Thrust Performance and Plasma Acceleration Process of Hall Thrusters

ホールスラスタの推進性能とプラズマ加速過程

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Abstract

Basic experiments were carried out using the THT-IV low-power Hall thruster to examine the influences of magnetic field shape and strength, and acceleration channel length on thruster performance and to establish guidelines for design of high-performance Hall thrusters. Thrusts were measured with varying magnetic field and channel structure. Exhaust plasma diagnostic measurement was also made to evaluate plume divergent angles and voltage utilization efficiencies. Ion current spatial profiles were measured with a Faraday cup, and ion energy distribution functions were estimated from data with a retarding potential analyzer. The thruster was stably operated with a highest performance under an optimum acceleration channel length of 20 mm and an optimum magnetic field with a maximum strength of about 150 Gauss near the channel exit and with some shape considering ion acceleration directions. Accordingly, an optimum magnetic field and channel structure is considered to exist under an operational condition, related to inner physical phenomena of plasma production, ion acceleration and exhaust plasma feature. A new Hall thruster was designed with basic research data of the THT-IV thruster. With the thruster with many considerations, long stable operations were achieved. In all experiments at 200-400 V with 1.5-3 mg/s, the thrust and the specific impulse ranged from 15 to 70 mN and from 1100 to 2300 sec, respectively, in a low electric power range of 300-1300 W. The thrust efficiency reached 55 %. Hence, a large map of the thruster performance was successfully made. The thermal characteristics were also examined with data of both measured and calculated temperatures in the thruster body. Thermally safe conditions were achieved with all input powers.

Introduction

The closed-electron-drift Hall-effect thruster is a promising propulsion device in space. The performance has been improved in Russia since 1960s[1]. Because 1-2 kW class Hall thrusters can achieve a high performance of thrust 50-100 mN and thrust efficiency 40-50 % at specific impulses of 1000-2000 sec, they are expected to be used as main thrusters for near-earth missions in the United States and Europe[2,3]. Even in Japan, the high performance attracts attention of mission planners[4-8]. However, the detailed physics on plasma characteristics and ion acceleration processes is still unclear. We need both basic and practical studies in order to improve Hall thruster performance by understanding inner physical phenomena.

In Osaka University, an experimental facility was constructed in 1997 to study plasma production and acceleration processes and unstable operational phenomena in low power Hall thrusters and also to examine spacecraft and plasma plume interactions[4,5]. Basic experiments were made using THT-series low-power Hall thrusters to obtain fundamental operational characteristics. The influences of material, width and length of acceleration channel on thruster performance were mainly investigated[6,7]. As a result, the THT-IIIA thruster could be stably operated in a wide range of magnetic field strength. A high thrust efficiency was achieved with a low discharge current and a high thrust for a preferable magnetic field strength regardless of discharge voltage at a constant mass flow rate. Both the thrust and the specific impulse ranged from 10 to 70 mN and from 1200 to 2300 sec, respectively, at discharge voltages of 200-500 V with mass flow rates of 1-3 mg/s in a wide input power range of 250-1800 W. The thrust efficiency ranged from 30 to 45 %. Furthermore, one-dimensional thruster flowfield calculation, in which an axial motion of ions; axial and azimuthal motions of electrons perpendicular to magnetic field were considered, was carried out[7-9]. The model included first ionization by direct electron-neutral collisions, electron-neutral elastic collisions, electron-ion Coulomb collisions, Bohm diffusion (anomalous diffusion); channel wall losses of ion flux and electron energy flux with secondary electron emission effect. The flowfield in an acceleration channel was divided into diffusion, ionization and ion acceleration regions. Both ionization and acceleration were found to, intensively and efficiently, occur in their thin regions with a few mm thick near the acceleration channel exit. The calculated thruster performance roughly agreed with experimental ones. Currently, a joint development of low power Hall thrusters between Osaka University and Ishikawajima-Harima Heavy Industries Co., Ltd. started in 1999[10,11].

In the present study, more basic experiments are made using the THT-IV thruster to examine the influences of magnetic field shape and strength, and acceleration channel length on thruster performance and to establish guidelines for design of high-performance Hall thrusters. Discharge currents and thrusts are measured with varying discharge voltage, mass flow rate, magnetic field shape and strength, and acceleration channel length; specific impulses and thrust efficiencies are evaluated. Exhaust plasma diagnostic measurement is also carried out to evaluate plume divergent angles and voltage utilization efficiencies. Ion current spatial profiles are measured with a Faraday cup, and ion energy distribution functions are estimated from data with a retarding potential analyzer. The characteristics of optimum magnetic field are discussed. A new Hall thruster is designed with basic research data of THT-series thrusters. With the thruster with many considerations, long stable operations are conducted so as to examine flight model design.

Experimental Apparatus

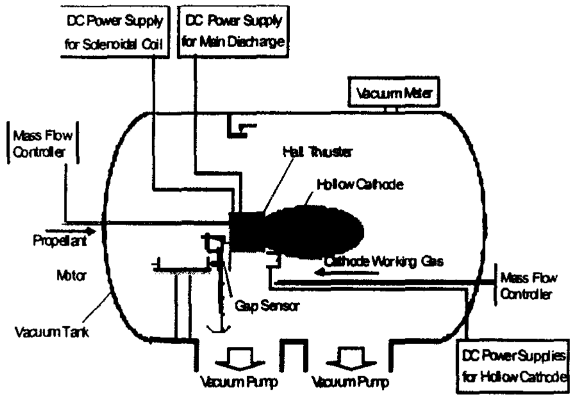


Fig.1 Experimental facility of Hall thruster for thrust measurement.

