Nozzle Wall Boundary-Layer Transition and Freestream Disturbances at Mach 5

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One of the principal design objectives for a "quiet" hypersonic tunnel, where low disturbance levels are required, is to maintain laminar boundary layers on the nozzle wall at sufficiently high Reynolds numbers to obtain transition on test models. Tests were conducted in a small conventional Mach 5 nozzle to investigate the effects of several factors on transition in the nozzle wall boundary layer. The profiles of mean pitot pressure were measured and compared with theoretical predictions. The freestream disturbance levels and spectra were also measured using a constant current hot-wire anemometer and a fluctuating pitot pressure probe. The results of these measurements were used to determine whether the boundary-layer on the nozzle wall was laminar, transitional, or turbulent. For the present tests, roughness in the vicinity of the nozzle throat was the dominant factor controlling transition.

Nomenclature

D = nozzle exit diameter
e = voltage
f = frequency
L = maximum model length
M = Mach number
P = pressure
Re = local Reynolds number per unit length, $\rho_e u_e/\mu_e$
R_∞ = freestream Reynolds number per unit length at nozzle exit, $\rho_\infty u_\infty/\mu_\infty$
r = nozzle radius
T = absolute temperature
u = velocity in streamwise direction
x = axial distance from throat of nozzle
y = coordinate normal to surface of wall
ρ = density
μ = viscosity
δ = boundary-layer thickness
ϕ = Mach angle

Subscripts
aw = adiabatic wall
e = edge of boundary layer
$t,_1$ = conditions in settling chamber
$t,_2$ = stagnation conditions behind normal shock
w = wall
∞ = freestream

Superscripts
$(\tilde{\ })$ = rms fluctuating value

Introduction

THE utility of wind tunnels depends on their ability to adequately simulate one or more conditions of flight. In general this simulation depends on several parameters that include Mach number, Reynolds number, wall-to-total temperature ratio, and total temperature. Another flight condition that is important for certain types of investigations, and yet is difficult to achieve in wind tunnels, is the low level of freestream fluctuating disturbances generally expected in flight.[1,2]

Supersonic wind tunnels are especially notorious for their high disturbance levels[3-9] which consist predominantly of noise radiated from the turbulent boundary-layer on the nozzle walls. Besides the well-known effects of these wind tunnel disturbances on boundary-layer transition,[4-8] the fluctuating surface pressures under fully turbulent boundary layers at supersonic speeds are dominated by wind tunnel noise.[1,10] The structure of turbulent free shear layers is affected by high noise levels[11] and turbulent boundary layers may also be affected.

One way to obtain low noise levels in wind tunnels is to maintain laminar boundary layers on the tunnel walls. However, there are very few wind tunnels that have been operated with laminar boundary layers on the walls[12-14] and none can operate at sufficiently high pressures to produce turbulent boundary layers on models. In addition, the characteristics of boundary-layer transition on the walls of nozzles are not well understood. Therefore, an experimental investigation was conducted to investigate the characteristics of boundary-layer transition on the wall of a small conventional Mach 5 nozzle. Boundary-layer profiles were measured along the walls of the nozzle for a wide range of Reynolds numbers and wall temperature in order to determine when transition occurred. These profiles are compared with finite-difference calculations for laminar, transitional, and turbulent flow by the method of Ref. 15. Factors affecting transition of the nozzle wall boundary layer such as settling chamber screens, two-dimensional steps in the subsonic approach, upstream piping and flow control valve size, wall temperature, and wall roughness in the throat region were investigated.

Freestream disturbance levels and spectra were also measured with a fluctuating pitot pressure probe and hot-wire anemometer in the same nozzle and for the same test flow conditions as for the mean boundary-layer profiles. Both sets of measurements were required to establish the relationship between the freestream disturbance levels and the boundary-layer state (laminar or turbulent).

Apparatus and Tests: Facility

The tests were made in the Nozzle Test Chamber at the Langley Research Center. A sketch of the nozzle and settling chamber is shown in Fig. 1. The facility operates at a maximum

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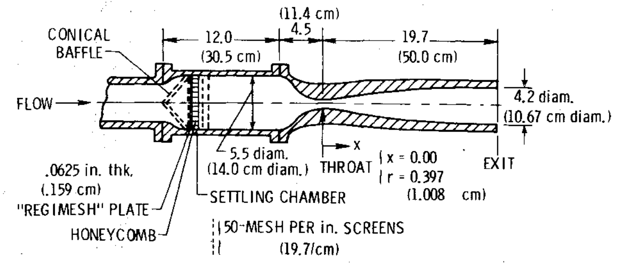

Fig. 1 Details of nozzle and settling chamber with screen configuration 1.[14] All dimensions in inches (cm).

pressure of 500 psi (345 N/cm^2). The maximum total temperature used at this pressure was about 400 K (720°R). For lower pressures the total temperature may be substantially lower—just enough to prevent condensation in the test section.

The axisymmetric nozzle was contoured to give a uniform exit Mach number of 5 at 500 psi (345 N/cm^2). The nozzle coordinates are given in Ref. 13. The exit diameter of the nozzle was 4.20 in. (10.7 cm). Measurements were made for several axial stations along and inside the nozzle from near the throat to a distance of 9.5 in. (33.6 cm) downstream of the exit (within Mach diamond).

The settling chamber and nozzle were mounted inside a vacuum chamber.[10] The over-all length of the settling chamber was 12 in. (30.5 cm) and the inside diameter was 5.5 in. (14.0 cm). Interchangeable screens, baffles, and honeycomb parts were used so that various configurations of these combined parts could be placed in the settling chamber for testing. The parts used during the present investigation are listed in Table II of Ref. 9 in the order of their arrangement from the upstream end of the settling chamber. The throat diameter of the nozzle was 0.794 in. (2.017 cm). The settling chamber-to-throat area ratio was about 50, and the nominal velocity in the settling chamber was 15 ft/sec (457 cm/sec).

