Performance Evaluation of TAL-type Hall Thruster with RF Plasma Cathode

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Radio frequency (RF) plasma cathodes have been developed as an electron source to liberate ion and Hall thrusters from the experiencing drawbacks associated with dispenser hollow cathodes. In this paper, we evaluate the discharge characteristics and thrust performance for the combination of an anode-layer-type Hall thruster and a RF plasma cathode. Normal ion beam extraction and neutralization for the combination were experimentally confirmed. From the data obtained for the discharge current and the amplitude of the discharge current oscillation, the discharge phenomenon is not affected by the different types of cathode. On the other hand, the thrust depends to a small extent on the differences in the cathode type because of the increase and decrease in the cathode-to-ground voltage. The anode efficiency of the RF plasma cathode is comparable to that of the hollow cathode. Based on this result, the feasibility of the RF plasma cathode as an electron source for the Hall thruster in ground tests was confirmed. However, because of the high RF power consumption, the total efficiency of the RF plasma cathode is lower than that of the hollow cathode at anode mass flow rate of 2.0 mg/s and 2.9 mg/s. This result confirms that for space-related applications, it is important to improve the power consumption of RF plasma cathodes.

Nomenclature

e	=	elementary charge
I_d	=	discharge current
$\dot{m}_a$	=	anode mass flow rate
$\dot{m}_c$	=	cathode mass flow rate
M	=	ion mass
P_d	=	discharge power
P_h	=	heater power
P_k	=	keeper power
P_{rf}	=	radio frequency (RF) power
T	=	thrust
V_b	=	average beam voltage
Δ	=	oscillation amplitude

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η_a = anode efficiency
η_t = total efficiency
τ = measurement time

I. Introduction

HOLLOW cathodes (H/Cs) are regularly employed as electron sources in Hall thrusters to ionize the propellant using electric discharges and to neutralize the ion beam leaving the thrusters[1-3]. Conventional hollow cathodes use a porous tungsten insert that is impregnated with an emissive mix of barium and calcium oxides, and alumina for thermionic emission[4]. Chemical reactions between the hot tungsten and the oxides at high temperature lead to the production of free barium, which flows through the pores, and which eventually reaches the tungsten surface. The surface becomes covered with a monolayer of barium and the thermionic emission increases significantly owing to the marked reduction in the work function from 4.5 eV to 1.5 eV[5]. Because the dipole effect of this monolayer will be modified by the adsorption of gas or metal vapor onto its surface, particularly if the gas or metal is electro-negative, the work function will increase and cause a decrease in the electron emission, usually termed emission poisoning[6]. To prevent this poisoning, which can shorten the lifetime of the dispenser hollow cathode, contact between the insert and the active gas should be avoided, and the type of operation gas entering the cathode, which is commonly shared with the thruster propellant, is restricted. In Addition, the lifetime of the dispenser hollow cathode is considered to be restricted by oxide depletion from the insert. As a result, Hall thrusters with dispenser hollow cathodes have some difficulties in long-term operation, and they should be controlled strictly from prelaunch to end-of-life.

In light of these constraints, the lifetime and erosion mechanisms in dispenser hollow cathodes were intensively investigated by researchers[7-11]. First, two solutions have been studied to liberate Hall thrusters from the drawbacks of the dispenser hollow cathode. One is the employment of boride, e.g., lanthanum hexaboride (LaB_6), as the thermionic emitter in the hollow cathode to replace the barium-impregnated tungsten[1,12,13]. The other is the use of a “plasma cathode” as the electron source in Hall thrusters. The plasma cathode is an electrical discharge device producing plasma that emits electrons from its boundary[14]. The LaB_6 hollow cathode has a higher resistance to poisoning than the dispenser cathode, and does not require the strict controls that are normally required for the dispenser cathode. However, it requires high-temperature operation (>1,600 °C) to achieve a high emission current density. Thus, the reliability of the heater system is critical for the life of the cathode and the evaporation of LaB_6 at high temperatures limits the cathode life. Although a plasma cathode requires additional discharge power to produce electrons, it does not have the drawbacks associated with a thermionic emitter, and may achieve high robustness and a long lifetime. Electron cyclotron resonance (ECR) plasma[15-17], capacitively coupled plasma (CCP)[18], inductively coupled plasma (ICP)[19-21], and helicon wave plasma[22] have been investigated for cathode applications in electric propulsion. The microwave discharge ion thruster “µ10”, which was installed in the Hayabusa asteroid explorer, is an attractive thruster that employs a thermionic-emitter-less design; it employed a microwave ECR discharge to ionize the propellant and a microwave ECR plasma cathode to neutralize the extracted ions. Its accumulated operational time was 35,000 h, and the thruster demonstrated that the removal of the hollow cathode benefits the operation sequence and lifetime of electric propulsion[23].

