Three-Dimensional Simulation of Ion Thruster Plume-spacecraft Interaction Using EX-PWS

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Abstract: The plume-spacecraft interactions of a 40 mN ion thruster are simulated by a three-dimensional hybrid PIC-DSMC method. A satellite scale model is established in this paper to simulate the impingement effects of thruster plume on the solar arrays. The plume-spacecraft interactions are analyzed in different relative positions. The results show that the charge exchange xenon ion density in the vicinity of solar array reaches the order of $10^{11}\ \mathrm{m}^{-3}$. And the magnitude of this additional force caused by the plume impact is $9.3\times10^{-4}\,\mathrm{mN}$ when the accommodation coefficient is 0.9 and the angle of the solar panel is 90 deg.

Nomenclature

n_e	=	number density of electron
n_{ref}	=	reference number density
ϕ	=	plasma potential
T_e	=	electron temperature
k	=	Boltzmann constant
t	=	time step
w_p	=	particle weight
p	=	momentum

I.Introduction

The electric propulsion thrusters have the advantages of higher specific impulse, longer lifetime and higher control precision. Thrusters convert electrical energy into the kinetic energy of the propellant. However, the impact of these high-energy particles on spacecraft surfaces will produce extra torque that affects the operating state of the spacecraft in orbit. The heat exchange generated by the collision of beam high-energy ions and spacecraft surface results in the change of the relevant characteristics of surface material.

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Many researchers have carried out experimental and simulation research on the influence of electric propulsion plume on spacecraft. Because in-orbit experiments are too expensive, most of the work focuses on numerical simulations. Manzella et al. [1] conducted on-board experimental data analysis of the Hall thruster plume on the Russian Express satellite. Korsun et al. [2] used a self-similar model approach to analyze the interaction of plasma plumes with spacecraft. Wang et al.[3] simulated the interaction between NSTAR ion thruster plume and the DAWN spacecraft. Corey et al. [4, 5] used the Maxwell model to analyze the pressure of the Hall thruster plume, indicating that the momentum transfer prediction is less than the flight data.

In this paper, we present the influence of plume-spacecraft interaction between a 40 mN ion thruster plume and a spacecraft model. The simulation cases are calculated by the Extension of Plume Work Station (EX-PWS) software.

II.Numerical Modeling

A. The EX-PWS software

The EX-PWS is a hybrid particle-fluid software package based on unstructured meshes, which employs the Particle-In-Cell (PIC) method and the direct simulation Monte Carlo (DSMC) method to model the plasma flow in three-dimensional plasma environments. The plume flow is assumed to be quasi-neutrality[6], which makes it feasible to represent the electron density by ion density. EX-PWS treats the electrons as fluid instead of computed particles to reduce computational load. Moreover, according to the isothermal, un-magnetized, collisionless flow assumption, and ideal gas law, the electron model is then shown as the Boltzmann relation[7]:

$$n_e = n_{ref} \exp\left(\frac{\phi}{kT_e}\right) \quad (1)$$

The PIC method is used to accelerate ions and solve the self-generated electric fields. The DSMC method is used to simulate the collisions between particles. The momentum exchange collision (MEX) and charge exchange collision (CEX) are included in EX-PWS, the cross-sections used in this study are the same as those in Ref. [8].

$$\mathrm{Xe}(p_1) + \mathrm{Xe}(p_2) \xrightarrow{\mathrm{MEX}} \mathrm{Xe}(p_1') + \mathrm{Xe}(p_2') \quad (2)$$

$$\mathrm{Xe}^{+}(p_1) + \mathrm{Xe}(p_2) \xrightarrow{\mathrm{MEX}} \mathrm{Xe}^{+}(p_1') + \mathrm{Xe}(p_2') \quad (3)$$

$$\mathrm{Xe}^{2+}(p_1) + \mathrm{Xe}(p_2) \xrightarrow{\mathrm{MEX}} \mathrm{Xe}^{2+}(p_1') + \mathrm{Xe}(p_2') \quad (4)$$

$$\mathrm{CEX}^{+}(p_1) + \mathrm{Xe}(p_2) \xrightarrow{\mathrm{CEX}} \mathrm{CEX}^{+}(p_1') + \mathrm{Xe}(p_2') \quad (5)$$

$$\mathrm{Xe}^{+}_{fast}(p_1) + \mathrm{Xe}_{slow}(p_2) \xrightarrow{\mathrm{CEX}} \mathrm{Xe}_{fast}(p_1) + \mathrm{CEX}^{+}_{slow}(p_2) \quad (6)$$

$$\mathrm{Xe}^{2+}_{fast}(p_1) + \mathrm{Xe}_{slow}(p_2) \xrightarrow{\mathrm{CEX}} \mathrm{Xe}_{fast}(p_1) + \mathrm{CEX}^{2+}_{slow}(p_2) \quad (7)$$

EX-PWS is based on unstructured grids, which allows the software to simulate the plasma plume flow field in complex space environments. The simulation cases of force effect, sputtering effect, and multi-thruster plumes have been described in detail in Ref. [8-10]. Furthermore, EX-PWS uses the Massage Passing Interface (MPI) method for parallel computing. In the following work, we will consider the improvement of computing speed and efficiency.

