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INCIDENCE ANGLE BOUNDS FOR LIP FLOW SEPARATION OF THREE 13.97-CENTIMETER-DIAMETER INLETS

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16. Abstract

Low-speed wind-tunnel tests were conducted to establish a procedure for determining inlet-lip flow separation and to make a preliminary examination of the incidence angle bounds for lip flow separation of inlets intended for the nacelles of STOL (short takeoff and landing) aircraft. Three inlets were tested. Two of the inlets had short centerbodies with lower lip area contraction ratios of 1.30 and 1.44. The third inlet had a cylindrical centerbody extended forward into the inlet throat with a lower lip area contraction ratio of 1.44. The inlets were sized to fit a 13.97-centimeter-diameter fan. For inlet throat Mach numbers less than about 0.43, the lip flow separation angle was increased by either increasing the ratio of throat velocity to free-stream velocity (V_t/V_o) or by increasing the lower lip area contraction ratio. For throat Mach numbers greater than a certain value (ranging from 0.43 to 0.52), increasing throat Mach number in some cases resulted in a decrease in the lip flow separation angle. Extending a cylindrical centerbody into the inlet throat increased the flow separation angle for nearly all values of V_t/V_o.

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INCIDENCE ANGLE BOUNDS FOR LIP FLOW SEPARATION OF THREE 13.97-CENTIMETER-DIAMETER INLETS

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SUMMARY

Tests were conducted to establish a procedure for determining inlet-lip flow separation and to make a preliminary examination of the incidence angle bounds for lip flow separation of inlets intended for the nacelles of STOL (short takeoff and landing) aircraft. Three inlets were tested: Two had short centerbodies with lower lip area contraction ratios of 1.30 and 1.44; the third had a cylindrical centerbody extended forward into the inlet throat with a lower lip area contraction ratio of 1.44.

The tests were conducted in a low-speed wind tunnel at nominal free-stream velocities of 25, 44, and 73 meters per second and over a range of inlet throat Mach numbers. The inlets were sized to fit a 13.97-centimeter-diameter fan.

A lip surface static pressure and a diffuser-exit total pressure on the inlet windward side were monitored and gave a strong and consistent indication of the incidence angle where lip flow separation occurred.

For inlet throat Mach numbers less than about 0.43, the incidence angle where lip flow separation occurred appeared to depend on the ratio of inlet throat velocity to free-stream velocity V_t/V_0, independent of the absolute level of free-stream velocity. In this range of throat Mach numbers the lip flow-separation angle was increased by either increasing the ratio of throat velocity to free-stream velocity or by increasing the lower lip area contraction ratio. For throat Mach numbers greater than a certain value (ranging from 0.43 to 0.52), increasing throat Mach number in some cases resulted in a decrease in the lip flow-separation angle. Extending a cylindrical centerbody into the inlet throat increased the flow-separation angle for nearly all values of V_t/V_0.

INTRODUCTION

Short takeoff and landing (STOL) aircraft require slow takeoff and landing speeds which are achieved by means of high wing lift coefficients. The high lift coefficients are achieved by blowing the engine exhaust into or over the wing flap system. The resulting airplane geometry has the engine inlet somewhat ahead of the wing leading edge. The high lift coefficient, combined with the airplane angle of attack can result in high local flow incidence angles at the engine inlet. A consequence of this high incidence angle can be flow separation on the inlet lower lip with a concommitant decrease in inlet pressure recovery and a reduction in engine thrust (refs. 1 to 5). The flow distortion accompanying a separation can also result in an increase in engine noise and an increase in fan and compressor blade stresses. To avoid inlet-lip separation, a knowledge of the incidence angle separation bounds and their relation to the inlet-lip design is required.

The purpose of this study was to establish a procedure for determining inlet-lip flow separation and to make a preliminary examination of the incidence angle separation bounds of 13.97-centimeter-diameter model inlets intended for the nacelles of STOL airplanes. These inlets are generally characterized by a large lip thickness inside the inlet highlight compared with the thickness outside the highlight.

The experiments were performed in a low-speed wind tunnel using three inlets mounted on a 13.97-centimeter-diameter fan. Two of the inlets had short centerbodies with lip contraction ratios of 1.30 and 1.44 on the windward side. The third inlet had a cylindrical centerbody extended forward into the inlet throat with a lip contraction ratio of 1.44 on the windward side. The incidence angle where lip flow separation occurred was determined at nominal free-stream velocities of 25, 44, and 73 meters per second and over a range of inlet throat Mach numbers.

