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Stabilization of a Nozzle Boundary Layer by Local Surface Heating

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On the basis of earlier experiments demonstrating that boundary-layer transition in a supersonic nozzle can be moved upstream by local surface cooling, transition delay was sought by locally heating the nozzle surface. This experiment was done in a two-dimensional Mach 3 DeLaval nozzle that had provisions for heating the nozzle surface at the nozzle throat by two different methods. During the tests the surface temperature was increased up to a maximum of about 12% of the stagnation temperature above adiabatic, and the nozzle boundary layer was probed with steady-state and dynamic pitot probes. Without heating, the test conditions were chosen so that the boundary layer downstream of the throat became turbulent by the growth and bursting of a low-frequency instability. With increasing surface temperatures the instability downstream of the throat decreased greatly in amplitude, as did the magnitude of the bursts and their frequency of occurrence. This suggests that the surface heating can play an important role in attenuating nozzle boundary-layer instabilities and delaying boundary-layer transition.

I. Introduction

IN the course of experimental studies dealing with the effect of surface cooling on boundary-layer development of a supersonic DeLaval nozzle,[1] it had been observed that boundary-layer transition was moved upstream when the surface temperature at the throat was artificially decreased below its adiabatic recovery value. In that experiment, the throat region of the nozzle had been cooled by circulating liquid nitrogen, and the nozzle-surface boundary layer was monitored some distance downstream of this region by a film anemometer probe. These results are summarized in Fig. 1, published previously,[1] showing that, at the location of the detector transition occurred in the tunnel stagnation pressure range $500 < p_0 < 600$ torr ($6.67 \times 10^4 < p_0 < 8 \times 10^4$ N/m^2) for adiabatic conditions, decreasing monotonically to about 300 torr (4×10^4 N/m^2) when the surface temperature T_w was decreased from 38°C (100°F, the adiabatic condition) to −62°C (−80°F). Figure 1 shows, for example, that at a fixed tunnel pressure of 400 torr (5.33×10^4 N/m^2) the boundary layer at the probe location was laminar for adiabatic conditions and became turbulent when $T_w = -62$°C (−80°F).

At first glance, this finding appears contrary to the simpler concepts of boundary-layer stability, for example, for flat-plate boundary layers at subsonic and low supersonic speeds.[2,3] Under such conditions, linear stability theory says that uniform wall cooling stabilizes the Tollmien–Schlichting waves, implying that transition should then move downstream. Flat-plate flow, of course, is a poor description of previously observed nozzle flow,[1] which involved pressure gradients, curvature, and strong three-dimensionalities and crossflows.[4] In the absence of stability computations for such nozzle flows, it had been hard to interpret the previous nozzle transition measurements[1] solely by using ideas from linear boundary-layer stability theory for uniformly cooled flat plates.

In 1975, Harvey and his co-workers[5] at NASA Langley Research Center had already observed the opposite effect, i.e., that wall heating near the throat can discernibly delay transition in a nozzle boundary layer. The mechanism postulated for this delay was that the wall heating increased the boundary-layer thickness relative to the height of the microscopic surface roughness present, thereby decreasing the effectiveness of such roughness in promoting transition. On this basis, previous data[1] could then be consistently interpreted as evidence of the opposite effect—that thinning of the boundary layer, caused by wall cooling, proportionately increases the roughness height and energizes the latter into an early-transition promoter. In fact, roughness has been inseparably associated with the heat-transfer effect in transition correlations for blunt bodies[6] (whose windward flow has common points with nozzle flow) and even held responsible,[7] because of ice formation, for the upstream movement of transition with cooling in experiments such as that of Ref. 1. However, the previous studies[1] were performed on the combined effect of cooling and roughness at the nozzle throat, the cooling effect on transition was observed even with a polished overlay covering the nozzle, and the polished surface to 500 boundary-layer thicknesses upstream of the throat was visually accessible and closely monitored during the test. On this portion of the nozzle, the distributed-roughness Reynolds number was estimated at less than unity. Isolated roughness elements were not seen, nor were any characteristic "turbulence wedges" emanating from such elements found to cause transition in this nozzle.[8] Thus, although roughness can frequently explain some of the heat-transfer effects on transition via the bypass concept,[9] it did not seem to explain previous observations.[1]

