Bleed System Design Technology for Supersonic Inlets

Jan Syberg* and Joseph L. Koncsek†
The Boeing Company, Seattle, Wash.

A boundary-layer bleed system design procedure for supersonic inlets, with emphasis on the selection of bleed hole geometry, is described. Available experimental bleed hole performance data, coupled with bleed drag calculations, show that holes with shallow inclination are superior to holes normal to the surface in terms of over-all inlet performance. Recent test results from large-scale inlet models indicate that bleed hole size, bleed hole length, and boundary-layer velocity profile upstream of the bleed region are important parameters in the design of an effective and efficient bleed system.

Nomenclature

A = area
A/A^* = sonic area ratio
C_d = drag coefficient
D = bleed hole diameter
H_i = boundary-layer shape factor
L/D = bleed hole length to diameter ratio
$\dot{m}$ = mass flow
M = Mach number
P = pressure
Q = sonic mass flow coefficient; ratio of actual mass flow to theoretical maximum mass flow at local total pressure and temperature
X/D = spacing between rows of bleed holes
Y/D = bleed hole spacing
α = bleed hole inclination to inlet surface
β = exit nozzle ramp angle
δ^* = boundary-layer displacement thickness
η = bleed efficiency factor

Subscripts

bl = bleed
epl = bleed exit plenum
l = cowl lip
loc = local condition
pl = bleed plenum
se = sonic exit
to = freestream stagnation condition
∞ = freestream

Introduction

THE internal aerodynamic performance of a supersonic inlet is defined in terms of total pressure recovery, distortion, angle-of-attack tolerance, stability margin, Mach tolerance, and controllability. The internal performance is strongly influenced by the boundary-layer development through the inlet. If uncontrolled, viscous effects related to boundary-layer growth and velocity profile distortion in adverse pressure gradients and shock interactions can seriously limit the effectiveness of the inlet. The inlet designer can partially eliminate the adverse effects associated with the boundary layer by using a bleed system to control the boundary-layer development. Removal of the low-momentum fluid near the wall reduces the thickness and improves the profile of the boundary layer. A boundary layer with a "full" velocity profile is less susceptible to separation through shock interactions and adverse pressure gradients, and grows at a slower rate than a boundary layer with a distorted velocity profile.

The bleed flow removed through the inlet surfaces is vented overboard through bleed exits, resulting in increased nacelle drag which on a high Mach number supersonic inlet significantly affects the over-all performance of the propulsion system. The goal of the inlet designer is to achieve good internal aerodynamic performance with minimum drag.

The purpose of this paper is to introduce a procedure which brings the inlet designer close to his goal of optimum inlet performance without expensive and time-consuming development work, and to present experimental data relating to the selection of the optimum bleed geometry. The method is applicable to both axisymmetric and two-dimensional supersonic inlets. Examples used to illustrate the design method are based on a research report prepared for the NASA Ames Research Center under contract NAS2-6643.

Design Goals

The primary objective in the design of a supersonic inlet is to achieve the internal aerodynamic performance necessary to meet the airplane mission requirements. These requirements include high total pressure recovery for maximum engine thrust; low distortion for satisfactory compressor operation; tolerance to transient changes in freestream Mach number, angle of incidence, and engine corrected flow demand for safety; and repeatable control signals for maximum performance and reliability.

In a high Mach number, mixed-compression inlet this objective can be met only through effective control of the boundary layer. Experience from the development of the SST inlet has shown that bleed must be provided in regions of strong adverse pressure gradients or oblique shock reflections to prevent excessive deterioration of the boundary-layer velocity profile in the supersonic diffuser. One of the inlet designer's goals is, therefore, to define the bleed configuration, both in terms of location and flow rate, that will provide sufficient boundary-layer control to meet the inlet performance requirements.

Bleed drag is incurred when the low-energy boundary-layer bleed flow is discharged overboard from the inlet. The drag force consists of the unrecoverable momentum loss of the bleed flow, the increase in the local external cowl surface pressure at the bleed exits, and the base drag on the trailing edge of the exit nozzle. Boundary layer bleed drag is the most significant component of inlet drag at the cruise Mach number, since spillage drag and excess air drag usually vanish at this condition. For the prototype Boeing SST the range loss due to bleed drag was estimated to be approximately 210 naut miles. Another goal is therefore to minimize the bleed drag while maintaining the boundary layer control needed to meet the performance requirements.

Presented as Paper 72-1138 at the AIAA/SAE 8th Joint Propulsion Specialist Conference, New Orleans, La., November 29–December 1, 1972; submitted December 7, 1972; revision received April 25, 1973.

Index category: Airbreathing Propulsion, Subsonic and Supersonic.

*Specialist Engineer.
†Senior Engineer.

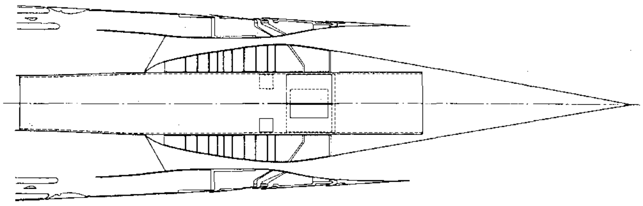

Fig. 1 Mach 3.5 inlet schematic.