SYMBOLS

A	inlet flow area
a	ellipse semimajor axis of internal lip
b	ellipse semiminor axis of internal lip
L	cowl length
M	Mach number
P_d	diffuser-exit total pressure selected for separation detection
p_l	lip static pressure selected for separation detection
r	radius from inlet centerline
V	velocity
X	axial distance from cowl highlight
α	incidence angle; angle between free-stream velocity and inlet axis

Subscripts:

d	diffuser exit

h	highlight

m	maximum

s	separation

t	throat

o	free stream

APPARATUS

Wind Tunnel and Model Installation

The tests were conducted in the Lewis 2.74- by 4.58-meter (9- by 15-ft) V/STOL wind tunnel (ref. 6). The model, located approximately in the center of the test section, was mounted on a rotating turntable which was used to vary the incidence angle (fig. 1).

The model (fig. 2) consisted of the test inlet, research instrumentation, and a 13.97-centimeter-diameter fan driven by a tip turbine supplied with high-pressure air. Varying the drive air pressure changed the fan rotational speed and hence the fan weight flow and inlet throat Mach number. The fan design pressure ratio is 1.25 at a weight flow of 2.49 kilograms per second and a rotational speed of 36 000 rpm. More details of the fan design are given in reference 7.

Instrumentation

The inlet weight flow was determined from total- and static-pressure measurements at the diffuser exit of the inlet as shown in figure 2. The inlet throat velocity and Mach number were calculated from the weight flow, the free-stream total temperature, the inlet pressure recovery, and the throat - diffuser-exit area ratio.

A lip static pressure and a diffuser-exit total pressure on the windward side of the inlet were used to detect flow separation based on data previously obtained for inlets similar to those tested here (ref. 8). Data from reference 8 (shown in fig. 3) indicate that, when the flow separates from the inlet lip at an incidence angle of 40°, the static pressure on the lip increases (fig. 3(a)) and the total pressure at the diffuser-exit decreases (fig. 3(b)) over more than half the flow passage on the windward side of the inlet. Hence, by varying inlet incidence angle and monitoring the lip static-pressure tap (at $X/L = 0.035$, $X/X_t = 0.20$) and the diffuser-exit total-pressure probe (at 0.18 of the passage height) indicated in figure 3, the incidence angle where lip flow separation occurs could be determined. The locations of this static-pressure tap and total-pressure probe on the model are indicated in figure 2.

It is necessary to monitor both the lip static pressure and the diffuser-exit total pressure to distinguish complete lip separation from other possible types of separation. For example, diffuser separation only would cause a decrease to appear in diffuser-exit total pressure but not an increase in lip static pressure. Also, a local lip separation bubble involving flow reattachment could appear as an increase in lip static pressure without a noticeable decrease in diffuser-exit total pressure. Complete lip separation, which is the interest in this report, appears as a concurrent increase in lip static pressure and decrease in diffuser-exit total pressure.

Inlet Configurations

The three model inlet configurations are shown in figure 4 along with the important inlet design parameters. Two of the configurations (figs. 4(a) and (b)) have a short centerbody with cowl lower lip area contraction ratios $(r_h/r_t)^2$ of 1.30 and 1.44. The 1.30 contraction ratio cowl has a symmetric lip with an elliptical internal lip shape defined by a semimajor axis to semiminor axis ratio a/b of 2.0. The 1.44 contraction ratio cowl is asymmetric, having a contraction ratio of 1.44 only at the lower lip, with a smooth circumferential transition to a value of 1.30 at the sides, which is then maintained over the entire upper half of the lip. The internal lip of this cowl also has an elliptical shape which is defined by an ellipse ratio of 2.0 at the lower lip with a smooth circumferential transition to a value of 2.9 at the sides which is then maintained over the upper half of the lip. These two inlet configurations have a design throat Mach number of 0.60 at the fan design weight flow (2.49 km/sec).

The third inlet configuration (fig. 4(c)) has the same inlet cowl as the configuration of figure 4(b), but it also has a cylindrical centerbody which extends into the inlet throat. The inlet throat area of this configuration is 15.8 percent less than the other configurations, resulting in a design throat Mach number of 1.0.

The inlet diffusers for the three configurations are considered to be conservative designs, reducing the possibility of diffuser separation preceding lip separation. Details concerning the external lip design of the inlet cowls is given in figure 4.