Preliminary fluctuating pitot pressure data were also obtained at the exit of a new, slotted nozzle.[10] This nozzle has an annular bleed just upstream of the throat to remove the turbulent boundary layer developed on the settling chamber wall. The exit Mach number is 5.

Instrumentation

The instrumentation used to obtain the data presented herein has previously been described in detail.[14] A conventional pitot tube was used to measure the boundary-layer profiles along the nozzle wall. Corresponding freestream disturbance levels and spectra were measured with a fluctuating pitot pressure probe and a constant current hot-wire anemometer.[14] A discussion of the heat-transfer characteristics of the hot-wire, the pressure transducers used for the conventional pitot tube and fluctuating pitot pressure probe, and data reduction techniques for each instrument are also given in Ref. 14.

Test Conditions

Pitot pressure surveys of the boundary layer were obtained for several stations along the nozzle axis. All survey data have been normalized by the appropriate stagnation values, recorded simultaneously with the probe data, to account for any small changes in settling chamber conditions during the surveys. The fluctuating pitot pressure probe and hot-wire probe were located on the tunnel centerline at several axial stations downstream of the nozzle throat. Tests were conducted for a wide range of nozzle exit freestream Reynolds numbers from about $1 \times 10^6 \leq R_\infty/\mathrm{ft} \leq 2.75 \times 10^7$ $(3.28 \times 10^6 \leq R_\infty/m \leq 9 \times 10^7)$ and for $0.8 \leq T_w/T_t \leq 1.4$.

Discussion of Nozzle Boundary-Layer Profiles

Analysis of Profiles

In order to verify that laminar flow did occur along the nozzle contour, boundary-layer profiles were compared with the finite-difference method presented in Ref. 15 for laminar, transitional, and turbulent boundary-layer flows. Turbulent flow is computed by using a two-layer eddy viscosity model, and for the present solutions a constant turbulent Prandtl number of 0.9 was used.

Pitot Profiles

Pitot pressure profiles at several stations along the nozzle were obtained in the lower Reynolds number test range to determine the maximum nozzle transition Reynolds number. Examples of these results are shown in Fig. 2 for $T_w/T_t = 0.9$. The nozzle wall boundary-layer profiles are compared with laminar and turbulent predictions[15] at $x = 8.7$, 12.2, and 16.9 in. ($x = 22.1$, 31.0, and 42.9 cm). The comparisons shown in Fig. 2 clearly indicate that the wall boundary-layer remains laminar up to a maximum $R_\infty/\mathrm{ft} = 3.08 \times 10^6$ $(R_\infty/\mathrm{cm} = 10.10 \times 10^4)$ for $8.7 \leq x \leq 14.7$ in. $(22.1 \leq x \leq 42.9$ cm) before becoming turbulent at the next highest test Reynolds number. These results indicate that the nozzle wall boundary layer is laminar for about $\frac{2}{3}$ of the nozzle length downstream of the throat. Somewhat disturbed laminar boundary layers were found to occur near the exit of the nozzle[14] (14.7 in. $\leq x \leq 18.9$ in; 37.4 cm $\leq x \leq 42.9$ cm) for Reynolds numbers up to $R_\infty/\mathrm{ft} = 3.08 \times 10^6$ $(R_\infty/\mathrm{cm} = 10.1 \times 10^4)$. The disagreement between data for $R_\infty/\mathrm{ft} \leq 3.08 \times 10^6$ $(R_\infty/\mathrm{cm} = 10.10 \times 10^4)$ and the laminar profile predictions shown in Fig. 2 for $x = 16.9$ in. (42.9 cm) were also found near the exit $x = 18.94$ in.; 48.1 cm)[14] and is attributed to the presence of Taylor-Goertler vortices.[10] These vortices develop in the concave region of the nozzle and would tend to change the laminar boundary-layer profile shapes. The next small increase in Reynolds number to $R_\infty/\mathrm{ft} = 3.50 \times 10^5$ $(R_\infty/\mathrm{cm} = 11.45 \times 10^4)$ causes transition to abruptly move upstream of all survey stations. A gradual decrease in boundary-layer thickness was observed with increasing Reynolds number before transition occurs.

Effect of Various Factors on Transition

Many factors such as nozzle wall temperature, wall roughness, wall curvature, flow disturbances in upstream piping and valves, and disturbances in nozzle settling chambers due to locally separated regions and high density screens may be expected to

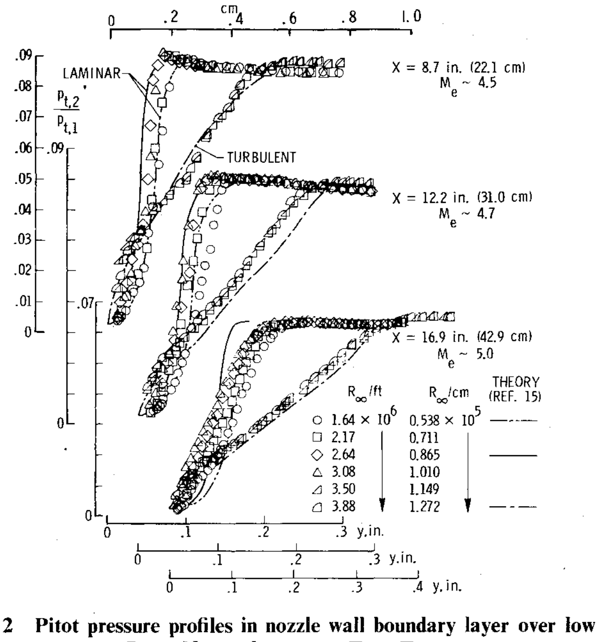

Fig. 2 Pitot pressure profiles in nozzle wall boundary layer over low Reynolds number range, $T_w \simeq T_{aw}$.