Design Procedure

The development of bleed systems for boundary-layer control in supersonic inlets has been based in the past on results of extensive wind-tunnel tests. The tests were complex and time consuming and did not always lead to an optimum system. A bleed system design procedure based on theoretical analysis and extensive empirical information was developed under the SST program. Portions of the procedure and technology have been applied and verified in the design of the SST inlet[1] and a NASA Ames Mach 2.65 inlet.[2] The entire procedure was recently used to design a bleed system for a Mach 3.5 inlet.[3] A schematic of this inlet with the bleed system incorporated is shown in Fig. 1. Application of the analytic design procedure indicated the need for, and resulted in, a bleed system with advanced and complex features that would be unlikely to evolve from normal wind tunnel development testing.

The bleed system design procedure, which is applicable to both two-dimensional and axisymmetric supersonic inlets, is outlined in Fig. 2. Computation of the inviscid flowfield in the inlet is the first step in this procedure. The calculations are carried out at small Mach number increments, say $\Delta M_{1_\infty} = 0.10$, over the started Mach range to define the operating characteristics of the inlet.

The boundary-layer development along the inlet surfaces is then computed. The first solution is computed without bleed at each Mach number for which an inviscid flowfield solution has been obtained. A map of boundary-layer properties on the inlet surfaces vs freestream Mach number is then used to identify regions of high profile distortion, i.e., regions where boundary-layer separation is likely, and thus help in determining bleed locations for optimum boundary layer control. A typical example is shown in Fig. 3. This map of the boundary layer shape factor, H_i, currently used in the procedure was developed for the Mach 3.5 inlet cowl. An H_i of about 1.3 corresponds to a full velocity profile, while an H_i between 1.8 and 2.0 indicates a highly distorted profile close to separation. The map clearly demonstrates where boundary-layer control is needed to avoid separation in the supersonic diffuser.

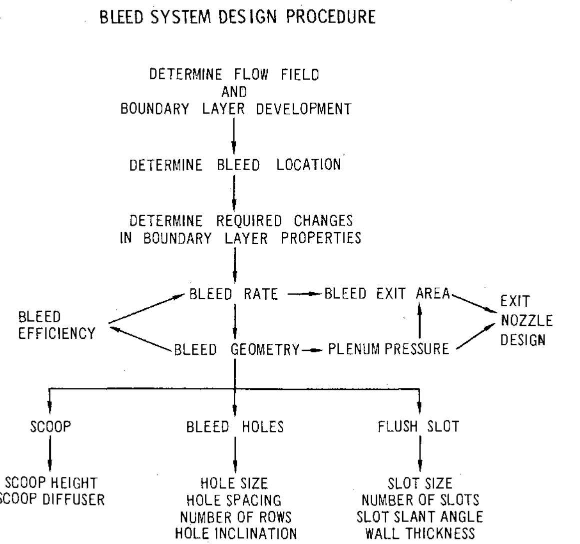

Fig. 2 Bleed system design procedure.

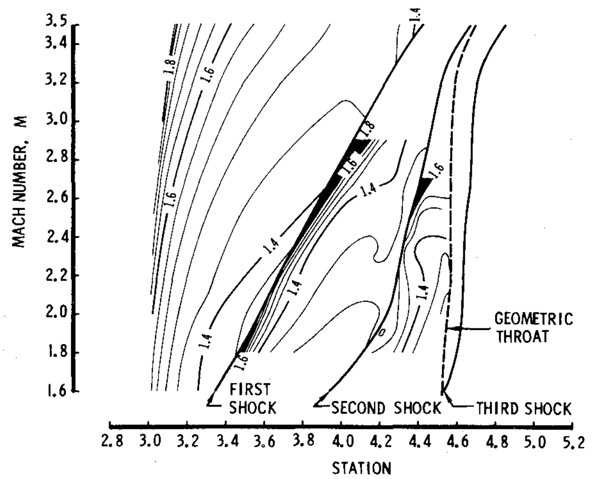

Fig. 3 Map of cowl boundary layer shape factor, H_i. No bleed.

Using the inlet surface pressures and boundary-layer properties, an over-all system is planned and preliminary bleed locations are chosen. The desired improvement in boundary-layer profile across the individual bleed bands must then be defined. The goals are to achieve a boundary-layer which will maintain a reasonably full profile through the pressure gradients or oblique shock reflections in the supersonic diffuser and provide a full profile in the throat to ensure a controllable normal shock/boundary layer interaction. The boundary-layer program used in this design procedure[4,5] includes an analysis of simulated bleed removal, either through a smooth, porous wall or through a sharp-edged scoop parallel to the surface, so that various bleed configurations can be investigated analytically until a satisfactory boundary layer development is achieved. A map of the predicted boundary layer shape factor with bleed incorporated is shown in Fig. 4 for the Mach 3.5 inlet cowl. The bleed regions were located and sized to achieve adequate boundary-layer control throughout the Mach number range while minimizing the bleed flow at the design Mach number.

