Technical Notes

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

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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 e^N 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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$N \approx 8$ 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 μm to 7 for particles with a radius of 50 μm; 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 was 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 ~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.

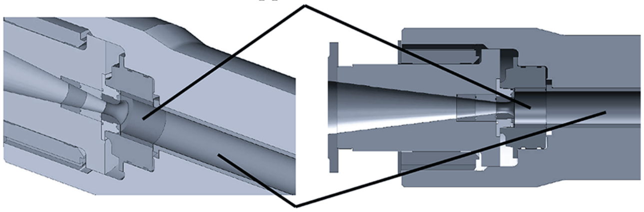

Fig. 1 Copper sleeve and insert at the shock-tube end.

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 μm. 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 relative O_2 (oxygen) to N_2 (nitrogen) balance for ALPHAGAZ air is tighter (±0.5% by partial pressure) than lower-grade gas, and the total hydrocarbons are specified to be less than 0.05 ppm.

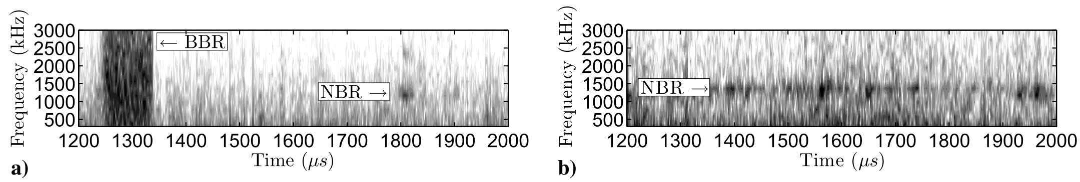

Fig. 2 Power spectral density of FLDI output as a function of time. Darker shading indicates larger amplitude. BBR is broadband response, and NBR is narrowband response.

broadband response would pass through the probe volume of the focused laser differential interferometer.

To illustrate these events, spectrograms (arbitrary units of power spectral density) of two runs at similar run conditions are compared in Figs. 2a and 2b. In Fig. 2a, we present a spectrogram of the FLDI data from experiment 2702, which was performed before the implementation of the new cleaning procedure. The spectrogram shows a sporadic and large swath of broadband response, followed by a period where minimal disturbances are detected, and followed by a period of narrowband response. The FLDI data show contrast to the data recorded after the new cleaning-procedure implementation: for example, data from experiment 2769. We present a spectrogram for experiment 2769 in Fig. 2b, which shows no broadband response and only a series of stochastic but sensible narrowband peaks.

The hypersonic quiet tunnel currently represents the state-of-the-art facility class in terms of disturbance environment. Quiet tunnel design and operation includes careful particulate mitigation, which is partially motivated by preserving the mirrorlike finish on the nozzle wall necessary to preserve low acoustic disturbance levels by preventing nozzle wall boundary-layer transition [40]. The FLDI data in Fig. 2b, recorded after the T5 cleaning procedure was implemented, exhibit a narrowband response at distinct frequencies associated with the second mode. This is qualitatively similar to the spectrograms of a slender-body hypersonic boundary-layer instability obtained in a low-disturbance facility by Hofferth et al. [5].

The FLDI measurements provide detailed spectral data enabling the narrow-band versus broadband characterization of boundary-layer disturbances; however, these data are limited spatially to the FLDI probe volume. Heat-flux measurements are performed to provide data to assess the effect of cleaning on the entire surface of the model, which enables the tracking of large turbulent spots suspected to have been caused by particulate in the shock tube before running the experiment.

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 nondimensionalized 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

