NASA Technical Memorandum 82847

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(NASA-TM-82847) EXPERIMENTAL AND ANALYTICAL RESULTS OF TANGENTIAL BLOWING APPLIED TO A SUBSONIC V/STOL INLET (NASA) 18 p HC A02/MF A01 CSCL 01A

N82-24165

Unclas G3/02 09905

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Prepared for the
Eighteenth Joint Propulsion Conference
cosponsored by the AIAA, SAE, and ASME
Cleveland, Ohio, June 21-23, 1982

NASA

E-1217

EXPERIMENTAL AND ANALYTICAL RESULTS OF TANGENTIAL BLOWING APPLIED TO A SUBSONIC V/STOL INLET

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Abstract

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 was 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 height
h blowing slot height
L inlet length
m mass flow rate
P total pressure
p static pressure
R Reynolds number
RBP relative blowing power,

$$\frac{m_B}{m_I}\left[\left(\frac{P_B}{P_o}\right)^{\frac{\gamma-1}{\gamma}} - 1\right] \times 10^4$$

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
o free stream
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° at flight speeds of 21 meters per second. 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 reenergize 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.

The paper first 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's 2.74- by 4.58-meter Low Speed Wind Tunnel, which is an atmospheric pressure facility with a free-stream velocity range from 0 to 75 meters per second. A photograph of the inlet/fan combination installed in the test section is shown in figure 1. The fan is a single stage 0.508 meter diameter 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 meters per second. 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 reference 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 a swivel joint provides a passage for the high pressure blowing 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 figure 1 is an axisymmetric design with a lip contraction ratio, 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 figure 2(a). Angle-of-attack, α, was varied from 0° up to 110°; free-stream velocity, V_0, was varied from 18 to 62 meters /sec, throat velocity, V_t, was varied between 52 and 201 meters/sec. (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 free-stream 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 will be discussed in connection with figures 2(b) and (c).

The seventh parameter that was varied was slot location. As already mentioned, one slot was located on the lip and the other was located in the diffuser. The lip slot was located as close to the highlight as practical (X/D_F = 0.008 fig. 2(b)). Two slot heights and three slot circumferential extents were investigated. A 0.0508-cm height slot ($h/D_F = 1x10^{-3}$) was tested at circumferential extents of 30°, 60° and 120°; a 0.152-cm height slot ($h/D_F = 3x10^{-3}$) was tested at circumferential extents of 60°, 90°, and 120°. The diffuser slot was located as close to the inlet throat as practical (h/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°.

Also shown in figures 2(b) and (c) are two total pressure rakes, one just downstream of the diffuser slot and the other just upstream of the fan face. Comparisons of experimental and analytical boundary layer velocity profiles are made at these locations.

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 reference 3. Essentially it consisted of first setting a low free stream 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 passes 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 assure 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 free stream velocity, angle-of-attack was increased in increments of 15° and the above procedure repeated until either the limiting value of blade stress or the desired angle-of-attack was reached. This process was repeated for increased free stream 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 unforseen 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 no blowing tests with the exception that blowing pressure ratio was set along with free stream velocity and angle-of-attack. Note that utilizing the same operating envelope for the blowing tests as for the non-blowing 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 non-blowing configuration.

Experimental Results

Non-Blowing 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 free stream velocity, V_t/V_0. How well it correlates the data for the baseline inlet (no slot) is shown in figure 3. The results are presented in terms of the angle-of-attack at which flow separation occurs, α, as a function of the velocity ratio, V_t/V_0, for a range of free stream velocities that might be encountered during the takeoff and landing maneuvers of V/STOL aircraft.

As can be seen from figure 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, the flow is separated. This correlating parameter also has been successfully applied to other inlet geometries without boundary layer control devices (ref. 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 (ref. 4).

Also shown on the abscissa of figure 3 is a range of values for the velocity ratio that might be encountered during the landing transition of a tilt-nacelle VTOL aircraft (ref. 2). At the start of this transition maneuver, 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 transitions from wing-borne to thrust supported operation. The combination of an increase in throat velocity and a decrease in free stream velocity results in an increase in velocity ratio during this maneuver. According to reference 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 figure 4 for a blowing slot height of 0.0508 cm (h/D_F = 1x10^{-3}) and a slot circumferential extent of 120°. Results are shown in figure 4(a) at a blowing pressure ratio, P_B/P_0, of 1.0; in figure 4(b) at a blowing pressure ratio of 1.2; and in figure 4(c) 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 diffuser blowing. It should be noted that a blowing pressure ratio of 1.0, i.e., when blowing total pressure is equal to free stream total pressure, does denote blowing since the static pressure at the exit of the blowing slot is below free stream total pressure.

As indicated in figure 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. 4(a)). 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 increased to 1.2, lip blowing becomes as effective as diffuser blowing (fig. 4(b)). 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. 4(c)). 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 (ref. 5). Moreover, the analytical results, which will be discussed later, indicate that flow separation is located in the diffuser. Hence, the separation must be occuring 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 on 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 figure 4 indicate that blowing on the lip not only can eliminate lip separation 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 of 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 figure 5(a) 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.

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 figure 4(a). To further explain this, a comparison is made in figure 5(b) 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 reference 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, a very steep adverse pressure gradient exists downstream of the lip slot as already mentioned. 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 figure 5(a) for the lip slot closed configuration compared to the separation boundary for the baseline configuration.

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 figure 6. Thus, the diffuser slot would not be expected to have much effect on the inlet flow separtion 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 aerodynamic performance of the inlet with lip blowing.

The lip blowing results presented so far have been for a slot circumferential extent of 120° (± 60° from the windward plane). The effect of changing the lip slot circumferential extent on the flow separation boundary is shown in figure 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 = 1×10^{-3}) at a blowing pressure ratio of 1.4. The circumferential extent of the slot was varied by closing the slot so as 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° was necessary for blowing to be effective. Blowing through a slot circumferential extent of 120° resulted in a very high angle-of-attack capability for the inlet. At a throat-to free stream 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° extent of blowing were capable of achieving an angle-of-attack of only 55°. Increasing the circumferential extent of blowing to 60° looks like it would increase the flow separation angle to about 70°; and blowing through a slot circumferential extent 120° increased the angle-of-attack capability to at least 110°.

