48th AIAA Aerospace Sciences Meeting Including the New Horizons Forum and Aerospace Exposition
4 - 7 January 2010, Orlando, Florida

AIAA 2010-1466

Summary of Hypersonic Transition Research Coordinated Through NATO RTO AVT-136*

Steven P. Schneider†
School of Aeronautics and Astronautics
Purdue University
West Lafayette, IN 47907-1282

Abstract

Hypersonic laminar-turbulent transition is one of the key unresolved issues in aerothermodynamics. Since the AVT has no resources of its own, it can only serve to coordinate efforts that are funded by the various member countries. The problem is complex and difficult, so the AVT-136 effort could make only an incremental advance. Since transition often depends on many subtle factors, and is known to depend on the freestream disturbance environment, it is important to perform both experiments and computations in several locations using different facilities and personnel [1]. Each contributor benefits from iteratively comparing their results to the results of others.

In addition, no single wind tunnel can simulate all aspects of hypersonic flight, so it is important to compare results from various facilities which can each simulate different aspects. This is particularly important because the facilities and associated instrumentation are very expensive and time consuming to develop. Computational simulations are also complex, involve numerous simplifying assumptions that differ between codes, and are time consuming to develop.

Therefore, transition work under AVT-136 focused on developing an international cooperation that compares experiments and computations in several nations, funded by the various national governments, and coordinated towards a goal of common interest. Such a cooperation is complex and time consuming, so the 3-year time-frame of AVT-136 could serve only as a beginning. Introductory information is omitted here, as the reader is assumed to be familiar with the field.

*AIAA-2010-1466, presented at the Jan. 2010 AIAA Aerospace Sciences Meeting

†Professor. Associate Fellow, AIAA.

Transition on Circular Cones Near Zero Angle of Attack

The group agreed to focus on transition on circular cones near zero angle of attack, both on the ground and in flight. This configuration was chosen because it is relevant to efforts that can be funded in several NATO countries. The Italian team supporting USV is studying transition on circular cones. The German DLR has taken an interest in both computational simulations and experiments in the high-enthalpy shock tunnel HEG. The experiments in the HEG are to follow similar experiments in the high-enthalpy HIEST shock tunnel operated by JAXA in Japan, with which the DLR has an exchange agreement. The Technical University at Braunschweig in Germany has made measurements in their Mach-6 Ludwieg-tube tunnel. The Mach-6 blowdown tunnel at DLR Cologne has also been used for related measurements.

In the U.S., a small-bluntness slender cone is to be flight tested as HIFiRE-1, which led to experimental measurements at the LENS shock tunnels at CUBRC, the Mach-6 blowdown tunnel at NASA Langley, and the Mach-6 quiet Ludwieg tube tunnel at Purdue. Sandia National Laboratory has an interest in the pressure fluctuations under transitional flow, which led to support for instability and transition measurements at Sandia and elsewhere. The HIFiRE-1 effort also led to computational simulations at the University of Minnesota and NASA Langley. The Minnesota STABL code is being used to compute instability-wave growth for comparison to the results at Langley, CUBRC, Purdue, Sandia, AEDC Tunnel 9, Braunschweig, HEG, and HIEST. The STABL code is also being used for comparisons to flight data. The DLR NOLOT code is being used for comparison to the STABL results.

The HIFiRE-1 flight geometry has a 7.0-deg. half angle and a 2.5-mm nose radius; the various researchers are all studying 7-deg. half-angle cones with small nose radii, although the actual nose radius that is used depends on scaling arguments and site-specific issues. In all cases, the second-mode instability is expected to dominate transition. The experimental research generally includes measurements of the second-mode wave amplitudes as well as the tunnel noise and transition location. At least three computational codes are being used to compare the second-mode wave amplification. Different models are being built using the instrumentation and methods appropriate to the various facilities. Transition is to be measured with similar instrumentation, to the extent feasible. In most cases, the model includes transducers for measuring the surface pressure fluctuations. The surface pressure fluctuations under laminar flow will be used to estimate the noise level in the various tunnels, so both the transition location and the noise level can be compared, as in the classic work of Dougherty and Fisher [2] at lower speeds. Measurements are to be made at various unit Reynolds numbers. In HEG and HIEST, measurements are being made at various enthalpy levels, at the same Mach and Reynolds numbers, to improve understanding of the effect of gas chemistry. These high-enthalpy measurements are being compared to stability analyses provided by the University of Minnesota.