B. Comparison with the experimental data

In order to verify the validity of the numerical method, we firstly established a small-scale flow field calculation grid with a length of 2 m and a diameter of 2 m. The experiments were performed in the Plume effects Experimental System(PES) [11] of Beihang university under the background pressure of 1.2 mPa. The simulation conditions and the parameters of the thruster have been introduced in detail in Ref.[9]. The simulation results of radial ion current density along the radius of 400 mm and 500 mm are shown in Fig. 2. These results are in good agreements with the experimental data measured by Faraday probes from -20 to 20 degrees[8].

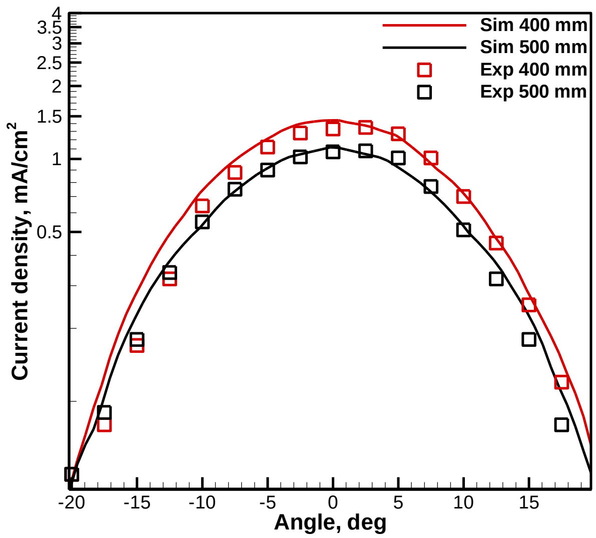

Figure 1. Current density comparison of simulation results from EX-PWS and experimental data.

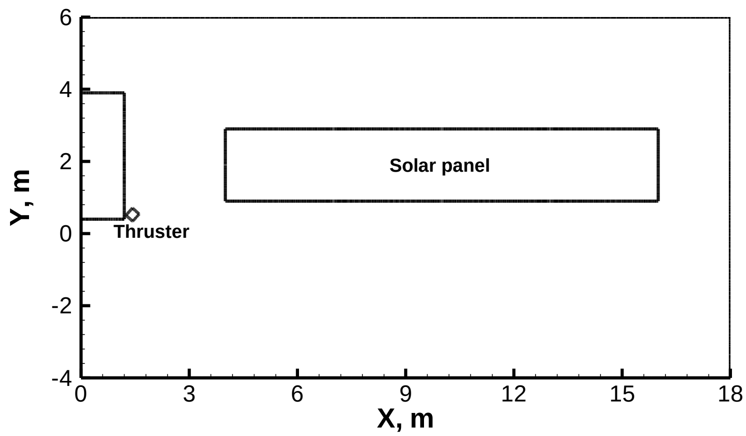

Figure 2. Computational domain.

C. Computational domain

A satellite scale grid is established in this paper to simulate the plume effects on the solar panel. The size of the computational domain is $18\ \mathrm{m} \times 10\ \mathrm{m} \times 3.2\ \mathrm{m}$, and the grid is shown in Fig. 2. The coordinate of the ion thruster is (1.522, 0.44, 0.0). The angle between ion thruster exit direction and solar panel center axis is 45 degree. The size of the solar panel model is $12\ \mathrm{m} \times 2\ \mathrm{m} \times 0.04\ \mathrm{m}$. The electric potential on all the surfaces is assumed to be zero, and the temperature is 300 K.

The Maxwell model is used to calculate the plume force on the solar panels. The accommodation coefficients for solar panel surfaces are uniformed to be 0.9, which means 90% of particles have a complete energy exchange with the surface. The new velocity of the reflected particles is obtained from Maxwell distribution.

III.Results and Discussion

A. Number density distribution

The single charged xenon ion has a higher number density and energy, which is the major component of the ion thruster plume. Fig. 3 shows the number density distribution of single charged xenon ions on the Z=0 plane when the angle of the solar panel is 30 degrees. From Fig. 3 we can see that due to the exit direction of the ion thruster and solar panel center axis is at an angle of 45 degrees, so the core region of the beam is far from the surface of the panel. The ion number density in the core region of the beam is above the order of $10^{14}\,\mathrm{m}^{-3}$ magnitude. High-energy ions do not directly bombard the solar panel, but some low-energy ions can reach, and the number density of these ions is on the order of $10^9\,\mathrm{m}^{-3}$ magnitude.

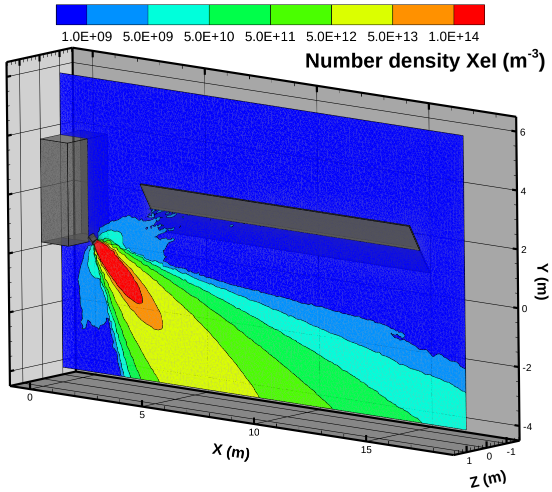

Figure 3. Distribution of particle number density.

