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Effect of Heating on Quiet Flow in a Mach 4 Ludwieg Tube

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Introduction

HIGH-SPEED, quiet-flow wind tunnels are needed for the study of boundary-layer transition to allow measurements under low-noise conditions comparable to flight.[1,2] Conventional facilities suffer from turbulent boundary layers on the nozzle walls. They radiate high levels of sound, which can dominate transition on the model.[3] Quiet-flow facilities maintain laminar boundary layers on the nozzle walls to provide freestream fluctuation levels of approximately 0.1% or less; these fluctuation levels are an order of magnitude less than those in conventional facilities and are comparable to flight measurements.[4] A low-Reynolds-number, Mach 4, quiet-flow Ludwieg tube was previously developed at Purdue University to achieve quiet flow at lower cost.[5] Reference 5 shows that pitot pressure fluctuations normalized by the mean pitot pressure are about 0.06% under conditions when noise radiated from turbulent spots on the nozzle walls is present about 1% of the time. This noise level was used as the criterion for quiet flow and corresponds to static pressure fluctuation levels that are also about 0.06% (Ref. 6).

A high-Reynolds-number, Mach 6, quiet-flow Ludwieg tube is now being built.[7] To reach Mach 6, the stagnation temperature must be raised by heating the driver tube and the air it contains. This raised two main issues. 1) Would free-convection currents be unavoidable in the driver tube, and would these be swept into the test section, possibly eliminating quiet flow? 2) What effects will the heated gas have on the instability of the nozzle wall boundary layer and therefore on the extent of the quiet flow?

The first issue has never been addressed before. The Gottingen hypersonic Ludwieg tube operates with a heated driver tube, but the conventional design results in pitot pressure fluctuations that are 1.8% of the mean.[8]

The second issue, the effect of nonuniform wall temperature on instability and transition, has been addressed many times.[9–12] Uniform cooling stabilizes low-speed airflow as well as the low-Mach-number first-mode waves; stabilization is also observed for localized heating when it is carried out upstream of the onset of instability. This is because the wall now looks cold to the preheated boundary-layer gas. Heating also thickens the boundary layer and thus reduces the effectiveness of the surface roughness. Harvey et al.[13] heated an early Mach 5, axisymmetric, quiet-tunnel nozzle by 40% above the total temperature and showed that transition was delayed by 19%. Demetriades[14] also reported a delay of transition using localized heating near the nozzle throat.

This Note reports measurements of quiet-flow extent carried out in the Purdue University Mach 4 Ludwieg tube with a heated driver tube. The facility, instrumentation, and notation are described in Ref. 5. Pitot pressure measurements were made with a fast-response pressure transducer located on the centerline. Temperature measurements were also made using a tungsten cold wire that was 3.8 μ in diameter and 0.5 mm long.[15] The measurements were recorded at 250 kHz with an eight-bit digital oscilloscope for 1 s.

Results

Figure 1 shows typical records for an unheated run. The stagnation pressure upstream of the pitot shock was inferred from the normal shock conditions. The recovery factor was taken as 1.11 for the cold-wire measurement, based on the hot-wire Reynolds number of 4.8 and Knudsen number of 1.2 (Ref. 16). The pressure and temperature decay with time as the flow exits the driver tube. An expansion wave reflects back and forth inside the driver tube during the run. When the expansion wave reflects from the contraction, the test section pressure suddenly drops. During the 122-ms intervals, the flow is quasisteady because the pressure drops only about 2% and the temperature drops 0.4%.

Pitot pressure statistics were computed for 80-ms intervals located in the middle of the 122-ms quasisteady periods. Figure 2 shows the rms pitot fluctuations divided by the mean pitot pressure for each such segment. The pitot probe was located on the tunnel centerline at $z = 33.86 \pm 0.16$ cm for the present measurements and at $z = 33.17$ cm for the measurements replotted from Ref. 5. Here, unlike in Ref. 5, $z = 0$ at the nozzle throat. Uniform flow begins at $z = 23.70$ cm, and so the probe is 10.16 cm downstream of the onset of uniform flow. The pitot fluctuations remain below the quiet-flow criterion of 0.06% of the mean[5] for stagnation pressures below about 90 kPa. This is true for all of the segments, not just for the first 122 ms until the first reflection of the expansion wave.[17] This allows measurement in an extended duration of quiet flow, during which

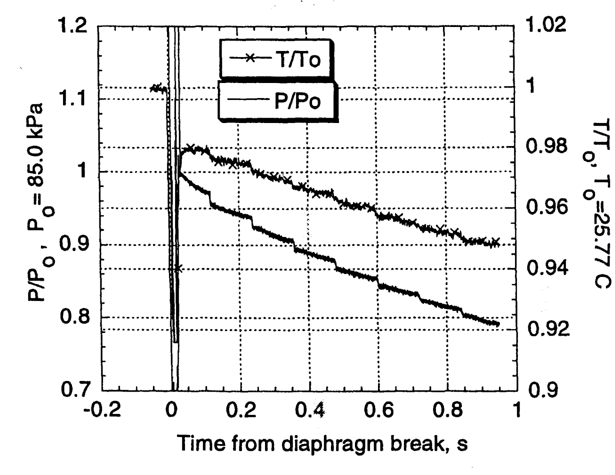

Fig. 1 Decay of mean pressure and temperature during run.

