Investigation of Tangential Blowing Applied to a Subsonic V/STOL Inlet

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Engine inlets for subsonic V/STOL aircraft must operate over a wide range of conditions without internal flow separation. An experimental and an analytical investigation were conducted to evaluate the effectiveness of tangential blowing to maintain attached flow to high angles of attack. The inlet had a relatively thin lip with a blowing slot located either on the lip or in the diffuser. The height and width of these slots were varied. Experimentally determined flow separation boundaries showed that lip blowing achieved higher angle-of-attack capability than diffuser blowing. This capability was achieved with the largest slot circumferential extent and either of the two slot heights. Predicted (analytical) separation boundaries showed good agreement except at the highest angles of attack.

Nomenclature

A	= area
CR	= contraction ratio
D	= diameter
h	= blowing slot height
L	= inlet length
m	= mass flow rate
P	= total pressure
p	= static pressure
R	= Reynolds number
RBP	= relative blowing power, $\frac{m_B}{m_I}\left[\left(\frac{P_B}{P_0}\right)^{(\gamma-1/\gamma)}-1\right]\times 10^4$
T	= total temperature
V	= velocity
x	= axial length from inlet highlight
y	= rake height
γ	= ratio of specific heats
θ	= blowing slot circumferential extent
μ	= viscosity
ρ	= density
ψ	= circumferential location

Subscripts

B	= blowing
d	= diffuser rake
de	= diffuser exit
e	= edge of boundary layer
F	= fan face
HL	= highlight
I	= inlet
max	= maximum
0	= freestream
t	= throat

Introduction

ENGINE inlets for tilt-nacelle subsonic V/STOL aircraft must operate efficiently over a wide range of flight speeds, engine throttle settings, and inlet angles of attack. Studies indicate that these inlets can experience angles of attack as high as 120 deg at flights speeds of 21 m/s. A major concern of the designer in maintaining efficient engine operation at these severe conditions is possible inlet internal boundary-layer separation. Separation free-flow is desirable to minimize both engine thrust losses and fan blade stresses.

The usual approach to achieving separation free inlet flow is to make the inlet lower lip thick enough to minimize the high surface velocities that occur on the lip as the flow is turned into the inlet. Another approach, however, is to use a thinner lip resulting in a shorter and lighter inlet plus some method of controlling the boundary layer. One such method is to blow a thin jet of high-pressure air tangentially into the boundary layer to re-energize it. Blowing is a particularly attractive method of inlet boundary-layer control because a source of high-pressure air is readily available from the engine.

First, the paper presents the results of an experimental investigation of tangential blowing applied to a subsonic V/STOL inlet to maintain attached flow to high angles of attack, and a brief discussion of some criteria that might be used to select the appropriate values of the blowing design parameters. Second, a brief description is given of an analytical method for calculating the performance of tangential blowing boundary-layer control systems. Finally, a comparison is made between experimental and analytical results.

Test Facility and Experimental Model

The experimental investigation was conducted in the Lewis Research Center 2.74×4.58-m Low Speed Wind Tunnel, which is an atmospheric pressure facility with a freestream velocity range from 0 to 75 m/s. A photograph of the inlet/fan combination installed in the test section is shown in Fig. 1. The fan is a single-stage 0.508-m-diam design with 15 rotor blades that have a hub-to-tip ratio of 0.46. Fan pressure ratio is about 1.17 at the design rotational speed of 8020 rpm resulting in a tip speed of 213.5 m/s. The fan is driven by a four-stage turbine powered by high-pressure heated air delivered to the turbine through flow passages in the model support strut. A more complete description of the fan is given in Ref. 1.

The inlet angle of attack is varied by rotating the model in a horizontal plane about a vertical support post. The post provides a passage for the high-pressure turbine drive air which comes up through the tunnel floor. A vertical pipe that comes down through the tunnel ceiling and is mounted on swivel joint provides a passage for the high-pressure blowing

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air for inlet boundary-layer control. A portion of the adjacent tunnel vertical wall was removed to allow the fan and turbine exhaust to pass through the wind tunnel wall during high-angle-of-attack operation.

The inlet shown in Fig. 1 is an axisymmetric design with a lip contraction rate, A_{HL}/A_t, of 1.46. This results in a relatively thin lip inlet for subsonic V/STOL application where contraction ratios of 1.69 and 1.76 have been suggested (Refs. 2 and 3, respectively). The internal lip shape is elliptical with a major-to-minor axis ratio of 2.0. The inlet is 1.029 fan diameters long. Two blowing slot locations were investigated; one on the lip and the other in the diffuser.

Figure 2 shows the parameters that were varied during the investigation as well as the different blowing configurations. Six of the seven parameters that were varied are shown in Fig. 2a. Angle of attack α was varied from 0 to 110 deg, freestream velocity V_0 was varied from 18 to 62 m/s, throat velocity V_t was varied between 52 and 201 m/s (corresponding to throat Mach numbers between 0.15 and 0.60), blowing total pressure P_B was varied from 1.0 to 1.4 times freestream total pressure P_0, blowing temperature T_B was not a variable. Also varied were blowing slot height and circumferential extent, h and θ, respectively, as well be discussed in connection with Figs. 2b and 2c.

The seventh parameter that was varied was slot location. As previously mentioned, one slot was located on the lip and other was located in the diffuser. The lip slot was located as close to the highlight as practical ($X/D_F=0.008$, Fig. 2b). Two slot heights and three slot circumferential extents were investigated. A 0.0508-cm height slot ($h/D_F=1\times10^{-3}$) was tested at circumferential extends of 30, 60, and 120 deg; a 0.152-cm height slot ($h/D_F=3\times10^{-3}$) was tested at circumferential extents of 60, 90, and 120 deg. The diffuser slot was located as close to the inlet throat as practical ($X/D_F=0.20$). The two diffuser slot heights investigated were the same as those for the lip slot. Diffuser slot circumferential extent, however, was held constant at 120 deg.

Test Procedure

A major concern during the test was the safety of the fan, which meant that the fan blade stresses should not exceed their limiting value. The procedure for ensuring this is detailed in Ref. 3. Essentially it consisted of first setting a low freestream velocity and angle of attack with the fan operating at a low speed (~2000 rpm). Then a "safety sweep" of fan speed was made during which time the inlet passed from a worst condition to a better condition (i.e., from separated to attached flow). The sweep consisted of increasing the fan speed to about 6500 rpm (this corresponds to the upper value of throat velocities associated with landing transition maneuvers of subsonic V/STOL aircraft) while continuously monitoring blade stress levels to ensure that they remain below their limiting value.