PROCEDURE

The lip static pressure and diffuser-exit total pressure selected to detect lip flow separation, were recorded on the two Y-axes of an XYY automatic plotter. The inlet incidence angle was recorded on the X-axis of the plotter. The incidence angle where lip flow separation occurred was determined by increasing the inlet incidence angle from 0° and observing the behavior of the two pressure measurements on the XYY plotter at a constant free-stream velocity. The incidence angle was changed at a rate of about 1° per second. After the lip flow had separated, the incidence angle was decreased, and the angle where lip flow reattachment occurred was determined. This procedure was followed at nominal free-stream velocities of 25, 44, and 73 meters per second and over a range of inlet throat Mach numbers.

RESULTS AND DISCUSSION

One would expect that the incidence angle where inlet lip flow separation occurred would be influenced by the following factors: (1) lip geometry, (2) inlet flow and free-stream velocity conditions, and (3) inlet size. In this investigation the effect of inlet lip geometry is examined by varying the inlet-lip contraction ratio $(r_h/r_t)^2$. This parameter is by no means fully descriptive of the lip geometry, however. Other important design parameters are a/b, if the internal lip contour is an ellipse, and the superellipse exponent and a/b, if the lip shape is a superellipse. A theoretical analysis of the effects of these various lip geometry parameters is reported in reference 5. The external lip design may also be important to the lip flow separation characteristics as demonstrated in reference 1.

The effects of inlet flow and free-stream velocity conditions are examined by changing inlet weight flow and the free-stream velocity.

The effects of inlet size were not investigated. The inlet diffuser-exit diameter was fixed at 13.97 centimeters.

Before discussing the lip flow-separation characteristics of the three inlet configurations, results of the technique used for detecting the lip flow separation will be presented.

Detection of Lip Flow Separation

An example of the basic experimental data used to determine the inlet-lip flow separation angle is shown in figure 5. The figure shows the variation of the selected lip static pressure and diffuser-exit total pressure with the inlet incidence angle at conditions of constant free-stream velocity and constant inlet weight flow. As the incidence angle increases the lip static pressure continuously decreases up to an angle of about 55° where there is an abrupt rise (fig. 5(a)). This sudden increase in static pressure is a consequence of flow separation from the inlet lip.

The total pressure remains relatively constant with increasing incidence angle up to about 35° (fig. 5(b)). At higher angles there is a gradual decrease, which is attributed to a thickening of the boundary layer on the windward side at the diffuser exit. Lip flow separation is associated with the precipitous drop in total pressure at an incidence angle near 55°, the angle where the sharp rise in lip static pressure was observed. Note that the angle for flow reattachment with decreasing incidence angle, is consistently lower than that for flow separation.

Data obtained at different values of free-stream velocity and inlet weight flow (in the format shown in fig. 5) were used to establish the inlet-lip flow-separation bounds that are presented in later figures. In all cases the sudden rise in lip static pressure was used to determine the lip flow separation angle. The diffuser-exit total pressure generally provided the same indication of lip flow separation; however, the gradual decrease in total-pressure indicated in figure 5(b) tended in some cases to make the determination of the flow separation angle a bit more difficult. This was particularly true for the inlet with the extended centerbody: In some cases occurrence of lip flow separation could not be detected from the diffuser-exit total pressure data because of the already low levels of total pressure at that particular probe location. The lower total pressures resulted because the boundary layer was considerably thickened by the higher cowl surface velocities (and possible shock-boundary layer interactions) encountered in the inlet throat region.

Lip Flow-Separation Bounds

Figure 6 shows the lip flow-separation bounds for the inlet with the lower lip area contraction ratio of 1.44 with the short centerbody. The data are shown in terms of the incidence angle for lip flow separation α_s versus inlet throat Mach number for three values of free-stream velocity. Attached flow exists for angles below the solid lines connecting the data, and separated flow above.

The data indicate that the lip flow-separation angle generally increases with increasing throat Mach number up to about Mach 0.43, where, at a free-stream velocity of 24.9 meters per second, the separation angle begins to decrease. At a free-stream velocity of 44.7 meters per second, the separation angle continually increases with increasing throat Mach number, although there is a noticeable decrease in slope of the data curve at a throat Mach number of about 0.43. At a free-stream velocity of 73.2 meters per second, the separation angle begins to decrease at a throat Mach number of about 0.49, although the limited number of data points makes it difficult to determine exactly where the change in slope occurs.

