Study on the Sputtering Mechanism of Keeper Electrodes in Hall Thruster

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Abstract: The keeper electrode that encloses the hollow cathode could help to facilitate the starting of the cathode and protect the cathode from ion bombardment from the cathode plume and the thruster plasma. The flight and extended life test results showed that the keeper electrode was completely eroded away by the end of the test, exposing the cathode orifice plate to the thruster discharge chamber plasma, which significantly eroded the cathode orifice plate and the sheath-heater surfaces. The sputtering erosion of the keeper electrode is one of the most important failure modes of the ion thruster, and actually there are also many high-energy Charged Exchange Xenon (CEX) ions in the Hall thruster plume. Most of the CEX ions will flow back to the thruster and may cause a sputtering erosion on the thruster surface. Some ions move towards the keeper electrode under the interaction of the electric field, which gives a serious threat to the lifetime of the keeper electrode because of their high energy and long sputtering. This paper focuses on the generation and movement of CEX ions and their interaction on the keeper electrode surface. A full-particle simulation method (PIC) is used to simulate the dynamics of the charged particles, including electrons and ions. Direct Simulation Monte Carlo (DSMC) is applied to modeling the movement of neutral atoms and the collision between them. The generation of high-energy CEX ions is described by the Monte Carlo Collision (MCC) method. By comparing the erosion rate of different particles, we can obtain the most important factor that affect the lifetime of the keeper electrode.

I.Introduction

HALL electric propulsion[1] is one kind of advanced space technology, which has the advantages of high ratio of thrust and power. By using the Hall electric propulsion system on a spacecraft, the satellite's effective payload mass can be reduced, the thruster's lifetime can be extended and the launching costs can be reduced.

A Hall electric propulsion is required to have longer operational life in future deep space missions or to be operated at different conditions of the long duration tests. The wear tests[2] and extended life tests[3-4] showed that there were more than 20 kinds of failure modes, of which the most important wear mechanism was cathode keeper electrode erosion.

As an essential component of the Hall electric propulsion, hollow cathode is used to be the electron sources for plasma production or beam neutralization. Early electric propulsion developed in the 1960s utilized directly heated

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tungsten filaments as the cathode for the plasma discharge. The 2000h wear tests[5-6] revealed unacceptably high erosion of the hollow cathode assembly, and the engineering solution was to use a sacrificial keeper maintained at an intermediate potential between the hollow cathode and anode. The functions of the keeper electrode are to facilitate turning on the cathode discharge, to maintain the cathode temperature, and to protect the cathode orifice plate and external heater from high energy ion bombardment that might limit the hollow cathode life. The 8200h wear tests[7-9] indicated that the cathode orifice plate erosion rate was reduced to less than 3μm/kh that is much smaller than the estimated acceptable threshold of 64μm/kh, which signified that the keeper electrode could mitigate hollow cathode wear. However, keeper surface pitting was observed after 5000h operation and keeper orifice diameter was increasing. During the 10000h wear test, the keeper plate had been eroded significantly and made partial cathode orifice plate exposed to the plasma. After the 15000h of operation[10], the keeper orifice plate had been eroded completely.
Ref.[11-12] pointed out that the sputtering of the energetic ions whose energy sources came from the substantial dip on axis of the radial plasma potential profile of downstream of the keeper electrode. By using experimental approaches[13-15], the discharge instability and the oscillation of plasma potential were detected in the plume of the keeper electrode. The experimental results in Ref.[16-17] showed that the plasma potential varied with discharge parameter and increased gradually up to keeper orifice where a potential discontinuity exists in that region. Actually, there are many researches including experimental tests[16-17], theoretical analysis[18-20] and numerical simulation[21-25] to investigate the effect of discharge parameters on the plasma's potential distribution, oscillation and the failure mechanism of the keeper electrode for ion thruster, and only few researches about erosion mechanism of the keeper electrode in Hall thruster[26-27]. This paper introduced a particle model for simulating the high-energy ions of the plasma in the Hall thruster plume.

II.DSMC Model

DSMC method is the Monte Carlo method for simulation of rarefied gas flows on molecular level, i.e. on the level of individual molecules. To date DSMC is the basic numerical method in the kinetic theory of gases and rarefied gas dynamics.

