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Simulations and visualizations of grid erosion in ion engines†

—Prediction of ion engine lifetime—

NAKANO Masakatsu *

KEY WORDS: (Prediction) (Numerical simulation) (Lifetime) (Grid erosion) (Sputtering) (Ion engine)

1. Introduction

Ion engines are a form of electric propulsion used for spacecraft that generate thrust by accelerating ions. Although ion engines can generate very high specific impulses, they produce much lower thrusts than conventional chemical rockets. Consequently, ion engines have to be operated for a very long time to achieve the velocity changes required by a particular mission.

In June 2010, the Hayabusa spacecraft returned to Earth after completing a seven-year mission. The ion engines on the Hayabusa spacecraft (μ10 ion engines) had been operated for more than 40,000 hours in space. Prior to the flight, the μ10 ion engines had been subjected to a series of 18,000 h ground-based lifetime tests.

These lifetime tests represent a major hurdle to using ion engines in the future because they are prohibitively time consuming and expensive. If lifetime tests are required after making minor improvements to an ion engine, it will be practically impossible to modify and improve ion engines. To increase the use of ion engines, it is thus essential to both shorten the lifetime verification process and lengthen the lifetimes of ion engines.

Particles (ions and neutrals) produced by charge-exchange and elastic collisions in ion engines can be directed toward the accel and/or decel grid with very high energies, which can cause grid erosion (see **Fig. 1**). End of life is reached when either the holes in the accel grid become so large that ion extraction is greatly affected by electron backstreaming or structural failure occurs in the grid. Grid erosion is unavoidable and it is the principle life-limiting factor in ion engines.

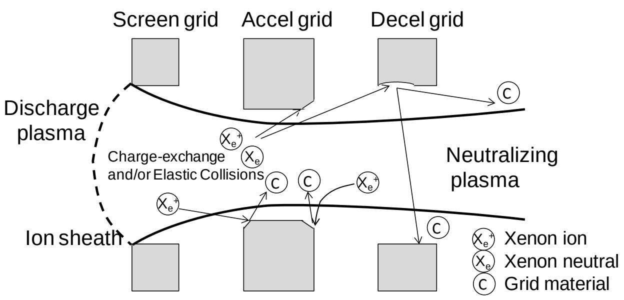

Fig. 1 Grid erosion mechanism in ion engines.

Since grid erosion occurs very slowly, taking several tens of thousands of hours to become life-threatening to ion engine operation, simulation of grid erosion is essential for cost-effective design and development of ion engines. In this study, numerical simulations are performed to assess grid lifetime.

2. Physical and numerical models

Figure 2 shows the computational domain and its boundaries. The symmetry of the grid hole distribution permits the computational domain size to be reduced to 1/12 of a grid hole. The simulation employs the finite element method and the domain is covered with a mesh of eight-node hexahedral elements.

The electrostatic potential in the computational domain can be calculated using Poisson's equation. The ion density term of Poisson's equation is obtained from the beam current, the velocity, and the stay times of the ion beams passing through the elements. The electron density is evaluated using the Boltzmann relation based on the potential difference from the local plasma. Grid voltages are specified at the boundaries that represent the screen, accel and decel grid surfaces. The plasma potential is applied for the inlet boundary and the zero Neumann boundary condition is specified for other boundaries. Poisson's equation is discretized using the normal finite element method and the resulting simultaneous equations are solved iteratively by the incomplete Cholesky conjugate gradient method.

Ion beams are injected from the upstream boundary. The inlet velocities of the ions are determined to satisfy the Bohm sheath criterion. Each ion beam trajectory is calculated from the equations of motion for electrostatic particles.

The amounts of sputtering particles generated by

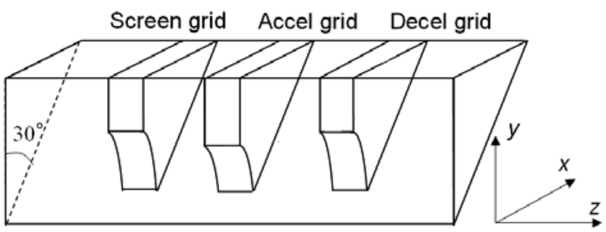

Fig. 2 Computational region.

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* Tokyo Metropolitan College of Industrial Technology, Tokyo, Japan

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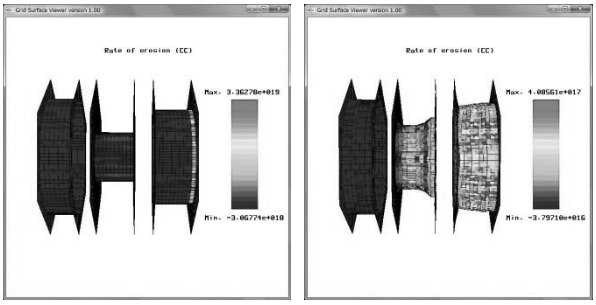
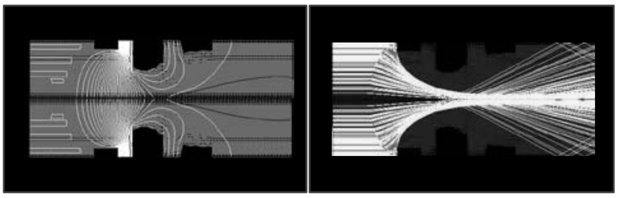


BOL After 20,000 h

Fig. 3 (a) Grid surfaces and erosion intensities in the high beam current region for ϕ_a = -350 V.



