ABLATION STUDY IN ROCKET NOZZLE

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- Introduction
- Ablation and its constitutive model
- Thermal Protection System(TPS) for rocket nozzle
- Results
- Conclusion

Introduction

- Heat shields for systems exposed to high heat flux.
- Highly porous and light weight.
- Applications
  - Thermal Protection System(TPS) for hypersonic re-entry vehicles
  - Liners for rocket nozzles

FIG 1. Ablative heat shield [1]

[1] Jean Lachaud, Thierry E. Magin, Ioana Cozmuta, and Nagi N. Mansour, A short review of ablative-material response models and simulation tools. 7th Aerodynamics Symposium(European Space Agency).

Ablation and its constitutive model

- Heat transfer to the TPS leads to increase in its temperature and ablation of the material.
- Virgin material successively undergoes pyrolysis and ablation.
- Material progressively carbonizes and releases pyrolysis gases.
- Char formed at the surface is continuously eroded.

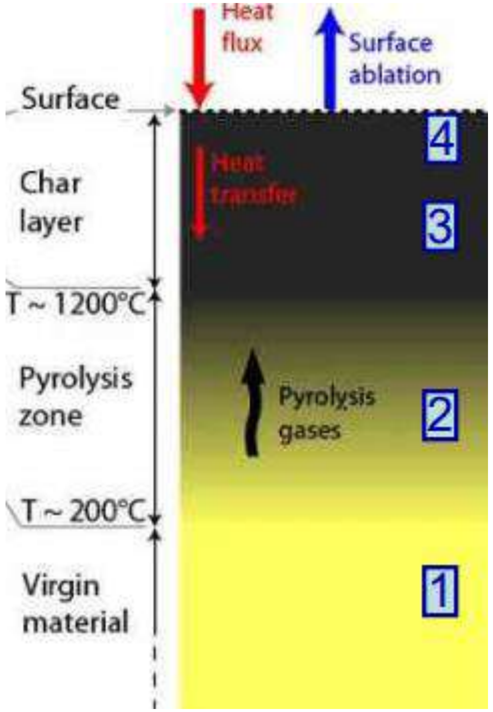


FIG 2. Various regions during ablation [1]

[1] Jean Lachaud, Thierry E. Magin, Ioana Cozmuta, and Nagi N. Mansour, A short review of ablative-material response models and simulation tools. 7th Aerodynamics Symposium(European Space Agency).

2.1 Mass Conservation

For gaseous phase-

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

π = pyrolysis gas production rate.

Velocity from momentum equation.

For the pyrolyzing phase -

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

where

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

and

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

2.2 Momentum Conservation

Momentum equation-

$$\mathbf{v_g} = -\frac{1}{\epsilon_g \mu} \bar{\bar{\mathbf{K}}} . \, \partial_x p$$

$\bar{\bar{\mathbf{K}}}$ is permeability tensor.

