OPERATIONAL CHARACTERISTICS OF CYLINDRICAL HALL THRUSTERS

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Abstract

Preliminary experiments were carried out using the cylindrical Hall thruster TCHT-I with circular cross-sectional area to examine the basic operational characteristics for design of high-performance very- low-power Hall thrusters for small satellites. The discharge current decreased with increasing magnetic field strength at a constant discharge voltage, although its characteristic for conventional coaxial Hall thrusters has a minimum. Both the thrust and specific impulse were almost kept constants or slightly decreased. Accordingly, the thrust efficiency increased with magnetic field strength and reached a maximum of about 22 % with a ratio of inner to outer magnetic coil currents of 3:2. The discharge current oscillations due to ionization instability were observed. A ratio of oscillation amplitude to average discharge current was below about 20 %. The ratio for the TCHT-I thruster was much smaller than those for coaxial Hall thrusters. Therefore, a stabler operation would be achieved with the TCHT-I thruster. When the magnetic field strength increased, a lower discharge current and a higher thrust were achieved with the coil current ratio of 3:2 compared with those only with an inner magnetic coil, an outer coil current of zero. As a result, a higher thrust efficiency was obtained. With the coil current ratio of 3:2, the discharge current increased from 1.8 A at a discharge voltage of 200 V to 2.25 A at 300 V with a radial magnetic field strength of 210 Gauss and a mass flow rate of 1.0 mg/s. Both the thrust and the specific impulse also increased from 12 mN and 1,200 s at 200 V to 18 mN and 1,800 s at 300 V. The thrust efficiency was kept about 21 % regardless of discharge voltage.

1. 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]. 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, basic experiments have been made using THT-series 1 kW-class Hall thrusters[5]-[12]. The influences of material, width and length of acceleration channel on thruster performance were mainly investigated. Furthermore, one-dimensional Hall thruster flowfield were calculated[8],[10],[12]. The calculated thruster performance roughly agreed with experimental ones. On the basis of the previous research experience, we started research and development of high-performance very-low-power Hall thrusters for small satellites.

From a simple scaling law of Hall thruster design, it is necessary to increase magnetic field strength applied in a Hall thruster as the thruster dimension becomes small. This may result in magnetic saturation of the magnetic circuit. As a result, it is difficult to design and make a suitable magnetic field. In downsizing coaxial Hall thrusters, ion losses on the acceleration channel wall are considered to increase, and heating and erosion of the thruster parts are expected to be enhanced. The thruster performance is considered to become very low. Therefore, the use of conventional coaxial configuration is not likely practical for small Hall thrusters.

Kaufman developed a non-conventional Hall thruster named End-Hall thruster, which had a circular cross-sectional discharge chamber made of metal with a divergent magnetic field[13]. Raitses studied a cylindrical Hall thruster with a circular-cross-sectional ceramic discharge chamber and a special magnetic

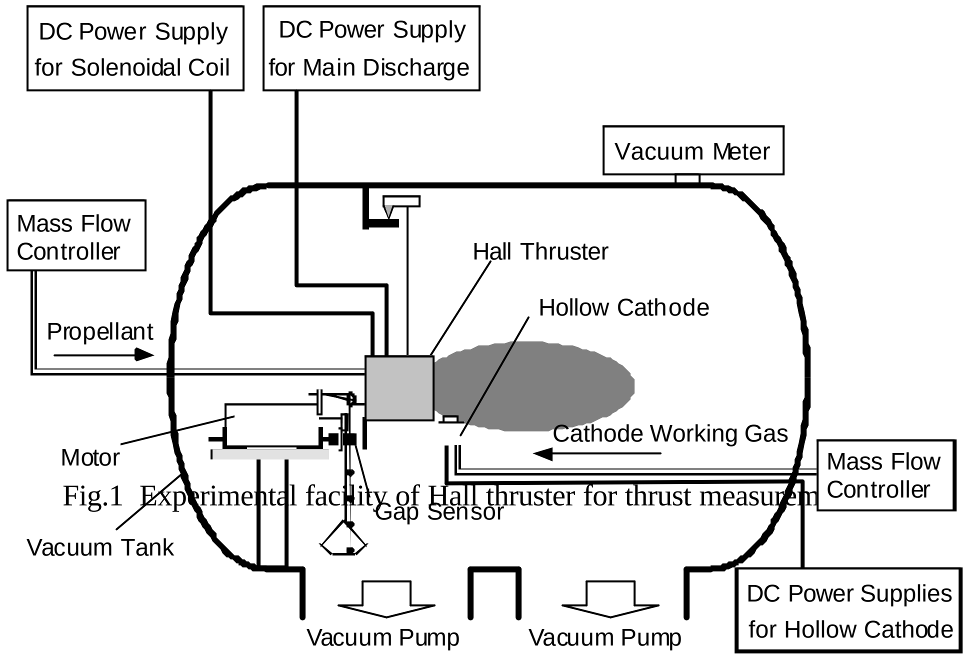


Fig.1 Experimental facility of Hall thruster for thrust measurem

field structure[14]-[17]. These thrusters have cylindrical configuration instead of conventional coaxial configuration. Because of larger volume-to-surface ratio of the thruster, it is considered to have smaller wall losses in the discharge chamber. Therefore, this approach is attractive for design of small Hall thrusters.

