Transition Research and Improved Performance in the Boeing/AFOSR Mach-6 Quiet Tunnel*

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Abstract

Laminar-turbulent transition is critical for vehicles which fly at hypersonic speeds for extended periods, yet conventional wind tunnels suffer from turbulent nozzle-wall boundary layers that produce freestream noise levels 10-100 times higher than flight. The Boeing/AFOSR Mach-6 Quiet Tunnel (BAM6QT) has been developed to provide quiet flow at high Reynolds number, with low noise levels comparable to flight. Laminar nozzle-wall boundary layers and the resulting quiet flow have now been achieved to freestream Reynolds numbers of more than 3.5×10^6/ft., after five years of shakedown. The flawed bleed lip of the original electroformed-nickel throat has been modified to eliminate separation bubbles that are predicted by Rutgers-University computations. The maximum quiet stagnation pressure for the electroformed nozzle has improved to as much as 153 psia. The BAM6QT is now the only operational hypersonic quiet tunnel, anywhere. This quiet flow is here shown to have a marked effect on the development of the stationary crossflow instability on a sharp cone at angle of attack.

Introduction

Hypersonic Laminar-Turbulent Transition

Laminar-turbulent transition in hypersonic boundary layers is important for prediction and control of heat transfer, skin friction, and other boundary layer properties. Vehicles that spend extended periods at hypersonic speeds may be critically affected by the uncertainties in transition prediction, depending on their Reynolds numbers. Although slender vehicles are the primary concern, blunt vehicles are also affected by transition [1]. However, the mechanisms leading to transition are still poorly understood, even in low-noise environments.

Many transition experiments have been carried out in conventional ground-testing facilities over the past 50 years [2]. However, these experiments are contaminated by the high levels of noise that radiate from the turbulent boundary layers normally present on the wind tunnel walls [3]. These noise levels, typically 0.5-1% of the mean, are an order of magnitude larger than those observed in flight [4, 5]. These high noise levels can cause transition to occur an order of magnitude earlier than in flight [3, 5]. In addition, the mechanisms of transition operational in small-disturbance environments can be changed or bypassed altogether in high-noise environments; any such changes in the mechanisms usually change the parametric trends in transition [4, 6]. Mechanism-based prediction methods must be developed, supported in part with measurements of the mechanisms in quiet wind tunnels.

Development of Quiet-Flow Wind Tunnels

Quiet tunnels have been a goal of high-speed transition researchers for more than 50 years (e.g., Refs. [7, 8, 9]). However, only in the last two decades have low-noise supersonic wind tunnels been developed [3, 10]. This development has been difficult, since the nozzle-wall boundary layers must be kept laminar in order to avoid high levels of eddy-Mach-wave acoustic radiation from the normally-present turbulent boundary layers [11]. The development of the wind tunnel is thus an expensive research project in high-risk laminar-flow control. A Mach-3.5 tunnel was the first to be successfully developed at NASA Langley [12]. Langley then developed a Mach-6 quiet nozzle, which

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was used as a starting point for the new Purdue design [13]. Unfortunately, this nozzle was removed from service due to a space conflict; it is now being reinstalled at Texas A&M. The Purdue Mach-6 tunnel is presently the only operational hypersonic quiet tunnel, anywhere in the world.

Background of the Boeing/AFOSR Mach-6 Quiet Tunnel

A Mach-4 Ludwieg tube was developed at Purdue in 1992-1994 [14]. Quiet flow was achieved at low Reynolds numbers, and the facility was used for development of instrumentation and for measurements of instability waves under quiet-flow conditions. However, the low quiet Reynolds number and the small 4-inch test section imposed severe limitations.

A hypersonic facility that remains quiet to higher Reynolds numbers was needed. Low operating costs had to be maintained, to make research affordable in the post-Cold-War environment. Beginning with Ref. [15], a series of more than 20 AIAA papers have reported on the design, fabrication, and shakedown of this facility, on the development of instrumentation, and on progress towards achieving Mach-6 quiet flow at high Reynolds number. Refs. [16] and [17] summarize the earlier papers, including the initial quiet flow achieved at low Reynolds numbers (8 psia stagnation pressure) with the 6th bleed-slot design. Ref. [18] reported initial achievement of quiet flow at 20 psia stagnation pressure, using the unpolished surrogate throat, along with measurements of the effect of downstream shock/boundary-layer interactions on upstream separation. Refs. [19] and [20] report hot-wire measurements of second-mode instabilities on sharp and blunt cones at conventional-noise conditions; under quiet conditions the noise level drops but so does the amplitude of the instability waves, so the natural waves disappear into the electronic noise. Ref. [21] reported initial achievement of quiet flow to freestream unit Reynolds numbers of 2.1×10^6/ft., using the surrogate throat, along with measurements of the flow in the contraction inlet. Ref. [22] reported initial achievement of quiet flow to a freestream unit Reynolds number as high as 2.7×10^6/ft., again using a surrogate throat, along with additional measurements in the contraction inlet.

The present paper reports progress in the latter half of 2006. Quiet flow has finally been achieved at the design unit Reynolds number, and maintained during regular operations for some five months. However, a full characterization of the quiet-flow performance remains to be carried out, along with the determination of the highest quiet Reynolds number that can be achieved with cost-effective modifications.

The Boeing/AFOSR Mach-6 Quiet Tunnel

Quiet facilities require low levels of noise in the inviscid flow entering the nozzle through the throat, and laminar boundary layers on the nozzle walls. To reach these low noise levels, conventional blow-down facilities must be extensively modified. Requirements include a 1 micron particle filter, a highly polished nozzle with bleed slots for the contraction-wall boundary layer, and a large settling chamber with screens and sintered-mesh plates for noise reduction [3]. To reach these low noise levels in an affordable way, the Purdue facility has been designed as a Ludwieg tube [14]. A Ludwieg tube is a long pipe with a converging-diverging nozzle on the end, from which flow exits into the nozzle, test section, and second throat, as shown in Fig. 1.

A diaphragm is placed downstream of the test section. When the diaphragm bursts, an expansion wave travels upstream through the test section into the driver tube. Since the flow remains quiet after the wave reflects from the contraction, sufficient vacuum can extend the useful runtime to many cycles of expansion-wave reflection, during which the pressure drops quasi-statically.

The contraction-wall boundary layer is bled off just upstream of the throat, beginning a fresh undisturbed boundary layer for the nozzle wall. The nozzle-throat bleed air can be ducted to two alternate locations. A fast valve remains connected directly between the bleeds and the vacuum tank, allowing the bleed air to be dumped directly into the tank. In addition, the original plumbing connecting the bleed air to the diffuser enables a faster startup, if the jets of air into the diffuser are not a problem. If the bleed valves remain closed, the air entering the throat is disturbed by passing over the bleed slots, tripping the nozzle-wall boundary layer. Thus, these tunnels can run quiet and noisy at the same nominal operating condition, by opening or closing the bleed valves.

Unless otherwise specified, the initial stagnation temperature in the driver tube is set to $160°C$. The stagnation temperature drops about 10% during the run, as the air flows out of the driver tube [23]. The air in the nozzle at Mach 6 is supercooled, making Reynolds number computations dependent on the somewhat uncertain value of air viscosity at very low temperatures, but no evidence of condensation has been observed under these conditions [24], although further studies are needed.

