Effects of Shock-Tube Cleanliness on Hypersonic Boundary Layer Transition at High Enthalpy

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DOI: 10.2514/1.J054897

I. Introduction

The prediction of a high-speed boundary-layer transition (BLT) location is critical to hypersonic vehicle design; this is because the increased skin friction and surface heating rate after transition result in increased weight of the thermal protection system. Experimental studies using hypervelocity wind tunnels are one component of BLT research.

The freestream disturbances in supersonic and hypersonic wind tunnels include acoustic waves, entropy inhomogeneity, and vortical perturbations, in addition to microscale and macroscale particles [1]. These disturbances, in whatever form, can significantly influence boundary-layer instability and transition-location measurements such that confidence in the experimental measurements is compromised. For this reason, transition researchers have made extensive efforts in minimizing and characterizing freestream disturbance levels.

Hypersonic wind tunnels exist where there are low disturbance levels, such as those at Purdue University [2–4] and Texas A&M University [5,6]. Currently, the parameter space available to low-disturbance hypersonic wind tunnels does not permit the study of the interaction of boundary-layer instability and thermochemistry, which is important for accurately modeling realistic reentry flows; this is because low-disturbance hypersonic tunnels have a low-ordered kinetic energy, or total enthalpy, in the freestream relative to relevant chemical or vibrational energy levels.

To study the effects of thermochemistry on BLT in a ground test, the total enthalpy of the flow must be sufficiently high. One such ground-test facility to generate “high-enthalpy” flows is the reflected-shock tunnel. In the past, researchers have used shock tunnels and reflected-shock tunnels to study BLT [7–13]. More recently, in the high-enthalpy reflected-shock tunnel at Gottingen, Germany (HEG), Laurence et al. [14–16] reported a schlieren-based technique for the investigation of disturbances in hypervelocity boundary layers. In those reports, high-resolution and time-resolved images of the second-mode instability of a hypervelocity boundary layer on a slender cone data were presented. At California Institute of Technology in the T5 reflected-shock tunnel, Germain and Hornung [17], Adam and Hornung [18], Rasheed et al. [19], Jewell et al. [20], and Parziale et al. [21] studied hypervelocity BLT on a slender cone; those researchers performed approximately 1000 experiments and made significant progress in developing visualization and direct measurement techniques. These diagnostic advances made possible the investigation of high-enthalpy effects on BLT in different gases and hypervelocity BLT control by porous coatings. However, special attention to potential particulate contamination in high-enthalpy impulse facilities is required, relative to conventional “cold” hypersonic tunnels, because of the harsh conditions in the facility before and after the test flow over the model.

To reduce the effects of particulates of BLT on slender cones [20–27], we devised a new cleaning and fill procedure for the shock tunnel, which is the subject of this Note. Possible sources of particles include piston buffer material, piston brakes, test gas impurities, and the Mylar secondary diaphragm. In particular, Parziale et al. [25] noted that experiments performed immediately after an experiment where the piston buffers shattered had less predictable noise profiles. With stringent cleaning of the shock tube, it was possible to mitigate particulate contamination and repeatedly obtain transition at specified locations through a careful selection of reservoir conditions.

Analyses of the current data with standard linear stability methods indicates that the transition location corresponds to second-mode amplification factors $\varepsilon^2$ with $N \approx 8–12$ at transition onset [20,26]. These values, even those obtained before implementation of the cleaning regimen, are high compared to the more typical values of $N \approx 5–6$ usually characterizing a “noisy” tunnel [2]. Although the transition $N$ factors recorded early in the current test campaign were higher than expected for a noisy tunnel, there was a larger than desired scatter in results. One reason for a higher transition $N$ factor for the current data may be the mismatch between freestream noise spectrum and boundary-layer unstable frequencies for second-mode disturbances, whereas the relatively large scatter may result from particulate-induced bypass transition affecting some experiments. Parziale et al. [25] found that noise in the T5 freestream was relatively low frequency compared with the most unstable boundary-layer frequencies. This hypothesis was implicitly supported by the recent analysis of Gronvall et al. [28], who found a transition onset value of