Pressure-density relation

$$p = \rho R T$$

2.3 Energy Conservation

Under the assumption of thermal equilibrium-

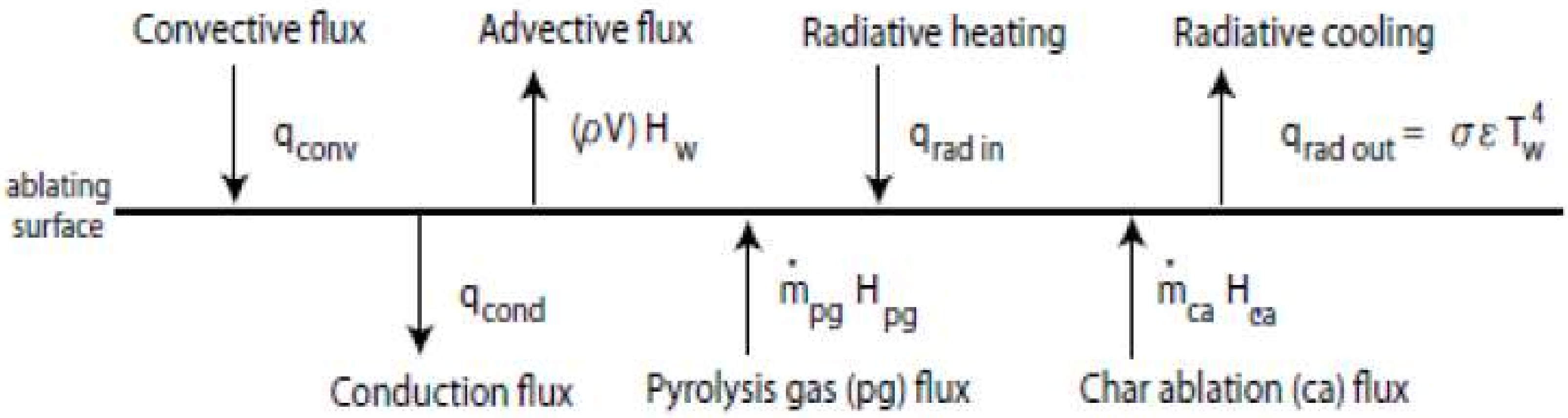
$$\partial_t \rho_a e_a + \partial_x . \left(\epsilon_g \rho_g h_g \mathbf{v}_{\boldsymbol{g}}\right) + \partial_x . \sum_{i=1}^{N_p} (h_i \beta_i) \qquad = \partial_x . \left(\bar{\bar{\mathbf{k}}} . \partial_x T\right) + \mu \epsilon_g{}^2 \left(\bar{\bar{\mathbf{K}}}^{-1} . \mathbf{v}\right) . \mathbf{v}$$

β_i is diffusion flux of the ith specie.

The total energy of the ablative material is sum of the energy of its components-

$$\rho_a e_a = \epsilon_g \rho_g e_g + \varepsilon_m \rho_m h_m + \epsilon_f \rho_f h_f$$

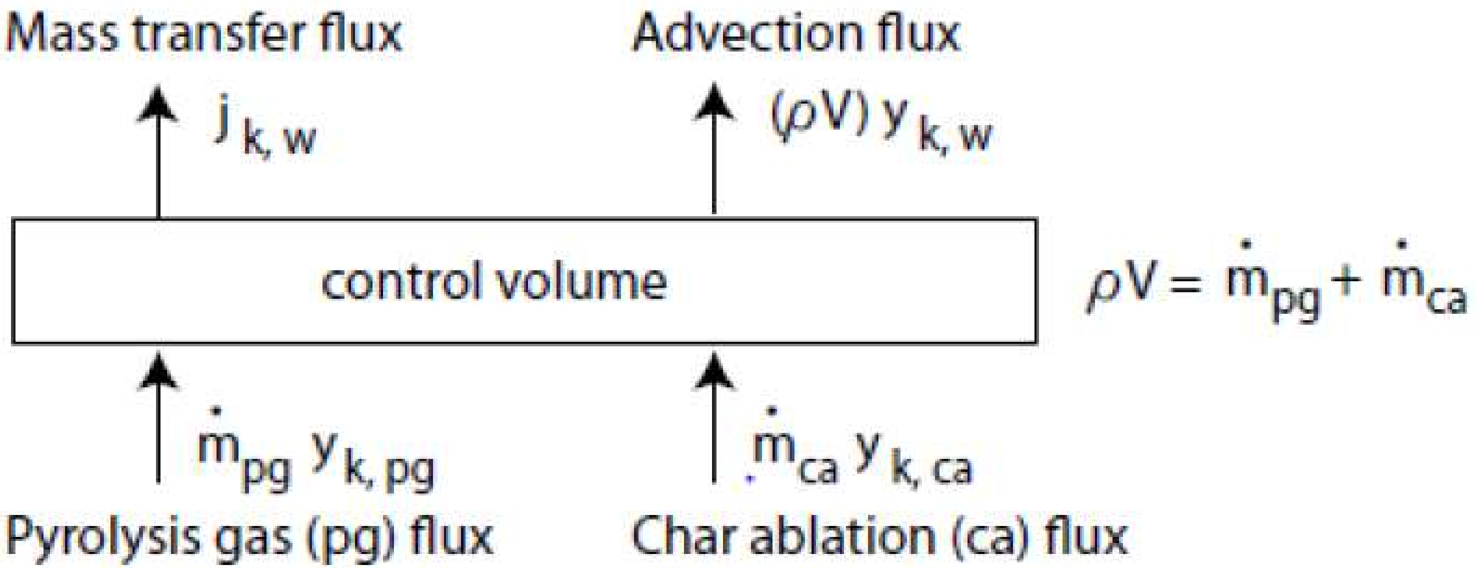
2.4 Surface Energy Balance



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

Here $\dot{m}_{ca}$ is unknown used to calculate volume of ablated material knowing density of the char.