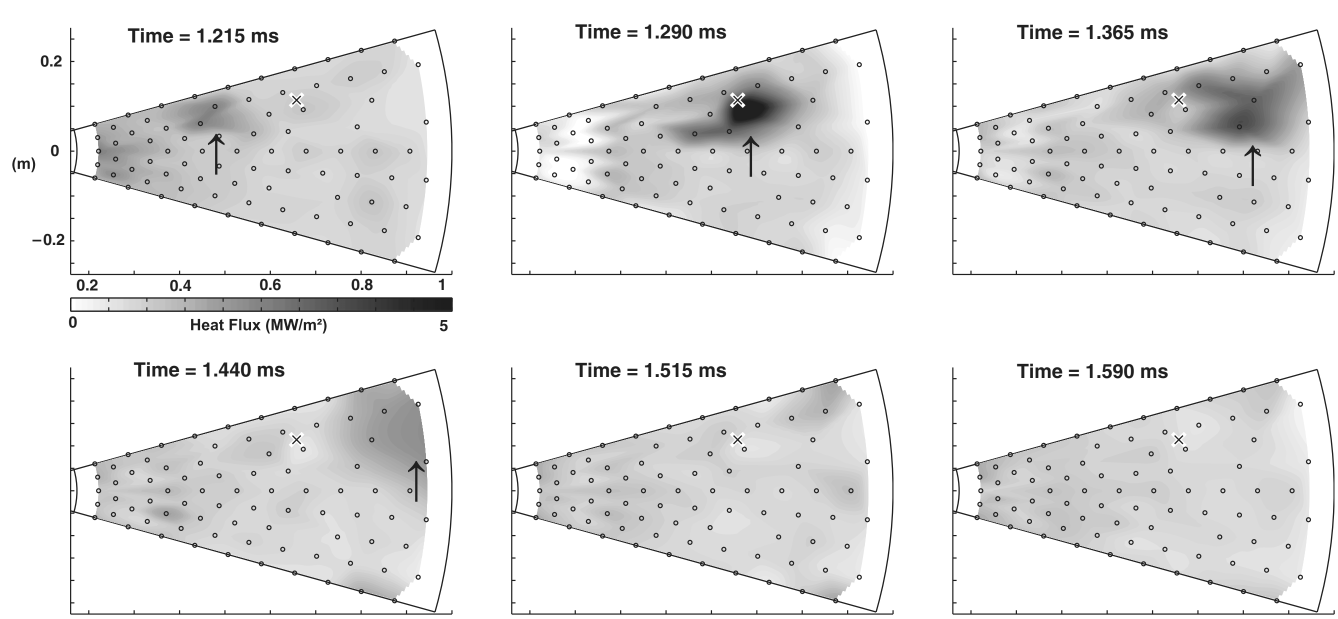

Fig. 3 Heat-flux spatial distributions, test 2702. A turbulent spot is observed and propagates downstream. "X" indicates FLDI location.