Figure 2 shows the nozzle. Here, z is an axial coordinate whose origin is at the nozzle throat. The region of useful quiet flow lies between the characteristics marking the onset of uniform flow, and the characteristics

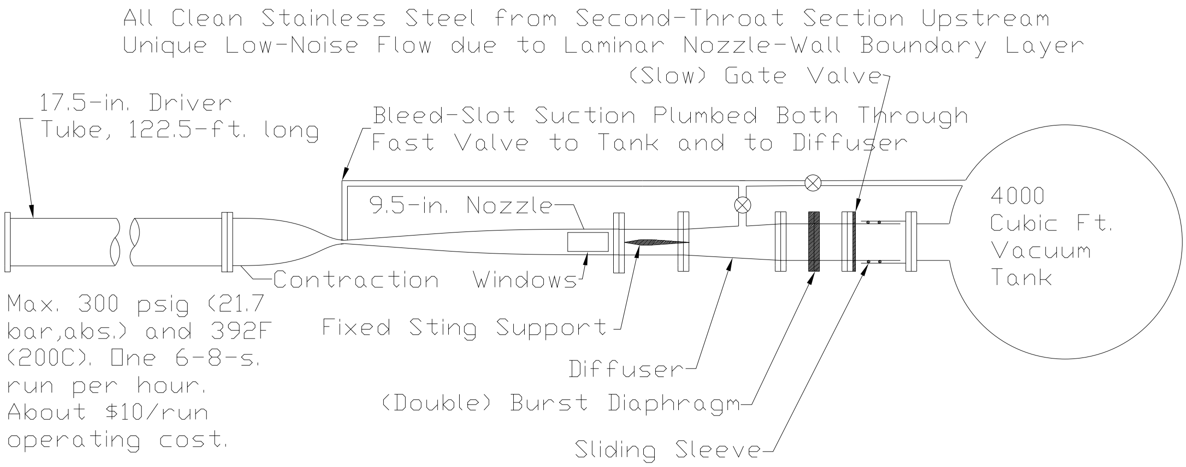

Figure 1: Schematic of Boeing/AFOSR Mach-6 Quiet Tunnel

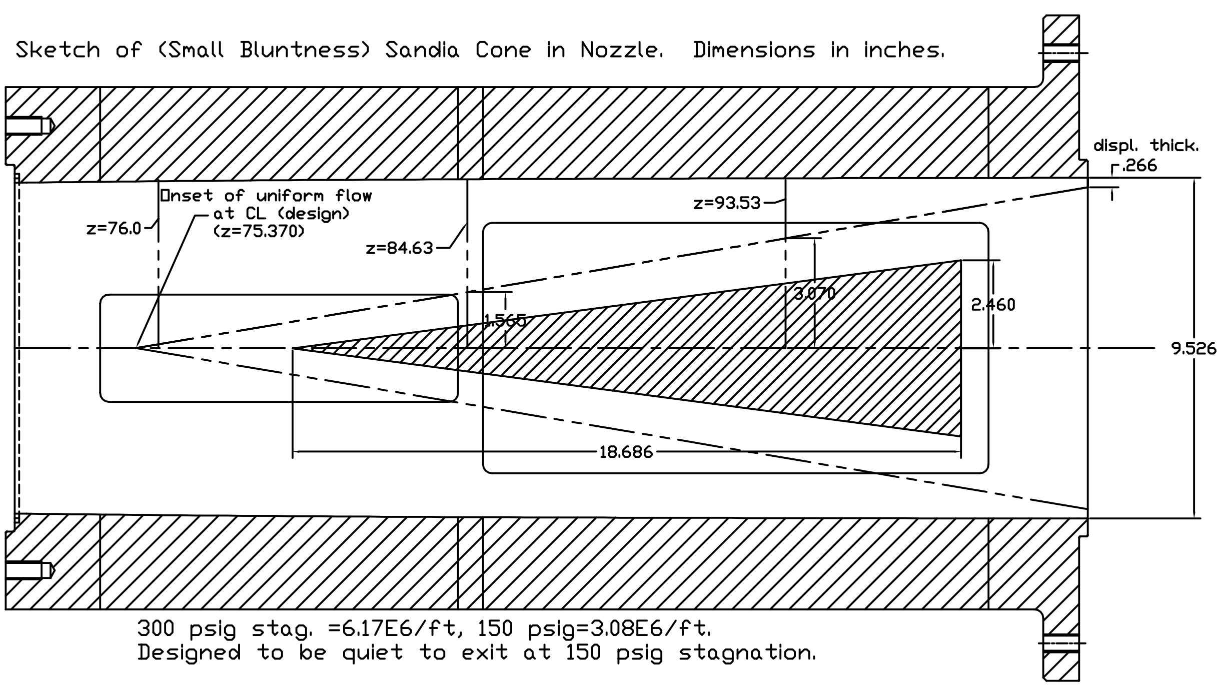

Figure 2: Schematic of Mach-6 Quiet Nozzle with Model

marking the upstream boundary of acoustic radiation from the onset of turbulence in the nozzle-wall boundary layer. A 7.5-deg. sharp cone is drawn on the figure. The rectangles are drawn on the nozzle at the location of window openings, all but one of which are presently filled with blank metal inserts. Images of the tunnel are available at `http://roger.ecn.purdue.edu/~aae519/BAM6QT-Mach-6-tunnel/`, along with earlier papers and other documentation.

Quiet Flow Achieved to High Reynolds Number

Quiet flow was finally achieved to the design Reynolds number during the second part of 2006, although much work yet remains. The present paper summarizes Ref. [25], which reports results only through August 2006. The present paper also reports on the substantial improvements observed since August.

Typical Traces for Pitot and Contraction Pressure

Three pieces of data were collected from each tunnel run on the Tektronix TDS7104 oscilloscope at a rate of 2×10^5 samples per second: the pressure in the contraction, the pitot pressure in the nozzle, and the high-frequency (ac) component of the pitot pressure. The pressure on the contraction wall, p_t, is measured near the entrance, where the Mach nunber is less than 0.01, so the pressure is very near stagnation pressure [24].

High-frequency Kulite pressure transducers (model XCQ-062-15A) are used to measure the pitot pressure. The stopped version of these transducers allows the test area to be pressurized to the high stagnation pressure without damaging the sensitive transducers. The DC pitot pressure is amplified by a factor of 100 before digitization, and the AC pitot pressure is high-pass filtered at about 840 Hz and amplified by an additional factor of 100 before digitization, using custom-built electronics based on INA103 instrumentation-amplifier integrated circuits. Hi-Res mode was used to increase resolution and decrease noise in the 8-bit scope, by averaging the sampled data on the fly before storing into memory at 11-12-bit resolution. The pressure transducers and associated electronics are calibrated quasi-statically using a Paroscientific quartz pressure transducer, by slowly filling the tunnel from vacuum.

Figure 3 is a typical oscilloscope trace, with the data converted from voltage to pressure using the calibrations. The oscilloscope records data for ten seconds and is triggered by the sudden drop in pitot pressure when the diaphragms burst. The first second of data is from before the trigger, and provides a baseline of electronic noise. At time $t \simeq 0.0$ s, the diaphragms burst and the run starts. Approximately 0.2 s is required to start up the Mach-6 flow. During this run, the tunnel runs at a conventionally high noise level until $t \simeq 1.0$ s. At $t \simeq 1.0$ s the boundary layer on the nozzle wall drops from turbulent to intermittent, becoming laminar and quiet at $t \simeq 1.2$ s. The contraction-wall pressure is shown in blue and referred to the right-hand axis. It drops from an initial value of 160 psia in stairsteps, each time the expansion wave reflects from the contraction. The contraction pressure at which the noise drops to quiet levels is about 146 psia. With the exception of five turbulent bursts between $t \simeq 2.8$ and 5.7 s, the tunnel is quiet until the run ends at $t \simeq 7.1$ s when the contraction-wall pressure has dropped 28% to about 105 psia. Every tenth point is plotted, to reduce the size of the data file. The pressure at which the nozzle drops quiet has always been essentially independent of the time during the run at which this pressure is achieved [25, Sec. 6.2.2].

Noise Levels

The pressure data is also used to calculate the tunnel noise level ($\tilde{p}/\bar{p}$). The noise level for the above run as a function of contraction pressure is shown in Figure 4. The noise is computed by breaking the run into 0.1-s intervals and calculating the root-mean-square ($\tilde{p}$) and mean ($\bar{p}$) pitot pressures over the segment. If the interval is quiet, the high-pass-filtered and amplified AC pitot pressure is used to find $\tilde{p}$; if not, the DC pitot pressure is used.