In the present study, preliminary experiments are carried out using the cylindrical Hall thruster TCHT-I with circular cross-sectional area to examine the basic operational characteristics for design of high-performance very-low-power Hall thrusters. Discharge currents and thrusts are measured with varying discharge voltage, and magnetic field shape and strength; specific impulses and thrust efficiencies are evaluated. The obtained performance characteristics are compared with those of conventional coaxial Hall thrusters.

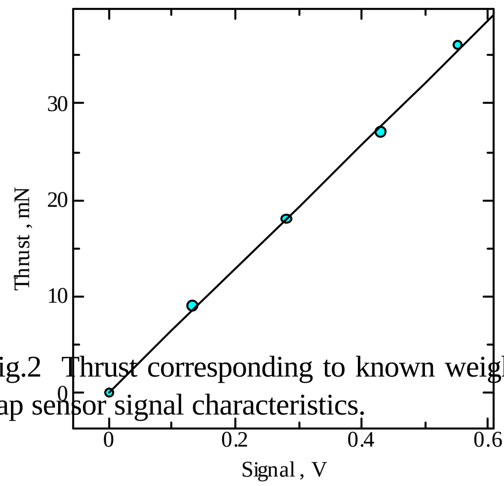


Fig.2 Thrust corresponding to known weight vs gap sensor signal characteristics.

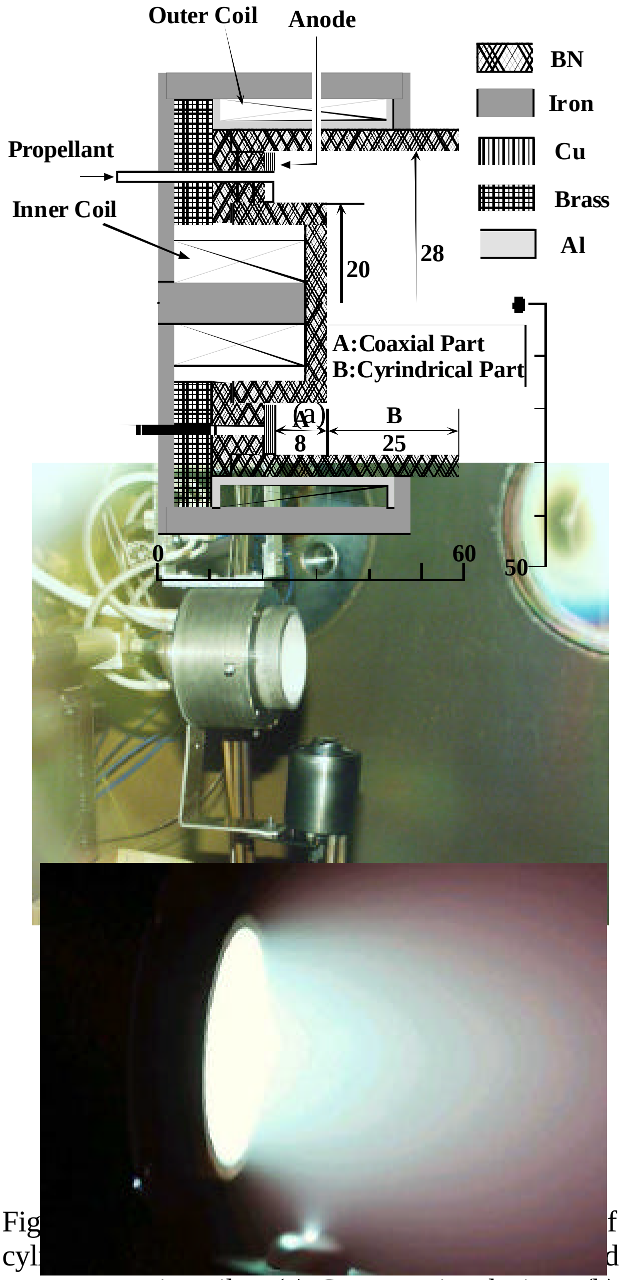
2. Experimental Apparatus

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[5]-[9],[11]. 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 evaluate 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, as shown in Fig.2, is conducted with a weight and pulley arrangement which is able to apply a known force to the thrust stand in vacuum environment. With this design, friction force was small, and it resulted in no measurable hysteresis.

