Study of Two Axisymmetric Inlets Designed for Mach 3.5

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Results are compared from wind-tunnel tests of two large-scale models of axisymmetric mixed-compression inlet systems designed for Mach number 3.5. One inlet, tested recently, incorporated a "traveling"-bleed system in an effort to achieve maximum transonic engine airflow supply. The other inlet, tested earlier, required only a "fixed"-bleed system but had 21% less transonic airflow supply. Even so, the inlet with fixed bleed appears more attractive with auxiliary airflow. Chiefly, this is because the fixed-bleed inlet can be 45% shorter and, therefore, would be considerably lighter than the traveling-bleed inlet. In addition, the fixed-bleed inlet offers more operating control margin at supersonic Mach numbers when the inlet is started. Further, its off-design performance is higher, because separation of the flow in the subsonic diffuser can be avoided-something that apparently cannot be done with a traveling-bleed inlet without reducing the transonic airflow supply. Finally, it appears that the management and efficiency of bleed airflow for the fixed-bleed inlet can be improved using analytical methods verified by the more recent tests.

Nomenclature

A_c = capture area
A_o = freestream tube area entering the inlet
A_x = area at axial station x
D = inlet lip diameter (capture diameter)
M_{des} = design Mach number
M_{th} = throat Mach number
M_∞ = freestream Mach Number
m_{bl} = bleed mass flow
m_∞ = capture mass flow
$pt_{2_{max}}$ = Maximum engine-face total pressure
$pt_{2_{min}}$ = minimum engine-face total pressure
$\overline{pt_2}$ = area weighted average engine-face total pressure
pt_∞ = freestream total pressure
R = cowl lip radius (capture radius)
x = axial station
Δx = incremental axial distance
α_u = unstart angle of attack

Introduction

A LARGE-scale model of a mixed-compression axisymmetric inlet system designed for Mach number 3.5 has been tested recently in the Ames Unitary Plan Wind Tunnel.[1,2] The boundary-layer bleed system of the model was designed using relatively new analytical methods.[3] When the new methods were used, expected performance was achieved in the throat. The inlet system required the complication of a traveling-bleed system aft of the on-design throat station on the translating centerbody. The traveling bleed was required because the throat of the inlet remained fixed on the cowl as the centerbody translated for off-design operation.

Prior to the existence of the new analytical methods, a large-scale model of an axisymmetric inlet system with a fixed-bleed system also was tested.[4] When "cut and try" methods were used in the wind tunnel, acceptable performance was achieved at the simulated engine face. The inlet was less complicated, in that no traveling-bleed system was required. This simplier inlet was feasible because the throat remained fixed on the centerbody instead of the cowl, as the centerbody was translated for off-design operation.

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In this paper the two inlets are studied and compared. The main objective is to describe their physical and performance differences and then show how the fixed-bleed inlet can be modified to achieve better performance than the traveling-bleed inlet.

Traveling-Bleed Inlet

One problem with axisymmetric inlet systems is the relatively low transonic engine airflow supply inherent with this type of inlet. That is, with only a translating centerbody for off-design operation, the maximum transonic airflow is limited.[5] The traveling-bleed inlet, shown in Fig. 1, is just such an inlet, with a theoretical maximum capture mass-flow ratio of 0.424 at Mach number 1.0. For this inlet, which was designed for high transonic airflow, the throat is fixed near the cowl minimum-diameter location, as the centerbody is translated for off-design supersonic operation. To design a boundary-layer control system that will remove boundary-layer flow on the centerbody opposite the cowl throat location, a traveling-bleed system must be provided, as shown. That is, each band of bleed holes aft of the design throat location on the centerbody is backed by a separate plenum chamber, which ports, in turn, to internal passageways in the centerbody support tube as the centerbody translates. Centerbody bleed, then, is directed through these internal passageways in the support tube into ducts in the support struts, and then exhausted overboard through louvers at the ends of the support struts. This system is not only complex, but the compartmentation in the aft part of the centerbody means that the centerbody support struts must be located downstream of the bleed regions, resulting in a rather long inlet (2.55D from the cowl lip to the engine face). Bleed from all other regions was removed through ducts that were isolated from each other and exhausted to the freestream through separate sets of louvers. This increased the average bleed pressure recovery‡ and, therefore, minimized the momentum drag of the bleed airflow.All holes were slanted forward 20° from the local surface (except in the cowl throat) to further maximize the bleed airflow pressure recovery and reduce the required duct size.