Planned HIFiRE-1 Flight Tests

Planning for the HIFiRE-1 flight test began ca. 2006, as described in Kimmel et al. [3]. A cone-cylinder-flare with a 7-deg. conical half-angle is to be flown from a Terrier-Orion launch vehicle at the Woomera range in Australia. Transition is to be measured on the nose-cone during reentry, at a Mach number near 7. Although angle of attack is to be minimized, non-zero values remain probable during transition. The nose radius of 2.5 mm was selected as large enough to be readily survivable but small enough to permit relatively low-Reynolds number transition that should be dominated by second-mode instabilities. The conical section is about 1.1 m long. The flight has experienced the usual delays but is now expected during 2010. Of course, there are many difficulties involved in implementing flight tests; one of the bigger challenges will involve making useful measurements as the cone nutates during reentry.

Kimmel [4] discusses the surface roughness on the flight vehicle. The roughness on the nosetip and at the joints between the vehicle sections is to be smooth enough to avoid affecting transition. Near the nose, this may not be trivial to attain, given the uncertainty in the requirements and the various correlations, and also given the exotic materials needed to withstand the high temperatures expected on the small-radius non-ablating nose. Since there is much uncertainty about the location where transition may occur on the smooth body during reentry, an isolated roughness was added to the design. This isolated roughness is to trip transition on one side of the vehicle even at relatively high altitude, so that trip-induced transition can be measured, even if the smooth side remains laminar to lower altitudes where the vehicle slows to supersonic speeds.

Kimmel [5] provides a summary of the computations and experiments carried out for the aerothermal analysis. The effect of gas dissociation is insignificant, and vibrational excitation has a small effect. An N-factor of 10 was used to extrapolate the wind-tunnel measurements to flight. The effects of wall temperature, angle of attack and tunnel noise are all discussed.

CUBRC Measurements And Computations for HIFiRE-1

Wadhams et al. [6] describe the measurements in the large shock tunnel at Buffalo, over Mach 6.5 to 7.4. Thin-film heat-transfer gauges were used to characterize intermittency and transition, and pulsed laser Schlieren images are also shown. Fast PCB132 piezoelectric pressure sensors have been used to measure second-mode waves in blowdown tunnels and Ludwieg tubes, and were here used in the first such attempt in a shock tunnel, which was not yet successful. The model was a full-scale version of the HIFiRE-1 vehicle, with a 7-deg. half-angle cone that is 1.1 m long and 275 mm in diam. The cone is followed by a cylinder section and a flare, which is used for study of shock/boundary-layer interaction. Wadhams et al. measured with a sharp nose, a 2.5-mm nose radius, and a 5.0-mm nose. The flight velocity was duplicated along with the Mach number, so the freestream temperature is nearly the same as flight, although the wall temperature is lower than flight. Pitot-pressure measurements found freestream fluctuations of 0.25-0.5%; the amplitude decreased with frequency.

Earlier measurements (reported in detail in Ref. [7]) were used to select the 2.5-mm nose radius, since a 5-mm nose radius delayed transition to the cone-cylinder junction. At Mach 6.5 to 7.2, and freestream Reynolds numbers of 16.4 to 9.8 million per meter, transition onset appears near 0.3 to 0.4 m from the nose, at zero angle of attack [6]. When the nosetip was heated from room temperature to about 440K, transition was mostly unaffected. Wadhams et al. also show a sequence of Schlieren images and thin-film records which show the passage of turbulent spots along the cone.

A small diamond-shaped roughness is to be attached to the flight vehicle on one side, 525 mm from the tip, to ensure the occurrence of hypersonic transition despite limited Reynolds numbers. The trip is 10 mm on a side and 2 mm high. Although the run conditions are not labeled in Figs. 25-27 of Ref. [6], it appears that the roughness caused transition to begin midway down the cone, even at a freestream Reynolds number of 3 million per meter.

