The Flow Modeling of Charge Exchange Ions in the Ion Thruster

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Abstract

One of the major life limiting phenomena for operating ion thruster is the accel grid erosion. A basic factor of the grid erosion is the sputtering of charge exchange ions (secondary ions) occurred between the primary beam ions and the neutral propellant particles. A considerable part of the charge exchange ions is formed in the downstream region. Determined portion of them comes back to the extraction system. The erosion rate is determined mainly by the secondary ion energy near the accelerator grid.

A attempt to estimate the secondary ion flow to the accel grid from downstream region was done. The process of secondary ions creation and motion were examined. In order to calculate both the total secondary ion current and the local current density distribution near the downstream surface of the accel grid a physical-mathematical simulation was developed. Measurements of the accel grid current from the downstream region were made and compared with the calculated data.

Nomenclature

e	electron charge, C
k	Boltzmann's constant (MKS)
v_0	neutral thermal velocity, m/s
I_i	primary (beam) ion current, A
μ_i	ion mass, kg
n_x	neutral density, m^{-3}
σ_{ce}	charge exchange cross-section, m^2
R_0	ion beam origin radius, m
β_i	propellant utilization efficiency
T	thermal wall temperature of neutrals, ^0K

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1. Introduction

Department of Spacecraft Electric Propulsion and Powerplants of Moscow State Aviation Institute has been investigating the electrostatic thruster family for more than thirty years.

The only Electric Propulsion, and especially the ion thruster enables to full fill various space missions (for example, the interplanetary missions, flights to comets and asteroid, etc.) due to its high specific impulse. Light weight, low power and long lifetime are the advantages of using ion thruster in comparison with other types of the electric propulsion. The required thruster lifetime is over than 10000 hrs.

One of the main problem is the ion thruster lifetime limiting. At first, it is the discharge chamber cathode and the neutralisator operation time. Secondly, it is the extraction system in which the accel grid is scattered by the charge exchange ions. The praxis shows that more often than not the ion thruster lifetime is determined by the time of accel grid operation. Especially the string extraction grid has this problem. Its lifetime is not more than some thousand hours. Therefore its usage for the serious space purpose is limited though it has some advanced feature.

It is known that the erosion rate and speed of the accel grid depends on the secondary ion current density near the accelerator grid surface. So it would be desirable to have simple theoretical model to estimate the secondary ion flow to accel grid. We have developed the techniques to evaluate how much charge exchange particles are caught by the grid.

In the following sections the physical model, the theoretical calculation, the experimental measurements are described and the results are discussed.

2. Physical Model

Though the up-to-date ion thruster have a very high propellant utilization efficiency however it is less than 100 per cent. Some percentage of propellant are ejected as neutral particles. Their thermal velocity is about 300 meter per second. First particles portion goes away to outer space through the accel grid apertures. Second portion falls to the grid and can be reflected back to the accelerating region and to the discharge chamber. As a result the various interactions between the primary ions and the neutral particles can be in the electrode gap and the ion beam region. The most probable process is the electron exchange between the fast ion and the slow atom. The propellant slow ions are created inside the beam due to charge exchange reactions of the following type:

$$Xe^{+}_{fast} + Xe^{0}_{slow} \rightarrow Xe^{+}_{slow} + Xe^{0}_{fast}$$

As a result: a fast neutral travels in a space like the fast ion, and a slow ion has now the velocity of the previous neutral.

The creation of the charge exchange ions are taken place in two region. First of all it is a space between both the screen and decel electrodes or to be more exact a space between both plasma sheaths. Secondly, it is a downstream region. The slow ions generated near the plasma source sheath are accelerated and passed through the grid region. But on the other hand, the slow ions generated near the accel grid and especially decel space are attracted by negative potential and impinged on the grid surface, causing erosion.

Besides the secondary ions from the electrode gap some portion of the created slow ions comes back from a downstream region. The analysis shows that this portion is the most percent from the total secondary ion flow to accel grid. The charge exchange ions come to a sheath of the beam plasma and accelerated by the electrostatic field in direction of the accel grid.

The charge exchange process takes place practically at any distance from the ion thruster. However really only the secondary ions from approximately one diameter of thruster are importance. It will be shown below.