While the sharp-edged scoop model used in the computer program is an accurate simulation of a boundary layer bleed scoop, the smooth, porous wall bleed model does not take into account the increased boundary layer growth rate across the bleed region. This increased growth rate is caused by the surface roughness due to the presence of slots or holes and the mixing of low- and high-energy air in the boundary-layer. The bleed flow rates required to provide adequate boundary-layer control as defined through application of this analytic model are thus "ideal" flow rates. The current technique is to apply an empirical correction to account for these effects when sizing the bleed geometry, resulting in "actual" bleed flow rates higher than the ideal flow rates.

The actual pressure distribution in the supersonic diffuser of an inlet will vary from the theoretical inviscid distribution used in the bleed system design due to displacement of the flow surface by the boundary layer, oblique shock/boundary-layer interactions, and removal of bleed for boundary-layer control. In a high Mach number inlet these discrepancies may be large enough to require a second iteration on the bleed system design. This can be done by repeating the above steps in the design procedure using the aerodynamic contours, i.e., the geometric contours plus the boundary-layer displacement thickness computed with the initial bleed configuration.

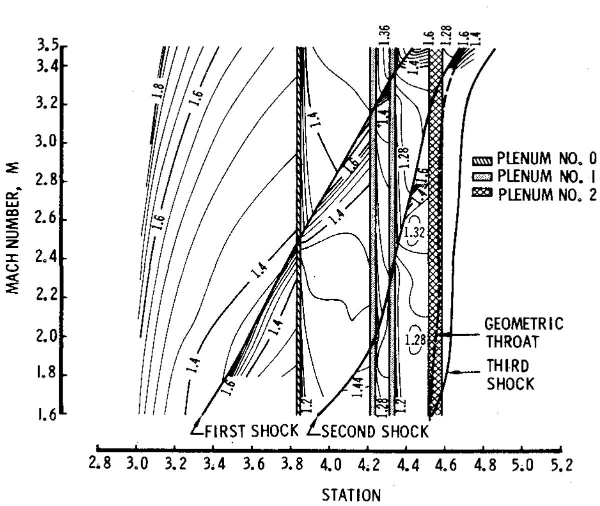

Fig. 4 Cowl H_i map with proposed bleed system.

The next step in the design procedure is to define the bleed geometry, including the bleed exit nozzles. Since the bleed flow rates and locations have been analytically optimized, the inlet bleed system can be optimized by selecting a bleed geometry which provides the desired boundary-layer control with minimum bleed drag. Empirical information used to define an effective and efficient bleed geometry is presented in the following sections, along with a discussion of present design philosophies and methods.

Selection of Bleed Geometry

The effects of bleed flow rate and bleed plenum pressure on drag must be known before the bleed geometry which produces the lowest drag can be selected. The results of drag calculations on an ideal (sharp trailing edge, matched exit pressure), low-angle exit nozzle are shown in Fig. 5. The bleed drag is proportional to the bleed flow rate for constant plenum pressure. Consequently, it is important not only to minimize the bleed flow rate but also to select a geometry which can operate at the highest possible plenum pressure. As shown in Fig. 2, there are basically three types of bleed geometries applicable to supersonic inlets: scoops, flush slots, and bleed holes. This paper primarily deals with bleed holes, but some of the important characteristics of scoops and slots are discussed below.

Scoop

A boundary-layer bleed scoop is a potential low-bleed-drag device, since the dynamic pressure of the captured boundary-layer can be recovered in a well-designed scoop diffuser. The effect of the scoop bleed on the downstream boundary-layer, as well as the maximum scoop recovery, can be accurately predicted when the upstream boundary-layer properties are known. However, the exit area for a boundary-layer bleed scoop must be adjusted such that the scoop will remain started during the "worst" local condition encountered in the entire flight regime. The worst condition in terms of scoop performance is the highest local Mach number in combination with the thickest and most distorted boundary-layer profile. This condition will usually occur at an extreme (and remote) airplane angle of yaw case. Nevertheless, the scoop exit must be sized for this condition, since a scoop unstart in a mixed-compression inlet will usually result in an inlet unstart. Consequently, the exit is oversized at the design point, and the high recovery of the flow captured by the scoop cannot be fully realized at the design Mach number and condition where the bleed drag should be minimized. In order to achieve acceptable performance at the worst condition the scoop

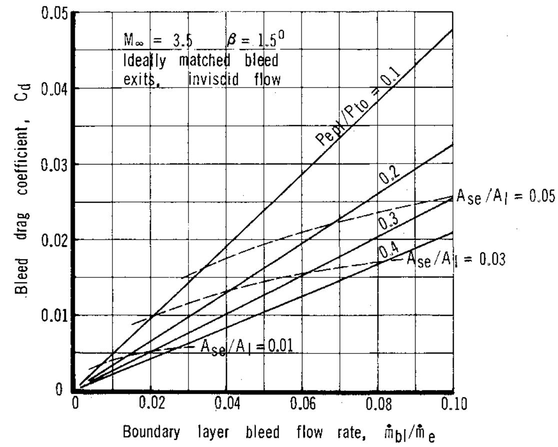

Fig. 5 Inlet bleed drag coefficient.

diffuser must be relatively long, i.e., 20 to 40 times the height of the scoop. The turning just downstream of the scoop lip should also be minimized, resulting in a long, thin lip that is vulnerable to foreign object damage. These disadvantages limit the usefulness of a boundary-layer bleed scoop in a supersonic inlet. Flowfields, boundary layer properties, and physical constraints should be carefully examined before a scoop is selected for boundary-layer control.

