

Investigation on plume interference effect of solid propellant micro-thruster

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Abstract: The three-dimensional numerical simulation of two-phase plume flow of solid propellant micro-thrusters was developed. Then it was used to investigate the plume interference effect by combining the direct simulation Monte Carlo (DSMC) method for multi-component gas flow with the two-way coupling model for two-phase rarefied flow. At different space between the two micro-thrusters and different wall temperature, the plume interference effect was analyzed specifically. The results show that under the plume interference effect the gas is compressed and the flow direction is changed, which resulted in the increasing of gas pressure and temperature; solid phase made no significant effect on the flow parameters of gas phase; with the rising of the space between the two micro-thrusters, the maximum pressure decreased and the maximum temperature increased in the domain under the plume interference effect; the wall temperature could influence the temperature of the gas which is extremely close to the wall, but not the gas pressure.

Key words: solid propellant micro-thruster; plume interference effect; two-phase plume flow; direct simulation Monte Carlo (DSMC) method; two-way coupling model

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Solid propellant micro-thruster is a subminiature solid rocket motor, which has a range of thrusts from a few micronewtons to several hundred millinewtons and is usually applied in accurate pointing and altitude control of miniature satellite. Over the past several years, lots of research have been focused on this field around the world^[1-6]. Because the manufacture of solid propellant micro-thruster mainly depends on micro-electromechanical systems (MEMS) technology, micro-thrusters always appear in the form of an array. And two or more micro-thrusters are acquired to ignite simultaneously in order to achieve a special mission, so the plume interference effect will occur at the same time. Research on plume interference effect could support us to understand the plume erosion and plume adherence to the wall of micro-thrusters and provide some scientific ideas for the design of the array of micro-thrusters.

The plume of micro-thruster is a typical micro-scale rarefied flow, which always contains a few solid particles. There are few reports on experimental research in this field around the world and even on numerical simulation. In the correlative field, HUANG, et al^[7] investigated the plume interference effect of attitude-control thruster. And the results show the plume interference effect could not be neglected. Moreover the values of physical quantities in plume interference field could not be calculated by the simple addition of the values obtained from a normal plume field.

This paper presents a three-dimensional numerical simulation of micro-thrusters' plume in which direct simulation Monte Carlo (DSMC) method for multi-component gas flow is combined with the two-way coupling model for two-phase rarefied flow. At different space between the two micro-thrusters and different wall tem-

perature, the plume interference effect is studied.

1 Numerical methods

1.1 DSMC method for multi-component rarefied gas flow

DSMC method proposed by Bird^[8] is a well-established method for obtaining solutions of Boltzmann equation, which has been successfully developed to simulate rarefied gas flow. In DSMC method for multi-component rarefied gas flow, movements and collisions of the computational molecules of each gas component must be taken into account. In the part of collision simulation, in addition of collision simulation for the same kind of computational gas molecules, the collision simulation for the different kind of computational gas molecules should also be considered, which is governed by the Boltzmann equation of gas mixture.

1.2 Description for particle movement

Just as the process of simulating the computational gas molecules in DSMC method, the properties of particles should also be characterized by its mass, diameter, position, velocity and internal energy. However, unlike the simulation of gas molecules, the changes of velocity and internal energy of particles are principally depended on collision between particles and surrounding gas molecules rather than the collision between particles^[9].

1.3 Two-way coupling model for gas-solid two-phase rarefied flow

In the rarefied flow, the force and heat flux between gas molecules and particles are determined from the rates of delivery and removal of momentum and energy by incident molecules, specularly reflected molecules, isothermally reflects molecules and adiabatically reflected molecules, respectively. On the other hand, the force and heat flux exerts by surrounding gas molecules on each particle could be calculated as the sum over individual force and heat flux contributions of all surrounding molecules in the same cell. Base on the above theory, the force

and heat flux to a particle due to the presence of a single computational gas molecule in the same cell is showed in Eq. (1) and Eq. (2)^[10].

$$F = c \frac{m F_{\text{num}}}{V_{\text{cell}}} \left\{ \left[1 + \frac{4}{9} \alpha_m (1 - \alpha_t) \right] g + \alpha_m \alpha_t \frac{\sqrt{\pi}}{3} \sqrt{\frac{2kT_p}{m}} \right\} \quad (1)$$

$$Q = \frac{\alpha_m F_{\text{num}} g}{V_{\text{cell}}} \left[\alpha_t \left[\frac{1}{2} m g^2 - 2kT_p \right] + \alpha_r \left[E_{\text{rot}} - \frac{\zeta_{\text{rot}}}{2} kT_p \right] + \alpha_v E_{\text{vib}} \right] \quad (2)$$

Here m is the mass of a actual gas molecule, F_{num} is the number of actual gas molecules represented by the computational molecule, c is the relative velocity of the gas molecule with respect to the particle, V_{cell} is the cell volume, $g = |c|$, T_p is the particle temperature, ζ_{rot} is the number of rotational degrees of freedom, α_m is the momentum accommodation coefficient, α_t is the translational energy accommodation coefficient, α_r is the rotational energy accommodation coefficient, α_v is the vibrational energy accommodation coefficient, E_{rot} is the molecular rotational energy, E_{vib} is the molecular vibrational energy.