The noise level before the run is recorded as the point where the total pressure measured on the wall at the contraction entrance, p_t, is just less than 160 psia. As expected, the pre-run noise level is very small. The noise increases to 2.4 to 2.6% until $p_t = 149$ psia at which point the noise increases to near 18% during the series of turbulent bursts. When $p_t < 146$ psia the noise level decreases below 0.05%, except for the occasional turbulent spot (Figure 5). The noise level increases dramatically when the run ends ($p_t < 100$ psia).

The modifications made to the tunnel did not change the basic pattern of pitot pressure vs. time or the noise level vs. contraction pressure. Rather, the goal was to increase the contraction pressure at which the changeover from noisy to quiet flow occurred. Thus, after most runs data analysis consisted simply of applying the transducer calibrations to the oscilloscope data and identifying the maximum quiet pressure for that run. The reduction in noise level at the onset of quiet flow is quite pronounced (it is nearly

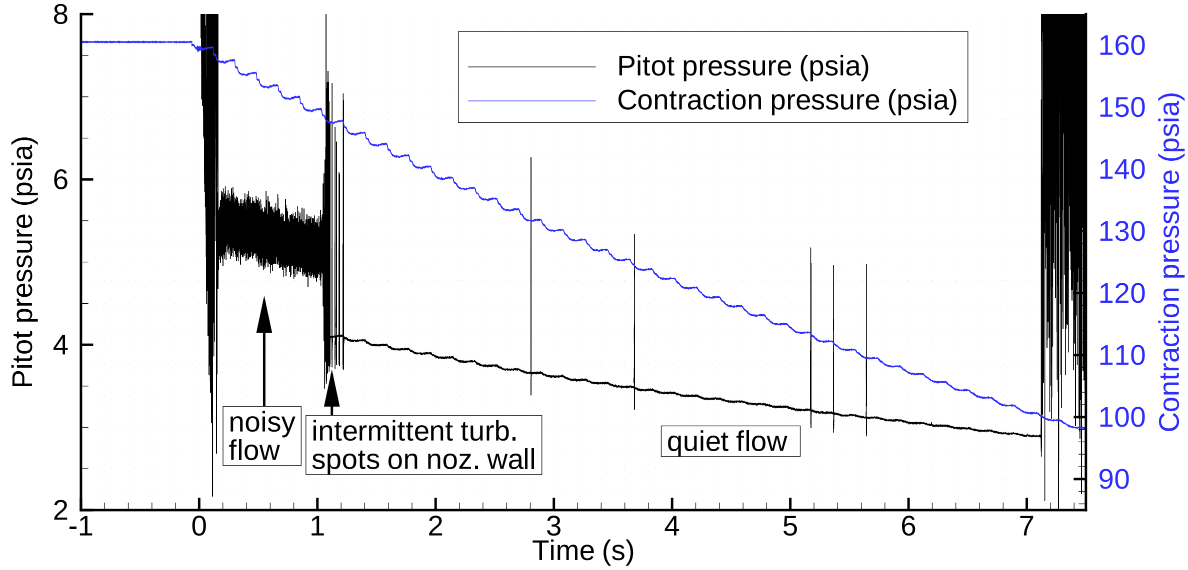

Figure 3: Pitot pressure for run becoming quiet at $p_t \simeq 146$ psia and $t \simeq 1.2$ sec

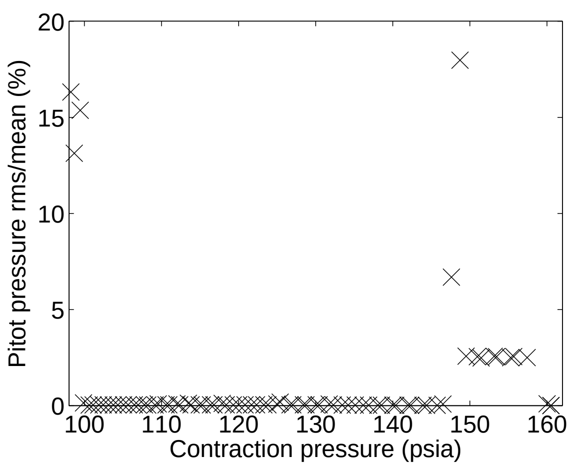

Figure 4: Typical Noise Level During a Run

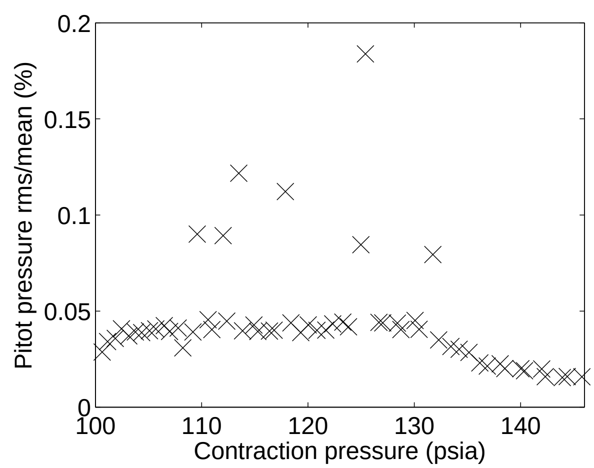

Figure 5: Typical Noise Level During Quiet Portion of Run

a factor of 100) and thus easily ascertained.

Turbulent Bursts

During the quiet portion of most runs that had one, one or more short-duration pressure spikes would occur. These bursts all had a similar structure, such as the one in Figure 6. Less than 1.5 ms elapses between the onset of the spike and the pressure minimum, then the pressure increases back to the pre-spike level over the next 3.5 ms. The magnitude of the pressure spike is proportional to the stagnation pressure for the run and is greater than the pressure variation during noisy

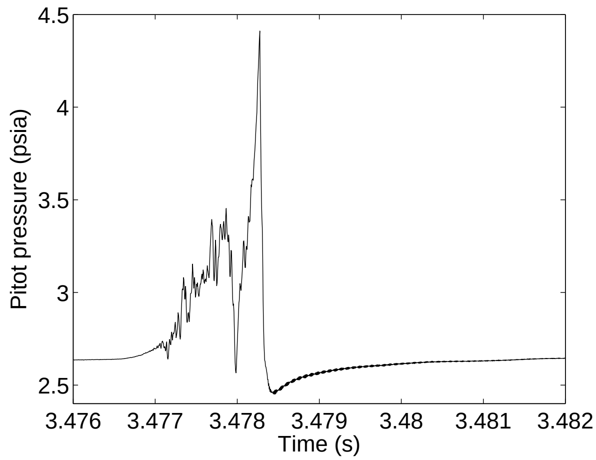

Figure 6: Turbulent burst

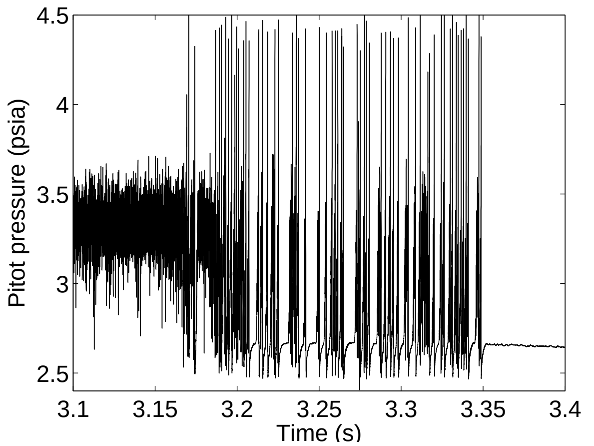

Figure 7: Turbulent bursts at onset of quiet flow

flow.