Computational efforts are reported in Refs. [6] and [8]. The Univ. of Minnesota STABL package was used to obtain Navier-Stokes mean-flow solutions and then linear parabolized stability analyses. The laminar heat transfer agreed well with the simulation. Transition onset appeared near where the most-amplified second-mode wave was computed to have a linear amplification of e^6 ($N = 6$). The seven cases computed in Ref. [8] yielded N factors of 4.9 to 6.8, with an average of 5.7. MacLean et al. [8] point out that the flight test should have lower noise than conventional ground tests, and also that the wall temperature in flight will be much higher than in the shock tunnel, perhaps near radiative equilibrium. Using radiative equilibrium, MacLean et al. compute a surface temperature in flight that falls from 1800-2100K near the nose to about 1200-1300K near 0.1 m to about 1000K near the end of the cone. For the Mach 7.2 flight point, the cold ground-test wall- temperature distribution yielded $N = 6.8$ at about 0.45 m (their Fig. 9), while the hot flight-test wall- temperature distribution yielded N of about 5 at 0.45 m (their Fig. 12). The plots shown in Ref. [8] do not permit a more detailed comparison of the wall temperature effects; since the wall temperature varies dramatically with arclength during flight, the effect is not easy to estimate. Additional figures from MacLean (private communication, Sept. 2009) show that when the wall temperature rises to radiative equilibrium from room temperature, the streamwise location at which $N = 6$ or $N = 10$ is reached increases by about 20%.

Purdue Measurements for HIFiRE-1

To reduce the risk of surprises in a flight test, it is generally advisable to make quiet-tunnel measurements under noise levels comparable to flight, to estimate the effect of tunnel noise on pre-flight ground tests in conventional facilities. However, available quiet tunnels cannot maintain laminar nozzle-wall boundary layers and the associated low noise levels to Reynolds numbers that are sufficient to achieve natural transition on a blunt cone at zero angle of attack [9]. In addition, the only existing hypersonic quiet tunnels are relatively small facilities that operate only with cold flow at Mach 6. Both the Purdue and Texas A&M tunnels can also operate with turbulent nozzle-wall boundary layers and noisy flow, by closing the valves providing suction to the bleed lips just upstream of the nozzle throat. Of course, the noise level under both conventional and quiet flow still varies with the tunnel and flow conditions. Even under quiet flow, the noise level is not zero and may still be higher than the unknown noise level in flight.

To study the effects of tunnel noise, Casper et al. performed experiments with the HiFire-1 geometry in the Purdue Mach-6 quiet tunnel [10]. The 7-deg. half-angle cone had a 4-inch base diameter and a 0.047-inch nose radius. Qualitative indications of heat transfer were measured using temperature-sensitive paint, and used to infer transition onset. Diamond-shaped roughness elements were applied at an axial location 5.1 inches from the nose.

As expected, the nominally smooth model remained laminar under quiet flow, to the maximum feasible Reynolds number of about 4 million, based on freestream conditions and cone length. Under noisy flow in the Purdue tunnel at a freestream Reynolds number of 5.5 million per foot, transition occurred on the model at about 1 foot from the nose, which is generally similar to the location in the Langley tunnel. The N factor at transition in the Purdue tunnel under conventional noise was 5.8, while it was 6.0 in the Langley tunnel.

The effect of tunnel noise on transition induced by the isolated roughness element was of primary interest. For 'effective' roughness elements, it was previously thought that tunnel noise would have little effect [11]. Surprisingly, Casper's measurements showed a large effect of tunnel noise on roughness-induced transition, even under conditions where the roughness was 'effective' under noisy flow. Fig. 1 summarizes the results. The roughness Reynolds number, Re_k, is based on the roughness height k and the conditions in the undisturbed boundary layer at that height. The axial distance to transition onset is x_{tr}. For the lowest value of Re_k, transition occurs only under noisy flow; the boundary layer is laminar to the end of the cone under quiet flow. For higher values of Re_k, the reduction in tunnel noise delays