2.5 Surface Mass Balance



1- Conservation of element mass fraction in the control volume

2- Equilibrium chemistry provides both ablation rate($\dot{m}_{ca}$)and the gas composition($y_{k,w}$)

[2] C.B. Moyer and M.R. Wool. Aerotherm equilibrium surface thermochemistry computer program – version 3. Technical report, Aerotherm, AD875385

3. Thermal Protection System (TPS) for Rocket Nozzle

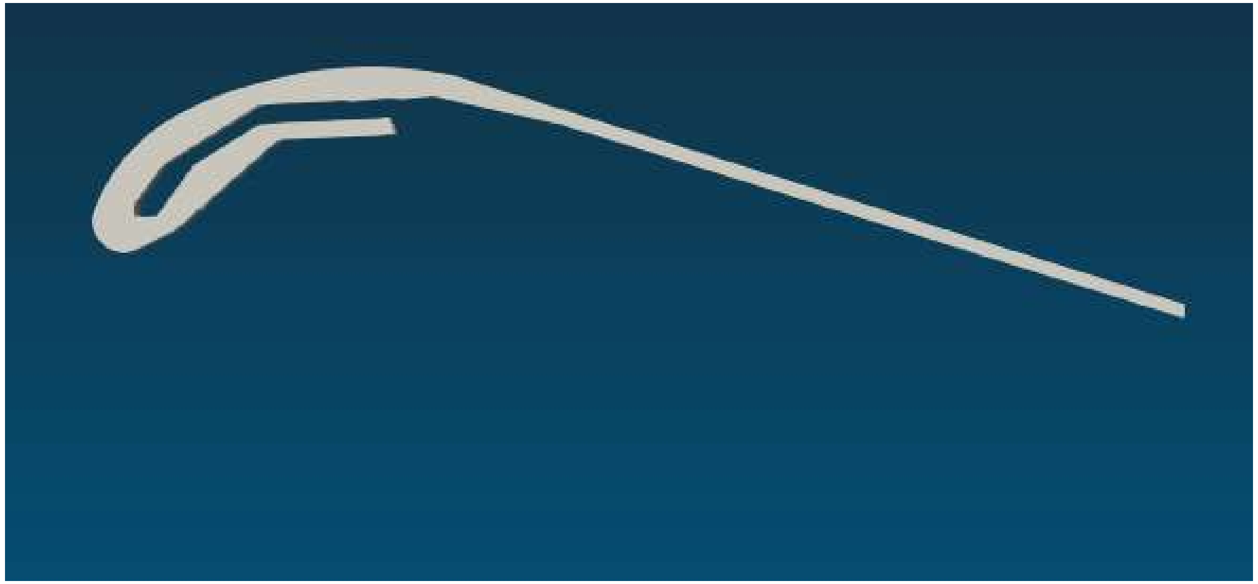


FIG 3. Geometry of the nozzle used(260-SL-3 nozzle)

