ABLATION STUDY IN ROCKET NOZZLES

ANSHUL SURI, ANKIT BANSAL

Indian Institute of Technology Roorkee, Department of Mechanical and Industrial Engineering, Roorkee, India

Abstract
Computational analysis of ablative materials in high-enthalpy flows is presented for a submerged rocket nozzle. The governing equation for creeping flow of reacting gases through porous matrix of the ablative material are presented. The boundary conditions for the surface are modelled as mass and energy balance. The temperature and density variation at the surface of the ablative material were analyzed and good agreement with the published results is observed.

Keywords: Ablative material, modeling, rocket nozzle.

Nomenclature

A_j	Arrhenius law pre-exponential factor, SI
e	Specific Energy,Jkg^{-1}
F_j	Fraction of mass lost through pyrolysis reaction j
h	Specific Enthalpy, Jkg^{-1}
N_g	Number of gaseous species
N_p	Number of pyrolysis reactions
q	Heat flux, Jkg^{-1}K^{-1}
R	Perfect Gas Constant, Jkg^{-1}K^{-1}
K	Permeability
Pr	Prandtl number
Le	Lewis number

Greek Symbols

ξ_j	Advancement of pyrolysis reaction j

Subscripts

a	Ablative material(gas, fiber, and matrix)
c	Char
f	Reinforcement (non-pyrolyzing phase)
g	Gas phase
m	Polymer Matrix
mv	Virgin Polymer Matrix
p	Pyrolysis
pg	Pyrolysis Gas
s	solid

1. Introduction

Ablative materials are used as heat shields in systems exposed to high temperatures or high heat fluxes. These materials are porous and very light in weight. The ablative materials are used as Thermal Protect System (TPS) for hypersonic vehicles during re-entry and as liners for rocket nozzle at the inside surface [1].

Heat transfer to the thermal protection system (TPS) leads to increase in its temperature and ablation of the material. The virgin material is successively transformed and removed by pyrolysis and ablation. During pyrolysis, the pyrolyzing phase of the material (often a polymer matrix) progressively carbonizes and loses pyrolysis gases. The pyrolysis gases are transported out of the material by diffusion and convection through the pore network. During ablation, the char—composed of residual carbonized matrix and the non-pyrolyzing phase (often a carbon or silicon-carbide fibrous preform)—is eroded away from the surface of the TPS. Ablation may be due to heterogeneous chemical reactions (oxidation, nitridation), phase change (sublimation), and/or mechanical erosion (spallation).

Computational models are used to calculate material response and peak temperature of the bondline at the interface of the TPS and the substructure. This paper presents computational results for thermal response of ablative material of TPS of a submerged rocket nozzle.

2. Constitutive Models

2.1. Mass Conservation

The mass conservation equations is given as [2]

$$\partial_t\left(\epsilon_g\rho_g\right)+\partial_x.\left(\epsilon_g\rho_g\mathbf{v}_g\right)=\Pi \tag{1}$$

where Π is the pyrolysis gas production rate. The pyrolysing matrix density is given by

$$\epsilon_m\rho_m=\epsilon_{mv}\rho_{mv}\sum_{j=1}^{Np}Fj(1-\xi_j) \tag{2}$$

Where rate of pyrolysis reaction is given as

$$\frac{\partial_t\xi_j}{(1-\xi_j)^{m_j}}=T^{n_j}A_j\exp\left(-\frac{\xi_j}{RT}\right) \tag{3}$$

The average pyrolysis–gas mass production rate is given by

$$\Pi=-\partial_t(\epsilon_m\rho_m)=\epsilon_{mv}\rho_{mv}\sum_{j=1}^{Np}F_j\partial_t(\xi_j) \tag{4}$$

A constant elemental fraction of the pyrolysis gas is assumed.

2.2. Momentum Conservation in porous media

For creeping flows, the volume-averaged momentum conservation equation reduces to Darcy's equation. The volume-averaged gas velocity is given as [3].

$$\mathbf{v_g} = -\frac{1}{\epsilon_g \mu} \overline{\overline{\mathbf{K}}}.\, \partial_x p \quad (5)$$

2.2. Energy Conservation

Under thermal equilibrium assumption, the energy conservation may be written as [3]

$$\partial_t \rho_a e_a + \partial_x.\left(\epsilon_g \rho_g h_g \mathbf{v_g}\right) + \partial_x.\sum_{i=1}^{N_p}(h_i \beta_i)$$

$$= \partial_x.\left(\overline{\overline{\mathbf{k}}}.\, \partial_x T\right) + \mu {\epsilon_g}^2 \left(\overline{\overline{\mathbf{K}}}^{-1}.\mathbf{v}\right).\mathbf{v} \quad (6)$$

