Effects of Magnetic Field Configuration and Electrically-Floating Metal Plates in Hall Thrusters with Circular Cross-Sectional Discharge Chambers

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Abstract: The effects of magnetic field configuration in Hall thrusters with circular cross-sectional discharge chambers, named TCHT series, and carbon graphite disks inside the discharge chambers on thrust performance and its plume were examined. The secondary electron emission coefficient of carbon graphite is much smaller than that of boron nitride which is used as main material of the discharge room. The diameters of disks were varied from zero to 18 mm. The discharge current was reduced when the carbon graphite disk was equipped at a fixed discharge voltage although the thrust was hardly changed. With a carbon graphite disk d=12mm, the discharge current was reduced by 6-12% at discharge voltages of 100-300V. The thrust efficiency was improved by 6% with carbon graphite disks. Both the divergent angle of ion beam and the ion energy distribution function were not changed. Consequently, it is confirmed that both magnetic field configuration and carbon graphite disks have an effect on TCHT operation.

I. Introduction

The Hall thruster is a promising propulsion device for small satellites because of its high efficiency and thrust density. However, reducing Hall thruster dimension and input power results in significant decline of thrust performance. Accordingly, special design is required for low power Hall thruster. Rai'tses proposed a cylindrical Hall thruster that has circular cross-sectional ceramic discharge chamber. Because of large volume-to-surface ratio of the thruster, it suppresses an increase in ion flux to the wall accompanied by downsizing Hall thruster, and it prevents from overheating and erosion of thruster parts. Therefore, it will be preferable configuration as low power Hall thrusters. Smirnov designed and investigated miniature cylindrical Hall thruster, and their thruster achieved thrust efficiency of 15-32% in the power range of 50-300W.

Detailed effects of magnetic field configuration in cylindrical Hall thrusters is unknown, although it is much important to improve thrust performance. Hence, we investigated the effects with the cylindrical Hall thrusters named TCHT series in Osaka Institute of Technology. By applying strong radial magnetic field at the downstream region, Hall thruster TCHT-3B achieved higher thrust performance than TCHT-3A did at low power level because of a decrease in wall losses. However, when the position applied strong magnetic field was far downstream, the thrust efficiency was declined because of a decrease in ionization utilization. The result indicates that the thrust efficiency is optimized by adjusting the region applied large magnetic field. The optimized TCHT-3B had a high efficiency of 18-39% in the power range of 35-140W.

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In this study, more improvement is made. An electrically-floating metal plate disk is located at the upstream end of the discharge chamber in order to change discharge feature and plasma acceleration mechanism. Performance characteristics are measured with variations in disk diameter. Furthermore, plasma exhaust plumes are studied in order to examine the effect of metal disks.

II. Experimental Apparatus

Figure 1 shows the cross-sectional view of a low power Hall thruster named TCHT-3A. The discharge chamber consists of only a circular cross-sectional part with no coaxial parts. Although cylindrical Hall thrusters made by Raitses and Smirnov had short coaxial part, the coaxial part was excluded from TCHT-3A. Previously, we compared the operational characteristics of Hall thrusters with and without coaxial parts using the Hall thruster TCHT-2. Then,
Figure 2. Magnetic field strength and shape for TCHT-3A.

(a) Radial components.  
(b) Axial components. 
(c) Magnetic field lines.

The TCHT-2 without a coaxial part achieved higher thrust performance than that with a coaxial part did. Furthermore, the operation of the thruster without a coaxial part was quite stable. Hence, we excluded a coaxial part from TCHT-3.

The anode located at the upstream end of the circular cross-sectional part is made of copper. The thruster has a permanent magnet on the central axis, and the length and radius of the discharge chamber are 16mm and 14mm, respectively. TCHT-3A has a coil on the inner surface of the outer cylinder and a magnet on the thruster axis. The magnet is Sm-Co one because the degradation of magnetic property by heating is relatively small. Figure 2 shows the calculated magnetic field shape and strength for TCHT-3A. The magnetic field has an axial component, and the strength is the highest near the anode located at the upstream region.

An electrically-floating graphite disk is set on the back plate upstream of the discharge chamber. As shown in Fig.3, the disk diameter is changed from 0 to 18mm in order to examine the effects of the metal disks on performance characteristics and discharge features.

The hollow cathode (Iontech HCN-252) is employed as the electron emission source. Propellant gas is injected into the discharge chamber through four lines behind the anode. Xenon is used as the propellant and the working gas of the cathode.
The experimental facility is shown in Fig. 4. The thruster is operated in a water-cooled stainless steel vacuum chamber with 1.2 m in diameter and 2.25 m in length. The chamber is equipped with two compound turbo molecular pumps that have a pumping speed of 10000 l/s on xenon, several DC power supplies, and a thrust measurement system. The vacuum chamber pressure is kept about $3.0 \times 10^{-2}$ Pa under operation. A clean and high vacuum environment can be created by using the oil-free turbo molecular pump system.

Thrusts are measured by a pendulum method. The thruster is mounted on a thrust stand suspended with an aluminum bar, and the position of thruster is detected by an eddy-current-type gap sensor (non-contacting micro-displacement meter). It has a high sensitivity and good linearity. Thrust calibration is conducted with a weight and knife-edge arrangement which can apply a known force to the thruster under vacuum condition.