The burst is almost certainly caused by noise radiated from a turbulent spot on the nozzle wall. These bursts have often been seen in shadowgraphs (e.g, Fig. 1 in Ref. [2]) and in other quiet tunnels when operated at higher pressures just above laminar quiet levels [14, 10]. The pitot pressure trace at the time of the change from noisy to quiet flow shows that a series of bursts occurs just before the flow becomes quiet (Figure 7). Regular noisy flow, on the other hand, produces irregular fluctuations and a histogram with a normally distributed band (Figure 8). These bursts are almost certainly the result of a turbulent nozzle-wall boundary layer dropping intermittently turbulent before it goes laminar, as the Reynolds number slowly falls.

With the surrogate nozzle throat, there will occasionally be a run with a large number of bursts during

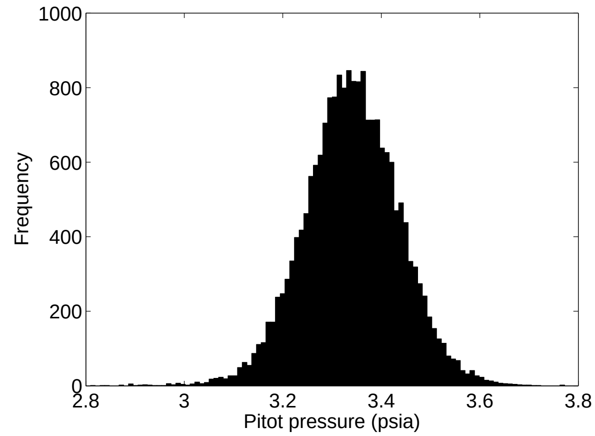

Figure 8: Histogram of pressures during 0.1 s of noisy flow

the otherwise quiet period (more than two per second on average). This problem could not be predicted before a run or replicated during subsequent runs. The electroformed nozzle throat has fewer bursts during the quiet period than the surrogate. This improvement could be due to its better polish or to the lack of seams between the first four sections. The bursts only occur during about 0.1% of the quiet period, so it should be readily possible to filter these periods out of the data acquisition.

Typical Trace for Nozzle-Wall Hot Film

Skoch installed a hot-film array on a window blank forward of the nozzle exit, and showed that constant-temperature-anemometer traces from the hot-film array were useful for detection boundary-layer separation and transition [18, 26]. After Sept. 2006, a sensor from the hot-film array on the nozzle wall was sampled for every run, to monitor transition and separation on the nozzle wall. Fig. 9 shows a typical record, obtained during a run with a model in the tunnel, on 30 Nov. 2006. The initial driver pressure was 160 psia. The hot-film array is shown in Figs. 2 and 3 of Ref. [18]; hot-film number 4, sampled for this trace, is located on the lower nozzle centerplane at $z \simeq 74$-1/4 in. The blue trace, referred to the right-hand axis, again shows the stagnation pressure as measured near the entrance to the contraction. Similar measurements were made earlier in the Mach-4 quiet tunnel [27].

The black trace shows the uncalibrated signal from the constant-temperature anemometer used to drive the hot film. At $t \simeq 0$ s, the burst diaphragms break and the run begins. The flow again takes about 0.2 s to stabilize at Mach 6. For $0.2 < t < 1.0$ s, the flow on the nozzle wall appears to be attached and turbulent, with

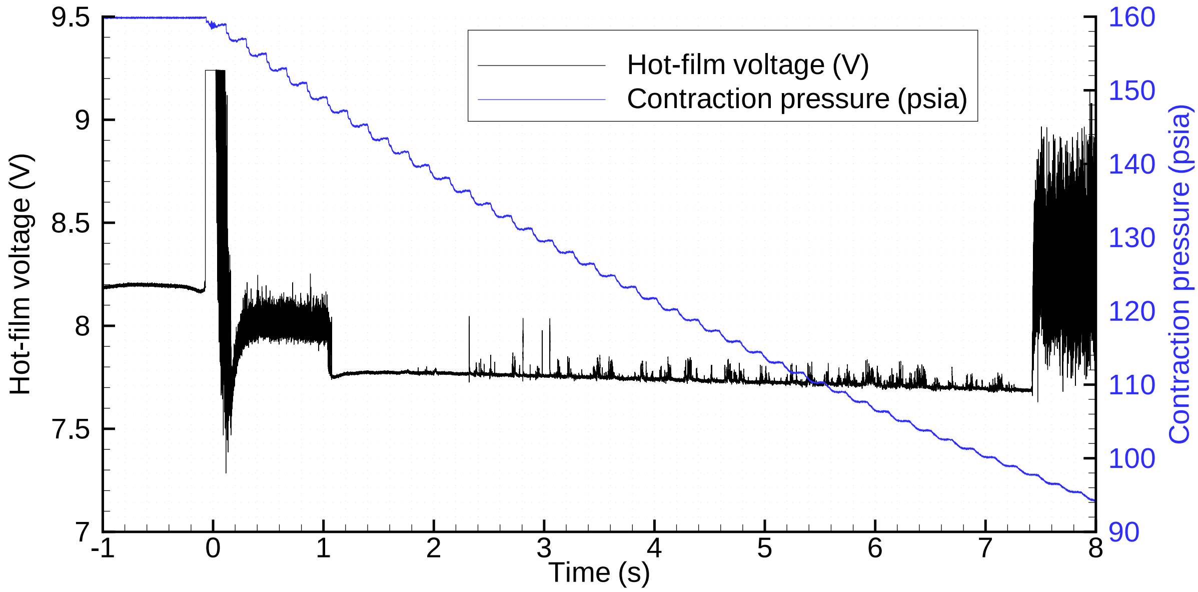

Figure 9: Nozzle-wall hot-film trace for run becoming quiet at $p_t = 147$ psia and $t = 1.1$ sec

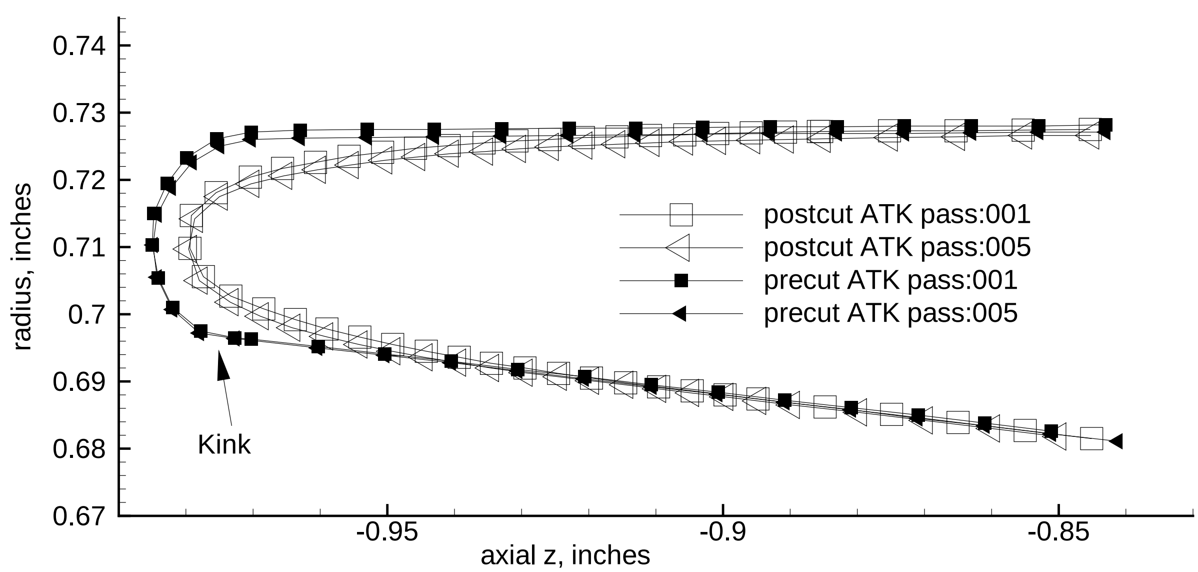

Figure 10: As-machined elliptical bleed lip profile (Ref. [22])

a fairly high level of RMS noise. At $t \simeq 1.1$ s and $p_t \simeq 147$ psia, the nozzle-wall boundary layer drops laminar at this location, with a signal from the hot-film of lower amplitude with much smaller fluctuations. After $t \simeq 2.4$ s, irregular fluctuations begin to appear in the hot-film trace, although these fluctuations do not rise to the turbulent levels. The run ends at $t \simeq 7.4$ s.

