Numerical Simulation of Grid Erosion for Ion Thruster

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ABSTRACT

The life time of the ion thruster is restricted by the erosion of the grids, which is caused by the backscattering of the charge exchange ions. A two-dimensional numerical code was developed to simulate the grid erosion, which provides insight into the details of the grid erosion process. The simulation code mainly consists of the calculation of the neutral density distribution, ion beam trajectories, charge exchange process, and modification of the grid geometry. The erosion maximizes at the interior surface of the acceleration grid, which enlarges the aperture diameter of the acceleration grid. It is concluded that structural failure determines the life of the grid system rather than electron backstreaming, and performance reduction. The carbon-carbon composite as the grid material makes the grid system work effectively over 100,000 hrs.

1. INTRODUCTION

Institution of Space and Astronautical Science (ISAS) plans the Mission to Asteroid and Earth Return (MASTER) with ion thrusters to the asteroid named Nereus. The only electric propulsion enables the MASTER mission due to its high specific impulse. Advantages of using ion thrusters are its light weight, low power, and long life in comparison with other types of the electric propulsion. As for its long life, grid erosion is one of the remaining major life limiting phenomena for operating ion thrusters. The required thruster lifetimes for the planned asteroid sample return mission, for example, is 16,000 hrs. It has been well established that a primary factor of the grid erosion is the sputtering of charge exchange ions which occurs between fast beam ions and neutral propellant atoms. Recently by introducing a deceleration grid or changing grid material from molybdenum to carbon-carbon composite material, thruster's lifetime was reported to be improved considerably. But it is difficult to estimate effective lifetimes in the ground tests because of its long duration and a considerable expense and so on. So it would be desirable to have an analytical model to simulate the sputtering of the grids in the ion thruster in detail.

We have developed a two-dimensional numerical code for simulating the grid erosion, which provides insight into details of the charge exchange process. It is based on the numerical code of ion beam trajectory which was developed by Arakawa. We improved and added it to charge exchange process, neutral density distribution process, erosion process and so on.

2. SIMULATION CODE

2.1 Flow of the simulation procedure

The numerical code has the grounds of a two-dimensional, axisymmetric, single set of grid aperture model. The numerical code includes the following assumptions.
1. Ions are singly charged.
2. No collision between ions.
3. No electrons exist in the region of grid aperture.
4. The extracted ion beam is neutralized by electrons in the downstream region.
In the numerical code a large number of test particles are distributed over computational domain with 6.5mm x 1.75mm, representing propellant ions. And their trajectories are followed in time until they leave the computational domain. The boundaries of the computational domain are at 0.85mm upstream from the screen aperture and at 2.85mm downstream from the decel aperture, respectively. The ion beam trajectory through the numerical grids interval of 0.05mm was calculated by the particle-in-cell method (PIC). The charge exchange ions were estimated at the point, \( v \), is the beam velocity of kth ion beam in each mesh point and their trajectories were also determined by PIC. As the fundamental equations Poisson’s equation and kinetic equation of ion are used.

\[
\begin{align*}
\nabla \cdot V &= \frac{\rho}{\varepsilon_0} \quad \text{(1)} \\
M \nabla \cdot V &= -q \nabla V \quad \text{(2)}
\end{align*}
\]

Where \( V \) is the electrostatic potential, \( \rho \) is the charge density.

The numerical code is input initial geometrical quantities to characterize the screen, accel, decel grids, the grid potentials, the discharge plasma electron temperature, the propellant ion mass, a desired perveance operating point and operation time.

The flowchart of the code is shown in Fig. 1. The simulation procedure consists of the following principal steps.