The second and third terms of the left-hand side are the advection and diffusion terms, respectively. Where β is the diffusion flux of ith specie. Heat transfer is modeled with the Fourier's law. The total energy of the ablative material is the sum of the energy of its components (gases, matrix and fiber) and is written as

$$\rho_a e_a = \epsilon_g \rho_g e_g + \varepsilon_m \rho_m h_m + \epsilon_f \rho_f h_f \quad (7)$$

2.3. Boundary Conditions

The boundary conditions at the wall may be as simple as fixed temperature or may be more complicated based on energy balance. We have adopted surface energy and mass balance as the boundary condition**.**

2.3.1 Surface Energy Balance

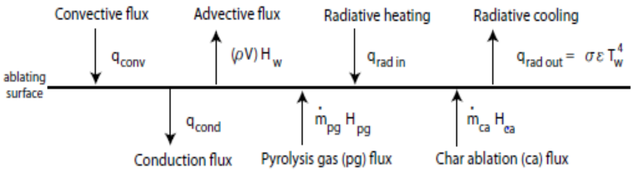

Fig. 1. Energy balance boundary condition [3].

The surface energy balance at the wall is shown in Fig. 1. This can be mathematically written as

$$q_{conv} - (\rho V) h_w + q_{rad,in} - q_{rad,out} - q_{cond}$$
$$\dot{m_{pg}} h_{pg} + \dot{m}_{ca} h_{ca} = 0 \quad (8)$$

The boundary condition includes contribution from three modes of heat transfer as well as energy transfer with ablating mass. The convective heat flux is given as

$$q_{conv} = \rho_e u_e \acute{C}_H (h_e - h_w) \quad (9)$$

where the corrected Stanton number, $\acute{C}_H$, accounts for blockage induced by pyrolysis-ablation gas-blowing.

$$\acute{C}_H = C_H \ln(1 + 2\lambda \acute{B}) / \ln(2\lambda \acute{B}) \quad (10)$$

where

$$\acute{B} = (\dot{m_{pg}} + \dot{m_{ca}}) / (\rho_e u_e C_M) \quad (11)$$

is a dimensionless mass flow rate and λ is a scaling factor usually taken to 0.5 [3].

2.3.2 Surface Mass Balance and Recession Rate

The pyrolysis gas flow rate is directly obtained by integration of equations of pyrolysis, transport, and mass. The ablation rate is a function of both mass transfer in the boundary layer and wall's thermo-chemical properties (pyrolysis-gas production rate and composition, temperature, pressure, boundary-layer gas composition).We applied the model based on element conservation in steady-state in control volume close to the wall as shown in Fig 2 [4].

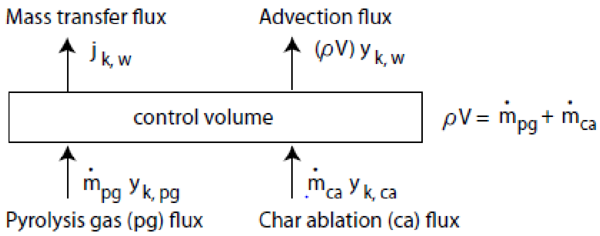

Fig. 2. Element mass-fraction conservation at the wall

Spallation and mechanical erosion are not included and char is assumed to be composed of carbon only. The conservation of mass-fraction of element *k* is given as:

$$j_{k,w} + (\rho V) y_{k,w} = \dot{m}_{pg} y_{k,pg} + \dot{m}_{ca} y_{k,ca} \quad (12)$$

Where pg= pyrolysis gases, ca = char ablation products. The relative mass fractions should sum to 1 in each phase

$\sum_k y_{k,w} = 1; \sum_k y_{k,pg} = 1; \sum_k y_{k,ca} = 1$

For *Pr* = *Le* = 1 and same diffusion coefficients for all the elements, Eq. 12 may be written as

$$\rho_e u_e C_H \left(y_{k,w} - y_{k,e}\right) + (\rho V) y_{k,w} = \dot{m}_{pg} y_{k,pg} + \dot{m}_{ca} y_{k,ca} \quad (13)$$

where

$$(\rho V) = \dot{m}_{pg} + \dot{m}_{ca} \quad (14)$$

3. Results and Discussion

For this study, the geometry of the submerged nozzle, 260-SL-3 nozzle, as depicted in NASA's Aerotherm report on study of ablative material performance for rocket nozzle application is taken [5].