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 figure 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 reference 8. The diffusion velocity ratio parameter can be used as an indicator of whether separation is likely to occur. Previous experimental results (ref. 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 figure 8 for three angles-of-attack at a throat-to-free stream velocity ratio of 2.5. The limiting value of the diffusion velocity ratio, 2.7, is shown on 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°, no separation would occur since the maximum value of the diffusion velocity ratio was below 2.7. At an angle-of-attack of 75°, however, separation would occur and the region of separation would extend about 50° on either side of the windward plane (ψ = 0°). At an angle-of-attack of 110°, the region of separation would extend about 70° 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°, the blowing slot would have to extend over at least 120° of the lip circumference.

Effect of Lip Slot Height

The effect of blowing through different lip slot heights on the flow separation boundary is shown in figure 9 for a slot circumferential extent of 120°. At blowing pressure ratios of 1.0 and 1.1 (figs. 9(a) and (b), 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 already 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 conditions (i.e., same values for free stream 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., free stream velocity and inlet mass flow) means that at any angle-of-attack the blowing jet velocity 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 Non-Blowing and Lip Blowing

A comparison of non-blowing and lip blowing results is shown in figure 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 relatively thick lip (CR = 1.69: ref. 2) and no blowing.

As indicated, lip blowing utilizing the larger slot height (h/D_F = 3×10^{-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 capability than using the thick lip inlet (dash-dotted line). For example at a throat to free stream 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°. Lip blowing increased this capability to 110°. By comparison, the thick lip inlet achieved an angle-of-attack of 82° at the same velocity ratio of 2.5.

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 figure 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 figure 10. It is a non-dimensional parameter that represents the ratio of the ideal amount of power required to increase the pressure of the blowing air from free stream 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 free stream 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 visa versa. Based on this, the large lip slot height configuration would be chosen. The results shown in the small table in figure 10 confirm 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 compared to 12).

Besides relative blowing power, another criterion that could be used to choose between the two lip slot heights is whether the air required for blowing can realistically be bled from the core-compressor. According to reference 7, a blowing mass flow ratio of 0.009 and a blowing pressure ratio of 2.6 are well within the bleed capability of 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 reference 7.

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 implies 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 at which flow separation occurred, α becomes a function of four dimensionless parameters:

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

By neglecting the Reynolds number effect, R_{ue}, 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. (Note that for the non-blowing geometry, i.e., when both V_B and h are zero, and by neglecting the effect of Reynolds number, the relationship reduces to that for non-blowing which has already been discussed in connection with fig. 3).

How successfully the relationship correlates the blowing results is shown in figure 11. The data are from the inlet configuration with lip blowing through the smaller slot height ($h/D_F = 1 \times 10^{-3}$) and the largest slot circumferential extent ($\theta = 120°$). 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.

Analytical Method

As mentioned earlier, 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 programs developed at the NASA Lewis Research Center. A flow chart depicting the sequence for using these programs is presented in figure 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 free stream 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. A more complete description of the analytical method utilizing suction and tangential blowing is given in reference 8.

Comparison of Analytical and Experimental Results

Separation Boundaries

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

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°: For the baseline configuration at a velocity ratio of 5.0, the predicted boundary was about 10° low. The reason for this is not yet completely understood but, because of this discrepencey, no attempt was made to predict separation boundaries for the two blowing configurations at angles-of-attack greater than 90°.

For the diffuser blowing configuration at a velocity ratio of 3.2, the predicted result also was about 10° low. This is felt to be a result of the predicted location of flow separation being different from the 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. But 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° 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 first occur 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 back to figure 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 zero degrees, there is a circumferential variation in internal static pressures in the forward part of the inlet resulting in a circumferential variation 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 reenergize the boundary layer sufficiently to maintain attached flow is different, and is proportional to the magnitude of the pressure gradient above that 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 discrepency between experimental and analytical results that occur at the higher angles-of-attack (see fig. 13(b)) may be a result of the analytical calculations being applicable only at the windward location.

Velocity Profiles

A comparison of experimental and analytical velocity profiles was made at two axial locations in the windward plane, one at the diffuser rake and the other at the fan face rake (see fig. 2). The results are shown in figure 14 for the baseline configuration and figure 15 for the diffuser blowing configuration with the larger slot height. Both configurations are at conditions where separation boundaries were compared in figure 13 ($\alpha = 40°$, $V_t/V_0 = 1.6$ for the no slot configuration; $\alpha = 70°$, $V_t/V_0 = 2.1$, $P_B/P_0 = 1.2$ for the diffuser blowing configuration).

For the baseline configuration, the predicted velocity profile is somewhat "stronger" than the experimental profile at both axial locations (fig. 14(a) and (b)). This difference, however, is small enough so as not to significantly effect the separation boundary.

For the diffuser blowing configuration, the predicted and experimental velocity profiles agree well at the diffuser rake location except in the vicinity of $y/H_d = 0.2$, where the predicted velocity is too high (fig. 15(a)). This difference probably results because the blowing velocity profile at the exit of the blowing slot, which must be specified in the prediction methods, is not the same as the experimental velocity profile at this location. A similar trend in blowing velocity profiles was observed in reference 9. By the time the flow has reached the fan face rake, however, enough mixing has taken place so that the predicted and experimental velocity profiles agree very well (fig. 15(b)).

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 is 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° 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).

