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Technical Notes

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Bleed Lip Geometry Effects on the Flow in a Hypersonic Wind Tunnel

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I. Introduction

LAMINAR-turbulent transition in boundary layers is important for the prediction and control of skin friction, heat transfer, and other boundary layer properties. Therefore, it is important to have reliable capabilities in predicting boundary layer transition to optimize hypersonic vehicle performance [1]. The mechanisms leading to transition are poorly understood [2]. Transition experiments have been carried out in conventional ground testing facilities for many decades. However, most of the experimental data obtained from these facilities are not reliable because they have much higher disturbance levels compared with actual flight conditions [3].

Quiet-flow wind tunnels are intended to replicate the low noise conditions of actual flight at hypersonic speed. Reaching quiet flow requires the maintenance of a laminar boundary layer on the nozzle wall to avoid acoustic fluctuations generated by boundary layer turbulence. One method to reduce noise is to delay boundary layer transition using a bleed slot before the nozzle throat. The Boeing/Air Force Office of Scientific Research (AFOSR) Mach 6 wind tunnel at Purdue University has been designed as a quiet tunnel with a bleed slot for which the noise level is an order of magnitude lower than that in conventional wind tunnels. It is a Ludwieg tube that is a long pipe having a converging-diverging nozzle followed by a test section as shown in Fig. 1. A close-up view of the tunnel geometry around the bleed slot lip is shown in Fig. 2.

However, the tunnel (which has been operational since 2001) is not yet quiet for the desired range of stagnation pressures of up to 150 psi. Two different nozzles have been fabricated and tested. The tunnel is quiet up to a stagnation pressure of 8 psi with the original electroformed nozzle. The original design of the outer surface of the bleed slot has been modified, and eight different bleed slot designs together with the original one have been tested [4]. A second nozzle throat has been fabricated from aluminum [5]. The tests on the tunnel with this aluminum surrogate throat show that the tunnel is quiet up to a stagnation pressure of 93 psi.

Early transition of the nozzle wall boundary layer has been identified as the cause of the test section noise for the tunnel at Purdue University. Separation bubbles on the bleed lip and associated fluctuations induced near the bleed lip were identified as the most likely cause of early transition [4]. The experimental study of Klebanoff and Tidstrom [6] showed that the presence of a separation bubble of sufficient size destabilizes the laminar boundary layer downstream of reattachment thereby leading to an earlier transition to turbulence, i.e., the location of transition moves upstream relative to where it would occur without the separation bubble. This hypothesis regarding a separation bubble was supported by the measurements showing an increase in quiet-flow stagnation pressure from 8 to 93 psia when the electroformed nozzle throat was replaced with the aluminum throat [5]. The bleed lip of the electroformed throat has a 0.001 in. kink that is not present in the aluminum throat, and it appears that the kink in the electroformed throat exacerbates a natural tendency to form a separation bubble near the lip. This separation bubble is highly unsteady and can lead to early transition downstream [7]. However, the separation bubble apparently still exists even at 93 psia, according to the computations presented herein. To achieve quiet flow above 93 psia, and to make the quiet flow less sensitive to the exact shape of the bleed lip, it is desirable to eliminate the separation bubble completely.

The situation in the hypersonic wind tunnel at Purdue University is an example illustrating the importance of the bleed lip geometry and the effects of separation bubbles that form around the bleed lip on the quality of the flow at the test section. The objective of this study is to demonstrate the effect of separation bubbles on flow structure by numerically investigating the existence of steady and unsteady separation bubbles on the main-flow or the bleed-flow side of the nozzle lip of the Boeing/AFOSR Mach 6 wind tunnel at Purdue University, and to design a new geometry to eliminate or reduce the size of the separation bubbles.

II. Methodology

Steady and time-accurate computations are performed for both the original geometry and the new designs using GASPex version 4.1.2 [8]. The laminar compressible Navier–Stokes equations are solved. For the modeling of inviscid fluxes, the third order Roe's scheme with Harten correction is used. The min-mod limiter is employed as a flux limiter. The boundary conditions are shown in Table 1.