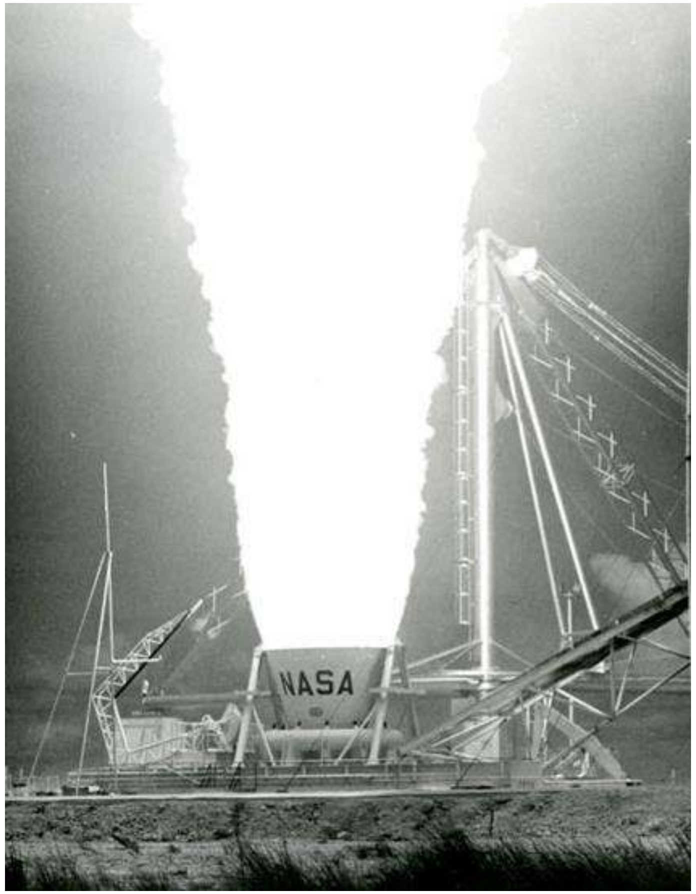


FIG 4. Testing of NASA's 260-SL-3 nozzle by NASA.

This geometry represents TPS for a 260-SL-3 nozzle as depicted in NASA's Aerotherm Report on study of ablative material performance for rocket nozzle application [2]

Lining of this ablative material on inner surface of the nozzle protects the nozzle from exposure to high heat flux due heated exhaust gases.

[3] John W. Schaefer, Thomas J. Dahm, David A. Rodriguez, John J. Reese, Jr., Mitchell R. Wool. Studies of ablative material performance for rocket nozzle application, NASA CR-72429, Aerotherm Report NO. 68-30.

4. Results

Computational analysis is done on OpenFOAM .
PATO (Porous Material Analysis Toolbox based on OpenFOAM, made opensource by NASA in 2016 [3]) is also employed along with OpenFOAM to conduct the simulations, with paraview as the post-processing tool.

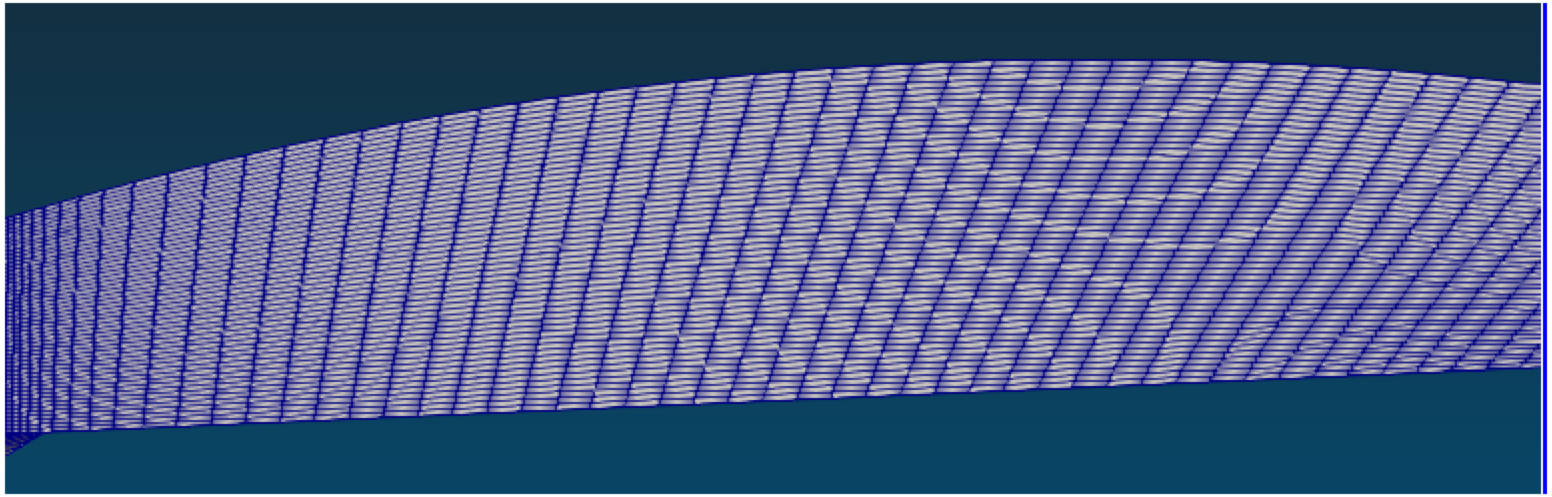
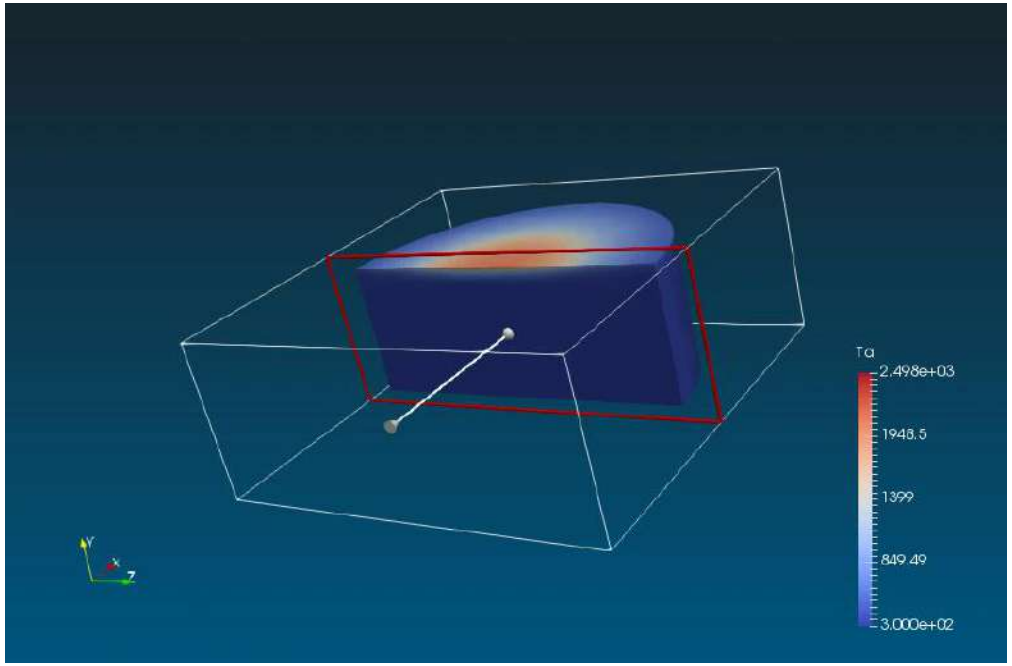