This general change in the behavior of the lip flow-separation bounds beyond a throat Mach number of about 0.43 may be attributed to the appearance of shock - boundary-layer interactions on the cowl surface (where the measured surface velocities are considerably higher) as the throat Mach number reaches this level. Similar results were shown in reference 1.

The data presented in figure 6 for the inlet with the 1.44 lip area contraction ratio and short centerbody are also shown in figure 7 (open symbols) but now in terms of the lip flow-separation angle versus the ratio of inlet throat to free-stream velocity V_t/V_o. The inlet throat Mach number is given beside each data point in parenthesis. As indicated in the figure, for throat Mach numbers less than about 0.43, the data for the three values of free-stream velocity form almost a continuous straight line as shown by the dashed line drawn in the figure. At the lower throat Mach numbers the separation angle increases with increasing V_t/V_o, that is, with increasing V_t for a fixed V_o or decreasing V_o for a fixed V_t. Thus, the parameter V_t/V_o appears to be an appropriate one to generalize the separation bounds for throat Mach numbers less than 0.43.

Data for the 1.30 lower lip area contraction ratio inlet with the short centerbody are also shown in figure 7, and, by comparison with the 1.44 contraction ratio inlet data, illustrate the effect of lip contraction ratio on lip flow separation. The inlet with the lower lip contraction ratio of 1.44 (the open symbols) has a significantly higher separation angle at a given value of velocity ratio than the inlet with the 1.30 contraction ratio (solid symbols). This is in agreement with the theoretical results of reference 9 where increasing area contraction ratio was found to result in lower peak Mach numbers and smaller Mach number gradients on the inlet lip

A dashed straight line has also been drawn through the data points for the 1.30 contraction ratio inlet. For both inlets the dashed lines were drawn through a flow separation angle of 28° at a velocity ratio V_t/V_o, of 1.0 and the linear equations describing these lines are indicated in the figure.

For both inlets as throat Mach number is increased beyond a certain value (ranging from 0.43 to 0.52) there is a significant change in the slope of the lip separation bounds curve. Possible reasons for this behavior were given in the discussion of figure 6.

The effect of extending the cylindrical centerbody into the inlet throat is shown in figure 8 for the inlet with a lower lip area contraction ratio of 1.44. With the centerbody in this position, the airflow in the inlet chokes at the fan design weight flow (ref. 8). At a free-stream velocity of 44.8 meters per second, figure 8 indicates that for V_t/V_o greater than about 4.0, the presence of the centerbody in the inlet throat results in an increase in the flow separation angle at a given value of velocity ratio. This is associated with an increase in the value of throat Mach number above which the slope of the separation bounds curve significantly decreases. At the highest velocity ratio corresponding to a throat Mach number of 0.85, the maximum angle for attached flow has been extended to 71°. At lower velocity ratios, corresponding to a free-stream velocity of 72.9 meters per second, the extended centerbody increased the flow separation angle at all velocity ratios.

SUMMARY OF RESULTS

Tests were conducted with 13.97-centimeter-diameter inlets to determine lip flow separation bounds. The results can be summarized as follows:

1. A lip static pressure and a diffuser-exit total pressure, both on the inlet windward side, give a good and consistent indication of lip flow separation.

2. For throat Mach numbers less than about 0.43, the ratio of inlet-throat velocity to free-stream velocity V_t/V_0 appeared to be an appropriate parameter to generalize the lip flow separation bounds. The flow separation angle was increased by either increasing the ratio of throat velocity to free-stream velocity or by increasing the lower lip area contraction ratio.

3. For throat Mach numbers above a certain value (ranging from 0.43 to 0.52), increasing throat Mach number further can decrease the flow separation angle.

