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Technical Notes

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Computational Fluid Dynamics Evaluation of Bleed Slot of Purdue Mach 6 Quiet Tunnel

Ezgi S. Taskinoglu* and Doyle D. Knight†
Rutgers—The State University of New Jersey, Piscataway, New Jersey 08854-8058
and
Steven P. Schneider‡
Purdue University, West Lafayette, Indiana 47907-1282

Introduction

THE Purdue Mach 6 quiet tunnel is a Ludwieg tube that was designed to study boundary-layer transition at hypersonic speeds.[1] For high-quality transition research, the noise level in the test section should be comparable to flight and an order of magnitude lower than in conventional wind tunnels.[2] To achieve these low "quiet" noise levels, laminar boundary layers must be maintained on the nozzle walls. NASA Langley Research Center pioneered the development of such quiet tunnels, with features that include highly polished nozzles and a bleed slot to remove the contraction-wall boundary layer upstream of the throat.[3] However, the tunnel (Fig. 1a), which has been operational since 2001, has achieved quiet flow at high Reynolds numbers only very recently. The probable cause for the lack of quiet flow during 2001–2005 is thought to be fluctuations generated at the nozzle throat as a result of flawed bleed slot design (as in Benay et al.[4]). Klebanoff and Tidstrom[5] showed experimentally that if the Reynolds number is sufficiently small, the presence of a separation bubble does not alter the stability characteristics of the boundary layer downstream of the bubble; however, for sufficiently high Reynolds number, the presence of a separation bubble destabilizes the boundary layer downstream of reattachment, leading to an earlier transition to turbulence. Thus, the original design of the bleed slot has been modified, and altogether eight different bleed slot designs have been built and tested using the highly polished electroformed throat.[6]

The objective of the study presented in this Note is to simulate the flow in the bleed slot of the Purdue Mach 6 quiet wind tunnel. In the course of this computational study, the bleed slot design currently in use was the bleed slot case 7; therefore, this particular bleed slot design is studied. The numerical analysis is conducted at two stagnation pressures that correspond to different noise levels in the experimental measurements using the electroformed throat. The noise level is determined from the rms pitot fluctuations in the nozzle normalized by the mean. For the Purdue tunnel with the electroformed throat, the rms fluctuations in the nozzle are measured to be much less than 0.5% for a driver tube pressure of 55.2 kPa. (The low noise is here limited by a poor signal-to-noise ratio.) However, it is above 1.5% for a driver tube pressure of 96.5 kPa (Ref. 6). Because the noise levels observed in flight are typically less than 0.1%, the Purdue tunnel is considered to be quiet at a stagnation pressure of 55.2 kPa but noisy at 96.5 kPa using the electroformed throat. (Subsequent to the study presented in this Note, an aluminum surrogate throat section was fabricated, and quiet flow was achieved at higher stagnation pressures, presently 646 kPa.) In addition, for comparison purposes the bleed slot design of the Langley Mach 6 quiet tunnel is numerically analyzed. The Langley Mach 6 tunnel was quiet up to 999.7 kPa (Ref. 3). A grid-sensitivity analysis was conducted to quantify the numerical error in the solutions.

Problem Description

Geometry

The axisymmetric flow domain for both the Purdue and Langley tunnels is represented mainly by two surface contours.[7] For the Purdue tunnel (Fig. 1b), the contraction surface that starts from $x = -1034$ mm is the first contour, where x is measured from the nozzle throat. The second contour is the nozzle surface that includes the bleed slot geometry and ends at $x = 120$ mm. The hemisphere at the slot tip has a diameter of 0.762 mm. The accuracy in machining is ± 0.03 mm. For the Langley tunnel, the hemisphere at the bleed slot tip has a diameter of 0.254 mm.

Methodology

By utilizing a commercial mesh-generation tool,[8] a grid with total number of 38,984 points is created (grid 1). Grid clustering is performed using the first cell height of 10^{-5} m and stretching parameter of 1.105. To analyze the effect of the grid resolution on the numerical solution, finer grid runs are also performed for the Purdue tunnel. The total number of grid points is increased to 195,414, and the first cell height is lowered to 10^{-6} m (grid 2). For the Langley tunnel using the first cell height of 10^{-6} m, 116,432 grid points are used (grid 3).

The commercial flow solver[9] used in this study solves the Reynolds-averaged compressible time-dependent Navier–Stokes equations with a finite volume spatial discretization. In our computations, the inviscid flux scheme is chosen to be Roe's method with the Harten entropy fix having third-order spatial accuracy reconstruction. The flux limiter is the min mod limiter. The steady-state solution is obtained by applying the Gauss–Seidel relaxation scheme. There are six run definitions. The first four are for the Purdue tunnel computations. They differ only in specified inflow stagnation pressure and grid resolution. The last two run definitions are for the Langley tunnel computations. In each run, a steady-state, laminar, axisymmetric flow solution is obtained for the flow conditions shown in Table 1.