The experimental facility, as shown in Fig.1, mainly consists of a water-cooled stainless steel vacuum tank 1.2 m in diameter x 2.25 m long, two compound turbo molecular pumps, several DC power supplies and a thrust measurement system[4-7,10]. The setup is changed in plasma plume diagnostic measurement. The vacuum tank pressure is kept a range of 10^{-3}-10^{-4} Pa under operations. A clean and high vacuum environment can be created by using the oil-free turbo molecular pump system, which is useful to study contamination due to Hall thruster plumes.

Thrusts are measured by a pendulum method, as shown in Fig.1. A Hall thruster is mounted on a thrust stand suspended with an aluminum bar, and the position of the thrust stand is detected by an eddy-current-type gap sensor (non-contacting micro-displacement meter). It has a high sensitivity and a good linearity. Thrust calibration is conducted with a weight and pulley arrangement which is able to apply a known force to the thrust stand under vacuum environment. With this design, friction force was small, and it resulted in no measurable hysteresis.

The THT-IV thruster, as shown in Figs.2 and 3, has an acceleration channel with an outer diameter of 70 mm and an inner diameter of 42 mm, i.e., with14 mm in width, and the channel length can be changed from 15 to 30 mm. The

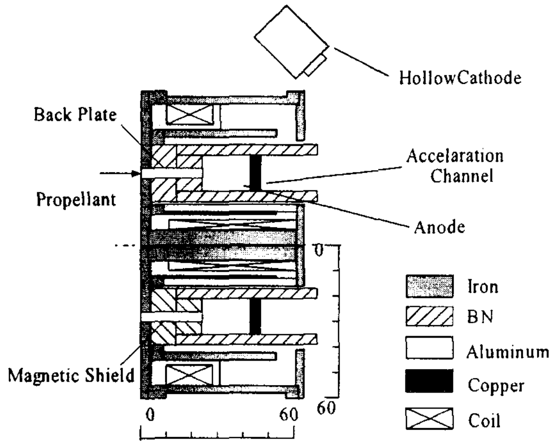
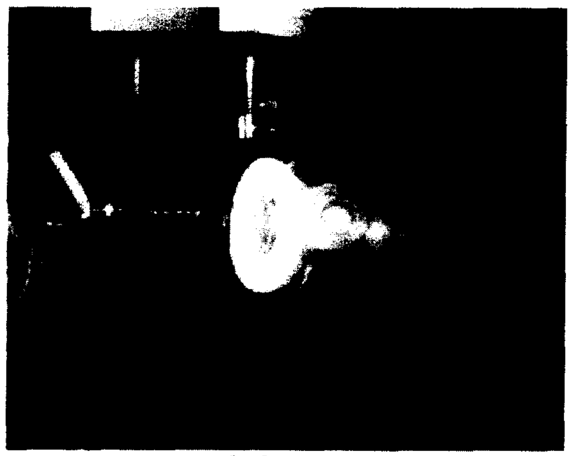


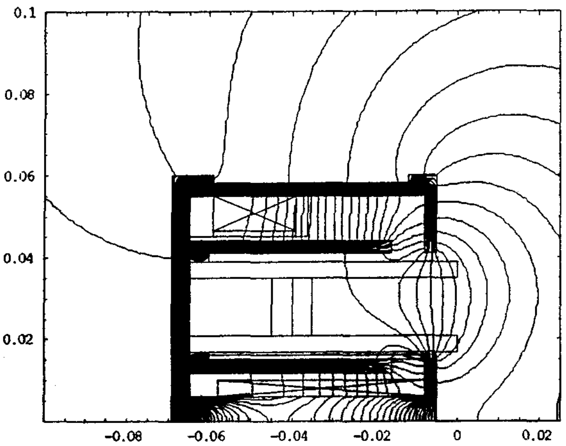
Fig.2 Cross sectional view of THT-IV Hall thruster.

(a) Thruster overview

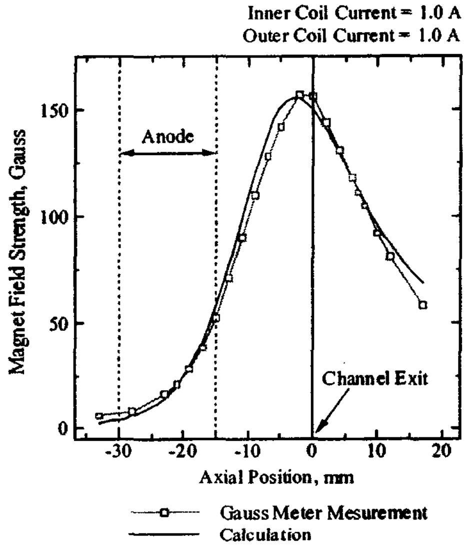


(b) Operation

Fig.3 Photographs of THT-IV thruster overview and operation.



(a) Calculated magnetic field shape.