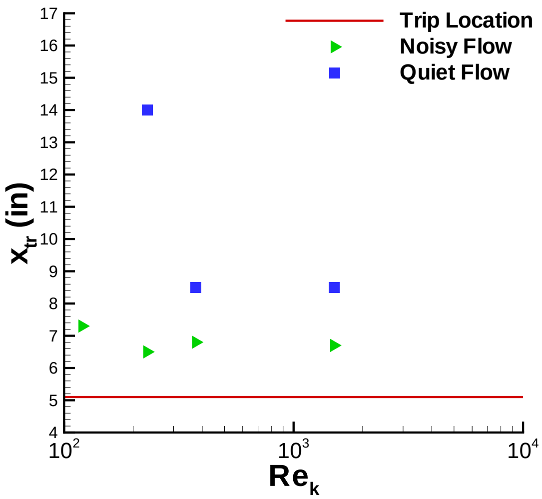

Figure 1: Effect of Trip Reynolds Number and Tunnel Noise on the Axial Location of Transition for the HiFIRE-1 Cone at Zero Angle of Attack and Mach 6

transition by factors of 2-6, even when the roughness is 'effective' under noisy flow. Further investigations of this effect should be carried out in the future.

NASA Langley Measurements for HIFiRE-1

Berger et al. [12] report measurements in the 20-inch Mach-6 blowdown tunnel at NASA Langley. The three models of the full vehicle were 20% scale. The nose radius was about 2.4 times larger than scale, due to the limitations involved in fabricating the ceramic phosphor models. There were also two models of the forecone alone, at 35% scale; one of these had a 0.047-in-radius nosetip (1.37 times scale), while the other had a 0.083-in.-rad. nosetip (2.4 times scale). Although this paper gives only the unit Reynolds numbers for each run, which are not sufficient to define the flow conditions, Table 1 in Alba et al. [13] gives the full flow conditions. The stagnation temperature is near 515K for all the runs. Transition is inferred from heat-transfer measurements using thermographic phosphor images that are compared to laminar Navier-Stokes computations.

Berger's Fig. 5 shows results for the 0.047-in-rad. forecone. At 2.5 million per ft., the flow is still laminar at 8.4 in. axially downstream from the nosetip. At 4 million per foot, transition onset occurs at about 0.6 ft., for a length Reynolds number of roughly 2.5 million. At 5.6 million per ft., it has moved upstream to about 0.45 ft. Data for transition on the other smooth forecones is not shown.

Berger et al. [12] also report measurements behind a diamond-shaped roughness 0.050-in. on a side. For the full-vehicle model with the 0.047-in. nose radius, and a roughness at 1.65 in. from the nosetip, transition did not occur for a roughness height of $k = 0.0045$ in.; the heat transfer behind the roughness is almost the same as the smooth-wall case. For a roughness height of 0.0065 in., transition onset occurs near 0.38 ft. A roughness of 0.0115 in. was nearly effective in tripping, at $k/\delta^\star = 3.2$, where $\delta^\star$ is the displacement thickness. This ratio was used to design the roughness in flight. The effect of the various model sizes is not examined in the paper.

Minnesota Computations for HIFiRE-1

Johnson et al. [14] report stability analyses for the earlier CUBRC experiments. A Navier-Stokes mean flow is analyzed using the linear parabolized stability equations (PSE) as incorporated in the STABL code. Four Mach-7 runs are analyzed along with five Mach-10 runs, and all the conditions are tabulated. An e^N analysis with $N = 5.5$ gave good agreement with the measured transition-onset locations, while an analysis using $Re_\theta/M_e = 150$ scattered widely. Here, Re_θ is the local Reynolds number based on edge conditions and momentum thickness, and M_e is the local Mach number based on edge conditions. At 4.6 MJ/kg and Mach 10, including chemistry and vibrational nonequilibrium increased the N factor by less than 5%.

Alba et al. [13] report stability analyses for the Berger et al. [12] experiments. The Navier-Stokes equations are solved for the mean flow. Instability is analyzed using the linear PSE method. Their table 1 lists 22 runs that were selected for simulation, including 9 runs at zero angle of attack (AoA). These include the two simple blunt cones, with axial lengths of 0.381 m and 1.19 or 2.10 mm nose radii, and the cone-cylinder-flare, with a nose radius of 1.19 mm and an axial cone length of 0.216 m. The simulations assume a uniform wall temperature of 300K, which seems to be within about 10-20% of the actual wall temperature.