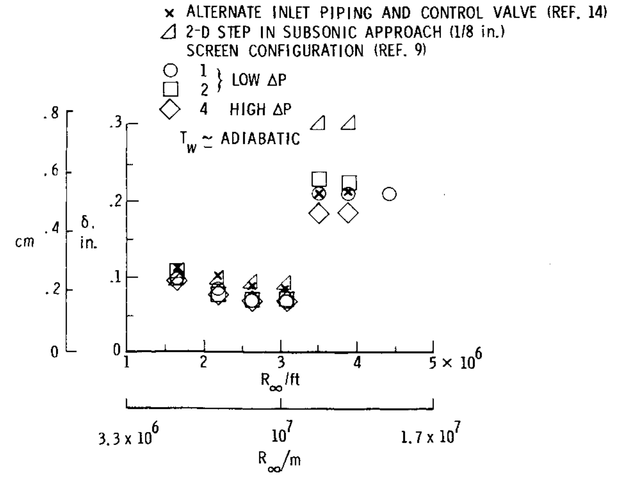

Fig. 3 Variation of boundary-layer thickness with unit Reynolds number for factors not affecting transition, $x = 10.7$ in. (37.9 cm).

influence transition of the boundary-layer on the nozzle side walls. A critical evaluation of such factors has been given earlier by Morkovin.[16] Some of the more obvious factors that might effect transition were investigated herein; the shape of pitot profiles was observed for a range of Reynolds numbers at the $x = 10.69$ in. ($x = 27.8$ cm) station for various system changes. Changes in boundary-layer thickness from the pitot profiles were used to assess the effect of these changes on transition.

Figure 3 shows the results for three factors investigated which were found not to affect transition. These factors are two-dimensional steps, settling chamber screen configurations, and changes in upstream piping and flow control valves. Effects of two-dimensional steps on transition were determined by a systematic misalignment of the nozzle-settling chamber flanges upstream of the throat (Fig. 1). Step heights were varied from 0–0.123 in. (0–0.3124 cm). Screen configurations 1, 2, and 4[9] were used to evaluate effects of screens on transition. Effects of different upstream piping and control valves were determined from tests made by directing the air supply through one pipe-valve system while an alternate passage remained isolated.[14] The ratio of the pipe diameters and valve sizes for the largest pipe-valve system to the smallest system was 4. The results in Fig. 3 indicate that no change in transition Reynolds number ($R_\infty/\text{ft} = 3.08 \times 10^5$; $Re/\text{cm} = 10.1 \times 10^4$) was observed for these factors. However, increases in boundary-layer thickness were observed from screen configuration 1–2 and with the step in the subsonic approach.

Figure 4 shows results for the factors which did affect transition. The nozzle wall was heated[14] by strip-type heaters wrapped around the exterior surface of the nozzle and subsonic

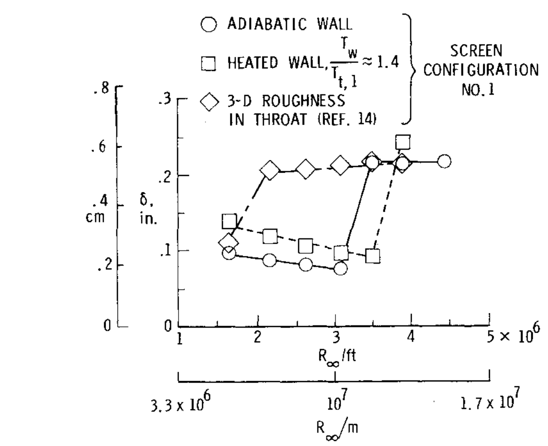

Fig. 4 Variation of boundary-layer thickness with unit Reynolds number for factors affecting transition, $x = 10.7$ in. (37.9 cm).

approach. Wall temperatures up to about 860°R (478 K) could be obtained. Again, the boundary-layer thickness from pitot profiles at $x = 10.7$ in. (27.2 cm) was used to determine the values of R_∞/ft for transition.

For a nozzle wall-to-total temperature ratio of about 1.4, the flow was laminar up to $R_\infty/\text{ft} = 3.5 \times 10^6$ ($R_\infty/\text{cm} = 11.48 \times 10^4$); at the same station for cold wall conditions the boundary-layer was laminar up to $R_\infty/\text{in.} = 3.08 \times 10^6$ ($R_\infty/\text{cm} = 10.10 \times 10^4$). Thus, heating the wall increased the transition Reynolds number approximately 20% (Fig. 4). As expected, the boundary-layer thickness is greater for the heated wall tests when compared to the cold wall data at the same longitudinal station and value of R_∞/ft. Heating the wall may reduce the boundary-layer sensitivity to local roughness. The value of $R_\infty/\text{ft} = 3.5 \times 10^6$ ($R_\infty/\text{cm} = 11.48 \times 10^4$) corresponds to $R_{\infty,D} = 1.22 \times 10^6$ which is the largest Reynolds number for laminar boundary-layers on nozzle walls ever reported.

Inspection of the nozzle during the present program revealed a very fine, nonuniform, powder-like deposit of alumina oxide on the wall of the subsonic approach section. It was determined that the alumina oxide came from the air dryer system and was passing through the screen configurations. Tests were made without disturbing the deposit and with the deposit removed from the approach section; no change in the previously determined transition Reynolds number was found for these tests. However, when the surface deposit in the approach region was randomly scribed with a pencil, resulting in a random three-dimensional roughness pattern[14] a change in profile shape and boundary-layer thickness occurred at $x = 10.69$ in. (27.2 cm) for $R_\infty/\text{ft} = 2.17 \times 10^6$ ($R_\infty/\text{cm} = 0.71 \times 10^5$) (Fig. 4). The nominal beginning of transition would be at the next lowest test Reynolds number of $R_\infty/\text{ft} = 1.65 \times 10^6$ ($R_\infty/\text{cm} = 5.41 \times 10^4$).