Data of this type has been obtained for many runs, and often cross-checked against pitot measurements. While much remains to done to quantify the relationship between pitot and hot-film measurements obtained at various locations, and to determine the effect of the flow on the hot-film traces, it seems clear from Fig. 9 that the nozzle is presently dropping quiet at about 147 psia.

Chronological Account of Nozzle Performance

The quiet performance of the BAM6QT through March 2006 was reported in Reference [22]. In April 2006, the aluminum surrogate throat was taken to Optek for more polishing. After several months of running, the aluminum polish had worn away slightly. It simply was not as shiny as it was after the previous polish, though it was still far better than before the original polish. Also, the seam at the joint between Sections 1 and 2 was visible. The nozzle was polished throughout with special attention at that joint. Also, a ding at the end of Section 4, probably the result of a tool bump during installation or removal, was repaired.

The surrogate nozzle was reinstalled and tested in late May. Initially, the flow was quiet for $p_t < 62$ psia. The nozzle was detached and cleaned. There was no grease to clean and the polish had not degraded. There was some dust in the nozzle that was probably from the tissue paper used to clean it. The nozzle was reattached and ran quietly only below 44 psia. This detach/clean/reattach process was repeated and the tunnel quiet pressure improved to 73 psia. This variability is similar to that experienced in February 2006, when simply opening and reclosing the nozzle achieved moderate fluctuations in performance.

ATK/GASL remachined the bleed lip of the electroformed nozzle throat into the elliptical profile provided by Professor Doyle Knight and Selin Aradag [28]. A small kink was removed from the lip, as shown in Fig. 10 and described in more detail in Ref. [22]; the kink appears more substantial in some of the other plots using other measurements. The separation bubble that was computed to be present even on a perfect half-circle lip was eliminated for the elliptical profile. Recall that z is an axial coordinate that is zero at the nozzle throat. Note that less than 0.010 in. of material was removed, over a small region within 1/4-inch of the tip. The modified electroform was installed and tested in June 2006. The flow became quiet at $p_t < 39$ psia. Within 0.2 s of becoming quiet, the flow on the nozzle wall separated until reattaching about one to three seconds later at $36 > p_t > 30$ psia. The finish of the electroformed nozzle within one inch of the bleed lip was degraded by the remachining, as shown in Fig. 11, and as expected. In June 2006 the nozzle was taken to Optek to restore the mirror-quality finish.

While the electroformed nozzle was being polished, the surrogate nozzle was used. It consistently ran quiet for $p_t < 94$ psia (up from 73 psia), even though no modifications had been made.

When the electroformed nozzle was returned from the polisher in July 2006, it was installed and inspected carefully. There were no visible scratches and the area near the remachined bleed lip was as highly polished as the rest of the electroformed nozzle. The first tests showed a maximum quiet pressure of $p_t = 61$ psia. The nozzle was cooled and opened. The nozzle was still extremely clean, so no cleaning was necessary. The nozzle was reattached and reheated for about 20 hours. Tests revealed quiet performance up to $p_t = 91$ psia, which was very near the current performance of the surrogate nozzle. After two weeks of frequent operation into August 2006, the quiet pressure was still $p_t = 91$ psia.

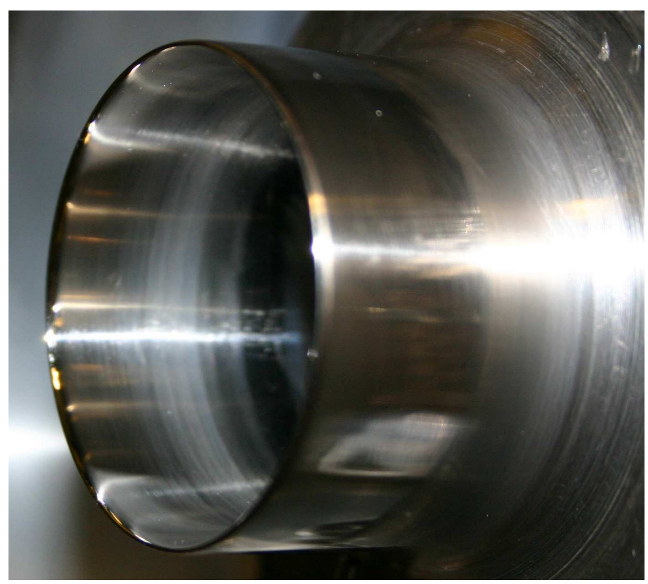

Figure 11: Remachined electroformed nozzle bleed lip before repolishing

The maximum quiet pressure of the electroformed nozzle was tested again in late August 2006. After one month of regular operation, the maximum quiet pressure had dropped slightly from 91 to 87 psia. The nozzle was cooled, detached, cleaned, reattached, reheated, and retested. The quiet pressure dropped to 77 psia (29 Aug.). This process was repeated with a slight change in the reattachment procedure. Normally, after the alignment of the nozzle has been completed, Section 1 is bolted to the contraction without delay. This time, at first only two bolts were used, at a low torque, in order to keep Section 1 and the contraction in contact, allowing the nozzle to come to thermal equilibrium with the contraction before torquing all bolts to specification. After one hour, the nozzle was warm and the normal procedure was resumed. The quiet pressure remained unchanged at 77 psia. The nozzle was opened and reattached once more. The usual reattachment procedure was used. The quiet pressure improved to 117 psia (30 Aug.). Clearly, there was some factor affecting performance which was still not well controlled.

In September 2006, runs were made for initial driver-tube pressures of $p_t = 135$ psia that were not producing the expected flow patterns on cones at angle of attack. The hot-film array was set up to measure the quiet pressure for additional runs. The first run for which hot-film data was recorded became quiet at $p_t = 128$ psia (7 Sept. 2006). Following this experience, sample hot films have been monitored for most runs in order to measure the quiet pressure. It is not as easy to distinguish noisy and quiet flow with hot films as it is with pitot transducers, but they have the advantage of not disturbing the flow over a model or occupying the traverse probe mount. Later in Sept. 2006, several runs were conducted with the pitot along the centerline at $z = 2.37$ m downstream of the throat. Over three days, at initial driver-tube pressures from 155 to 180 psia, the tunnel consistently became quiet at $p_t \simeq 145$ psia (18 Sept.). Figure 3 contains the pressure data from one such run.

In late October 2006, the maximum quiet pressure improved spontaneously once again, this time to 153 psia (30 Oct.). Since its installation in August, the electroformed nozzle has thrice improved maximum quiet pressure from 117 psia, to 128 psia, to 145 psia, and to 153 psia, which is the current maximum ever achieved with either throat, although by 27 Nov. the performance had decreased slightly to about 147 psia (Fig. 9). This performance is comparable to the design target of 150 psia [15, 29], and better than the performance of the earlier 7.5-inch Mach-6 quiet nozzle at Langley [13]. No changes have been made to the tunnel during this period, and the tunnel has been in regular operation. The nozzle has not been detached since August 2006. It is possible that several runs at high pressures were necessary to blow dust out of the nozzle throat.

Nozzle Modifications and Their Effect on Quiet Pressure

An itemized discussion of the issues faced has been reported previously [22, 25]. This list contains the updates from the work since August 2006.

Polish In July 2006, improving the finish of the electroformed nozzle from machined to mirror-like achieved an increase in quiet pressure from 39 psia to 91 psia.

