

Multi-phase flow effect on SRM nozzle flow field and thermal protection materials

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Abstract: Multi-phase flow effect generated from the combustion of aluminum based composite propellant was performed on the thermal protection material of solid rocket motor (SRM) nozzle. Injection of alumina (Al_2O_3) particles from 5% to 10% was tried on SRM nozzle flow field to see the influence of multiphase flow on heat transfer computations. A coupled, time resolved CFD (computational fluid dynamics) approach was adopted to solve the conjugate problem of multi-phase fluid flow and heat transfer in the solid rocket motor nozzle. The governing equations are discretized by using the finite volume method. Spalart-Allmaras (S-A) turbulence model was employed. The computation was executed on the different models selected for the analysis to validate the temperature variation in the throat inserts and baking material of SRM nozzle. Comparison for temperatures variations were also carried out at different expansion ratios of nozzle. This paper also characterized the advanced SRM nozzle composites material for their high thermo stability and their high thermo mechanical capabilities to make it more reliable simpler and lighter.

Key words: solid rocket motor nozzle; multiphase flow; thermal protection material; temperature distribution; finite volume method

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Nomenclature

$\bar{U}$	gas phase time averaged velocity in each direction
$\bar{U}$	gas phase unsteady velocity in each direction
U_i	gas phase turbulent velocity in each direction
U_p	particle phase unsteady velocity
ϕ	universal variable
Γ	transport term
S_ϕ	source term for gas phase
$S_{p\phi}$	source term for gas and particle
T	gas phase temperature
T_p	particle phase temperature
$\dot{m}_p$	particles mass flow rate
m_p	single particle mass
c_p	gas specific heat
c_{pp}	specific heat for particle
μ	gas dynamic viscosity
ρ_g	gas density

ρ_p	particle density
d_p	single particle diameter
Re_p	particle phase Reynolds number
F_x	thermophoretic force thrust
λ	gas mean free path impulse
κ	gas thermal conductivity
κ_p	particle phase thermal conductivity

Introduction

The aluminum powders are used in solid rocket motor propellant for the purpose of increasing motor specific impulse. During the combustion of aluminized propellant, high combustion energy is generated along with the aluminum particles that melt and form liquid aluminum at the burning propellant surface. Several

liquid droplets merge into large agglomerates^[1] that contain droplets and smoke particles of Al_2O_3 ; therefore the flow within the rocket is multiphase or two phases. Many combustion scientists and propulsion engineers have conducted studied aimed at determining the size distribution of the Al_2O_3 droplets present in the motor, nozzle and exhaust plume, because of the large effect on the impulse efficiency. Sabnis et al^[2] refer to Salita's^[3] quench-bomb investigations, where the size distribution was found to be log-normal and bimodal. The two phase flow representing bimodal distribution of aluminum oxide representing the smoke and the caps, which are on the order 1.5 and 100 μm in size respectively. The presence of the Al_2O_3 droplets also contributes to the conduction and convection flux regime towards the thermal insulation. So as the aluminum burns and passes through the chamber and nozzle, it significantly affects the flow field of the chamber and nozzle. So it is necessary to consider two phase or multiphase flow effect^[4] for solid rocket motor (SRM) nozzle aerodynamic and thermal design. In past gas particle two phase flow, Miura^[5] Glass, Saito^[6] studied the shock wave propagating in a dusty gas using Eulerian method, which is treated particles phase as a continuum medium. Ishii^[7] analyzed gas particles jet flow using lagrangian method, which is treated particle phase as a discrete medium and compute each particle behavior.

The thermal protection in the solid rocket motor nozzle has to fulfill multiple functions: the throat diameter^[8,13] should be unchanged throughout the whole burning period and also to ensure that case wall should not be over heated due the baking or thermal protection provided. The design of a proper thermal protection layer has to take all these requirements into account.