Flush Slot

The risk of normal shock spillage from the boundary-layer control device is eliminated in a flush slot. The bleed exit can, therefore, be adjusted for maximum performance at the design point. In addition, the efficiency of a slot in terms of improving the boundary-layer profile is believed to be very high due to the two-dimensional removal of flow from the boundary layer. However, flush slots have had only limited application in inlet models due to both complex and costly fabrication and restricted variability of bleed patterns on a given model. As a result, little experimental data are available to determine the efficiency and flow characteristics of slots applicable to bleed systems in high performance supersonic inlets.

Bleed Holes

Simplicity of model fabrication has made bleed holes the preferred type of bleed geometry for boundary-layer control. In addition, considerable flexibility is available in terms of bleed location as well as bleed flow rate in inlet model testing simply by opening or plugging bleed holes. This method has been widely used in the past for the development of bleed systems for supersonic inlets. The model

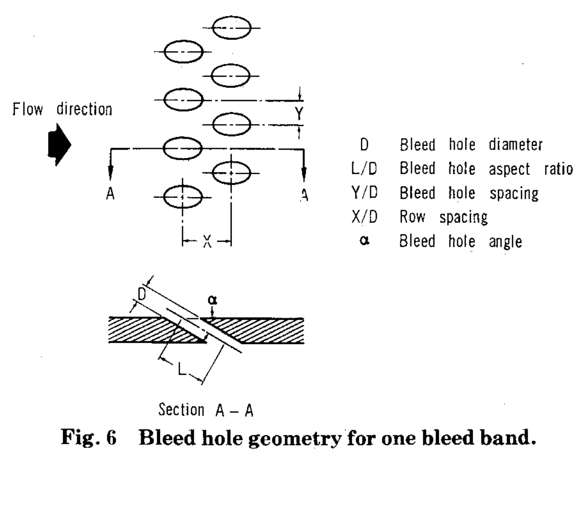

Fig. 6 Bleed hole geometry for one bleed band.

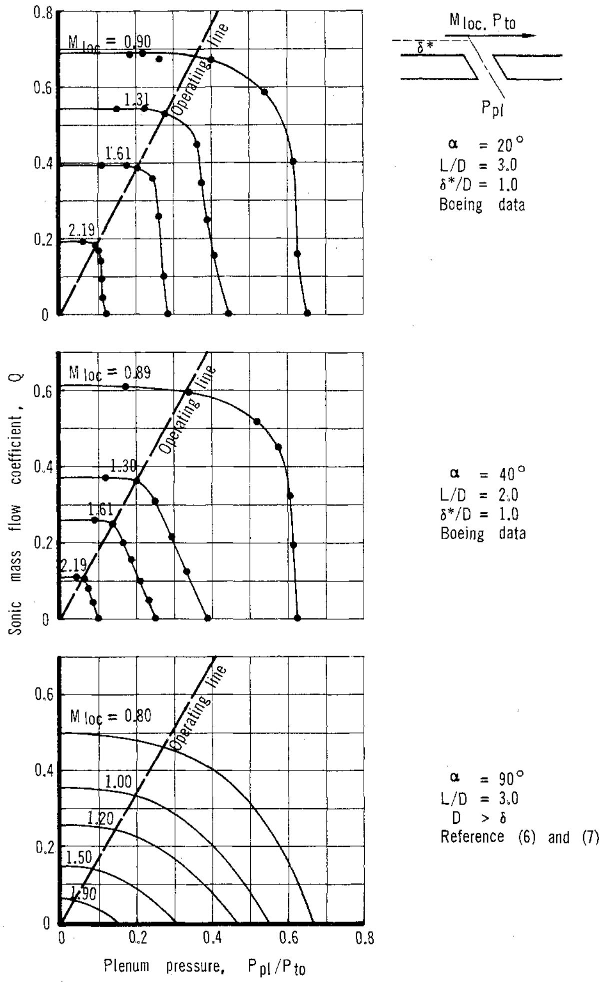

Fig. 7 Bleed hole characteristics.

surfaces were perforated with large bleed holes normal to the inlet surface, and an "optimum" configuration was defined through testing of numerous bleed patterns. The result was usually a pattern which provided good performance at the design point but had shortcomings at off-design conditions. An improved model and more testing would then be needed to define a more complete bleed system.