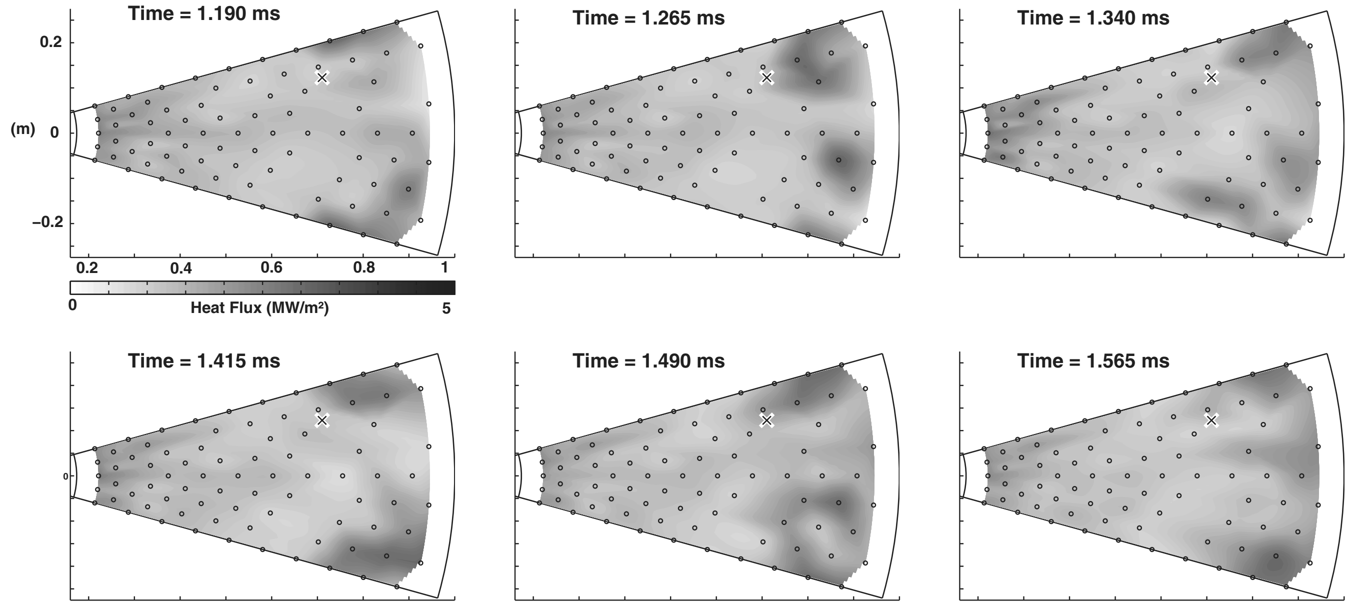

Fig. 4 Heat-flux spatial distributions, test 2769. Intermittent turbulent bursts, but no propagating spots, are observed. "X" indicates FLDI location.

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].

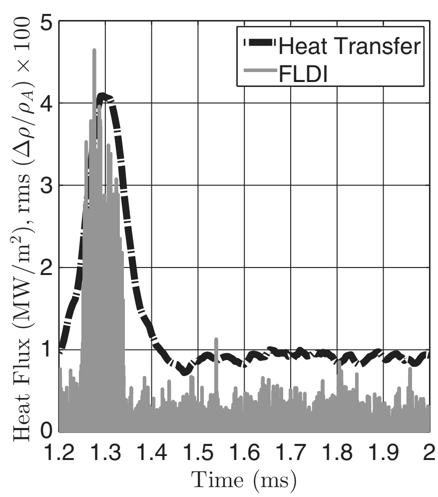

Fig. 5 Interpolated heat-flux from test 2702 compared to FLDI. A turbulent spot at 1.3 ms elevates local heat transfer and broadband density disturbance.

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_{res}; reservoir enthalpy h_{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's initial state. 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_{Tr} and Re^*_{Tr}. Re_{Tr} and Re^*_{Tr} are the edge Reynolds numbers at the transition onset location and the Reynolds number evaluated at reference conditions at the transition onset

Table 1 Summary of edge conditions for tests 2702 and 2769 in air

Test	h_{res}, MJ/kg	P_{res}, MPa	U_e, m/s	P_e, kPa	T_e, K	Tv_e, K	ρ_e, kg/m^3	M_e	Unit Re_e, 1/m
2702	8.45	49.9	3680	36.9	1420	1420	0.090	4.84	6.34×10^6
2769	10.5	60.8	4030	47.1	1830	1830	0.092	4.66	6.00×10^6

e, edge; v, vibrational.

location, respectively. Stepwise regression is performed twice: once with each transition Reynolds number as the response variable.

The reverse-stepwise regression model for Re_{Tr} retained P_{res}, h_{res}, and x_3, as well as the $P_{\mathrm{res}} \cdot x_3$ and $h_{\mathrm{res}} \cdot x_3$ cross terms, indicating that the null hypothesis of a zero coefficient is rejected for pressure, enthalpy, and tunnel cleanliness. The rearward-stepwise regression model for Re^*_{Tr} retained P_{res}, h_{res} x_3, and the $h_{\mathrm{res}} \cdot x_3$ cross term, indicating that the null hypothesis of a zero coefficient is rejected for pressure, enthalpy, and tunnel cleanliness. In both cases, the pressure and enthalpy cross term is excluded from the final model, which indicates that reasonable linear models for both transition Reynolds numbers may be constructed using only the pressure and enthalpy parameters if the data are divided into precleaning regimen and post-cleaning regimen data subsets to eliminate the influence of x_3 and the two x_3 cross terms.

