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"Dirty Flow" in Hypersonic Wind Tunnels

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A chief service of the DoD IACs is free technical inquiry (TI) research, limited to 4 research hours per inquiry. This TI response report summarizes the research findings of one such inquiry jointly conducted by DSIAC.

ABSTRACT

The Defense Systems Information Analysis Center (DSIAC) received an inquiry from a Department of Defense scientist about hypersonic wind tunnel testing with dirty flow and its limitations regarding speed, type of debris, etc. This report summarizes the sources of particulates and their effects on wind tunnel flow, transition locations, and component erosion.

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1.0 TI Request

1.1 INQUIRY

What is hypersonic wind tunnel testing with "dirty flow," and what are its limitations regarding speed, debris used, etc.?

1.2 DESCRIPTION

A Department of Defense scientist inquired about hypersonic wind tunnel testing with dirty flow and its limitations regarding speed, type of debris, etc. Experts at Texas Research Institute, Austin researched this topic using the Defense Technical Information Center and open literature sources to compile this response.

2.0 TI Response

2.1 EFFECT OF DIRTY FLOW ON FLOW AND TRANSITION

Particulate matter within hypersonic flows in wind tunnel testing (rather than smoke, such as for lower speed wind tunnels that can be operated continuously) is often used as part of flow visualization in hypersonic experiments, particularly for impulse experiments. The sizes of particles used for these purposes differ depending on the requirements of the particular flow visualization method. Intense laser light is scattered by the particles. However, particulate matter within the flow can cause a number of issues as discussed in the remainder of this section and in Section 2.2.

Special attention must also be given to potential particulate contamination in high-enthalpy impulse facilities (in contrast to conventional "cold" hypersonic tunnels) because of the harsh conditions in the facility before and after the test flow over the model.

Possible sources of particulate not associated with flow visualization include piston buffer material, piston brakes, test gas impurities, and the Mylar secondary diaphragm. As an example, Parziale et al. noted that experiments performed immediately after an experiment where the piston buffers shatter had less predictable noise profiles [1]. It was found that 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.

The freestream disturbances in supersonic and hypersonic wind tunnels include acoustic waves, entropy inhomogeneities, and vertical perturbations, in addition to the presence of micro- and macro-scale particles [2]. These disturbances, regardless of the form, can significantly influence boundary-layer instability and transition-location (from laminar to transition to turbulent flow) measurements on the test models in the wind tunnels, such that confidence in any subsequent experimental measurements is compromised. For this reason, transition researchers have made extensive efforts in minimizing and characterizing freestream disturbance levels.

Work by Jewell et al. 2017 showed 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 [3]. Focused laser differential interferometry (FLDI) (measures boundary-layer density disturbances) and heat transfer (determined via 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 (Figure 1). It is believed that these turbulent spots are the result of bypass transition initiated by an instance of particulate striking the test model surface.

Jewell et al. described a statistical analysis of the correlation of tunnel parameters to transition location, which indicated 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 enables repeatable, systematic characterization of transition locations on the test article by carefully selecting run conditions (R^2 values for Re_{Tr}, Re^*_{Tr}, and an N factor increase significantly with the introduction of a more stringent cleaning procedure). Jewell et al. state that 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.

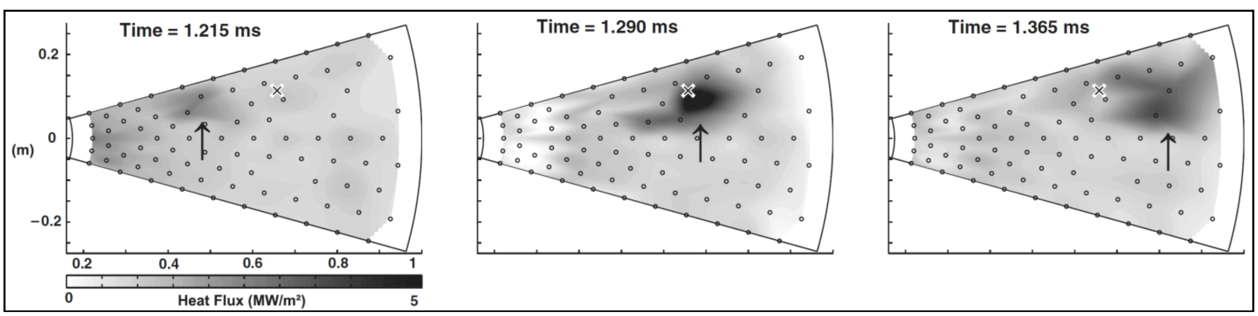

Figure 1: Turbulent Burst Occurring and Propagating Down a 5° Aluminum Cone from Testing at the T5 Wind Tunnel at the California Institute of Technology [3].

Alexander Federov also investigated these effects (laminar to turbulent transitions initiated by small particles present in the freestream) [4]. His work showed that particulates interacting with the boundary-layer flow generate unstable wavepackets related to Tollmien–Schlichting (TS) waves, which grow downstream and ultimately break down to turbulent spots. This result is reflected in the experimental work mentioned in Jewell et al. [3].

As an example, Federov performed calculations for a 14° half-angle sharp wedge flying in the standard atmosphere at an altitude of 20 km (65,600 ft), M = 4, and a zero degree angle of attack. For a flow containing spherical particles with radii ranging from 10 to 20 microns and at a density of 1 g/cm^3, the corresponding transition onset can result in an amplification factor N = 9−10, which is in the empirical range of flight data. The most important conclusion from this work is that the results indicate that atmospheric particulates may be a major source of TS-dominated transition on aerodynamically smooth surfaces at supersonic and low hypersonic speeds.

2.2 OTHER EFFECTS

In addition to triggering instabilities in the flow, dust and particulates associated with dirty flows can also damage wind tunnel facilities. Several reports have noted that “dust” or particulate picked up in the wind tunnel by the high-speed air can erode various components within the hypersonic test facilities [5]. This result also can extend to the models being tested, such as was reported by Sandia National Labs in their Mach 5 wind tunnel test [6].

Some facilities are hardened to allow dust to be used as part of the test to determine ablation and erosion rates. The 1994 report by Matthews et al. discusses the HEAT-H1 tunnel at Arnolds Air Force Base, which allowed graphite particulates (60−400 microns) to be injected into the stream to 3,000−6,000 ft/s at flow rates from 5−60 g/sec [7]. This tunnel is still operable, but it is unknown if this particulate injection capability still exists.

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BIOGRAPHIES

Richard Piner currently serves in the Mechanical Engineering Department at the University of Texas at Austin. He has over 48 years of industry experience spanning a wide variety of technical topics, including, but not limited to, the four broad categories of reactors, graphene, graphene oxide, and scanning technique. He has hundreds of scholarly publications yielding over 40,000 citations to his work. Dr. Piner holds a Ph.D. in physics from Purdue, where he studied scanning tunneling microscopy.

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