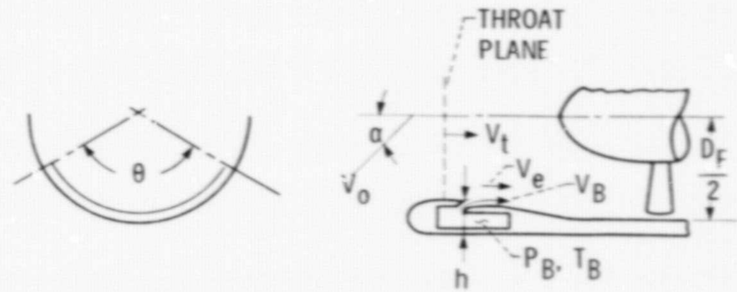
Analytical

1. For both non-blowing and blowing configurations, the analytical and experimental flow separation boundaries agree well at angles-of-attack below 90°.
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.

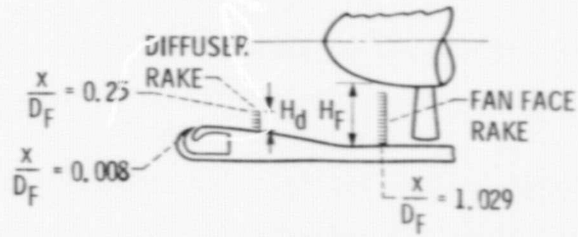
References

1. Lewis, G. W., Jr. and Tysl, E. R., "Overall and Blade - Element Performance of a 1.20 - Pressure-Ratio Fan Stage at Design Blade Setting Angle," NASA TM X-3101, 1974.
2. Potonides, H. C., Cea, R. A., and Nelson, T. F., "Design and Experimental Studies of a Type A V/STOL Inlet," Journal of Aircraft, Vol. 16, No. 8, Aug. 1979, pp. 543-550.
3. Shaw, R. J., Williams, R. C., and Koncsek, J. L., "V/STOL Tilt Nacelle Aerodynamics and its Relation to Fan Blade Stresses," NASA TM-78899, 1978.
4. Boles, M. A. and Stockman, N. O., "Use of Experimental Separation Limits in the Theortical Design of V/STOL Inlets," AIAA Paper 77-878, July 1977.
5. McGregor, I., "Some Applications of Boundary Layer Control by Blowing to Air Inlets for V/STOL Aircraft," Inlets and Nozzles for Aerospace Engines, AGARD 91, Sept. 1971, Paper No. 12.
6. Chang, Paul K, "Separation of Flow, Pergamon Press, Oxford, 1980, p. 279.
7. Cawthon, J. A., "Design and Preliminary Evaluation of Inlet Concepts Selected for Maneuver Improvements of Transonic Tactical Aircraft," AIAA Paper 76-701, July 1976.
8. Hwang, D. P., "A Summary of V/STOL Inlet Analysis Methods," NASA TM-82725, 1981.
9. Herring, H. J., "Numerical Calculations of Slot Injection in a Two-Dimensional Boundary Layer," DYNALYSIS of Princeton, Report Number 68, Apr. 1981.

Figure 1. - 0.508 meter dia. fan/inlet installed in V/STOL tunnel.



(a) Test variables.



(b) Lip blowing configuration.

(c) Diffuser blowing configuration.

Figure 2. - Test variables and blowing configurations.

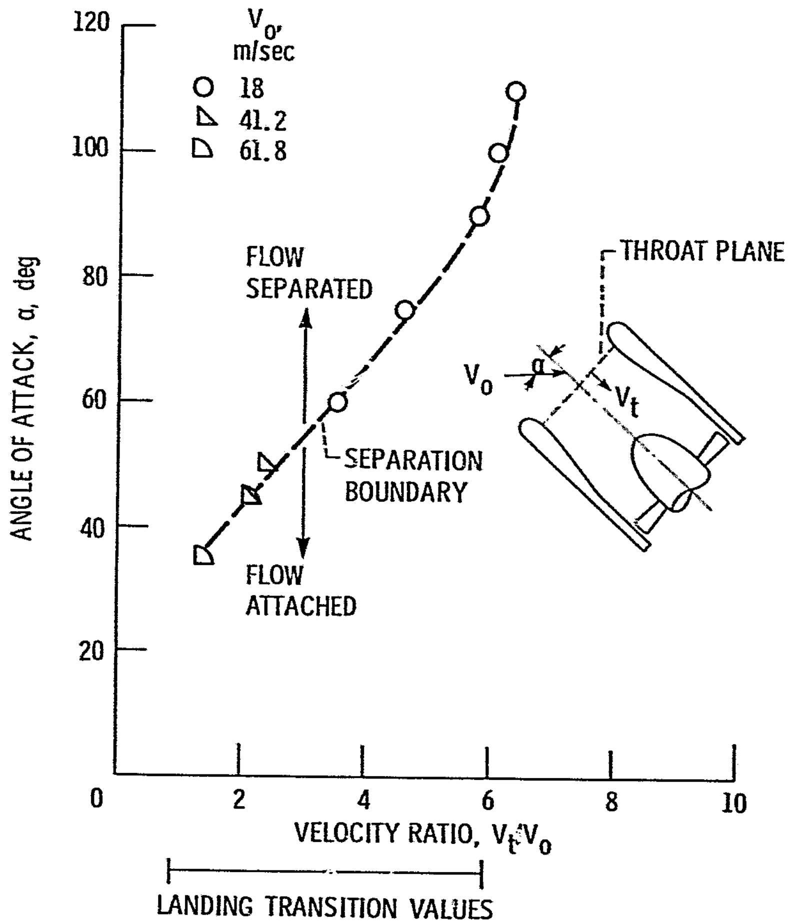


Figure 3. - Flow separation boundaries for baseline (no slot) configuration.