This paper extends our previous numerical computational fluid dynamics work on solid rocket motor^[11], to perform a comprehensive heat transfer analysis, by constructing simulation model using multiphase flow. Two different models of the solid rocket motor of 55s and 60s

durations are used. Multiphase flow effect involving 5% and 10% alumina Al_2O_3 particles has been considered. Computational calculations have been carried out for 100s and 110s respectively. Simulation is accomplished with same thermal baking protection with different throat inserts. Emphasis is placed on the temperature variation results in the thermal protection layer and its relation with baking material, thermal and structure properties for duration of SRM firing.

Results from this study also identify factors that have the most potential to improve performance and thermal properties of the underlying SRM nozzle structure material. Also that has a major impact on the thickness selection of the baking and throat inserts material.

1 Models

1.1 Mathematical model

The governing fluid dynamic equations for chemically reacting flow are describes in this section.

1.1.1 Gas phase control equations

Gas phase equation can be expressed as in universal form:

$$\frac{\partial}{\partial t}(\rho_g \phi) + \frac{\partial}{\partial x_j}(\rho v_j \phi) = \frac{\partial}{\partial x_j} \left(\Gamma \cdot \frac{\partial \phi}{\partial x_j} \right) + S_{\phi} + S_{p\phi}$$

1.1.2 Particle phase control equations

Particle momentum equation

$$\frac{dU_p}{dt} = (U - U_p)/\tau_p + \frac{F_{M,pi}}{n_p m_p} + (U - U_p)\dot{m}_p/m_p$$

Particle energy equation

$$\frac{dT_p}{dt} = [\dot{m}_p(c_p T - c_{pp} T_p) - Q_k - Q_p]/(m_p c_{pp})$$

Particle track equation

$$\frac{du_p}{dt} = F_D(\bar{U} - U' - U_p) + \frac{g_x(\rho_p - \rho)}{\rho_p} + F_x$$

$$F_D = \frac{18\mu C_D Re}{\rho_p d_p^2 24}, \quad Re_p = \frac{\rho U_p |U_p - U|}{\mu}$$

$$C_D = \frac{24}{Re_p} (1 + b_1 Re_p^{b_2}) + \frac{b_3 Re_p}{b_4 + Re_p}$$

$$b_1 = -1.6807, \quad b_2 = 0.6529,$$

$$b_3 = -0.8271, \quad b_4 = 8.8798$$

$$F_x = \frac{6\pi d_p \mu^2 C_s (K + C_i K_n)}{\rho (1 + 3C_m K_n) (1 + 2C_i K_n) m_p T_\infty} \frac{\partial T}{\partial x}$$
$$K = K_p, \quad K_n = 2\chi d_p$$
$$C_s = 1.17, \quad C_i = 2.18, \quad C_m = 1.14$$

1.1.3 Solid phase control equation

In solid region, the energy transport equation has the following form:

$$\frac{\partial}{\partial t}(\rho_s h) + \nabla \cdot (\rho_s \mathbf{u} h) = \nabla \cdot (\kappa \nabla T) + S_h$$

here S_h = volumetric heat source

1.2 Numerical method and computational approach

The computational fluid dynamics approach was used to evaluate the thermal parameters and temperature intensity which the thermal protection has to withstand during the propellant combustion of multiphase flow. The governing equations are discretized for accurate flow field time history in SRM nozzle by using the finite volume method. An implicit Navier Stokes solver which simulates two dimensional, axial symmetry, unsteady, turbulent flows of compressible fluids had been set. Second order upwind scheme has been used in the flow, and first order upwind scheme has been used on modified turbulent viscosity. Roe-FDS (flux difference splitting) schemes also has been used^[9]. For viscous model Spalart-Allmaras (S-A) scheme is employed. After combustion both single phase and multiphase flow effect has been considered as burning gas. Fig. 1 shows the configuration of SRM, with multiphase flowfield heat transfer effect on the nozzle wall.

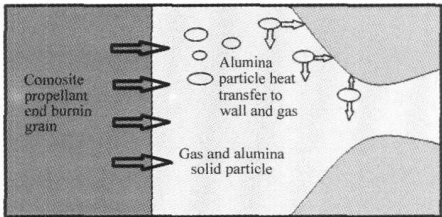


Fig 1 SRM configuration with multiphase flow

Inflow designed condition of gas pressure and temperature with zero tangential velocity components is assumed on the inlet surface of

nozzle. A pressure boundary with prescribed pressure is assumed on the outlet surface of nozzle. Heat insulation condition is assumed on the surfaces which get in touch with air. Thermal couple condition has been set on the other surface which touches different materials. For the axis, only a symmetry conditions has been applied. A no-slip condition is also imposed on the boundary portion representing the thermal protection together.

