $\alpha = 5$ and $Re = 100$ this result suggests that, if R/w is less than -5×10^4 anywhere locally, then the instability will be present. Put another way, we see that only very small amounts of curvature are required for the instability. This finding prompted an examination of the flow downstream of the slot using hydrogen-bubble flow visualization. Despite efforts to find any instabilities, none were observed and the flow preserved its two-dimensionality and steadiness.

This finding is not in conflict with the analysis leading to Eq. (13) because the analysis has given no consideration to the intensity of the instability or the growth rates associated with the instability. Furthermore, the fluid exists in the unstable region for only a short time so that the influence of the instability is apparently small and cannot be observed. On the basis of these experiments, it would seem that this aspect of the problem need not be of concern for LFC applications.

Summary

This report describes an experimental investigation of the flow from a laminar boundary layer as it enters and passes through a suction slot. The flow has been visualized in a water channel facility using dye from which quantitative information has been extracted. Also reported are some measurements of the pressure loss across the slot as well as measurements of the mean boundary-layer development downstream of the slot.

The following conclusions are drawn from this work:

1) A dimensional analysis of the problem, in which the boundary layer above the slot is approximated by a uniform shear, has shown that the flowfield is characterized by its Reynolds number Re and by the dimensionless wall gradient α.

2) The characteristics of the separation bubble that is always observed to form on the upstream lip of the slot are found to be uniquely specified by the values of α and Re.

3) The slot-pressure-loss coefficient has been measured for three different slot depth-to-width ratios. The minimum pressure loss does not always correspond to the case of zero shear flow above the slot. For reattached flow within the slot, the pressure losses have a very strong Reynolds number dependency; that is not the case when the flow remains separated.

4) The presence of the slot, characterized by an induced favorable upstream pressure gradient, can be felt as much as 15 slot widths upstream of the slot.

5) The problem of the potential centrifugal instability of the curved flow above the slot has been addressed. Although the necessary conditions were undoubtedly present, they were effective over such a short region that no evidence of such an instability was observed.

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