Comparison of Wind Tunnel Transition and Freestream Disturbance Measurements

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Boundary-layer transition measurements have been made on two 5° half-angle cones at $M_\infty \approx 7$ in the Ames 3.5-ft Hypersonic Wind Tunnel and the Langley Variable Density Wind Tunnel. Although there were differences between the measured freestream disturbance scales and pressure fluctuation levels, the choice of consistent locations within the transition region, using either thin-film fluctuation or surface heat-transfer data results in excellent agreement between the transition Reynolds number in both facilities. However, there is an apparent connection between changes in freestream pressure fluctuation levels and movement of boundary-layer transition location in the two facilities.

Nomenclature

D = wind-tunnel test section diameter
f = frequency
p = pressure
p_c = surface pressure on cone
p_{o_2} = pitot pressure
Re = local Reynolds number based on distance from cone apex
R_{xx}, R_{zz} = spatial correlation coefficients along the wind-tunnel axis and normal to the axis, respectively
S_T = Stanton number
T_o = stagnation temperature
T_w = wall temperature
u = velocity
ρ = density
θ_c = cone half-angle
x, z = separation distances along the wind-tunnel axis and normal to the axis, respectively

Superscripts
$(\ )'$ = fluctuating value
$\langle(\ )\rangle$ = root mean square

Introduction

THIS investigation, one of the activities of the NASA Transition Study Group, was undertaken to resolve previously reported differences between boundary-layer transition Reynolds number data measured at similar test conditions in two different wind tunnels. These data (see Fig. 1) were obtained on two similar 5° half-angle cones in the Ames 3.5-ft Hypersonic Wind Tunnel using thermocouples and in the Langley 18-in. Variable Density Wind Tunnel using thermal paint and thermocouples.

To investigate these transition Reynolds number differences, new measurements were made in what are now slightly modified versions of both test facilities. However, since the parameters affecting boundary-layer transition are numerous and complex, the same models and detection techniques (thermocouples and thin film gages) were used in both facilities. This was done in an attempt to alleviate any inconsistencies due to the effects of unknown model influence and differences between the various detection techniques. In addition, since recent results[1] indicated that discrepancies between wind-tunnel transition data could be primarily attributed to differences in freestream disturbance levels, hot wire turbulence and pressure fluctuation levels were also measured in the two facilities.

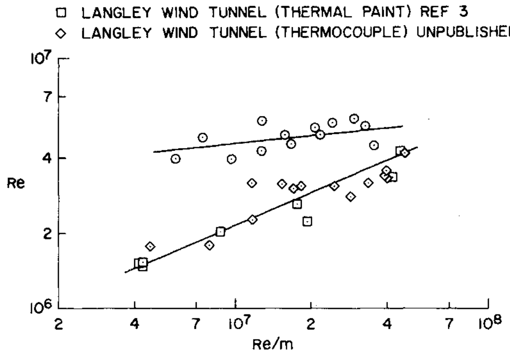

Fig. 1 Comparison of previous transition Reynolds number data (beginning) from two wind tunnels, $M_\infty \approx 7.5$, $\theta_c = 5°$, $T_w/T_o \approx 0.4$.

Experimental Details

Wind Tunnels

The nominal test conditions were $T_o = 835°K$, $p_o = 13$ to 122 atm, and $M_\infty \approx 7.3$ in the Ames facility and $T_o = 800°K$, $p_o = 14$ to 150 atm and $M_\infty = 7.9$ in the Langley facility. The ratio of wall to freestream total temperature was approximately 0.4. A full description of the two facilities is given in Ref. 4.

Transition Models

Boundary-layer transition measurements were obtained in both facilities on two different 5° half-angle cone models. One was a thin-skin thermocouple model, 1 m long, instrumented with 110 iron-constantan thermocouples with an average spacing of about 6.35 mm along one ray. The second model, which was

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0.71 m long, was machined from a solid steel billet and was instrumented with five platinum thin-film gages installed flush with the model surface and equally spaced along one ray at distances between 20.3 and 61.0 cm from the cone apex.