Misshapen Bleed Lip The electroformed nozzle has a better polish than the surrogate and no seams between sections, yet it was not quiet for $p_t > 8$ psia. The leading suspect was the 'kink' discovered in the electroformed bleed lip. The first tests of the remachined electroformed nozzle with the elliptical cross-section yielded quiet flow for $p_t < 39$ psia despite its imperfect polish.

Separation Bubble on Bleed Lip Very small changes in the installation of the nozzle might modify the separation bubble enough to cause the erratic performance of the surrogate nozzle. Initial testing of the modified electroformed nozzle with the elliptical bleed lip indicated greater stability between installations, but this result may have been an effect of the poor finish. During August 2006, the electroformed and surrogate nozzles had similar performance with similar polishes but different bleed lip profiles, suggesting that the separation bubble may not be critical, the bleed lip redesign had no effect, or that some other factor had become dominant for a quiet pressure near 90 psia. However, since that time, a reinstallation of the electroform resulted in a quiet pressure that has increased in steps to 153 psia. This better performance could be due to the elimination of the separation bubble on the elliptical bleed lip.

Nozzle Installation Procedure A modified nozzle installation procedure was used in September 2006 to minimize the distortions caused by bolting the room-temperature electroformed nozzle to the 160°C contraction. This alteration resulted in no change to the maximum quiet pressure.

Dust The maximum quiet pressure is frequently consistent from run to run, but it often has changed when the nozzle is detached and reattached, even if no changes were made. One possible explanation is dust in the nozzle. Care is taken to clean the nozzle before closing it, but the test area is not a clean room, and dust is inevitably introduced.

The tunnel is operated like a clean room, with highly filtered air introduced at the upstream end of the driver tube, so the improvemennts in performance between runs could be due to dust blowing out of the tunnel. Because the dust level before, during, and after a run cannot be measured, it is difficult to assess its effect. It is difficult to understand how the tunnel can be operated for weeks and then suddenly become quiet at higher pressure. Perhaps small amounts of dust do not blow out except after repeated runs at higher pressures, but this explanation does not yet appear convincing.

Future Plans

The tunnel's current high performance has only been characterized by the stationary hot films and a pitot transducer set near the middle of the test region. It is therefore unknown at present whether the nozzle-wall boundary-layer transition is due to a bypass mechanism at the throat or a linear growth of disturbances along the nozzle wall. Previous measurements with a 'far-forward' pitot 1.15 m from the throat found that the flow dropped quiet at the same pressure, both there and near the nozzle exit; however, these measurements were made when the tunnel was quiet for $p_t < 37$ psia and 93 psia. These results suggested that a bypass mechanism near the throat (such as the separation bubble) was causing transition. An axial dependence of the maximum quiet pressure, on the other hand, would indicate linear growth of disturbances. Until further tests with the far-forward pitot, it is unknown which transition mechanism is responsible for the current limit on quiet pressure. The effect of Reynolds number on the movement of transition along the nozzle wall remains to be determined, along with the usual quiet-flow Reynolds number parameter [30].

Two unresolved reliability issues remain. The first is the sensitivity of the performance to individual nozzle installations. The mounting of a dial indicator at the throat joint is planned in order to measure the repeatability of nozzle alignment. Secondly, it is evident after four months of running the electroformed nozzle with elliptical bleed lip that the performance from run to run is mostly constant, which is desirable. However, there have been three significant and unexplained performance increases. Although these might be explained by clean tunnel air blowing dust out of the throat, this hypothesis remains to be verified.

Tunnel Blockage & Separation

Shocks emanating from a model in the test section or the model mount in the diffuser of a supersonic wind tunnel will interact with the boundary layer on the tunnel wall. Disturbances in supersonic flow can only travel downstream, but previous studies in the BAM6QT have shown that disturbances in the subsonic flow in the boundary layer can lead to separated flow upstream in the tunnel nozzle [18, 26]. Laminar boundary layers are more likely to separate than turbulent ones, so shock/boundary layer interactions are more likely to affect upstream flow now that the tunnel runs with laminar boundary layers to higher Reynolds numbers. In many cases, the tunnel-wall boundary layer is laminar beyond the nozzle exit, all the way to the sting-support struts or the impingement of the model bow shock. Laminar shock/boundary-layer interactions are thus a critical issue for determining the largest possible model that can be started in the quiet tunnel.

In November 2005, a 4-inch-base-diameter 7-deg. half-angle sharp cone was mounted in the tunnel at zero angle of attack with its tip at $z = 2.035$ m. A pitot pressure transducer was located at $z = 2.373$ m, 0.060 m above the center line. The uncalibrated hot-film array was employed for its ability to identify noisy, quiet, and separated flow in the boundary layer.

Figure 12 contains pitot pressure and hot-film voltage traces from a run beginning at $p_t = 90.4$ psia. At the time, the surrogate nozzle throat was quiet for $p_t < 94$ psia. This run is quiet from $t = 0$ s for about 0.6 s, at which point the nozzle-wall boundary layer separates. The separation is revealed by the increase in pitot pressure and hot-film voltage during $0.6 < t < 2.2$ s. After the flow reattaches, the noise level is low again.

Figure 13 is similar to Figure 12, except the run begins at $p_t = 104.9$ psia, above the maximum quiet pressure. The run begins noisy but becomes quiet when $p_t = 96$ psia. As soon as the nozzle-wall boundary layer becomes laminar, the flow separates. Unfortunately, the pitot DC pressure trace is off the oscilloscope scale during separation. As in the previous case, the flow reattached at $t \simeq 2.5$ s and was quiet thereafter. The noisy, separated, and quiet flow as well as turbulent bursts are all visible in both the pitot and hot-film traces.

One surprising feature of the flow in these cases is that the flow reattaches after the Reynolds number has decreased. Lower Reynolds numbers correspond to thicker boundary layers and greater risk of disturbances feeding forward. It would therefore be expected that a run would start noisy and attached, become quiet while remaining attached, and eventually separate for the rest of the run when the pressure drops too low. However, the trend of increased separation earlier in the run at higher Reynolds number agrees with

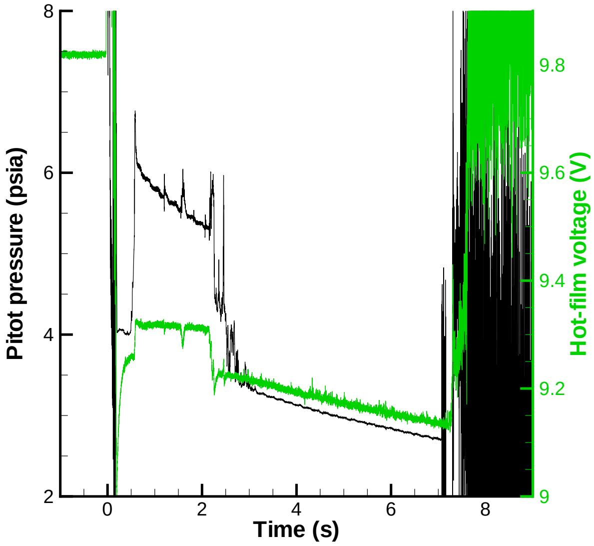

Figure 12: Nozzle-wall boundary-layer separation for run starting at $p_t = 90$ psia

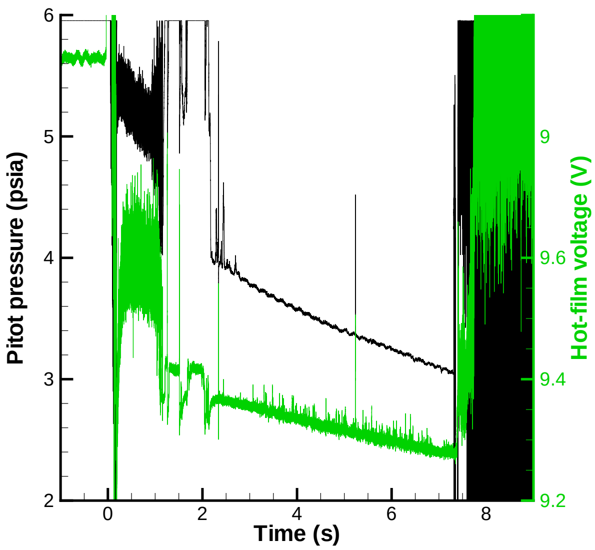

Figure 13: Nozzle-wall boundary-layer separation for run starting at $p_t = 105$ psia