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Article in Advance / TECHNICAL NOTES

$N \approx 8$ for the experiments of Tanno et al. [12], which were also performed in a reflected-shock tunnel, although at lower enthalpy than the present study, and for a limited range of conditions, with unspecified cleaning procedures. At the start of the present test campaign, before the implementation of the cleaning regimen, we encountered difficulty in achieving repeatable transition Reynolds numbers and $N$ factors. Our hypothesis was that bypass transition was caused sporadically by particulate left over from prior experiments; thus, it became a focus to reduce particulate.

Recently, Fedorov [22] examined receptivity to particulate-laden flows, modeling the particulates as spherical solids impacting the supersonic boundary layer, and making numerical estimates for particulate-driven transition onset for various sizes and densities. Fedorov found that both the $N$ factor and the transition Reynolds number were strongly influenced by particle characteristics, including size and number density. For computations with a 14 deg half-angle sharp wedge at Mach 4 in the standard atmosphere at 20 km, the transition onset $N$ factor dropped from 12 for particles of radius of 5 $\mu$m to 7 for particles with a radius of 50 $\mu$m; this provides the motivation to minimize particulates in the freestream, which is apparent for ground tests of BLT in impulse facilities.

Examples of data from experiments before and after the cleaning regimen were instituted are presented, and these results are compared. Then, a statistical analysis of transition Reynolds number is presented to quantify the change in repeatability of the experiment.

II. Facility

All measurements are made in T5, which is the free-piston-driven reflected-shock tunnel at the California Institute of Technology. T5 is designed to simulate flow conditions and aerodynamics of hypervelocity vehicles at total enthalpies up to 25 MJ/kg and freestream velocities of up to 6000 m/s. During each T5 experiment, a piston-compressed helium/argon driver ruptures a scored stainless-steel primary diaphragm. Following the primary diaphragm rupture, a shock wave propagates in the shock tube; is reflected off the endwall, breaking the secondary diaphragm and reprocesses the test gas, which is then expanded through a converging-diverging contoured nozzle to $\sim$Mach 5.5 in the test section [24,26,29].

The measured primary shock speed and reservoir pressure are used to compute the reservoir conditions for each test. Thermochemical equilibrium calculations are performed using Cantera [30] with the Shock and Detonation Toolbox [31], using thermodynamic data found valid for the high-temperature conditions in T5 [32,33]. The test gas reaches its highest temperature in the stagnation region. For the 74 tests comprising the present dataset, the calculated reservoir temperature ranged from 3380 to 6930 K, with the mean and median both 5510 K. The cone mean flow was computed with the STABL software suite, as described by Johnson [34] and Johnson et al. [35], and recently applied by Wagnild [36]. Boundary-layer profiles and edge properties were extracted from the mean flow solutions during postprocessing.

III. Shock-Tube Fill Gas Quality and Cleaning Procedure

Experience with testing in T5 revealed an opportunity to increase the quality of the flow over the model. Improvement was achieved by using higher-quality gas to fill the shock tube and cleaning the shock tube more thoroughly between experiments. The most repeatable results were obtained with the “ALPHAGAZ” grade of Air Liquide products.

Even after changing to research quality test gas, we found it difficult to repeatedly specify a transition location with a choice of run conditions. We hypothesized that this was due to the particulates in the shock tube left over from the previous run. However, the lack of a comprehensive test series carried out after changing to higher-quality gas, but before extensive particulate reduction efforts, precluded conclusively separating the effects of higher test gas quality from the effects of the improved cleaning procedure. Experience in other facilities has shown that particulate contamination is very effective at promoting transition [3]. To minimize particulates, the cleaning procedure between each operational cycle was changed to 1) clean the shock-tube end with a Scotch-Brite pad; 2) clean the shock-tube end with acetone on a mop; 3) pass four shop towels rolled into a cylinder and drag them through the shock tube, with the outermost towel being misted with acetone; 4) repeat step 3 until the outermost towel does not become dirty after a pass through the shock tube (as many as 20 times); and 5) repeat step 3 with the outer towel misted with isopropyl alcohol to remove any remaining acetone residue. The nozzle and nozzle throat were cleaned by hand with Kimwipes using the same sequence of solvents.

