1,000-hour Running of a 20-mN Ion Thruster with Pyrolytic Graphite Grids

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Abstract: To extend the life of an ion thruster, its original molybdenum grids were replaced by ones made of Pyrolytic Graphite (PG), whose sputter yields were lower than those of molybdenum. The objective of this study is to find unknown problems in a 1,000-hour running. The thruster with the PG grids ran for 1,061 hours and showed no degradation in thrust. Increase in the aperture diameter of the accelerator grid was 6% at most. A mechanism that carbon deposit on the accelerator grid could emit electrons, which virtually increased accelerator grid current and the deposit could be decreased by high voltage breakdowns might work frequently enough to suppress monotonical deposit growth. No significant issues to restrict the lives of the grids in further running were found.

Nomenclature

- g = gravity acceleration
- I = current
- M = atomic mass of xenon
- $\dot{m}$ = propellant flow rate
- α = thrust coefficient
- q = electric charge
- T = thrust
- V = voltage

Subscripts

- a = accelerator grid
- b = beam
- ck = main hollow cathode keeper
- d = discharge
- nk = neutralizer hollow cathode keeper
- MHC = main hollow cathode
- MPF = main propellant feed
- NHC = neutralizer hollow cathode

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I.Introduction

Japan Aerospace Exploration Agency (JAXA) has developed ion thrusters for KIKU-6, KAKEHASHI, and KIKU-8. The 20-mN ion thruster for KIKU-8 is applied to Super Low Altitude Test Satellite (SLATS), which is going to be launched in December 2017. However, practical super low altitude satellites succeeding SLATS require ion thrusters of longer lives. The endurance test of the KIKU-8 ion thrusters showed that their lives depended on the erosion of their grids, which were made of molybdenum and coated with ceramic. To extend the life of the ion thruster, its original molybdenum grids were replaced by ones made of Pyrolytic Graphite (PG), whose sputter yields were lower than those of molybdenum. We have already addressed matters in applying the PG grids to the ion thrusters: We conducted vibration testing of a PG screen gird and confirmed that it was sufficiently tough; we found that the thrust of the thruster with a set of PG grids was about 9.8% less than that of one with a set of molybdenum grids because the PG screen grid was thicker and the PG screen aperture was smaller than those of the molybdenum one[1]. The decrease in thrust is small enough and allowable for the use. The objective of this study is to find unknown problems in 1,000-hour running.

II.Pyrolytic Graphite

A PG screen grid is shown in Fig. 1. PG is produced by heating hydrocarbon to its decomposition temperature threshold, and permitting the graphite to crystallize. Carbon materials such as graphite and carbon-carbon(C/C) have been used for ion thruster grids because their sputter yields are lower than those of molybdenum[2-6]. Pyrolytic graphite (PG) is also a candidate for grids in ion thrusters[7]. PG is widely used for grids of ion accelerators at facilities of semiconductor manufacturing. The PG grid has lower structural stiffness than that a molybdenum one does and it must be thicker and have a lower aperture fraction.

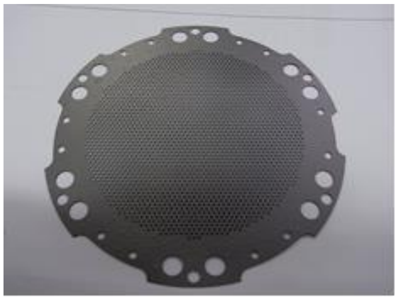

Figure 1. PG screen grid.

III.Thruster

A schematic view of the original thruster and a photograph of the thruster with PG grids are shown in Figs. 2 and 3, respectively. The thruster used in this study is of Kaufman type and characterized by series of two permanent magnets. It was an engineering model for KIKU-8 and had run for 17,456 hours in an endurance testing. We refurbished it and replaced both cathodes in addition to the grids. The original thruster adopted the three-grid ion optics while the refurbished one did the two-grid ion optics.

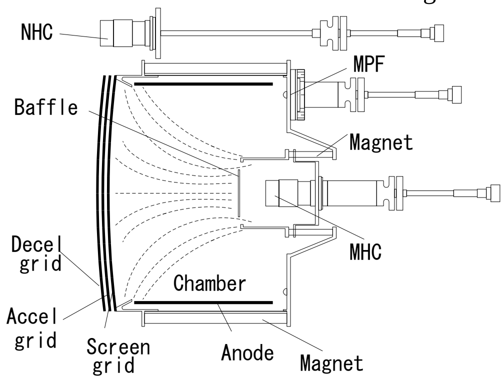

Figure 2. Schematic views of original thruster.