The effect on the molecule exerts by the particle embodied in the change of velocity vector after a collision. This effect could be explained by the principle of phenomenology. The number n_s of computational gas molecules that are selected as potential collision partners for particles is showed in Eq. (3)^[11-12].

$$n_s = N_p n_g \pi R_p^2 c_{r\text{max}} \Delta t / V_{\text{cell}} \quad (3)$$

Here N_p is the number of actual solid particles represented by the computational particle, n_g is the number of computational gas molecules in the same grid cell, $c_{r\text{max}}$ is the maximum pre-collision relative velocity.

After the collision between a computational gas molecule and a computational particle, the post-collision relative speed could be written as Eq. (4) ~ Eq. (6).

$$u_r^* = \frac{c_r^*}{c_r} [-u_r \cos \delta + \sin \delta \sin \epsilon (\mathcal{U}_r^2 + \mathcal{W}_r^2)^{1/2}] \quad (4)$$

$$u_r^* = \frac{c_r^*}{c_r} \left[-v_r \cos \delta / (v_r^2 + w_r^2)^{1/2} + \sin \delta (c_r v_r \cos \epsilon - u_r v_r \sin \epsilon) / (v_r^2 + w_r^2)^{1/2} \right] \quad (5)$$

$$w_r^* = \frac{c_r^*}{c_r} \left[-w_r \cos \delta / (v_r^2 + w_r^2)^{1/2} - \sin \delta (c_r v_r \cos \epsilon + u_r w_r \sin \epsilon) / (v_r^2 + w_r^2)^{1/2} \right] \quad (6)$$

Here u_r , v_r and w_r are the relative velocity component before a collision, δ is the deflection angle and could be closely approximated by the following polynomial,

$$f(\delta) = 0.02042 \delta^6 - 0.2515 \delta^5 + 1.104 \delta^4 - 1.903 \delta^3 + 0.4938 \delta^2 + 1.248 \delta$$

ϵ is direction angle of a reflection velocity vector and subjected to an uniform distribution in the range of 0 to 2π , c_r and c_r^* are the pre-collision relative velocity and the post-collision relative velocity respectively, c_r^* could be sampled by applying the acceptance-rejection method from the distribution function of

$$f(c_r^*) = 2\beta^4 c_r^{*3} \exp(-\beta^2 c_r^{*2}),$$

$$\beta = [m/(2k_B T_p)]^{1/2}.$$

2 Computational conditions

The micro-nozzle's cross section is square and the side length at the exit is 6.0×10^{-4} m. The parameters of gas phase and solid phase at the entrance are obtained by solving the Navier-Stokes (N-S) equations of internal flow field. The gas in this simulation is a mixture of CO, H₂ and CO₂, with a molar ratio of 0.5 : 0.3 : 0.2. The solid phase is spherical alumina particles, of diameter 1.0×10^{-6} m, with a mass flow rate of 2.5×10^{-1} kg/(s · m²). The particle material density is 3970 kg/m³, with a specific heat of 765 J/(kg · K). The computational domain is showed in Fig. 1. The side A₁D₁H₁E₁ is the entrance of flow and the rest of domain in side ADHE is the wall with the boundary type of diffuse reflection. The side ABFE and EFGH are symmetric plane. The others are absorption boundary. In the calculation, the wall boundary is assigned a temperature of 373 K, the space between the nozzles is 1.0×10^{-3} m, and the colli-

sions within the gas phase are considered using the variable hard sphere model.

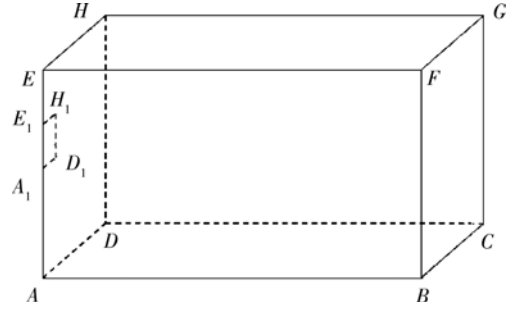


Fig. 1 Schematic drawing of the computational domain

3 Results and discussion

3.1 Distributions of plume parameters

The distributions of x -velocity component, pressure and temperature in gas phase are showed in Fig. 2~Fig. 4 respectively. In the domain under the plume interference effect, the plume did not expand sufficiently and the direction of gas flow had an obvious change, as showed in Fig. 2. Also the gas pressure and temperature in this domain increased obviously because the gas is compressed to a certain extent and the molecular chaos went up due to the violent collision of the two gas flows, as showed in Fig. 3 and Fig. 4 respectively. The plume interference effect of micro-thrusters mainly appeared in the domain which is between the two micro-nozzles with a distance of 0.003 mm away from the wall, and the gas near the wall had a high temperature.