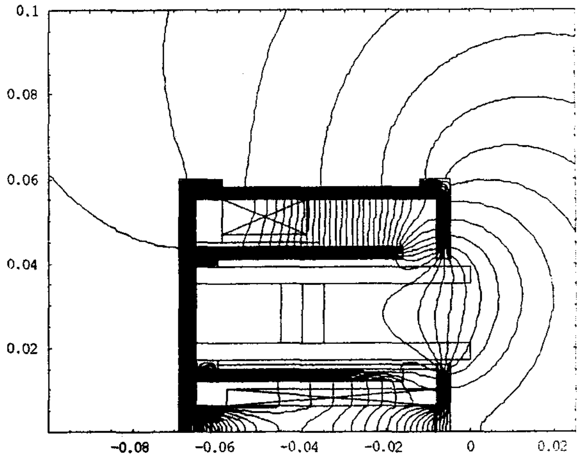


(b) Calculated and measured radial magnetic field strengths on radially intermediate region in acceleration channel.

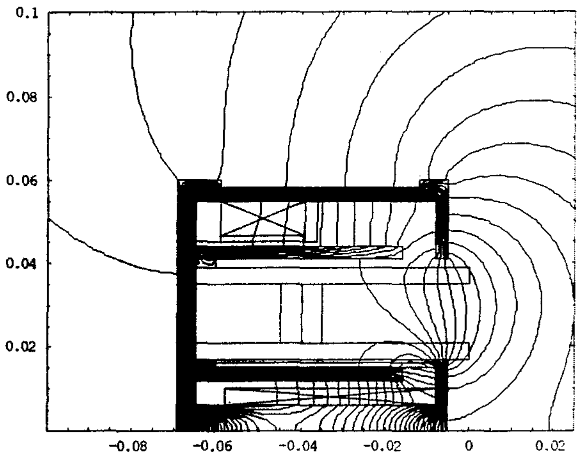
Fig.4 Magnetic field shape and strength with inner and outer coil currents of 1 and 1 A.

wall material of the acceleration channel is boron nitride (BN) ceramics. The anode is made of copper. The hollow cathode (Iontech HCN-252) is used as the main cathode. After propellant gas is introduced from 4 lines into a plenum chamber behind the anode, it is uniformly injected from 24 ports azimuthally drilled on the anode into the acceleration channel.

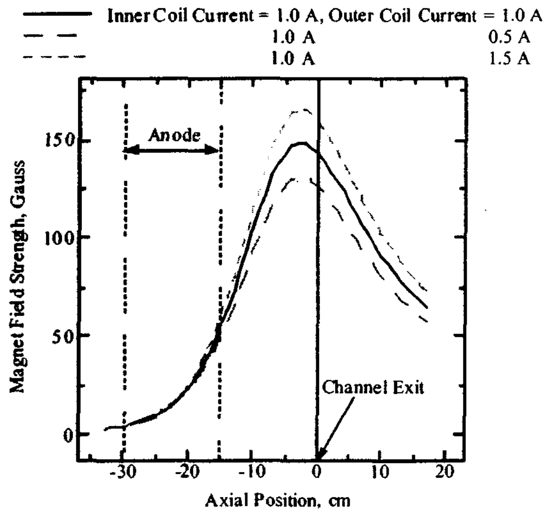
The thruster has the magnetic coils on the central axis and on the inner surface of the outer cylinder. Because the two coil currents can be separately controlled, magnetic field shape and strength in the acceleration channel can be changed in order to find out optimum magnetic field structure. Figure 4 shows the magnetic field shape and strength with an inner coil current of 1 A and an outer one of 1 A. In Fig.4(b), the radial magnetic field strengths on the radially intermediate region in the acceleration channel are presented. The measurement was made with a Gauss meter. The calculated magnetic field strength agrees with the measured one. The magnetic field strength decreases



(a) With inner and outer coil currents of 0.75 and 1.5 A.



(b) With 1.25 and 0.5 A.



c) Radial magnetic field strengths on radially intermediate region in acceleration channel.

Fig.5 Calculated magnetic field shapes and strengths with several inner and outer coil currents.