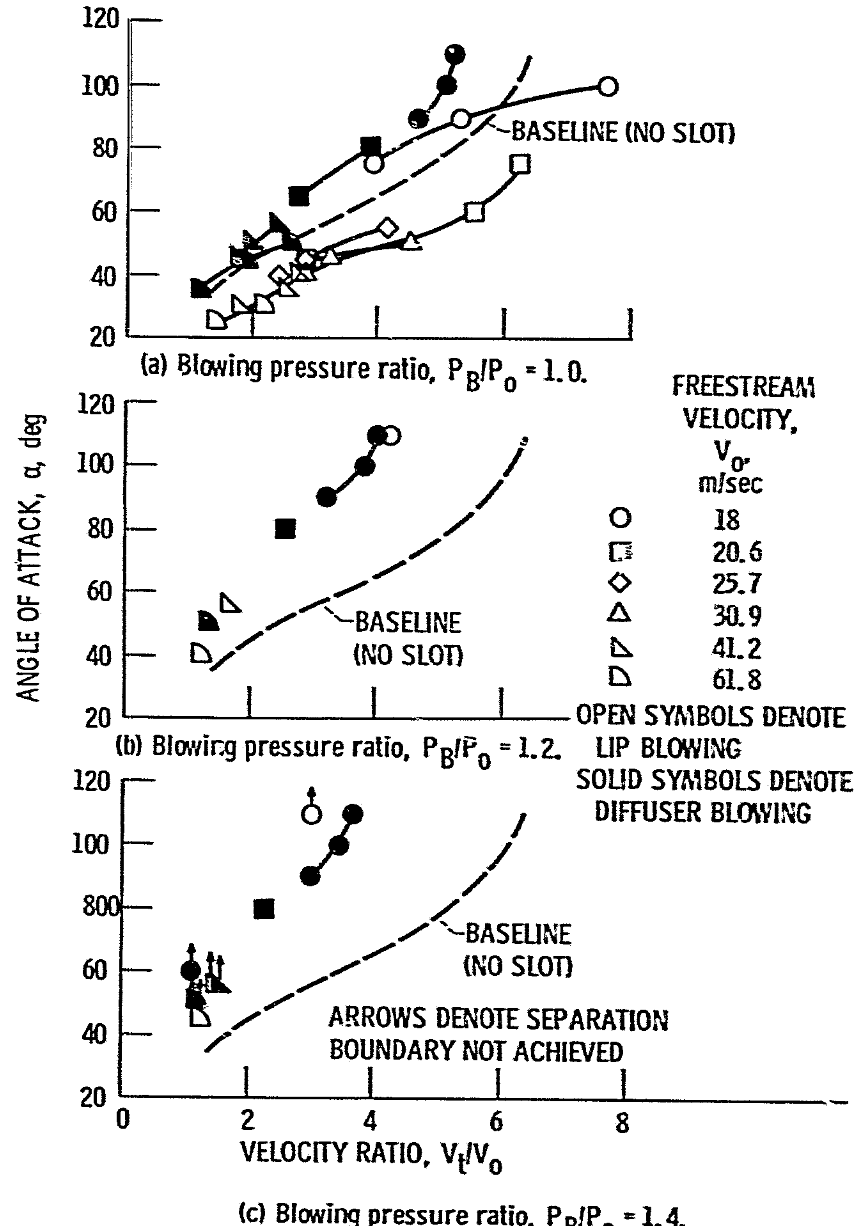


Figure 4. - Effect of blowing location on separation boundary. $h/D_F = 1x10^{-3}$; $\theta = 120^0$.

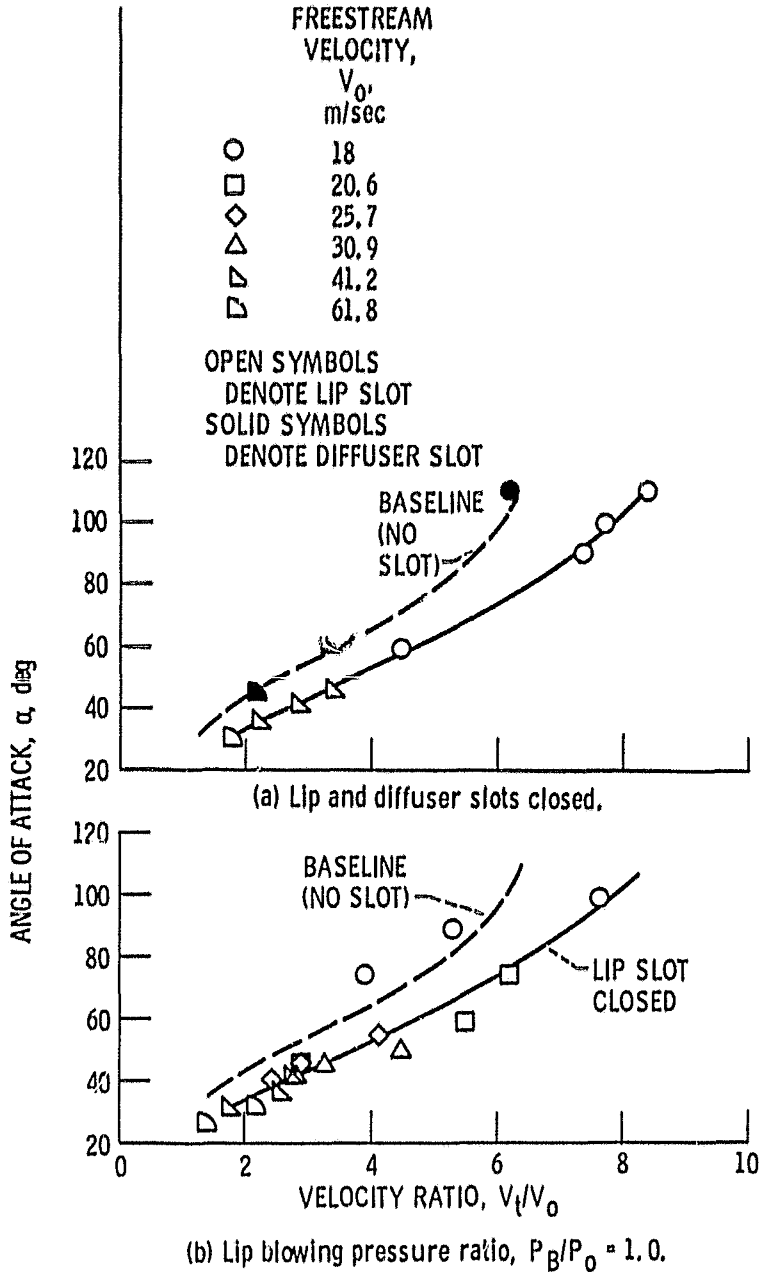


Figure 5. - Effect of closed slots on separation boundary and comparison of lip slot closed results with lip blowing at a pressure ratio of 1.0. $h/D_F = 1\times10^{-3}$; $\theta = 120^0$.