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 number Re_{Tr} for both the present datasets and the historical T5 transition data of Germain 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

$$Re_{\mathrm{Tr}}(P_{\mathrm{res}}, h_{\mathrm{res}}) = Re_{\mathrm{intercept}} + C_{P_{\mathrm{res}}} P_{\mathrm{res}} + C_{h_{\mathrm{res}}} h_{\mathrm{res}}$$

Here, the constant coefficients that define the regression plane, $C_{P_{\mathrm{res}}}$, $C_{h_{\mathrm{res}}}$, and the Reynolds number intercept are computed via multivariable-linear regression as implemented in MATLAB. The complete model results for the data acquired before the implementation of new shock-tube cleaning procedures are recorded in Table 2, and the results for the data acquired after the implementation of the cleaning procedures are recorded in Table 3. Both the Re_{Tr} and Re^*_{Tr} models have normally distributed errors, and each set of residuals exhibits limited heteroskedasticity.

The position of the best-fit Reynolds number plane computed relative to the h_{res}-P_{res} plane (i.e, the intercept) is 5.90×10^5 for the dirty tunnel data and 1.83×10^6 for the clean tunnel data. The larger intercept value for the clean results is an indication that the tunnel cleaning procedure tends to increase the transition onset Reynolds number. Moreover, the clean tunnel results show less dispersion than the dirty results, which is consistent with the stochastic effect that would be expected in dirty flow from an unknown and probably inconsistent variation in particle size and number density. Linear 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 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 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}, $R^2 = 0.70$ before cleaning procedure implementation and $R^2 = 0.86$ subsequently.

Table 2 Multivariable linear regression analyses with Re_{Tr} ($R^2 = 0.50$) and Re^*_{Tr} ($R^2 = 0.70$) as the response variables for "dirty" tunnel results ($n = 40$) acquired before the implementation of the new cleaning regimen[a]

	Re_{Tr}	Re^*_{Tr}
$Re_{\mathrm{intercept}}$	5.90×10^5	$\mathbf{-1.38 \times 10^6}$[b]
p value	0.37394	0.00834
Standard error	6.55×10^5	4.95×10^5
$C_{P_{\mathrm{res}}}$	$\mathbf{4.82 \times 10^4}$[b]	$\mathbf{3.54 \times 10^4}$[b]
p value	2.18×10^{-4}	2.99×10^{-4}
Standard error	1.18×10^4	8.87×10^3
$C_{h_{\mathrm{res}}}$	9.18×10^5	$\mathbf{2.98 \times 10^5}$[b]
p value	0.34578	2.12×10^{-4}
Standard error	9.61×10^4	7.26×10^4
Model F statistic	18.4	43.4
Model p value	2.82×10^{-6}	1.99×10^{-10}

[a]We use a significance level of 5% (i.e., requiring a p value less than 0.05 to reject the null hypothesis that a given coefficient is zero).

[b]Coefficients found to be statistically significant under this criterion.

Table 3 Multivariable linear regression analyses with Re_{Tr} ($R^2 = 0.80$) and Re^*_{Tr} ($R^2 = 0.86$) as the response variables for "clean" tunnel results ($n = 34$) acquired after the implementation of the new cleaning regimen

	Re_{Tr}	Re^*_{Tr}
$Re_{\mathrm{intercept}}$	$\mathbf{1.83 \times 10^6}$[a]	-1.08×10^5
p value	6.86×10^{-5}	0.73991
Standard error	3.99×10^5	3.23×10^5
$C_{P_{\mathrm{res}}}$	$\mathbf{7.20 \times 10^4}$[a]	$\mathbf{3.54 \times 10^4}$[a]
p value	2.30×10^{-10}	1.29×10^{-9}
Standard error	7.84×10^3	6.34×10^3
$C_{h_{\mathrm{res}}}$	$\mathbf{-2.01 \times 10^5}$[a]	3.39×10^4
p value	0.00718	0.55180
Standard error	6.97×10^4	5.64×10^4
Model F statistic	61.9	95.1
Model p value	1.49×10^{-11}	5.94×10^{-14}

[a]Coefficients found to be statistically significant ($p < 0.05$).

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.

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References

[1] Bushnell, D., "Notes on Initial Disturbance Fields for the Transition Problem," *Instability and Transition*, edited by Hussaini, M., and Voigt, R., ICASE/NASA LaRC Series, Springer, New York, 1990, pp. 217–232.