1. Density distribution of the neutral particles is calculated in the computational region.
2. Each grid is applied its potential. Laplace’s Equation solves an approximate potential distribution in finite difference form as an initial step. The sheath of the upstream plasma is assumed to be a spherical segment near the screen hole with a large radius.
3. Test particles are extracted from the sheath surface. Each of them represents a large number of ions, and carries a corresponding current which used in a finite difference form of Poisson’s Equation to solve via the successive over-relaxation (SOR) technique for new values of potential. To determine trajectories of ion beams, an axisymmetric, two-dimensional kinetic equation is applied successively. The ion density at the sheath is established at the value needed to assure operation at the prescribed perveance condition.
4. At each mesh point along each trajectory, charge exchange takes place and charge densities associated with each trajectory are then summed and used in solving a Poisson’s Equation. The newly created charge exchange ion is tracked by the code in exactly the same manner as the primary beam ions. Charge density at the mesh point \((i, j)\) is calculated by the following equation

\[
\rho(i, j) = \sum_{k=1}^{n} J_k \cdot \frac{S}{V_{ak}}
\]

where \( S \) is the area which the point represents, \( J_k \) is the ion current which attributes to the kth ion beam across the point, \( v_{ak} \) is the beam velocity of kth ion beam in the axial direction.
5. The axial location and shape of the sheath is adjusted in the solution procedure so that the separation between the sheath and the equipotential contour at a few tens of voltage negative satisfies the space-charge-
limited current density condition on the extracted ions.

6. Geometry of grids are made to be transformed by calculating the erosion depth from the accel current which charge exchange ions carried.

The sequential procedure of computing neutral density, ion beam trajectories, space-charge densities, potentials, sheath position and geometry modification is repeated until the solution becomes to converge.

2.2 Charge exchange process

Charge exchange collision takes place at each mesh point along ion beam trajectory. Each newly created charge exchange ion is affected by ambient potential with its initial velocity zero. When one strikes the accel or decel grid surface it was removed from the computational domain and its energy is calculated to be equal to the difference of the grid potential and the potential where charge exchange occurred. The grid impingement currents are determined by the total charge carried by the ions which strike the grid.

The probability of charge exchange is determined by the cross-section and neutral particle density at each point.

\[ P(j) = n_a \sigma h \]  \hspace{1cm} (4)

where \( n_a \) is the neutral particle density, \( \sigma \) is the charge exchange cross-section and \( h \) is the calculational mesh size. The cross-section data for the charge exchange reaction between xenon ions and xenon neutrals is taken from Ref. 7 and following relationship could be derived.

\[ \sqrt{\alpha e^{-18}} v_{\text{om}/j} = 19 - 2 \log_{10} v_{\text{om}/j} \]  \hspace{1cm} (5)

Every time an ion beam crosses the mesh, its ion current decreases gradually by that probability like following.

\[ k_0 \rightarrow (1 - P(j))k_0 \rightarrow (1 - P(j))(1 - P(j + 1))k_0 \rightarrow \]

where \( k_0 \) is the initial ion current which is provided by particle. After all ion beams passed through the computational region charge exchange ion current are summed at each mesh point. The charge exchange ions are tracked in exactly the same manner as the primary beam ions.

2.3 Calculation of neutral density profile

The distribution of the neutral particle density in intergrid region resulting from the escaping neutral propellant gas was calculated by a particle simulation in the numerical code. A large number of test particles is injected from the upstream boundary at each cell. Total resident time is regarded as neutral density at the point. The only collisions between the neutral particles and the surfaces of the grids are considered in the calculation of the neutral particle density.

A sketch of the computational domain is shown in Fig. 2. At first particles are introduced into the computational domain at the upstream boundary(b.c.1). Whenever a particle strikes the grid surface (b.c.2) the particle is assumed to be once accommodated, and it leaves the surface with cosine distribution. Whenever a particle reaches the outer cylindrical boundary of the computational domain or central axis (b.c.3), it is reflected back in a specular manner into the computational domain. The simulation continues until all injected particles reach the downstream boundary (b.c.4).

\[ \eta_p = \frac{IA_{c}}{IA_{e} + \frac{1}{\alpha A_{s}} v n_{\text{c}} e A_{p}} \]  \hspace{1cm} (6)

where \( \eta_p \) is the propellant utilization, \( I \) is the current density, \( A_{c} \) is the area of screen grid aperture, \( A_{p} \) is the area of accel grid aperture, \( v \) is the mean velocity and
\( P_{\text{wa}} \) is the effect of the width of the accel grid. Current density is calculated by the following equation

\[
J = \frac{4}{9} \varepsilon_0 \frac{2q V_i^3}{M l^2}
\]  

(7)

where \( \varepsilon_0 \) is the permittivity of free space, \( q \) is the charge of ion particles, \( M \) is the mass of the ion particles, \( V_i \) is the total voltage, \( l \) is the effective acceleration length.