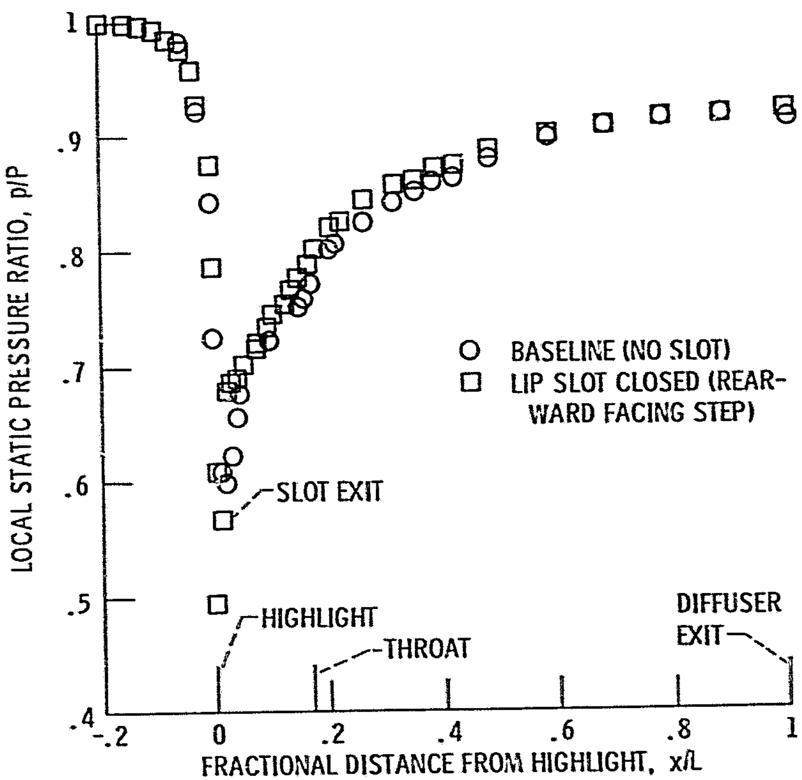


Figure 6. - Effect of lip slot on windward surface static pressure distribution. $\alpha = 110^0$; $V_0 = 18$ m/sec; $h/D_F = 1x10^{-3}$.

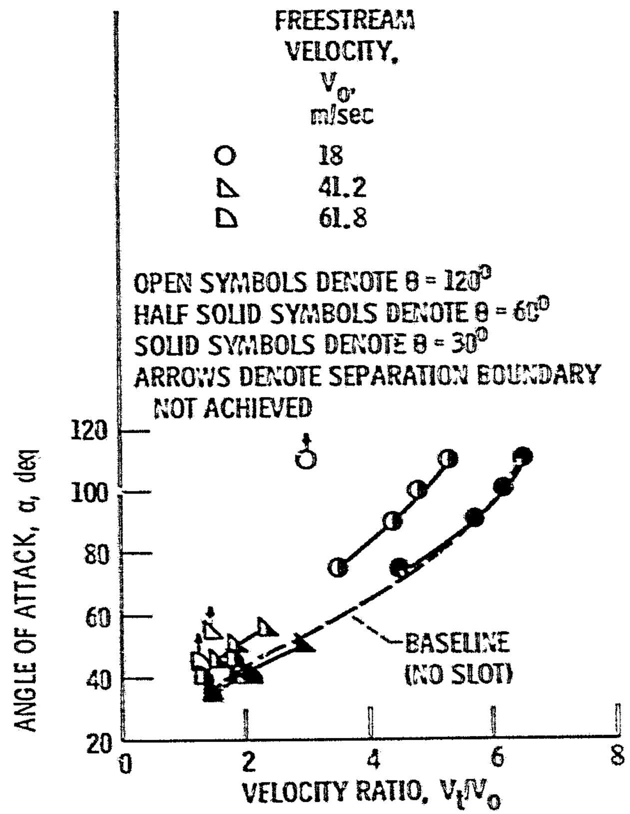


Figure 7. - Effect of lip slot circumferential extent on separation boundary. $h/D_F = 1x10^{-3}$; $P_B/P_0 = 1.4$.