The implicit dual time stepping method was utilized for the time-accurate computations. The time for the flow to go from the bleed lip to the end of the computational domain was calculated to be 0.28 ms. The velocities used for calculating the average velocity are the velocities in the steady state solution. The total simulation time was taken to be 4 times the time necessary for the flow to go from the bleed lip to the exit of the computational domain, corresponding to 1.1 ms. The values obtained from the steady state solution were used for all the flow parameters as an initial condition for the time-accurate computations.

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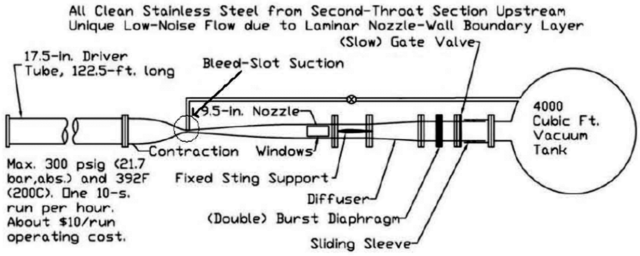

Fig. 1 Boeing/AFOSR Mach 6 wind tunnel.

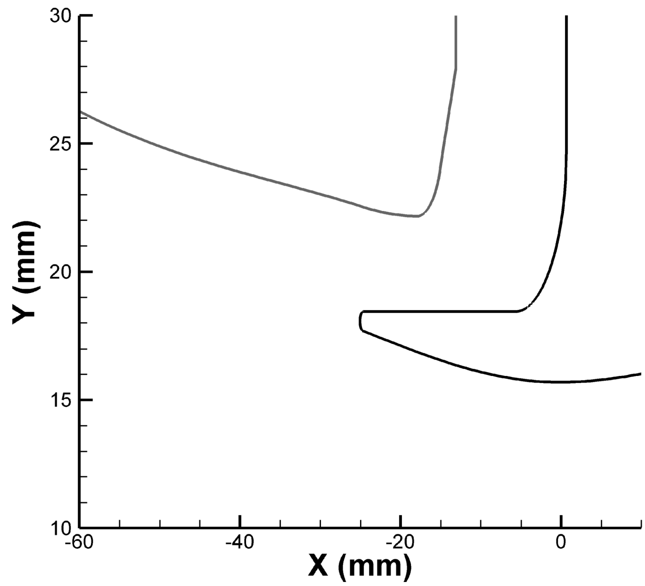

Fig. 2 Case 7 bleed slot geometry (not to scale).

III. Analysis of Existing Bleed Slot

The computations were performed for the bleed slot geometry case 7 of the original electroformed nozzle of the Boeing/AFOSR Mach 6 wind tunnel, which was the most successful design that reached the highest stagnation pressures with quiet flow among all the bleed slots tested for the electroformed nozzle.

Two different grids generated using GridPro [9] were used in the computations. For the first grid, the domain was divided into eight different zones. The total number of grid points is 99,928, and the minimum grid spacing is 0.01 mm around the bleed lip. For the second grid, the minimum grid spacing around the bleed lip is 0.001 mm, and the total number of grid points is 192,184. Grid clustering was performed around the bleed lip with a stretching parameter of 1.105 for both of the grids.

Steady simulations of case 7 had been performed at 8 and 14 psi stagnation pressures [10]. Steady simulations at 150 psi and time-accurate computations at 8 and 14 psi stagnation pressures are presented here.

A. Results of Steady Flow Computations

Separation bubbles exist on both the main-flow and the bleed-flow sides of the bleed lip of the case 7 geometry for a stagnation pressure of 150 psi. The lengths of the separation bubbles on the main- and bleed-flow sides of the bleed lip are 1.15 and 2.2 mm, respectively. The streamlines superimposed with Mach number contours for the flow at 150 psi are shown in Fig. 3. The magnified plot around the bleed lip is shown in Fig. 4.

Table 1 Boundary conditions

Boundary	Boundary condition
Inflow	Po–Riemann subsonic inflow
Bleed slot exit	Forced outflow
Nozzle exit	Forced outflow
Solid walls	No slip-adiabatic
Symmetry plane	X-axis axisymmetric
Side walls	Axisymmetric wall