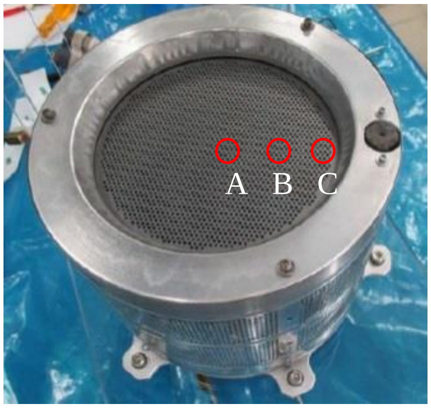

Figure 3. Photograph of thruster with PG grids (Red circles indicate locations where aperture diameters were measured.)

IV.Test Facility

The test was conducted in a vacuum chamber (3 m in diameter and 5 m in length) at JAXA and which chamber provided a vacuum pressure of about 1.8-2.5$\times 10^{-4}$Pa when the thruster was running. The power processing unit (PPU) and flow controllers are shown in Figs. 4 and 5, respectively. PPU was the bread board model for the SLATS thruster and the ratio of its accelerator grid voltage to screen grid voltage(-Va/Vb) had been fixed at 1/2. PPU was modified to change the ratio and we could choose it among 1/4, 1/3, and 1/2. Propellant was fed to the discharge and neutralizer cathodes and the plenum using a mass flow controller for each.

Figure 4. PPU.

Figure 5. Flow Controllers.

V. Continuous Running

Operating parameters are shown in Table 1. Before the continuous running, we switched the accelerator grid voltage to -1/3V_b to reduce the erosion of the accelerator grid by charge-exchange ions and to reduce beam divergence. Propellant flow rates were fixed at the same ones as of the SLATS thruster.

Table 1. Operating parameters.

Parameter	Value
V_b, V	900
V_a, V	-1/3V_b
I_d ,A	3
I_{ck} ,A	0.5
I_{nk} ,A	0.5
$\dot{m}_{MPF}$, sccm	6.5
$\dot{m}_{MHC}$, sccm	2
$\dot{m}_{NHC}$, sccm	2

The thrust is calculated using the following equation:

$$T = \alpha \cdot I_b \sqrt{2M \cdot V_b / q}$$

where the thrust coefficient α is 0.93 (Ref. 8).

The continuous running was conducted from Dec. 9, 2016 to Feb. 27, 2017 and the total operating time was 1061 hours. Shown in Fig. 6 is the thrust for 1061hours and no degradation in thrust occurred during the period. The thrust varied within 5% of its average and it was due to room temperature variation.

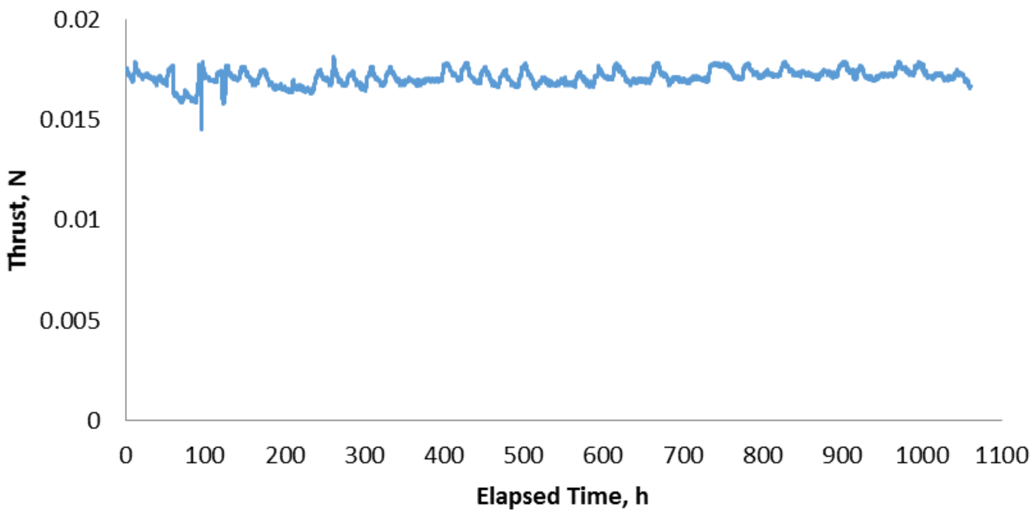

Figure 6. Thrust variation.