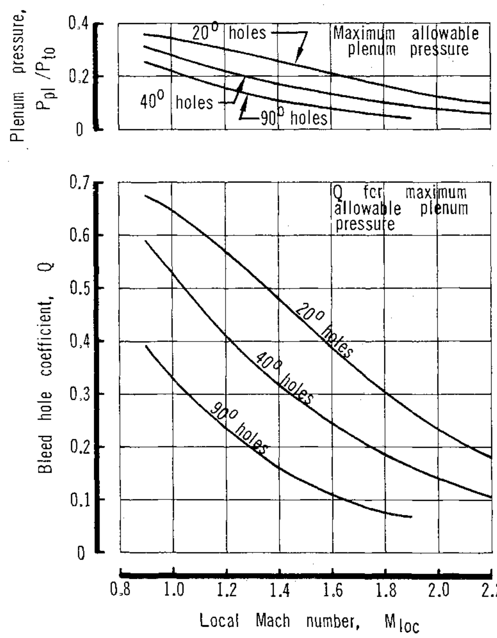

Fig. 8 Bleed hole characteristics for choked holes.

This is time-consuming and expensive and does not give the designer an understanding of the real boundary layer problems in the inlet. Consequently, achievement of an optimum system cannot be expected through application of this method.

The analytic tools used in the present bleed system design procedure allow definition of the optimum bleed locations and the required ideal (smooth, porous wall) bleed flow rates without prior wind-tunnel development tests. Therefore, emphasis can be placed on determining the bleed hole geometry which will provide the desired boundary layer control with minimum bleed drag. The geometric parameters to be considered are defined in Fig. 6.

Flow characteristics for bleed holes must be known to determine the bleed flow rate and the maximum allowable plenum pressure for a given bleed configuration and local flow condition. Empirical information from Boeing tests and from other studies[6,7] has been used to define the characteristics shown in Fig. 7. Knowing the sonic mass flow coefficient, the bleed flow rate can be computed from the following equation:

$$\dot{m}_{bl}/\dot{m}_l = (A_{bl}/A_l) \times (A/A^*)_\infty \times Q \qquad (1)$$

To avoid problems of recirculation between bleed holes within a bleed plenum, and to minimize the bleed hole area and hence the surface roughness, the bleed holes should be choked. To minimize bleed drag the plenum pressure should be as high as possible. Consequently, it is desirable to operate the bleed holes near the "knees" of the curves. For all three bleed hole angles the knees can be closely represented by straight lines through the origins of the plots as shown in Fig. 7. The intersection points between the curves and the straight lines are plotted vs local Mach number in Fig. 8. Both the choked bleed hole mass flow coefficients and the maximum allowable bleed plenum pressures for choked holes are shown. The low-angle holes have higher flow coefficient and can be operated at a higher plenum pressure than the steeper holes; consequently, both bleed hole area and bleed drag will be less for the low-angle holes. The difference in bleed drag is significant, particularly at the higher local Mach numbers, as illustrated in Fig. 9. For the same bleed flow rate the drag coefficient for 90° holes is 80% higher than that for 20° holes at a local Mach number of 1.80. The low-angle holes are therefore superior to the steeper holes in terms of minimizing bleed drag for a given amount of bleed.

For bleed holes located in the throat region of a mixed-compression supersonic inlet there may be another requirement influencing the selection of the bleed hole angle. In addition to boundary-layer control, the throat holes may be required to provide maximum normal shock stability. This requirement calls for holes with a high rate of change in bleed with local Mach number. Figure 10 shows that 90° bleed holes have the highest gain in bleed flow rate

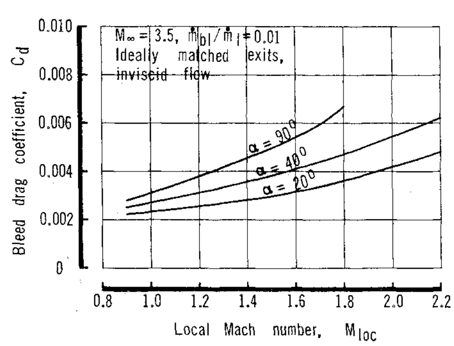

Fig. 9 Effect of bleed hole angle on bleed drag.

vs Mach number. If the local Mach number decreases from 1.2 to 0.8 (typical condition in the throat when the normal shock moves to the critical position) the bleed rate for the 90° holes almost doubles. For 20° holes the increase is only about 25%.

The ratio of critical to supercritical flow rates can be increased beyond that of the 90° holes by using "educated" or rearward facing bleed holes. However, the penalty for the increased normal shock stability is again increased bleed drag at the operating point. The characteristics of these types of bleed holes are not included due to insufficient amount of empirical data.

The efficiency of the actual bleed as compared to ideal bleed through a smooth, porous wall must be taken into account before the actual bleed rate and thus the bleed hole area can be defined. This is presently done by assigning an efficiency factor to the selected hole configuration. If, for example, an ideal bleed rate of 0.010 $\dot{m}_l$ is required to achieve the desired change in boundary layer properties and the efficiency factor, η, for the selected bleed hole configuration is 0.50, then the bleed holes will be sized to provide a bleed rate of 0.020 $\dot{m}_l$. The efficiency factor, as defined above, is a function of hole size, hole spacing, hole inclination to the wall, amount of bleed removed from the boundary layer, local flow conditions, and local boundary-layer properties. Since the bleed configuration affects both the bleed rate and the efficiency factor, an iteration is required to define the configuration which will provide the desired profile improvement. Only a limited amount of data is presently available to determine the efficiency factor for a given bleed configuration. However, analyses of test results from previous test programs,[3-5] indicate that η = 0.80 can be used as a good approximation if the selected bleed hole configuration satisfies certain requirements of hole spacing and hole size. These requirements are discussed below along with geometry requirements that must be met to minimize bleed drag.

