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Assessing the Effects of Various Surface Textures and Features on Turbulent Heat Transfer in Hypersonic Flight

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Experiments were conducted in the NASA Ames Hypervelocity Free Flight Aerodynamic Facility (ballistic range) to quantify the effects on turbulent convective heat transfer of distributed surface roughness, and of isolated features, representative of thermal protection systems on atmospheric entry vehicles. The surface textures and features were applied on the conic frusta of 45º sphere-cone models having a nose-to-base radius ratio of 0.5, similar to the forebody geometry of the Galileo and Pioneer-Venus entry probes. Test conditions were selected to provide turbulent roughness Reynolds numbers, k^+, in the ranges expected for outer planet entry missions. Turbulent flow on the conic frustum was achieved by tripping the flow on the sphere-segment nose cap with distributed surface roughness, created by sand-blasting the nose cap.

Surface textures included distributed, acreage, roughness, as well as cavity and groove discrete features. The majority of the data to be presented are results for distributed roughness, which includes both random, sand-grain-like roughness, and regular pattern roughness. The pattern roughness was designed to represent the roughness on woven thermal protection system materials, such as NASA's 3-D Medium Density Carbon Phenolic (3MDCP), also known as HEEET, developed by the Heatshield for Extreme Entry Environments Technology project. The pattern roughness tested is a 3-D wavy surface, and includes three different roughness element height-to-spacing ratios representative of two configurations of 3MDCP, and spanning ratios measured both before, and after, ablation in an arc jet test facility. The patterns tested in the ballistic range were laser-etched on metal models, and represented an idealized version of the real-world materials in which each roughness element was nearly identical. Additional tests were performed wherein the laser-etched patterns were degraded by sand-blasting with various sized grit media, to produce regular patterns with superimposed irregular roughness, more representative of flight materials. Results of each will be compared.

The discrete features tested included cylindrical cavities and rectangular grooves of various width-to-depth ratios. Cavities represent either heatshield damage, such as from micro-meteoroid and orbital debris (MMOD) damage, or from designed penetrations, such as on the Genesis sample return capsule. The grooves were scaled representations of seams between segments of HEEET material in a notional tiled thermal protection system. The tests examined the effects on turbulent heating downstream of the isolated features.

The tests were conducted at speeds between 3 km/s and 4 km/s in air between 0.15 atm and 0.25 atm (Mach numbers between 9 and 12). Roughness Reynolds numbers, k^+, ranged from 12 to 70 for the sand roughness, and as high as 200 for the pattern roughness. Boundary-layer parameters required for calculating k^+ were evaluated using computational fluid dynamics simulations using the DPLR (Data Parallel Line Relaxation) code. Each model included both rough- and smooth-wall segments, and heat transfer augmentation factors were determined as the ratio of the rough-wall to smooth-wall heat flux measured on each test.