The neutral densities obtained from this calculation and the uniform density of the residual gas in the vacuum chamber were then added together and used as the neutral particle density.

2.4 Neutralization process

The primary ion beams extracted by the grid system eventually have to be neutralized by electrons from the neutralizer. A calculational technique is applied in order to include the effect of neutralizing electrons. As mentioned previously Poisson's equation does not include electrons. So in the downstream region of the accel grid, Poisson's equation is modified to

\[
\nabla^2 V = -\frac{\varepsilon_0}{n_e} (n_i - n_e)
\]

(8)

\[
n_e = n_0 \exp\left(\frac{eV}{kT}\right)
\]

(9)

where \( n_i \) is the ion density determined by ion trajectories, \( n_e \) is the electron density determined by Boltzmann distribution dependent on the local potential, \( n_s \) is the plasma density. Now, \( f \) is defined as

\[
f = n_i - n_e
\]

(10)

As shown in Fig. 3, when absolute value of \( V \) is large, \( f \) is dependent only on \( n_i \)

\[ f_e = n_i \quad (V=0) \]  

(11)

On the other hand, with the increase of \( V \), the \( f \) becomes dependent on \( n_e \)

\[
f_e = n_i - n_e \exp\left(\frac{eV}{kT}\right) \\
= n_i \left(\frac{-eV}{kT}\right) \\n\]

(12)

where \( kT \) is the downstream electron temperature.

Combining Eqs. (9) and (10), we can construct a single analytical formula as follows,

\[
f = \frac{1}{\left[\frac{1}{f_e^2} + \frac{1}{f_0^2}\right]^{\frac{1}{2}}}
\]

(13)

This \( f \) is substituted in Poisson's equation in the downstream region.

![Figure 3. V Dependence on \( n_i \), \( n_e \), and \( f \) under One Dimension](image)

2.5 Calculation of grid surface erosion depth

The numerical code includes the process of changing grid configuration due to the erosion of the grid surface depending on the collisional energy. Fig. 4 shows the experimental obtained erosion rate for xenon ion on the carbon-carbon composite material. The density of the carbon-carbon composite material was 1.68 (g/cm\(^3\)) and these data were obtained under pressure of 4.0×10\(^{-4}\) torr. The erosion rate is analytical formulated as

\[
Y_{\text{[c/a]}} = 5.46 \times 10^{-2} V_{\text{[c/a]}}
\]

(14)

This erosion rate is assumed to be independent of the angle of incidence of ions, and the re-deposition of the sputtered material is not under consideration.
3. SIMULATION RESULTS

The geometrical configuration and the bias voltage of each grid for the numerical simulation are shown in Fig. 5. The open area fractions of the screen, accel and decel grids are 0.67, 0.24 and 0.67, respectively. As other input parameters, electron temperature is assumed to be 5eV, normalized pervance per hole is $0.9 \times 10^{-9}$ (A/V$^2$), and total number of grid holes is 857.

Fig. 6 shows the ion beam trajectories, and Fig. 7 shows an example potential contour.

3.1 Charge exchange process

Fig. 8 shows the location where charge exchange ions generate. Charge exchange ions which generate in the hatched region are accelerated and passed through the grid region. On the other hand, ones in the dotted region are attracted by the negative potential and impinged on the grid surface, causing erosion. Some of them which generate in the aperture of the accel grid impinged on the decel grid surface. The ratio of charge exchange ions which strike the grids to the total charge exchange ions is calculated to be 0.28.

Neutralization plane represents equipotential line corresponding to the downstream plasma potential. Primary beam ions are regarded perfectly neutralized, so that charge exchange ions generated in the downstream region of the neutralization plane are not accelerated back to the grid system.
the charge exchange ions rather than the decel grid. Almost all of the charge exchange ions strike the interior of the accel grid aperture.

