FULL-SCALE MSL HEATSHIELD MATERIAL RESPONSE USING DSMC AND CFD TO COMPUTE THE AEROTHERMAL ENVIRONMENTS

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Introduction
During Mars atmospheric entry, the Mars Science Laboratory (MSL) was protected by a 4.5 meters diameter ablative heatshield assembled in 113 tiles [1]. The heatshield was made of NASA's flagship ablative material, the Phenolic Impregnated Carbon Ablator (PICA) [2]. Prior work [3] compared the traditional one-dimensional and three-dimensional material response models at different locations in the heatshield. It was observed that the flow was basically one-dimensional in the nose and flank regions, but three-dimensional flow effects were observed in the outer flank. Additionally, the effects of tiled versus monolithic heatshield models were also investigated. It was observed that the 3D tiled and 3D monolithic configurations yielded relative differences for in-depth material temperature up to 18% and 28%, respectively, when compared to the a 1D model.

Aerothermal environments from SPARTA and DPLR
The MSL flight environment was simulated using the following assumptions for both the CFD and DSMC simulations:
• Super-catalytic wall BC: CO₂ and N₂ recombination to freestream mole fractions
• Radiative equilibrium wall with e = 0.89
• Mars atmosphere YCO₂ ≈ 0.97 and YN₂ ≈ 0.03
• 8 species and 24 reactions (12 forward + 12 backward): Mitchelltree model [6]
• Park hyersonics correction to vibrational relaxation

DSMC

The objective of this work is to study the effects of the aerothermal environment on the material response. We extend prior work [3] by computing aerothermal environments using the direct simulation Monte Carlo (DSMC) code SPARTA [4] and the CFD code Data Parallel Line Relaxation (DPLR) [5]. SPARTA is used to compute environment in the rarefied regime prior to 48.4 s of entry where the Knudsen number is such that the Navier-Stokes equations can be inaccurate. Similarly to previous work, the DPLR software is used to compute the hypersonic environment for a laminar boundary layer assumption from 48.4 s up to 100 s after Entry Interface (EI) along the MSL 08-TPS-02/01a trajectory.

Differences between CFD and DSMC:
• DPLR uses a 2 temperature model and SPARTA a 3 temperature model
• Laminar boundary layer model in DPLR
• Binary diffusion coefficients from Gupta collision integrals [7] in DPLR
• SPARTA uses Variable Soft Sphere (VSS) model with high temperature transport calibration
• Parker equation for rotational relaxation and Millikan-White equation + Park correction for vibrational relaxation in SPARTA

Material response from PATO
The Porous material Analysis Toolbox based on OpenFOAM (PATO) [10, 11] is used for the material response calculations. The governing equations are volume-averaged forms of solid mass, gas mass, gas momentum and total energy conservation, including pyrolysis gas production. The thermodynamics and chemistry properties are computed using the Mutation++ library [12]. The boundary conditions at the heatshield front surface are interopolated in time and space from the aerothermohal environment at discrete points of the MSL trajectory [3], using a Galerkin projection. For this study, the Theoretical Ablative Composite for Open Testing (TACOT) database developed by the TPS community was used to define the porous material properties. TACOT is a fictitious material that was inspired from low density carbon/phenolic ablator. The boundary layer edge (BLE) quantities from DPLR are extracted using a curvature-based method with the BLAYER code [9]. For the DSMC results, a Boundary Layer utility was created in PATO and an edge-based method is used (location of BLE such that h₇ = 99.5% of h₈). At 40 s after EI, the peak pressure value computed from SPARTA is reached in the stagnation point region (MISP4) around 150 Pa (Fig. 5). We compute the PATO material response of the MSL heatshield in a monolithic 3D configuration, with the Martian aerothermohal environments derived from DPLR only and DSMC+DPLR. For both cases, a uniform initial temperature is imposed. The addition of the DSMC results modifies the temperature prediction for the first 60 s after EI (Fig. 6). For MISP4, in-depth thermal effects are as important as surface thermal effects especially before 60 s (Fig. 7). Fig. 8 shows the surface recession computed in PATO with the highest recession at MISP5 as expected for a laminar aero thermal environment. Almost no recession is observed before 60 s due to the low heat flux. Only subtle differences in the recession are found between DPLR only and DSMC+DPLR derived environments.

References