The internal flow in the analyzed motors has been investigated by Fluent 6.3, and the mesh has been generated by Gambit 2.2. The grid points are equally spaced in each direction within the SRM nozzle. The number and spacing of the grid points used defines the accuracy and resolution of the local variations of flow variables in the axial and transverse directions.

1.2.1 Model descriptions

The combustion gas parameters and SRM nozzle materials being used are listed in Table 1 and Table 2.

2 Computational results

The CFD approach has been employed to predict the temperature distribution inside thermal protection layer material of SRM nozzle when subjected heat fluxes of multiphase flow having Al_2O_3 particles in it. Analysis has been carried out on the configuration used for SRM model 1 with copper sintered tungsten (W-7Cu) throat insert, and model 2 with carbon-carbon composite material. The end burning grain configuration with composite propellant has been used in both the models. Basic models detail with grid generation has been shown in Fig 2 and Fig 3. The numerical scheme is implemented to investigate the evolution of the temperature disturbances causes due to the instantaneous heat transfer at the inner surface of the SRM nozzle throat insert surface that varies significantly with time. The basic variables those are influencing the overall field is discussed in detail as follows.

Table 1 Combustion gas parameter

SRM model	Working time t/s	Computational time t_c/s	Temperature at inlet surface T_i/K	Combustion chamber pressure p_c/MPa	Specific heat capacity $c_{pg}/(\text{J}/(\text{kg}\cdot\text{K}))$	Gas constant R
Model 1	55	100	2856	1.25	1690	316
Model 2	60	110	2940	5		

Table 2 Materials parameter

	Structure	Thermal conductivity $\kappa/(\text{W}/(\text{m}\cdot\text{K}))$	Density $\rho/(\text{kg}/\text{m}^3)$	Specific heat capacity $c_p/(\text{J}/(\text{kg}\cdot\text{K}))$
Throat insert	Model 1	W-7Cu	140	17100
	Model 2	C/C	2.09	1360
Baking	Model 1	High Silica	1.63	1700
	Model 2	Phenolic		1741.7
Case	Model 1	30CrMnSiA	54	7833
	Model 2			464.7