The roughness pattern was contained within a surface distance of about 3-in. (7.62 cm) upstream of the throat minimum and circumferentially around the surface. Microscopic examination of the alumina oxide particles and random three-dimensional "clumps" of deposit, formed by scraping through the deposit, gave estimates of the average deposit thickness to be of the order 0.001 in. (0.00254 cm). Values calculated by the method of Harris[15] of the laminar boundary-layer thickness and the displacement thickness at a distance of 1 in. (2.54 cm) upstream of the throat are 0.035 in. (0.0889 cm) and 0.0028 in. (0.00711 cm), respectively. The corresponding ratios of three-dimensional roughness height to boundary-layer thickness and displacement thickness are about 0.03 and 0.35, respectively.

It is apparent that very small three-dimensional roughness located in the throat region of a supersonic nozzle can cause transition of the boundary-layer to occur at low Reynolds numbers (Fig. 4). Results from the present experiments indicate that three-dimensional type roughness located in the subsonic approach near the throat influences transition while two-dimensional type roughness located at the beginning of the subsonic approach, caused by nozzle-settling chamber flange misalignment, does not.

Disturbance Measurements

Settling Chamber

The disturbance levels in the settling chamber can have a pronounced effect on boundary-layer transition on the wall of a nozzle; this is particularly true if transition is initiated in the subsonic or supersonic portion of the nozzle where $M_e < 2.5$. Because of this, fluctuating pitot pressure measurements were made in the settling chamber.

Effect of screens

The results of the measurements made with the various screens are presented in Fig. 5. A description of the screen configurations is given in Ref. 9. Tests without screens in the settling chamber resulted in the highest pressure fluctuation levels over the test Reynolds number range, while three of the screen configurations had relatively constant disturbance levels

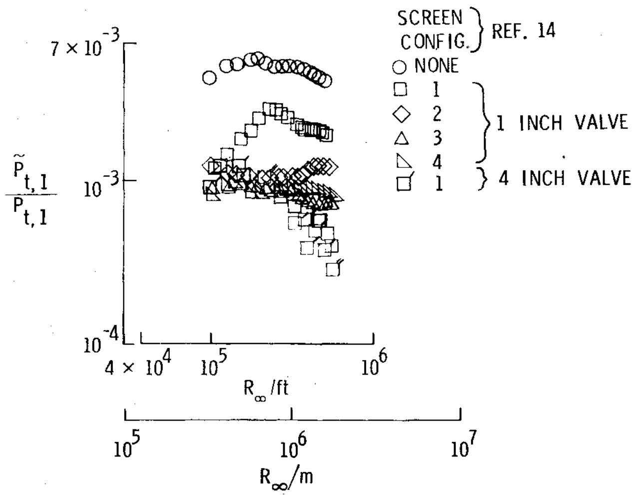

Fig. 5 **Effect of screens on disturbance levels in the settling chamber, 2.45 cm (1 in.) valve.**

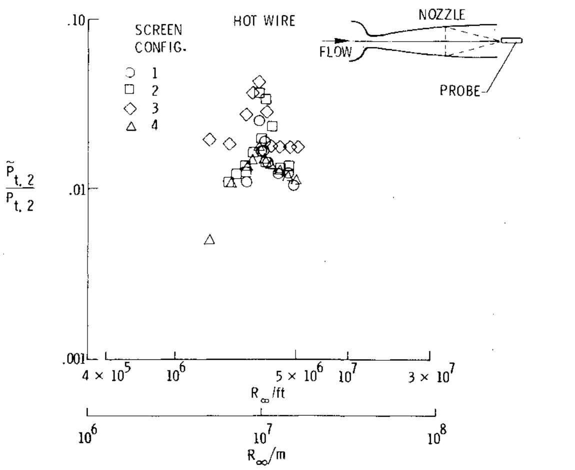

Fig. 7 **Effect of screens on disturbance level in freestream, hot-wire data, x = 53.3 cm (21.0 in.).**

of approximately 0.1% of the total pressure. This represents an rms pressure of 0.1 psi (0.07 N/cm^2) at the highest unit Reynolds number. While at low Reynolds numbers the disturbance level was about the same for all configurations, the fluctuating pressure increased for configuration 1 as Reynolds number was increased to a peak of about 0.3% before decreasing slowly with further increases in unit Reynolds number.

Effect of control valves

The effect of alternate control valve operation on disturbance levels in the settling chamber was investigated.[14] The air supply to the settling chamber may be regulated through an alternate pipe-valve system.[14] The fluctuating pressure measured with the pitot probe indicated a significant reduction in the disturbance level when the 4-in. (10 cm) valve rather than the 1-in. (2.54 cm) valve was used (Fig. 5). This reduction was as great as 80% at the higher unit Reynolds number.