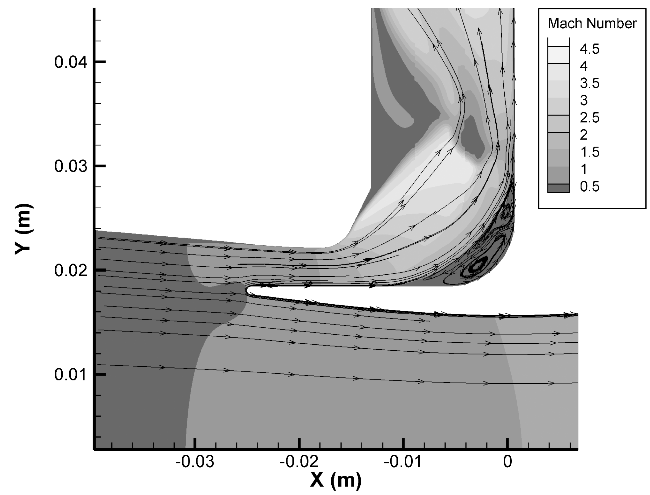

Fig. 3 Mach number contours for case 7.

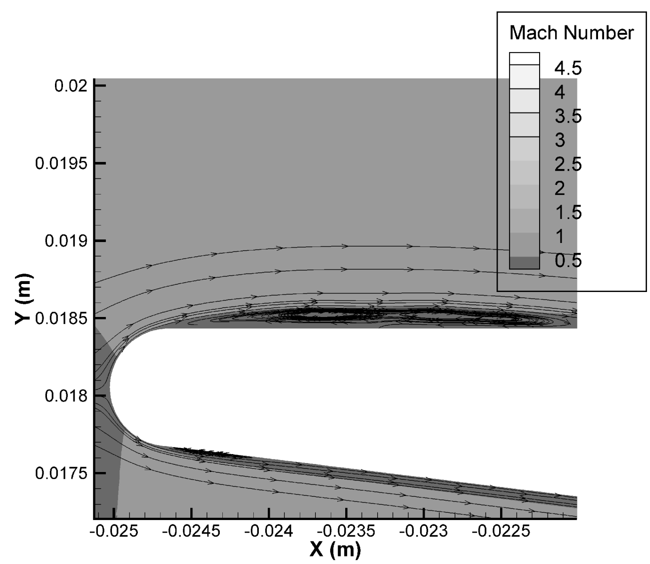

Fig. 4 Streamlines around the bleed slot for case 7 at 150 psi.

B. Results of Time Dependent Flow Computations

For the flow at 8 psi, no unsteadiness was observed in the flow. For the flow at 14 psi, unsteadiness was observed in the flow around the separation bubble on only the bleed-flow side of the bleed lip. The wall shear stress values were calculated for the points around the bleed slot lip. The definitions of the vectors representing the surface around the bleed lip are shown in Fig. 5. The vectors are taken as positive in the positive x direction for both the upper and the lower surfaces.

The shear stress at the wall is defined as

$$\tau_w = \mu_w \frac{\boldsymbol{s} \cdot \boldsymbol{V}}{\Delta n} \tag{1}$$

where μ_w is the viscosity, $\boldsymbol{s}$ is the vector parallel to the surface, $\boldsymbol{V}$ is the velocity vector, and Δn is distance between the wall and the next grid point.

The shear stress variation for the upper surface at 14 psi for several time values is shown in Fig. 6. There is unsteadiness in the shear stress at 14 psi. The first location where the shear stress is negative corresponds to the separation bubble on the bleed-flow side of the lip.

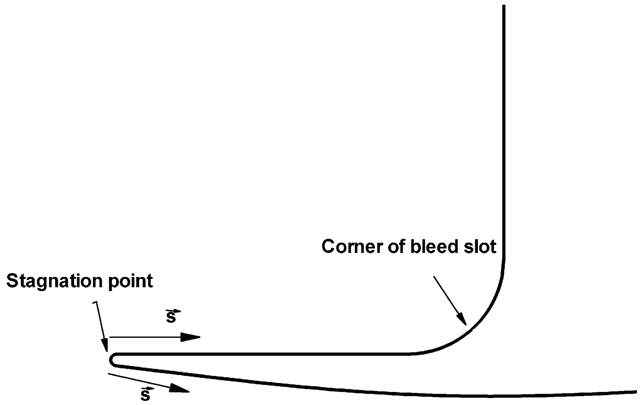

Fig. 5 Surface vectors.