Once the safety sweep established that the fan blade stresses remained below their limiting value, fan speed was decreased until flow separation occurred. Data were taken just before and after separation.

At each freestream velocity, angle of attack was increased in increments of 15 deg and the preceding procedure repeated until either the limiting value of blade stress or the desired angle of attack was reached. This process was repeated for increased freestream velocities. In this manner, the envelope of safe operating conditions for the baseline configuration was established.

This same operating envelope also was adhered to for the blowing tests. Thus, if some unforeseen event shut off the blowing air supply during the test, fan blade stresses would still remain below their limiting value. The procedure for the blowing test was the same as that for the nonblowing tests, with the exception that blowing pressure ratio was set with freestream velocity and angle of attack. Note that utilizing the same operating envelope for the blowing tests as for the nonblowing tests meant that sometimes the separation boundary for the blowing configuration was not achieved because the upper limit on angle of attack was set by the nonblowing configuration.

Experimental Results

Nonblowing Correlating Parameter

Before discussing the effect of blowing, a parameter for correlating separation bounds for inlets without blowing will be described. This parameter is the ratio of inlet throat velocity to freestream velocity, V_t/V_0. How well it correlates the data for the baseline inlet (no slot) is shown in Fig. 3. The

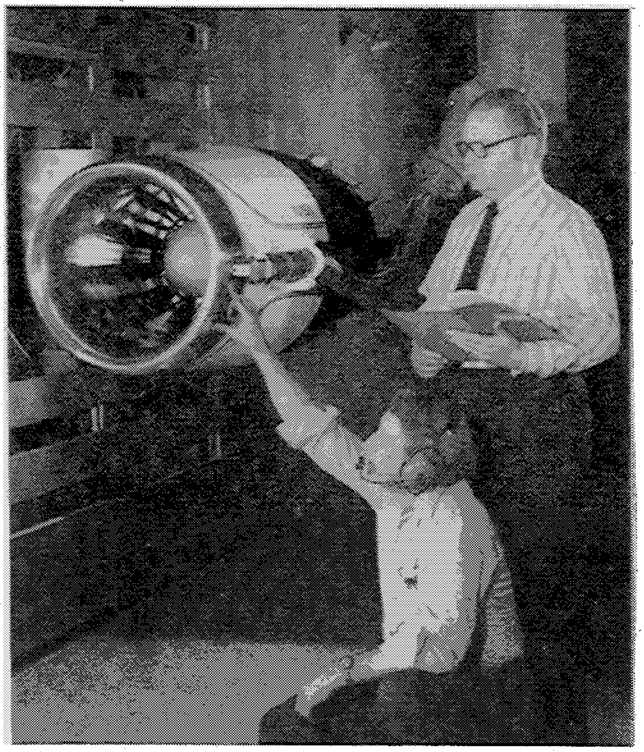

Fig. 1 0.508-m-diam fan/inlet installed in V/STOL tunnel.

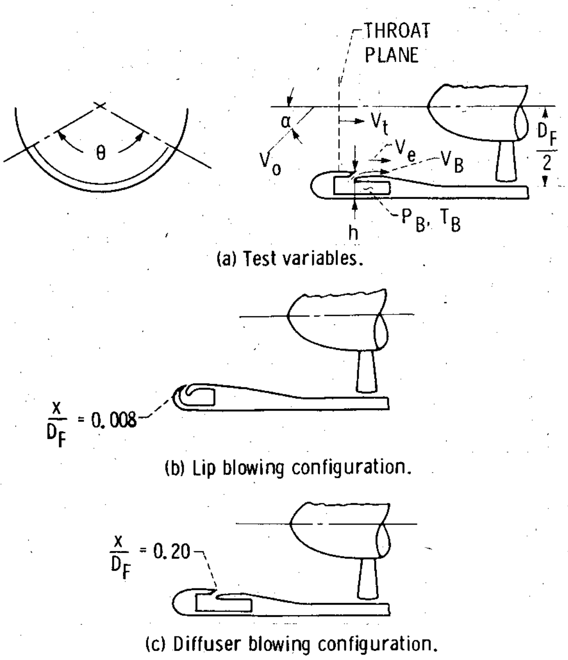

Fig. 2 Test variables and blowing configurations.

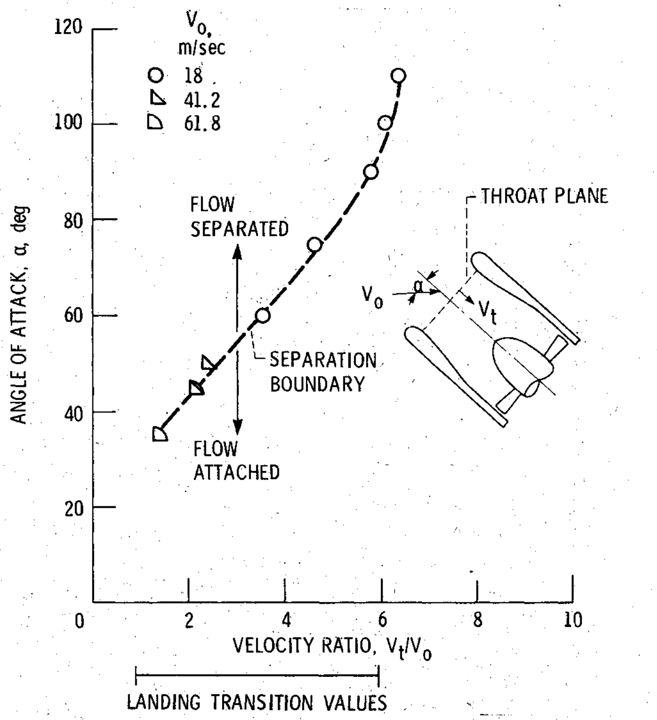

Fig. 3 Flow separation boundaries for baseline (no slot) configuration.

results are presented in terms of the angle of attack α at which flow separation occurs as a function of the velocity ratio V_t/V_0 for a range of freestream velocities that might be encountered during the takeoff and landing maneuvers of V/STOL aircraft.