Freestream

Effect of screens

The effects of different screen configurations on the disturbance level in the freestream is presented in Figs. 6 and 7. The pitot probe results, obtained at low unit Reynolds numbers, show low noise levels associated with a laminar boundary layer on the wall of the nozzle. As the unit Reynolds number was increased, the noise level increased rapidly indicating transition of the boundary layer. At still higher unit Reynolds numbers

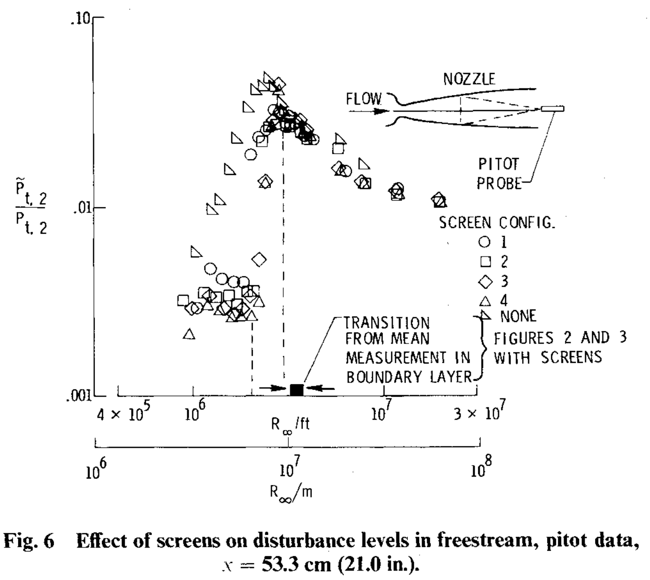

Fig. 6 **Effect of screens on disturbance levels in freestream, pitot data, x = 53.3 cm (21.0 in.).**

the noise level reached a peak and then decreased with further increases in the unit Reynolds number presumably corresponding to a fully turbulent boundary layer on the nozzle wall.

Figure 6 indicates that the fluctuating pitot pressure level was about 0.3–0.4% of the total pressure behind a normal shock when the boundary-layer on the nozzle wall was laminar. The hot-wire results (Fig. 7), reduced by the method described in Ref. 14, are not detailed enough to define the noise level when the boundary layer was laminar. One point obtained with the hot wire for screen 4 indicates that the noise level for the laminar boundary-layer was less than 0.5% for a unit Reynolds number of 1.52×10^6/ft (5×10^6/m). There was, however, a high noise level measured with screen 3 at the same unit Reynolds number. The results obtained with the pitot probe do not indicate any significant difference between screen 3 and the other screens. The reason for the higher noise levels measured with the hot wire with this screen configuration is not known.

The rms pitot pressure data indicate that the beginning of transition occurred at unit Reynolds numbers between 1.95–2.13×10^6/ft (6.4 and 7.0×10^6/m). This is only a 10% change in the unit Reynolds number at transition due to changes in the screens. Since the screens resulted in changes in the disturbance levels in the settling chamber, it can be tentatively concluded that for these tests something other than the disturbance level in the settling chamber was controlling transition on the wall of the nozzle.

The rms pitot pressure probe data taken without screens in the settling chamber (Fig. 6) indicate a significant change in the unit Reynolds number at the beginning of transition. In fact, all the data taken without screens at low unit Reynolds numbers indicate that the boundary layer was transitional down to a unit Reynolds number of 1.01×10^6/ft (3.3×10^6/m).

The peak output of the pitot probe occurred at a unit Reynolds number of about 2.74×10^6/ft (9×10^6/m). The peak output for the hot wire occurred at a unit Reynolds number of about 2.90–3.05×10^6/ft (9.5 to 10×10^6/m). The peak output in the noise level probably occurs near the end of the transition process; therefore, the hot wire and the fluctuating pitot probe indicate almost identical values for the unit Reynolds number at the end of transition.

The range of unit Reynolds number for transition as measured by the mean pitot probe in the nozzle wall boundary layer is shown in Fig. 6. The results obtained with the fluctuating pitot pressure probe indicate a lower unit Reynolds number for transition than obtained from the mean measurements. Part of this apparent discrepancy is probably due to the greater sensitivity of the fluctuating pressure gage to slight changes in the boundary-layer. However, the mean flow measurements indicate the boundary layer is still laminar when the rms pressures have reached their peak values which are presumably caused

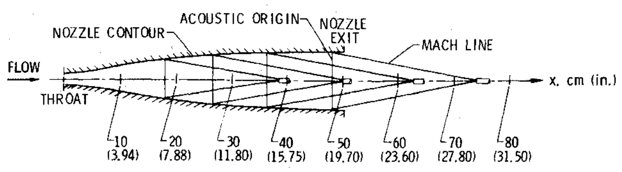

Fig. 8 Nozzle schematic showing acoustic origins for several probe positions.

by large disturbances in the boundary layer. Hence, part of the discrepancy in transition Reynolds numbers indicated by the fluctuating and mean measurements may be real and can be tentatively attributed to small differences in wall roughness in the critical throat region during the two sets of tests.

Propagation of transition

An attempt was made to determine how transition progressed along the nozzle as the unit Reynolds number was increased. This was done by making fluctuating pressure measurements with the pitot probe at several axial stations in the freestream. The fluctuating pitot probe measures the noise generated by the boundary layer at the acoustic origin of a disturbance that intersects the probe at a given station as illustrated in Fig. 8. Therefore, if transition progressed up the nozzle with increasing unit Reynolds number, the increase in the noise level would be detected first at the most downstream station.

The results of these tests are shown in Fig. 9. The beginning of transition ranged from a unit Reynolds number of 2.29×10^6/ft (7.5×10^6/m) to 2.50×10^6/ft (8.2×10^6/m) at stations 24.88 in. (63.2 cm) and 29.21 in. (74.2 cm), respectively. This variation in the unit Reynolds number is probably within the accuracy of the measurements. Hence, the beginning of transition apparently occurred at or upstream of each acoustic origin for essentially the same unit Reynolds number. The peak output from the pitot probe also occurred at the same unit Reynolds number for the three stations. This suggests that a fully developed turbulent boundary layer also was established at the three stations at essentially the same unit Reynolds number. This behavior of abrupt transition from laminar to fully turbulent flow would be expected for roughness dominated transition. This mode of transition is dominant for all data reported herein. Preliminary tests with the throat region highly polished showed that transition occurred at values of R_∞/ft up to 3 to 4×10^6 (9.83×10^4 to 13.1×10^4 cm).