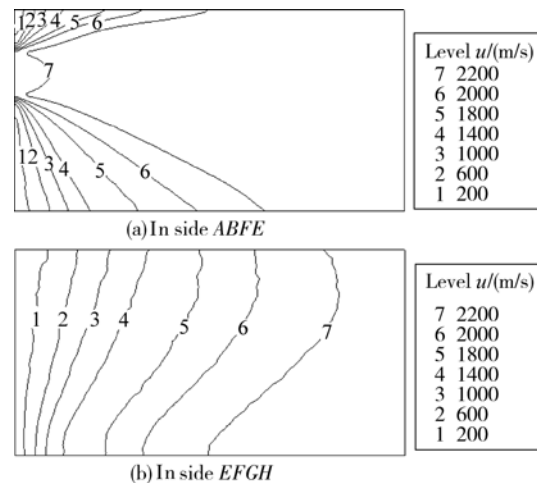


Fig. 2 x -velocity component contours of gas phase

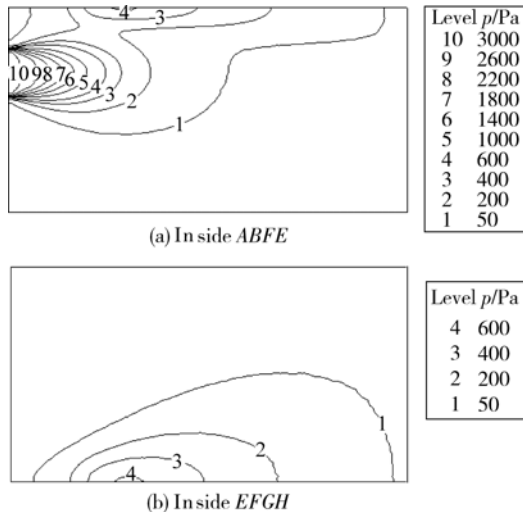


Fig. 3 Pressure contours of gas phase

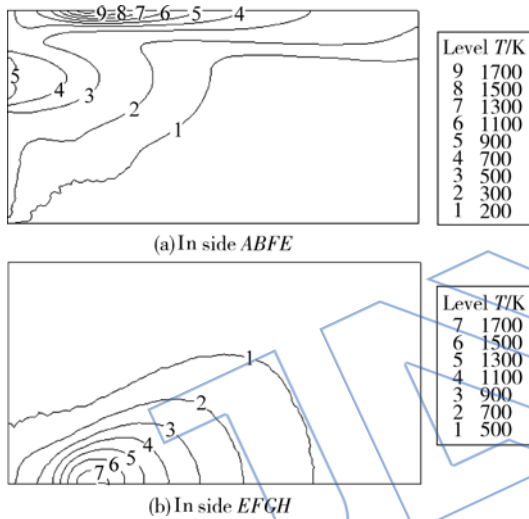


Fig. 4 Temperature contours of gas phase

The distributions of solid temperature and x -velocity component are showed in Fig. 5. There is no significant effect to gas phase due to a small amount of solid phase in the plume field. And the degree of the effect to solid phase exerted by gas phase gradually weakened with the decreasing of gas density because of the rapid expansion of gas. The transmission of momentum and energy between gas phase and solid phase result in the increasing of solid speed and the decreasing of solid temperature along the flow direction.

3.2 Plume interference effect at different space between the two micro-thrusters

The distributions of gas pressure and temperature along line EF at different space between the two micro-thrusters are showed in