The cylindrical Hall thruster used for this study is shown in Fig.3. The thruster named TCHT-I has a discharge chamber consisting of coaxial and cylindrical parts. The former has an inner diameter of 40 mm and an outer one of 56 mm, and the latter has the same diameter as the outer one of the coaxial part. The lengths of the coaxial and cylindrical parts are 8 and 25 mm, respectively. The coaxial part might be useful for stabilizing discharge[14]-[17]. The wall material of the discharge chamber is boron nitride (BN) ceramics. The anode located at the upstream end of the coaxial part is made of copper. The hollow cathode (Iontech HCN-252) is used as the main cathode. Propellant gas is introduced from four lines behind the anode.

The thruster has 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 discharge chamber can be changed in order to find out optimum magnetic field structure. Figure 4 shows the measured radial magnetic field strength vs inner coil current characteristics of the TCHT-I thruster. The measurement was made with a Gauss meter, and the measurement point, as shown in Fig.4(a), is at the corner of the coaxial part. The ratio of inner to outer magnetic coil currents is set to 3:2. The measured magnetic field strength is almost proportional to inner coil current. Figure 5 shows the magnetic field shape and strength with an inner coil current of 3.0 A and an outer one of zero. The calculated magnetic field has a magnetic nozzle shape; that is, a larger axial component of magnetic field exists compared with cases with conventional coaxial Hall thrusters[5]-[9],[11]. In Fig.5(b), the axial variation of the measured radial magnetic field strengths strongly depend on radial position. Near the axis, i.e., at radial positions of 16 and 20 mm, the axial variation has a peak of 180 and 250 Gauss, respectively, near an axial position of -25 mm, and it rapidly decreases downstream from that position. Near the outer wall, at 24 and 28 mm, the magnetic field strength is kept about 100 Gauss axially from the upstream end to an axial position of -10 mm, and it gradually decreases downstream as well as those at 16 and 20 mm. At a constant axial position, as approaching the axis, the magnetic field strength increases except at downstream positions from -10 mm to zero. Figure 6 shows the magnetic field shape and strength with a ratio of inner to outer coil currents of 3:2 at an inner coil current of 1.8 A and an outer one of 1.2 A. The calculated magnetic field shape has a larger ratio of axial to radial component of magnetic field than that with an inner coil current of 3.0 A and an outer one of zero shown in Fig.5(a). Particularly, the magnetic field lines



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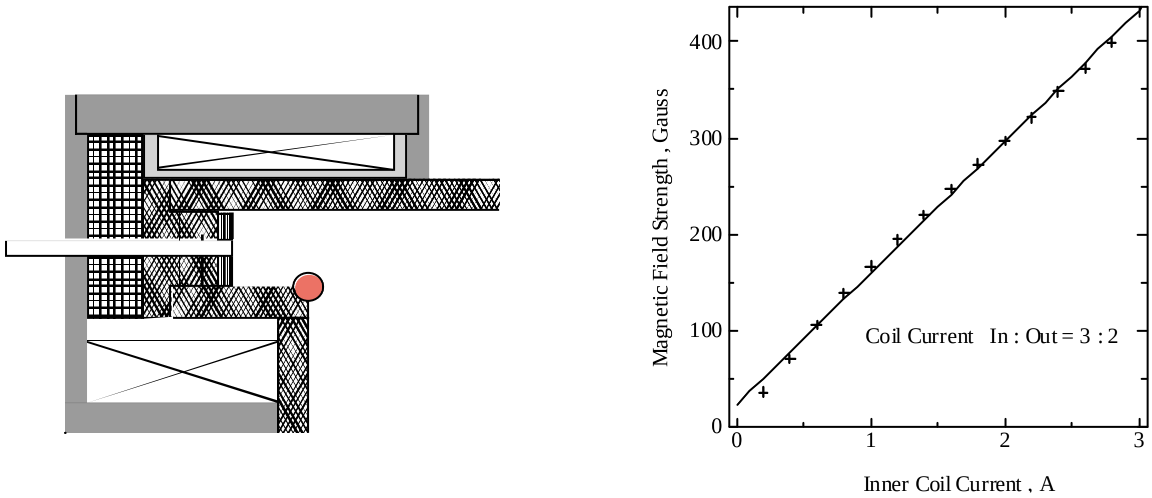
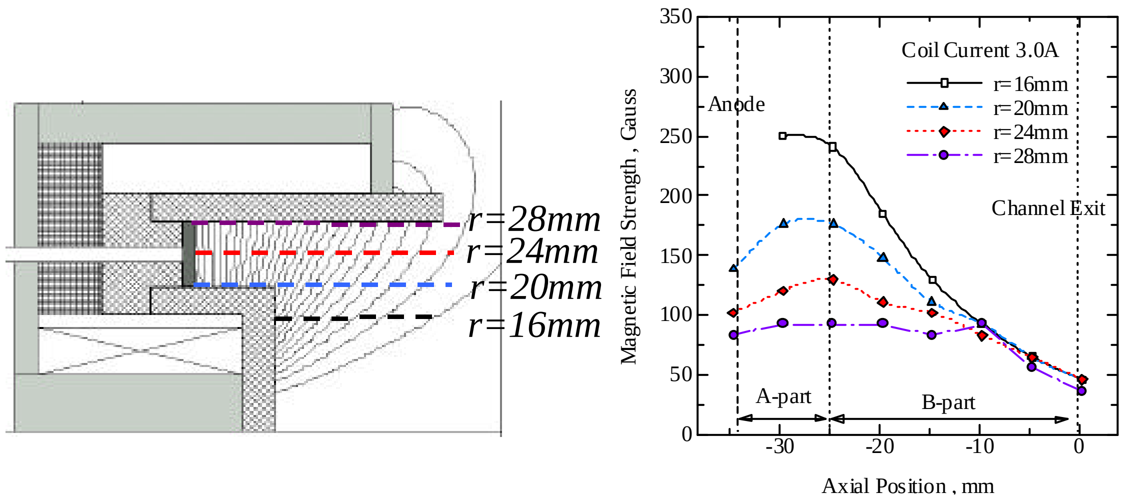
outer magnetic coils. (a) Cross-sectional view; (b) Experimental Setup in vacuum chamber; (c) Operational view.



