Effects of Al_2O_3 Particle on Convective and Radiative Heat Flux to Rocket Base Surface

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Abstract: An exhausted plume of rocket transfers a lot of heat to rocket base surface. The effects of Al_2O_3 particles and radiation heat transfer of plume are considered to study the heat flux to the base surface. Non-equilibrium 2D-axisymmetric Navier-Stokes equation with kω-SST turbulent model is solved in the numerical analysis. As a radiation heat transfer model, P-1 radiation model is employed

Keywords: Heat Flux, P-1 Radiation Model, Rocket Base Surface, Plume, Al2O3 particle

1 Introduction

The plume which is exhausted from the launch vehicle is high temperature and complex mixture gas. It passes through near the base surface since the flow of the plume under-expands as the flight altitude increases. Therefore, a large amount of heat transfers to the base surface of the vehicle. It is difficult to simulate the plume flow accurately and estimate the rate of heat transfer since the plume flow shows complex phenomena including a shear layer, a plume induced shock and separation, etc. Moreover, In the case of solid propellants Al_2O_3 particles are included in the plume as products of combustion of aluminum. These particles affect the distribution of temperature of the plume and the rate of heat transfer.

Many related researches have been performed by various researchers. Ebrahimi et al. point out a consideration of the turbulent flow, finite-rate chemistry for accurate simulations [1]. Rao et al. analyze influences of turbulent model on plume. Change of turbulent energy causes a few hundred degrees of temperature differences in the shear layer when a two-equation turbulent model is used [2]. As an consideration of non-equilibrium flow effect, Hall et al. compare the four different model, perfect gas, “equivalent” species that is calorically perfect, “equivalent” species that is calorically imperfect and multi-species model with finite-rate chemistry [3]. Burt and Boyd carry out the simulation of flow including Al_2O_3 particles by using direct simulation Monte Carlo (DSMC) method. In the simulation, particle temperature is higher than that of gaseous mixture. And the increase in particle size leads to the increase in the temperature of particle because of difference of heat capacity [4]. According to studies mentioned above, turbulent flow, chemically non-equilibrium flow and gas-particle two phase flows should be considered for accurate simulations of the plume. Also, an accurate estimation of the heat flux to the base surface requires radiative heat flux as well as convective heat flux.

The objective of this paper is to simulate the base flow with plume and estimate the heat flux to the base surface accurately. Therefore, the simple particle model and the P-1 radiation model are adopted. And consequently influences of the particle size and the flight altitude on the heat flux are investigated.

2 Problem Statement

In the present study a) 2D-axisymmetric non-equilibrium flow, b) kw-SST turbulent flow, c) Al_2O_3 particle model, d) P-1 radiation model are considered. The AUSMPW+ scheme [12] is used for spatial discretization and 3th order Multi-dimensional Limiting Process (MLP3) [13] is used as a limiter. LU-SGS scheme is used for time integration.

A. Governing equation

Two dimensional axisymmetric Navier-Stokes equation that include species equations is expressed in Eq. (1) as a vector form

$$\frac{\partial Q}{\partial t}+\frac{\partial E}{\partial x}+\frac{\partial F}{\partial y}+H=\frac{\partial E_v}{\partial x}+\frac{\partial F_v}{\partial y}+H_v-S_p \tag{1}$$

where

$$Q=\left(\rho,\rho u,\rho v,\rho e_t,\rho_i\right)^T \tag{2}$$

We considered CO, CO2, CL, CL2, H, H2, H2O, HCL, N2, O, OH, and O2 as plume speciese. [2] Also 8 reaction model were used as a chemical reaction model in the Evans and Schexnayder hydrogen-air model.

B. Turbulent Model

In this study kω-SST turbulent model is used since it show good results in sensitivity test and goodness test at mixing layer and round jet which are important parameters in calculating the exhausted plume . The kω-SST turbulent model adopts blending function, so this model utilizes the k-ω model in the boundary layer region and switches to the k-ε model in the outer region and free shear flow .

C. Al2O3 Particle Model

Governing equations of Al_2O_3 particles are written in Equations. (3 - (5). Subscript *p* means particle.

$$\frac{\partial \rho_p}{\partial t}+\frac{\partial \rho_p u_p}{\partial x}+\frac{\partial \rho_p v_p}{\partial y}+\frac{\rho_p v_p}{y}=0 \tag{3}$$

$$\rho_p\frac{D\vec{V}_p}{Dt}=\frac{\pi D_p^2\rho C_D}{8m_p}\rho_p\left|\vec{V}-\vec{V}_p\right|\left(\vec{V}-\vec{V}_p\right) \tag{4}$$

$$\rho_p\frac{DH_p}{Dt}=\frac{Nu_p\pi k D_p\left(T-T_p\right)}{m_p} \tag{5}$$

where H is an enthalpy, D_p is a diameter of particle and m_p is a mass of one particle. In this study m_p is $4004.8\times\left(\frac{1}{6}\pi D_p^3\right)$. Drag coefficient C_D and Nusselt number Nu_p proposed by Hwang [9] are employed in this study.

D. P-1 Radiation Model

For plume radiation, we employed P-1 radiation model which approximates the equation of radiative transfer. P-1 model can be calculated by the finite volume method, thus it has an advantage in CFD.

Equation (6) are the transport equations about incident radiation G.

$$\nabla(\Gamma\nabla G) - \kappa G + 4\kappa\sigma T^4 = 0 \qquad \Gamma = \frac{1}{3(\kappa + \sigma_s) - C\sigma_s} \tag{6}$$

We calculated the incident radiation G, after that radiative heat fluex obtained through eq.(7).

$$\nabla q_{rad} = \kappa(-G + 4\kappa\sigma T^4) \tag{7}$$

3 Conclusion and Future Work

The effects of Al_2O_3 Particle on convective and radiative heat flux to rocket base Surface are studied. Simple particle equation is introduced and P-1 radiation model is adopted. The comparison between P-1 radiation model and discrete ordinate method would be carried out.

References

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