4. Extending a centerbody into the inlet throat increases the flow separation angle for nearly all values of V_t/V_0.

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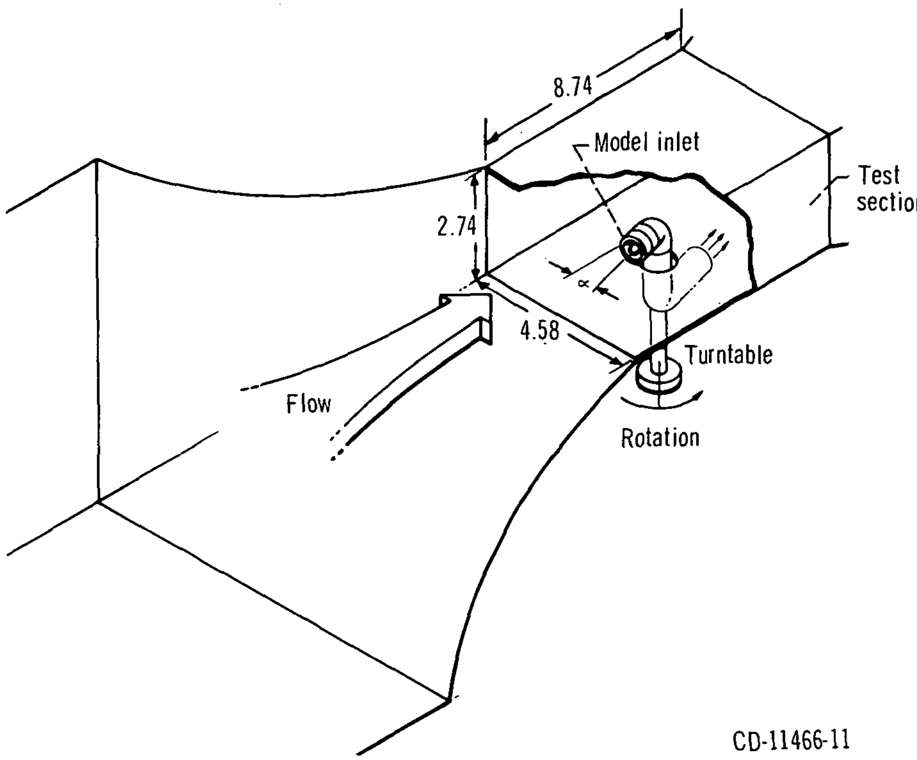


Figure 1. - Schematic view of V/STOL wind tunnel showing model installation. (All dimensions in meters.)

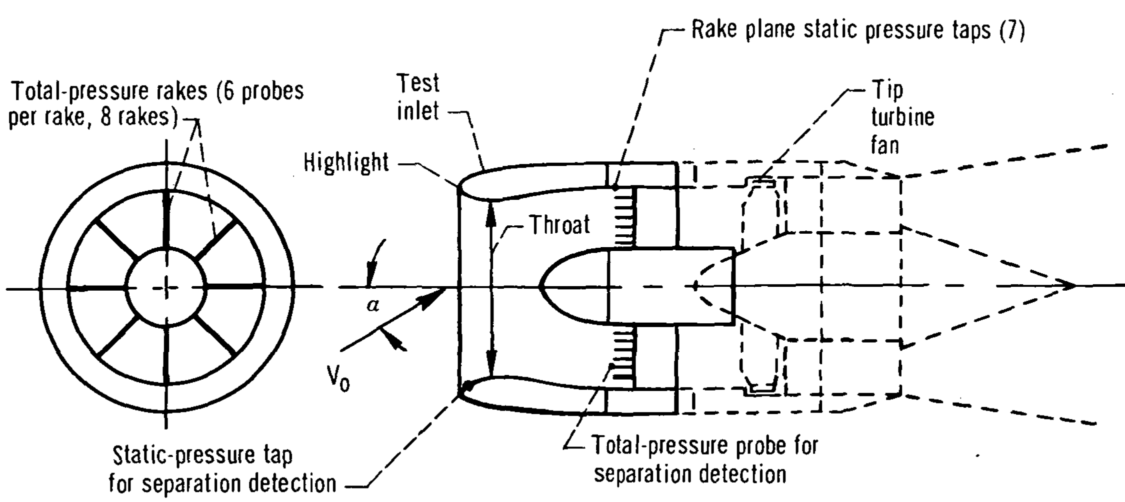
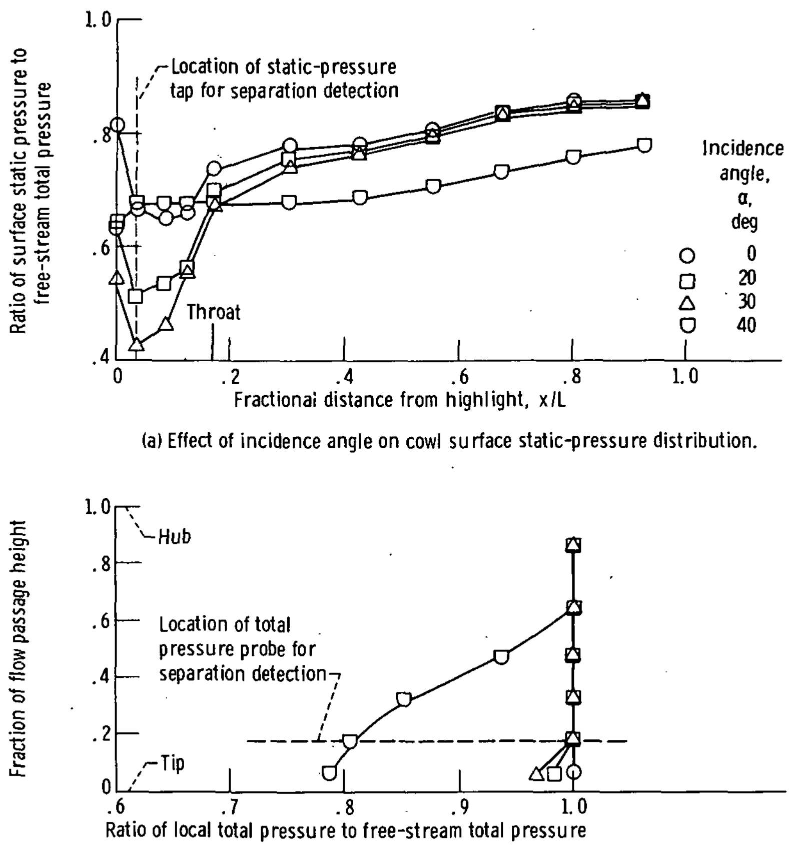