All the simulation were done on OpenFOAM, an open source CFD platform. PATO [6] (Porous material Analysis Toolbox based on OpenFOAM) which was made open source by NASA in 2016 is also employed to study the thermal response of ablative materials applied to rocket nozzle. The obtained temperature results are found to be in agreement with the experimental results given in NASA's Aerotherm report on use of ablative materials for rocket nozzle application [4]. The variation of temperature and density with depth in the TPS is shown in Fig. 3. The maximum temperature in the TPS is around 1650 K at the surface of the TPS liner. The variation of surface temperature with time, shown in Fig 4., is qualitatively similar to those in NASA's report and also to results published by Steg and Lew. The variation of density of the ablative material at the surface with time is also shown in Fig. 4. The surface density varies from an initial value of 280 kg/m^3 (density of virgin material) to about 220 kg/m^3 after 15 seconds. The final density of the material is almost same as that of char formed after complete pyrolysis.

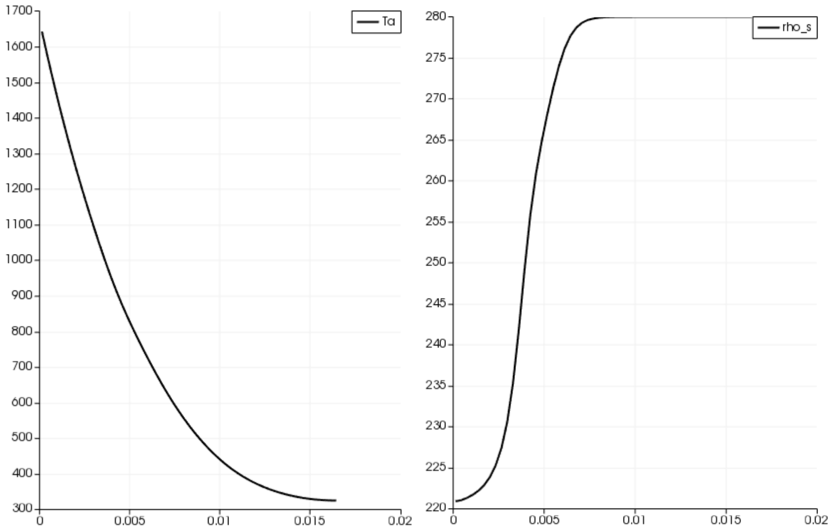

Fig. 3. **Temperature (left) and density (right) variation with depth of material coating in ablative material coating at t=15**

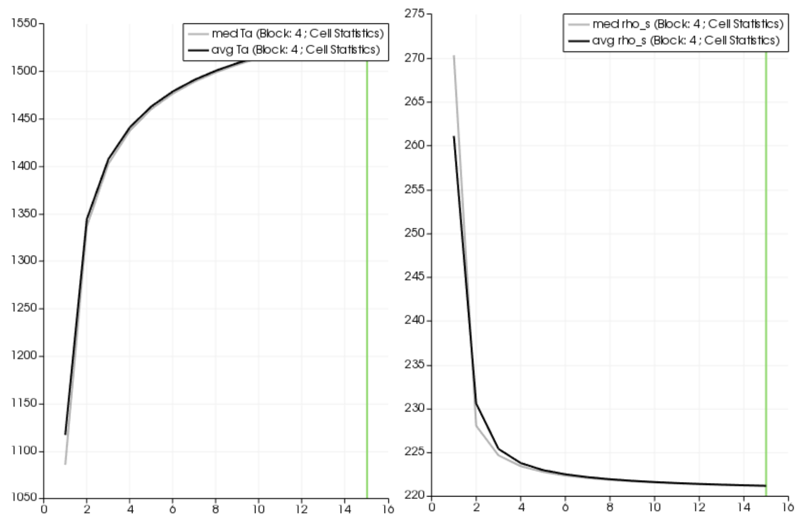

Fig. 4. **Variation of average and median surface temperature (left) and surface density (right) over time**

4. Conclusion

Response of ablative materials subjected to high-enthalpy flows, as in rocket nozzle, was analyzed numerically. The results for the variation of the surface temperature and density were compared with the experimental as well as numerical results published earlier, and were found to be in good agreement.

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