The DSMC method models fluid flows using simulation molecules which represent a large number of real molecules in a probabilistic simulation to solve the Boltzmann equation. Molecules are moved through a simulation of physical space in a realistic manner that is directly coupled to physical time such that unsteady flow characteristics can be modeled. Intermolecular collisions and molecule-surface collisions are calculated using probabilistic, phenomenological models. Common molecular models include the Hard Sphere model, the Variable Hard Sphere (VHS) model, and the Variable Soft Sphere (VSS) model. The fundamental assumption of the DSMC method is that the molecular movement and collision phases can be decoupled over time periods that are smaller than the mean collision time.

III.MCC Model

A. Electron-Xe+ Collisions

The electron-Xe+ collisions include elastic and ionization collisions. The Coulomb elastic collision only makes the velocity of the particles changed. The reaction considered in ionization collision simulation is described by

$$e + X_e^{+} \rightarrow X_e^{++} + e \tag{1}$$

The corresponding collision cross section is determined by

$$\sigma_{ei} = \frac{4.34\times10^{-18}}{T_{ev}^{\;2}} \ln \Lambda \tag{2}$$

Where T_{eV} is the temperature of electrons, $ln\Lambda$ is the Coulomb logarithm[6].

The scattered electron's energy becomes

$$\varepsilon_{scat,e} = B(\varepsilon_{inc,e}) \tan[R_3 \tan^{-1}(\frac{\varepsilon_{inc,e} - 21.1}{2B(\varepsilon_{inc,e})})] \tag{3}$$

Where $\varepsilon_{inc,e}$ is the energy of electrons, R_3 is the random number.

The energies of Xe+ and Xe++ ions satisfy

$$\varepsilon_{scat,X_e^{++}} = \varepsilon_{scat,X_e^{+}} = \varepsilon_{scat,X_e^{+}} \text{-21.1} \tag{4}$$

The scattered electron's speed is then calculated using

$$v_{z,X_e^{++}} = \sqrt{\frac{2eT_{X_e^{++}}}{m_e}}\cos(2\pi R_3)$$
$$v_{r,X_e^{++}} = \sqrt{\frac{2eT_{X_e^{++}}}{m_e}}\sin(2\pi R_3) \quad (5)$$

B. Xe+-Neutral Collisions

The charge exchange collisions usually exist in accelerator grid's failure mode analysis[28] and the lifetime prediction of ion optics[29], that is because the CEX ions impinging on the downstream surface of the accelerator are the major life-limiting mechanism observed during the NSTAR flight tests. Different from the mechanism appeared in the keeper electrode, the CEX ions generated in the grids will sputter away material from the downstream surface of the accelerator and cause the pit erosion between two apertures and groove erosion among three apertures, which leads to structural failure of the grids if the erosion penetrates all the way through the grid and results in the life ending of the thruster.

The collision between Xe+ ions and neutrals can be described as

$$X_e{}^{+}{}_{fast} + X_{e,slow} \rightarrow X_{e,fast} + X_e{}^{+}{}_{slow} \quad (6)$$

Where the cross section is given by

$$\sigma = (k_1 \ln\Delta v + k_2)^2 \times 10^{-20} \quad (7)$$

C. Generation Probability of Charged Particles

All particle collisions are handled with the MCC technique that simulates particles collisions using statistical techniques. The collisions between electrons and neutrals can be found in Ref.[29]. Here we will particularly introduce the double ionization of the Xe+ ions and their charge exchange collisions with neutrals.

At each time step Δt, the probability of a collision is calculated using a constant collision frequency and corresponding collision section,

$$p = 1 - \exp(-n_0 v_{inc} \sigma(\varepsilon_{inc}) \Delta t) \quad (8)$$

Where n_0 is the density of neutrals. v_{inc} and ε_{inc} are the velocity and energy of the target particles, respectively. $\sigma(\varepsilon_{inc})$ is the collision cross section. In electron-Xe+ collisions, the electrons are treated as the target particles. The heavy ions are treated as the target particles in Xe+-neutrals collisions.

Whether a collision happens, it depends on a comparison between a random number generated by computer and the possibility. If the random number is less, it is believed that these two particles change their own properties and a new particle produces.