Shown in Fig. 7 are cumulative number of high voltage breakdowns (HVBD) and accelerator grid current. The number of HVBDs counted for 1,061 hours was 1,260. HBVDs are usually undesirable because they may accumulate damage in the grids and PPU and lose impulse expected. The damage was not evaluated quantitatively in this study and further study is required. A recycle after a HVBD was completed in 10 seconds and the loss in impulse was 0.33%. Comparing the inclination in the plot of the cumulative number of HVBDs−that is, the frequency of HBVDs−and the accelerator grid current suggests us a relation between them: The accelerator grid current suddenly decreased when the frequency of HVBDs were extremely high: For example, around 330 hours after and 560 hours after .

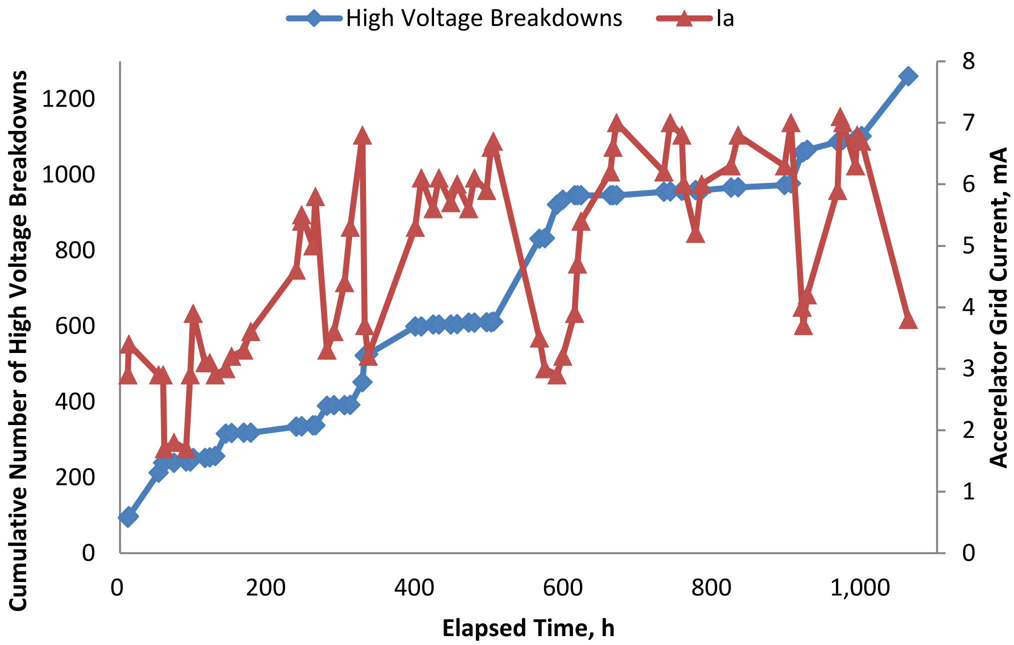

Figure 7. Cumulative number of high voltage breakdowns and accelerator grid current.

Growth in the aperture diameters of the accelerator grid in the running is shown in Table 2 and measurement was conducted at three locations shown in Fig. 3. The maximum growth was 1.06 and found in one of the diameters at Position B. The maximum growth was not found near the center of the grids−that is, at Position A−probably because the thruster was of Kaufman type, which had a baffle. On the other hands, erosion of the screen grid was unnoticeable. Shown in Fig. 8 are the downstream surface of the accelerator grid at Position B after 1,061 running and a magnification of it. The aperture shown in the magnification had deformed non-circularly and was not even symmetric with respect to the grid radius that penetrated the center of the aperture. This must be due to grid misalignment and the aperture was the most enlarged at five o'clock position. Furthermore, carbon deposit was found in an arc region, which was next to the perimeter and symmetric with respect to eleven o'clock position. Ion sputtering was not severe to suppress the growth in this region. Carbon deposit was not found in the regions in the middles of three neighboring apertures.