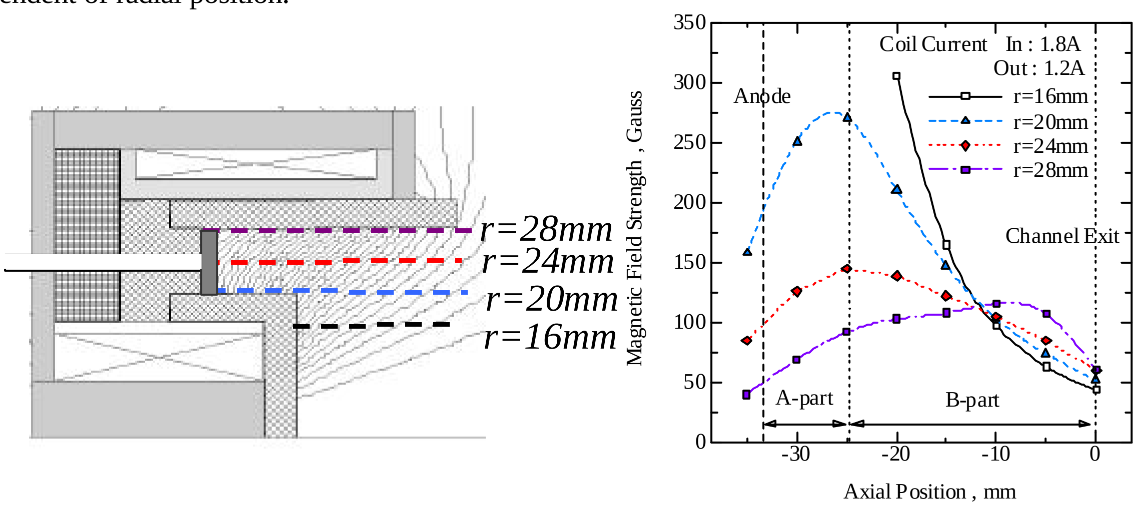
(a) (b)

Fig.4 Measured radial magnetic field strength vs inner coil current characteristics of cylindrical Hall thruster TCHT-I with inner and outer magnetic coils. (a) Measurement point; (b) Radial magnetic field strength. The ratio of inner to outer magnetic coil currents is set to 3:2.



(a) (b)

Fig.5 Magnetic field shape and strength with inner coil current of 3.0A and outer one of zero. (a) Calculated magnetic field shape; (b) Axial variations of measured radial magnetic field strength dependent of radial position.



(a) (b)

Fig.6 Magnetic field shape and strength with inner coil current of 1.8 A and outer one of 1.2 A. (a) Calculated magnetic field shape; (b) Axial variations of measured radial magnetic field strength dependent of radial position.