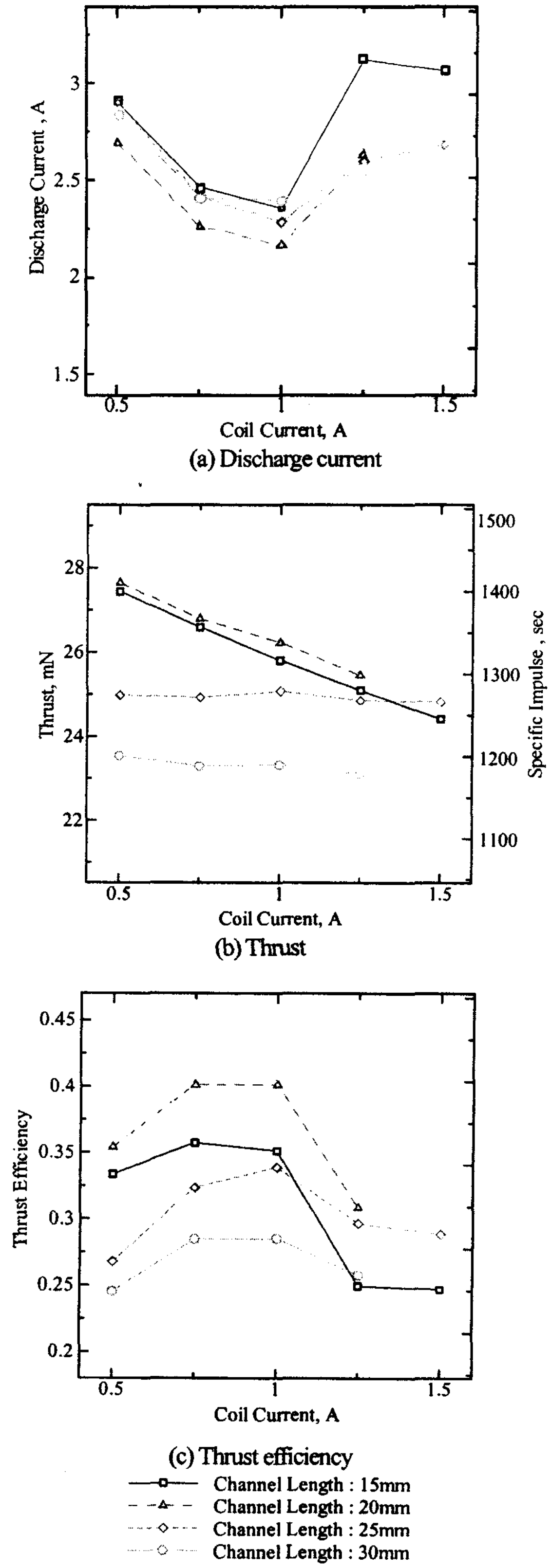


Fig.6 Performance characteristics with inner and outer coil current ratio of 1:1 dependent on acceleration channel length at discharge voltage of 200 V and mass flow rate of 2 mg/s.

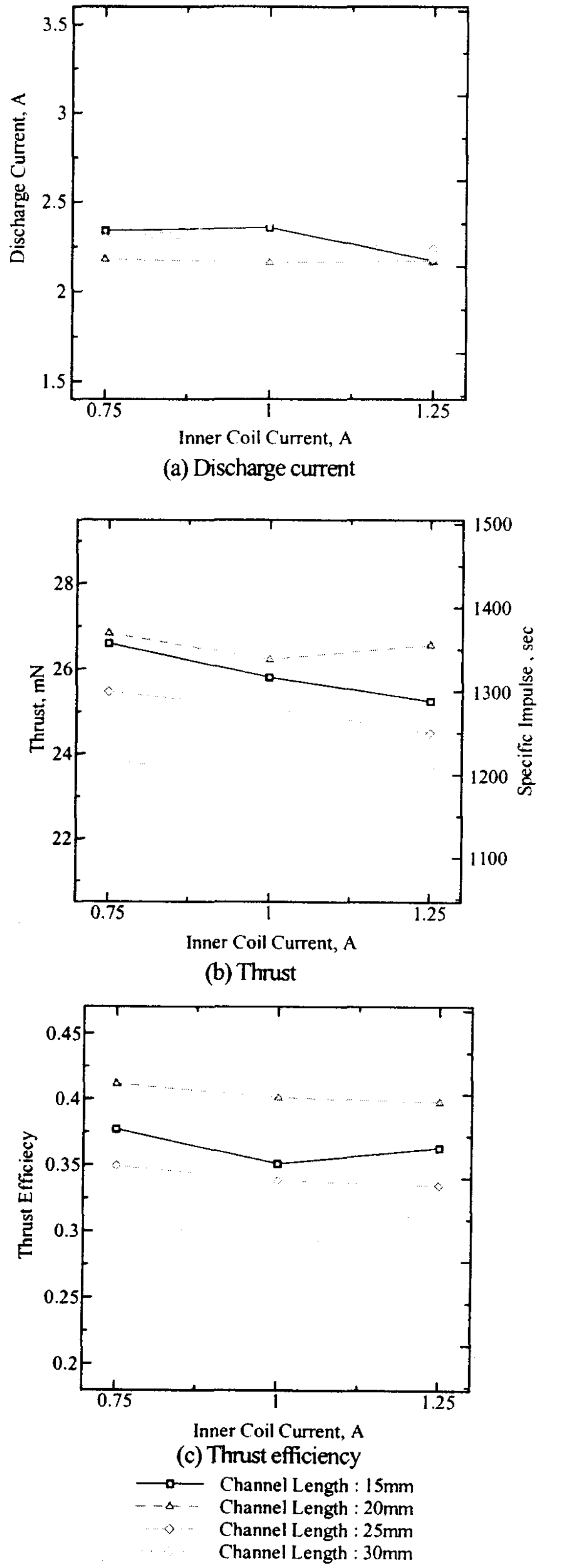
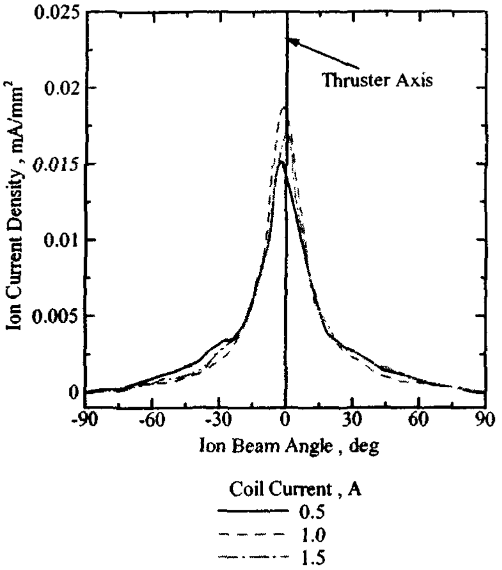
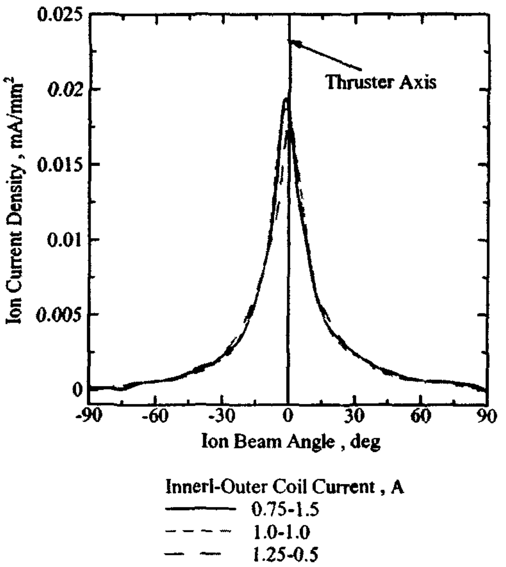