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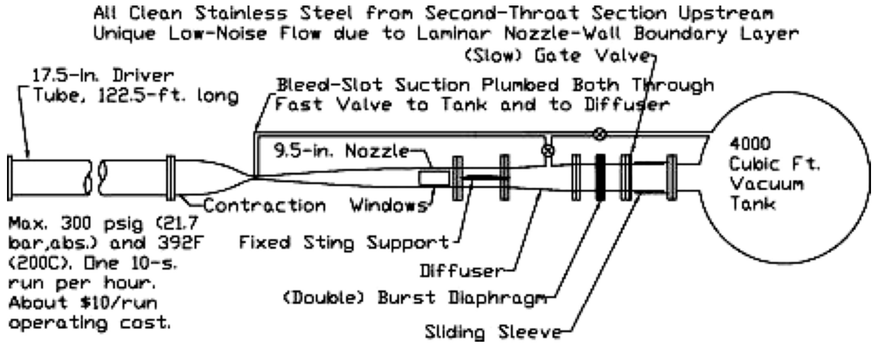
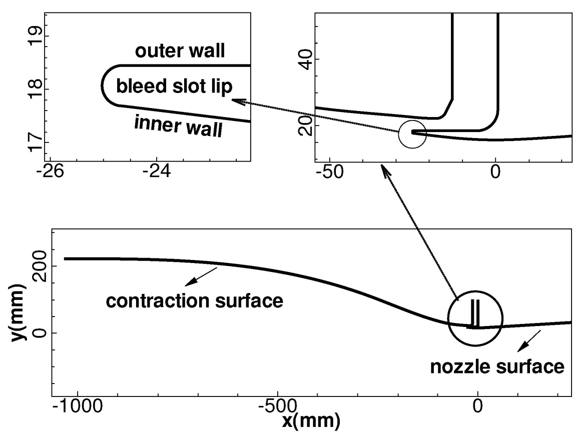
*Postdoctoral Associate, Department of Mechanical and Aerospace Engineering, 98 Brett Road. Member AIAA.
†Professor, Department of Mechanical and Aerospace Engineering, 98 Brett Road. Associate Fellow AIAA.
‡Professor, School of Aeronautics and Astronautics. Associate Fellow AIAA.



a) Schematic of Boeing Mach 6 quiet flow Ludwieg tube[1]



b) Flow Domain

Fig. 1 Purdue tunnel.

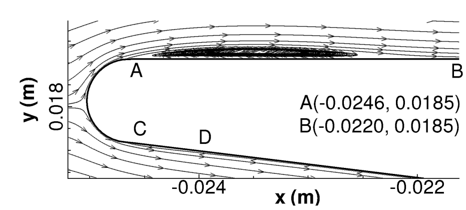
Table 1 Flow conditions for the run definitions

Run	Tunnel	Grid	P_0, kPa	T_0, K	ρ_0, kg/m^3
RUN 1	Purdue	1	56	434	0.45
RUN 2	Purdue	1	96.6	433	0.78
RUN 3	Purdue	2	56	434	0.45
RUN 4	Purdue	2	96.6	433	0.78
RUN 5	Langley	3	96.6	433	0.78
RUN 6	Langley	3	1034	433	8.33

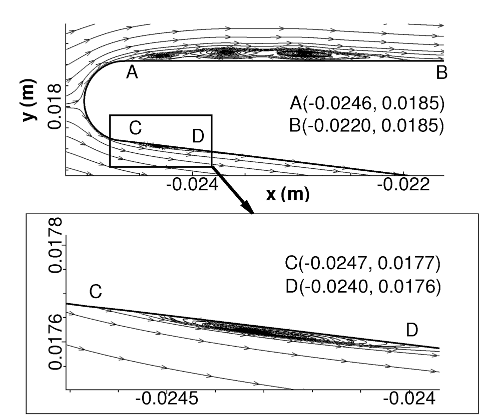
Results

The specific area of interest in this study is the flow behavior close to the bleed slot lip. In Fig. 2, streamtraces near the bleed slot lip are displayed for both run definitions RUN1 and RUN2 defined for the Purdue tunnel geometry. On the outer wall of the bleed slot lip, a recirculation region is observed in both solutions. For RUN1, the recirculation length on the outer (bleed slot) wall is 2.38 mm. For this run definition ($P_0 = 56$ kPa, grid 1), there is no reverse flow on the inner (nozzle) wall (Fig. 2a). For RUN2 ($P_0 = 96.6$ kPa, grid 1), the recirculation region on the outer wall is 2.66 mm. In Fig. 2b, a detailed view of the inner wall below the slot is shown, to determine any existing recirculation bubble. A very small recirculation zone (between points C and D in Fig. 2b) is seen. The recirculation length is 0.60 mm.