Another problem with designing an inlet with a fixed cowl throat location (which provides a high-transonic airflow supply) is that unfavorable contours on the centerbody occur in the subsonic diffuser. That is, the rapidly curving aft cen-

‡If all bleed regions were vented to a common plenum chamber, the region with the lowest plenum pressure recovery would determine the pressure recovery for all the regions.

terbody is a result of avoiding a second throat in the subsonic diffuser when the centerbody is translated to its operating position. This rather extreme curvature is not conducive to maintaining attached flow and, as we shall see later, leads to relatively low off-design performance at the engine face.

The effect of the extreme curvature on the duct area distribution is shown in Fig. 2. The design area distribution at $\Delta x/R = 0$, shows a relatively rapid expansion aft of the throat. As indicated, the throat remains nearly fixed near the cowl minimum diameter location as the centerbody translates. Rapid expansion aft of the throat always occurs until the centerbody is positioned for transonic speeds at $\Delta x/R = 1.5$, where the throat moves forward near the cowl lip.

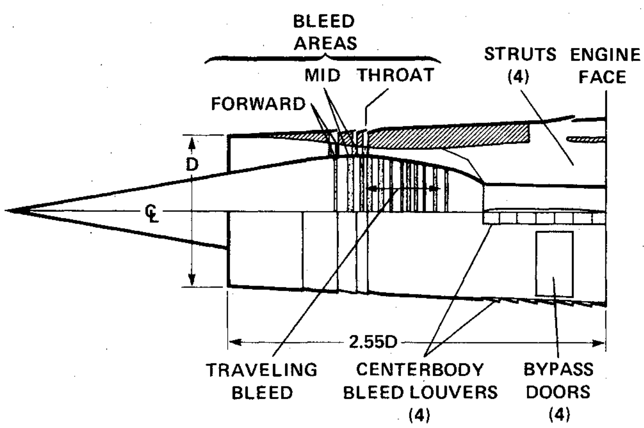

Fig. 1 Traveling-bleed inlet, $M_{des} = 3.5$.

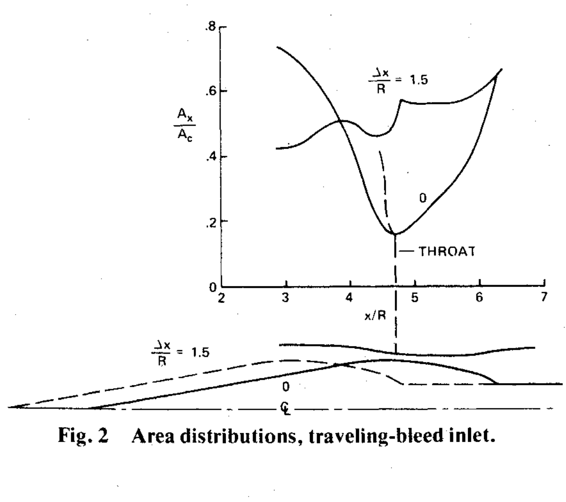

Fig. 2 Area distributions, traveling-bleed inlet.

Fixed-Bleed Inlet

Some of the problems of the traveling-bleed inlet can be avoided with a fixed-bleed inlet design, but at the cost of lower transonic airflow supply. The design of such an inlet having high-pressure recovery, generally, has a maximum centerbody diameter somewhat larger than that of the traveling-bleed inlet. Further, for a fixed-bleed inlet design the throat is fixed near the maximum diameter of the centerbody as the centerbody translates. Such an inlet is shown in Fig. 3.[4] This inlet is 45% shorter (1.4D from the cowl lip to the engine face) than the traveling-bleed inlet. Vortex generators were installed just downstream of the throat to control the airflow distortion at the engine face. The inlet was tested without centerbody support struts, but as will be shown, struts can be incorporated without increasing the length. Boundary-layer bleed was removed in four separate regions: two on the cowl and two on the centerbody. As with the traveling-bleed inlet, flow from each region was ducted overboard through separate exits to maintain high bleed pressure recovery from each region. The bleed holes, however, were not slanted but were normal to the surface.

