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Multidimensional material response simulations of a full-scale tiled ablative heatshield

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ABSTRACT

The Mars Science Laboratory (MSL) was protected during Mars atmospheric entry by a 4.5 meter diameter heatshield, which was constructed by assembling 113 thermal tiles made of NASA's flagship porous ablative material, Phenolic Impregnated Carbon Ablator (PICA). Analysis and certification of the tiles thickness were based on a one-dimensional model of the PICA response to the entry aerothermal environment. This work provides a detailed three-dimensional heat and mass transfer analysis of the full-scale MSL tiled heatshield. One-dimensional and three-dimensional material response models are compared at different locations of the heatshield. The three-dimensional analysis is made possible by the use of the Porous material Analysis Toolbox based on OpenFOAM (PATO) to simulate the material response. PATO solves the conservation equations of solid mass, gas mass, gas momentum and total energy, using a volume-averaged formulation that includes production of gases from the decomposition of polymeric matrix. Boundary conditions at the heatshield forebody surface were interpolated in time and space from the aerothermal environment computed with the Data Parallel Line Relaxation (DPLR) code at discrete points of the MSL trajectory. A mesh consisting of two million cells was created in Pointwise, and the material response was performed using 840 processors on NASA's Pleiades supercomputer. The present work constitutes the first demonstration of a three-dimensional material response simulation of a full-scale ablative heatshield with tiled interfaces. It is found that three-dimensional effects are pronounced at the heatshield outer flank, where maximum heating and heat loads occur for laminar flows.

1. Introduction

The Mars Science Laboratory (MSL) spacecraft, launched on November 2011, successfully landed the Mars Curiosity rover in the Aeolis Palus region of the Gale Crater on August 2012. The MSL entry vehicle was equipped with a 4.5 m diameter Thermal Protection System (TPS) that effectively protected the spacecraft and its payload during entry into Mars' atmosphere. The MSL TPS used the Phenolic Impregnated Carbon Ablator, or PICA, as heatshield material [1]. PICA is a low density (≈274 kg/m^3) carbon/resin composite, manufactured via impregnation of a rigid carbon fiber preform (FiberForm) with a phenolic resin (Durite® SC-1008), followed by a proprietary high temperature curing and vacuum drying process [2]. The material was successfully used on the Stardust Sample Return Capsule (SRC), assembled in a 0.8 m diameter monolithic aeroshell [3]. Due to manufacturing constraints, it was unfeasible to construct a 4.5 m diameter heatshield out of a single piece of PICA. Instead, the MSL heatshield was developed as an assembly of 113 PICA tiles containing 23 unique shapes. There were also gaps between the TPS tiles to allow for thermal expansion and contraction. These gaps were filled using a silicone elastomer bonding agent. The MSL heatshield was instrumented with temperature and pressure sensors; therefore, the MSL is an established validation case for ablator response models. The MEDLI (MSL Entry, Descent, and Landing Instrument) suite recorded, among others, time-resolved in-depth temperature data using thermocouple sensors assembled in the MEDLI Integrated Sensor Plugs (MISP). Several studies in the literature have used MISP data as a benchmark for state-of-the-art ablation codes [4–6]. Modeling of heat and mass transfer in porous materials during at-

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Nomenclature

$\mathcal{A}_{i,j}$	Arrhenius law pre-exponential factor	$\mathrm{K}^{-n_{i,j}}\,\mathrm{s}^{-1}$
$\mathcal{E}_{i,j}$	Arrhenius law activation energy	$\mathrm{J\,mol}^{-1}$
$\mathcal{R}$	Perfect gas constant	$\mathrm{J\,mol}^{-1}\,\mathrm{K}^{-1}$
$\dot{m}_{ca}$	Char ablation rate	$\mathrm{kg\,m}^{-2}\,\mathrm{s}^{-1}$
$\dot{m}_{pg}$	Pyrolysis gas production rate	$\mathrm{kg\,m}^{-2}\,\mathrm{s}^{-1}$
St_H	Stanton number for heat transfer	
St_M	Stanton number for mass transfer	
$\underline{\underline{\mathbf{K}}}$	Permeability tensor	m^2
$\underline{\underline{\mathbf{k}}}$	Effective thermal conductivity tensor	$\mathrm{W\,m}^{-1}\,\mathrm{K}^{-1}$
$\mathbf{n}$	Front surface normal	
$\mathbf{v}_g$	Gas velocity	$\mathrm{m\,s}^{-1}$
$\mathbf{v}_{ca}$	Char ablation velocity	$\mathrm{m\,s}^{-1}$
A_k	Element k	
B'	Dimensionless mass blowing rate	
C'_H	Corrected heat transfer coefficient	$\mathrm{kg\,m}^{-2}\,\mathrm{s}^{-1}$
C_H	Heat transfer coefficient $= \rho_e u_e St_H$	$\mathrm{kg\,m}^{-2}\,\mathrm{s}^{-1}$
C_M	Mass transfer coefficient $= \rho_e u_e St_M$	$\mathrm{kg\,m}^{-2}\,\mathrm{s}^{-1}$
c_p	Specific heat capacity	$\mathrm{J\,kg}^{-1}\,\mathrm{K}^{-1}$
e	Specific energy	$\mathrm{J\,kg}^{-1}$
$F_{i,j}$	Fraction of subphase j in phase i	
h	Specific absolute enthalpy	$\mathrm{J\,kg}^{-1}$
K_i	Equilibrium constant	
$m_{i,j}$	Arrhenius law advancement pyrolysis reaction factor	
N_s	Number of gaseous species	
N_p	Number of solid phases	
N_e	Number of gaseous elements	
$n_{i,j}$	Arrhenius law temperature factor	
p	Pressure	Pa
P_i	Number of subphases in solid phase i	
q	Heat flux	$\mathrm{W\,m}^{-2}$
S_i	Specie i	
T	Temperature	K
x_i	Mole fraction of specie i	
x_k	Mole fraction of element k	
y_i	Mass fraction of specie i	
z_k	Mass fraction of element k	