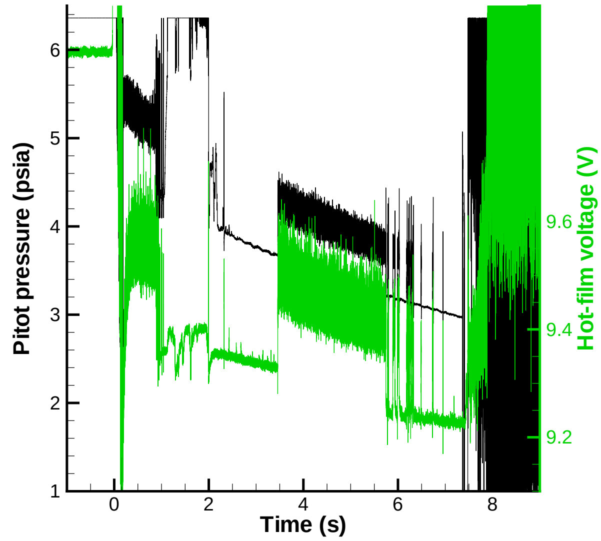

Figure 14: Nozzle-wall boundary-layer separation for run starting at $p_t = 106$ psia

experimental results for a compression ramp at Mach 6 presented in Ref. [31], as well as the free-interaction theory explained in Ref. [32], which attributes the separation at higher Reynolds number to the lower skin friction. Unfortunately, the theory offers no explanation for why separation does not occur for the present laminar boundary layers when $p_t > 50$ psia.

Shortly after the previous data were collected, the tunnel quiet pressure changed from $p_t = 94$ to 72 psia. This change occurred *during* a run. Two segments of both noisy and quiet flow as well as separation are all visible in Figure 14. This run is the only one to exhibit this behavior. For $0 < t < 3.5$ s, the run appears normal with some separation. (The separated pitot pressure is again cut off at the top.) The second half of the run, for $3.5 < t < 7$ s, also appears mostly normal, although the period of intermittent turbulence has distinct laminar portions. The peculiar and unique element is the switch from quiet to noisy flow that occurs at $t \simeq 3.5$ s, which is very abrupt, and occurs as the Reynolds number is decreasing.

After the run shown in Fig. 14, the tunnel remained quiet below $p_t = 73$ psia until the surrogate nozzle was swapped out. This subsequent repeatability is evidence against dust or other detritus flying through the tunnel and tripping the nozzle-wall boundary layer. Perhaps some dust deposited on the nozzle throat at $t \simeq 3.5$ sec. in Fig. 14, and remained there until the nozzle was swapped out. Further runs

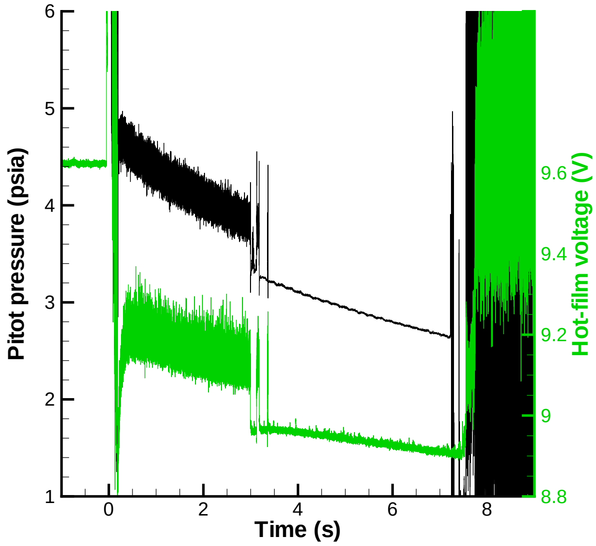

Figure 15: No separation for run starting at p_t = 90 psia

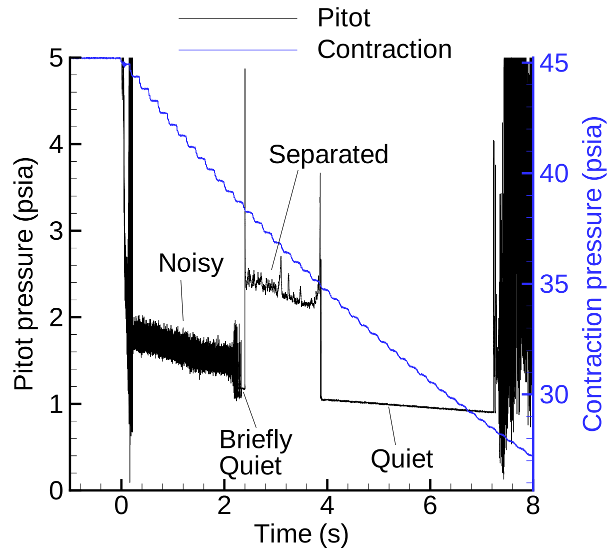

Figure 16: Separation with no model for run starting at p_t = 45 psia

with the cone model installed were conducted, but no separation was detected for this lower quiet pressure, as shown in Figure 15. The same tendency as in Figure 14 to have some laminar flow interspersed with intermittent turbulence is also present here.

Nozzle-wall boundary-layer separation was observed even without a model in the tunnel (but with the sting mount struts installed). Tests of the electroformed nozzle with the newly-cut elliptical bleed lip exhibited quiet flow at $p_t = 39$ psia but separation was evident within 0.2 s with the pitot on the centerline at $z = 2.37$ m, as shown in Fig. 16 (where the initial short-duration quiet flow near $t = 2.5$ s is just visible). The test was repeated with the probe further upstream at $z = 2.14$ m and no separation was detected. Similar separation with the surrogate nozzle and no model has been detected at quiet pressures near 50 psia.

Stationary Crossflow Vortices on Cones at Angle of Attack

Crossflow vortices have been observed on a sharp cone at 6-deg. angle-of-attack under quiet and noisy conditions, in the Boeing/AFOSR Mach-6 Quiet Tunnel. The freestream unit Reynolds number was 3 million/ft. The cone has a base radius of 2.0 inches and a half-angle of 7.0 deg. The frustum was fabricated from nylon 6/6 and painted with a temperature-sensitive paint consisting of Ru(bpy) luminophore molecules in DuPont ChromaClear paint. The paint was calibrated for temperature. The aluminum nosetip has a tip radius of 0.002 in. and was not roughened. The model was viewed through the downstream 5-in.-dia. opening of the dual porthole window in the nozzle [17]. A Photometrics SenSysB scientific-grade CCD camera was used to acquire the images. The paint was excited with 464-nm light from a 4-inch diameter ISSI LM4 blue LED array. A grid of rub-on microdots was applied to the frustum as reference marks. The stagnation temperature was $160°C$.

Figure 17 shows the temperature distribution on the downstream portion of the yawed cone in quiet flow. Several crossflow vortices can be seen. The boundary layer is laminar. The vortices correspond to the vortices seen in the oil flow images shown in Figures 16 and 18 of Ref. [33], which were taken under noisy conditions. The vortices increase the temperature of the cone surface very little over the initial 300 K. The low heat transfer under the thick laminar boundary layer on the downstream portion of the cone contributes to the noisiness of the image. A new coat of TSP would probably help to increase the signal-to-noise ratio.