Figure 2. - Test model and instrumentation.



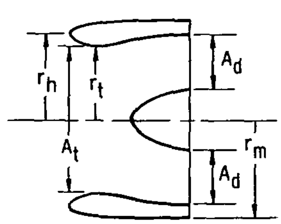
(a) Effect of incidence angle on cowl surface static-pressure distribution.

(b) Effect of incidence angle on diffuser-exit total-pressure distribution in windward flow passage.

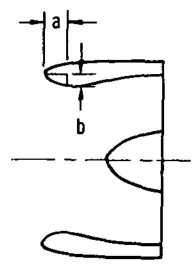
Figure 3. - Selection of lip surface static-pressure tap and diffuser-exit total-pressure probe for lip flow separation detection. Free-stream velocity, 45 meters per second.

Figure part	Internal lip			External lip		Diffuser
	Lip location	Area contraction ratio, $(r_h/r_t)^2$	Semimajor to semiminor axis ratio, a/b	Shape	Radius ratio, r_h/r_m	Area ratio, A_d/A_t
(a)	-----	1.30	2.0	NACA-1	0.87	1.09
(b)	Upper	1.30	2.9	Ellipse[a]	.87	1.09
	Lower	1.44	2.0	↓	.91	1.09
(c)	Upper	1.30	2.9		.87	1.30
	Lower	1.44	2.0		.91	1.30

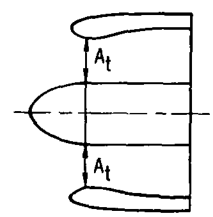
[a]a/b = 4.5.



(a) Lower lip area contraction ratio, 1.30.

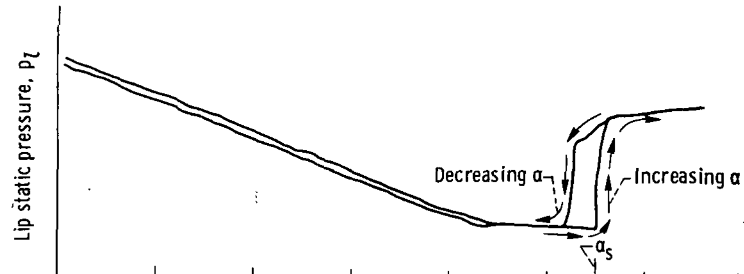


(b) Lower lip area contraction ratio, 1.44.