While plasma cathodes are a viable solution, there are challenging problems such as the need to improve the ratio of the electron emission current to the power consumption such that they are comparable to conventional hollow cathodes. The key to obtaining a high electron-emission current from plasma cathodes is the production of a dense plasma within the cathode. ICP provides a sufficiently high electron number density without the need of an external magnetic field because the plasma does not require a high voltage to drive the displacement current through the powered radio frequency (RF) sheath[24]. In addition, the limited electron density, which is attributed to the cutoff frequency, as in ECR plasma, is not important for ICP. Because of these features of ICP, a plasma cathode employing RF discharge was studied as a simple and robust electron source for Hall thrusters in Tokyo Metropolitan University[25]. Moreover, applications of the RF plasma cathode (RF/C) in ion and Hall thrusters have been demonstrated[21,26]. However, in previous studies, evaluations of the thrust characteristics for Hall thrusters using an RF plasma cathode were not sufficient to confirm the feasibility of the RF plasma cathode as an electron source for Hall thrusters. Thus, the objectives of this study were to evaluate the discharge characteristics and thrust performance such as discharge oscillation, thrust, cathode potential, and anode efficiency, together with the combination of an anode-layer-type Hall thruster and an RF plasma cathode.

II. Experimental Apparatus and Procedure

A. Anode-Layer-Type Hall Thruster

Figure 1 shows a schematic representation of the 1-kW class anode-layer-type Hall thruster developed at Tokyo Metropolitan University. The thruster consists of an anode, guard rings, electromagnets, and insulators. The inner and outer diameters of the acceleration channel are 38 mm and 66 mm, respectively. The thruster has a copper hollow anode, which comprises two cylindrical rings, and the propellant is fed through them. The insulator is made of alumina and the guard rings are made of stainless steel (SUS316L). The thruster has six outer magnetic windings consisting of 68-mm-long, 10-mm-diameter cores of commercially soft iron wrapped with eight layers of polyamide-imide insulated copper magnetic wire. The inner core is 68 mm in length and 8 mm in diameter, and has six layers of copper magnetic wire. Because of the magnetic saturation in the inner core, the maximum magnetic flux on the channel center line is 16 mT.

B. Outer Coil-Type RF Plasma Cathode

Figure 2 shows a schematic representation of the outer coil-type RF plasma cathode, which consists of a discharge vessel, an orifice plate, an induction coil, and an ion collector. The cylindrical vessel is made of alumina, and its inner diameter and length are 40 mm and 80 mm, respectively. Copper wire whose diameter is 5 mm is wrapped around the vessel as the induction coil. The orifice plate is made of graphite, and there is a 2-mm diameter orifice at the center of the plate for electron emission. Because an ignition of ICP will obey Paschen's law, the orifice diameter is much smaller than the vessel's inner diameter, and this will enable to sustain a sufficiently high pressure in the RF plasma cathode for the self-ignition of plasma. When electrons are emitted from the orifice, an equivalent quantity of ions then has to be collected at the ion collector in the cathode to maintain quasi-neutrality in the ICP. Thus, the graphite collector, which is inserted into the vessel, is necessary during the steady operation of the RF plasma cathode. The cylindrical collector is inserted into the vessel along its wall to act as an ion collector and Faraday shield. The collector has an axial slit that allows the axial dB/dt fields into the plasma, but suppresses the circumferential dE/dt field, effectively serving as a Faraday shield[27]. The RF plasma cathode achieved an electron emission current of 3.3 A at a RF power of 140 W and a xenon mass flow rate of 0.3 mg/s[25]. The electron emission current is sufficient high to operate the anode-layer-type Hall thruster.