IV.PIC Model

PIC is used in this paper to track the following particles including the primary electrons, secondary electrons, ions and neutral atoms. The collisions between particles is studied by the MCC method. There are several assumptions in the simulation. Firstly, the primary electrons, whose energy is about 2eV, is emitted evenly from a grid of the keeper electrode to the discharge chamber and the angle of the symmetric axis is less than 15°. Secondly, the energy loss of the elastic collision between the particles are ignored. Lastly, the dynamic magnetic field generated by the moving plasma is far less than the static magnetic field, so the influence of the dynamic magnetic field on the motion behavior of the plasma is not considered in this paper.

Dynamic electric filed caused by the charged particles are represented by

$$\frac{\partial^2\phi}{\partial r^2} + \frac{1}{r}\frac{\partial\phi}{\partial r} + \frac{\partial^2\phi}{\partial z^2} = -\frac{e}{\varepsilon_0}(n_i - n_e) \quad (9)$$

Where e is the electron charge; ε_0 is the permittivity of free space constant; ni and ne are the number density of the ions and electrons. A super particle represents a number of simulation particles and its weight is taken as 1.0×10^{11}.

Movement of the single and double charged ions in the interaction of the electromagnetic field satisfies the Newton's second law.

$$M\frac{d\vec{v}_i}{dt} = e\vec{E} \quad (10)$$
$$\frac{d\vec{x}_i}{dt} = \vec{v}_i$$

Where M, $\vec{x}_i$, $\vec{v}_i$ are the mass, position and velocity of ions, respectively; $\vec{E}$ is the electric field.

The movement of electrons is described as follows,

$$m\frac{d\vec{v}_e}{dt} = -e(\vec{E}+\vec{v}_e\times\vec{B})$$
$$\frac{d\vec{x}_e}{dt} = \vec{v}_e \qquad (11)$$

Where m, $\vec{x}_e$, $\vec{v}_e$ are the mass, position and velocity of electrons, respectively; $\vec{B}$ is the magnetic field.

V.Results and Analysis

A. Validation of Simulation Model

In order to check whether the simulation model and method is right, a erosion simulation model of hollow cathode is established and the simulation results are compared to with the results showed in Ref.[27]. Fig.1 shows the simulation model in Ref.[27], which is a hollow cathode in ion thruster.

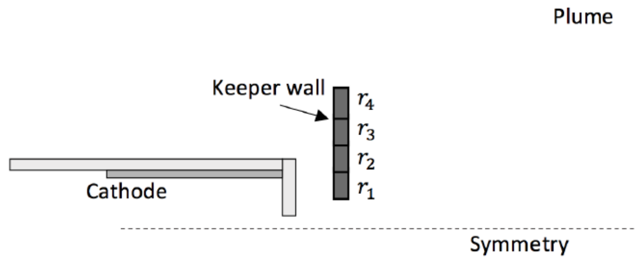

Fig.1 Hollow cathode model in ion thruster from Ref.[27]

The author divides the keeper electrode surface into four parts, r1, r2, r3 and r4 and calculate the erosion rate of different particles on the keeper surface. Erosion rate is calculated as the product of incident flux on a target surface and the sputter yield.

The sputter yield consists of energy-dependent yield and angle-dependent yield, which are related to the energy and angle. Fig.2 shows the experimental results of normalized energy and angle-dependent sputter yield.

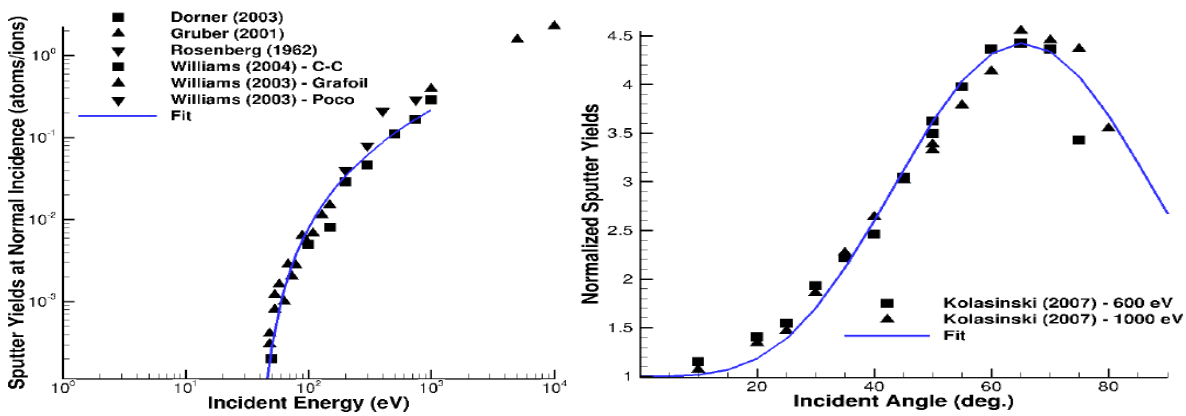

Fig.2 (a)Energy-dependent yield, (b)Angle-dependent yield from Ref.[27]