[2] Schneider, S. P., "Effects of High-Speed Tunnel Noise on Laminar-Turbulent Transition," *Journal of Spacecraft and Rockets*, Vol. 38, No. 3, 2001, pp. 323–333.
doi:10.2514/2.3705

[3] Schneider, S. P., "Hypersonic Laminar-Turbulent Transition on Circular Cones and Scramjet Forebodies," *Progress in Aerospace Sciences*, Vol. 40, Nos. 1–2, 2004, pp. 1–50.
doi:10.1016/j.paerosci.2003.11.001

[4] Schneider, S. P., "Development of Hypersonic Quiet Tunnels," *Journal of Spacecraft and Rockets*, Vol. 45, No. 4, 2008, pp. 641–664.
doi:10.2514/1.34489

[5] Hofferth, J. W., Humble, R. A., Floryan, D. C., and Saric, W. S., "High-Bandwidth Optical Measurements of the Second-Mode Instability in a Mach 6 Quiet Tunnel," *51st AIAA Aerospace Sciences Meeting Including the New Horizons Forum and Aerospace Exposition*, AIAA Paper 2013-0378, 2013.

[6] Kocian, T. S., Perez, E., Oliviero, N. B., Kuehl, J. J., and Reed, H. L., "Hypersonic Stability Analysis of a Flared Cone," *51st AIAA Aerospace Sciences Meeting Including the New Horizons Forum and Aerospace Exposition*, AIAA Paper 2013-0667, 2013.

[7] Stetson, K. F., and Rushton, G. H., "Shock Tunnel Investigation of Boundary-Layer Transition at $M = 5.5$," *AIAA Journal*, Vol. 5, No. 5, 1967, pp. 899–906.
doi:10.2514/3.4098

[8] Mee, D. J., "Boundary-Layer Transition Measurements in Hypervelocity Flows in a Shock Tunnel," *AIAA Journal*, Vol. 40, No. 8, 2002, pp. 1542–1548.
doi:10.2514/2.1851

[9] Holden, M. S., Wadhams, T. P., and Candler, G. V., "Experimental Studies in the LENS Shock Tunnel and Expansion Tunnel to Examine Real-Gas Effects in Hypervelocity Flows," *42nd AIAA Aerospace Sciences Meeting and Exhibit*, AIAA Paper 2004-0916, 2004.

[10] Wadhams, T. P., Mundy, E., MacLean, M. G., and Holden, M. S., "Ground Test Studies of the HIFIRE-1 Transition Experiment, Part 1: Experimental Results," *Journal of Spacecraft and Rockets*, Vol. 45, No. 6, 2008, pp. 1134–1148.
doi:10.2514/1.38338

[11] MacLean, M., Wadhams, T., Holden, M., and Johnson, H., "Ground Test Studies of the HIFiRE-1 Transition Experiment, Part 2: Computational Analysis," *Journal of Spacecraft and Rockets*, Vol. 45, No. 6, 2008, pp. 1149–1164.
doi:10.2514/1.37693

[12] Tanno, H., Komura, T., Sato, K., Itoh, K., Takahashi, M., and Fujii, K., "Measurements of Hypersonic Boundary Layer Transition on Cone Models in the Free-Piston Shock Tunnel HIEST," *47th AIAA Aerospace Sciences Meeting Including the New Horizons Forum and Aerospace Exposition*, AIAA Paper 2009-0781, 2009.

[13] Fujii, K., Noriaki, H., Tadao, K., Shoichi, T., Muneyoshi, N., Yukihiro, I., Akihiro, N., and Hiroshi, O., "A Measurement of Instability Wave in the Hypersonic Boundary Layer on a Sharp Cone," *41st AIAA Fluid Dynamics Conference and Exhibit*, AIAA Paper 2011-3871, 2011.

[14] Laurence, S. J., Wagner, A., Hannemann, K., Wartemann, V., Lüdeke, H., Tanno, H., and Itoh, K., "Time-Resolved Visualization of Instability Waves in a Hypersonic Boundary Layer," *AIAA Journal*, Vol. 50, No. 1, 2012, pp. 243–246.
doi:10.2514/1.J051112

[15] Laurence, S., Wagner, A., and Hannemann, K., "Schlieren-Based Techniques for Investigating Instability Development and Transition in a Hypersonic Boundary Layer," *Experiments in Fluids*, Vol. 55, No. 8, 2014, Paper 1782.
doi:10.1007/s00348-014-1782-9

[16] Laurence, S. J., Wagner, A., Ozawa, H., Schramm, J. M., and Hannemann, K., "Visualization of a Hypersonic Boundary-Layer Transition on a Slender Cone," *19th AIAA International Space Planes and Hypersonic Systems and Technologies Conference*, AIAA Paper 2014-3110, 2014.