The possibility therefore remains that the previously observed surface-heating effect[1] (and possibly that of Harvey et al.[5]) works not through a bypass but directly through profile effects on a boundary-layer instability. Boundary-layer instabilities—for example, those leading to the breakdown of Goertler vortices—are known causes of transition on nozzle walls.[10] Recently, Mueller[8] found that, under adiabatic conditions, transition in the nozzle used previously[1]

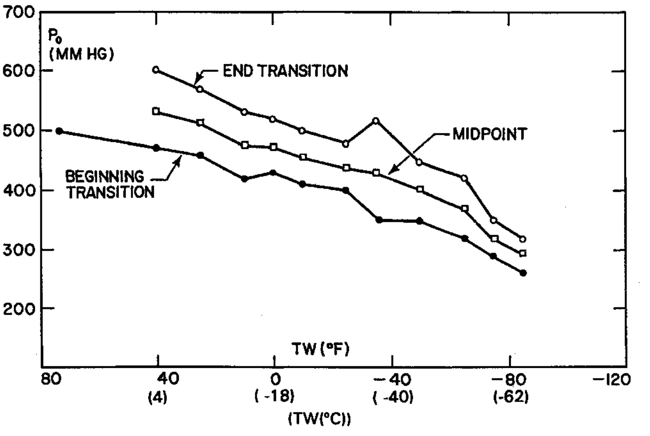

Fig. 1 Effect of the local nozzle surface temperature on its boundary-layer transition behavior, observed near the sonic point (from Ref. 1).

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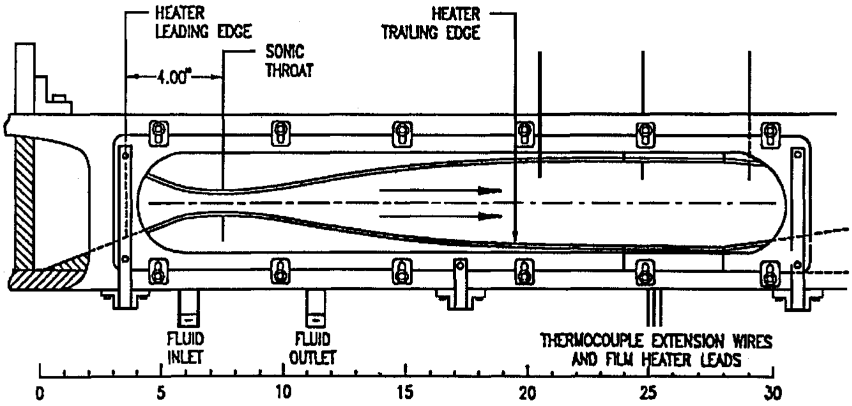

Fig. 2 Test section of the wind tunnel showing the location of the electric film heater. Fluid inlet and outlet service the second, circulating film heater interior to the nozzle (scale in inches).

is apparently caused by the gradual breakdown of a low-frequency disturbance into bursts. It therefore appeared worthwhile to study transition in this nozzle with wall heating as a supplement to the previous cooled-wall work,[1] and as a more detailed look at the results of Harvey et al.[5] If the heat-transfer effects on transition found there[1,5] could be verified by the new experiments, the results could have obvious implications for quiet-tunnel design,[11] or even in the adaptation of existing tunnels for quiet operation by minor modifications.

II. Nozzle Heater Design

The measurements were conducted in the same two-dimensional nozzle as previously,[1] which is that of the continuous-air supersonic wind-tunnel at Montana State University. The top and bottom nozzle blocks are 7.9 cm wide, 35.8 cm long from the throat to the nozzle exit, and have a throat radius of curvature of 30 cm and an inflection point at $x = 9.8$ cm measured from the throat. The 7.9 × 8.1 cm cross section of the tunnel remains constant for 12.5 cm past the nozzle exit. The tunnel side walls are made of one-piece optical glass allowing unobstructed view of the nozzle interior from upstream of the throat to the diffuser entrance. The nozzle is pictured in Fig. 2, and the tunnel is described in detail elsewhere.[12] The test rhombus contains uniform flow at Mach number 3.0, and over the normal stagnation-pressure and stagnation-temperature ranges of $250 < p_0 < 620$ torr ($3.3 \times 10^4 < p_0 < 8.3 \times 10^4$ N/m^2) and $16 < T_0 < 77$°C ($60 < T_0 < 170$°F), has a unit Reynolds number range from 1.9×10^4 to 6.5×10^4 per cm.