In Fig. 3, the results of the grid-sensitivity analysis are shown. For an inflow stagnation pressure of 56 kPa, a recirculation bubble on the inner wall with length of approximately 0.37 mm is observed. For the same pressure RUN1 (grid 1) did not show this bubble. Given that the maximum height of recirculation region, approximately 0.005 mm,

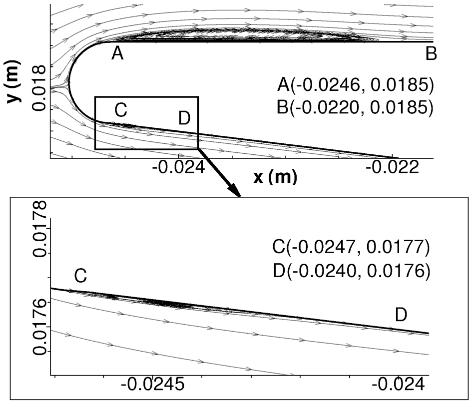


a) at $P_o = 56\ kPa$(**RUN1**)

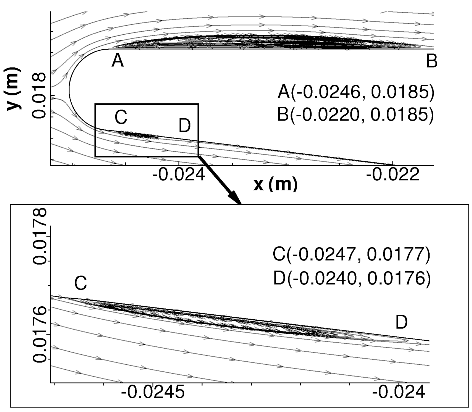


b) at $P_o = 96.6\ kPa$(**RUN2**)

Fig. 2 Streamtraces for the Purdue tunnel with grid 1.



a) at $P_o = 56\ kPa$(**RUN3**)



b) at $P_o = 96.6\ kPa$(**RUN4**)

Fig. 3 Streamtraces for the Purdue tunnel with grid 2.

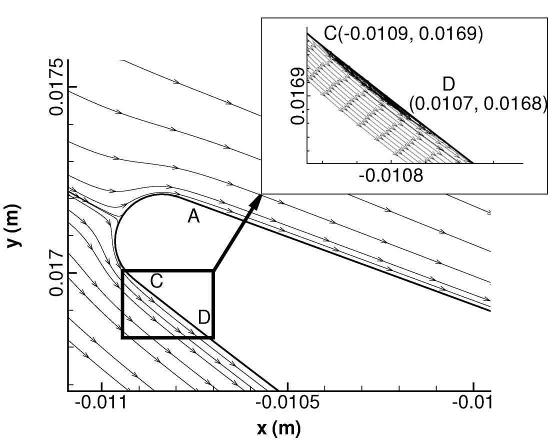


Fig. 4 Streamtraces for the Langley tunnel at P_0 = 1034 kPa (RUN6).

is smaller than the first cell height used for RUN1 (10^{-5} m), it is clear why this bubble was not seen in the solutions of RUN1. On the outer wall the reverse flow region length is computed to be 2.61 mm. For an inflow stagnation pressure of 96.6 kPa, similar to the solution of RUN2, a recirculation bubble on the inner wall with maximum height of approximately 0.018 mm is seen. The recirculation region length on the inner and outer wall is approximately 0.71 mm and 3.06 mm, respectively.

In Fig. 4, streamtraces obtained for the Langley tunnel at P_0 of 1034 kPa (RUN6) near the bleed slot lip are shown. At point A (−10.73, 17.18 mm) on the outer wall, there is a very small reverse flow region of length 0.085 mm (not seen in the figure). Between points C and D on the inner wall a larger recirculation region of length 0.235 mm is seen. For RUN5 ($P_0 = 96.6$ kPa), no separation is seen on either side of the bleed slot lip.

Conclusions

In this study a numerical analysis for the Purdue tunnel bleed slot design (case 7) is conducted for two stagnation pressures. For both of these conditions, recirculation bubbles are observed on the inner (nozzle) and outer (bleed slot) walls of the bleed slot lip. When the Langley tunnel is analyzed for the same order of magnitude stagnation pressure (96.6 kPa), no separation bubble is observed. Reverse flow regions are observed on both sides of the bleed slot lip for this tunnel, when the stagnation pressure is increased one order of magnitude (1034 kPa).

The main conclusions of this study are as follows:

1) For the Purdue tunnel, our results show that as the inflow stagnation pressure increases the recirculation bubble formed on the inner (nozzle) wall becomes bigger. This suggests an explanation for observing quiet flow only for low stagnation pressures of 55.2 kPa for bleed slot design case 7 (Ref. 6). Based on the experiments of Klebanoff and Tidstrom, we thus conjecture that the small (0.37-mm) bubble at 56 kPa does not affect the stability properties of the nozzle wall-boundary layer, but the large (0.71-mm) bubble at 96.6 kPa destabilizes it.

2) Although the Langley tunnel computations displayed reverse flow regions on both walls of the bleed slot lip, the recirculation length is smaller than that seen in the Purdue tunnel computations. In addition, computations that yield separation for the Langley tunnel were performed at a stagnation pressure which is an order of magnitude higher than the stagnation pressures chosen for the Purdue tunnel computations. This might be caused by the position and shape of the bleed slot lip, but the size of the bleed slot lip must also be taken into account. The bleed slot tip diameter is three times smaller for the Langley tunnel.

3) To relate the relative size of the separation bubbles seen on the Langley and Purdue tunnels to the appearance of the premature transition of the tunnel wall boundary layer, an appropriate scaling must be developed.

Acknowledgments

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K. Fujii
Associate Editor