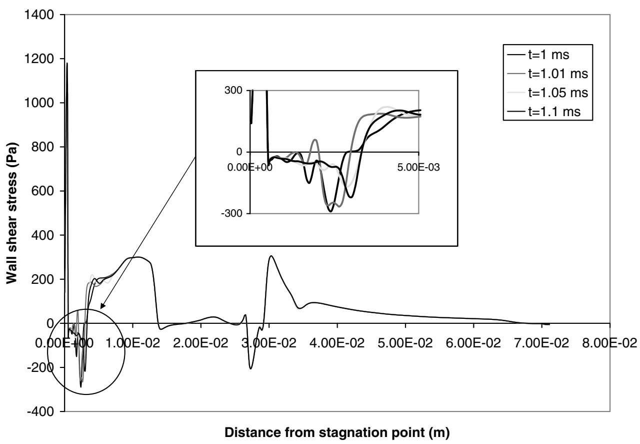

Fig. 6 Shear stress variation for the upper surface at 14 psi.

The second location where the shear stress has negative values corresponds to the recirculation region on the corner of the geometry (Fig. 5).

IV. Redesign of Bleed Slot

Several modifications were made to the case 7 geometry by cutting the bleed lip over an axial region that covers less than 0.1 in. (2.54 mm). An adverse pressure gradient is present just aft of the blunt nose on a flat plate in uniform flow. As a semi-elliptical nose becomes more slender, this gradient is reduced [11]. The basic idea in the modifications of the bleed lip is to make the lip more slender to eliminate the separation bubbles. Several different geometries were designed for the bleed lip of the tunnel. The computational results obtained with the most successful geometry will be summarized.

The original and new geometries are shown in Fig. 7. To obtain the new geometry, the nozzle coordinates after point (−22.9826817, 17.4838357) mm were not altered. The coordinates of the upper portion of the bleed lip were not changed after point (−22.5, 18.44801907) mm. Three arbitrary points were put between these two unaltered original geometry points, and four different cubic splines were fit to these five points to create the new geometry. Also, to remove the scratches on the existing lip surface and to eliminate the offset of 0.002 in. between the aluminum surrogate nozzle and the original geometry, the tip point of the lip was moved 0.005 in. inside.

Steady and unsteady computations were performed on the new geometry for three different pressures, 50, 150, and 300 psi, at a stagnation temperature of 433 K. The Mach number contours for the steady simulations of the new geometry at 300 psi are shown in Fig. 8. The results for 50 and 150 psi stagnation pressures are similar to those at 300 psi. The separation bubbles on both the lower and upper parts of the bleed lip are eliminated up to a stagnation pressure of 300 psi.

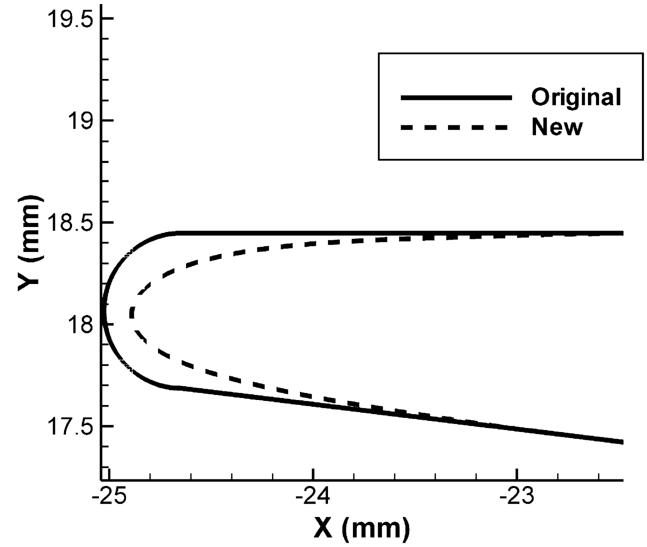

Fig. 7 Original and new geometries.