Figure 18 shows the temperature distribution for the yawed sharp cone under noisy conditions, with the tunnel bleed valves closed, at the same tunnel pressure and temperature, and the same yaw angle. Leeside-forward transition is evident through the higher temperature (and corresponding higher heat transfer) on

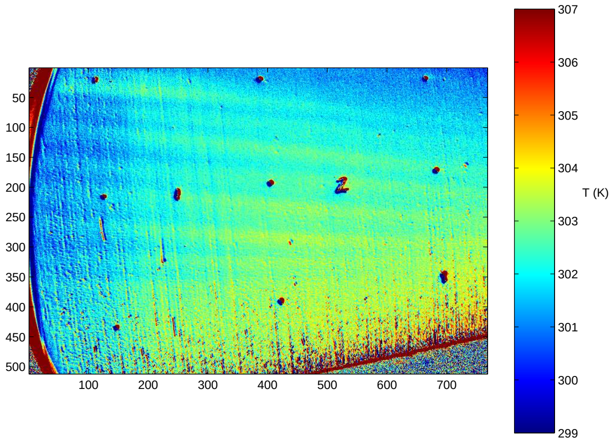

Figure 17: Crossflow Vortices on Cone at AOA in Quiet Flow at $Re_\infty = 3 \times 10^6$/ft.

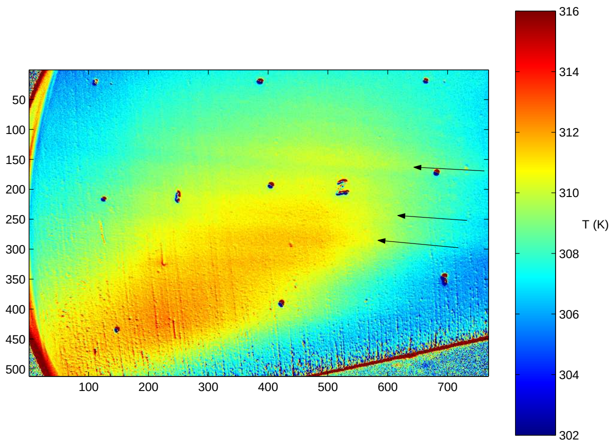

Figure 18: Crossflow Vortices on Cone at AOA in Noisy Flow at $Re_\infty = 3 \times 10^6$/ft.

this section of the cone. Since this relatively small image was acquired through the 5-inch porthole window, the leeside-forward transition is not as evident as in full-model images acquired earlier through the large 7x14-inch rectangular window. Transition in the noisy flow appears to occur near the region where vortices are first seen in quiet flow.

The black arrows in Figure 18 point to streaks of slightly higher heat transfer that seem to correspond to the crossflow vortices seen in Figure 17. This could mean that the vortices maintain organization some distance into the turbulent boundary layer; they are not yet broken apart by the turbulence. This might be why vortices were observed on this downstream section of the cone under noisy conditions in the oil-flow images of Ref. [33]. The small, random turbulent eddies may not disturb the oil as much as the organized motion of the vortices.

These are the first hypersonic measurements of the effect of tunnel noise on crossflow instability. The role of the crossflow instability in the transition process will be investigated further. Roughness will be applied to the cone in the region where the vortices are first seen to determine the effect of roughness on vortex development, following Ref. [34]. A 7-deg. cone with a 0.06-in spherically-blunt nose also exhibits leeside-forward transition under noisy conditions in our tunnel. This cone will be tested under quiet conditions to look for crossflow vortices.

Summary

Quiet flow has been achieved in the BAM6QT to freestream unit Reynolds numbers of more than 3.5×10^6/ft. The kink in the original bleed lip is almost certainly the cause of the initially low maximum quiet pressure. The bleed lip has been redesigned and recut to minimize separation bubbles that could trip the nozzle wall boundary layer to turbulent. Initial tests of the recut and repolished electroform demonstrated quiet flow for $p_t < 117$ psia. Since then, the performance has spontaneously improved to a maximum of $p_t < 153$ psia; perhaps this improvement can be explained by the removal of dust particles from the nozzle throat by the clean airflow of many runs. The tunnel has consistently run quiet at or above $p_t = 145$ psia for over three months.

Nozzle wall boundary layer separation is more likely for laminar boundary layers. A 4-inch-base-diameter 7-deg. sharp cone at zero angle of attack caused separation when running quietly when p_t was less than about 45 psia. The separation was detected with a hot-film array mounted on the test-section wall. There was no separation for this model at higher stagnation pressures.

Measurements of instability and transition on a sharp cone at 6-deg. angle of attack show a dependence on the tunnel noise level. For quiet flow, crossflow vortices are easily visible, whereas for noisy flow transition occurs farther upstream.

Future Plans

Even with quiet flow at a Reynolds number that appears to be higher than was previously achieved, natural transition is not expected to occur under quiet-flow conditions for stable geometries such as slightly blunted cones at zero angle of attack [15]. To achieve natural transition on a sharp cone at zero AOA under quiet conditions will require the development of a much larger tunnel, such as the one proposed in Ref. [15], with a 33-ft-long nozzle having a 2-ft. exit diameter. Such a large quiet tunnel can be expected to cost several million dollars, and there appear to be no immediate prospects for funding such a facility.

For configurations exhibiting transition at moderate Reynolds number, the effect of quiet flow on transition can be determined, at least to some extent. But the main objective of the BAM6QT is to enable the study of the instability mechanisms that lead to transition, under quiet flow conditions comparable to flight, to enable the development and validation of mechanism-based prediction methods. These mechanism-based prediction methods are then to be used to compare quiet and conventional tunnel measurements, and to extrapolate to flight. Instrumentation for the measurement of instability waves needs to be combined with controlled perturbers for introducing the waves, and the results need to be compared to high-quality computations. This combination needs then to be applied to the study of those transition mechanisms thought to be most important for future flight vehicles.

Acknowledgments

The development of this complex and difficult facility over the past 17 years would not have been possible without the support of many people, too numerous to mention here. The research is presently funded by AFOSR under grant FA9550-06-1-0182, by Sandia National Laboratory under PR 858548, and by NASA Johnson under grant NNJ06HD32G. Mr. Gerald Hahn of the AAE machine shop machined the surrogate throat section, and Optek Technologies of Batavia, Illinois provided the high-quality polishes. Prof. Garry Brown of Princeton University suggested the use of a surrogate nozzle throat; the manufacture and testing of this surrogate throat was the key to discovering the critical impact of the bleed lip shape on the nozzle transition, although the lip shape itself had been an open issue since 1990. Prof. Doyle Knight's group from Rutgers University provided critical computations for the effect of the bleed lip shape on separation. ATK Microcraft of Tullahoma, Tennessee performed the very tricky machining of the 0.030-in.-dia. nickel bleed lip. Detailed design and fabrication of the original Mach-6 quiet nozzle was performed by DEI of Newport News, Virginia, led by Doug Weber and Larry DeMeno. Many Purdue graduate students have contributed to the development of the facility and its instrumentation.

The development of this tunnel began in 1990, when the third author spent the summer at NASA Langley learning about quiet tunnels from Ivan Beckwith's group. Ivan and his co-workers Steve Wilkinson and Frank Chen have been very helpful in many ways over many years. The initial development of the Mach-4 prototype was supported by NASA Langley and a gift in memory of Kenneth Hobbie. James Kendall, Eli Reshotko, Ken Stetson, and Dennis Bushnell provided encouragement and many useful suggestions. Since the middle 1990's, the bulk of the funding has been provided by AFOSR, under three successive program managers: Len Sakell, Steve Walker, and John Schmisseur. The initial funding for the Mach-6 facility was provided by a $0.5m gift from the Boeing Company, which began to arrive in 1995, when construction of the Mach-6 facility began. Major funding has also been provided by Sandia National Laboratories, the Ballistic Missile Defense Organization, NASA Langley, NASA Johnson, and Purdue University. Without the long-term vision of these program managers, and their patient support and encouragement over many frustrating years, the successful development of this first University hypersonic quiet tunnel would not have been possible.

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