As can be seen from Fig. 3, the velocity ratio successfully correlates the results for the baseline inlet. The dashed curve in the figure represents the flow separation boundary for the inlet. Below the curve the flow is attached; above the curve it is separated. This correlating parameter also has been successfully applied to other inlet geometries without boundary-layer control devices.[3] Moreover, as will be shown later, this parameter also correlates the results for inlet configurations that have the blowing slot closed. It should be noted that for all of the results in this paper the inlet maximum internal surface velocity was always subsonic. This is an important point because the V_t/V_0 correlating parameter is applicable only as long as no shocks are present in the internal flow.[4]

Also shown on the abscissa of Fig. 3 is a range of values for the velocity ratio that might be encountered during the landing transition of the tilt-nacelle VTOL aircraft.[2] At the start of this transition manuever the fan is at part throttle (i.e., the throat velocity is low), because the thrust was reduced to decrease the aircraft speed from cruise conditions. During the landing transition maneuver the aircraft continues to slow down but the throat velocity now increases as the aircraft makes the transition from wing-borne to thrust supported operation. The combination of an increase in throat velocity and a decrease in freestream velocity results in an increase in velocity ratio during this maneuver. According to Ref. 2, the velocity ratio could increase from 0.85 to 6.0.

Effect of Blowing Location

The effect of blowing slot location, i.e., on the lip or in the diffuser, on the flow separation boundary is shown in Fig. 4 for a blowing slot height of 0.0508 cm ($h/D_F = 1\times10^{-3}$) and a slot circumfernial extent of 120 deg. Results are shown in Fig. 4a at a blowing pressure ratio P_B/P_0 of 1.0, in Fig. 4b at a blowing pressure ratio of 1.2, and in Fig. 4c at a blowing pressure ratio of 1.4. The open symbols denote data points for lip blowing and the solid symbols denote data points for

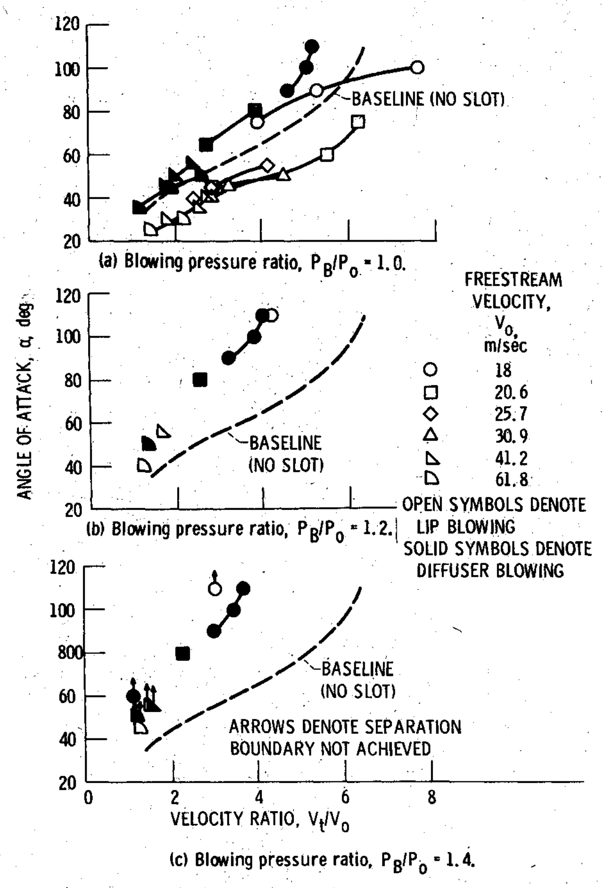

Fig. 4 Effect of blowing location on separation boundary; $h/D_F = 1\times10^{-3}$, $\theta = 120$ deg.

diffuser blowing. It should be noted tha a blowing pressure ratio of 1.0, i.e., when blowing total pressure is equal to freestream total pressure, still denotes blowing.

As indicated in Fig. 4, lip and diffuser blowing were effective in maintaining attached flow to high angles of attack. Diffuser blowing (solid symbols) was more effective at the low value of blowing pressure ratio, $P_B/P_0 = 1.0$ (Fig. 4a). Lip blowing (open symbols) is less effective at this pressure ratio due to the adverse effect of the lip slot itself as will be explained later. As blowing pressure ratio increases to 1.2, lip blowing becomes as effective as diffuser blowing (Fig. 4b). At the high value of blowing pressure ratio, $P_B/P_0 = 1.4$, lip blowing becomes more effective than diffuser blowing at high velocity ratios (Fig. 4c). At this blowing pressure ratio the full benefit of lip blowing at the highest angle of attack, as well as both lip and diffuser blowing at the low angles of attack, could not be demonstrated (symbols with arrow pointing up). The separation boundary could not be determined and still stay within the envelope of safe operating conditions (see discussion of procedure).

The decrease in the effectiveness of diffuser blowing relative to lip blowing with increasing blowing pressure ratio is probably the result of where flow separation is located within the inlet. As the inlet angle of attack is increased with no blowing, separation probably starts in the diffuser and not on the lip. This is inferred from the fact that diffuser blowing is effective and the fact that blowing downstream of where the flow separates generally is not effective.[5] Moreover, the analytical results, which will be discussed later, indicate that flow separation is located in the diffuser. Hence, the separation must be occurring downstream of the diffuser blowing slot in the inlet diffuser. (Where separation started in the inlet had to be inferred because the slow responding steady-state measurements of lip and diffuser separation indicated that flow separation on the lip and in the diffuser occurred at essentially the same time). Applying a sufficiently high diffuser blowing pressure ratio as inlet angle of attack is increased can completely eliminate diffuser separation. At the higher angles of attack, however, further increases in diffuser blowing pressure ratio are not effective because the diffuser is no longer the critical element. Instead, at the higher angles of attack separation occurs on the lip and this, of course, cannot be eliminated by blowing in the diffuser. To eliminate this flow separation problem requires blowing in the lip. And by increasing the lip blowing pressure ratio, inlet angle-of-attack capability can be increased beyond that which can be achieved by diffuser blowing. Moreover, the results in Fig. 4 indicate that blowing on the lip not only can eliminate lip separation but it can also eliminate diffuser separation. Thus, higher angle-of-attack capability can be achieved by lip blowing than by diffuser blowing because at higher angles of attack the separation point moves upstream to the inlet lip.

As previously mentioned, there is an adverse effect on the slot when it is located on the lip but no significant effect when the slot is located in the diffuser. This is shown in Fig. 5a where the flow separation boundaries for the lip slot closed configuration (open symbols), the diffuser slot closed configuration (solid symbols), and the baseline configuration (i.e., no slot, dashed line) are compared. (The slot was closed in a way that formed a rearward facing step.) The separation boundary for the diffuser slot closed configuration is essentially the same as that for the baseline configuration, indicating no effect of the diffuser slot. The separation boundary for the lip slot closed configuration, however, is considerably less than that for the no slot configuration, indicating the adverse effect of the lip slot. The reason for this will be explained shortly.