Unfortunately, of the 9 candidate runs at zero AoA, only two were at Reynolds numbers high enough to clearly show the onset of transition. Three laminar runs had computed N factors of about 5-6 at the end of the cone, which is consistent with the observed laminar flow, since the onset of hypersonic transition in conventional-noise tunnels generally seems to occur near $N = 5 - 6$. When the larger nose radius of 2.10 mm was studied at a higher Reynolds number of 20 million per meter, the N factor at the end of the cone is similar to the value for a 1.19-mm nose radius at 7 million per meter.

When $N = 5.5$ was used to estimate the onset of transition, the two Langley runs with the 1.19-mm nose radius agreed well, as did 9 runs in the shock tunnels at CUBRC, as shown in Fig. 2. In these figures, the caption gives the freestream Mach number and unit Reynolds number, along with the nose radius. By contrast, when the common simple correlation of $Re_\theta/M_e = 150$ is used, the data scatter widely, as shown in Fig. 3, and the trend is not captured. Both figures are redrawn from those in Johnson et al. (2008), using additional data supplied by them. Transition Reynolds number generally increases with nose radius, for these small radii, or as transition moves closer to the nose. The CUBRC runs near Mach 7, shown in red, delivered the highest transition-onset Reynolds numbers, based on edge conditions and the axial length from the nose. This is curious, since higher Mach numbers are usually associated with higher transition Reynolds numbers, presumably because the noise is effectively smaller (see, for example, Ref. [15, Fig. 74]). However, these higher transition Reynolds numbers are well correlated with $N = 5.5$. The CUBRC runs near Mach 10 provided the lowest transition Reynolds numbers, which is again curious with respect to Pate [15]. The NASA Langley Mach-6 data fall in between. Since the tunnel noise varies with tunnel, Mach number, and unit Reynolds number, the receptivity may vary with nose radius, and the nonlinear second-mode breakdown amplitude may also vary, it's not obvious why $N = 5.5$ works as well as it does. Further investigation is needed; measurements of the wave amplitude would be particularly helpful.

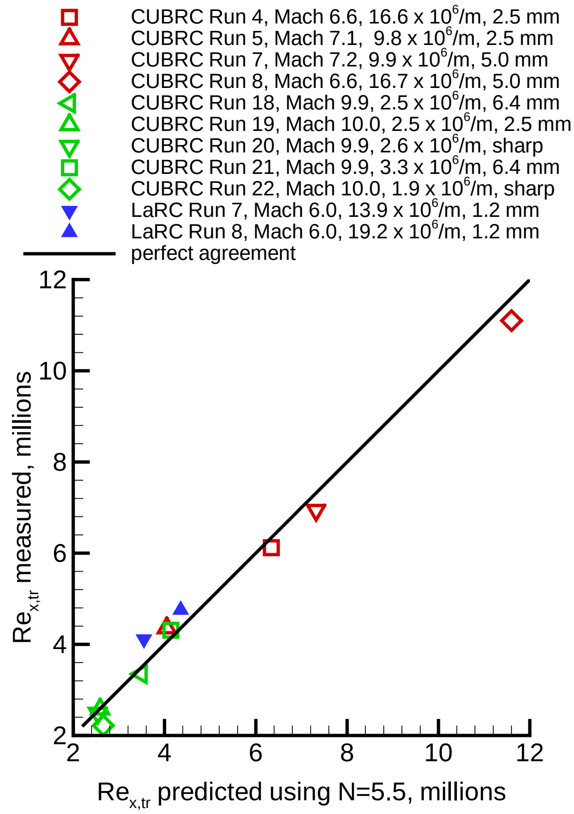

Figure 2: Stability-Based Correlation for Transition-Onset Reynolds Number for 7-deg. Half-Angle Cones with Small Nose Radii in Three Hypersonic Wind-Tunnel Nozzles

Measurements on 7-deg. Cone at Purdue and Braunschweig

It has been well known for several decades that hypersonic tunnel noise affects transition on models [9]. When tunnel conditions are varied, the turbulent boundary layer on the nozzle wall varies, and the