Fig.7 Performance characteristics with maximum magnetic field strength of about 150 Gauss dependent on acceleration channel length at discharge voltage of 200 V and mass flow rate of of 2 mg/s.



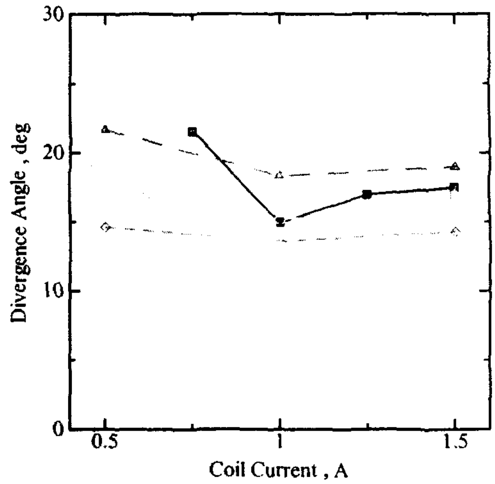
(a) With inner and outer coil current ratio of 1:1.



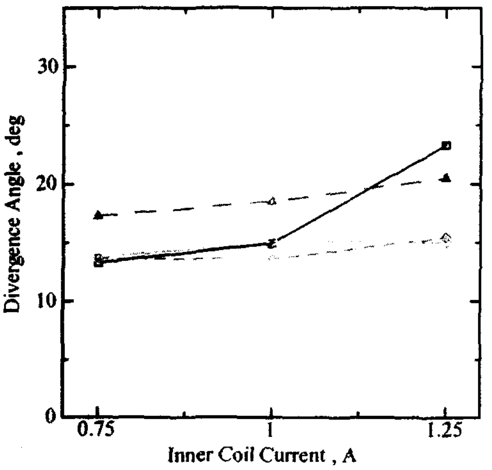
(b) With maximum magnetic field strength of about 150 Gauss.

Fig.8 Ion current density profiles by Faraday cup with acceleration channel length of 20 mm at discharge voltage of 200 V and mass flow rate of 2 mg/s.

as distance to the anode decreases, and it has a maximum near the channel exit and a minimum at the anode. Figure 5 shows the magnetic field shapes and strengths calculated with inner and outer coil currents of 0.75 and 1.5 A; 1.25 and 0.5 A. Although the all axial variations in radial magnetic field strength, as shown in Fig.5(c), have a same maximum of about 150 Gauss near the channel exit, the field shapes are extremely different. When the ratio of inner coil current to outer one increases from 0.75/1.5 to 1.25/0.5, the downstream directions perpendicular to magnetic field lines near the channel exit are changed from radially-inward directions to radially-outward ones.



(a) With inner and outer coil current ratio of 1:1.



(b) With maximum magnetic field strength of about 150 Gauss.

Fig.9 Plasma plume divergent half-angle characteristics dependent on acceleration channel length at discharge voltage of 200 V and mass flow rate of 2 mg/s.

Accordingly, because main discharge location and ion trajectory can be roughly predicted from these characteristics, ionization process in the acceleration channel, ion losses on the channel wall and plasma plume feature are inferred.

Xenon is used as propellants. In a series of experiments, discharge currents and thrusts are measured with varying discharge voltage, mass flow rate, magnetic field shape and strength, and acceleration channel length; specific impulses and thrust efficiencies are evaluated. Exhaust plasma diagnostic measurement is also carried out to evaluate plume divergent angles and voltage utilization efficiencies. Ion current spatial profiles are measured with a Faraday cup, and ion energy distribution functions are estimated from data with a retarding potential analyzer

(RPA). The Faraday cup and the RPA are located at 20 cm downstream from the thruster exit, and a motor rapidly, semi-circularly moves them.