According to experimental results, the expressions of two kinds of sputter yields are obtained as follows

$$Y(E) = A\sqrt{E}(1-\sqrt{\frac{E_{th}}{E}})^B \qquad (12)$$

$$Y(\theta) = 1+c_0[1-\cos(c_1\theta)]^{c_2} \qquad (13)$$

Then, the total sputter yield is described

$$Y = Y(E)Y(\theta) \qquad (14)$$

Fig.3 shows the verification simulation model. In this model, the whole simulation domain includes the hollow cathode plume, the left boundary is the keeper electrode surface, which is divided into four parts that is the same as the Ref.[27]. Electrons are emitted from the keeper exit into the simulation domain. Before that the atoms are distributed from the keeper exit firstly. The flow chart of simulation is shown in Fig.4.

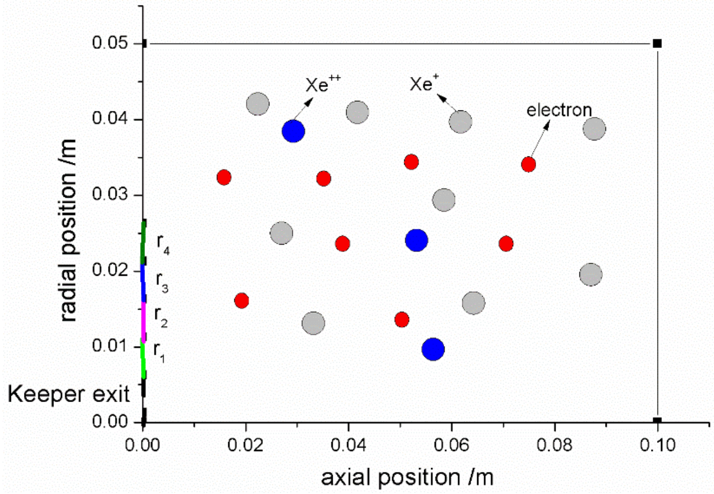

Fig.3 Verification simulation model

When the movement of neutral atoms is in steady state, electrons are ejected into simulation domain and they collide with the atoms. Ionization collision between electrons and atoms lead to the generation of single xenon ions. Some of double charged xenon ions are generated because of the higher energy of electrons. After the numbers of ions exit from the simulation domain equal to the enter ones, the steady state of discharge is obtained. Then the erosion numbers of particles hit on the keeper electrode surface is calculated, and the erosion rate can be gotten based on the relationship between the number of particles and sputter yield.

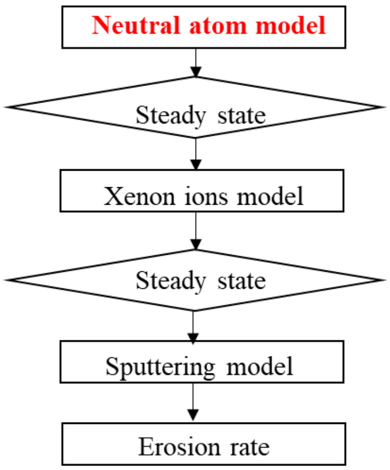

Fig.4 Flow chart

The simulation conditions is shown in Table.1.

Table.1 Simulation conditions

Gas flow/mg/s	Anode potential/V	Thruster potential/V	Divergence angle	Initial velocity/m/s	
				Xe+	Xe++
3.68	300	50	20	5.35e4	7.566e4

There are four boundaries in this simulation. The left boundary is composed of the keeper electrode surface, keeper exit and other part. Electrons hit on the left boundary will be deleted, which is the same as the atoms and ions. But the number of ions and atoms that collide with the keeper electrode surface will be summed statistically during the simulation. All of particles on the bottom boundary will be reflected into the simulation domain and continue to move. Particles including the atoms, single and double ions are deleted on the top and right boundary.