The bleed hole spacing is defined in Fig. 6. This is the spacing that determines the circumferential bleed distribution in a given bleed band. The philosophy that is used in the bleed system design is to bleed the entire circumference in each bleed band. Mixing between bled and unbled regions, with its attendant total pressure loss, is not relied on for boundary-layer profile improvement; therefore, a spacing as close as possible to 1.0 is used. It is felt that the use of significantly wider spacing and the reliance on mixing between bled and unbled regions will produce a less efficient bleed system than one with a fully bled circumference. To achieve the fully bled circumference the pattern will always be a pair or pairs of rows with staggered holes.

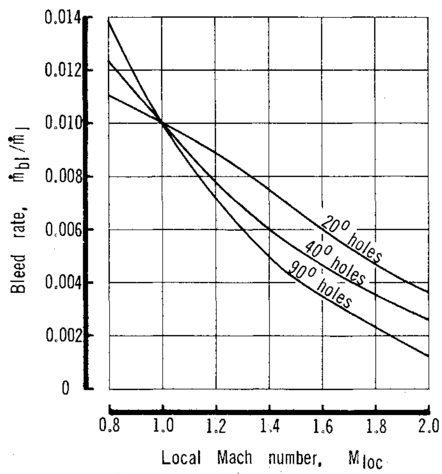

Fig. 10 Effect of local Mach number and bleed hole angle on bleed mass flow.

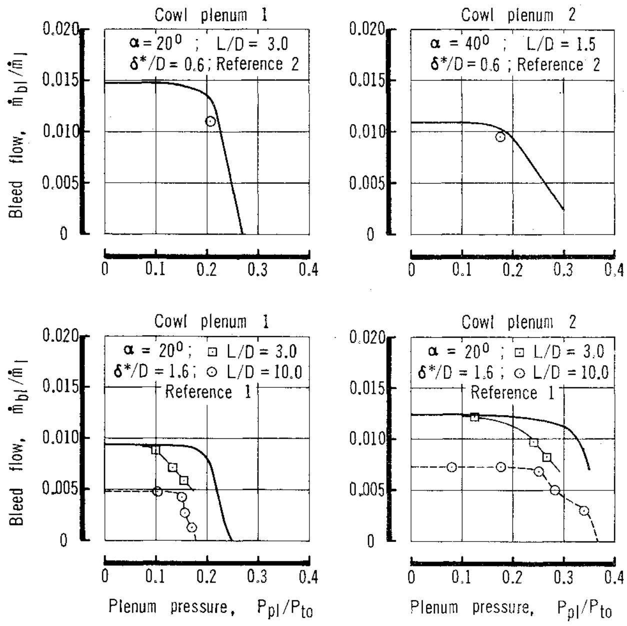

Fig. 11 Comparison of predicted and experimental bleed rates for 1/3-scale inlet tests.

The criteria for selecting axial spacing between rows in a bleed band are not well established. Obviously, the minimum spacing will be determined by structural considerations, and there are no clear-cut maximum spacing criteria. If the holes are very widely separated considerable mixing will take place between rows, and since the concept of bleed hole selection does not rely on mixing, it would seem that very large spacing is not desirable. As a result, a center-to-center spacing of three to five hole diameters for 20° holes and about two hole diameters for 90° holes is presently used.

The bleed hole diameter and the aspect ratio (hole length to diameter) are important geometric parameters in the selection of a highly efficient bleed system. Experience from development of the SST supersonic inlet[1] has indicated that the efficiency of the bleed system improves as the hole diameter decreases. However, if the holes are too small they may significantly affect the bleed hole characteristics from Figs. 8 and 9. This is illustrated in Fig. 11, which shows test results from two inlet test programs.[1,2] The bleed holes on both inlets were sized to provide the desired bleed flow rates using the predicted local flow conditions at the individual bleed regions in combination with the bleed hole flow characteristics from Fig. 8. As indicated in Fig. 8, these characteristics were obtained for $\delta^*/D = 1.0$. In addition, the data are limited to conditions with fully developed boundary layer profiles upstream of the bleed region. The test results in Fig. 11 indicate that good agreement between inlet data and the empirical hole characteristics is obtained if the hole diameter is larger than δ^*. When the holes are much smaller than δ^* they unchoke at a lower plenum pressure than predicted. The data also show that the hole length has a significant effect on the bleed hole performance for the small holes. The fact that the boundary-layer profiles in front of bleed bands in a supersonic inlet normally are distorted, due to upstream compression regions and oblique shock reflections, may have contributed to these deviations. It appears that more experimental information is needed to predict the performance of bleed holes accurately, and thus define the best configuration. However, the existing data indicate that a near-optimum design, i.e., maximum bleed efficiency coupled with high bleed plenum pressure, is obtained for $\delta^*/D = 1.0$ and $L/D \leq 4$.