Exhaust plasma diagnostic measurement, as shown in Figs. 5-8, is also carried out to evaluate plume divergent angles and voltage utilization efficiencies. Ion current spatial profiles are measured with an ion collector, and ion energy distribution functions are estimated from data with a retarding potential analyzer (RPA). The ion collector and the RPA are located at 20 cm downstream from the thruster exit, and a motor rapidly, semi-circularly moves them.

**Figure 3.** Graphite disk arrangement for TCHT-3A.
Figure 4. Experimental facility system for Hall thrusters.

Figure 5. Configuration of ion collector.
Figure 6. Sweep system for ion collector.

(a) Retarding potential analyzer. (b) Photo.

Figure 7. Configuration of retarding potential analyzer.
Figure 8. Typical signal of retarding potential analyzer.

### III. Experimental Results and Discussion

Figure 9 shows the performance characteristics dependent on disk diameter at a xenon mass flow rate of 0.37g/s. The discharge current increases with increasing discharge voltage with all diameters of metal disks, and with above 250 V a rate of increase becomes small. The discharge current with a disk diameter of 12mm is the lowest of all diameters at a constant discharge voltage. The thrust, as shown in Fig.9(b), linearly increases with discharge voltage. When the disk diameter is changed, the difference in thrust is very small. Accordingly, although the thrust efficiency also increases linearly, it is the highest with a disk diameter of 18mm, and a rate of increase is 2-6% compared with cases with no disk.

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Figure 10 shows the spacial profiles of ion current with discharge voltages of 100, 200 and 300V. Figures 11 and 12 show the total ion current and the divergent half-angle of ion beam, respectively, dependent on discharge voltage with variations of disk diameter. All spacial profiles of ion current are almost axisymmetric ones. The total ion current increases with increasing discharge voltage although a rate of increase gradually become small. The total ion current is independent of diameter of metal disks. On the other hand, the divergent half-angle of ion beam, as shown in Fig.12, linearly decreases with increasing discharge voltage. The divergent half-angle ranges from 70 to 80%, and it is very large compared with those with conventional coaxial Hall thrusters like SPT, resulting from existance of large axial component of magnetic field in the cylindrical thruster. The divergent half-angle is also independent of disk diameter.

The ion energy distribution function is shown in Fig.13. Those profiles are well-known ones dependent on discharge voltage in ground-based experiments. The dependence of disk diameter is unclear.

Figure 14 shows the oscillation of discharge current dependent of disk diameter at a constant discharge voltage of 300V, and Figure 15 shows the oscillation amplitude at 200 and 300V. The oscillation observed is also popular one as well as those with coaxial Hall thrusters, and its frequency ranges from 10 to 20kHz. The oscillation

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(a) Discharge current.

(b) Thrust.

(c) Thrust efficiency.

Figure 9. Performance characteristics dependent on disk diameter at xenon mass flow rate of 0.37g/s.
Figure 10. Spacial profiles of ion current with discharge voltages of 100, 200 and 300V at xenon mass flow rate of 0.37g/s.
Figure 11. Total ion current vs discharge voltage characteristics dependent on disk diameter at xenon mass flow rate of 0.37g/s.

Figure 12. Divergent half-angle vs discharge voltage characteristics dependent on disk diameter at xenon mass flow rate of 0.37g/s.
Figure 13. Ion energy distribution functions with discharge voltages of 100, 200 and 300V at xenon mass flow rate of 0.37g/s.
Figure 14. Discharge current oscillations dependent on disk diameter at xenon mass flow rate of 0.37g/s.
Figure 15. Oscillation amplitude vs disk diameter characteristics with discharge voltages of 200 and 300V at xenon mass flow rate of 0.37g/s.

Figure 16. Mechanism of current conduction with carbon graphite disk in TCHT-3A.
amplitude, as shown in Fig.15, becomes small with metal disks compared with no disk. The oscillation amplitude at 300V decreases with increasing disk diameter although with a diameter of 18mm it increases.

Accordingly, the effect of metal disks in discharge chambers of cylindrical Hall thrusters is considered as follows. Electrons in the discharge chamber, as shown in Fig.16, move toward the upstream end near the central axis, and they are collides with the metal disk; just after it, secondary electrons are emitted from the metal disk. However, a number of the secondary electrons are very small compared with cases with boron nitride (BN) plate of electrically insulator. In other words, electron scattering on the upstream plate is hardly done with metal disks. As a result, it is difficult for electrons to move radially-outward; that is, because radial transport of electron across the magnetic field is difficult, the discharge current becomes small with metal disks. On the other hand, because high-energy electrons are kept in the discharge chamber, ionization may be enhanced although the thrust is almost constant with or without metal disk and regardless of disk diameter.

IV. Conclusions

A laboratory-model Hall thruster TCHT-3A was operated with carbon graphite disks at the bottom of the discharge room in order to change the performance characteristics. The diameters of disks were varied from zero to 18 mm.

1) The discharge current was reduced when the carbon graphite disk was equipped at a fixed discharge voltage although the thrust was hardly changed.

2) With a carbon graphite disk d=12mm, the discharge current was reduced by 6-12% at discharge voltages of 100-300V. The thrust efficiency was improved by 6% with carbon graphite disks.

3) Both the divergent angle of ion beam and the ion energy distribution function were not changed.

Consequently, it is confirmed that carbon graphite disks have an effect on TCHT operation. The effect can be explained from the difference in secondary electron emission coefficient between carbon graphite and boron nitride.

References