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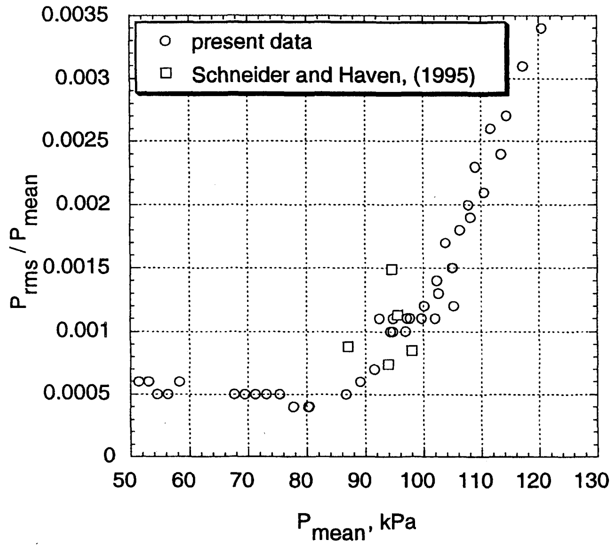

Fig. 2 The rms pitot pressure vs Reynolds number, unheated; all segments.

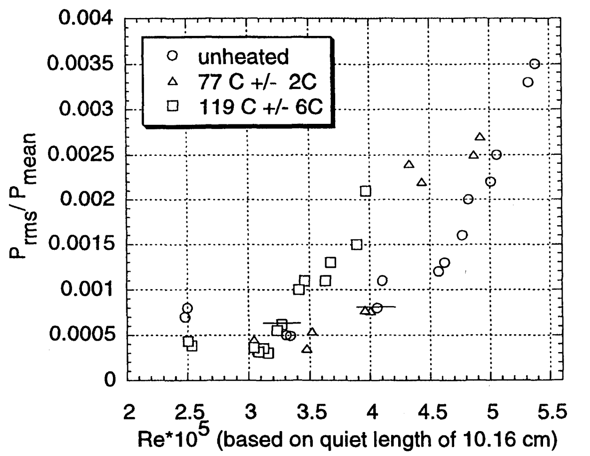

Fig. 3 The rms pitot pressure vs Reynolds number, heated; first two segments.

the unit Reynolds number slowly drops. Because the pressures were varied randomly, the scatter in the data shows the repeatability.

Figure 3 shows the effect of heating the driver tube and the gas it contains. Only the first two segments from each run are shown, to limit the error in the mean-flow measurement. This error is shown in the representative error bars.[15] Under unheated conditions, the quiet-flow Reynolds number is just under 4×10^5. The quiet-flow Reynolds number is based on the unit Reynolds number in the test section and the length along the tunnel centerline from the onset of uniform flow to the appearance of radiation from the nozzle walls.[5] The Reynolds number extent of quiet flow decreases with increasing temperature. Because the decrease is small, any convection currents that may be present in the driver tube do not have catastrophic effects. The value of 4×10^5 in the Mach 4 tunnel is sufficient for the study of receptivity and instability but not for the study of natural transition under quiet-flow conditions.[5] A quiet-flow Reynolds number of at least several million will be needed to achieve natural transition for some models under quiet conditions; the design value for the new 9.5-in. Mach 6 tunnel is 13×10^6 (Ref. 7).

Recall that Harvey et al.[13] obtained a 20% increase in quiet Reynolds number by heating the nozzle to a wall-to-total-temperature ratio of 1.4. Here, the driver tube was heated, thereby heating the gas and the contraction. Because of conduction into the downstream plumbing, the temperature decreases downstream along the nozzle, and the throat temperature is less than the stagnation temperature. Although the nozzle wall temperature distribution was not measured in detail, the temperature halfway down the nozzle was recorded, allowing an estimate of the wall-to-total-temperature ratio in the nozzle. For the 77°C data, the wall-to-total-temperature ratio was 0.89, and a 7% drop in quiet-length Reynolds number occurred. The 119°C data had a temperature ratio of 0.85 and a corresponding drop of 15% in quiet-length Reynolds number. Because a relatively cold throat thus reduces the quiet Reynolds number, the results agree with those of Demetriades[14] and Harvey et al.[13] Cooling the throat decreases the boundary-layer thickness and increases the effectiveness of the residual roughness, whereas heating the throat has the opposite effect. It is likely that this effective-roughness phenomenon causes the transition movement in all three cases.

Summary

The Purdue University quiet-flow Ludwieg tube was operated at Mach 4 with a heated driver tube. The flow remains quiet for the entire duration of supersonic flow, through multiple reflections of the expansion wave inside the driver tube. Air heated to a wall-to-total-temperature ratio of 0.85 reduces the quiet-flow Reynolds number by 15%, consistent with previous observations.

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