Greek

α	Absorptivity	
$\chi_{i,j}$	Advancement of pyrolysis reaction j within phase i	
ϵ	Porosity	
$\epsilon_{i,0}$	Initial porosity of phase i	
λ	Scaling factor for C'_H	
μ	Viscosity	$\mathrm{kg\,m}^{-1}\,\mathrm{s}^{-1}$
$\nu_{i,k}$	Number of atoms of element k in molecule of specie i	
Π	Total pyrolysis gas production rate	$\mathrm{kg\,m}^{-3}\,\mathrm{s}^{-1}$
π_k	Pyrolysis gas production rate of specie k	$\mathrm{kg\,m}^{-3}\,\mathrm{s}^{-1}$
ρ	Mass density	$\mathrm{kg\,m}^{-3}$
$\rho_{i,0}$	Initial mass density of phase i	$\mathrm{kg\,m}^{-3}$
σ	Stefan–Boltzmann constant, 5.670367×10^{-8}	$\mathrm{W\,m}^{-2}\,\mathrm{K}^{-4}$
$\underline{\underline{\beta}}$	Klinkenberg correction tensor	$\mathrm{m}^2\,\mathrm{s}^{-1}$
ε	Emissivity	
ζ	Mass stoichiometric coefficient	

Subscripts

0	Initial
∞	Infinity
a	Ablation
adv	Advection
c	Char
$cond$	Conduction
$conv$	Convection
$diff$	Diffusion
e	Boundary layer edge
$flux$	Corrected convection
g	Gas phase
p	Pyrolysis reaction
pla	Plasma
rad	Radiation
s	Solid phase
t	Total (solid and gas phases)
v	Virgin
w	Wall

Subperscripts

in	Inside the material
out	Outside the material

mospheric entry of spacecrafts is a complex and computationally expensive problem. Traditionally, NASA TPS design has been done using one-dimensional ablation and thermal response solvers [7,8]. Research by Chen and Milos [9,10] investigated multi-dimensional effects on the thermal response of a monolithic Apollo-shaped heatshield, using the 3dFIAT code developed at the NASA Ames Research Center. The convective aerothermal environment over the exterior TPS surface were derived from the Configuration Based Aerodynamics (CBAERO) analysis of Lunar return trajectories [11]. The analysis indicated that, for a high angle of attack entry, the peak heat flux and heat load are located at the windside heatshield outer flank. At this location, the planar approximation was shown to underpredict the peak bondline temperature. In this study, detailed three-dimensional heat and mass transfer analyses are undertaken on the tiled MSL heatshield to assess the validity and limitations of the traditional one-dimensional design assumption. The Porous material Analysis Toolbox based on OpenFOAM (PATO) software program is used to simulate the TPS response [12]. PATO is released as open source software by NASA.[1] The aerothermal environment at the heatshield surface, at discrete points along the MSL entry trajectory, is obtained from hypersonic Computational Fluid Dynamics (CFD) simulations performed using the Data Parallel Line Relaxation (DPLR)[2] Navier–Stokes software program [13]. A procedure for temporal and spatial interpolation was used to loosely couple the aerothermal environment to the material response. Simulations were performed for both monolithic and tiled heatshield configurations. Tiles are normally not included in 3D material response analysis because of the high computational costs associated with such simulations. The massively parallel simulation support inherited in PATO from its OpenFOAM architecture now makes such studies possible.

The paper is organized as follows. In section 2, we describe the MSL monolithic and tiled heatshield grid used for the simulations. Section 3 presents the governing equations used in the material response model. Section 4 details the spatial and temporal interpolation from DPLR to PATO. In section 5, the overall material response is presented where monolithic and tiles configurations are compared. Detailed heat and mass transfer analyses

[1] https://software.nasa.gov/software/ARC-16680-1A.

[2] https://software.nasa.gov/software/ARC-16021-1A.