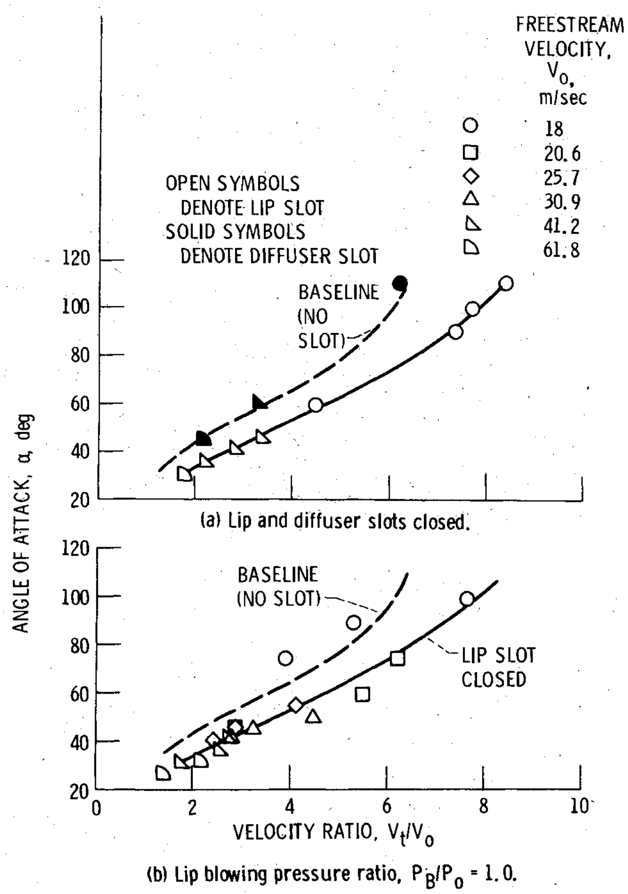

Fig. 5 Effect of closed slots on separation boundary and comparison of lip slot closed results with lip blowing at a pressure ratio of 1.0; $h/D_F = 1 \times 10^{-3}$, $\theta = 120$ deg.

This same effect accounts for the reduction in the separation boundary with lip blowing at a blowing pressure ratio of 1.0 that was shown in Fig. 4a. To explain this further a comparison is made in Fig. 5b of lip blowing at a blowing pressure ratio of 1.0 with the lip slot closed configuration (solid line). Also shown is the baseline configuration (dashed line). The symbols, which denote the lip blowing results, generally have the same separation boundary as that for the lip closed configuration. Consequently, lip blowing at this blowing pressure ratio does not re-energize the boundary layer enough to overcome the adverse effect of the lip slot. The result is that lip blowing is not as effective as diffuser blowing at the low value of blowing pressure ratio.

The adverse effect of the lip slot is composed of two parts. One part can be seen by examining the axial distribution of internal surface static pressures on the windward side of the inlet. Figure 6 compares this pressure distribution for the baseline configuration and the small lip slot closed configuration. For both configurations, the minimum value of static pressure occurs at the highlight (i.e., at $x/L = 0.0$). The lip slot closed configuration, however, has a lower value for this minimum static pressure which results in an increase in the already steep adverse pressure gradient downstream of the lip slot. This, in turn, increases the tendency of the flow to separate from the lip slot closed configuration compared to the baseline configuration. An increase in the curvature of the lip slot closed configuration in the region of the highlight compared with that of the baseline configuration could be responsible for the observed effect. No such effect was observed for the diffuser slot closed configuration.

The other part of the adverse effect of the lip slot is due to the fact that at the lip slot the flow separates as it passes over the rearward facing step formed by the closed slot and then reattaches at some distance downstream. Based upon Ref. 6, it is reasonable to assume that at the location where flow reattachment occurs, the boundary-layer profile is relatively "weak" compared with the profile that exists at this location for the baseline configuration. Also, as already mentioned, a very steep adverse pressure gradient exists downstream of the lip slot. Consequently, the "weak" profile associated with the lip slot configuration is much more likely to separate due to this steep adverse gradient than is the profile associated with the baseline configuration. Both parts of the adverse effect of the lip slot contribute to the lower separation boundary shown in Fig. 5a for the lip slot closed configuration compared to the separation boundary for the baseline configuration.

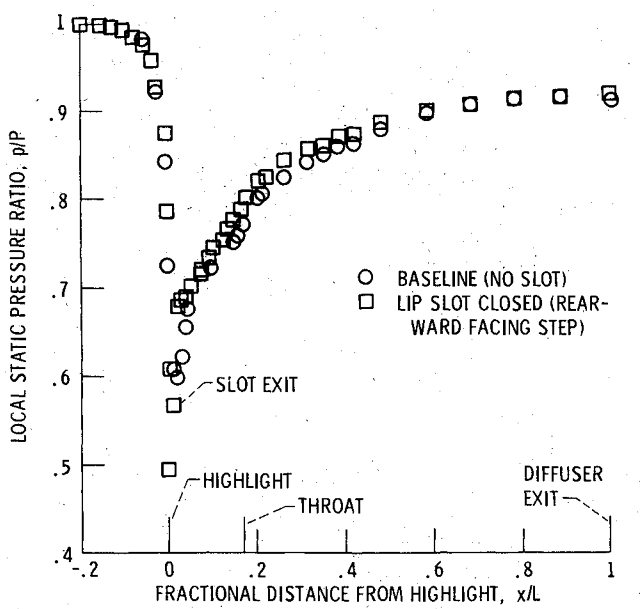

Fig. 6 Effect of lip slot on windward surface static pressure distribution; $\alpha = 110$ deg, $V_0 = 18$ m/s, $h/D_F = 1 \times 10^{-3}$.

In contrast to the lip slot, the diffuser slot is located downstream of the adverse pressure gradient. At the location where flow reattachment occurs due to the rearward facing step formed by the diffuser slot, the boundary-layer profile probably is not much "weaker" than the profile that exists at this location for the baseline configuration. Both have had to overcome the same adverse pressure gradient shown in Fig. 6. Thus, the diffuser slot would not be expected to have much effect on the inlet flow separation boundary.

Effect of Lip Slot Circumferential Extent

As previously discussed, higher angle-of-attack capability can be achieved by lip blowing than by diffuser blowing. Therefore, the remainder of the paper will present further details of the aerodynanmic performance of the inlet with lip blowing.