[17] Germain, P. D., and Hornung, H. G., "Transition on a Slender Cone in Hypervelocity Flow," *Experiments in Fluids*, Vol. 22, No. 3, 1997, pp. 183–190.
doi:10.1007/s003480050036

[18] Adam, P. H., and Hornung, H. G., "Enthalpy Effects on Hypervelocity Boundary-Layer Transition: Ground Test and Flight Data," *Journal of Spacecraft and Rockets*, Vol. 34, No. 5, 1997, pp. 614–619.
doi:10.2514/2.3278

[19] Rasheed, A., Hornung, H. G., Fedorov, A. V., and Malmuth, N. D., "Experiments on Passive Hypervelocity Boundary-Layer Control Using an Ultrasonically Absorptive Surface," *AIAA Journal*, Vol. 40, No. 3, March 2002, pp. 481–489.
doi:10.2514/2.1671

[20] Jewell, J. S., Wagnild, R. M., Leyva, I. A., Candler, G. V., and Shepherd, J. E., "Transition Within a Hypervelocity Boundary Layer on a 5-Degree Half-Angle Cone in Air/CO_2 Mixtures," *51st AIAA Aerospace Sciences Meeting Including the New Horizons Forum and Aerospace Exposition*, AIAA Paper 2013-0523, 2013.

[21] Parziale, N. J., Shepherd, J. E., and Hornung, H. G., "Differential Interferometric Measurement of Instability in a Hypervelocity Boundary Layer," *AIAA Journal*, Vol. 51, No. 3, 2013, pp. 750–754.
doi:10.2514/1.J052013

[22] Fedorov, A. V., "Receptivity of a Supersonic Boundary Layer to Solid Particulates," *Journal of Fluid Mechanics*, Vol. 737, Dec. 2013, pp. 105–131.
doi:10.1017/jfm.2013.564

[23] Jewell, J. S., Parziale, N. J., Leyva, I. A., Shepherd, J. E., and Hornung, H. G., "Turbulent Spot Observations Within a Hypervelocity Boundary Layer on a 5-Degree Half-Angle Cone," *42nd AIAA Fluid Dynamics Conference and Exhibit*, AIAA Paper 2012-3062, 2012.

[24] Parziale, N. J., "Slender-Body Hypervelocity Boundary-Layer Instability," Ph.D. Thesis, California Inst. of Technology, Pasadena, CA, 2013.

[25] Parziale, N. J., Shepherd, J. E., and Hornung, H. G., "Free-Stream Density Perturbations in a Reflected-Shock Tunnel," *Experiments in Fluids*, Vol. 55, No. 2, 2014, pp. 1–10.
doi:10.1007/s00348-014-1665-0

[26] Jewell, J. S., "Boundary-Layer Transition on a Slender Cone in Hypervelocity Flow with Real Gas Effects," Ph.D. Thesis, California Inst. of Technology, Pasadena, CA, 2014.

[27] Parziale, N. J., Shepherd, J. E., and Hornung, H. G., "Observations of Hypervelocity Boundary-Layer Instability," *Journal of Fluid Mechanics*, Vol. 781, Oct. 2015, pp. 87–112.
doi:10.1017/jfm.2015.489

[28] Gronvall, J. E., Johnson, H. B., and Candler, G. V., "Boundary-Layer Stability Analysis of High Enthalpy Shock Tunnel Transition Experiments," *Journal of Spacecraft and Rockets*, Vol. 51, No. 2, 2014, pp. 455–467.
doi:10.2514/1.A32577

[29] Hornung, H. G., "Performance Data of the New Free-Piston Shock Tunnel at GALCIT," *17th AIAA Aerospace Ground Testing Conference*, AIAA Paper 1992-3943, 1992.