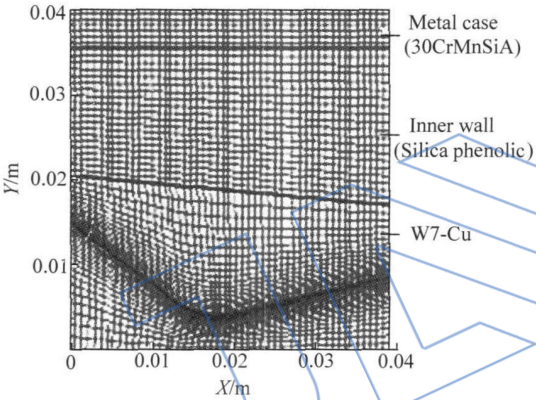


Fig. 2 Computational grid for SRM model-1

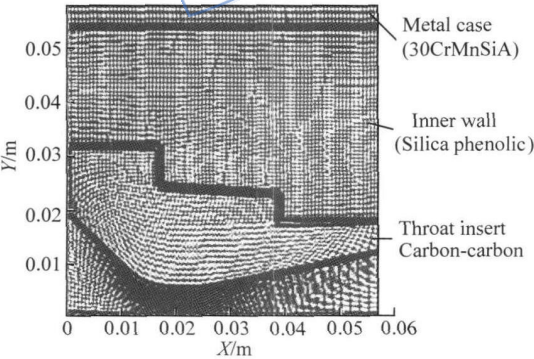
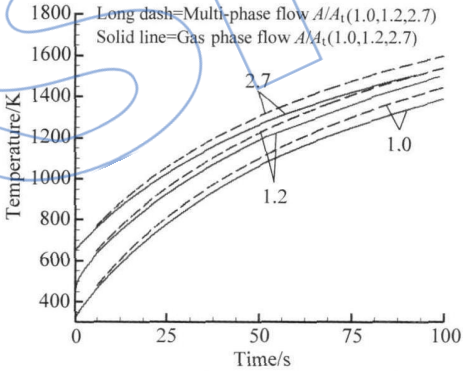
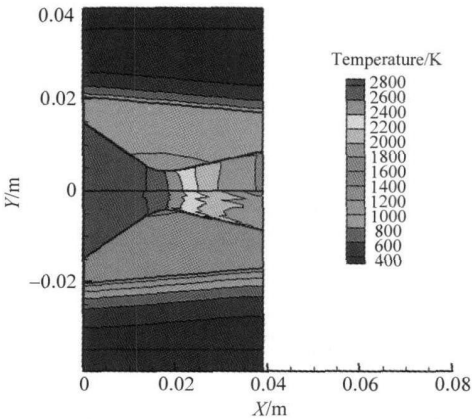


Fig. 3 Computational grid for SRM model-2 multiphase flow effect on SRM nozzle

Fig. 4 and Fig. 5 respectively. Fig. 4(a) and (b) shows the computational results, where the



(a) Inner wall temperature comparison



(b) Overall temperature comparison at $t=60\text{ s}$

2.1 Multiphase flow effect on SRM nozzle

The time history of wall temperature gradient at the throat and divergent section of nozzle in SRM model-1 and model-2 is presented in

effect of gas flow field and multiphase flow including particles of Al_2O_3 is considered. Comparing temperature curve history at different nozzle

expansion ratio, relatively large temperature rise is observed with multiphase flow. Fig 4 (b) shows temperature comparison at 60s time.

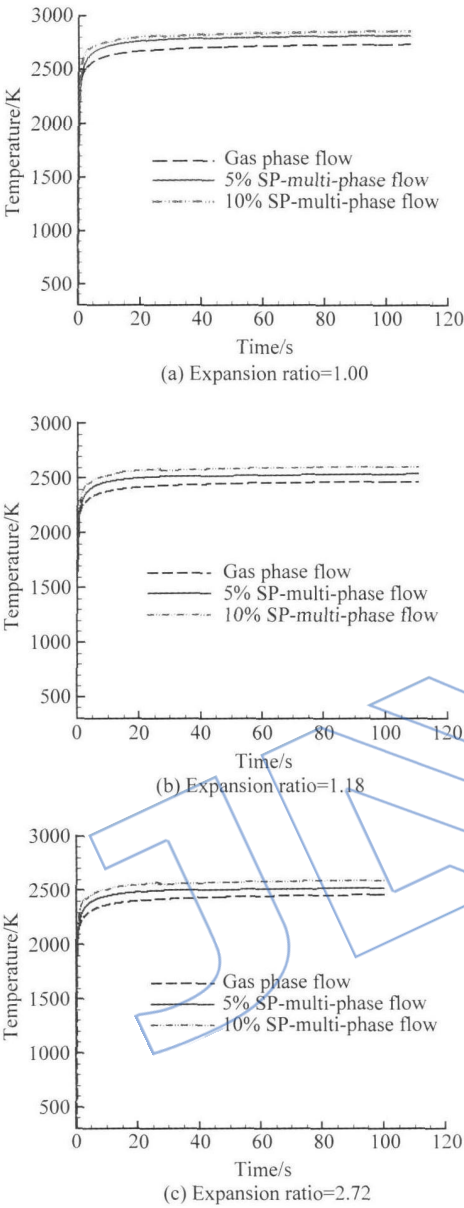


Fig 5 Model 2 inner wall temperature curve

On the other hand we also examined the influence of gas and multi-phase differences on model-2 having a carborr carbon composite material as nozzle insert, results are shown in the Fig 5(a), (b) , (c) for different SRM nozzle expansion ratios. There is an obvious difference between the results. The temperature at the throat insert and divergent sections are in increases with time as per ideal law. However in Fig 4

a lot of thermal heat is transferred into baking and case materials, so the internal wall temperature gradient is lower than model-2. The internal wall temperature gradient in model-2 is very high and nearly constant that it attains in almost first few sec.