In addition to the beginning and end of transition occurring at three stations at essentially the same unit Reynolds number, the extent of transition in the boundary layer, as determined by the frequency of turbulent bursts measured at the locations of the pitot probe, appeared to be essentially the same for the three stations at identical unit Reynolds numbers. Further details of the frequencies of the turbulent bursts can be found in Fig. 13 of Ref. 14. The initiation of transitional processes in the boundary layer and their propagation downstream without becoming turbulent at some downstream station appears to be a new observation. Both of these results indicate that transition was always initiated upstream of the acoustic origin of the probe and agree qualitatively with the results obtained with the conventional pitot tube. This behavior of the transitional processes might be explained by the action of a pressure gradient on the transitional boundary layer. The pressure gradient would tend to damp disturbances and prevent the transitional boundary layer from becoming turbulent. This persistence of the transitional boundary layer might be limited to small nozzles where the local Reynolds numbers do not become large enough to result in a turbulent boundary layer independent of the influence of its upstream history.

Effect of nozzle wall temperature

Tests were made with the nozzle unheated and heated. The disturbance levels measured with the pitot probe are presented in Fig. 10. The results show that transition occurred at about 2.38×10^6/ft (7.8×10^6/m) when the nozzle was unheated and at about 2.83×10^6/ft (9.3×10^6/m) when the nozzle was heated. This delay in the beginning of transition is in qualitative agreement with the mean boundary-layer survey results (Fig. 4) and could be due to thickening of the boundary-layer with increased wall temperature and the decrease in sensitivity of the boundary layer to wall roughness.[12] Also, the delay in transition could be caused by an increase in the relaminarization parameter defined using the wall temperature to evaluate density and viscosity.[13] Finally, the flow through the subsonic part of a nozzle is similar to the flow in the vicinity of the stagnation point of a sphere in supersonic flow. It has been experimentally shown[17] that wall cooling reduces transition Reynolds number in such a flow.

Spectra

Examples of spectra obtained with the pitot probe are shown in Figs. 11a and 11b. The effect of valve size on the spectra measured in the settling chamber is shown in Fig. 11a. In general, the 4-in. (10 cm) valve produced lower disturbance levels at the higher frequencies than the 1-in. (2.54 cm) valve. The larger valve did, however, produce several large disturbances ("spikes") having narrow frequency ranges. As noted previously, the over-all rms disturbance level was much greater with the smaller pipe-valve system.

Spectra measured in the freestream are shown in Fig. 11b. The upper figure presents a typical spectrum when the boundary

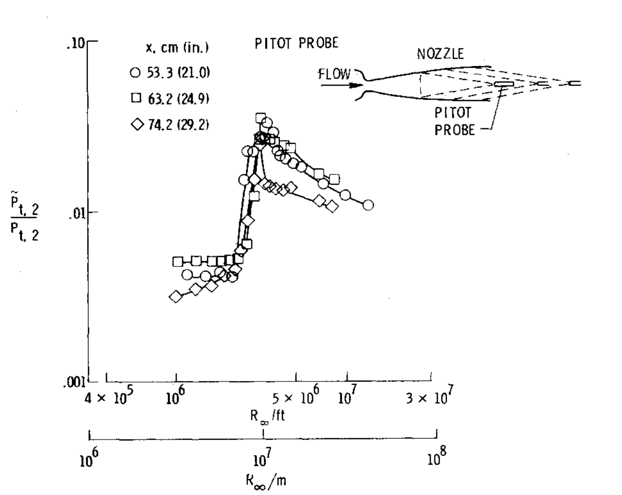

Fig. 9 Disturbance measurements at several locations in flow, screen configuration 1, pitot probe.

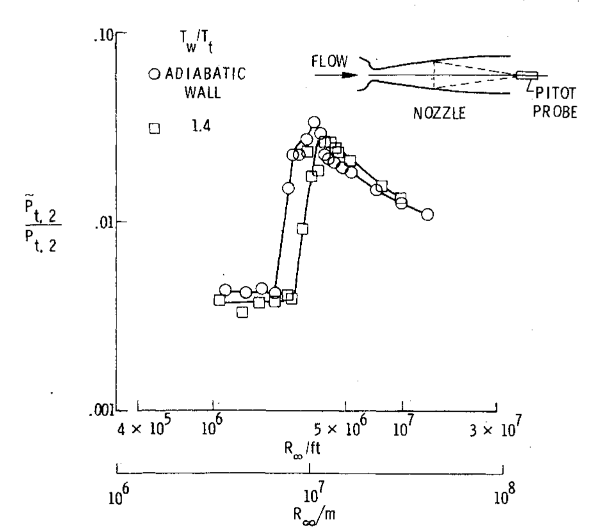

Fig. 10 Effect of nozzle wall temperature on disturbance levels in freestream, pitot probe, screen configuration 1, x = 53.3 cm (21.0 in.).