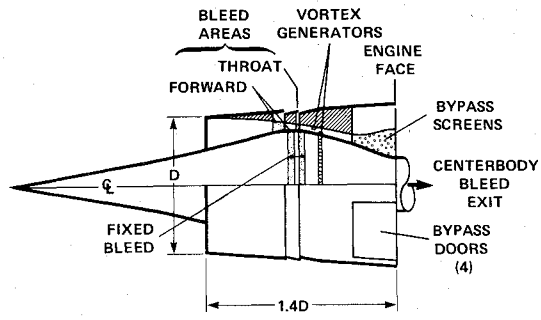

Fig. 3 Fixed-bleed inlet, $M_{des} = 3.5$.

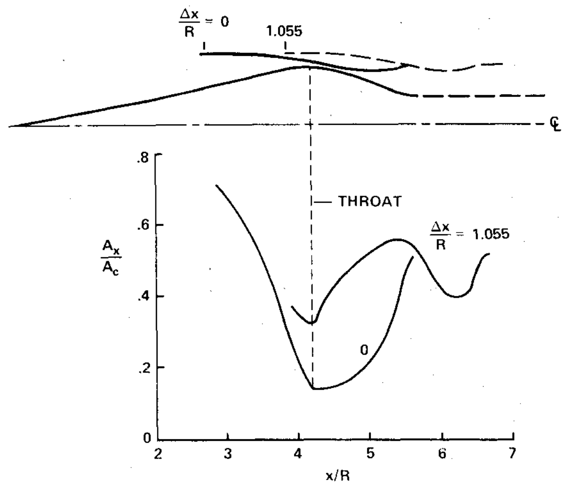

Fig. 4 Area distributions, fixed-bleed inlet.

The result of designing an axisymmetric inlet with the throat fixed near the centerbody maximum diameter essentially is to eliminate the rapid expansion in the region aft of the throat at the design condition. This can be seen by the area distribution at $\Delta x/R = 0$ shown in Fig. 4. It should be noted that this figure differs from Fig. 2 in that the cowl translates instead of the centerbody to illustrate the fixing of the throat on the centerbody. At off-design conditions the expansion aft of the throat station becomes greater as the centerbody approaches the position for transonic speeds. The throat remains fixed on the centerbody even at transonic speeds ($\Delta x/R = 1.055$).

As mentioned previously, the fixed-bleed inlet provides less transonic airflow supply than the traveling-bleed inlet. This is illustrated in Fig. 5, where the airflow supply of each inlet is plotted as a function of Mach number. With an assumed maximum throat Mach number of 0.85, the fixed-bleed inlet has 0.087 less mass-flow ratio at Mach number 1.0 than the traveling-bleed inlet – a decided disadvantage when matched to the demand of advanced variable cycle engines.

Performance Comparisons

The traveling-and fixed-bleed inlets exhibit very different performance characteristics at both on and off-design Mach numbers. The differences stem basically from the differences in design objectives—high transonic airflow supply for the traveling-bleed system, and better subsonic diffuser performance, particularly in the throat region, for the fixed-bleed inlet. The effect of the different objectives on the on-design performance is shown in Fig. 6, where engine-face total-pressure recovery and distortion are plotted as a function of bleed mass-flow ratio. For the traveling-bleed inlet at an operating-point pressure recovery of 0.813, the contraction ratio of the inlet is such that it can tolerate 0.05 sudden reduc-

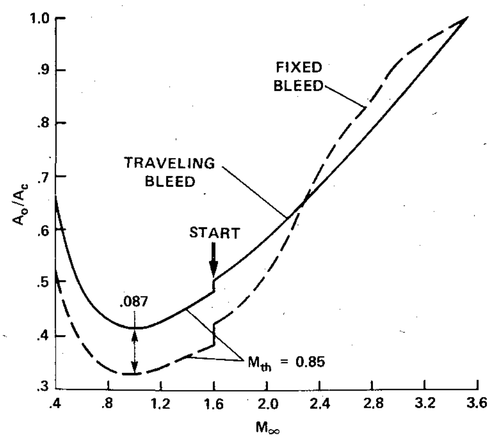

Fig. 5 Inlet supply.