The lip blowing results presented so far have been for a slot circumferential extent of 120 deg (±60 deg from the windward plane). The effect of changing the lip slot circumferential extent on the flow separation boundary is shown in Fig. 7. Also shown is the separation boundary for the baseline configuration (dashed line). The results are presented for the smaller lip slot height of 0.0508 cm ($h/D_F = 1 \times 10^{-3}$) at a blowing pressure ratio of 1.4. The circumferential extent of the slot was varied by closing the slot to minimize the change in the contour of the internal surface in the vicinity of the slot rather than causing a rearward facing step to occur.

As the figure indicates, a lip slot circumferential extent of greater than 30 deg was necessary for blowing to be effective. Blowing through a slot circumferential extent of 120 deg resulted in a very high angle-of-attack capability for the inlet. At a throat-to-freestream velocity ratio of 3.0 (which, as already mentioned, is representative of an operating condition that might be encountered during the landing phase of a V/STOL aircraft), the no slot configuration, as well as the inlet with a 30 deg extent of blowing, was capable of achieving an angle of attack of only 55 deg. Increasing the circumferential extent of blowing to 60 deg looks like it would increase the flow separation angle to about 70 deg; and blowing through a slot circumferential extent of 120 deg increased the angle-of-attack capability to at least 110 deg.

The reason for this improvement with increasing circumferential extent of blowing can be explained by examining the circumferential variation of the diffusion velocity ratio shown in Fig. 8. Diffusion velocity ratio is defined as the ratio of maximum-to-diffuser exit surface velocities. The results shown in this figure were obtained from the potential flow analysis method described in Ref. 7. The diffusion velocity ratio parameter can be used as an indicator of whether separation is likely to occur. Previous experimental results[4] indicated that separation would occur in this inlet when the ratio exceeded a value of about 2.7.

The analytical circumferential variation of diffusion velocity ratio is shown in Fig. 8 for three angles of attack at a throat-to-freestream velocity ratio of 2.5. The limiting value of the diffusion velocity ratio, 2.7, is shown in the figure and illustrates that the circumferential extent of the separated region increases with increasing angle of attack. At an angle of attack of 50 deg no separation would occur since the maximum value of diffusion velocity ratio was below 2.7. At an angle of attack of 75 deg, however, separation would occur and the region of separation would extend about 50 deg on either side of the windward plane ($\psi = 0$ deg). At an angle of attack of 110 deg, the region of separation would extend about 70 deg on either side of the windward plane. Thus, to prevent flow separation at high angles of attack requires blowing through a lip slot that has a large circumferential extent. For example, to avoid flow separation at an angle of attack of 110 deg, the blowing slot would have to extend over at least 120 deg of the lip circumference.

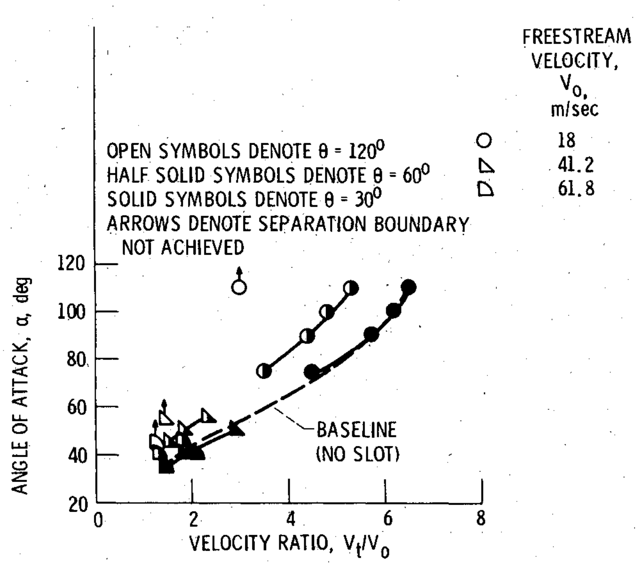

Fig. 7 Effect of lip slot circumferential extent on separation boundary; $h/D_F = 1 \times 10^{-3}$, $P_B/P_0 = 1.4$.

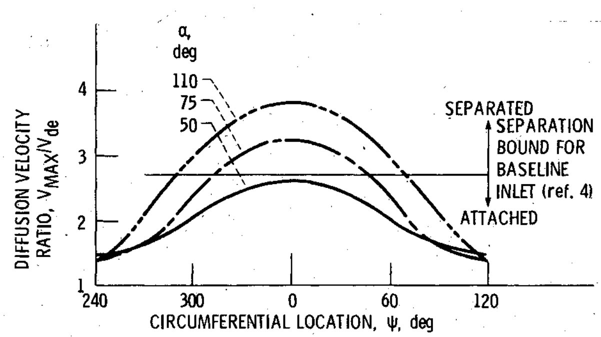

Fig. 8 Analytical circumferential variation of diffusion velocity ratio, $V_t/V_0 = 2.5$.

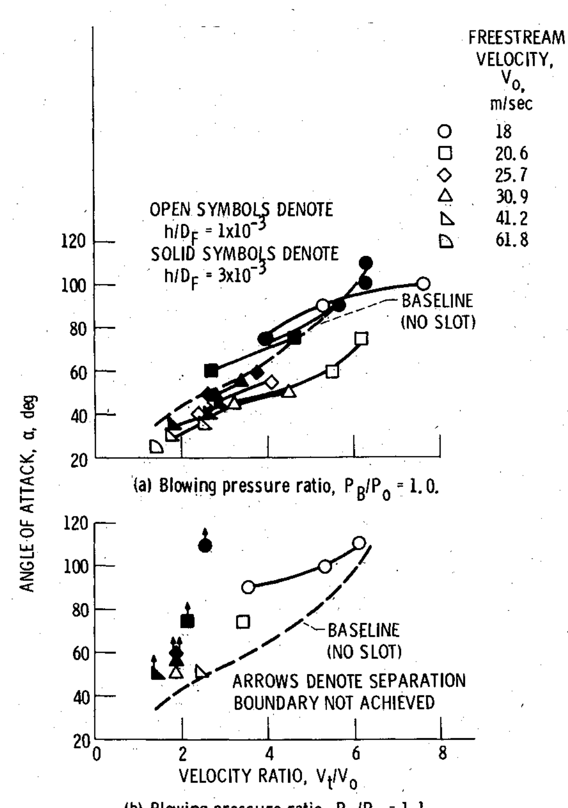

Fig. 9 Effect of lip slot height on separation boundary, $\theta = 120$ deg.

Effect of Lip Slot Height

The effect of blowing through different lip slot heights on the flow separation boundary is shown in Fig. 9 for a slot circumferential extent of 120 deg. At blowing pressure ratios of 1.0 and 1.1 (Figs. 9a and 9b, respectively), blowing through the larger slot height ($h = 0.152$ cm, solid symbols) was more effective than blowing through the smaller slot height ($h = 0.0508$ cm, open symbols).