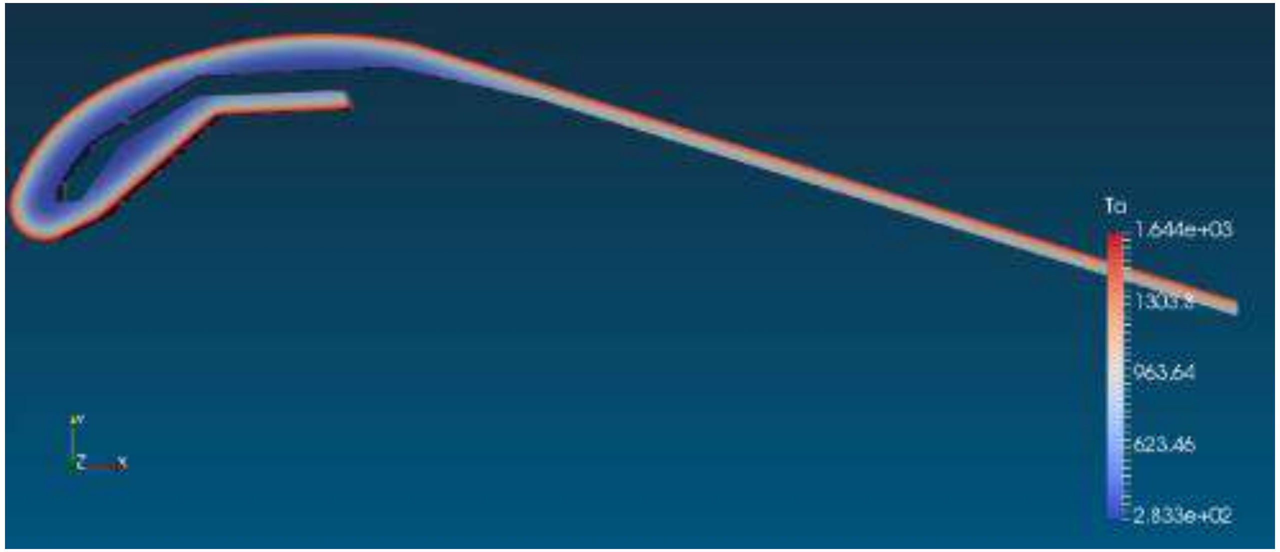
FIG 4. Mesh quality in throat region

[4] J. Lachaud, N.N. Mansour. Porous-material Analysis Toolbox based on OpenFOAM and Applications.
[5] https://pato.ac/index.php/about/