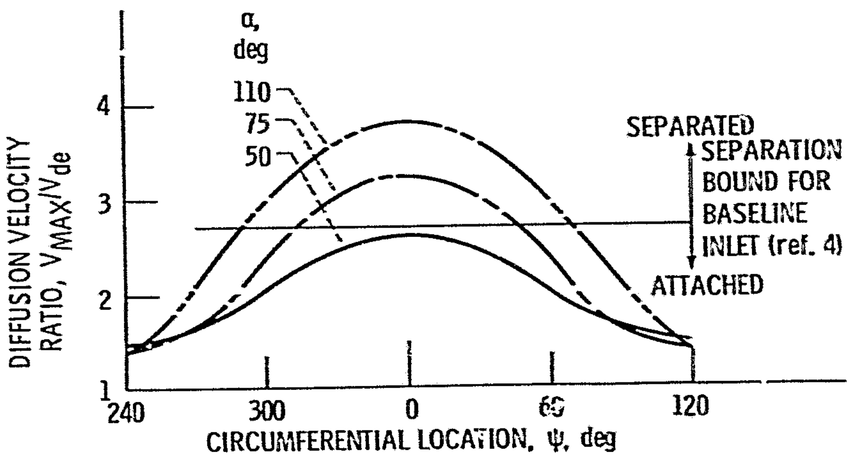
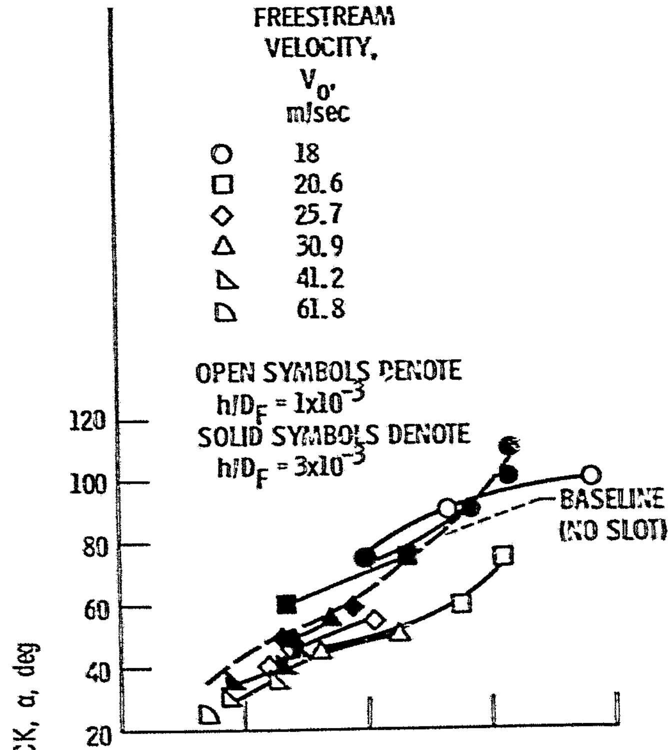
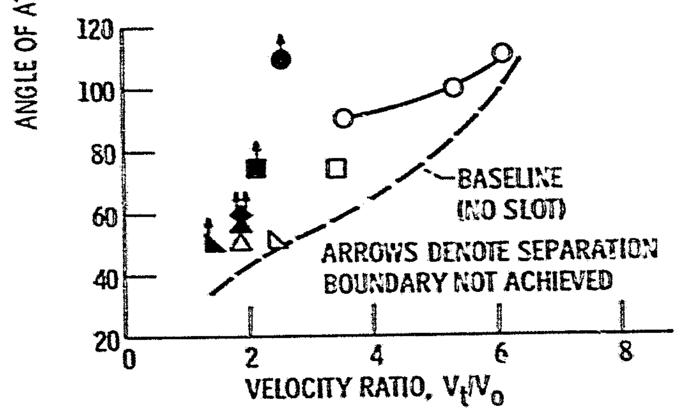


Figure 8. - Analytical circumferential variation of diffusion velocity ratio. $V_t/V_0 = 2.5$.



(a) Blowing pressure ratio, $P_B/P_0 = 1.0$.



(b) Blowing pressure ratio, $P_B/P_0 = 1.1$.

Figure 9. - Effect of lip slot height on separation boundary. $\theta = 120^0$.

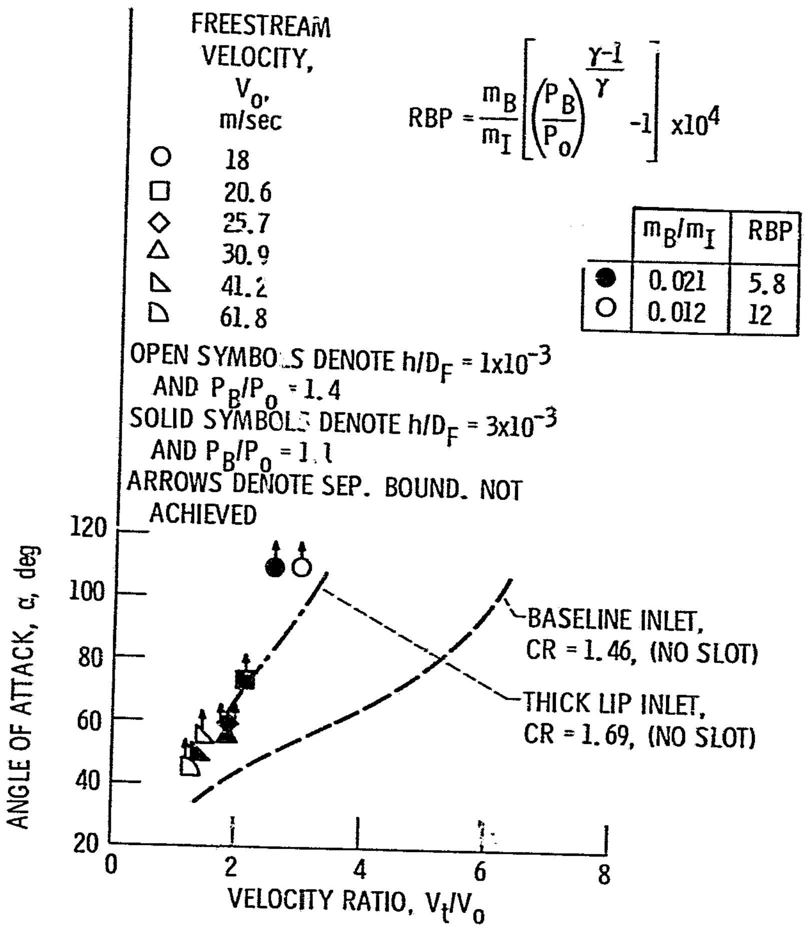


Figure 10. - Comparison of nonblowing and lip blowing.