The region at the end of the shock tube in a reflected-shock tunnel is an additional area of concern with respect to shot-to-shot variation. In T5, this region comprised a copper insert and sleeve, shown in a detailed view in Fig. 1. Taylor and Hornung [37] noted that wall roughness in the reflected-shock region could increase the shock bifurcation asymptotic height, which was the distance above the sidewall within which wall effects were important behind a reflected shock wave. This behavior was undesirable because of the induced nonuniformity of the reservoir gas and decreased test time due to driver gas contamination of the reservoir gas [38].

After completing the cleaning, the copper insert and copper sleeve had a smooth finish. The roughness of the 90-mm-diam shock tube was estimated to be less than 25 $\mu$m. Throughout the test campaign, the copper insert and sleeve were maintained in this condition to avoid the detrimental effects of shock bifurcation as much as possible.

IV. FLDI and Heat-Flux Measurements Examples: With and Without Cleaning

In this section, we present two examples of heat-flux and focused laser differential interferometry (FLDI) data: experiment 2769 performed with the cleaning procedure explained in this Note, and experiment 2702 performed without adequately cleaning T5.

The focused laser differential interferometry is an optical technique, developed by Smeets [39] and recently used in T5 [21,27], which permits the high-speed and nonintrusive interrogation of small-amplitude density perturbations within a small sensitive region of the beam path while rejecting perturbations outside of the sensitive region, including those resulting from the nozzle shear layer. The effect of cleaning on transition location and repeatability is examined in a series of tests using the FLDI to measure disturbances within the boundary on a 5 deg half-angle smooth cone at a zero angle of attack. The FLDI is located at a fixed point relative to the cone, and the reservoir conditions are changed to adjust the Reynolds number at the FLDI probe volume. Previous test data and numerical simulations of tunnel performance enable carrying out the testing at specified Reynolds numbers and total enthalpy. For conditions with a sufficiently low Reynolds number, laminar response would be expected based on past heat-flux measurements. However, in some instances where laminar flow was expected, boundary-layer instability measurements revealed that a sporadic and initially inexplicable period of
The model is a smooth 5 deg half-angle aluminum cone 1 m in length, similar to that used in a number of previous experimental studies in T5, and is composed of three sections: a nominally sharp tip (radius less than 0.175 mm) fabricated of molybdenum; an interchangeable midsection (in the present experiments, this section is a smooth, solid piece of plastic); and the main body, which is instrumented with a total of 80 flush-mounted annular thermocouples evenly spaced at 20 lengthwise locations beginning at 221 mm from the tip of the cone, with each row located 38 mm from the last. This sensor spacing corresponds to uncertainty estimates in the edge Reynolds number at transition onset from \( \pm 9.34 \times 10^4 \) to \( \pm 4.80 \times 10^5 \), and in reference Reynolds number at transition onset from \( \pm 6.00 \times 10^4 \) to \( \pm 3.33 \times 10^5 \). Heat flux on the cone is obtained from the thermocouples, which are of a design first used by Sanderson [41] and Sanderson and Sturtevant [42]. These thermocouples have a response time on the order of a few microseconds and have been successfully used for boundary-layer transition onset determination (i.e., the most forward departure of the non-dimensionalized heat flux from an appropriate laminar correlation) as was more fully described in the works of Adam and Hornung [18], Rasheed et al. [19], and Jewell et al. [20], as well as for tracking the propagation of turbulent spots by Jewell et al. [23]. Time- and spatially-resolved heat-flux data allow the presentation of a “movie” of heat flux over the entire instrumented surface of the cone by interpolating the processed thermocouple signals.