Carbon deposit was also found on the upstream surface of the accelerator grid and downstream surface of the screen grid (see Figs. 9 and 10). The aperture shown in Fig. 9 is not the same as that shown in the magnification in Fig. 8. The carbon deposit looks black and the original surface of the screen grid looks gray in Fig. 10. Although the thickness of the deposit on the downstream surface of the screen grid looked uniform, that on the downstream and upstream surfaces of the accelerator grid looked nonuniform: The deposit looked thicker where the erosion of the accelerator grid aperture was more significant. What we can guess from these facts is that most of the carbon sputtered out of the accelerator grid did come back to the accelerator grid. Carbon deposit on the grids did not seem solid or dense but seem sparse and fibrous. It can contain many nanotubes, which can work as micro cathodes if certain conditions are satisfied. We have not yet known the ability of the carbon deposit as micro cathode, however, the relation, which we showed using Fig. 7, may be explained as follows:

When the accelerator grid current increased, the deposit was growing and emitted more electrons; when the frequency of HVBDs was extremely high, the deposit was decreased and the accelerator grid current decreased as a result. The deposit might enhance the local electric field on the grid surface and cause HVBDs.

Table 2. Growth in Aperture Diameter of Accelerator Grid. (Diameter was normalized by that before running)

Position		A	B	C
Diameters	X	1-1.04	1.04-1.06	1
	Y	1	1	1

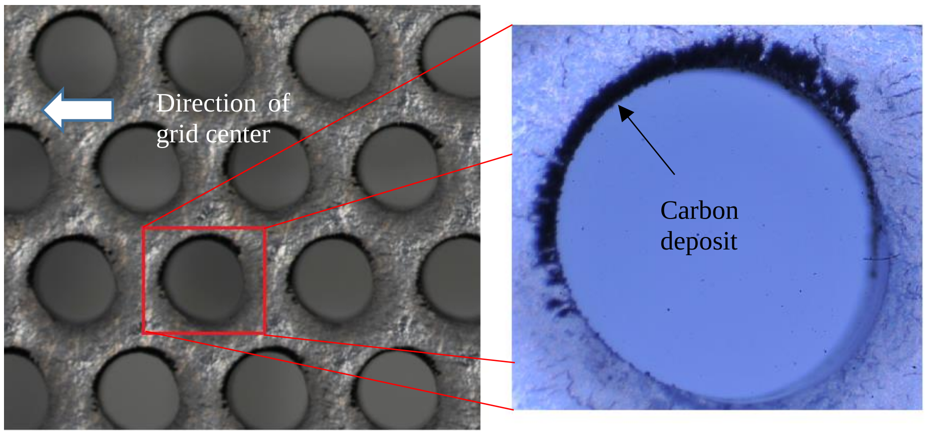

Figure 8. Accel grid downstream surface at Position B after 1061-hour running.

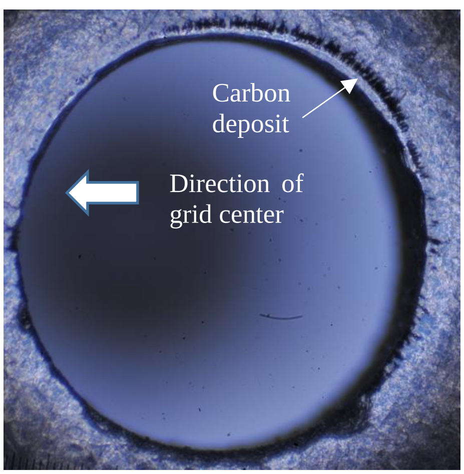

Figure 9. Upstream surface of accelerator grid at Position B after 1061-hour running.

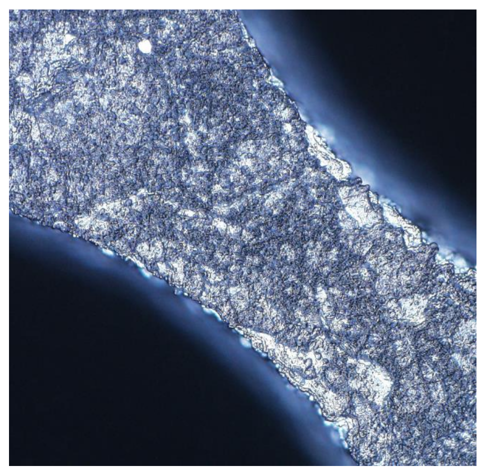

Figure 10. Deposit on downstream surface of screen grid after 1061- hour running.

VI.Conclusion

The thruster with the PG grids ran for 1,061 hours and showed no degradation in thrust. The aperture diameter growth in the accelerator grid was 6% at most and no significant issues to restrict the lives of the grids in further running were found. Carbon deposit was found on the downstream surface of the screen grid and both surfaces of accelerator grid. The frequency of HVBDs and the accelerator grid current were related to each other. A mechanism, which could explain the relation, was proposed.

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