Experimental Results and Discussion

Operational Characteristics Dependent on Magnetic Field Shape and Strength

Figure 6 shows the performance characteristics with an inner and outer coil current ratio of 1:1 dependent on acceleration channel length at a discharge voltage of 200 V and a mass flow rate of 2 mg/s. As shown in Fig.4, the maximum magnetic field strength near the channel exit is changed from 105 Gauss at 0.5 A to 210 Gauss at 1.5 A although the field shape is not changed. The discharge current characteristic has a minimum at a coil current of 1 A, i.e., at a maximum magnetic field strength of about 150 Gauss. The thrust and the specific impulse decrease with increasing magnetic field strength. The ratio of decrease is constant with channel lengths of 15 and 20 mm although it is very small with channel lengths of 25 and 30 mm. As a result, the thrust efficiency has a maximum near 150 Gauss. With a channel length of 20 mm, a high thrust efficiency of 40.1 % is achieved at a specific impulse of 1337 sec. These characteristics agree with those for the THT-III thruster[7].

Figure 7 shows the performance characteristics with a maximum magnetic field strength of about 150 Gauss dependent on acceleration channel length at a discharge voltage of 200 V and a mass flow rate of 2 mg/s. As shown in Fig.5, the magnetic field shape is changed with inner and outer coil currents of 0.75 and 1.5 A, 1 and 1 A; 1.25 and 0.5 A although the maximum field strength near the channel exit is kept about 150 Gauss. In Fig.7, an inner coil current is represented. When the inner coil current increases and the outer coil current decreases, the thrust and the specific impulse decrease. This is expected because the magnetic field strength near the anode slightly becomes large, as shown in Fig.5(c), resulting in ionization and wall loss enhanced in the upstream region of the channel. As an another reason, it is considered that the exhaust plasma intensively expands radially-outward as predicted from the magnetic field lines in Figs.4 and 5; that is, the divergent angle of plasma plume becomes large as shown below. The discharge current also slightly decreases with increasing inner coil current although the ratio of decrease is very small. Accordingly, a maximum thrust efficiency is achieved with the smallest inner coil current of 0.75 A and the highest outer coil current of 1.5 A, and then it reaches 41.2 % at a specific impulse of 1367 sec.

Operational Characteristics Dependent on Acceleration Channel Length

As shown in Figs.6 and 7, the thruster performance is very sensitive to acceleration channel length. The discharge current shown in Figs.6(a) and 7(a) is the smallest with a channel length of 20 mm at a constant coil current although the thrust and specific impulse shown in Figs.6(b) and 7(b) are the highest. As a result, the thrust efficiency is the highest with 20 mm. This is explained as follows. A short channel of 15 mm does not have an enough length for ionization. On the other hand, with long channels of 25 and 30 mm, ion losses on the channel wall are relatively large. Accordingly, there exists an optimum channel length to achieve high performance.

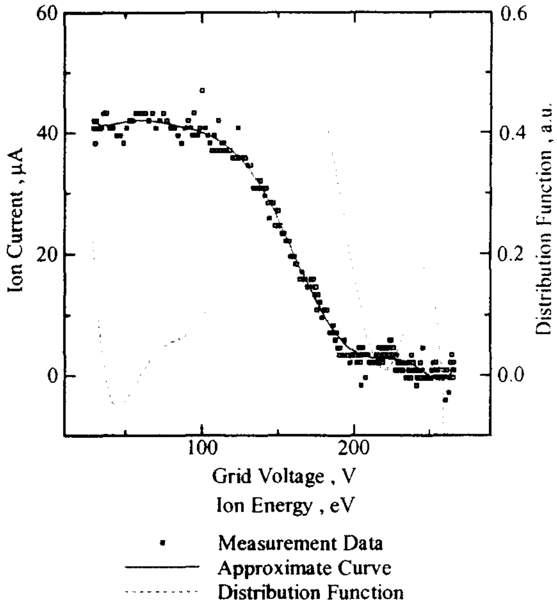
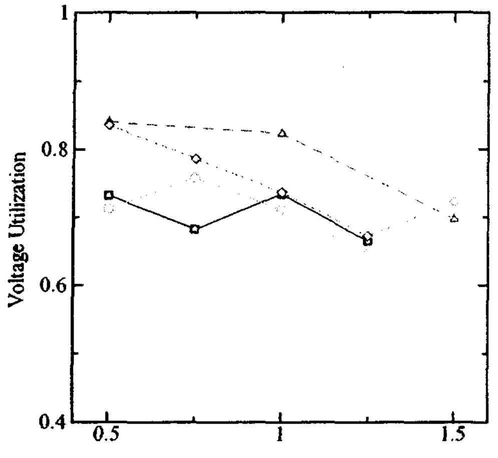


Fig.10 Ion current and ion distribution function profiles by retarding potential analyzer on central axis with 30 mm at 200 V and 2 mg/s for inner and outer coil currents of 1 and 1 A.

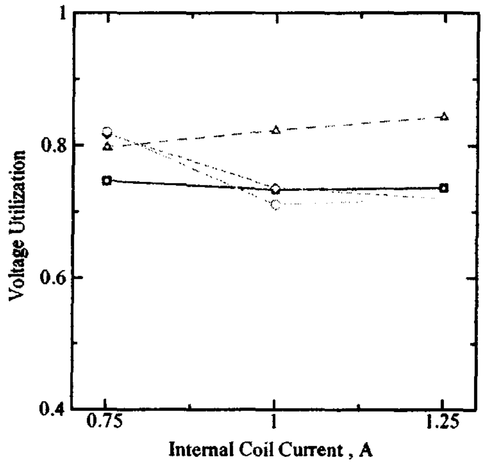
Exhaust Plasma Plume Characteristics

Figure 8 shows the ion current density profiles by a Faraday cup with an acceleration channel length of 20 mm at a discharge voltage of 200 V and a mass flow rate of 2 mg/s. Figure 9 shows the plasma plume divergent half-angle characteristics independent on acceleration channel length. The divergent half-angle is calculated from a half-width of the fitting profile. As shown in Fig.8(a), the peak of ion current density on the central axis increases with coil current, i.e., with magnetic field strength, and in ranges from -60 to -20 deg and from +20 to +60 deg the ion current density decreases. As a result, an increase in magnetic field strength produces a more convergent ion beam. The divergent half-angle, as shown in Fig.9(a), decreases from 21.7 deg at 0.5 A to 18.2 deg at 1.5 A with a channel length of 20 mm.