As previously mentioned, blowing through the smaller lip slot height at a low blowing pressure ratio does not re-energize the boundary layer enough to overcome the adverse effect of the slot. However, blowing through the larger lip slot height at the same conditins (i.e, same values for freestream velocity, angle of attack, blowing pressure ratio, and throat Mach number) triples the amount of momentum injected into the boundary layer. Having the same flow conditions for both slot heights (i.e., freestream velocity and inlet mass flow) means that at any angle of attack the blowing jet velociy was the same. Changing the slot height resulted in changing only the mass flow rate. The mass flow rate tripled because the larger slot height has a slot area three times that of the smaller slot height.

Comparison of Nonblowing and Lip Blowing

A comparison of nonblowing and lip blowing results is shown in Fig. 10. The separation boundary of the relatively thin lip inlet (CR = 1.46) with and without lip blowing is compared to the separation boundary of an inlet having a relativley thick lip (CR = 1.69, Ref. 2) and no blowing.

As indicated, lip blowing utilizing the larger slot height ($h/D_F = 3 \times 10^{-3}$) at a blowing pressure ratio of 1.1 (solid symbols), can at some conditions double the angle-of-attack capability of the baseline inlet (dashed line). Furthermore, this lip blowing configuration is as effective and, in some cases, more effective in achieving high angle-of-attack capabilty than using the thick lip inlet (dashed-dotted line). For example, at a throat-to-freestream velocity ratio V_t/V_0 of 2.5, the relatively thin lip baseline inlet was capable of achieving an angle of attack of only 50 deg. Lip blowing increased this capability to 110 deg. By comparison, the thick lip inlet achieved an angle of attack of 82 deg at the same velocity ratio of 2.5.

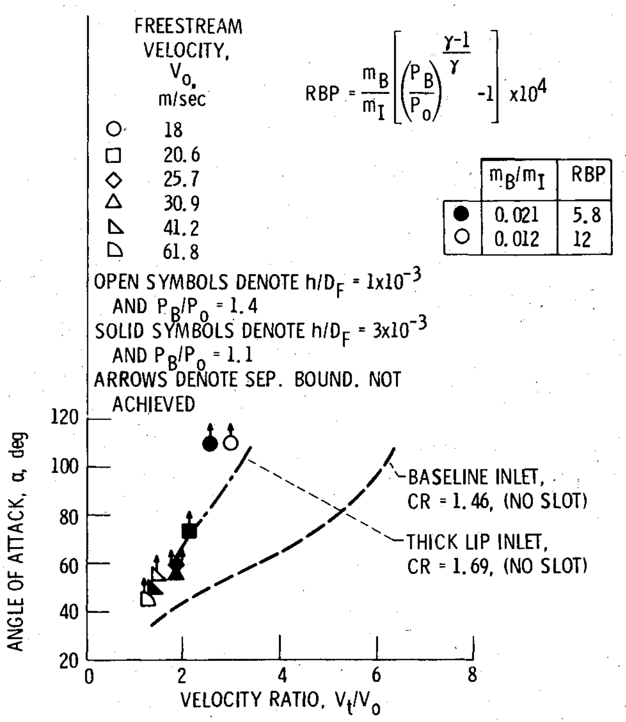

Fig. 10 Comparison of nonblowing and lip blowing.

The final decision about whether to use a thick lip or a thinner lip with blowing is beyond the scope of this paper. It requires analyzing the entire nacelle, not just the inlet. With the thick lip, of course, there is no question of reliability. However, with the thinner lip it is possible to reduce the nacelle length by shortening the diffuser. (The thinner lip results in an increased throat area which means less diffusion is required.) The thinner lip and the shorter diffuser then result in a lighter weight nacelle with lower drag at cruise conditions, thereby increasing the aircraft payload.

Penalties associated with the blowing system would reduce, but not necessarily eliminate, the payload benefit. Weight penalties would be associated with hardware for ducting the blowing air from the core engine and also for ensuring a highly reliable blowing system. Some thrust penalty would also be assessed the blowing system for bleeding air from the core engine. These factors, in addition to those presented in this paper, must be considered before deciding whether to use lip blowing to attain the required inlet angle-of-attack capability.

Some Criteria for Selecting Lip Blowing Parameters

The same angle-of-attack capability achieved by blowing through the larger lip slot height with a blowing pressure ratio of 1.1 can, of course, also be achieved by blowing through the smaller lip slot height. However, to accomplish this requires increasing the blowing pressure ratio to a value of about 1.4 as shown in Fig. 10 by the open symbols. Since essentially the same angle-of-attack capability can be achieved by blowing through either lip slot height, some criterion is needed to choose between them. One criterion is relative blowing power (RBP). The equation used for calculating RBP is shown in Fig. 10. It is a nondimensional parameter that represents the ratio of the ideal amount of power required to increase the pressure of the blowing air from freestream total conditions to the desired value P_B divided by the ideal amount of power in the inlet air stream. Note that when the blowing total pressure P_B is equal to the freestream total pressure P_0 the relative blowing power is zero. This means that ram air can be used as the source of the blowing air and, consequently, no power from the propulsion system is needed.

The equation also shows that, at the low blowing pressure ratios, blowing power is much more sensitive to changes in blowing pressure ratio than it is to changes in blowing mass flow ratio (blowing mass flow divided by inlet mass flow). Thus, it is more efficient (i.e., requires less power) to re-energize the boundary layer using a high blowing mass flow ratio at a low blowing pressure ratio than vice versa. It is on this basis that the large lip slot height configuration would be chosen. The results shown in the small table in Fig. 10 confirm

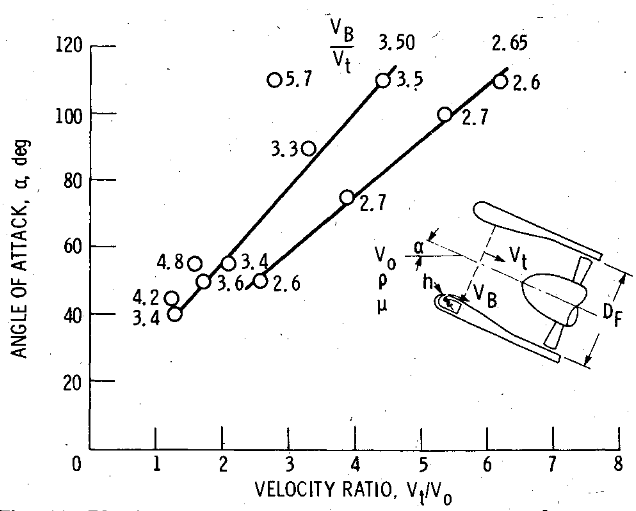

Fig. 11 Blowing correlating parameter; $h/D_F = 1 \times 10^{-3}$, $\theta = 120$ deg.

this. In order to achieve the same angle-of-attack capability, the smaller slot height required a blowing mass flow ratio of about 0.012 at a blowing pressure ratio of 1.4, while the larger slot height required a blowing mass flow ratio of about 0.021 at a blowing pressure ratio of 1.1. This resulted in the larger slot height requiring only about half the relative blowing power of the smaller slot height (5.8 vs 12).