A discussion of the nozzle-heating equipment appears elsewhere.[13] All measurements were made on the lower nozzle block, which was heated by two different methods. A circulating heater injected heated water through the same internal passages, just under the nozzle surface, employed for injecting liquid nitrogen during the cold-wall tests.[1] The water circulation and temperature were maintained and controlled by a 1-gal, 800-W, closed-loop pump-driven bath. The heated nozzle region started 4 in. (10 cm) upstream of the throat and ended an equal distance downstream of it. Seven J-type thermocouples were incorporated on the nozzle surface along its centerline, located at $x = -3$ in. (−7.6 cm), −2 in. (−5.1 cm), −1 in. (−2.5 cm), 0 (at the throat), 1 in. (2.5 cm), 2 in. (5.1 cm), and 3 in. (7.6 cm).

To supplement the circulating heater for reaching higher temperatures, a commercial electric film heater was simultaneously used on the nozzle surface. This second heater consisted of an electric coil embedded within a 3 × 15 in. (7.6 × 38 cm) strip of thin (0.008 in. = 0.02 cm), flexible polyamide film, rated to 7.5 A at about 60 Ω. The heater was attached to the nozzle surface with 0.002-in.-thick pressure-sensitive adhesive tape, spanning the test section, beginning 4.5 in. ($x = 11.4$ cm) upstream of the throat and ending 10.5 in. ($x = 26.7$ cm) downstream of it (Fig. 2). Five type-K bare-wire thermocouples were positioned along the nozzle centerline at $x = -3.5$ in. (−8.9 cm), 0 (the throat), 3.5 in. (8.9 cm), 7 in. (17.8 cm), and 10 in. (25.4 cm), to supplement the J-type thermocouples mentioned above. The thermocouple wires and heater power leads were carefully routed outside the tunnel through an access hole downstream of the heater. During the tunnel tests, the film heater was powered by a set of variable transformers, a thyristor and a thermocouple controller connected to one of the K-type surface thermocouples, which provided set-point surface temperature control. Maximum power utilized in the tests was 500 W at 170 V off the transformer; discernible effects of heating on boundary-layer transition were obtained in some cases employing only 240 W, which is about 0.2% of the power needed to run the tunnel itself. The location of the heaters and the measured flow properties above them are shown in Fig. 3.

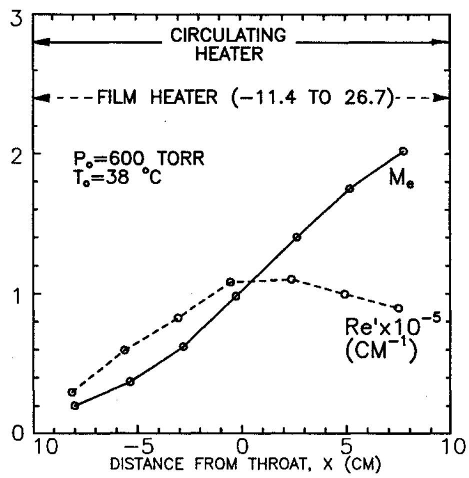

Fig. 3 Measured variation of the boundary-layer edge Mach and unit Reynolds numbers in the wind tunnel relative to the sonic throat and heater locations.

Because the total thickness of the film heater, as installed, was small (0.01 in. = 0.025 cm) the thickening of the nozzle contour due to its presence was not sufficient to materially change the mean flow in the nozzle; the addition of the heater decreased the throat height only by 0.01 in. (0.025 cm), theoretically causing only a 0.4% change in stream Mach number. There was no indication of flow disturbance due to the 0.01-in.-high heater leading edge 4.5 in. (11.4 cm) upstream of the throat, probably for the same reasons for which the Langley tests[5] had shown insensitivity to such geometric disturbances in the stilling chamber.

III. Heater Performance and Instrumentation

Besides the fixed instrumentation commonly used to run this wind tunnel, equipment was assembled to attend to the performance of the heaters and to probe the boundary layer.