The above criteria for bleed hole size, spacing, and inclination to the surface were used in the analytic design of

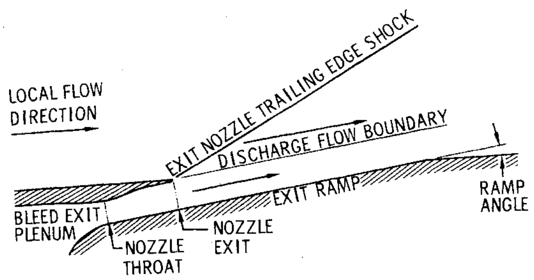

Fig. 12 Bleed exit nozzle schematic.

a bleed system for a Mach 3.5 inlet.[3] The resulting system includes advanced features such as:

1) Bleed hole diameters varying from bleed region to bleed region to maintain a hole spacing near unity, meet the requirement of $\delta^*/D \approx 1.0$, and provide the desired bleed flow rate.

2) Bleed holes inclined 20° to the surface on the centerbody and forward cowl, primarily to achieve maximum plenum pressures thereby minimizing bleed drag.

3) Cowl throat bleed holes normal to the surface to maximize the normal shock stability margin.

A large-scale model of this inlet will be tested in a wind tunnel in the near future and will provide additional information to improve the accuracy and completeness of the bleed system design procedure.

Bleed Flow Discharge

Plenum Arrangement

To adequately control the boundary layer development in a supersonic inlet, bleed must normally be provided at one or more locations in the supersonic diffuser. In addition, bleed is required in the throat region to control the normal shock/boundary layer interaction. The bleed regions are thus located at different local flow conditions such that the maximum allowable plenum pressures vary from region to region. To minimize the bleed drag each bleed region must be operated at the highest possible pressure. This is achieved by collecting the bleed from the regions into separate plenums and ducting the flow to individually sized exits.

The ducting arrangement between bleed plenums and exits is an important part of the bleed system design. Pressure losses in this system should be minimized, since bleed drag increases with decreasing total pressure at the bleed exit. Using the predicted bleed flow rate and the maximum allowable plenum pressure for choked bleed holes, the duct should be sized to maintain low Mach numbers in the flow channels, in particular, in areas of sharp turns.

Bleed Exit Area

Having defined bleed flow rates, plenum pressures, plenum arrangement, and ducting losses, the bleed exits for the individual plenums can be sized. Assuming that the total pressure in the bleed exit is high enough to choke the flow and that the blockage in the nozzle is negligible, the sonic exit area can be computed from the following equation:

$$A_{se}/A_l = \frac{\dot{m}_{bl}/\dot{m}_l}{(P_{epl}/P_{to}) \times (A/A^*)_\infty} \tag{2}$$

Combining Eqs. (1) and (2) it can be seen that the relationship between sonic exit area and bleed area is independent of the bleed flow rate and the freestream Mach number:

$$A_{se}/A_l = [Q/(P_{epl}/P_{to})] \times (A_{bl}/A_l) \tag{3}$$

If the pressure loss in the ducting between bleed holes and exit is negligible the following equation is obtained:

$$A_{se}/A_l = [Q/(P_{pl}/P_{to})] \times (A_{bl}/A_l) \tag{4}$$

The term $Q/(P_{pl}/P_{to})$ is the slope of any straight line through the origins of the bleed characteristics plots in Fig. 7. As mentioned earlier, the knees of the characteristics for a given bleed hole angle can be well represented by a straight line and, therefore, by a slope, $Q/(P_{pl}/P_{to})$. The sonic exit area which pressurizes the bleed holes to the maximum allowable pressure is simply:

$$A_{se}/A_l = C_\alpha \times (A_{bl}/A_l) \tag{5}$$

where $C_{20°} = 1.90$, $C_{40°} = 1.80$, and $C_{90°} = 1.70$.

The simple relationship between the two flow areas also means that if the exit is sized for optimum operation at one condition (freestream and local), the system will maintain its optimum operation, i.e., near the knees on the bleed hole characteristics, as the freestream and local flow conditions change. If the bleed area for a given bleed exit changes, for example through translation of a centerbody with a traveling bleed system, the sonic exit area must be changed correspondingly to avoid inefficient operation or unchoking of the bleed holes.

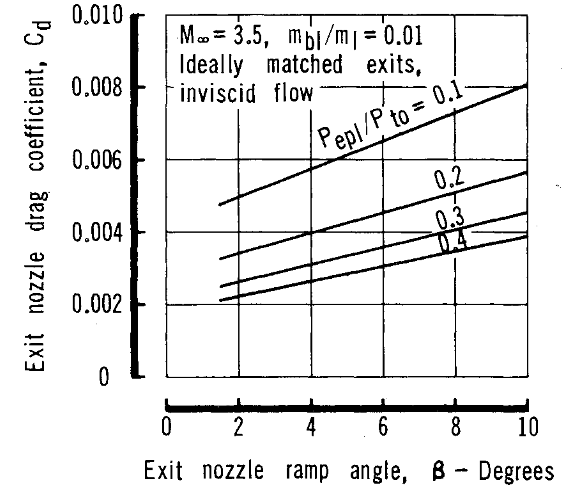

Fig. 13 Effect of ramp angle on exit nozzle drag coefficient.