As shown in Fig.8(b), when the inner coil current increases and the outer coil current decreases under a maximum magnetic field strength of about 150 Gauss near the channel exit, the peak of ion current density on the central axis decreases, and near -20 and +20 deg the ion current density slightly increases. Accordingly, the exhaust plasma expands more radially-outward as predicted from the thrust characteristics in Fig.7(b). The divergent half-angle, as shown in Fig.9(b), increases from 17.2 deg at inner and outer coil currents of 0.75 and 1.5 A to 20.5 deg at1.25 and 0.5 A with a channel length of 20 mm. Also, a ratio of plasma divergence loss to total kinetic energy is roughly estimated to be below 10 %.



(a) With inner and outer coil current ratio of 1:1.



(b) With maximum magnetic field strength of about 150 Gauss.

Fig.11 Voltage utilization efficiency characteristics dependent on channel length for inner and outer coil currents of 1 and 1 A.at 200 V and 2 mg/s.

Figure 10 shows typical ion current and ion distribution function profiles by a RPA on the central axis with an acceleration channel length of 30 mm at a discharge voltage of 200 V and a mass flow rate of 2 mg/s for inner and outer coil currents of 1 and 1 A. Figure 11 shows the voltage utilization efficiency characteristics dependent on acceleration channel length. In Fig.10, two peaks near ion energies of 160 and 250 eV in the ion distribution function exist with a discharge voltage of 200 V. They correspond to single and double charged ions, respectively. It is expected that the double charged ions are produced through the enough downstream plasma. A number ratio of the single to double charged ions is roughly estimated to be about 10 % from their area ratio in the ion distribution function. It is not negligible for improving thruster performance.

The voltage utilization efficiency, as shown in Fig.11(a), decreases with increasing coil current, i.e., with increasing magnetic field strength. This is expected because the ionization and acceleration region become longer with a stronger magnetic field inside the acceleration channel. With this, the thrust characteristics shown in Fig.6(b) can be explained. As shown in Fig.11(b), the voltage utilization efficiency decreases with increasing inner coil current and with decreasing outer coil current except for case with a channel length of 20 mm. This is also because the magnetic field strength inside the acceleration channel, specially near the anode, slightly increases with a higher inner coil current and a smaller outer coil current, resulting in ionization and acceleration enhanced in the upstream region of the channel.

In Fig.11, the voltage utilization efficiency is the highest at an acceleration channel of 20 mm with a constant magnetic field strength although it is relatively low at 15 and 30 mm. This dependence on channel length agrees with the thruster performance shown in Figs.6 and 7.

Ion acceleration features dependent on magnetic field strength are summarized as follows. With a high magnetic field strength inside the acceleration channel, ionization and acceleration occur in a relatively upstream region in the channel. Therefore, although ion beam divergence is suppressed, ion losses on the channel wall are enhanced. With a weak magnetic field, ion production and acceleration concentrate near the channel exit. Although ion beams are slightly expanded radially-outward, wall losses are very small. In magnetic field shape, on the viewpoint of plasma plume feature it is suitable that downstream directions perpendicular to magnetic field lines near the channel exit are parallel to the central axis or slightly radially-inward. As for acceleration channel length, total wall losses are relatively large with a long channel although an ionization and acceleration region is too short in a short channel. Consequently, an optimum magnetic field and channel structure is expected to exist under an operational condition, related to inner physical phenomena of plasma production, ion acceleration and exhaust plasma feature.

New Thruster Design and Performance

A new Hall thruster, as shown in Fig.12, was designed with basic research data of the THT-IV Hall thruster in collaboration with Ishikawajima-Harima Heavy Industries Co., Ltd.[10,11]. The thruster has some heat shields for protection of heat from high temperature walls of the acceleration channel to the main body and a gas manifold for azimuthally-uniform propellant injection. The inner and outer channel walls are parts of a solid sintered body, and magnetic coils are made from a special wire for high temperature use. Furthermore, both electrical power and propellant gas are introduced from the cylindrical side of the thruster body. Accordingly, long stable operations can be achieved so as to examine flight model design.