The erosion rate of neutral atoms, single and double charged ions are studied in this paper. Fig.5 shows the comparison results. The results show that the results in our paper is agree good with the Reference ones. By comparing the erosion rate of three different particles, the erosion rate of double charged particles is largest, and the neutral atoms is smallest.

According to the simulation results, we can also have the parameters of the energy and angle sputter yields.

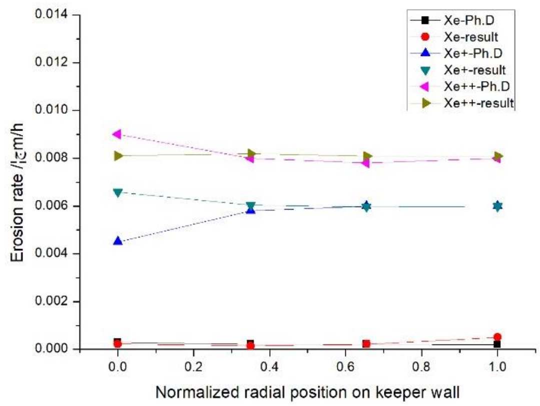

Fig.4 Comparison results

B. 2-D Simulation Model

Based on the verification model, a two-dimension simulation model is established and the DSMC/MCC/PIC method are used to simulate the sputtering process of hollow cathode in Hall thruster. In this simulation, we just choose the half discharge channel as our object because of its axisymmetric geometry. The simulation domain is the hall thruster plume, which is very larger than the thruster exit that locates in the left boundary. Fig.5 shows the simulation results of density distribution of single and double charged ions in Hall thruster.

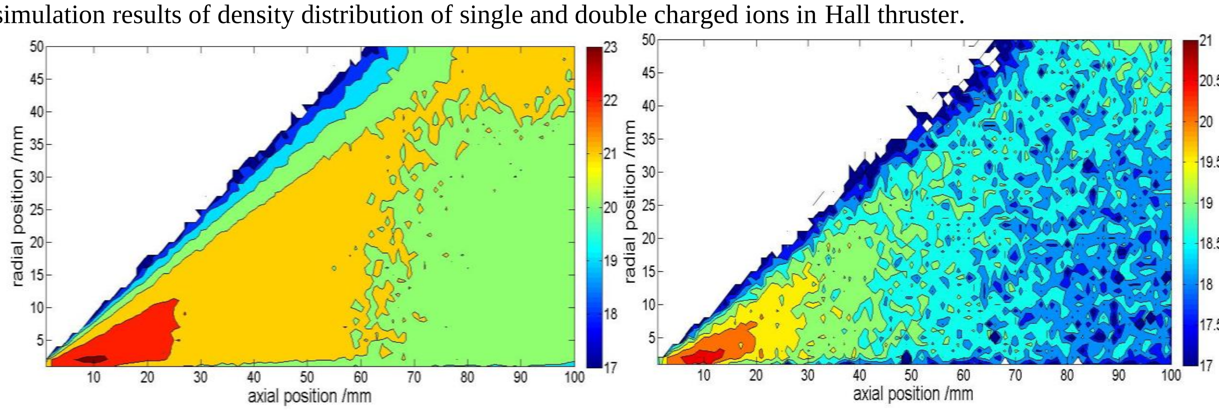

Fig.5 Density distribution of single and double charged ions

The simulation results show that it's impossible for ions to hit the keeper electrode surface, because of the electric field distribution in Hall thruster plume and its velocity of ions. Fig.6 shows the density distribution of neutral atoms and CEX ions. It is found that the atoms and CEX ions could hit the keeper electrode surface, therefore, they will taken into account in our paper.

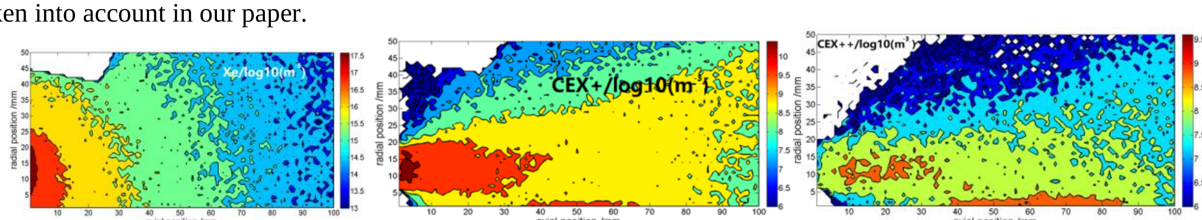

Fig.6 Density distribution of neutral atoms and CEX ions

Fig.7 shows the simulation model of Hall thruster. The simulation domain includes the Hall thruster plume. Thruster exit is in the left boundary, where the atoms and ions are ejected. The hollow cathode locates on top boundary, α is the rotational angle of hollow cathode. The numbers of atoms and ions are summed statistically.