Facility Disturbance Characteristics

Freestream turbulence measurements were made in the Ames tunnel with a constant-current anemometer, as described previously in Ref. 4. In addition, comparative rms pitot pressure fluctuation measurements together with fluctuating surface pressure measurements on a 16° cone were obtained in the two facilities. These probes are described in detail in Ref. 4.

Transition Detection

The variation of the rms thin-film voltage fluctuations of a single gage over a range of unit Reynolds numbers is shown in Fig. 2a. The curves clearly show a rise from the laminar to the turbulent level, with an intermediate peak. These curves enable three distinct points in the transition region to be accurately and consistently determined: namely, the onset of transition, defined as the point where the rms signal begins to increase from its laminar value (this onset of intermittency can be clearly seen on the oscilloscope traces); the peak rms signal, which coincides with the point of maximum turbulent burst frequency,[5] and the end of transition. Examples of the characteristics of the film voltage fluctuations through the transition region are also shown on Fig. 2a.

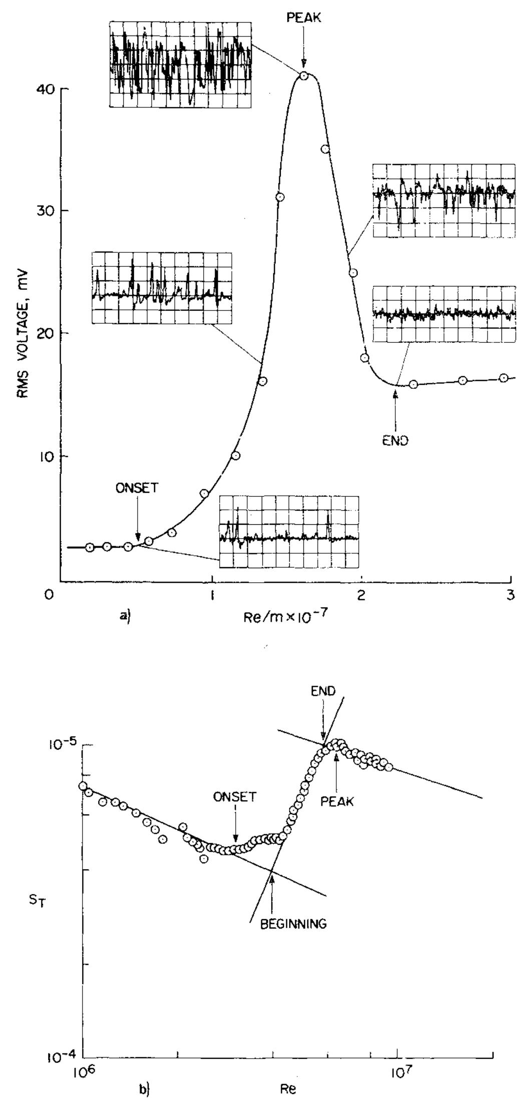

Fig. 2 Determination of transition location. a) Thin-film technique. b) Thermocouple technique.

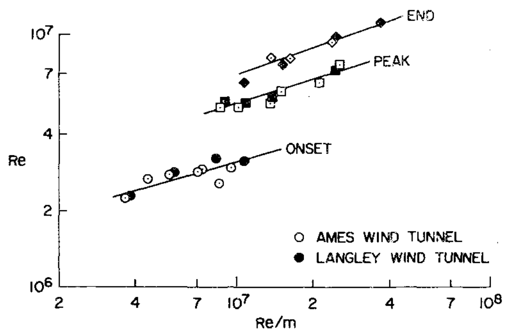

Fig. 3 Comparison of thin-film transition data in the two wind tunnels, $M_\infty \approx 7.5$, $\theta_c = 5°$, $T_w/T_o \approx 0.4$.

