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Three-dimensional particle simulation of back-sputtered carbon in electric propulsion test facility

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ABSTRACT

The back-sputtering deposition on thruster surface caused by ion bombardment on chamber wall material affects the performance of thrusters during the ground based electric propulsion endurance tests. In order to decrease the back-sputtering deposition, most of vacuum chambers applied in electric propulsion experiments are equipped with anti-sputtering targets. In this paper, a three-dimensional model of plume experimental system (PES) including double layer anti-sputtering target is established. Simulation cases are made to simulate the plasma environment and sputtering effects when an ion thruster is working. The particle in cell (PIC) method and direct simulation Monte Carlo (DSMC) method is used to calculate the velocity and position of particles. Yamamura's model is used to simulate the sputtering process. The distribution of sputtered anti-sputtering target material is presented. The results show that the double layer anti-sputtering target can significantly reduce the deposition on thruster surface. The back-sputtering deposition rates on thruster exit surface for different cases are compared. The chevrons on the secondary target are rearranged to improve its performance. The position of secondary target has relation with the ion beam divergence angle, and the radius of the vacuum chamber. The back-sputtering deposition rate is lower when the secondary target covers the entire ion beam.

1. Introduction

Electric propulsion has become an important issue in orbit correction and deep space exploration. Electric propulsion thrusters have advantages in higher specific impulse, lower costs and longer endurance. The lifetime of an ion thruster is usually designed over 10,000 h [1,2]. During the ground based endurance test, high-energy particles ejected from the thruster bombard the chamber walls, leading to a large number of sputtering products. The back-sputtering deposition on the grid surface covers up the bombardment effect from charge exchange xenon ions, and gives rise to an undervalued molybdenum erosion rate compared with the situation in space [3–5]. The sputtering product possibly forms a deposition layer on critical surfaces including cathode igniter, acceleration chamber and discharge channel, which will narrow the thruster performance [6,7]. Moreover, the back-sputtering deposition on probes increases the collection area and results in measurement errors [8]. Fig. 1 shows the areas sputtered and deposited on grid surfaces during the NEXT and NSTAR ion thrusters longtime endurance tests. It can be seen that the central region exhibits a sputtering effect due to the higher ion beam density, and the edge region is blackened due to the deposition of carbon returned from the chamber.

In order to decrease back-sputtering deposition, ion beam targets or anti-sputtering targets (AST) named in previous references are equipped in the bottom of vacuum facilities. Numerous international vacuum chambers designed for electric propulsion experiments are structured as flat, peculiar, and chevrons. All of the targets are covered with a low sputtering rate material. Single layer AST is appropriate to small scale chambers, such as the LEEP2 [10] with a flat shape, the IV10 [11] with a peculiar shape, and a chamber of JAXA [12,13] with chevrons. However, as for the larger scaled vacuum chambers, a cylindrical target is generally added to protect the chamber walls from ion beam bombardment. For example, the LVTF [14] with a cylindrical target and a flat target in the bottom. In [15], a double layer AST is certified to have a better performance than the case without secondary target, which includes a cylindrical target, a flat target and a secondary target with chevrons.

For purpose of assessing the amount of back-sputtering product, the ion beam model presented by Reynolds is usually employed by previous investigators [16,17]. This model provides a preliminary estimate, however, including a certain deviation with the actual plasma environment. For example, the interactions between particles and surfaces influence the flow field while neglected in the model.

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Fig. 1. The net erosion and net deposition areas on the accelerator grids of NEXT LDT (left) [3] and NSTAR ELT (right) [9].

Moreover, the numerical model is generally based on axisymmetric region, or some transformed simple shapes like flat. This simplification contributes to a further deviation. Therefore, it is difficult to apply this model in calculating the deposition rate in three-dimensional complicated domain. In recent years, the Particle in Cell (PIC) and direct simulation Monte Carlo (DSMC) methods occupy an important position in the electric thruster plume plasma environment simulation [18]. Studies have shown that hybrid PIC-DSMC method can conduct the three-dimensional simulation and give a satisfactorily agreement with the experimental results. Although a number of investigators have calculated the deposition rate, they have the main limitation of two-dimensional simulation domains. Little work has been conducted by three-dimensional PIC-DSMC method. The purpose of this paper is to analyze the sputtering effects of double layer anti-sputtering target with different shapes and locations. All the cases are simulated in three-dimensional unstructured grids by a hybrid PIC-DSMC code.