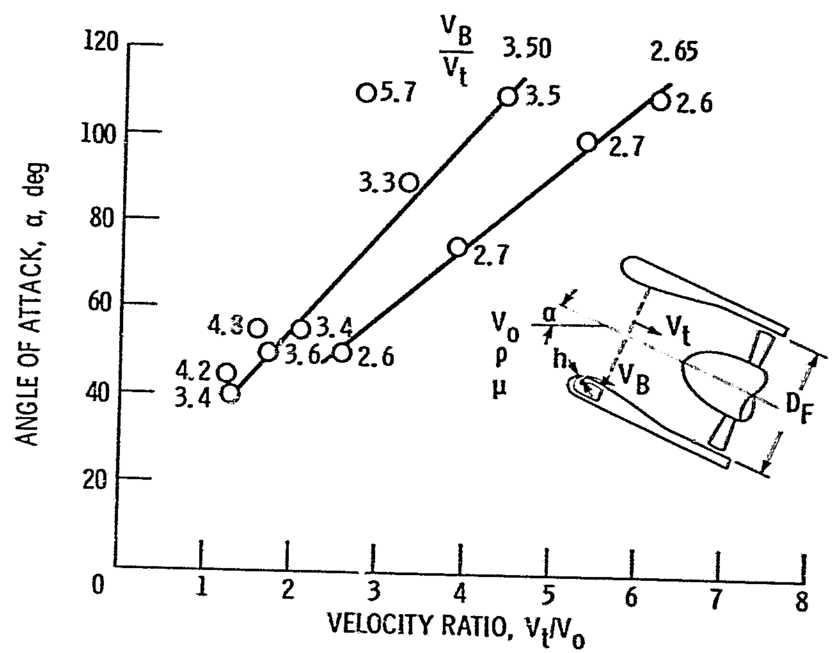


Figure 11. - Blowing correlating parameter. $h/D_F = 1x10^{-3}$; $\theta = 120^0$.

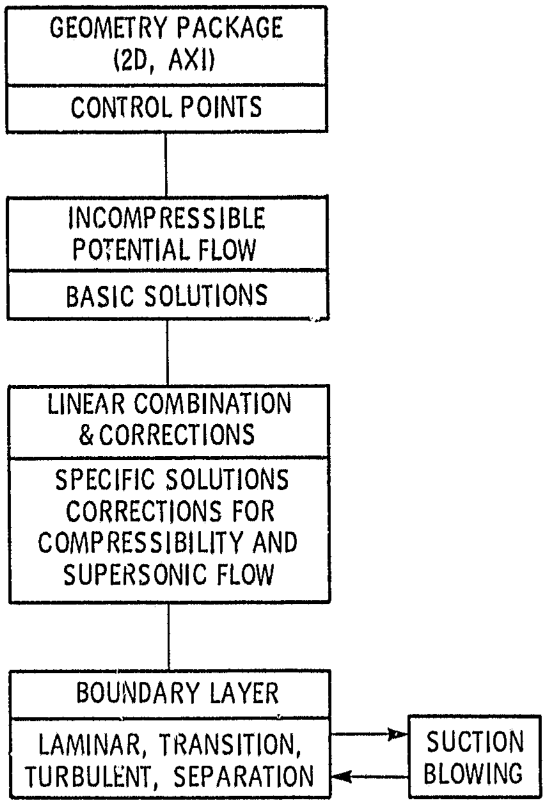


Figure 12. - Schematic diagram of inlet flow prediction computer programs.

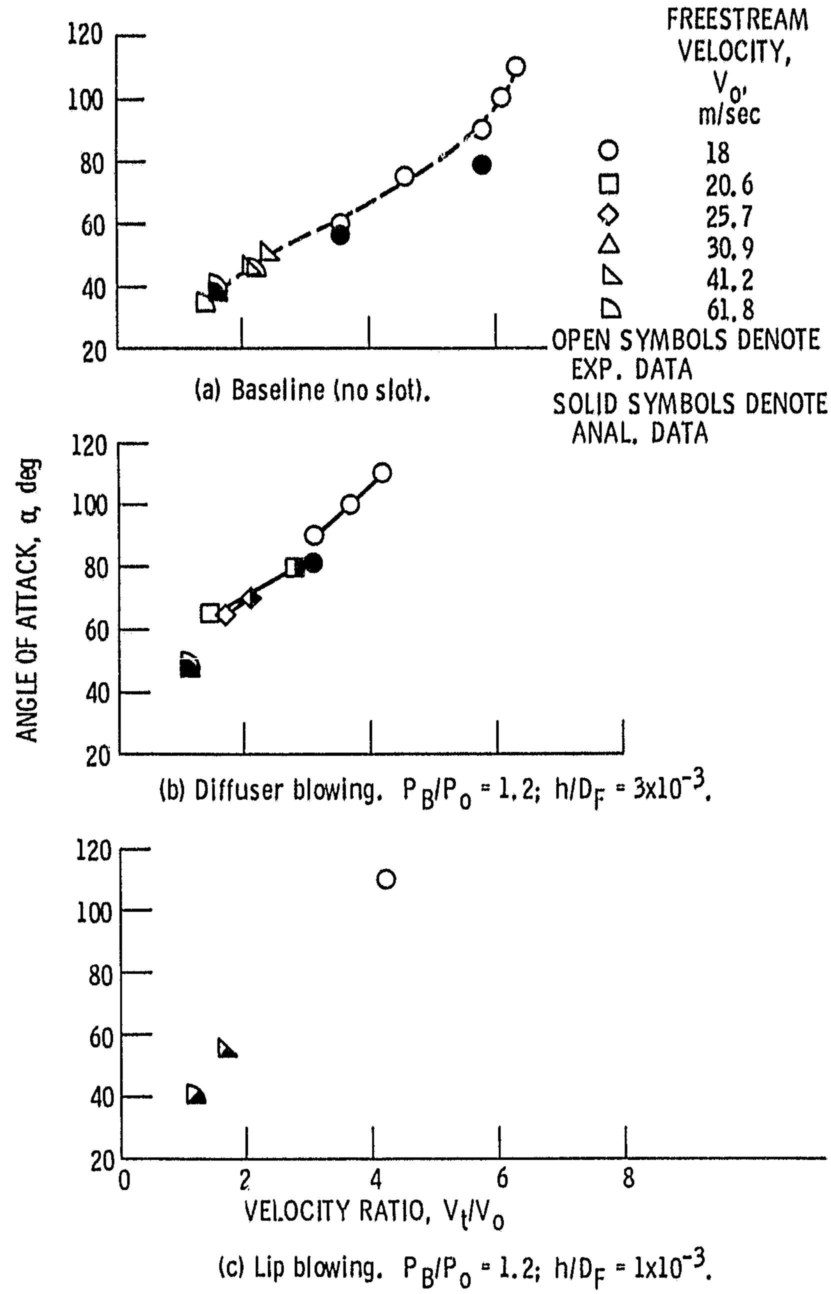
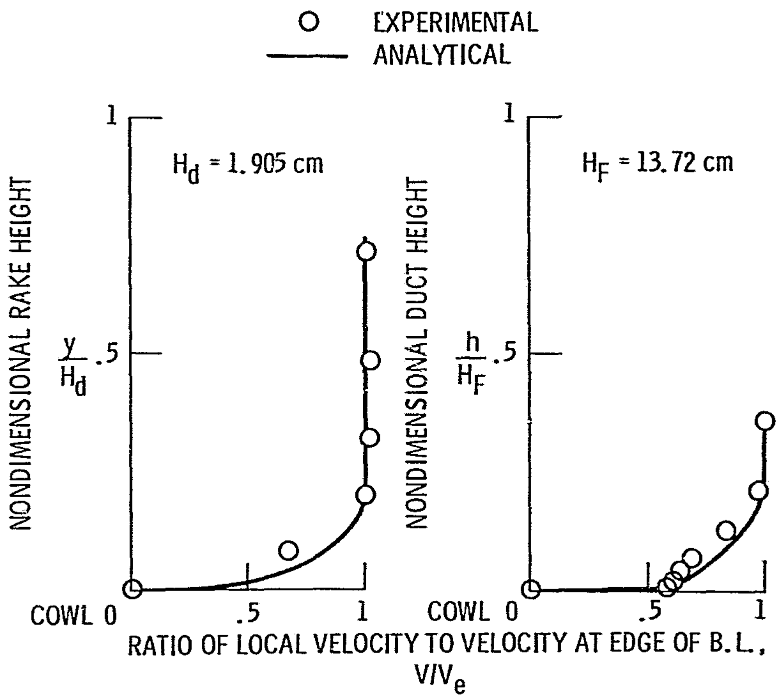