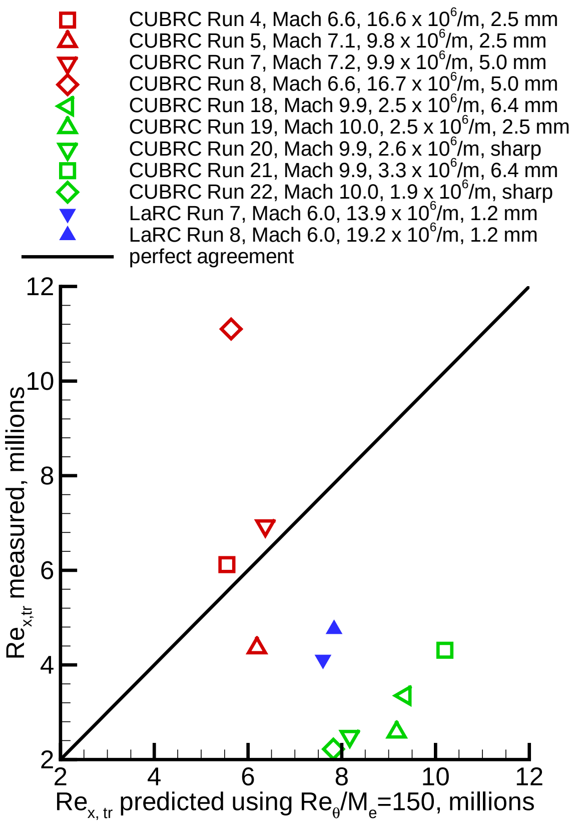

Figure 3: Typical Algebraic Correlation for Transition-Onset Reynolds Number for 7-deg. Half-Angle Cones with Small Nose Radii in Three Hypersonic Wind-Tunnel Nozzles

tunnel noise varies, along with the physics of instability and transition in the boundary layer on the model. It has been nearly impossible to separate the changes in boundary-layer instability from the changes in tunnel noise. Both affect transition, and usually only transition is measured. Measurements of the high-frequency instabilities required difficult and delicate instrumentation such as hot wires, which did not survive well enough in most hypersonic tunnels. However, if wave measurements could become less difficult and more common, it might be possible to separate the effects of tunnel noise from the effects due to changes in the boundary-layer instability.

As part of a study of hypersonic roughness effects, Fujii [16] found that it was possible to measure second-mode waves in a hypersonic tunnel using high-frequency piezoelectric pressure sensors that are robust and inexpensive. This was surprising, since it was the first measurement of second-mode waves using surface pressure sensors, and the 1MHz PCB-132 sensors were only designed to measure the passage of shock waves. Since this instrumentation promised a significant advance in general measurement of instability and transition, Estorf et al. [17] carried out further experiments at Braunschweig and Purdue. Second-mode instability waves were successfully measured in both tunnels.

The frequencies and amplification rates agreed well with theory. Under noisy flow at Purdue and Braunschweig, the second-mode waves broke down to turbulence at about the same Reynolds number and the same amplitude, suggesting that nonlinear breakdown is not too sensitive to the details of the tunnel noise environment. Second-mode waves were measured under quiet flow in the Purdue tunnel, for the first time; the wave amplitude under quiet flow was about 450 times lower than under noisy flow. The PCB-132 sensors are robust and easy to use, although reliable quantitative use will require further calibration efforts.

Similar measurements were also carried out using Atomic Layer Thermopile gauges that were invented in Germany (e.g., Roediger et al. [18]). These surface heat-transfer sensors use the Seebeck effect to achieve very high sensitivity at frequencies to 1MHz. Although they work better in flowfields with higher levels of heat transfer, second-mode waves were successfully measured in the Purdue Mach-6 tunnel under quiet and noisy conditions. As they become more readily available they may complement the pressure sensors for robust measurements of high-frequency instability waves and other phenomena.

Sandia Measurements on 7-deg. Cones

Casper et al. [19] measured the surface-pressure fluctuations on a sharp 7-deg. half-angle cone at Mach 5, 6 and 8, in the wind tunnels at Purdue and Sandia National Laboratory. Most measurements were carried out with a 0-50 kHz bandwidth, and were focused on the vibrations induced by transitional pressure fluctuations. The onset of transition was inferred from this peak in the streamwise distribution of the pressure fluctuations, which was previously measured to occur between the onset and end of transition. Under quiet flow at Mach 6, the boundary layer was laminar, so all measurements were obtained under conventional noise levels.