This paper is organized as follows. First, a brief description of numerical models and initial parameters used in the simulations are presented in Section 2. Second, the distribution of sputtering products when a 20 cm diameter ion thruster bombarding the double layer AST is presented in Section 3.1. Third, targets with different number of chevrons are employed in Section 3.2 to study their effects. Finally, the location of the secondary target is analyzed in Section 3.3 to obtain a lower back-sputtering deposition.

2. Numerical methods

Simulation cases in this study are accomplished by Extension of Plume Work Station (EX-PWS) software. EX-PWS is an extension part of Beihang University's Plume Work Station package [19,20] designed for electric propulsion simulation. EX-PWS employs Particle in Cell (PIC) method [21] to model plasma dynamics and uses the direct simulation Monte Carlo (DSMC) method [22] for collision dynamics. Three-dimensional unstructured grids are employed in EX-PWS to adapt complex space conditions. Massage Passing Interface (MPI) method is implemented to improve computational efficiency.

2.1. Plasma physics

The full electron momentum equation is used as the governing system by EX-PWS to simulate the ion thruster plume.

$$m_e n_e \frac{\mathrm{d}\mathrm{v}_e}{\mathrm{d}t} = m_e n_e\left[\frac{\partial \mathrm{v}_e}{\partial t} + (\mathrm{v}_e \cdot \nabla \mathrm{v}_e)\right] - n_e e(\mathrm{E} + \mathrm{v}_e \times \mathrm{B}) - \nabla p - n_e m_e v_{ei}(\mathrm{v}_e - \mathrm{v}_i) \tag{1}$$

where m_e is the electron mass, n_e is the electron density, v_e is the electron velocity, e is the electron charge,E is the electric field, B is the magnetic field, p is the pressure, v_{ei} is the collision rate between electron and ion, and v_i is the ion velocity.

The plume field of ion thruster consists of the xenon atom and the xenon plasma. Xenon atoms and xenon plasmas are extremely thin. The Debye length is much less than the molecular free path, which makes the plasma quasi-neutrality. That is, the electron charge density is equal to the ion charge density everywhere in the flow field. The gyration radius of charged particles in the magnetic field is large. Therefore, the effect of the magnetic field can be neglected. Because of the large molecular free path of electrons, the electron motion is considered as a collisionless flow. Then the momentum equation can be simplified as

$$en_e E = -\nabla p \tag{2}$$

According to the ideal gas law and the isothermal assumption, the electron model employed is obtained and shown as the Boltzmann relation [23]:

$$p = n_e k T_e \tag{3}$$

$$n_e = n_{ref} \exp\left(\frac{\phi}{kT_e}\right) \tag{4}$$

where n_{ref} is a reference number density where the plasma potential ϕ is zero,T_e is the electron temperature, and k is the Boltzmann constant. The reference electron number density n_{ref} used in all simulation cases is $1 \times 10^{16}\mathrm{m}^{-3}$, and the electron temperature T_e is assumed to 3.5 eV.

2.2. Collision physics

EX-PWS uses compute particles to accomplish collisions between propellant atoms by the DSMC method, and utilizes virtual particles in collisions with background gas. Collisions between particles in this study include the elastic collision and charge exchange collision (CEX). Carbon atoms are neglected in collision effects.

The Xe-Xe elastic collision uses the variable hard sphere model [22], and the collision cross section is:

$$\sigma_{el}(Xe, Xe) = 2.12 \times 10^{-18}/{c_r}^{0.24}[m^2] \tag{5}$$

where c_r is the relative velocity. The cross section given by [24] is employed for the Xe-Xe+ and Xe-Xe++ elastic collision:

$$\sigma_{el}(Xe, Xe+) = 6.416 \times 10^{-16}/c_r[m^2] \tag{6}$$

$$\sigma_{el}(Xe, Xe++) = 2\sigma_{el}(Xe, Xe+) \tag{7}$$

Cross section given by Rapp et al. [25] is used for the Xe-Xe+ charge exchange collision:

$$\sigma_{cex}(Xe, Xe+) = (k_1 ln c_r + k_2)^2 \times 10^{-20}[m^2] \tag{8}$$

where $k_1 = -0.8821$, $k_2 = 15.1262$, and $k_1 = -2.7038$, $k_2 = 35.006$ for the Xe-Xe++ charge exchange collision.

The finite background pressure in PES during ground-based experiments is contained in simulations. In this study, the background gas is considered as temporary particles with static parameters. The temporary particles are created in each iteration to change the velocity