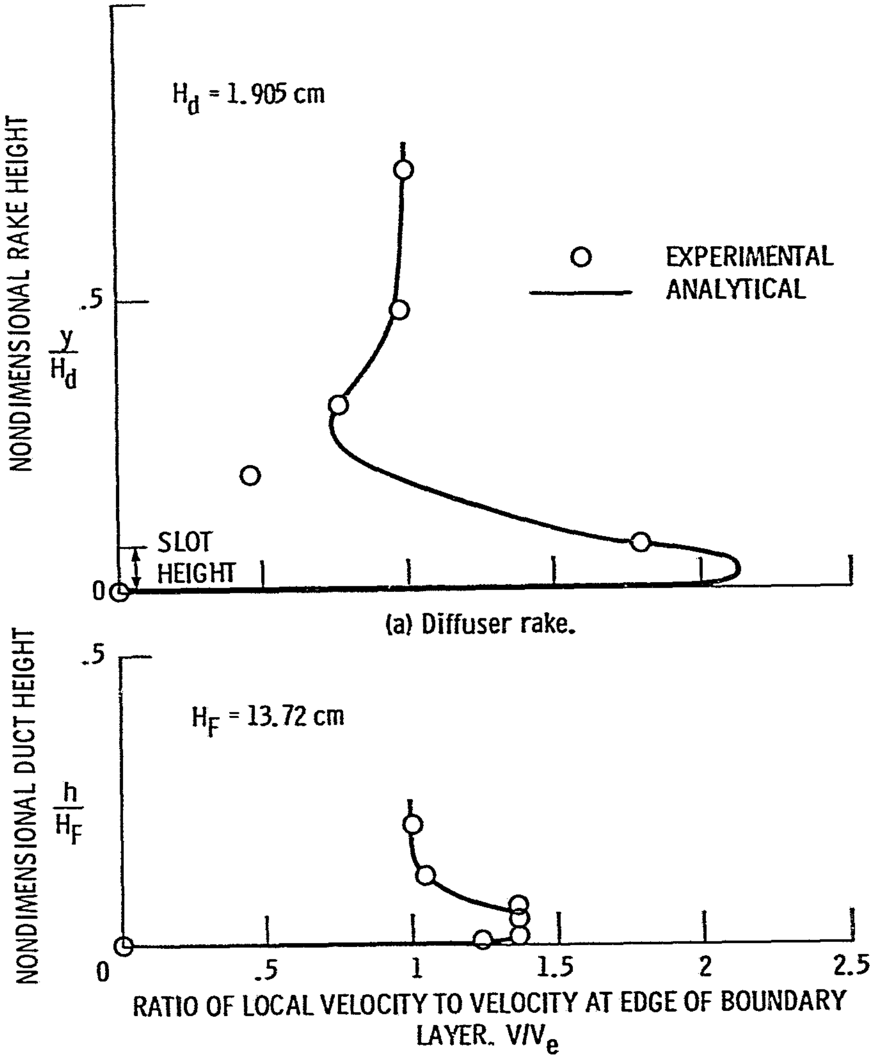
Figure 13. - Comparison of experimental and analytical separation bounds. $\theta = 120^0$.



(a) Diffuser rake.

(b) Fan face rake.

Figure 14. - Comparison of experimental and analytical velocity profiles for baseline configuration. $\alpha = 40^0$; $V_0 = 61.8$ m/sec; $V_t/V_0 = 1.6$.



(b) Fan face rake.

Figure 15. - Comparison of experimental and analytical velocity profiles for diffuser blowing. $\alpha = 70^0$; $V_0 = 25.7$ m/sec; $V_t/V_0 = 2.1$; $h/D_T = 3\times10^{-3}$; $P_B/P_0 = 1.2$; $\theta = 120^0$.