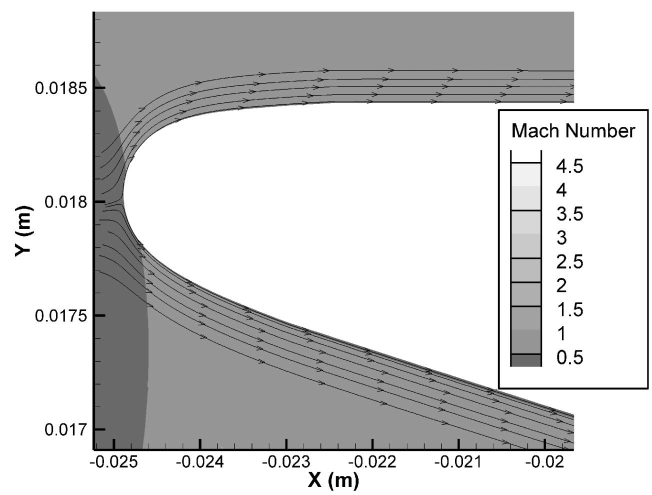

Fig. 8 Mach number contours for the new geometry at 300 psi.

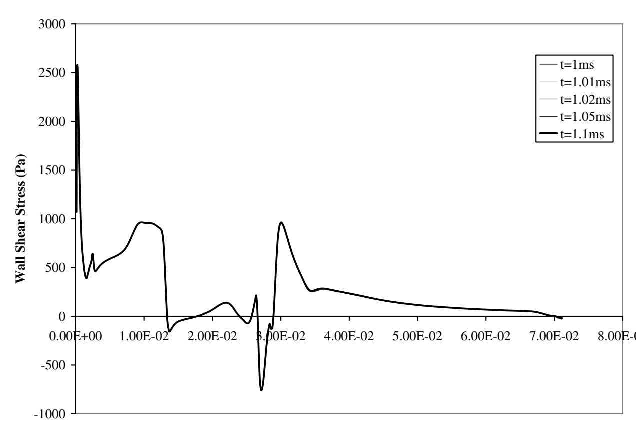

Fig. 9 Shear stress variation for the upper surface of the new geometry.

The wall shear stress plots are shown for the upper and lower sides of the stagnation point at a stagnation pressure of 150 psi in Figs. 9 and 10, respectively. There is no unsteadiness in wall shear stress at 150 psi. The shear stress at the location of the separation bubble that previously existed on the upper side of the bleed lip is high and positive, as seen in Fig. 9.

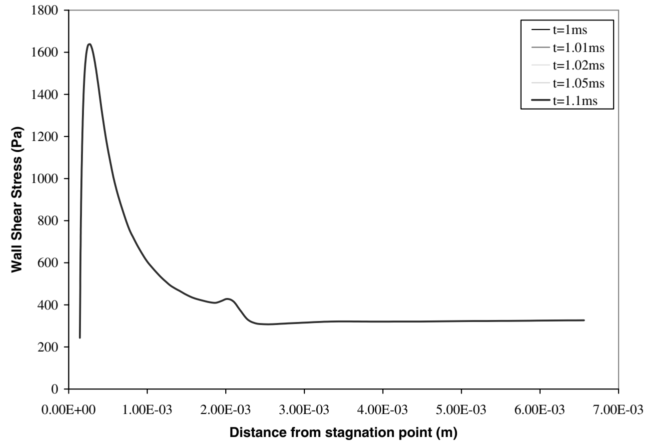

Fig. 10 Shear stress variation for the lower surface of the new geometry.

V. Conclusion

The study demonstrates the effect of the bleed lip geometry on the quality of flow in a hypersonic wind tunnel. A slight change in the bleed lip geometry of the Boeing/AFOSR Mach 6 wind tunnel at Purdue University changes the flow characteristics in the test section.

The existence of steady and unsteady separation bubbles on the main-flow and the bleed-flow side of the nozzle lip of the Boeing/AFOSR Mach 6 wind tunnel in Purdue University is investigated numerically. Separation bubbles induce earlier transition to turbulent flow by destabilizing the boundary layer. Steady and time-accurate simulation results at several stagnation pressures show that separation bubbles with varying sizes exist on both the main-flow and the bleed-flow sides of the bleed lip of the original electroformed nozzle for all stagnation pressures tested.

A new geometry is designed by changing the nozzle lip of the tunnel to eliminate the separation bubbles on both sides of the bleed lip. Steady and unsteady computations with this nozzle lip geometry show that the separation bubbles on both the main- and bleed-flow sides of the nozzle lip are eliminated with this new geometry up to a stagnation pressure of 300 psi. It is shown that the separation bubbles that cause earlier transition in the test section of a hypersonic wind tunnel can be eliminated by a slight change in the geometry of the bleed lip.

Acknowledgments

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