Besides relative blowing power, another criterion that could be used to choose between the two lip heights is whether the air required for blowing can realistically be bled from the core-compressor. According to Ref. 8, a blowing mass flow ratio of 0.009 and a blowing pressure ratio of 2.6 are well within the bleed capability of the contemporary core-compressor. Based on this criterion the smaller lip slot height would be selected. It requires a blowing mass flow ratio of only 0.012 at a blowing pressure ratio of 1.4. The larger mass flow ratio required for blowing through the larger slot height ($m_B/m_I=0.021$) falls far outside the core-compressor bleed capability reported in Ref. 8.

However, the low blowing pressure ratio ($P_B/P_0=1.1$) associated with the larger lip slot height raises the possibility that the required air could be bled off downstream of the fan rather than from the core-compressor. To achieve this means that when the fan is throttled back during the landing maneuver the fan total pressure ratio must stay above a value of 1.1 (at least in the region where the air is bled off). It also imples that, to some extent, the fan operational characteristics are influenced by the separation characteristics of the inlet, because when the fan is throttled back to a pressure ratio of about 1.1 the fan airflow must remain high enough so that inlet flow separation does not occur. Thus, blowing through the larger lip slot height to keep the blowing power requirement low probably means that the blowing air is supplied from the fan, and that the fan operational characteristics are influenced, to some extent, by the separation characteristics of the inlet.

Blowing Correlating Parameter

The potential correlating parameter to be examined is the ratio of blowing velocity to inlet throat velocity, V_B/V_t. It was derived by applying the Buckingham Pi theorem for dimensional analysis. The result was that the angle of attack α at which flow separation occurred became a function of four dimensionless parameters:

$$\alpha=f\left[\frac{V_0}{V_t},\ \frac{V_B}{V_t},\ \frac{1}{R_{\mathrm{de}}},\ \frac{h}{D_F}\right]$$

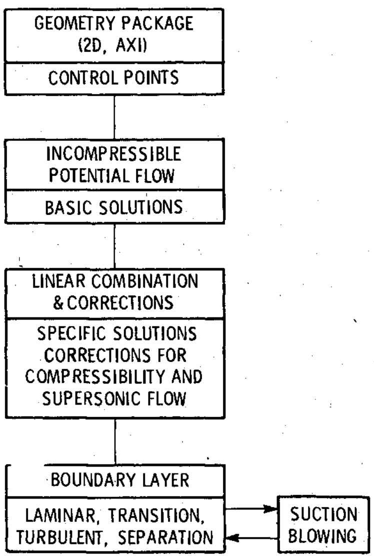

Fig. 12 Schematic diagram of inlet flow prediction computer programs.

By neglecting the Reynolds number effect R_{de} and by assuming h/D_F to be constant, the relationship reduces to

$$\alpha=g\left[\frac{V_0}{V_t},\ \frac{V_B}{V_t}\right]$$

This relationship must be applied to each blowing geometry since h/D_F is assumed to be constant. For the baseline inlet (i.e., the inlet with no blowing slot), the relationship reduces to

$$\alpha=j\left[\frac{V_0}{V_t}\right]$$

This correlation is shown in Fig. 3.

How successfully the relationship correlates the blowing results is shown in Fig. 11. The data are from the inlet configuration with lip blowing through the smaller slot height ($h/D_F=1\times10^{-3}$) and the largest slot circumferential extent ($\theta=120$ deg). Values of the correlating parameter V_B/V_t range between 2.6 and 5.7. Very few data points have the same value of V_B/V_t because of the procedure for acquiring the data. However, preliminary indications are that the parameter successfully correlates the data as evident from the lines of constant V_B/V_t drawn through the data. This was true not only for the particular blowing geometry shown, but also for all blowing geometries investigated with this inlet. Further investigations specifically designed to test this correlation are needed before a final determination of its validity can be made.

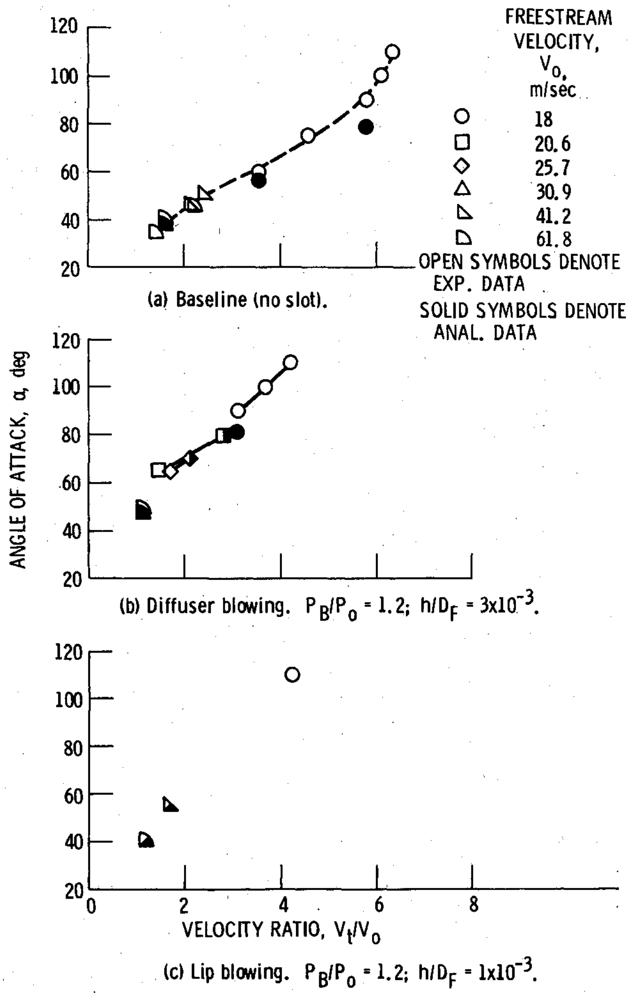

Fig. 13 Comparison of experimental and analytical separation bounds, $\theta=120$ deg.