Casper et al. [19] also measured the surface pressure fluctuations using fast PCB132 quartz sensors, with an 11kHz-1MHz bandwidth. For frequencies between 11 and 50kHz, the two types of sensors agreed well. The PCB132 sensors were able to measure second-mode instability waves in all three nozzles. Prior to breakdown, the maximum second-mode amplitude increased from 5% at Mach 5 to 12% at Mach 6 (under noisy flow) to 24% at Mach 8. The peak wave amplitude prior to transition clearly increased with Mach number, as did the tunnel noise level. More research is needed to understand these observations (see Ref. [20]).

Measurements on 7-deg. Cone at HIEST

Work on the 7-deg. cone has stimulated further international interest. Existing measurements of second-mode waves have all been carried out in blowdown tunnels with low enthalpy and relatively long run times. Can the waves also be measured under high-enthalpy conditions, enabling a possible separation of tunnel noise effects from model boundary-layer effects? The large free-piston shock tunnels in Germany and Japan may be capable of generating and measuring second-mode waves under high-enthalpy conditions where aerothermochemistry affects instability and transition. Tanno et al. [21] report the first attempt at such measurements, in the large free-piston shock tunnel at the Kakuda Space Center in Japan. Transition is observed at a length Reynolds number of about 4 million, apparently based on freestream conditions. Power spectra obtained from PCB132 pressure signals suggest the presence of second-mode waves, although the data are not conclusive. Work continues [22].

Summary: Collaborative Efforts Initiated under AVT-136

Hypersonic laminar-turbulent transition is a complex and difficult field in which significant progress is being made, using modern computational and experimental tools. No single ground-test facility can simulate all aspects of transition in flight. Likewise, computational models must make many assumptions in order to simulate flight. Efficient progress requires collaboration. Detailed comparisons between computational models and experimental measurements leads to improvements for all.

Second-mode wave measurements on a 7-deg. half-angle cone have been made in several wind tunnels, for comparison to stability results from several computational tools. New instrumentation has been developed to enable these measurements in the harsh environment typical of hypersonic tunnels. This progress has involved collaboration among researchers in the United States, Germany, Japan, and Russia.

AVT-136 efforts have initiated a number of continuing collaborations. The Technical University of Braunschweig is collaborating with Purdue University, Texas A&M University, the University of Minnesota, NASA Langley, and others to study crossflow-induced transition on a sharp cone at angle of attack. Measurements of second-mode waves are being carried out with PCB and ALTP sensors at Braunschweig, Stuttgart Univ., the DLR in Göttingen, NASA Langley, Sandia National Laboratory, AEDC Tunnel 9, HIEST, CUBRC, Purdue and elsewhere, with computational comparisons provided by the Univ. of Minnesota, AFRL, and NASA Langley. Windside-forward transition on a blunt cone at angle of attack is being investigated by CIRA in Italy, DLR Cologne, and Purdue. The Von Karman Institute in Belgium is collaborating with Purdue regarding the effect of tunnel noise on roughness-induced transition. Comparisons to the HiFIRE-1 and HIFiRE-5 flights involve collaboration among AFRL, NASA Langley, CUBRC, Purdue, the University of Minnesota and others. For efficient progress, these efforts should continue and more investigators should begin to participate.

Acknowledgements

This effort has involved the cooperation of many persons, too numerous to mention. The list of authors in the References section includes a substantial fraction of the participants. The author's work has been supported by AFOSR.

REFERENCES

[1] Eli Reshotko. A program for transition research. *AIAA Journal*, 13(3):261–265, March 1975.

[2] N.S. Dougherty and D.F. Fisher. Boundary layer transition on a 10-degree cone: Wind tunnel/ flight data correlation. Paper 80-0154, AIAA, January 1980.

[3] Roger L. Kimmel, David Adamczak, Datta Gaitonde, Albert Rougeux, and James R. Hayes. HIFiRE-1 boundary-layer transition experiment design. Paper 2007-0534, AIAA, January 2007.

[4] Roger L. Kimmel. Roughness considerations for the HIFiRE-1 vehicle. Paper 2008-4293, AIAA, June 2008.

[5] Roger L. Kimmel. Aerothermal design for the HIFiRE-1 flight vehicle. Paper 2008-4034, AIAA, June 2008.