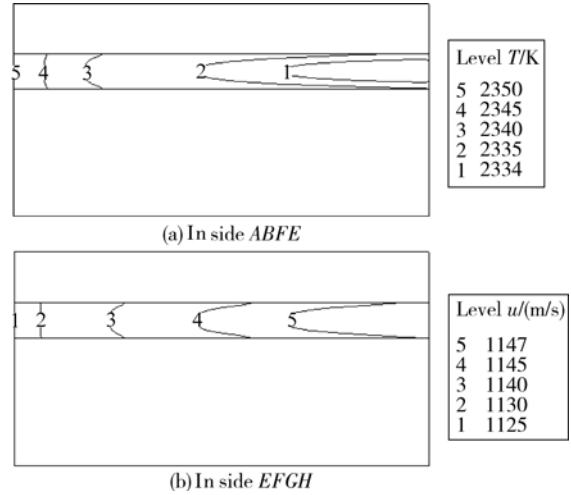
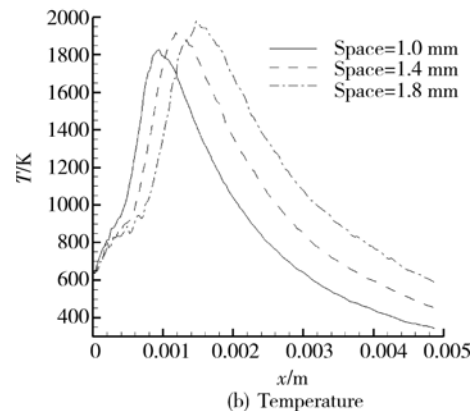
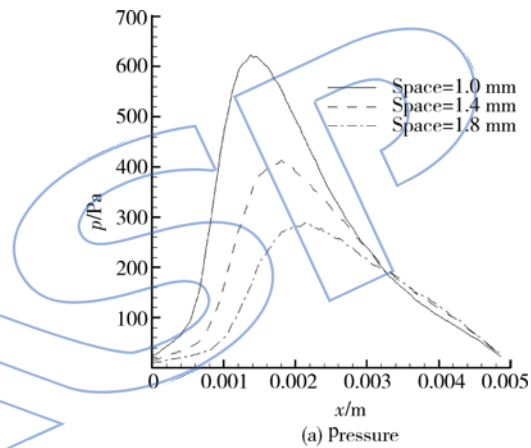
Fig. 5 Temperature and x -velocity component contours of solid phase

Fig. 6 Distributions of gas pressure and temperature along line EF

Fig. 6(a) and Fig. 6(b). With the increasing of the space, the molecular number of gas phase in the domain under the plume interference effect decreased, which resulted in the decreasing of maximum pressure along line EF. Because the decline of molecular number in this domain intensified the degree of molecular chaos, the

maximum temperature along line EF increased. Moreover, the domain under the plume interference effect shifted outward with the increasing of the space.

3.3 Plume interference effect at different wall temperature

The distributions of gas pressure and temperature along line EF at different wall temperature are showed in Fig. 7(a) and Fig. 7(b). The wall temperature does not effect the distribution of gas pressure along line EF , as showed in Fig. 7(a). But because of the low pressure and low molecular number density near the wall ($x < 0.0005\text{ m}$), the high wall temperature could easily make the gas temperature increase in this domain, as showed in Fig. 7 (b).

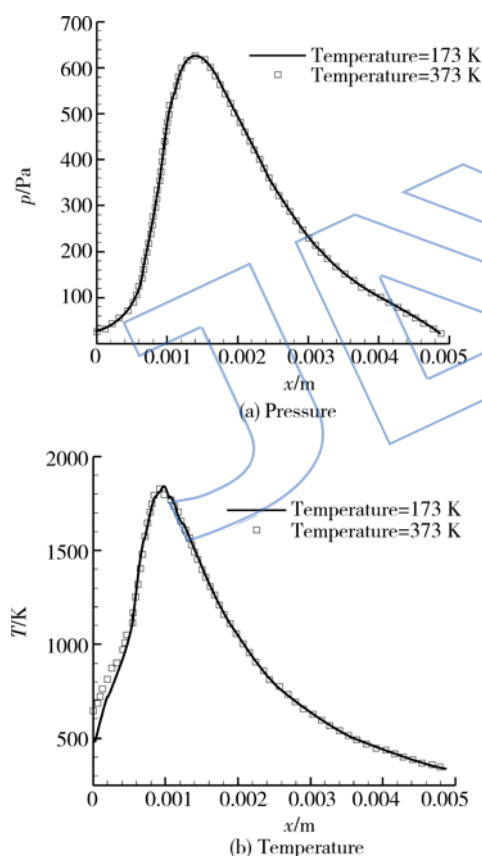


Fig. 7 Distributions of gas pressure and temperature along line EF

4 Conclusions

The plume interference effect could greatly influence the gas pressure and temperature and make them increase. The transmission of momentum and energy between gas phase and solid

phase resulted in a major change in solid temperature and x -velocity component, but no such influence on gas phase. With the increasing of the space between the two micro-thrusters, the maximum pressure decreases and the maximum temperature increases in the domain under the plume interference effect. The wall temperature does not effect the distribution of gas pressure in the domain under the plume interference effect, but it could partly increase the gas temperature near the wall.

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