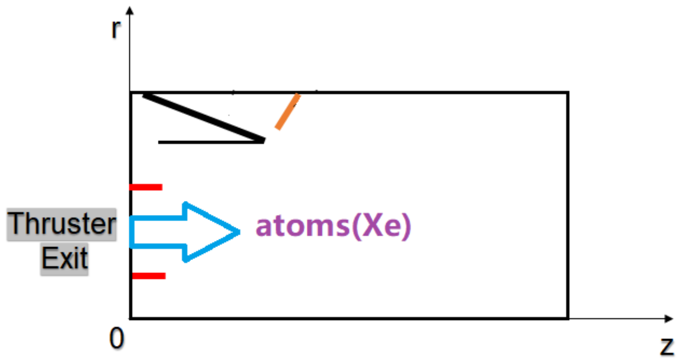

Fig.7 Simulation model

Fig.8 shows the erosion rate of atoms and CEX ions for different rotational angles. The results show that the erosion rate of atoms isn't affected with the rotational angle, while the erosion rate of CEX ions varies seriously. For the CEX ions, its erosion rate increases linearly with the rotational angle of hollow cathode and it is larger than the atoms. The unit of the erosion rate is μm/h.

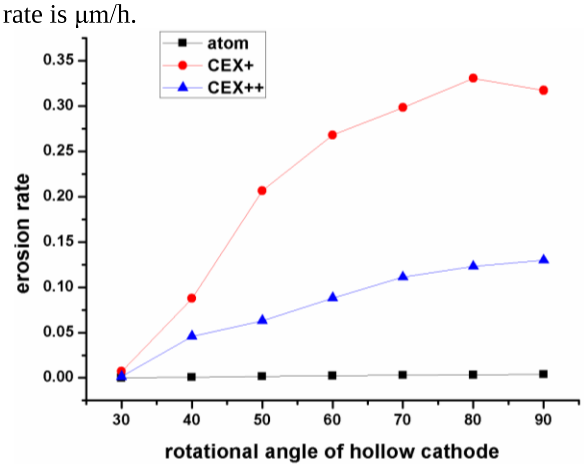

Fig.8 The erosion rate of atoms and CEX ions for different rotational angles

Fig.9 shows the erosion rate of atoms and CEX ions for the 30 degree angle. It is showed that the erosion rate of CEX ions is the largest, while it is the smallest at the 30 degree of rotational angle. At the 30 degree of rotational angle, the ratios of erosion rate for atoms, CEX+ and CEX++ are 1.07%, 82.9% and 16.03%, respectively. The unit of the erosion rate is μm/h. It is concluded from Fig.8 and Fig.9 that the erosion rate of keeper electrode is much smaller than the estimated acceptable threshold of 64μm/kh and is larger than the 3μm/kh in the 8200h wear tests of NSTAR ion thruster.

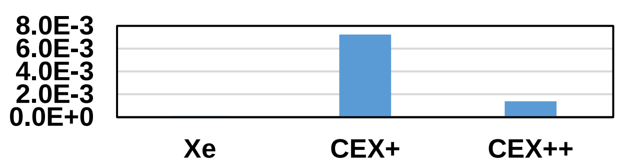

Fig.9 Erosion rate of atoms and CEX ions at 30 degree of hollow cathode

VI.Conclusion

As one of the failure modes of hollow cathode, the sputtering process of the hollow cathode in Hall thruster is studied in this paper. Because of its dynamic behavior and the distribution of electric field in the Hall thruster plume, single and double charged ions are impossible for them to be the main factor that affect the lifetime of hollow thruster. So the neutral atoms and two kinds of CEX ions, which are generated by the collision between atoms and single and double charged ions, are taken into account in this paper and its erosion rate on the keeper electrode surface are calculated and compared. It is concluded that the erosion rate of charged particles is larger than the atoms, and the CEX+ ions are the most important factor that limit the lifetime of hollow cathode in Hall thruster.

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