The magnetic field shape and strength in the acceleration channel could be changed with varying inner and outer coil currents. Because the operational characteristics were sensitive to magnetic field structure, an optimum magnetic field condition was determined from

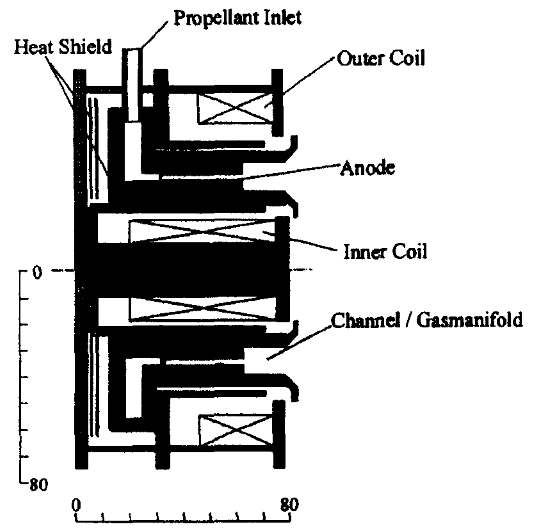
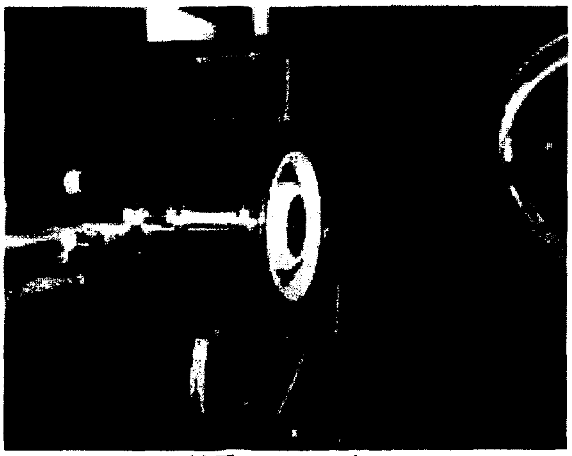
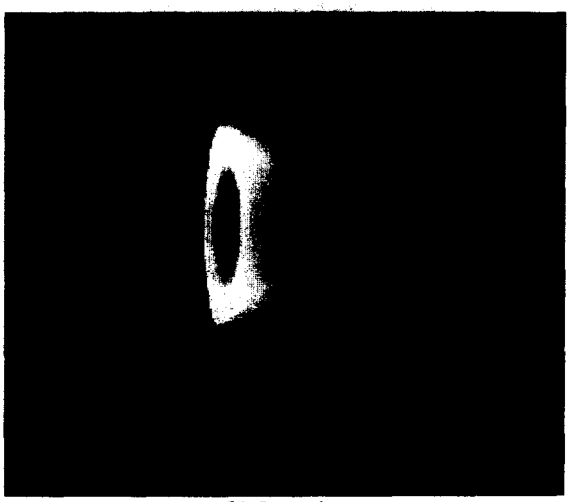


Fig.12 Cross sectional view of new Hall thruster with high performance and high durability.



(a) Thruster overview



(b) Operation

Fig.13 Photographs of new thruster overview and operation.

discharge stability, thruster performance and plasma plume feature. The Hall thruster, as shown in Fig.13, was operated at discharge voltages of 200-400 V with mass flow rates of 1.5-3 mg/s in a low electric power range of 300-1300 W. The thrust and the specific impulse ranged from 15 to 70 mN and from 1100 to 2300 sec, respectively. The thrust efficiency reached 55 %. Hence, a large map of the thruster performance was successfully made.

Temperature distributions of the thruster body were measured with lots of thermocouples in order to examine the thermal characteristics[11]. Unsteady thermal analysis was also carried out. The temperatures measured with 700 W rapidly increased just after the discharge ignition and approached some values around 550 K after about 50 min. As a result, thermally safe conditions were achieved with all input powers. The experimental results roughly agreed with the calculated ones. With both the thermal characteristics and the thruster performance, a flight model is under design.

Conclusions

Basic experiments were made using the THT-IV Hall thruster to examine the influences of magnetic field shape and strength, and acceleration channel length on thruster performance and to establish guidelines for design of high-performance Hall thrusters. The thruster was stably operated with a highest performance under an optimum acceleration channel length of 20 mm and an optimum magnetic field with a maximum strength of about 150 Gauss near the channel exit and with some shape considering ion acceleration directions. With a higher magnetic field strength inside the acceleration channel, ionization and acceleration occur in a relatively upstream region in the channel. Therefore, although ion beam divergence is suppressed, ion losses on the channel wall are enhanced. With a weaker magnetic field, ion production and acceleration concentrate near the channel exit. Although ion beams are slightly expanded radially-outward, wall losses are very small. In magnetic field shape, it is suitable that downstream directions perpendicular to magnetic field lines near the channel exit are parallel to the central axis or slightly radially-inward. As for acceleration channel length, total wall losses are relatively large with a longer channel although an ionization and acceleration region is too short in a shorter channel. Consequently, an optimum magnetic field and channel structure is considered to exist under an operational condition, related to inner physical phenomena of plasma production, ion acceleration and exhaust plasma feature. A new Hall thruster was designed with basic research data of the THT-IV thruster. With the thruster with many considerations, long stable operations were achieved. In all experiments at 200-400 V with 1.5-3 mg/s, the thrust and the specific impulse ranged from 15 to 70 mN and from 1100 to 2300 sec, respectively, in a low electric power range of 300-1300 W. The thrust efficiency reached 55 %. Hence, a large map of the thruster performance was successfully made. The thermal characteristics were also examined with data of both measured and calculated temperatures in the thruster body.

Thermally safe conditions were achieved with all input powers. With both the thermal characteristics and the thruster performance, a flight model is under design

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