Control and monitoring functions for the heaters and surface thermocouples were performed by a Hewlett–Packard Model 3054 Data Acquisition System (HPDAS). This system set and maintained the heater power levels during the run and, at predetermined intervals, recorded the power and thermocouple readings. Real-time displays could be obtained with the HPDAS of the maximum surface temperatures, their uniformity along the nozzle, and the time needed to reach temperature equilibrium, usually on the order of an hour in the flow.

The mean-flow characteristics of the unheated-wall boundary layer on this nozzle were accurately known from previous work[1,4] and required no further study. Changes in these characteristics caused by wall heating were detected with two types of sensors. These sensors were suspended on the wind-tunnel automatic traverse mechanism with which boundary-layer profiles can be obtained quickly. One of the two sensors was a 0.01-in.-diam pitot probe with an encapsulated transducer connected to a x-y plotter, for obtaining the mean (average) pitot pressure p_p; this probe was calibrated in situ to an accuracy of 2% in p_p. Fluctuations p'_p in pitot pressure were recorded with a dynamic pitot probe (DPP) employing a Kulite CQ-030-100D transducer. According to its manufacturer, this transducer should be able to record fluctuations up to its resonant frequency of 1.5 MHz; with it, in fact, Tritz[14] detected signals exceeding 1 MHz in the turbulent boundary layer of this wind tunnel, even though he found that the bulk of the turbulence energy lay below the boundary-layer frequency u_e/δ, which, in the present case, was about 100 kHz (u_e is the edge velocity ranging to 650 m/s and δ is the boundary-layer thickness, which averaged 0.7 cm in this test). The DPP signal was augmented by a Tektronix 1A6 plug-in differential ac amplifier operated in a Tektronix 545A oscilloscope, calibrated in situ to confirm a flat response to 300 kHz and a 3-dB point at 1 MHz, which also attenuated the 1.5-MHz resonance of the transducer. The DPP sensitivity was additionally checked by direct calibrations, and the errors in p'_p as quoted herein were found to be about 15%. This accuracy, although marginal for quantitative turbulence measurements, is certainly adequate for the qualitative detection of turbulence in the present work. The spatial resolution of the DPP (and of the pitot probe, above, used for the mean measurements), based on an active probe-tip diameter of 0.01 in. (0.025 cm), was about 1:30 when compared to the typical boundary-layer thickness of 0.3 in. ($\approx$0.7 cm).

IV. Experimental Results

All measurements were carried out at a nominal tunnel stagnation pressure $p_0 = 600$ torr (8×10^4 N/m^2) and nominal stagnation temperature T_0 of 25°C (77°F). Under these conditions the boundary layer on the nozzle is known to be almost fully turbulent starting from a position near the nozzle throat.[4] Operating at these p_0 and T_0 settings and with the circulating heater working to capacity and the film heater at 240 W, the results of Fig. 4 were obtained for the nozzle temperature distribution. The film-heater set point in this case was 90°C. Note that the temperatures are uniform at about 85°C and change little after about 15 min into the run. This wall temperature T_w of about 85°C was the highest attempted as a precaution (later

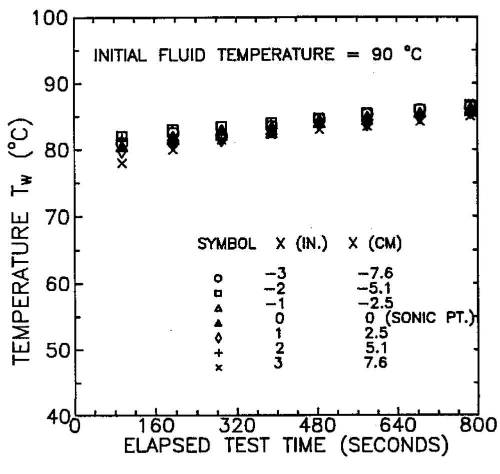

Fig. 4 Temporal temperature distribution along the nozzle centerline, in the vicinity of the nozzle throat, with both heaters active.