In addition, another portion of the particles bombarding the solar panel is the CEX ions. Fig. 4 shows the number density distribution of CEX ions on the Z=0 plane when the angle of the solar panel is 30 degrees. As can be seen from Fig. 4, the number density of CEX ions near the edge of the solar panel near the satellite can reach the order of $10^{11}\,\mathrm{m}^{-3}$ magnitude, while the number density of CEX particles near most areas of the solar panel is at the order of $10^9\,\mathrm{m}^{-3}$ magnitude. Moreover, most of the CEX ions move in a direction perpendicular to the beam, which has a greater impact on solar panels.

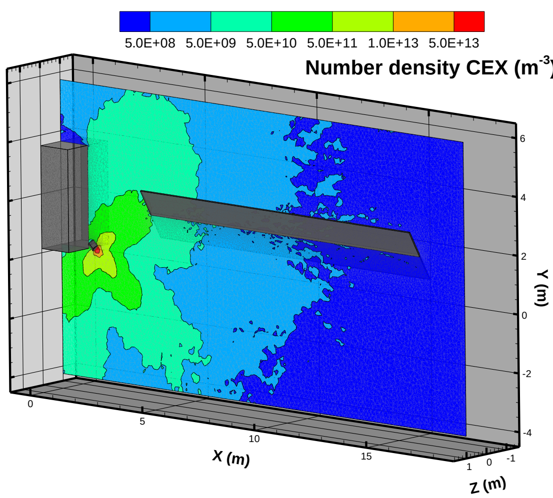

Figure 4. Distribution of particle number density.

B. Plume effects on the solar

Fig. 5 shows the changes of force on the solar panel with the angle. The simulation results in the range of 0-90 degrees are calculated and the results in the range of 90-180 degrees are obtained through the mirror image. The force comes from the momentum statistics of incident particles on the solar panel. As can be seen from Fig. 5, when the adaptation coefficient is 0.9, the maximum force on the solar panel appears at the position of 90 degrees, where F_x is about $9.3\times10^{-4}\,\mathrm{mN}$.

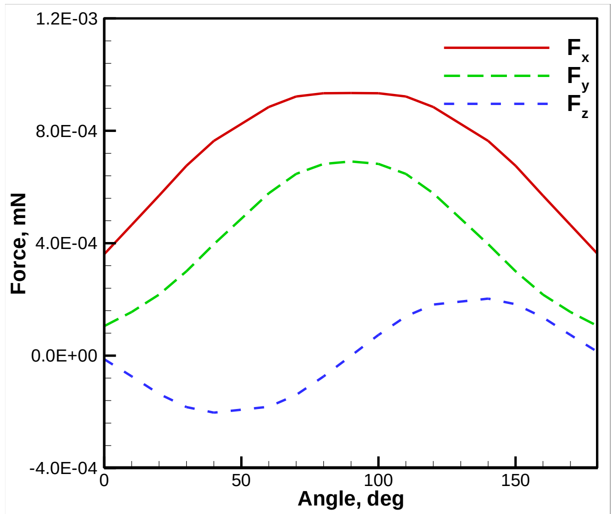

Figure 5. The change of force and torque on solar panel with the angle.

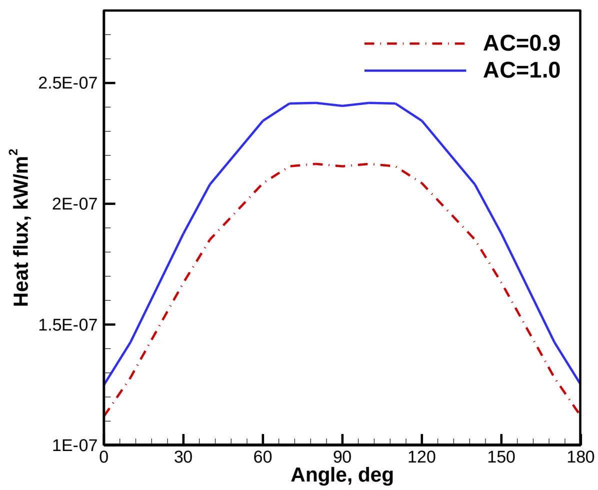

Figure 6. The heat flux on the solar panel at different angles.

Fig. 6 shows the change of heat flux on the solar panel at different angles. The statistical results with two different accommodation coefficients are shown in the figure. When the accommodation coefficient is 1.0, all incident particle energy is transferred to the surface of solar panels, so the heat flux value is significantly higher than that of 0.9. The maximum heat flow occurs around 70 degrees, which is about $2.4\times10^{-7}\,\mathrm{kW/m^2}$.

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