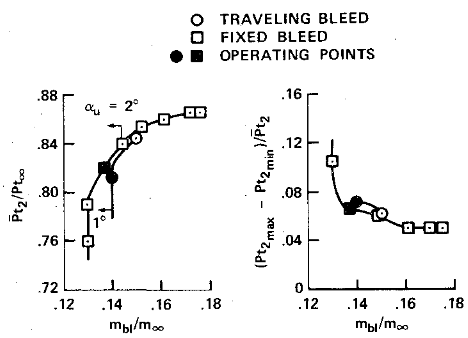

Fig. 6 On-design performance, $M_\infty = 3.5$.

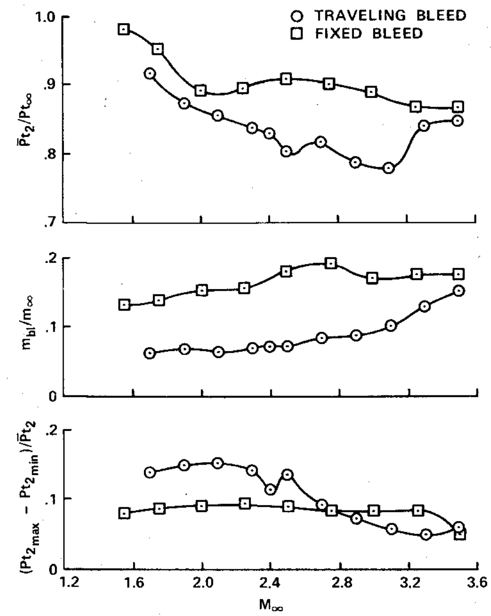

Fig. 7 Supersonic performance.

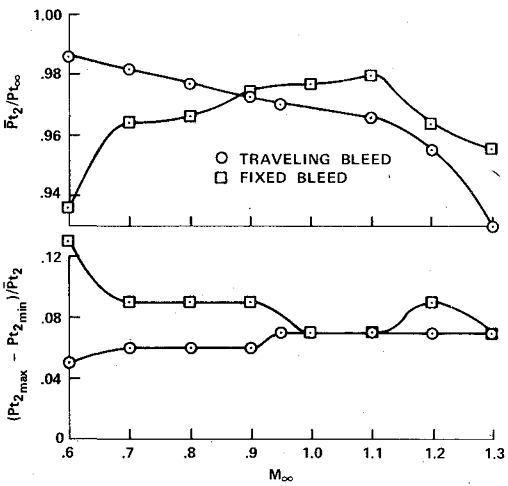

Fig. 8 Transonic performance.

tion in freestream Mach number before unstarting. In addition, the inlet can tolerate 0.05 sudden decrease in engine-face mass-flow ratio (5% corrected weight flow) before unstarting, but the inlet can tolerate only 1° in angle of attack before unstarting. These mass-flow ratios and tolerances are exceeded by the fixed-bleed inlet at a slightly higher pressure recovery of 0.820. Here, the tolerance to sudden reduction in engine mass-flow ratio is increased to approximately 0.086 from 0.05 and the angle-of-attack tolerance to 2° from 1°. As can be seen from Fig. 6, a large part of the 0.086 corrected weight flow tolerance comes from the 0.039 change in bleed mass-flow ratio (0.137 operating to 0.176 unstart) and the remaining 0.047 tolerance from the change in pressure recovery (0.820 to 0.866). This benefit results from the very low rate of increase in flow area aft of the throat of the fixed-bleed inlet. For this inlet the longitudinal distribution of bleed area is greater and, hence, allows the terminal shock wave to move forward over the bleed holes a greater distance from its operating position, hence, forcing more bleed flow through the throat bleed holes. The throat bleed was concentrated in a small area for the traveling-bleed inlet because of the more rapid rate of increase in flow area aft of the throat. Consequently, only a 0.01 change in bleed mass-flow ratio contributed to the corrected weight flow tolerance. Both inlets had a relatively low distortion factor of approximately 0.07 (the fixed-bleed inlet had vortex generators).