[30] Goodwin, D. G., "An Open-Source, Extensible Software Suite for CVD Process Simulation," *Proceedings of CVD XVI and EuroCVD Fourteen*, edited by Allendorf, M., Maury, F., and Teyssandier, F., The Electrochemical Soc., Inc., Pennington, NJ, 2003, pp. 155–162.

[31] Browne, S., Ziegler, J., and Shepherd, J. E., "Numerical Solution Methods for Shock and Detonation Jump Conditions," California Inst. of Technology GALCIT-TR-FM2006.006, Pasadena, CA, 2006.

[32] Gordon, S., and McBride, B., “Thermodynamic Data to 20000 K for Monatomic Gases,” NASA Rept. TP-1999-208523, 1999.

[33] McBride, B. J., Zehe, M. J., and Gordon, S., “NASA Glenn Coefficients for Calculating Thermodynamic Properties of Individual Species,” NASA Rept. TP-2002-211556, 2002.

[34] Johnson, H. B., “Thermochemical Interactions in Hypersonic Boundary Layer Stability,” Ph.D. Thesis, Univ. of Minnesota, Minneapolis, MN, 2000.

[35] Johnson, H. B., Seipp, T. G., and Candler, G. V., “Numerical Study of Hypersonic Reacting Boundary Layer Transition on Cones,” *Physics of Fluids*, Vol. 10, No. 10, 1998, pp. 2676–2685. doi:10.1063/1.869781

[36] Wagnild, R. M., “High Enthalpy Effects on Two Boundary Layer Disturbances in Supersonic and Hypersonic Flow,” Ph.D. Thesis, Univ. of Minnesota, Minneapolis, MN, 2012.

[37] Taylor, J. R., and Hornung, H. G., “Real Gas and Wall Roughness Effects on the Bifurcation of the Shock Reflected from the End Wall of a Tube,” *Shock Tubes and Shock Waves: Proceedings of the 13th International Symposium on Shock Waves*, State Univ. of New York Press, Albany, NY, 1981, pp. 262–270.

[38] Davies, L., and Wilson, J. L., “Influence of Reflected Shock and Boundary-Layer Interaction on Shock-Tube Flows,” *Physics of Fluids*, Vol. 12, No. 5, 1969, Paper I-37. doi:10.1063/1.1692625

[39] Smeets, G., “Laser Interferometer for High Sensitivity Measurements on Transient Phase Objects,” *IEEE Transactions on Aerospace and Electronic Systems*, Vol. AES-8, No. 2, 1972, pp. 186–190. doi:10.1109/TAES.1972.309488

[40] Wilkinson, S. P., Anders, S. G., Chen, F.-J., and Beckwith, I. E., “Supersonic and Hypersonic Quiet Tunnel Technology at NASA Langley,” *17th Aerospace Ground Testing Conference*, AIAA Paper 1992-3908, 1992.

[41] Sanderson, S. R., “Shock Wave Interaction in Hypervelocity Flow,” Ph. D. Thesis, California Inst. of Technology, Pasadena, CA, 1995.

[42] Sanderson, S. R., and Sturtevant, B., “Transient Heat Flux Measurement Using a Surface Junction Thermocouple,” *Review of Scientific Instruments*, Vol. 73, No. 7, 2002, pp. 2781–2787. doi:10.1063/1.1484255

[43] Jewell, J. S., and Shepherd, J. E., “T5 Conditions Report: Shots 2526–2823,” California Inst. of Technology, GALCIT TR FM2014.002, Pasadena, CA, June 2014.

[44] Draper, N. R., and Smith, H., *Applied Regression Analysis*, John Wiley & Sons, London, 1998.

[45] “Matlab v. 8.1.0.604 (R2013a), Linear Model Documentation Page,” MathWorks, Natick, MA, 2013.

[46] Jewell, J. S., Shepherd, J. E., and Leyva, I. A., “Shock Tunnel Operation and Correlation of Boundary Layer Transition on a Cone in Hypervelocity Flow,” *Proceedings of the 29th International Symposium on Shock Waves*, Springer International, Cham, Switzerland, July 2013, pp. 723–728.

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