In Fig. 3, we present several heat-flux frames from the test time of experiment 2702, which corresponds to the FLDI result shown in Fig. 2a and is performed before the new cleaning-procedure implementation. A turbulent spot is observed (first frame, top left, marked with an arrow) at 0.075 ms intervals covering a total time of 0.375 ms, and propagates downstream and eventually off the end of the cone in the subsequent three frames. The location of the FLDI is marked with an “X” at 665 mm from the tip. In addition, Fig. 4 presents several heat-flux frames from the test time of experiment 2769, which correspond to the FLDI result shown in Fig. 2b and are performed...
following cleaning-procedure implementation 2769. Although intermittent turbulent flow is observed near the end of the cone, no propagating turbulent bursts are visible during the experiment. The location of the FLDI is marked with an “X” at 718 mm from the tip. The boundary-layer edge conditions for these two shots are recorded in Table 1.

In test 2702 with a dirty shock tube, a turbulent spot is observed to propagate downstream, crossing the location of the FLDI sensor at the same time the broadband response is observed in the spectrogram for test 2702 (Figs. 2a and 3 at ∼1250–1350 s). This spot is generated independently of the other transition events that are typically observed in natural transition, and is therefore believed to be the result of particulate impact on the boundary layer during the test time, following the mechanism outlined by Fedorov [22]. The large amplitude of the FLDI signal correlates with elevated heat transfer as the turbulent spot passes the thermocouples nearest the FLDI sensitive region, as shown in Fig. 5, lending confidence to the conclusion that the FLDI and heat-flux gauges are measuring the same turbulent spot.

In contrast, in test 2769 with a clean shock tube, no turbulent spots are observed near the FLDI during the test time, although intermittent turbulent flow typical of natural modal transition is observed near the end of the cone. This observation is consistent with the lack of broadband response observed in the spectrogram for test 2769 (Figs. 2b and 4). The spot in test 2702 is first observed at a location on the cone where stability computations [43] find that $N \approx 4$, which indicates that it is unlikely to be the result of modal transition, whereas the natural transition front in test 2769 is observed at a location where $N \approx 10$.

V. Transition Onset Correlations

To test our hypothesis of tunnel cleaning improving transition location repeatability, we carried out a statistical analysis of a total of 74 tests before ($n = 40$) and after ($n = 34$) improvements in the cleaning regimen. Evidence of correlation between transition location, tunnel parameters, and tunnel cleanliness is sought using reverse-stepwise regression [44] as implemented in MATLAB [45]. The $p$ value required to remove a parameter from the regression is 0.1.

The predictor parameters chosen to seek correlation with transition Reynolds numbers are reservoir pressure $P_{\text{res}}$, reservoir enthalpy $h_{\text{res}}$, and $x_3$, which is a cleaning status indicator variable consisting of a vector of ones and zeros, where one and zero designate an experiment performed before and after the cleaning procedure was implemented, respectively. The three predictor values, as well as the three cross terms, are included in the model.

If the cleaning variable, or a cross term with the cleaning variable, remains in the final model after reverse-stepwise regression, this is a statistically significant indication that the cleaning procedure affects the resulting response variables, which are $Re_{\text{Tr}}$ and $Re_{\text{Tr}}$, $Re_{\text{Tr}}$, and $Re_{\text{Tr}}^c$ are the edge Reynolds numbers at the transition onset location and the Reynolds number evaluated at reference conditions at the transition onset.
The coefficient of determination of correlation between the tunnel parameters and the transition Reynolds number was used as a metric of repeatability within each data subset. A higher coefficient of determination indicates higher repeatability. Jewell et al. [26,46] showed that the tunnel parameters $h_{res}$ (reservoir enthalpy) and $P_{res}$ (reservoir pressure) could be used as predictor variables to construct statistically significant linear models of the transition Reynolds numbers $Re_{Tr}$ for both the present datasets and the historical TS transition data of German and Hornung [17] and Adam and Hornung [18] for air, CO$_2$, and N$_2$. In the present work, only air transition data are considered. These linear models take the form

$$Re_{Tr}(P_{res}, h_{res}) = Re_{int} + C_{P\cdot res} P_{res} + C_{h\cdot res} h_{res}$$