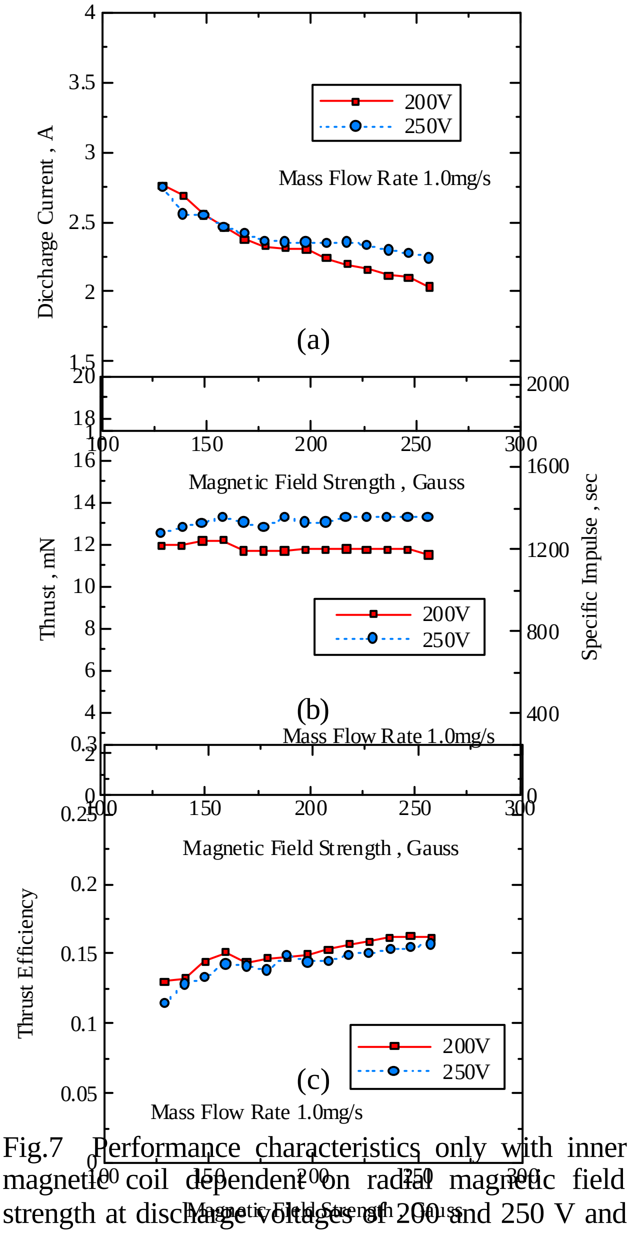


Fig.7 Performance characteristics only with inner magnetic coil dependent on radial magnetic field strength at discharge voltages of 200 and 250 V and mass flow rate of 1.0 mg/s. (a) Discharge current; (b) Thrust and specific impulse; (c) Thrust efficiency.

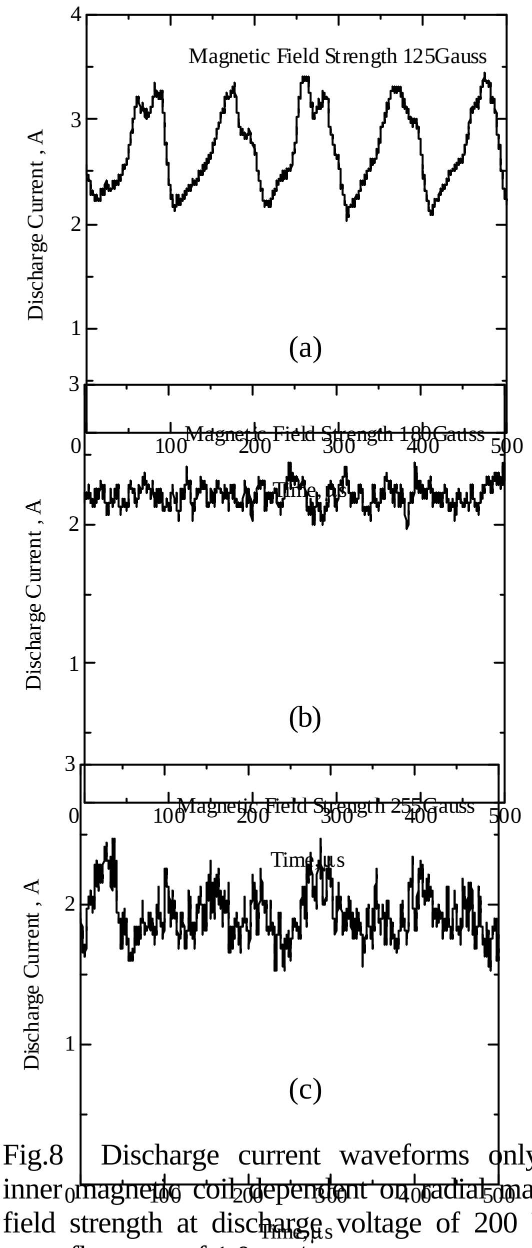


Fig.8 Discharge current waveforms only with inner magnetic coil dependent on radial magnetic field strength at discharge voltage of 200 V and mass flow rate of 1.0 mg/s.