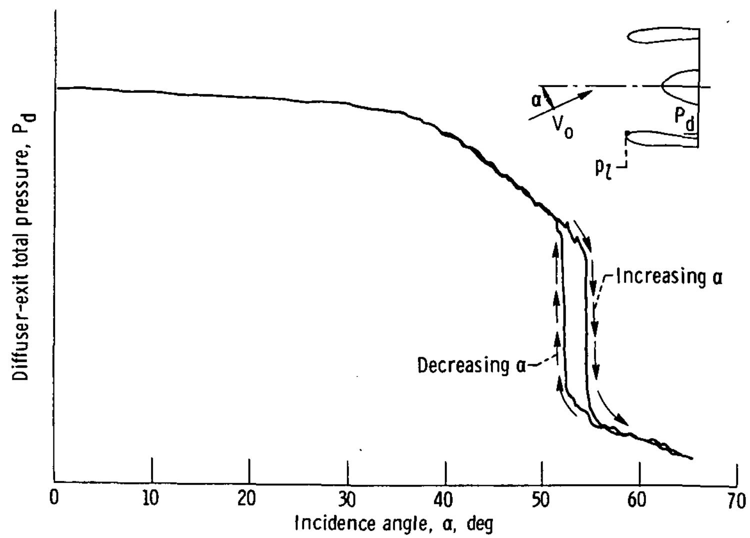


(c) Lower lip area contraction ratio, 1.44; extended cylindrical centerbody.

Figure 4. - Model inlet configurations.



(a) Variation of lip static pressure with change in incidence angle.



(b) Variation of diffuser-exit total pressure with change in incidence angle.

Figure 5. - Typical inlet-lip separation detection data. Free-stream velocity, constant; throat Mach number, constant.

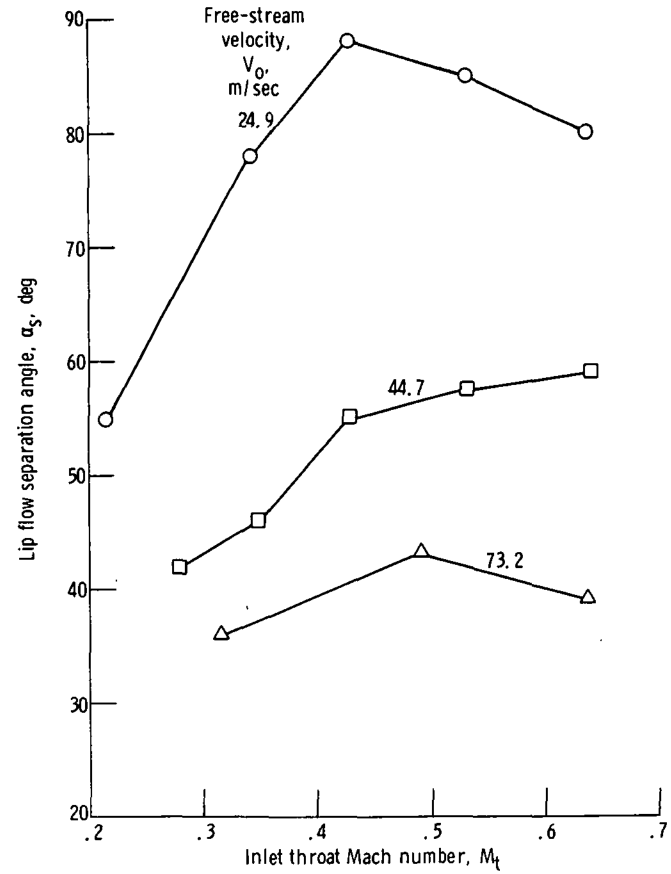


Figure 6. - Inlet flow separation bounds. Inlet lower lip area contraction ratio, 1.44; short centerbody.