Figure 2b shows variations in Stanton number through transition, as measured using the thermocouple technique obtained in the Langley facility. In this case, four values of transition Reynolds number can be determined: namely, the onset of transition, defined as the point where the Stanton numbers first consistently exceed the laminar value: the "beginning," obtained by fairing straight lines through the laminar and transitional data; the "end," obtained by fairing straight lines through the turbulent and transitional data; and finally the peak Stanton number. However, at the lower unit Reynolds numbers, anomalous heat-transfer data similar to those reported in Ref. 6 were observed only in the Langley facility and can be clearly seen in Fig. 2b. That is, apart from the scatter in the laminar data, an initial unexplained deviation from the laminar value occurs before what appears to be the "true" onset of transition. This region of anomalous heating decreased with increasing Reynolds number.

Discussion of Results

Transition Data

Figure 3 shows the influence of unit Reynolds number on the magnitude of the transition Reynolds number and the extent of the transition region as measured in both facilities with the thin-film gage model. Contrary to the previous measurements there is excellent agreement between the two sets of data obtained in the two facilities. However, comparison of the thermocouple transition data obtained in the two wind tunnels still shows some differences when the conventional beginning and end of transition points are used (Fig. 4). The beginning data clearly show that the thermocouple technique does not provide consistent transition point data. This is probably caused by the anomalous heating data discussed earlier since this causes the beginning of transition to be determined at different values of intermittency depending on the unit Reynolds number and test facility.

For this reason, the thermocouple and hot-film data were compared, using locations in the transition region that were more compatible and that would check the consistency of the thermocouple data. Previous results[5] indicate that the thin-film peak-voltage fluctuation and the peak overshoot of some macro-

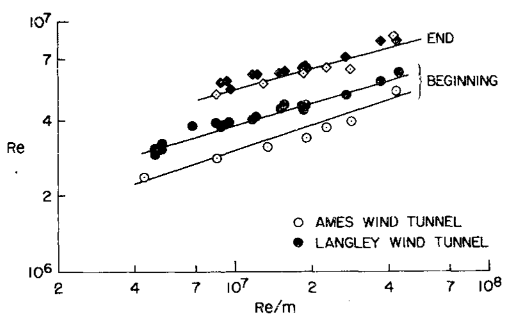

Fig. 4 Comparison of thermocouple transition data in the two wind tunnels, $M_\infty \approx 7.5$, $\theta_c = 5°$, $T_w/T_o \approx 0.4$.

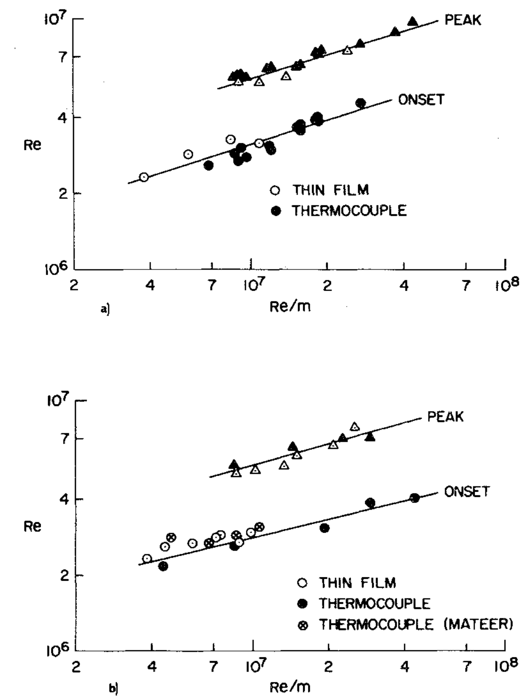

Fig. 5 Comparison of transition detection techniques, $M_\infty \approx 7.5$, $\theta_c = 5°$, $T_w/T_o \approx 0.4$. a) Langley wind tunnel. b) Ames wind tunnel.

scopic quantity such as heat-transfer, skin-friction, or surface pitot pressure should be in close agreement and that "onset" rather than "beginning" data should be used to compare with the hot film results since significant departures from these laminar values can be determined only when intermittency is appreciably greater than zero.