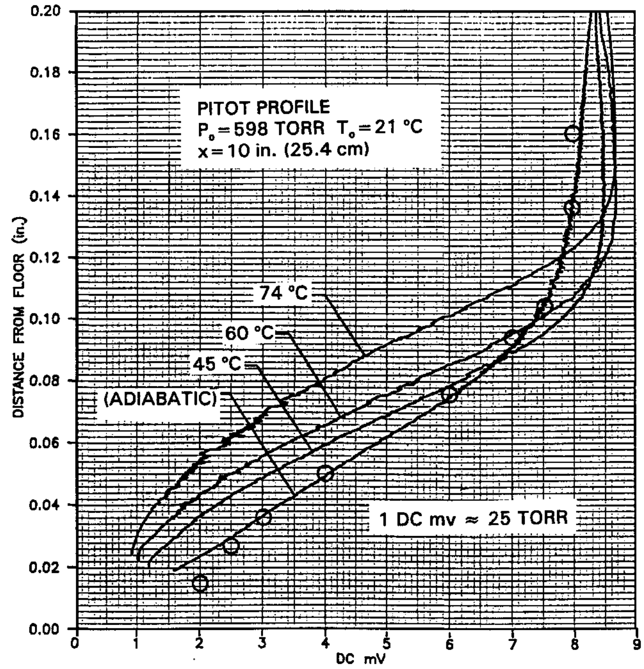

Fig. 5 Pitot-probe traverses showing the effect of surface heating on mean flow. The slight shift of origin is caused by plotter offset. The adiabatic curve (28°C) is compared with earlier measurements from Ref. 15 at the same conditions (points).

found to be too conservative) against damaging tunnel components by overheating. In all cases the surface temperature distribution did not seem to be affected by the type of heater (film or circulating) in use at the moment.

The quality of the mean flow was next examined on the nozzle surface centerline at a point at $x = 10$ in. (25.4 cm), i.e., about 0.5 in. (1.2 cm) upstream of the film-heater trailing edge (see Fig. 2). One of the first issues addressed was whether the presence of the film heater (in the idle, unpowered mode) affected the flow. To do this, pitot traverses were performed inside and outside of the boundary layer at that position with the pitot probe. Typically, the unpowered heater produced the profile marked adiabatic in Fig. 5. This is distinguished by a turbulent-like boundary-layer profile and a large thickness (about 0.2 in. or 0.5 cm from Fig. 5). Although there was no extensive probing of the freestream without the film heater in this particular experiment, a large backlog of pitot traverses on the same bare nozzle at the same p_0, T_0 and x was available for comparison from 25 years of tests. It was therefore easy to distinguish possible disturbances caused by the presence of the heater by comparing with this earlier work. For example, this pitot profile has the same shape as that shown in Laderman's[15] Fig. 6, taken under identical conditions and shown by sample points in Fig. 5. The smoothness of the trace in the freestream, especially, indicates that there were no upstream surface anomalies caused by the presence of the film heater, which would generate mean-flow disturbances in that stream. Also, from the trace, an edge Mach number of 2.88 is computed, exactly as expected for $x = 10$ in. (25.4 cm), which is still upstream of the $M = 3.0$ rhombus. We conclude that the presence of the heater did not affect the (turbulent) boundary layer or the freestream.

The heaters were next turned on and, as shown in Fig. 5, boundary-layer pitot profiles were taken for a number of T_w levels differing, in this figure, by about 15°C from one another. Although these traces, for the moment, can be interpreted only qualitatively, they clearly differ substantially from each other. From 28°C (the adiabatic condition) to 45°C, the layer thins, as would occur in laminarization, and then starts thickening again as a laminar boundary layer would when the wall warms up. It is significant that the 0.12-in. (0.3 cm) boundary-layer thickness δ discerned in Fig. 5—for example, for the 45 and 60°C cases—compares fairly well with the laminar $\delta = 0.25$ cm typically computed for this nozzle at this position.[4] By all of these indications,