The different inlet designs also had a marked effect on the off-design supersonic performance, as shown in Fig. 7. Here, critical (i.e., just before unstart) engine-face pressure recovery, bleed, and distortion are plotted from Mach 1.55-3.performance is comparable, pressure recovery for the traveling-bleed inlet is considerably lower, below Mach number 3.1, because of flow separation on the centerbody side of the subsonic diffuser.[1,2] However, the traveling bleed mass-flow ratio is about one-half that for the fixed bleed, largely because the forward cowl bleed on the fixed-bleed inlet translates into the subsonic diffuser at off-design Mach numbers and merely acts as a bypass of the main duct flow on its was to the engine face. The distortion for the traveling-bleed inlet is not as low as for the fixed bleed inlet below Mach number 2.7 because vortex generators could not be located on the (traveling-bleed) centerbody without translating the generators into the supersonic diffuser at off-design Mach numbers; this would further reduce the off-design pressure recovery.

At transonic speeds, the inlets were not started and operated with the centerbody fully extended (i.e., $\Delta x/R > 1.0$) only in the external compression mode. For comparison of performance, therefore, matching to a typical engine was necessary to establish an operating point. The engine used was fictitious (but typical) in that the maximum corrected engine weight flow was constant from takeoff to Mach 1.4 and decreased linearly thereafter to 54.5% of maximum at Mach 3.5. The performance resulting from this match is compared in Fig. 8, where pressure recovery and distortion are plotted from Mach 0.6-1.3. The pressure recovery of the fixed-bleed inlet above Mach 1.0 was 1-2.5% higher than the traveling-bleed inlet, partly because separation of the subsonic diffusion process in the fixed-bleed centerbody may have been controlled by the vortex generators. Also, the external normal shockwave losses at Mach numbers above 1.0 were less for the fixed-bleed inlet since the turning angle on the cone was greater resulting in a lower terminal shockwave Mach number. Below Mach 0.9, pressure recovery was higher for the traveling-bleed inlet than for the fixed-bleed inlet. At Mach 0.6, pressure recovery for the fixed-bleed inlet suddenly dropped approximately 0.03 to a value of 0.936 because of cowl lip flow separation.[1] This later problem can be alleviated only by increasing the minimum area of the airflow passages by opening takeoff doors or by other openings, which will be described later. As expected, separation increased the distortion factor but only from 0.09-0.13. Distortion for both inlets is relatively low at all transonic Mach numbers. However, it appears that more consideration (testing) should be given to the regime between takeoff and Mach 0.6 to reveal possible performance problems as indicated for the fixed-bleed inlet at Mach 0.6.

Another important aspect of overall performance is the pressure recovery of the bleed airflow. That is, high recovery can reduce the momentum loss through the bleed exits and hence reduce the internal drag, and, as mentioned previously, the bleed ducting size can be reduced. The plenum pressure recovery at critical inlet conditions is compared in Fig. 9. The plenum pressure recoveries in the throat region on both the cowl and centerbody are comparable. Slanting the centerbody throat bleed holes did not increase the plenum recovery by a significant amount. In the forward and mid-bleed plenum chambers, the results are inconclusive. On the cowl, the traveling-bleed inlet with slanted holes in the forward and midregions had higher plenum pressure recovery than the forward region of the fixed-bleed inlet, while on the centerbody the reverse is true. Note, however, that the forward centerbody bleed for the fixed-bleed inlet was closer to the throat where the surface pressures are somewhat higher than for the traveling-bleed inlet (compare Figs. 1 and 2). Slanted holes do have a subtle advantage in that a smaller hole area is required to remove a given amount of bleed flow in the supersonic diffuser; for the forward cowl bleed, this will reduce the off-design overboard bleed mass-flow ratio when the centerbody is translated so that the forward cowl bleed area is exposed to the high pressure subsonic diffuser airflow§ In addition, disturbances caused by the presence of the holes may be minimized since there are fewer holes.¶

	TRAVELING-BLEED INLET		FIXED-BLEED INLET	
	PLENUM	Pt_{bl}/Pt_∞	PLENUM	Pt_{bl}/Pt_∞
COWL	FORWARD	0.06	FORWARD	0.05
	MID	0.15		
	THROAT	0.21	THROAT	0.25
CENTER-BODY	FORWARD	0.09	FORWARD	0.18
	MID	0.15		
	THROAT	0.34	THROAT	0.32

Fig. 9 Critical bleed plenum recovery, $M_\infty = 3.5$.