Exit Nozzle Design

A typical bleed exit nozzle is shown schematically in Fig. 12. For minimum bleed drag, the axial thrust of the nozzle should be maximized while minimizing the wave drag on the exit ramp and the base drag on the trailing edge of the nozzle. No applicable drag data have been found in the literature for geometries that meet these requirements, i.e., nozzles with low discharge angle. The drag coefficients presented in this paper are based on theoretical analysis assuming inviscid flow within the exit nozzle as well as on the external cowl surface. In addition, it was assumed that the flow in the nozzle is expanded isentropically to match the pressure downstream of a shock which turns the external flow parallel with the exit ramp (i.e., the nozzle is "matched" to the external conditions) and that the nozzle has a sharp trailing edge. Although the magnitude of the calculated drag coefficients may be somewhat in error due to these assumptions, the trends indicated are considered to be correct.

The nozzle thrust is a function of the plenum pressure and the exit Mach number. The wave drag is determined by the discharge angle. Trailing edge base drag is zero in the analysis, as a result of the sharp trailing edge assumption. Figure 13 shows the analytic results for the effect of exit ramp angle on nozzle drag coefficient, and indicates that drag increases rapidly with ramp angle. For instance, the overall drag coefficient for a nozzle with a 10° exit ramp is about 75% higher than for a nozzle with a 2° ramp.

Figures 5 and 13 indicate that the sizing and design of the bleed exit nozzles have a significant effect on over-all inlet performance. Drag coefficients for various plenum pressures and nozzle throat (sonic) areas are shown as a function of bleed flow rate on Fig. 5. Note that if the flow rate is held constant, increasing the throat area results in decreased plenum pressure and increased drag. If the throat area is too small, the increased plenum pressure will unchoke the bleed holes, resulting in reduced boundary layer control efficiency. For this reason, close manufacturing tolerances must be maintained in the throat region of the nozzle. On Fig. 13, the constant plenum pressure lines also represent constant nozzle throat areas. It is seen that once the nozzle is properly sized, the bleed drag coefficient can still be greatly influenced by varying the discharge angle. It is further indicated that the ramp angle should be selected as the minimum allowed by structural design limits.

Concluding Remarks

The design procedure described in this paper allows definition of an effective and efficient bleed system without time-consuming and costly wind-tunnel development testing. Boundary-layer control requirements are defined analytically, while the bleed geometry providing the desired control with minimum drag is selected on the basis of empirical information.

The bleed hole inclination relative to the surface is an important parameter in the design of a low-drag bleed system, because the maximum allowable bleed plenum pressure increases as the angle of inclination decreases. Since bleed drag is a strong function of plenum pressure, holes with shallow inclination to the surface are superior to holes normal to the surface in terms of over-all inlet performance. Bleed hole diameter, length, and spacing can also significantly affect the efficiency of the bleed system. These parameters should be sized on the basis of local flow conditions and boundary layer properties. Bleed from the various regions should be collected in separate plenums and ducted to individually sized exits with low discharge angles to further reduce the bleed drag.

The bleed system design procedure presents a significant advance in supersonic inlet design technology. Additional experimental data and analytical tools can be incorporated in the basic procedure, as they become available, to expand the applicability of the procedure and improve the accuracy of the predictions.

References

[1]Syberg, J. and Koncsek, J. L., "Transonic and Supersonic Test of the SST Prototype Air Intake," Rept. FAA-SS-72-50, April 1972, Federal Aviation Administration, Washington, D.C.

[2]Koncsek, J. L. and Syberg, J., "Transonic and Supersonic Test of a Mach 2.65 Mixed-Compression Axisymmetric Intake," CR-1977, March 1972, NASA.

[3]Syberg, J. and Hickcox, T. E., "Design of a Bleed System for a Mach 3.5 Inlet," CR-2187, Jan. 1973, NASA.

[4]Reyhner, T. A., "A Computer Program for Finite Difference Calculation of Compressible Turbulent Boundary Layers," D6-23236, 1970, The Boeing Co., Seattle, Wash.

[5]Reyhner, T. A. and Hickcox, T. E., "A Procedure for Combined Viscous-Inviscid Analysis of Supersonic Inlet Flowfields," *Journal of Aircraft,* Vol. 9, No. 8, Aug. 1972, pp. 589–595.

[6]Dennard, J. S., "A Transonic Investigation of the Mass-Flow and Pressure Recovery Characteristics of Several Types of Auxiliary Air Inlets," RM L57B07, 1957, NACA.

[7]McLafferty, G. and Ranard, E., "Pressure Losses and Flow Coefficients of Slanted Perforations Discharging from Within a Simulated Supersonic Inlet," R-0920-1, 1958, United Aircraft Corp., East Hartford, Conn.