In each of the Fig 5, influence of solid particles with 5% and 10% of alumina (Al_2O_3) in the flow field is observed at different expansion ratios of SRM nozzle. Comparing the results it is obvious that temperature intensity is raising by increasing solid particles (Al_2O_3). The temperature rise is from 4.0% to 4.32%. These differences are caused by the gas-mist interaction, which is kinetic and thermal energy exchange. It is supposed that more mass loading ratio of alumina at the inflow condition causes more difference in the temperature change.

2.2 Thermal effect of multiphase flow on SRM nozzle material

The temperature variation at the internal wall and axis of the nozzle in model-1 and model-2 till ending time are presented in Fig 6(a) and (b). The internal wall temperature in model-1 gets little increase at the convergence section when approaching towards the nozzle throat and the temperature at the axis starts reducing at the throat section and continues till exit as shown in Fig 6(a). This variation of temperature is very much different in model-2, as show in Fig 6(b). It is due to the copper sintered tungsten (W-7Cu) material, which has a large thermal conductivity and a small specific heat capacity that transfer most of thermal heat to the materials at the back of throat insert, therefore the temperature gradient is lower than the one in axis.

The time history of temperature gradient in different material layers is presented in Fig 7(a) and (b). The same baking and case material with different throat inserts are being used in both the models. The thermal property of copper sintered tungsten (W-7Cu) and carborr carbon composite C/C are very much different as shown in Table 2. All of the temperatures in model-1 are higher than the temperature in mod-

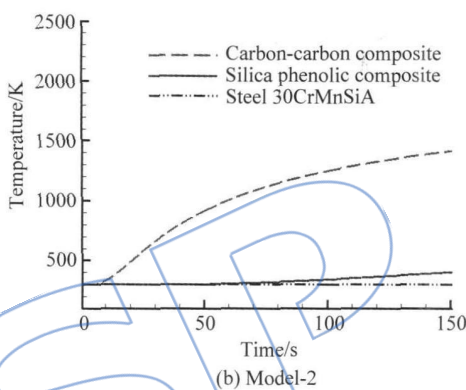
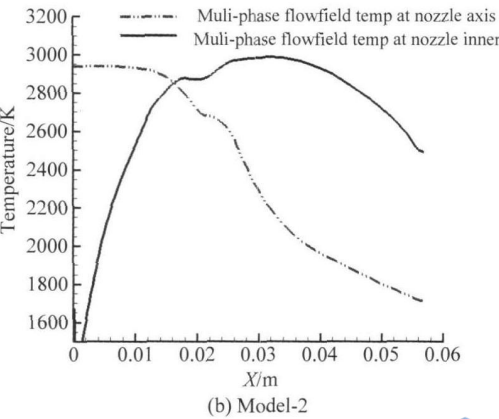
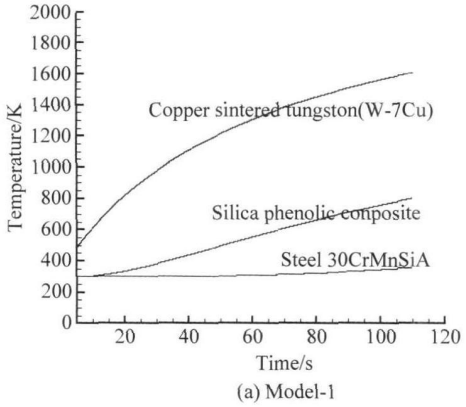
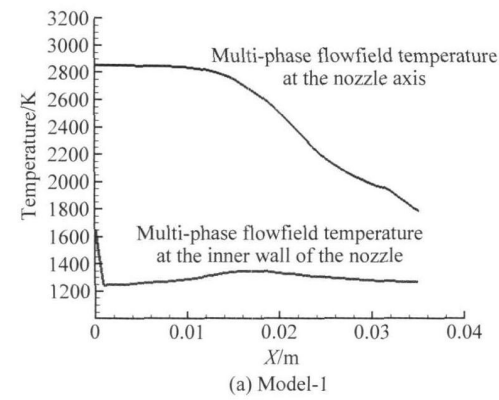