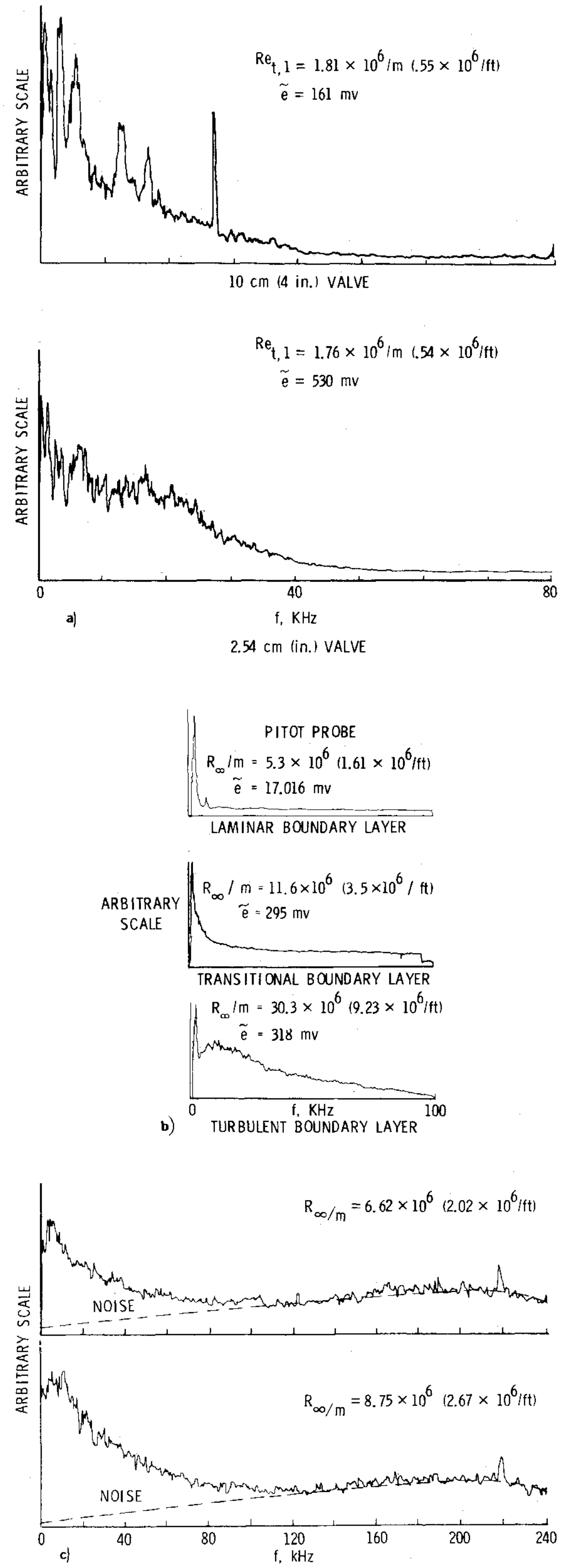

Fig. 11 Examples of spectra. a) Settling chamber, screen configuration 1, rms pitot pressure probe. b) Freestream, screen configuration 1, rms pitot pressure probe. c) Freestream, screen configuration 4, hot wire.

layer on the nozzle wall was laminar. Not only is the disturbance level low but the disturbances that are present are limited to frequencies below about 10 KHz. Therefore, the major disturbances in a hypersonic quiet tunnel would probably be limited to relatively low frequencies. At higher unit Reynolds numbers where the boundary layer on the nozzle wall becomes transitional, there is a significant amount of energy occurring at

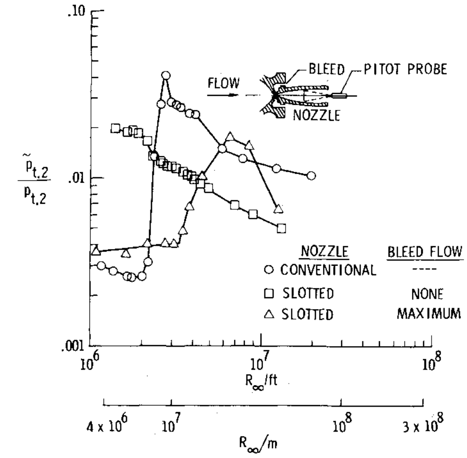

Fig. 12 Effect of boundary-layer bleed on freestream disturbance levels in slotted nozzle (Ref. 10), pitot data, x = 53.3 cm (21.0 in.).

higher frequencies. With further increases in Reynolds number, the boundary layer became turbulent and the spectrum had large energies at relatively low frequencies and significant energies up to 100 KHz. Therefore, for conventional "noisy" hypersonic wind tunnels the boundary-layer on models are subjected to high intensity disturbances having relatively wide bands of frequencies.

The freestream hot-wire spectra are shown in Fig. 11c for conditions where the boundary layer on the nozzle wall was transitional, and they show that more energy is shifted to higher frequencies when transition occurs, in agreement with the results from the pitot probe.

Slotted Nozzle

Some preliminary data were obtained with the pitot probe at the exit of the new, slotted nozzle described in Ref. 10. This nozzle incorporates an annular bleed just upstream of the nozzle throat to remove the turbulent boundary layer formed on the settling chamber wall. It is believed that removal of this turbulent boundary layer just prior to the supersonic expansion will allow laminar flow on the nozzle wall to persist to higher unit Reynolds numbers. Data for the slotted nozzle are shown in Fig. 12 and indicate that the boundary layer on the nozzle wall was turbulent for Reynolds numbers as low as 1.5×10^6/ft (5.0×10^6/m) when the bleed exhaust valves were closed. (Representative data from the conventional nozzle are shown for reference.) With the bleed valves closed the flow would spill around the lip of the slot which would then act as an efficient tripping device and cause early transition.

The disturbance level generated by the turbulent boundary layer on the wall of the slotted nozzle (with bleed valves closed) was surprisingly low—only about 40% of the level for the conventional nozzle. At the highest unit Reynolds number of the tests with the slotted nozzle, the normalized disturbance level was only 0.005. This reduction in the disturbance level at high unit Reynolds numbers is significant, and investigations of the effects of wind-tunnel disturbance levels[3-9] on transition can now be extended to much lower disturbance levels than were previously possible.