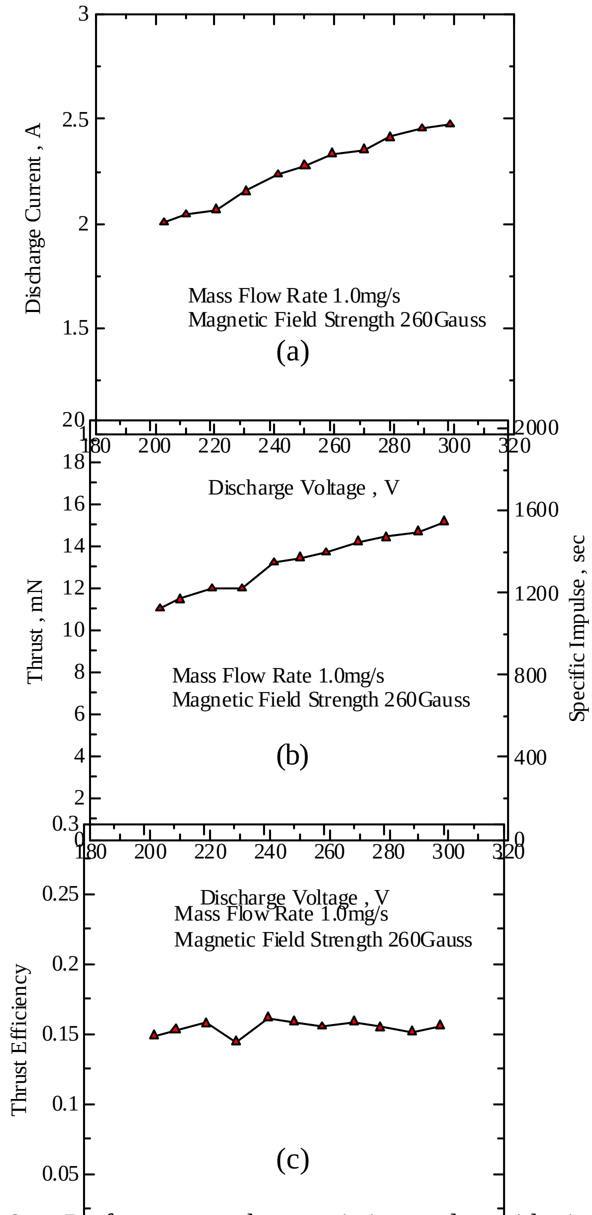


Fig.9 Performance characteristics only with inner magnetic coil dependent on discharge voltage at radial magnetic field strength of 260 Gauss and mass flow rate of 1.0 mg/s. (a) Discharge current; (b) Thrust and specific impulse; (c) Thrust efficiency.

have large inclinations to the anode surface in the coaxial part, although with an outer coil current of zero they are almost parallel to the anode surface; i.e., they show radial directions. In Fig.6(b), the axial variation of the measured radial magnetic field strengths are similar to that with an inner coil current of 3.0 A and an outer one of zero shown in Fig.5(b). However, at a radial position of 28 mm the radial magnetic field has a peak at -10 mm, at the more downstream position compared with the case with an outer coil current of zero. Furthermore, the magnetic field strength near the downstream exit, at axial positions from -10 mm to zero, increases radially-outward with the inner and outer magnetic coil currents. Accordingly, because main discharge location and ion trajectory might be roughly predicted from these characteristics, ionization process in the discharge chamber, ion losses on the wall and plasma plume feature are inferred.

Xenon is used as propellants. In a series of experiments, discharge currents and thrusts are measured as varying discharge voltage, mass flow rate and magnetic field strength and shape, and specific impulses and thrust efficiencies are evaluated.

3. Results and Discussion

3.1 Operational Characteristics Only with Inner Magnetic Coil

Figure 7 shows the performance characteristics only with an inner magnetic coil, an outer coil current of zero, dependent on radial magnetic field strength at discharge voltages of 200 and 250 V and a mass flow rate of 1.0 mg/s. The discharge current gradually decreases with increasing magnetic field strength although in a range of magnetic field strengths from 175 to 200 Gauss the characteristic is almost flat. At a constant magnetic field strength, the discharge current at a discharge voltage of 250 V is higher than that at 200 V with strong magnetic fields above 200 Gauss. Although the discharge current characteristic for conventional coaxial Hall thrusters has a minimum with varying magnetic field strength, the cylindrical Hall thruster TCHT-I does not show that[8],[11]. Both the thrust and specific impulse are almost kept constants. As a result, the thrust efficiency gradually increases and reaches about 16 % in this experimental condition.