This comparison of the two detection techniques in the Langley facility is shown in Fig. 5a, which shows excellent agreement between the two techniques. Unfortunately, a number of thermocouples were damaged during the tests in the Ames facility so that insufficient Stanton number data were available to determine onset and peak for all tests. However, the few data points that are available, together with additional 5° cone thermocouple data obtained by Mateer (private communication, 1973), are also in good agreement with the thin-film gage results as shown in Fig. 5b.

Freestream Disturbance Measurements

The fluctuating pitot and surface pressure measurements are presented in Fig. 6, which shows that the dimensionless disturbances obtained with the pitot probe and the conical model are in good agreement over the entire range of unit Reynolds numbers, although there are significant pressure fluctuation level differences between the two facilities, especially at the lower unit Reynolds numbers. These data, together with the

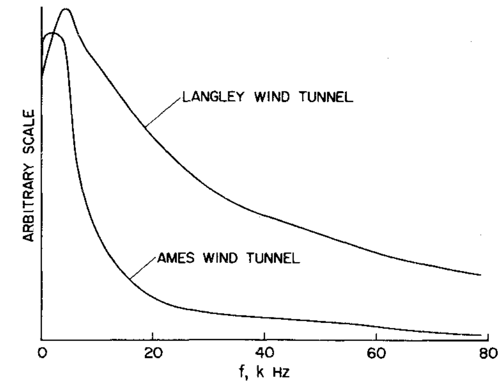

Fig. 7 Comparison of power spectra of the pitot pressure fluctuations in the two wind tunnels.

data in Fig. 5, show that in each facility increased boundary-layer transition Reynolds numbers are associated with decreasing dimensionless freestream pressure fluctuation levels, as noted previously.[1] The pressure disturbance spectra, presented in Fig. 7, show that, although most of the energy is concentrated at low frequencies, the spectra levels are quite different at high frequencies, reflecting expected differences in fluctuation scale due to wind-tunnel size.

Figure 8 shows rms values of the mass flow and total temperature fluctuations in the Ames 3.5-Foot Wind Tunnel calculated assuming a correlation coefficient of -1.0. Due to the scatter in the data, no trends in turbulence level with operating pressure could be established. However, the mean values indicated in Fig. 8 of $\langle(\rho u)'\rangle/\rho u = 2.65\%$ and $\langle T_o'\rangle/T_o = 0.83\%$ should be representative of the freestream turbulence levels over the unit Reynolds range used in the tests.

Some interesting features of the freestream disturbances have been determined from two-wire, space-time correlation measurements. Streamwise disturbance convection velocities were measured in both facilities and found to be independent of scale and equal to 70% of the freestream velocity. This result is in good agreement with an extrapolation of Laufer's lower Mach number data.[7] Figure 9 shows the variation of the optimum spatial correlation functions in the streamwise and lateral directions as measured on the tunnel centerline in the Ames facility. These results, which indicate that the disturbance length scales (calculated for $R_{xx} = 1/e$) are several times their width, are consistent with the concept of radiated sound from the side wall turbulent boundary layer[7]; i.e., the indicated ratio of streamwise scale to lateral length scale of ≈ 3.0 agrees with that predicted assuming wall boundary-layer source propagation angles originating upstream of the test section where $M_{\text{source}} \approx 3$. These streamwise fluctuation scales correspond to over-all wind tunnel wall boundary-layer source lifetimes of several boundary-layer thickness.

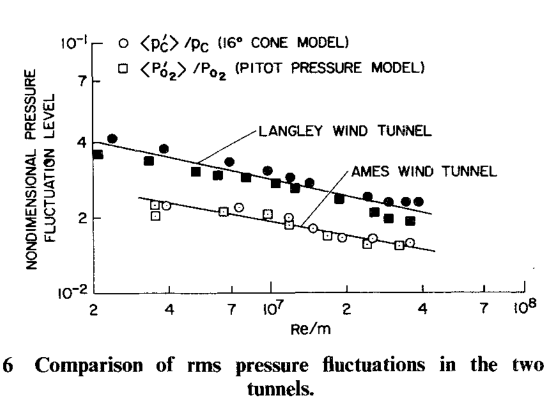

Fig. 6 Comparison of rms pressure fluctuations in the two wind tunnels.