The primary ion flow in space of the neutral particles are considered. The charge exchange rate depends mainly on the neutral particles density. The needed neutrals distribution along radius and central axis can be obtained through calculation of a molecular flow near the round aperture in a thin diaphragm. This distribution can be found in the monograph about a gas dynamics[1]. It is represented in the Fig. 1.

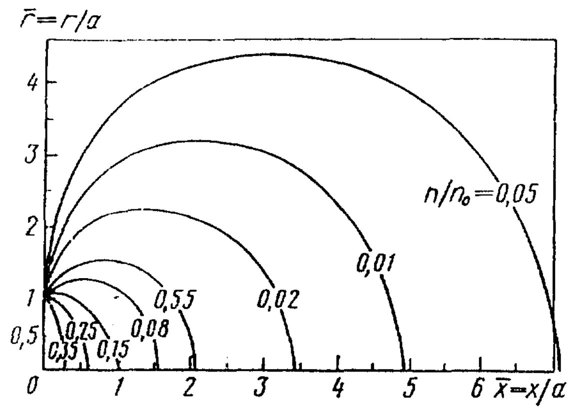

Fig.1 The distribution of the neutral density ($a=R_0$).

To determine the secondary ions portion which comes to the accel grid we assume the following. In spite of the fact that there is some potential distribution in the ion beam area the motion of the created secondary ions is equiprobable in all directions.

3. The calculation of the charge exchange ion flow from downstream region

3.1 The total current of the secondary ions

The schematic draw of physical-mathematical simulation is presented in the Fig.2.

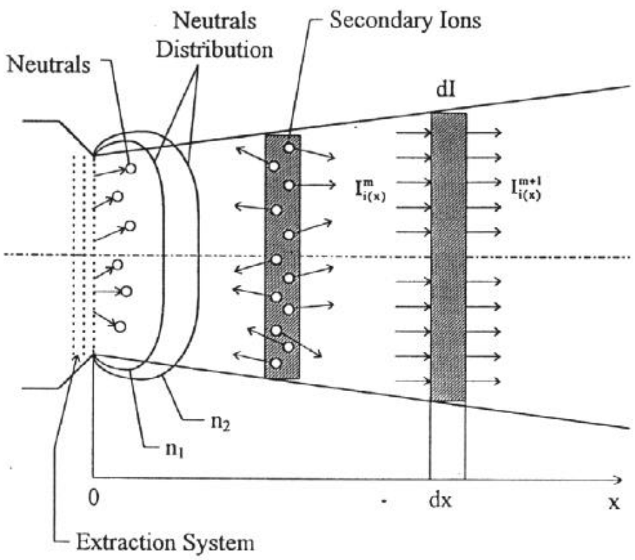

Fig.2 Schematic draw of physical-mathematical simulation.

The collimated ion beam is separated in the elementary disk with thickness dx. Within the range of the each disk the neutral particles density (n_x) and the ion beam current ($I_{i(x)}$) are assumed to be constant. In this application the flow of the created secondary ions in one disk is defined as:

$$dI_x = I_{i(x)} \cdot \sigma_{ce} \cdot n_x \cdot dx$$

The neutral particle density depends on the distance from thruster (x) through the following distribution:

$$n_x = n_0\left(1 - \frac{x}{\sqrt{x^2 + R_0^2}}\right)$$

The flux of the neutrals is the Knudsen efflux. It can be determined as $n_0 v_0/4$, where $v_0 = \sqrt{8kT/\pi\mu_i}$. The neutral density at the thruster exit is defined by the beam current and the propellant utilization efficiency by the relation:

$$n_0 = \frac{4I_{i0}}{ev_0S_n}\left(\frac{1-\beta_i}{\beta_i}\right)$$

where S_n is the flow-through area of the neutral propellant through the grids. Decreasing of the primary ion current can be defined as

$$I^{m+1}_{i(x)} = I^m_{i(x)} - dI_x,$$

where m is the disk number.

Now it is necessary to find that part of the flow (dI_x) which will be caught by the accel grid. In the radiation heat exchange theory there is the coefficient showing how much of the radiation flow from one surface will be irradiated to the other one. The coefficient depends on the geometric only. Therefore it is usually called the view factor. In our case it can be applied to an elementary disk (dx) and a disk placed on the accel grid surface. It serves to show how much of the secondary ions come down to the accel grid surface from the elementary disk (dx).