C. Experimental Configuration

Figure 3 shows the experimental setup. All of the experiments were conducted in a vacuum chamber, whose diameter and length were 1.6 m and 3.2 m, respectively. The backpressure in the chamber was brought to approximately 4.5×10^{-3} Pa using two cryogenic pumps under a xenon mass flow rate of 3.2 mg/s. The anode-layer-type Hall thruster, the cathode, and a pendulum-type thrust stand were placed in the chamber, whereas an RF transmission system, a gas feed system, and DC power supplies were attached from outside of the chamber. Research-grade xenon (99.995% pure) was fed to the vessel as the propellant via thermal sensing mass flow controllers. The thrust was measured using the pendulum-type thrust stand. The thruster was mounted on the thrust stand with electrical isolation between the thruster and the stand to bias the guard rings to the cathode potential. On the other hand, the cathode was not mounted on the thrust stand. The error in the thrust measurement was below 2.2 mN, as shown in Fig. 4.

Figure 5 shows the electric diagram of the anode-layer-type Hall thruster with the hollow cathode and the RF plasma cathode. To compare the RF plasma cathode and the hollow cathode, an Ion Tech, Inc., HCN-252 hollow

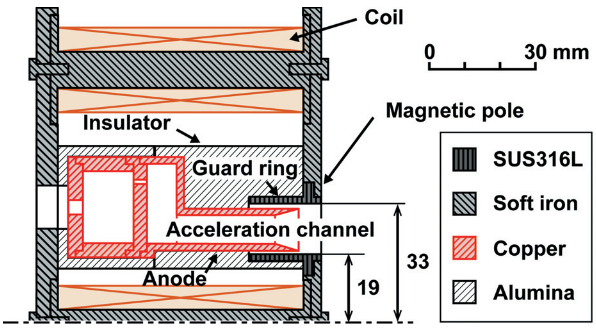

Figure 1. Cross section of the anode-layer-type Hall thruster developed at Tokyo Metropolitan University.

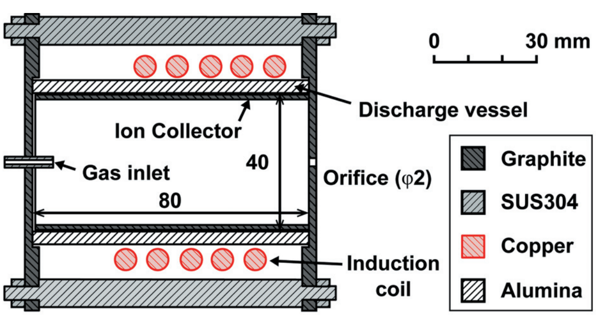

Figure 2. Cross section of the outer coil-type RF plasma cathode.

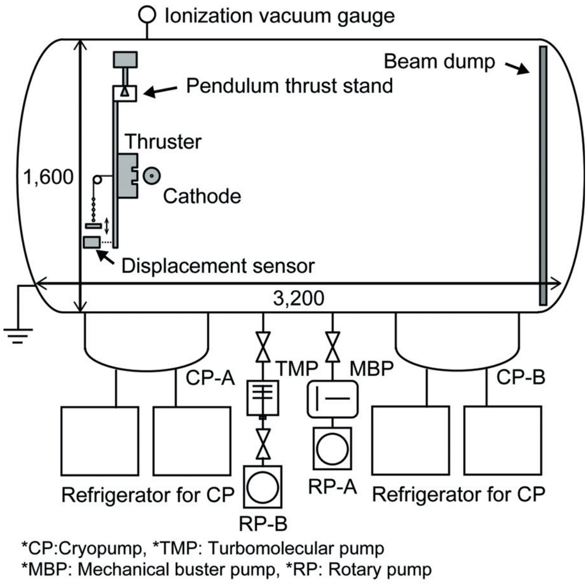

Figure 3. Experimental setup (not to scale).