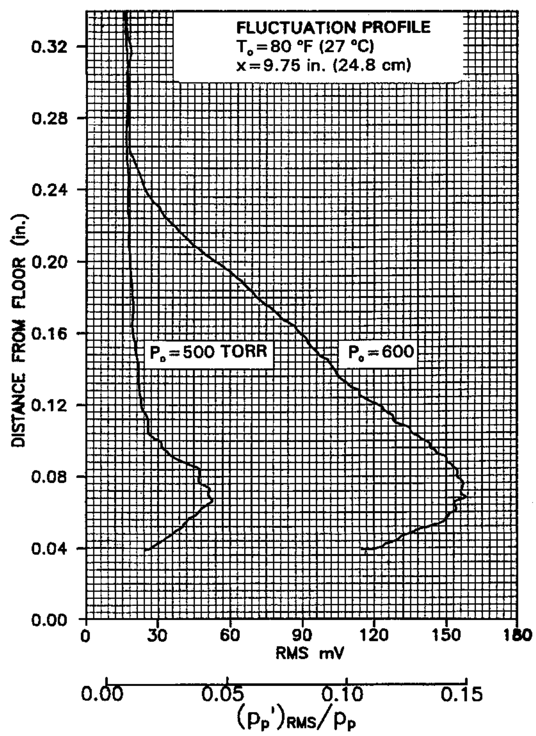

Fig. 6 DPP profiles of the boundary-layer fluctuations on the nozzle centerline, showing the effect of p_0 for an unheated wall; the finite signal in freestream is due to electronic noise.

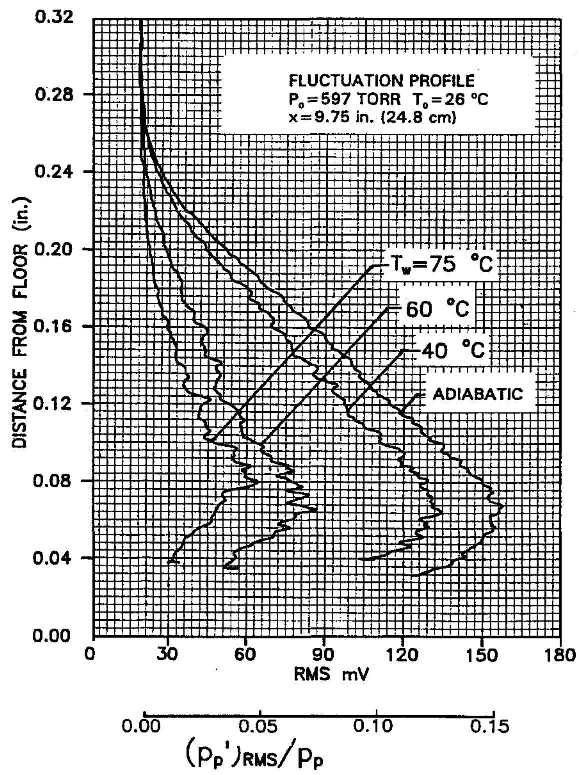

Fig. 7 DPP traverses in the boundary layer for various wall-temperature levels T_w, at constant tunnel pressure. The freestream level is due to electronic noise.

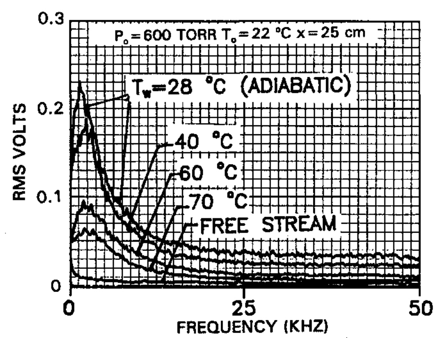

Fig. 8 Effect of surface heating on the low-frequency end of the DPP output spectrum. Ordinate is linear and proportional to the rms signal at each frequency.

we conclude that the mean-average pitot data showed an inclination of wall heating to return the boundary layer to a laminar state.

Flow fluctuations along the centerline of this nozzle surface have been documented over a period of years for adiabatic (unheated) flow, and have been summarized recently.[4,8] Reference 4, especially, shows a map of p_0 vs x, which is separated into regions of quiescent laminar, unstable, intermittent, and turbulent boundary layers. With this map in mind, the DPP was next positioned at the same x and profiles of the fluctuations were obtained, first again with the heaters idle (adiabatic flow) but with changes in p_0 to see whether the presence of the film heater affected the fluctuations. Wideband (spectrally unresolved) fluctuation profiles obtained in this manner, shown in Fig. 6, showed that the turbulence present at $p_0 = 600$ torr (8×10^4 N/m^2) is greatly decreased at $p_0 = 500$ torr (6.7×10^4 N/m^2), in agreement with the previous knowledge[4,8] from which this p_0 change indicated a change from a turbulent to an unstable/intermittent regime. The physical presence of the film heater does not seem to alter the fluctuation profiles (see also Fig. 8 of Ref. 16).