So the total secondary ion flow to the accel grid from a downstream region is calculated as

$$I_a = \sigma_{ce}\int_0^{\infty} I_{i(x)} n_x \varphi_x dx$$

The charge exchange cross-section (σ_{ce}) is taken according to a beam ion energy. It is enough to compute this integral approximately up to two ion beam radius (Fig.3).

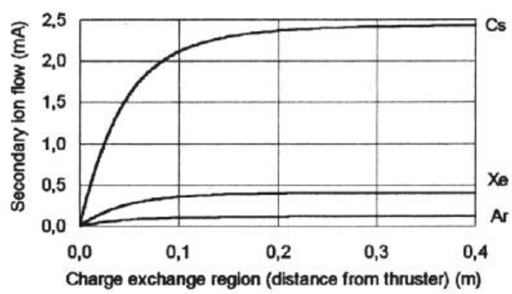

Fig.3 The secondary ion flow to accel grid depending on the length of a charge exchange region (R_0=0.1m; I_0=100mA).

The secondary ion current density depends on the ion thruster size (Fig.4).

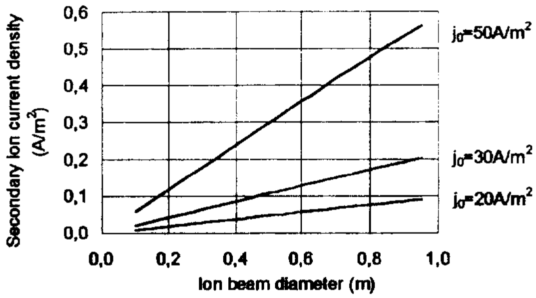

Fig.4 The influence of ion thruster diameter on secondary ion current density for various primary ion current density (j_0).

3.2 The view factor

Under uniform flux distribution along the irradiation surface the view factor is expressed as

$$\varphi = \frac{1}{A_1}\int_{A_1}\int_{A_2}\frac{\cos\beta_1\cos\beta_2}{\pi r^2}dA_1dA_2 \qquad (*)$$

where β_1, β_2 are the angles between normal vectors to elementary areas dA_1, dA_2 and a line connecting area center; r is the distance between the elementary areas.

As it was mentioned above the motion of the created secondary ions is equiprobable over all directions. It implies that the particle flow from a point must be distributed along a sphere surface uniformly.

To find the particle flow from any point of the remote disk dx to the accel grid disk one must calculate the integral (*) along two surfaces namely, the sphere (A_1) and the disk (A_2). Let us call the such view factor as the sphere(point)-disk view factor (φ_{SD} or φ_{PD}). Analytically the integral can be determined only if the sphere is placed at the centerline of the ion beam. In this case the result is given by

$$\varphi = \frac{1}{2}\left(1 - \frac{x}{\sqrt{x^2 + R_0^2}}\right).$$

In other cases the integral is calculated numerical only. The ring-disk view factor (φ_{RD}) is equal to the point-disk view factor (φ_{PD}) if the ring radius is equal to the distance between the point and the axis. The disk-disk view factor is calculated through the following equation

$$\varphi_{DD} = \frac{2\varepsilon}{R^2}\sum_{i=0}^{k}\varphi_{RD(i)}\, r_{(i)},$$

where $\varepsilon = R/(k+1)$ is the ring width, R is the radius of the irradiating disk, k is the ring count, $r_{(i)}$ is the average ring radius. The dependence of φ_{DD} on the distance from thruster is represented in Fig.5.

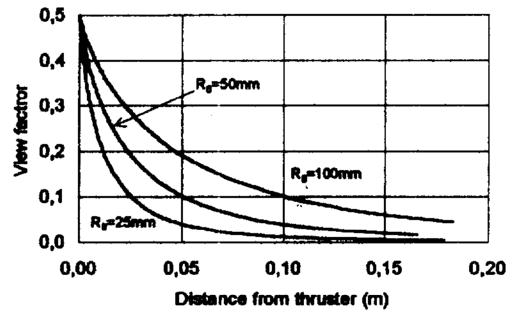

Fig.5 The view factor as a function of distance from thruster for various beam radiuses (beam divergence is 15^0).