Initial Test Case

- Initially the simulation is conducted on a cylindrical block made of carbon phenolic based ablative material.
- The temperature variation and boundary recession is visible the animation.
- Such study helps to quantify the variation in thickness of the TPS with change in temperature or at various heat flux.





Temperature variation at t=15

Variation of temperature can be given as an input in form of constant temperature or constant heat flux or input the temperature variation with time as per testing data.

We can see(FIG 6.) along the depth temperature falls to the value corresponding initial temperature, the temperature at the surface of nozzle being unaffected by the outer temperature.

The plot in FIG 5. is in agreement with results in NASA's aerotherm report

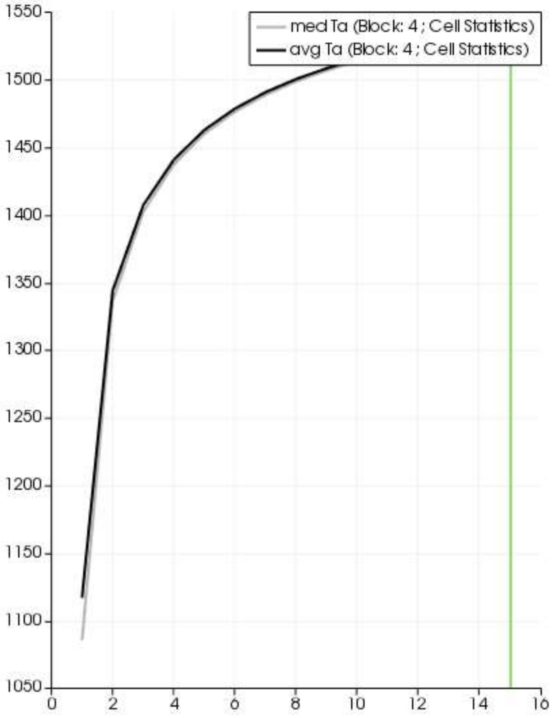


FIG 5. Time history plot for Temperature at throat region

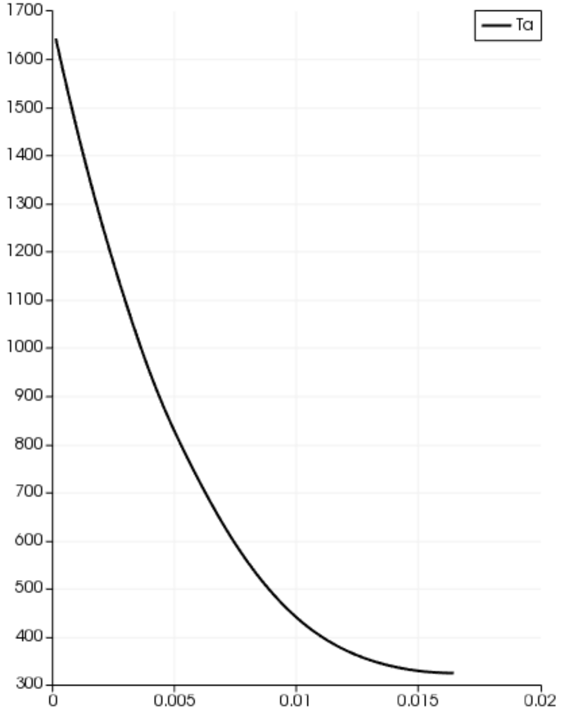


FIG 6. Variation of Temperature along depth at throat region at t=15

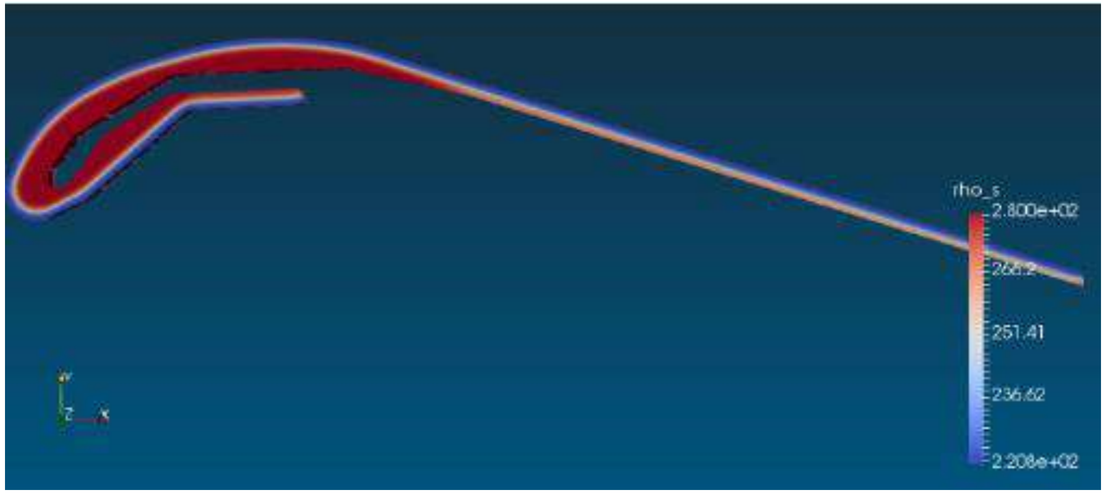


FIG 6.Density variation at t=15

As per the curves, density falls from initial density of the virgin material to a value near to the density of the char.

In FIG 8. , **with the depth the value of density rises from the value for char then after certain depth becomes constant in virgin region**.

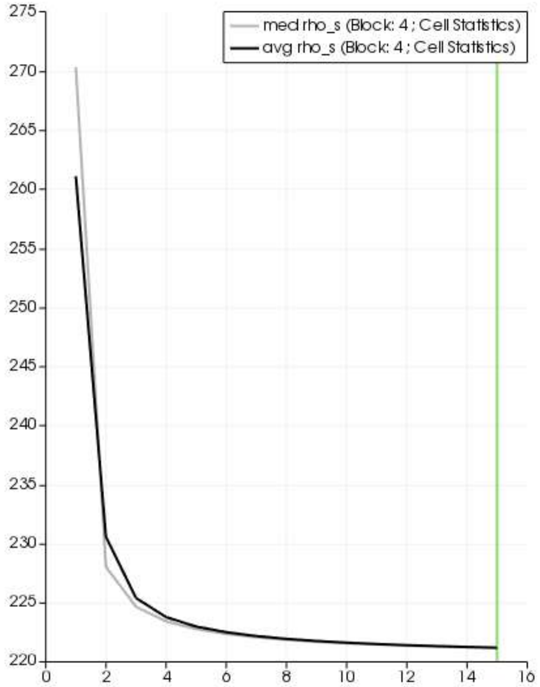


FIG 7. Time history plot for Density in throat region

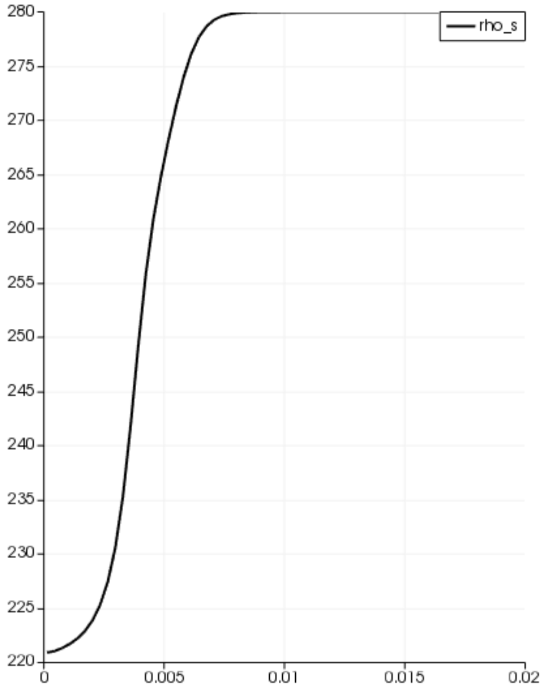


FIG 8.Variation of Temperature along depth at throat region at t=15

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.

Thank You