Here, the constant coefficients that define the regression plane, $C_{P\cdot res}$, $C_{h\cdot res}$, and the Reynolds number intercept $Re_{int}$ are computed via stepwise regression analysis performed using the tunnel parameters, reservoir enthalpy $h_{res}$, and reservoir pressure $P_{res}$ as the predictor variables and the edge Reynolds number at the transition onset location as the response variable had a modeled $R^2$ value of 0.50 for the experiments before cleaning procedure implementation and an $R^2$ value of 0.80 subsequent to the implementation of the cleaning procedure. When the same regression analysis is performed using the Reynolds number calculated at reference conditions at the transition onset location $Re_{Tr}$ as the response variable had a modeled $R^2$ value of 0.50 for the experiments before cleaning procedure implementation and an $R^2$ value of 0.80 subsequently. Transition onset measurements, the full details of which were described by Jewell [26] and Jewell and Shepherd [43], were more consistent in experiments after the shock-tube cleaning procedures described in Sec. III were implemented ($n = 34$) than in those prior ($n = 40$). Reservoir temperatures were similar for each subset of the data. The 34 tests after the implementation of the cleaning procedure had calculated reservoir temperatures ranging from 3380 to 6410 K, with a median of 5520 K and a mean of 5490 K. The 40 tests before the implementation of the cleaning procedure had calculated reservoir temperatures ranging from 4010 to 6930 K, with a median of 5510 K and a mean of 5520 K.

### VI. Conclusions

It was shown that an improved cleaning procedure in a hypervelocity shock tunnel improves the repeatability of transition measurements, demonstrating the need for researchers using impulse facilities for hypervelocity boundary-layer instability and transition research to operate the facility in a manner least likely to introduce particulate to the test flow.

FLDI (boundary-layer density disturbances) and heat transfer (surface-mounted heat transfer thermocouples) results were compared before and after a stringent cleaning regimen was implemented. Before the implementation of the cleaning regimen, unpredictable turbulent spots were observed in both FLDI and thermocouple data at locations uncharacteristic of natural transition: it is believed that it is likely these turbulent spots are the result of bypass transition initiated by particulate striking the model surface.

A statistical analysis of the correlation of tunnel parameters to transition location indicates that the coefficient of determination was significantly increased after the implementation of the cleaning regimen. This increase in the coefficient of determination is consistent with more repeatable transition locations and flow quality. The new cleaning regimen makes it possible to systematically characterize transition locations on the test article in a repeatable manner by carefully selecting run conditions. $R^2$ values for $Re_{Tr}$, $Re_{Tr}^*$, and the $N$ factor increase significantly with the introduction of a more stringent cleaning procedure. This ability to repeat transition locations...
facilitates fundamental hypervelocity boundary-layer stability and transition research.

The measurement of the time and size distribution of particulate matter in shock tunnel experiments warrants further study, and it could aid in future experimental–computational comparisons.

Acknowledgments

This work was an activity that was part of the National Center for Hypersonic Laminar-Turbulent Research, sponsored by the “Integrated Theoretical, Computational, and Experimental Studies for Transition Estimation and Control” project, supported by the U.S. Air Force Office of Scientific Research and NASA (FA9552-09-1-0341). Additionally, this work was part of the “Transition Delay in Hypervelocity Boundary Layers by Means of CO2/Acoustic Interactions” project, sponsored by the U.S. Air Force Office of Scientific Research (FA9550-10-1-0491). J. S. Jewell received additional support from the National Defense Science and Engineering Graduate Fellowship, the Jack Kent Cooke Foundation, and the National Research Council Research Associateship. The authors would like to thank Bahram Valiferdowsi (California Institute of Technology) for help with the program to compute the run conditions, and Elizabeth Jewell (University of Michigan) for statistical advice.

References