3.3 The irregularity of the secondary ion current density

The experimental data show that on the accel grid there are some areas which are sputtered with the highest intensity. There is some irregularity of the secondary ion flow near the accel grid even if it is assumed regular distribution of the primary ion current density. So, with the highest intensity the grid central point is sputtered. The secondary ion current density is maximum here.

In order to calculate the irregularity the disk with thickness dx is separated to the rings with width dr. The disk placed on the accel grid is separated by the same manner. Then we must consider the flows from all rings of the disk dx to all rings of the accel grid disk.

The ring-ring view factor (φ_{RR}) can be defined by the following simple way:

$$\varphi_{RR} = \varphi_{RD1} - \varphi_{RD2}$$

where φ_{RD1}, φ_{RD2} is ring-disk view factors for external, internal disks correspondingly.

Summing up all flows near the accel grid and stepping through all disks in the interval $[0;x_{max}]$ one can obtain a dependence of the secondary ion current density on the accel grid disk radius. Furthermore, there is some flow in the area outside the ion thruster.

The qualitative view of irregularity is shown in the Fig.6.

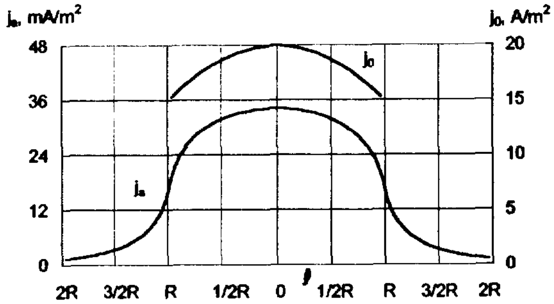

Fig.6 The irregularity of the secondary ion current density.

4. Experiment

To argument more exactly on the facts of the examined physical-mathematical simulation and to confirm its truth were carried out series of experimental measurements of the secondary ion flow to accel grid from downstream region.

4.1 Experimental apparatus

The ion thruster with diameter 50mm is used for experiment[2]. Its extraction system was hexagonal perforated with apertures. The screen and accel grid were manufactured by the same manner, in the form of molybdenum disks with cylindrical holes 2.5mm and 4.3mm correspondingly. The propellant can be fed through the cathode and discharge chamber independently. Xenon is used as propellant.

All the experiments were conducted with the thruster mounted on vertical centerline into vacuum chamber of $3m^3$ in volume. It was evacuated by two 50cm-diameter diffusion pumps in series with rotary vacuum pump. Total pumping efficiency was about 5000 liter per second. Under operating thruster conditions, vacuum chamber pressure was about 10^{-5} Torr. Propellant flow rate was within the range from 30 to 70 eq. mA.

4.2 The experiment procedure and results

In order to measure the secondary ion flow from downstream region only, a special construction was designed and assembled.