Fig. 7 Temperature curve at different material layers

Fig. 6 Inner wall and axial temperature curve

Model-2 Especially the baking temperature in model-1 at ending time is nearly 600 K, and the same one in model-2 is nearly 360 K. It is shown that the motor which adopt the copper sintered tungsten (W-7Cu) as throat insert need a better thermal protection in baking layer and case layer, keeping it more safe for all the installed instruments and components in the tail section and especially near the motor nozzle.

The temperature change with time at radial positions of nozzle throat for both the models are presented in Fig. 8 (a) and (b). The temperature gets increase with passage of time. The curve of Fig. 8 (a) could be split into 3 parts; each part is representing one material. The horizontal line in the first part shows the temperature change in W-7Cu, which is due to the thermal property of W-7Cu as temperature is nearly constant with the time. The temperature gradient decreases more in the second part, which shows the material layer is high silica/phenolic. High silica phenolic is a material which also has

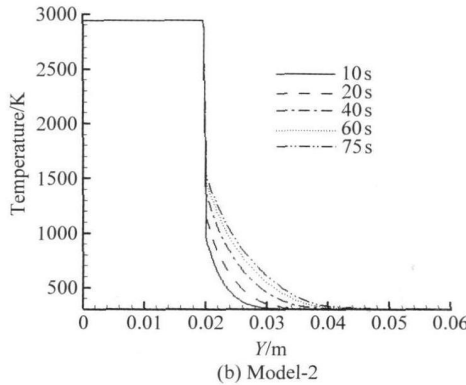
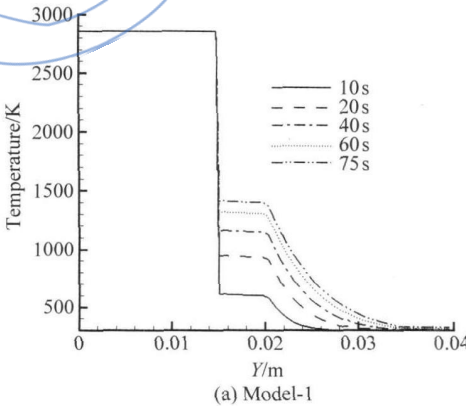


Fig. 8 Radial temperature curve with time at nozzle throat

a large specific heat capacity and a small thermal conductivity, so a large temperature change is shown in second part. The last line, a horizontal line, is the third part which shows the temperature change in case. The material in case is steel 30CrMnSiA which has a nearly same thermal property as of W-7Cu. So the case temperature is nearly constant.

3 Conclusion

A coupled heat transfer and multiphase flow field problem for SRM nozzle thermal protection layer has been solved. The fluid dynamics analysis has been simulated by considering injections of 5% and 10% alumina (Al_2O_3) particles in the mass flow rate. These promising results provided wide variety of investigations for future study and its application for thermal protection design work. Therefore a number of clear conclusions with far-reaching implications become apparent from the results of these studies. The most important of these are:

1) As the mass loading ratio of alumina (Al_2O_3) particles is relatively increasing, the heat flux intensity at the nozzle surface raises by exchanging the thermal and kinetic energy between gas and alumina (Al_2O_3) particles. So therefore during thermal design of SRM nozzle, the effect of (Al_2O_3) particles should be incorporated.

2) The thermal properties of the structure material can have a great effect on the thermal performance. The heat capacity of the structural material, which includes both the specific heat and temperature limit, should be as high as possible. Like carbon/carbon composite throat inserts required significantly less thermal baking material as compared with copper sintered tungsten (W-7Cu).

3) Results from this study also identify most potential factors those are required to improve thermal material performance. The thermal properties of the throat inserts and baking material underlying the SRM nozzle were found

to have a major impact on the thickness and mass of material required to protect the structure, leading to the conclusion that the throat and baking structure should be designed concurrently. These results provide a basis for guiding the direction of future research in metallic thermal properties and throat inserts structure.

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