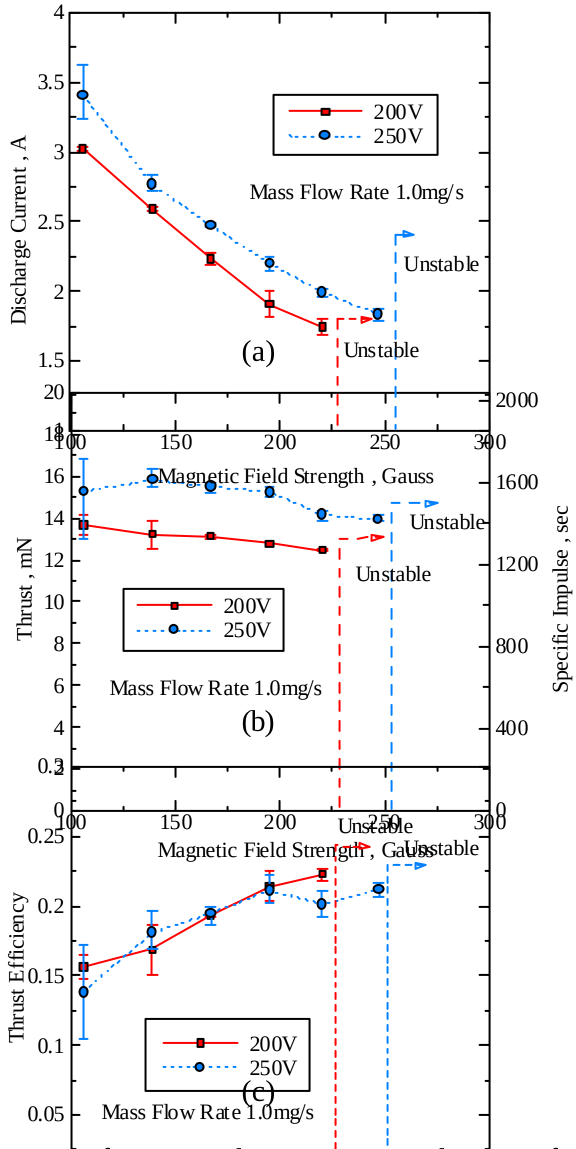


Fig.10 Performance characteristics with ratio of inner to outer magnetic coil currents of 3:2 dependent on radial magnetic field strength at discharge voltages of 200 and 250 V and mass flow rate of 1.0 mg/s. (a) Discharge current; (b) Thrust and specific impulse; (c) Thrust efficiency.

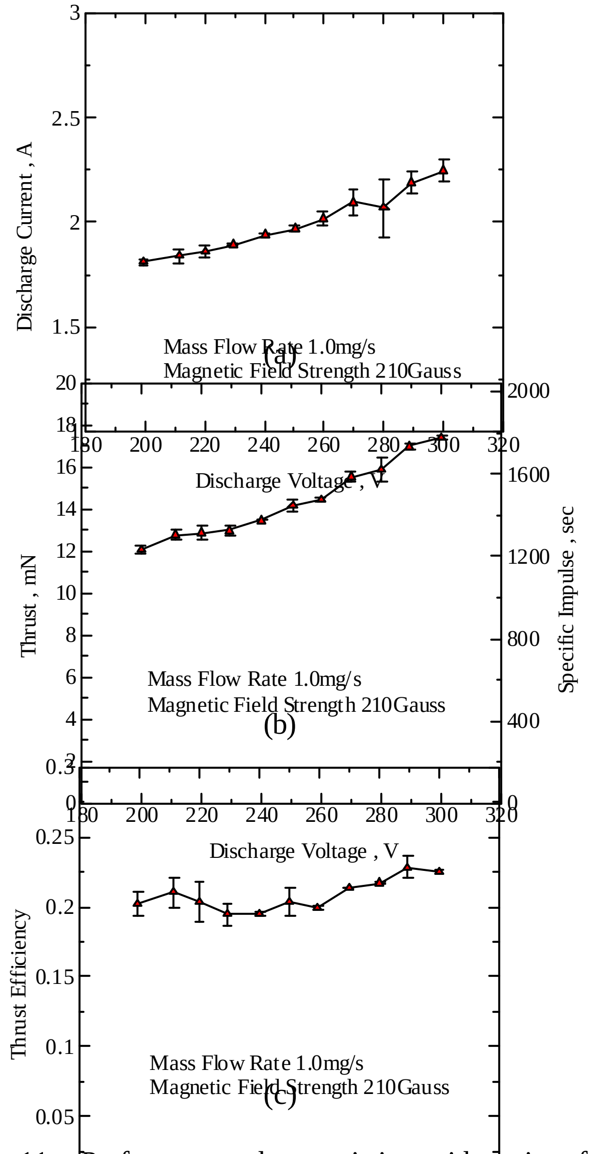


Fig.11 Performance characteristics with ratio of inner to outer magnetic coil currents of 3:2 dependent on discharge voltage at radial magnetic field strength of 210 Gauss and mass flow rate of 1.0 mg/s. (a) Discharge current; (b) Thrust and specific impulse; (c) Thrust efficiency.