Potential distribution Ion beam trajectories

Fig. 3 (b) Potential distribution and ion beam trajectories in the high beam current region for ϕ_a = -350 V.

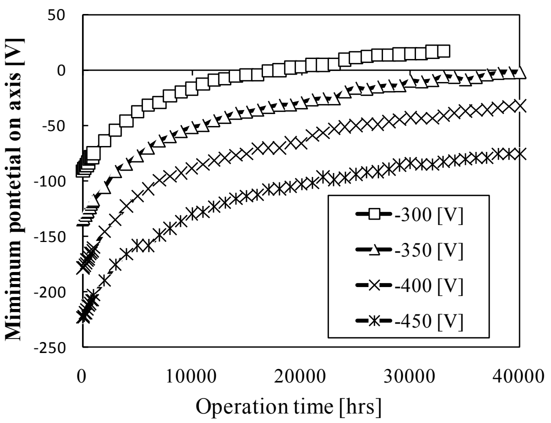
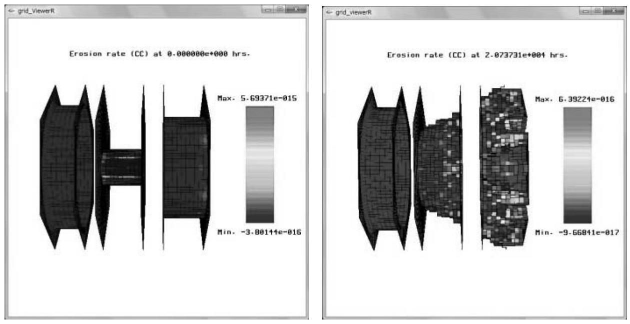


Fig. 4 Minimum potential on axis.

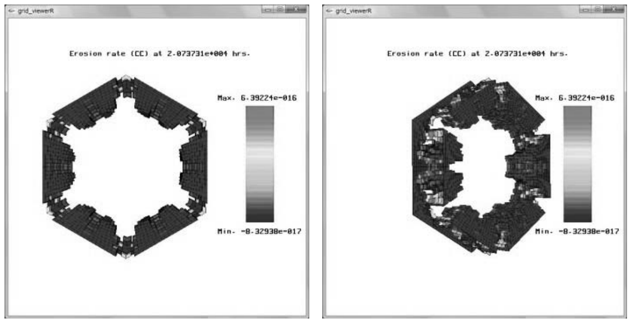
charge-exchange and elastic collisions are evaluated from the ion beam current, collision cross section, and local neutral density. Neutral densities are obtained prior to performing the potential and beam trajectory calculations using the free molecular flow approximation. Sputtering of the grid material is incorporated using experimental data in the form of tables of values for incident energies and incident angles. Since redeposition of the sputtered grid materials is a very complex process that involves interactions between the incident sputtered particles and the grid surface atoms, it is modeled by a simplified approach using a sticking factor, in which the redeposition flux is given by the product of the incoming sputtered particles and the sticking factor.

The grid surface profile is updated from the rate of change of the grid surface obtained by the sputtering and redeposition calculations. This update is repeated until the accumulated operating time reaches the specified value. A detailed description of the simulation is given in Ref. 1.



BOL After 20,000 h

Fig. 5 (a) Grid surfaces and erosion intensities in the low beam current region for ϕ_a = -350 V.



Downstream view Diagonal view.

Fig. 5 (b) Decel grid after 20,000 h of operation for ϕ_a = -350 V.

3. Results and discussion

Parametric calculations for the μ20 ion engine grid were performed by varying the accel grid voltage. Calculations were performed for high and low ion beam currents and a fixed total acceleration voltage. Detailed grid and operation parameters are given in Ref. 2.

Figure 3(a) shows the grid surfaces and erosion intensities for grid holes in the high ion beam current region at the beginning of life (BOL) and after 20,000 h of operation. The downstream edge of the accel grid hole is severely eroded, which may lead to electron backstreaming. Fig. 3(b) represents the potential distribution and ion beam trajectories. From the figure, the downstream edge erosion of the accel grid is explained by the impact of cross-over ions.

Figure 4 shows the variation of the minimum electrostatic potential on axis as a function of the accumulated operating time for ϕ_a = -300 to –450V. If electron backstreaming is assumed to occur when the minimum axial potential exceeds $-T_e$ [V] (T_e: electron temperature), the lifetimes are predicted to be about 14,000 h for ϕ_a = -300 V, 32,000 h for ϕ_a = -350 V, and over 40,000 h for ϕ_a = -400 and -450 V.

Figure 5 shows the grid surfaces at the BOL and at after 20,000 h of operation for grid holes in the low ion beam current region. Since ion beams tend to diverge at lower beam currents, the inner surfaces of the accel and decel grids are significantly eroded and the decel grid is close to structural failure due to six-point star-shaped erosion.

Based on these simulations, it is concluded that the end of life of the grid holes in the high beam current region is caused by electron backstreaming, whereas the end of life of the grid holes in the low beam current region is caused by structural failure of the decel grid in the μ20 grid system.

The total calculation time was about one week using a PC (Intel Core i7 965), which is two orders of magnitude smaller than actual lifetime tests.

4. Conclusions

The following conclusions were obtained:

(1) Numerical simulations can be employed to determine the lifetimes of ion engines.

(2) Two major failure modes (electron backstreaming and structural failure) of the μ20 ion engine were successfully analyzed.

(3) Using numerical simulations accelerates the lifetime verification process by two orders of magnitude or more.

Acknowledgement

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