Here, considering the number of the grid holes, total accel grid ion current is calculated to be 0.3 mA. The virtual accel ion current was experimentally measured at 1.0 mA under the same grid configuration. The simulation result is one third as much as the experimental result. The direct impingement of primary ion beam to the accel grid might cause such a large accel current in the experiment due to the mechanical misalignment and/or thermal deformation of the grids.

3.2 Neutral density distribution

Fig. 9 shows the neutral particle density contours. It indicates that neutral density in the upstream region is about ten times as much as in the downstream region. The background neutral density from residual gas in the vacuum chamber is assumed uniform throughout the computational domain at a density of $1.0 \times 10^{16}$ (m$^{-3}$), which is correspond to the virtual facility pressure of $1.0 \times 10^4$ torr. The neutral density in the downstream region of the accel grid is equal to the background neutral density. In the upstream region of the accel grid, the neutral density resulting from the escaping neutral propellant is dominant.

3.3 Ion current to the grids

Fig. 10 and Fig. 11 shows the distribution of the ion current to the accel and decel grids around each aperture. The accel grid collects a considerable number of
3.4 Change of accel grid’s appearance

Fig. 12 shows the time-dependent appearance of accel grid aperture’s interior. When compared these figures with Fig. 10, the erosion profile is more uniformly than the current profile. That is why charge exchange ions which strike the upstream part of the aperture interior have higher energy than others. These figures also indicate that for the first few tens thousand hours the interior grid surface was eroded almost uniformly but after that, downstream part of the aperture’s interior was eroded more severely than other part.

As seen from Fig. 12 the accel grid inter-hole web is eroded only 40% after 100,000 hrs. Electron back-streaming barrier is defined at the bottom of the potential well along the center-line of a grid aperture as seen in Fig. 13. Fig. 14. shows the decrease of the potential barrier as a function of time. It indicates that the value of the negative potential barrier to prevent electron back-streaming is gradually reduced but sufficiently large (about -70 V) after 100,000 hrs operation. Fig. 15. shows the change of propellant utilization efficiency as a function of time. Propellant utilization

3.5 Estimation of the lifetime

The causes to limit the operation of the ion thruster are thought to be the structural failure of the grids, the electron back streaming and the degradation of the propellant utilization efficiency. The structural
efficiency is defined as the following equation:

\[ \eta_p = \frac{I_0}{I_0 + R_s} \]  \hspace{1cm} (15)

\[ R_s = \frac{1}{4} \bar{v} S_s (1 - P_n) \eta_s \]  \hspace{1cm} (16)

where \( I_0 \) is the beam current, \( S_s \) is the cross-section of the computational domain, \( P_n \) is the neutral confining ratio and \( \eta_s \) is the neutral density in the discharge chamber. Fig. 15 indicates that the degradation of propellant utilization efficiency after 100,000 hrs is only 4%.

Figure 13. Potential Distribution along the Center-line of a Grid Aperture (Initial State)

Figure 14. Change of the Potential Barrier as a function of Time

Figure 15. Change of Propellant Utilization Efficiency as a function of Time

The numerical simulation predicts that the grid system will be within its service life after 100,000 hrs operation in the stand point of the erosion on the accel and decel grid. Among the three life-limit elements, structural failure will come true first after about 220,000 hrs. However, as mentioned above, accel grid current obtained from the simulation is one third as much as the one from the experiment. Moreover, if the grid material is molybdenum, erosion rate increases 5 times or 7 times as much as carbon-carbon composite. Then the lifetime of the grid system is about 10,000 hrs, if the grid material is molybdenum.

4. CONCLUSIONS

We have developed a two-dimensional numerical code for simulating the grid erosion including time dependent grid modification process.

In a three grid system, most of the grid erosion is concentrated on the downstream part of the accel grid aperture's interior.

Structural failure is the most dominant as grid service life limitation. But using the carbon-carbon composite as the grid material, grid system will be within its service life over 100,000 hrs.

References
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