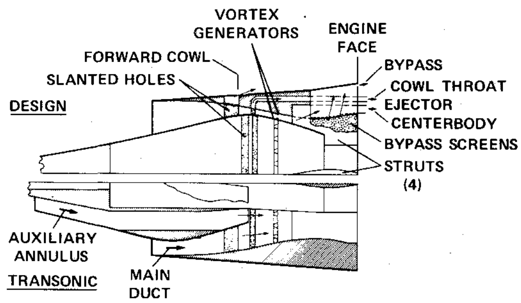

Fig. 10 Advanced fixed-bleed inlet.

Advanced Fixed-Bleed Inlet

The foregoing discussion suggests several possible modifications that can improve the design of the fixed-bleed inlet. Further, new developments are in progress that can favorably influence the performance of the fixed-bleed inlet.

First, it appears that to increase the transonic airflow supply of the fixed-bleed inlet, some form of auxililary opening is required. One possible auxiliary airflow system is shown in Fig. 10, where the centerbody spike is retracted within the centerbody when the centerbody is in the transonic position.[8] An annulus is created which allows auxiliary airflow to pass through the centerbody, exiting aft of the centerbody, and mixing with the main duct flow on its way to the engine face. Approximately a 0.11 increase in Mach 1.0 mass-flow ratio is possible with this design. An alternate means of increasing the airflow (not shown) is to design cowl scoops that will duct air through the bypass screens and mix with the main duct flow.[8] The added complication of the auxiliary airflow system is really a substitute for a traveling-bleed system, but with added advantages. Namely, as mentioned before, the inlet can be short because the struts can penetrate the aft part of the centerbody.

Second, at supersonic operating conditions, properly slanting the forward bleed holes on the cowl and centerbody can increase the pressure recovery in the bleed plenum chambers. In addition, slanting the holes will reduce the exposed hole area and at off-design Mach numbers, where the cowl forward bleed is in the subsonic diffuser, much less flow will be bypassed through this bleed area and hopefully will be bypassed more efficiently through the bypass and/or an engine ejector system.

Third, with the high plenum pressures available for the throat bleed and the even higher pressures (higher than shown in Fig. 9) expected in the centerbody forward bleed, it would seem possible to combine and exit these flows more efficiently through an engine ejector[9] rather than overboard through louvers. (The cowl forward plenum recovery is not expected to be high enough to be used for this purpose.) Also, by exiting the bleed flows through the ejector, the inlet size can be reduced since the flow also substitutes for cooling airflow, which would otherwise have to be extracted from the main duct flow through the bypass screens.

Finally, advances in vortex generator configurations can be applied. That is, instead of the many equally spaced rectangular generators used previously, it has veen found that triangular pairs of generators space approximately two pair spacings apart have been effective.[1] Not only is the number of generators required reduced for similar effectiveness, but the blockage and losses are reduced. Additionally, the cowl generators can be moved farther downstream opposite the centerbody generators without fear of creating excessive blockage at the design condition. Moving the cowl generators farther downsteram should then enable the terminal shockwave system to move farther aft without increasing the supercritical distortion, thus increasing the usable supercritical control margin discussed earlier.

Conclusions

The basic reason for using traveling-bleed systems in axisymmetric inlets is to achieve maximum transonic airflow supply. However, if transonic airflow supply is not a problen in inlet-engine matching, or, if auxiliary airflow openings are employed, a fixed-bleed inlet system appears more attractive. A fixed-bleed inlet system could be made approximately 45% shorter (measured from the cowl lip to engine face) and, hence, lighter than a traveling-bleed inlet design, mainly because the centerbody support struts can penetrate the aft

§It can be readily shown[6] that slanted and normal hole sonic flow coefficients differ much less at subsonic speed than at supersonic speeds. Thus, normal and slanted holes pass about the same airflow per unit hole area when in the subsonic diffuser.

¶Also, recently, it has been shown[7] that slanted holes in the supersonic diffuser of a mixed-compression inlet disturbed the boundary layer less than normal holes.

strut of the centerbody, which cannot be done with a traveling-bleed inlet without adversely disturbing the bleed system. Since the throat of a fixed-bleed inlet remains stationary on the centerbody as the centerbody translates for off-design operation, the throat and subsonic diffuser design results in a relatively larger engine airflow control margin, and the off-design operating performance remains relatively higher than for the traveling-bleed inlet. Finally, it appears that the performance of the fixed-bleed inlet can be further enhanced using the advancements in bleed design methods verified by the tests completed on the traveling-bleed inlet.

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