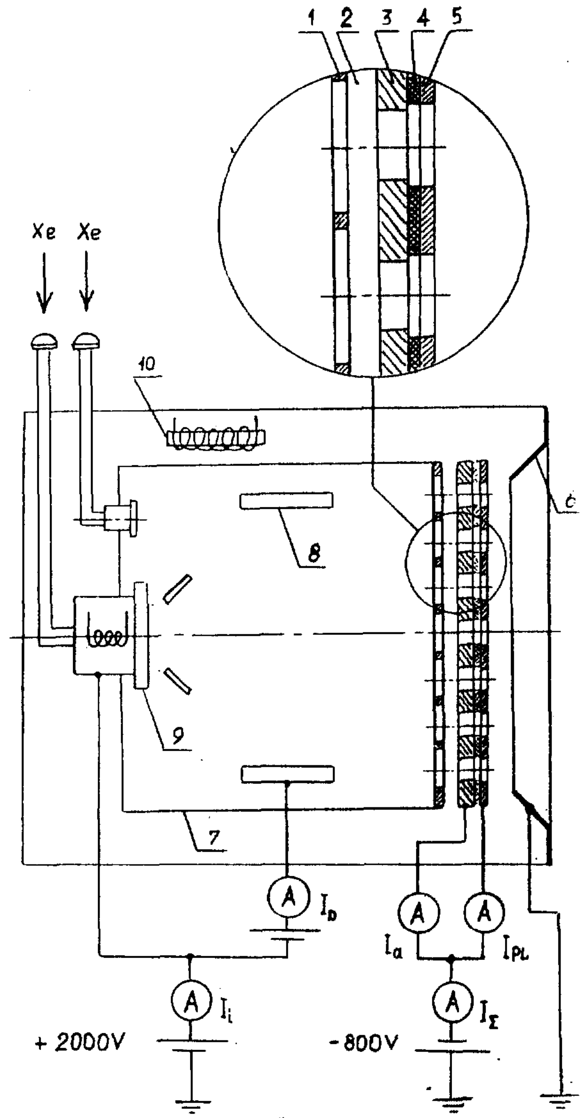

Fig.7 The measurement procedure. (1 - screen grid (Mo); 2 - intergrid gap; 3 - accel grid (Mo); 4 - insulator (kapton film); 5 - plate (stainless steel); 6 - decelerating electrode; 7 - discharge chamber; 8 - anode; 9 - cathode; 10 - magnet.

A metal plate was fixed on the accel grid from the side of ion beam exit. Its potential was equated the accel grid potential. The nonconductivity material was placed between the grid and the plate. The plate was made of stainless steel with 0.5mm thickness. The distance between the accel grid and the plate was 0.3mm. The plate was fixed to the accel grid with three screws by means of three ceramic inserts at the expense of three aperture in the accel grid. The screen grid aperture opposite to the screw was shutted up by the copper disk. The plate aperture diameter was some more than the accel grid one.

Of course, we sacrificed by three apertures from eighty five one. But under estimation, the error was about 5%. The wire lead was placed on the plate surface. The wire lead was conducted with a ammeter. Because the primary ion direct impingement to the plate was eliminated the plate registrated the ion flow from downstream region only.

Apart the plate current the primary ion current, the accel grid total current were measured. As a result of the experiment the dependence of the plate current (the secondary ion current from downstream region) on the primary ion current was plotted. A comparison between theoretical numerical values obtained with the help of above described method and experimental data is shown in Fig.8. As one can see there is a good correlation between them.

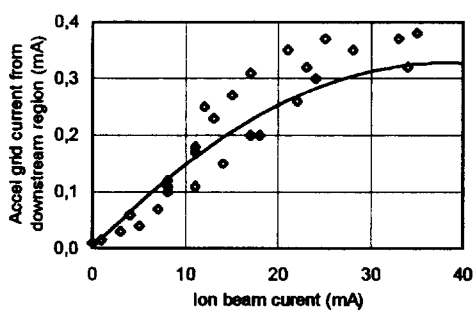

Fig.8 The experimental and theoretical data comparison (diamonds is experiment; a solid line is calculation).

Under calculation the background pressure in vacuum chamber was taken into account. We have to do it because the background pressure increases the neutral density in ion beam. This fact denotes that the charge exchange process carries more intensive.

Then, the numerical results were compared with the experimental data for ion thruster which operated in space. The data about space test missions of satellites ETS-III[3], ETS-VI[4] were used for this purpose. The calculation shows that a share of the secondary ion flow to accel grid from downstream region is about 90% of the measured accel grid total current.

5. Conclusion

We tried to estimate the secondary ion flow to accel grid from downstream region by simple way. The technique of the irregularity calculation of the secondary ion current density is considered. The experimental measurements of secondary ion flow are made. We obtained a good agreement between the theoretical and experimental data.

It is possible to conclude that the secondary ion current to accel grid from downstream region is the most part of total current to accel grid. We found that under beam constant current density there is the influence of the thruster size on the secondary ion current density.

Future work will be devoted more detailed analysis of the charge exchange process in a intergrid gap and a ion beam region. We plan to make additional experiments for another ion thruster sizes.

References

1. Koshmarov Yu.A., Rizhov Yu.A. Diluted gas applied dynamics. - Moscow.: Mashinostroenie, 1977 (in Russian).
2. Gorshkov O.A., Grigorian V.G., Kanev S.V., Minakov V.I., Muravlev V.A. An ion engine for small satellites. IEPC-95-94, 24th International Electric Propulsion Conference, Moscow, 1995.
3. Yoshihiro Nakamura. Development of Ion Thruster and Its Test Technology. IESJ, 1992 (REPRINT).
4. Sh. Kitamura. Review of electric propulsion in Japan. IEPC-95-2, 24th International Electric Propulsion Conference, Moscow, 1995.