Analytical Method

As previously mentioned, an analytical method has been developed that can calculate the performance of V/STOL inlets that utilize tangential blowing for boundary-layer control. It consists of a series of computer progams developed at the NASA Lewis Research Center. A flowchart depicting the sequence for using these programs is presented in Fig. 12. All programs start with the geometry program which creates the discrete control points for each geometric configuration. Then the incompressible potential flow program is used to calculate the basic solutions to the problem. These basic solutions are combined into a solution that satisfies the desired inlet operating conditions of freestream velocity, angle of attack, and inlet mass flow. Next, the incompressible flow is corrected for compressibility and supersonic effects. The compressible potential flow solution is then used as an input to the two-dimensional, compressible, boundary-layer program which calculates the laminar, transition, and turbulent boundary-layer characteristics, and predicts flow separation. A recent extension to this boundary-layer program allows the performance of suction and tangential boundary-layer control concepts to be calculated.[9] A more complete description of the analytical method utilizing suction and tangential blowing is given in Ref. 7.

Comparison of Analytical and Experimental Results

Separation Boundaries

A comparison of analytical and experimental separation boundaries is given in Fig. 13 for three inlet configurations: the baseline configuration (Fig. 13a); the diffuser blowing configuration with the larger slot height (Fig. 13b); and the lip blowing configuration with the smaller slot height (Fig. 13c). The blowing results are shown for a blowing pressure ratio of 1.2 and a blowing circumferential extent of 120 deg.

For all three configurations the predicted (i.e., analytical) and experimental separation boundaries agree well at the lower velocity ratios, i.e., at angles of attack below 90 deg. For the baseline configuration at a velocity ratio of 5.8 the predicted boundary was about 10 deg low. The reason for this is not yet completely understood but, because of this discrepancy, no attempt was made to predict separation boundaries for the two blowing configurations at angle of attack greater than 90 deg.

For the diffuser blowing configuration at a velocity ratio of 3.2 the predicted result also was about 10 deg low. This is attributed to the fact that the predicted location of flow separation differs from experimental location. This does not cause a significant difference between the predicted and experimental separation boundaries as long as both the predicted and experimental separation locations occur downstream of the diffuser blowing slot. However, at high angles of attack, the predicted separation location occurs upstream of this slot. The analytical calculations cannot be done beyond the separation point. Therefore, the angle of attack is reduced in order to move the separation location downstream of the blowing slot. The analytical separation boundary then falls below the experimentally determined boundary.

As previously mentioned, the analytical method for predicting internal flow separation with tangential blowing utilizes a two-dimensional blowing jet. Thus the analytical results are strictly applicable only in one plane; namely, the windward plane of the inlet. The good agreement between predicted and experimental separation boundaries at angles of attack below 90 deg implies that internal flow separation starts in the windward plane rather than at some other circumferential location.

At other angles of attack and blowing pressure ratios, internal flow separation might also occur first in the windward plane. However, it may also be possible for the flow to separate at some other circumferential location. This can be explained by referring to Fig. 8 and noting that the diffusion velocity ratio is a measure of the adverse pressure gradient. When the inlet is at an angle of attack greater than 0 deg there is a circumferential variation in internal static pressures in the forward part of the inlet resulting in a circumferential vairation in the adverse pressure gradient, with the steepest gradient occurring in the windward plane. At very high angles of attack, a considerable circumferential extent of the flow must diffuse through an adverse pressure gradient greater than that required for separation to occur (i.e., above $V_{max}/V_{de}=2.7$). At each circumferential location, the amount of momentum required to re-energize the boundary layer sufficiently to maintain attached flow is different, and is proportional to the magnitude of the pressure gradient above the value where flow separation is likely to occur. Thus, there is a circumferential variation in the amount of momentum required to keep the boundary layer attached with the greatest amount required in the windward plane.

Also, when the inlet is at angle of attack, the circumferential variation in inlet surface static pressure combined with a constant blowing total pressure results in a circumferential variation in total-to-static blowing pressure ratio at the exit of the blowing slot. Thus there is a circumferential variation in the amount of momentum injected into the boundary layer, with the greatest amount injected at the windward plane.

The necessary condition for attached flow is that the amount of momentum injected at each circumferential location must be at least equal to the amount of momentum required at each circumferential location. As just discussed, the circumferential variation in injected momentum has a trend similar to the circumferential variation in required momentum. However, there is no guarantee that at each circumferential location the proper amount of momentum will be injected to ensure the attachment of the boundary layer. Consequently, it is not obvious at which circumferential location flow separation would start and, therefore, some of the discrepancy between experimental and analytical results that occur at the higher angles of attack (see Fig. 13b) may be a result of the analytical calculations being applicable only at the windward location.

In addition to predicting the inlet flow separation bounds, the analytical method was used to predict the boundary-layer velocity profiles both with and without blowing. In general these results agree very well with measured velocity profiles.

Summary of Results

Experimental and analytical investigations were conducted to evaluate the effectiveness of tangential blowing in preventing internal flow separation over the range of operating conditions likely to be encountered by inlets for subsonic V/STOL aircraft. The results of the investigation can be summarized as follows.

Experimental:

1) Both lip and diffuser blowing were effective in maintaining attached flow to high angles of attack.

2) Higher angle-of-attack capability was achieved by lip blowing rather than by diffuser blowing.

3) The angle-of-attack operating range of this inlet was, at some conditions, doubled by utilizing lip blowing.

4) Lip blowing was effective using either of the two slot heights. Using the larger lip slot height required less power. The boundary layer lip slot height required less power. The boundary layer was more efficiently re-energized using a high blowing mass flow at a low blowing velocity than using a low blowing mass flow at a high blowing velocity.

5) To increase the angle-of-attack capability of this inlet required increasing the circumferential extent of lip blowing. Lip blowing had to cover a circumferential extent of 120 deg to maintain attached flow at the highest angles of attack.

6) The ratio of blowing velocity to inlet throat velocity, V_B/V_t, successfully correlates the blowing results for a given blowing geometry (i.e., fixed slot height, location, and circumferential extent).

Analytical:

1) For both nonblowing and blowing configurations, the analytical and experimental flow separation boundaries agree well at angles of attack below 90 deg.

2) At the lower angles of attack, the analytical and experimental boundary-layer velocity profiles show good agreement at the two inlet axial locations where comparisons were made.

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