Wideband fluctuation profiles with other conditions constant (at $p_0 = 600$ torr) but elevated T_w are shown in Fig. 7. As with decreasing pressure, the fluctuations diminish greatly as T_w increases from 28 to 70°C, in keeping with the impressions gathered from the mean-flow data. By comparison with Fig. 6, it appears that the effect of increasing the wall temperature at constant pressure simulates that of decreasing pressure at constant wall temperature, and that this effect is once more caused by a rather small temperature increase.

To find the spectral contributions to the wideband signals in the boundary layer, the DPP was next positioned at that point in the layer yielding the maximum wideband signals, i.e., 0.08 in. (0.2 cm) from the wall for the Fig. 7 data. The typical effect of the wall temperature on the spectrum is shown in Fig. 8. For these data the film heater was idle. When the circulating heater, too, was idle (adiabatic case), the spectrum showed a strong prominence around 2.5 kHz, and, more significantly, spectral activity continuing beyond 50 kHz; in fact, this activity extended to several hundred kilohertz in this case. The 2.5-kHz peak is the resident instability in this boundary layer, referred to in Sec. I, which, although seemingly dominant, contributes less to the total spectrum than the turbulence seen beyond it. The boundary layer at this point is thus characterized as nearly turbulent, as indicated above. (Tritz[14] found that, farther downstream at this tunnel pressure, the boundary layer of this nozzle is fully turbulent with a homogeneous, achromatic spectrum extending, as indicated, to beyond 1 MHz.)

When the wall was heated to the temperatures indicated in Fig. 8 by the circulating heater, the fluctuations decreased uniformly with frequency. At the highest wall temperature of 70°C, the instability has attenuated considerably and the accompanying turbulence has been reduced greatly. This was strongly supported by the time-domain view of the same events, illustrated in Fig. 9. Here, four 2-ms-long oscillograms of the DPP signal are shown in terms of p'_p/p_p, each at progressively higher T_w beginning with the adiabatic condition. Several significant events are discernible. First, there appears to be a waviness in these traces with a period, roughly, of $\frac{1}{2}$ to $\frac{1}{3}$ ms; this corresponds to the resident instability mentioned previously (the spectrum peak). Second, this instability breaks up into turbulent bursts at the crest of the waves, but only when the waves are large, for example, of order $p'_p/p_p = 0.05$ or larger. Third, as T_w increases, the instability is attenuated; as that happens, the occurrence of large waves becomes rare and, therefore, so do the turbulent bursts. Consequently, an increase in T_w has suppressed the instability in unison