The results obtained with sonic flow in the slot (maximum bleed flow) are also shown in Fig. 12. There is a significant increase in the unit Reynolds number where transition occurred when compared with the data obtained for the conventional nozzle. The "end" of transition corresponding to the peak disturbance level occurred at $R_\infty/\text{ft} = 6.5 \times 10^6$ which is considerably larger than obtained in the conventional nozzle. The much larger range of unit Reynolds number required to complete transition in the slotted nozzle than observed in the conventional nozzle implies that a different mechanism was responsible for transition. Further investigation is required to identify this mechanism.

The unit Reynolds number for the "beginning" of transition in the slotted nozzle has been increased by about 50% above the values in the conventional nozzle. To achieve the larger projected[10] values of $R_\infty/\mathrm{ft} = 7$ to 10×10^6 may require redesign of the flow passage in the vicinity of the slot, changes in the shape of the scoop, or other improvements in the nozzle design.

Comparison with Other Results

One of the purposes of a quiet tunnel is to simulate the transition process for flight conditions.[10] As pointed out in Ref. 13, the nozzle size is an important factor in this simulation. Small nozzles may allow higher unit Reynolds numbers at the same Mach number than larger nozzles, but the maximum model length determines the maximum test Reynolds number. Therefore, the present experimental results have been compared to similar results from other nozzles and to flight transition correlations to evaluate wind tunnel-flight simulation.

Figure 13 shows a comparison of the maximum unit Reynolds number obtained while maintaining a laminar sidewall boundary layer for several different nozzles. The Reynolds number based on a length L, which approximates the maximum length of a model that can be tested in each tunnel, is plotted against the unit Reynolds number. This maximum model length L (see sketch in Fig. 13) was computed from the enclosed inviscid test rhombus (dashed lines on sketch) formed by the intersection of Mach lines from the exit diameter with the tunnel axis.

The open symbols (Fig. 13) represent the present results for various factors affecting transition. The faired lines are based on correlations[10] of flight data for local transition Reynolds number and local "mean" unit Reynolds numbers on sharp cones at $M_e = 5$ and 8. The present results show that laminar nozzle wall boundary layers were maintained at $M_\infty = 5$ for higher Reynolds numbers than previously reported. Also, the maximum Reynolds numbers approach the transition Reynolds numbers measured in flight. However, the maximum Reynolds numbers are based on an optimistic length and represent the beginning of transition. Therefore, higher maximum Reynolds numbers are required before a fully developed turbulent boundary layer can be obtained on models.

Conclusions

An experimental investigation was conducted in a conventional Mach 5 nozzle to determine the effects of various settling chamber screen arrangements and upstream piping changes, wall roughness, nozzle wall temperature, and other factors on transition in the nozzle wall boundary layer. The state of the boundary layer (laminar, transitional, or turbulent) was determined by mean pitot pressure measurements in the boundary layer and by rms and spectral measurements of disturbances in the inviscid flow with a hot-wire anemometer and a pitot pressure probe.

In general, these three measuring techniques agree as to the state of the boundary-layer on the nozzle wall. However, the unit Reynolds numbers for transition was somewhat higher as determined from the mean profile measurements than from the hot-wire and fluctuating pitot pressure measurements. The freestream disturbance levels increased abruptly to their peak values over a small Reynolds number range while the mean profile data indicated the boundary layer was still laminar. The mean profiles in the boundary layer and the fluctuating pitot pressure data indicated essentially the same invariability of transition Reynolds number with measuring station and the same variation of transition with wall temperature and wall roughness.

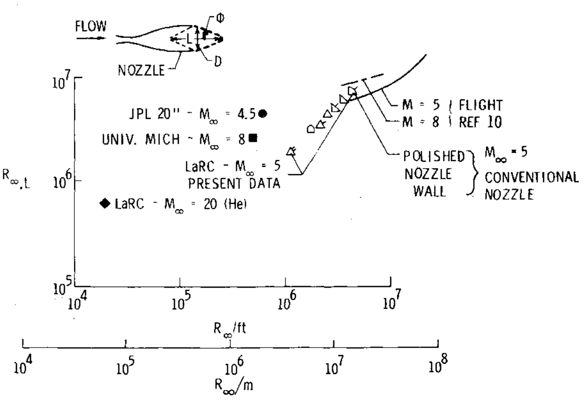

Fig. 13 Comparison of maximum transition Reynolds numbers for nozzle wall boundary-layers. Flagged symbols for fluctuating data.

The fluctuating pitot pressure measured in the settling chamber ranged from about 0.1 to 0.26% of the total pressure depending upon screen configuration. Tunnel air supply line piping and valve size had a significant effect on fluctuating pitot pressures in the settling chamber at the higher test unit Reynolds numbers but had no effect on the mean boundary-layer flow profiles on the nozzle wall. The presence of low or high pressure drop screen configurations had negligible effects on the unit Reynolds number for which transition in the boundary layer on the nozzle wall began and ended.

The unit Reynolds number at which transition occurred did not change with measuring station along the nozzle. This result indicates that for these tests transition always moved forward abruptly from the exit of the nozzle to upstream stations near or at the throat. This behavior of transition would be expected for roughness dominated transition. Indeed, roughness did appear to be the dominant factor affecting transition on the nozzle wall. Furthermore, the unit Reynolds number for which the beginning of transition occurred could be increased by about 20% by a 40% increase in the nozzle wall temperature. This effect is therefore attributed to thickening of the laminar boundary layer with increased wall temperature and the decreased sensitivity of the thicker boundary layer to wall roughness.

In general, the implicit-finite-difference theoretical method used gave good predictions of the experimental results. The disagreement between measured and theoretical profiles near the nozzle exit may be attributed to freestream disturbances or the presence of Taylor-Gortler vortices that develop in the concave region of the nozzle.

Results from the combined measuring techniques indicate that the conventional nozzle could be operated with a laminar boundary-layer on the nozzle wall to higher Reynolds numbers based on exit diameter and freestream conditions than previously reported in the literature.

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