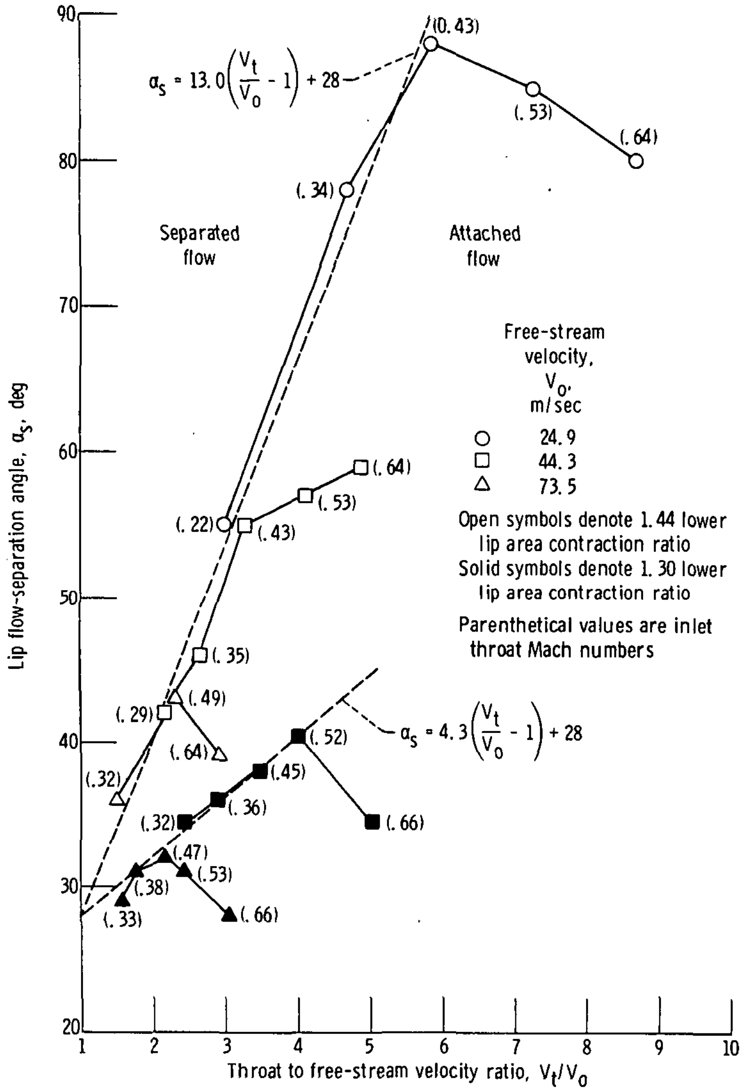


Figure 7. - Inlet-lip flow-separation bounds. Inlets with short centerbody.

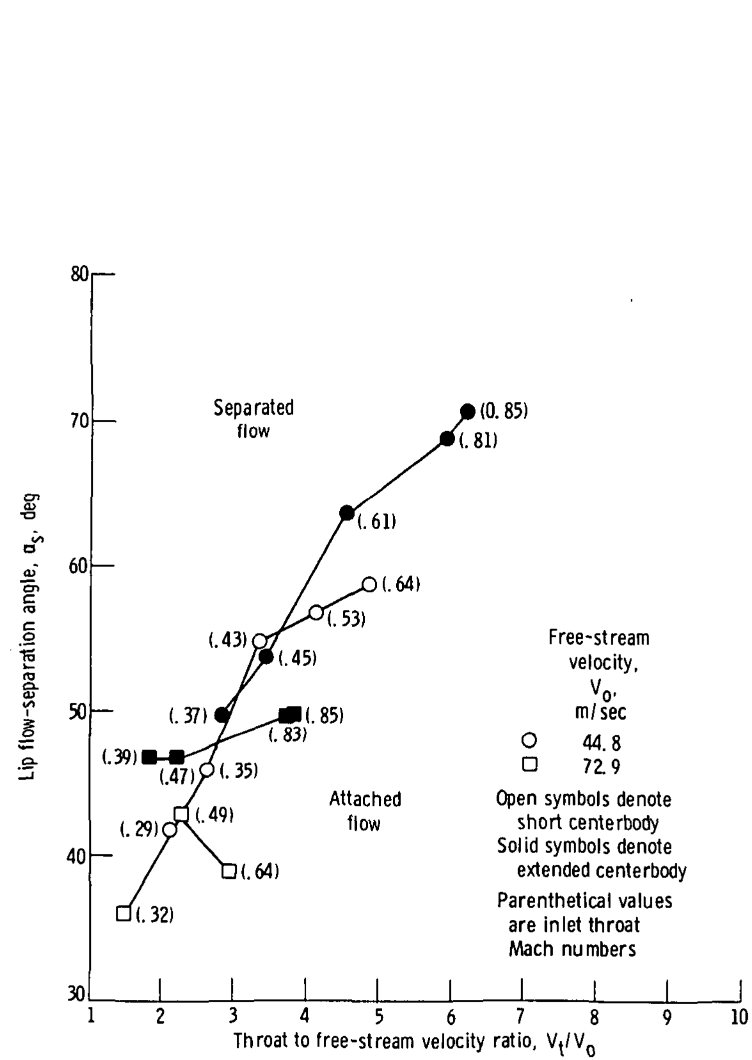


Figure 8. - Effect of extending centerbody forward into inlet throat on inlet-lip flow-separation bounds. Lower lip area contraction ratio, 1.44.

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