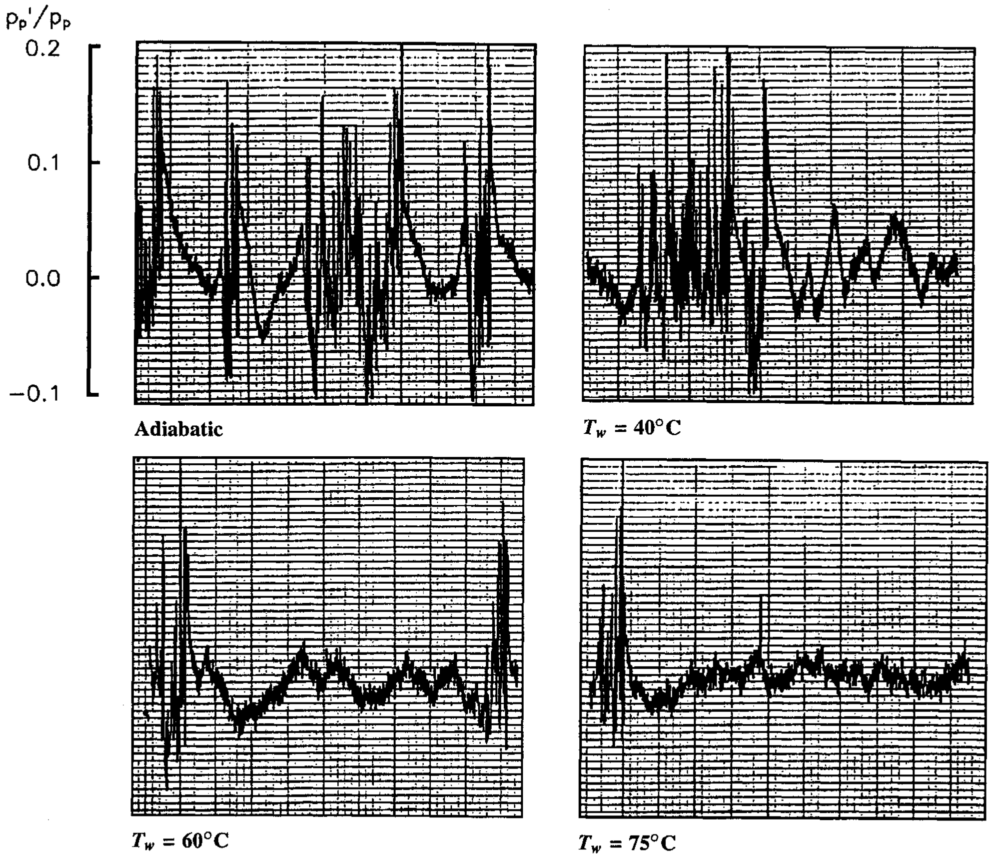

Fig. 9 Two-millisecond segments of the DPP output, obtained at a distance from the wall yielding the maximum wideband signals, at various surface temperatures. Signal at top left is for adiabatic flow (heaters idle); signal at lower right is for the maximum T_w employed in this experiment (75°C).

with a suppression of the generated turbulence—in complete agreement with Fig. 8, which shows a uniform drop of the signal at all frequencies.

V. Discussion

Viewed collectively, the experimental results show that local surface heating delays transition in the boundary layer of this nozzle. These data are then completely consistent with those reported earlier.[1,5] The significant addition of the present work is to show that this delay is caused by a suppression of a resident low-frequency instability in the boundary layer and by the resulting decrease in turbulence production by bursts. Such a sequence of events does not support the premise that transition in this nozzle can be attributed to the surface-roughness bypass. On the other hand, the observed low-frequency instability still remains to be rationalized by appropriate stability calculations even without, and preferably before, heat-transfer effects. Although identified as the cause of transition in this nozzle, the source of this instability remains obscure. Calculations by King and Demetriades[4] have shown that Tollmien–Schlichting waves amplify very little in this boundary layer; furthermore, the Goertler mechanism[10] may not explain events either—in the adiabatic case because of the same calculations, and in the heated case by the fact that the nozzle inflection point lay downstream of the region heated with the circulating heater. It may well be that the instability is peculiar to the generic geometry of a two-dimensional supersonic nozzle with all its encumbrances of pressure gradient, curvature, crossflow, and so forth.

The source of the instability notwithstanding, it is significant that its attenuation could be so achieved with only moderate local heating of a relatively small portion of the nozzle, i.e., the nozzle throat region. For geometries much simpler than that of the DeLaval nozzle, recent stability analyses[17] have drawn attention to the role of streamwise nonuniformities in the wall temperature distribution, such as the one reported here. Masad and Nayfeh[18] calculated that the heating or cooling of surface strips, finite in the streamwise direction, produces stability phenomena on flat plates that are very different from stability-theory predictions for uniformly heated or uniformly cooled surfaces. For example, whereas uniform heating can destabilize a boundary layer, the same result can be achieved with a cooled strip of strategically chosen width and location, presumably because the heat transfer reverses direction downstream of the trip and the fluid is once again heated by the wall. Analogous results can be achieved with heating strips; experiments at low speeds by Dovgal et al.[19] have shown conclusively that heated surface strips near the leading edge of an airfoil can cause transition to move downstream. Significantly, Dovgal et al.[19] obtained these results even for modest strip temperatures, consistent with the present results; and they demonstrated that the heated strip delayed transition by suppressing a boundary-layer instability exactly as found here, albeit of a different center frequency.

VI. Conclusion

Considered jointly with these previous findings, the present experimental results could have an important bearing on the modification or design of quiet wind-tunnel facilities, by providing means for delaying nozzle boundary-layer transition and thus alleviating the noise radiated into the freestream.

Acknowledgments

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