Figure 8 shows the discharge current waveforms dependent on radial magnetic field strength at 200 V and 1.0 mg/s. Oscillations with a frequency and an amplitude of about 10 kHz and 0.6 A, respectively, are observed with the smallest magnetic field strength of 125 Gauss. This oscillation is expected because of ionization instability. A ratio of oscillation amplitude to average discharge current is about 20 % with 125 Gauss. As the magnetic field strength increases, the ratio decreases and then reaches a minimum. After that the ratio increases. Although these phenomena agree with those with coaxial Hall thrusters, the ratio of oscillation amplitude to average discharge current for the cylindrical Hall thruster TCHT-I is much smaller than those for coaxial Hall thrusters[8]. Therefore, a stabler operation would be achieved with the TCHT-I thruster.

Figure 9 shows the performance characteristics dependent on discharge voltage at a radial magnetic field strength of 260 Gauss and a mass flow rate of 1.0 mg/s. The discharge current increases from 2.0 A at a discharge voltage of 200 V to 2.5 A at 300 V. Both the thrust and the specific impulse also increase from 11 mN and 1,100 s at 200 V to 15 mN and 1,550 s at 300 V. As a result, the thrust efficiency is kept about 16 % regardless of discharge voltage.

3.2 Operational Characteristics with Inner and Outer Magnetic Coils

Figure 10 shows the performance characteristics with a ratio of inner to outer magnetic coil currents of 3:2 dependent on radial magnetic field strength at discharge voltages of 200 and 250 V and a mass flow rate of 1.0 mg/s. The discharge current decreases with increasing magnetic field strength. At a constant magnetic field strength, the discharge current at 250 V is higher than that at 200 V, and at 250 V a stable operation is achieved with a stronger magnetic field. Both the thrust and the specific impulse slightly decrease with an increase in magnetic field strength. At a constant magnetic field strength, the thrust and the specific impulse at 250 V are higher than those at 200 V. Accordingly, the thrust efficiency increases with magnetic field strength and reaches a maximum of about 22 %.

When the magnetic field strength increases, a lower discharge current and a higher thrust are achieved with a ratio of inner to outer magnetic coil currents of 3:2 compared with those only with an inner magnetic coil, an outer coil current of zero, as shown in Fig.7. As a result, a higher thrust efficiency is obtained. One of the reasons may be that, as shown in Figs.5(b) and 6(b), the magnetic field shape and strength near the downstream exit, at axial positions from -10 mm to zero, is preferable with the inner and outer magnetic coil currents; that is, as approaching the cylindrical wall from the central axis, the magnetic field becomes strong[9]. This results in suppressing axial current near the cylindrical wall, enhancing ionization near the axis at the exit and lowering ion losses on the discharge chamber wall.

Figure 11 shows the performance characteristics dependent on discharge voltage at a radial magnetic field strength of 210 Gauss and a mass flow rate of 1.0 mg/s. The discharge current increases from 1.8 A at a discharge voltage of 200 V to 2.25 A at 300 V. Both the thrust and the specific impulse also increase from 12 mN and 1,200 s at 200 V to 18 mN and 1,800 s at 300 V. As a result, the thrust efficiency is kept about 21 % regardless of discharge voltage.

4. Conclusions

Preliminary experiments were made using the cylindrical Hall thruster TCHT-I to examine the basic operational characteristics. The discharge current decreased with increasing magnetic field strength at a constant discharge voltage, although its characteristic for conventional coaxial Hall thrusters has a minimum. Both the thrust and specific impulse were almost kept constants or slightly decreased. At a constant magnetic field strength, the thrust and the specific impulse increased with discharge voltage. Accordingly, the thrust efficiency increased with magnetic field strength and reached a maximum of about 22 % with a ratio of inner to outer magnetic coil currents of 3:2. The discharge current oscillations due to ionization instability were observed. A ratio of oscillation amplitude to average discharge current was below about 20 %. As the magnetic field strength increased, the ratio decreased and, after reaching a minimum, then increased. Although these phenomena agree with those with coaxial Hall thrusters, the ratio for the TCHT-I thruster was much smaller than those for coaxial Hall thrusters. Therefore, a stabler operation would be achieved with the TCHT-I thruster. When the magnetic field strength increased, a lower discharge current and a higher thrust were achieved with the coil current ratio of 3:2 compared with those only with an inner magnetic coil, an outer coil current of zero. As a result, a higher thrust efficiency was obtained. The preferable magnetic field was expected to result in suppressing axial current near the cylindrical wall, enhancing ionization near the axis at the exit and lowering ion losses on the discharge chamber wall. With the coil current ratio of 3:2, the discharge current increased from 1.8 A at a discharge voltage of 200 V to 2.25 A at 300 V with a radial magnetic field strength of 210 Gauss and a mass flow rate of 1.0 mg/s. Both the thrust and the specific impulse also increased from 12 mN and 1,200 s at 200 V to 18 mN and 1,800 s at 300 V. The thrust efficiency was kept about 21 % regardless of discharge voltage. At present, a half-size thruster of TCHT-I is under design on the basis of these experimental data.

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