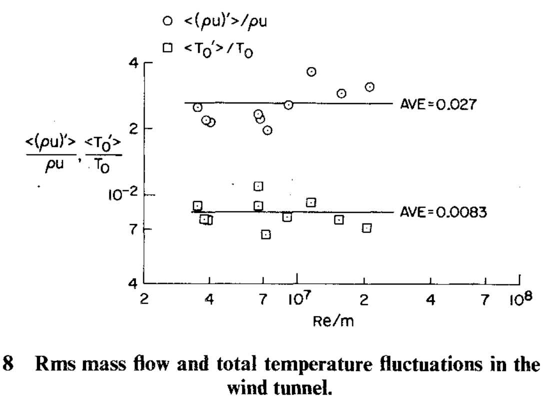

Fig. 8 Rms mass flow and total temperature fluctuations in the Ames wind tunnel.

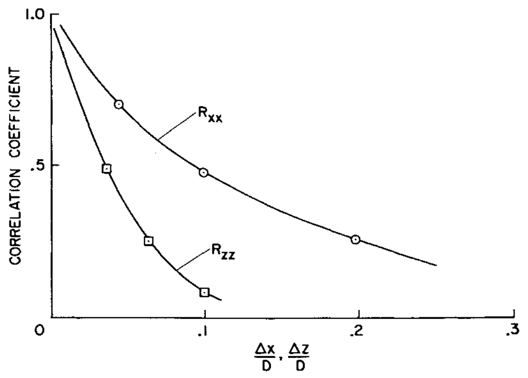

Fig. 9 Spatial correlation coefficients in the Ames wind tunnel.

Conclusions

Previously reported differences between transition data obtained on similar models at similar test conditions in the Ames 3.5-ft and the Langley Variable Density Wind Tunnels were not apparent in the present experiments. Indeed there was good agreement between data obtained in the two facilities, although the measured freestream pressure-fluctuation levels and disturbance spectra were somewhat different. However, there was an apparent connection between changes in freestream pressure-fluctuation levels and transition location in each facility.

A comparison between the thermocouple heat-transfer and thin-film gage fluctuation techniques has shown that anomalous heat-transfer data can affect the thermocouple technique of transition detection which could lead in some cases to inconsistent results. But, when consistently defined onset and peak are used for comparison, there is excellent agreement between the two methods. However, the authors feel that more reliable results will always be obtained using thin-film gages since these locations can be most easily distinguished using this technique.

References

[1] Wagner, R. D., Maddalon, D. V., and Weinstein, L. M., "Influence of Measured Freestream Disturbances on Hypersonic Boundary Layer Transition," *AIAA Journal*, Vol. 8, No. 9, Sept. 1970, pp. 1664–1670.

[2] Mateer, G. G. and Larson, H. K., "Unusual Boundary Layer Transition Results on Cones in Hypersonic Flow," *AIAA Journal*, Vol. 7, No. 4, April 1969, pp. 660–664.

[3] Stainback, P. C., "Effect of Unit Reynolds Number, Nose Bluntness, Angle of Attack, and Roughness on Transition on a 5° Half-Angle Cone at Mach 8," TN D-4961, Jan. 1969, NASA.

[4] Stainback, P. C., Wagner, R. D., Owen, F. K., and Horstman, C. C., "Experimental Studies of Hypersonic Boundary-Layer Transition and the Effects of Wind Tunnel Disturbances," TN D-7453, March 1974, NASA.

[5] Owen, F. K., "Transition Experiments on a Flat Plate at Subsonic and Supersonic Speeds," *AIAA Journal*, Vol. 8, No. 3, March 1970, pp. 518–523.

[6] Softley, E. J., "Transition of the Hypersonic Boundary Layer on a Cone," GE Rept. R 68SD, Oct. 14, 1968, General Electric Corp., Schenectady, N.Y.

[7] Laufer, J., "Some Statistical Properties of the Pressure Field Radiated by a Turbulent Boundary Layer," *The Physics of Fluids*, Vol. 7, No. 8, Aug. 1964, pp. 1191–1197.