[6] T.P. Wadhams, E. Mundy, M.G. MacLean, and M.S. Holden. Ground test studies of the HIFiRE-1 transition experiment, part 1: Experimental results. *Journal of Spacecraft and Rockets*, 45(6):1134–1148, Nov.-Dec. 2008.

[7] T. Wadhams, M. MacLean, M. Holden, and E. Mundy. Pre-flight ground testing of the full-scale FRESH FX-1 at fully duplicated flight conditions. Paper 2007-4488, AIAA, June 2007.

[8] Matthew MacLean, Timothy Wadhams, Michael Holden, and Heath Johnson. Ground test studies of the HIFiRE-1 transition experiment, part 2: Computational analysis. *Journal of Spacecraft and Rockets*, 45(6):1149–1164, Nov.-Dec. 2008.

[9] Steven P. Schneider. Development of hypersonic quiet tunnels. *Journal of Spacecraft and Rockets*, 45(4):641–664, Jul.-Aug. 2008.

[10] Katya M. Casper, Brad M. Wheaton, Heath B. Johnson, and Steven P. Schneider. Effect of freestream noise on roughness-induced transition at Mach 6. Paper 2008-4291, AIAA, June 2008.

[11] Steven P. Schneider. Effects of roughness on hypersonic boundary-layer transition. *Journal of Spacecraft and Rockets*, 45(2):193–209, Mar.-Apr. 2008.

[12] Karen T. Berger, Frank A. Greene, Roger Kimmel, Christopher Alba, and Heath Johnson. Aerothermodynamic testing and boundary-layer trip sizing of the HIFiRE flight 1 vehicle. *Journal of Spacecraft and Rockets*, 45(6):1117–1124, Nov.-Dec. 2008.

[13] Christopher R. Alba, Heath B. Johnson, Matthew D. Bartkowicz, Graham V. Candler, and Karen T. Berger. Boundary-layer stability calculations for the HIFiRE-1 transition experiment. *Journal of Spacecraft and Rockets*, 45(6):1125–1133, Nov.-Dec. 2008.

[14] Heath B. Johnson, Chris R. Alba, Graham V. Candler, Matthew MacLean, Timothy Wadhams, and Michael Holden. Boundary-layer stability analysis of the hypersonic international flight research transition experiments. *Journal of Spacecraft and Rockets*, 45(2):228–236, March-April 2008.

[15] Samuel R. Pate. Effects of wind tunnel disturbances on boundary-layer transition with emphasis on radiated noise: A review. Paper 80-0431, AIAA, March 1980. Paper was distributed in person at the conference, and missed the usual archiving. Available online from DTIC as citation AD-A384962.

[16] Keisuke Fujii. Experiment of two dimensional roughness effect on hypersonic boundary layer transition. *Journal of Spacecraft and Rockets*, 43(4):731–738, July-August 2006.

[17] Malte Estorf, Rolf Radespiel, Steven P. Schneider, Heath B. Johnson, and Stefan Hein. Surface-pressure measurements of second-mode instability in quiet hypersonic flow. Paper 2008-1153, AIAA, January 2008.

[18] Timothy Roediger, Helmut Knauss, Malte Estorf, Steven P. Schneider, and M.V. Smorodsky. Hypersonic instability waves measured using fast-response heat-flux gauges. *J. of Space-*

craft and Rockets, 46(2):266–273, March-April 2009.

[19] Katya M. Casper, Steven J. Beresh, John F. Henfling, Russell W. Spillers, and Steven P. Schneider. Pressure fluctuations in laminar, transitional, and turbulent hypersonic boundary layers. Paper 2009-4054, AIAA, June 2009.

[20] Christopher R. Alba, Katya M. Casper, Steven J. Beresh, and Steven P. Schneider. Comparison of experimentally measured and computed second-mode disturbances in hypersonic boundary layers. Paper 2010-0897, AIAA, January 2010.

[21] H. Tanno, T. Komura, K. Sato, K. Itoh, M. Takahashi, and K. Fujii. Measurements of hypersonic boundary layer transition on cone models in the free-piston shock tunnel HIEST. Paper 2009-0781, AIAA, January 2009.

[22] H. Tanno et al. Measurements of hypersonic high-enthalpy boundary layer transition on 7-degree cone model. Paper 2010-0310, AIAA, January 2010. To appear.