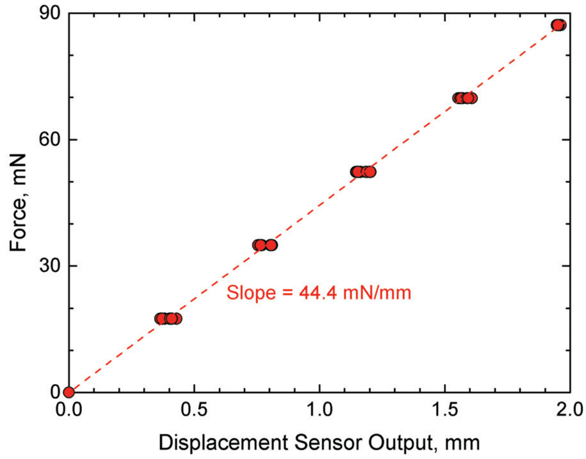

Figure 4. Applied calibration force and curve fits to the data plotted as a function of displacement sensor response.

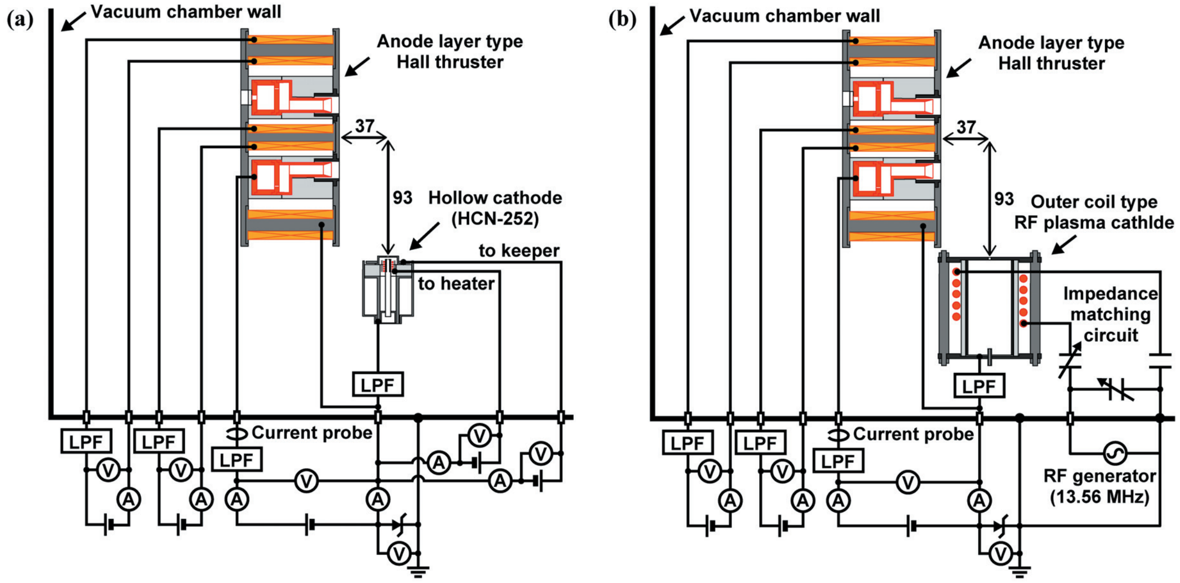

Figure 5. Electrical diagram of the anode-layer-type Hall thruster with (a) the hollow cathode and (b) the RF plasma cathode. "LPF" is a low-pass filter for elimination of RF noise from the RF plasma cathode.

cathode was employed. The orifice position of each cathode relative to the thruster remains fixed, as shown in Fig. 5. To operate the hollow cathode, a keeper DC power supply and a heater DC power supply were connected to the cathode, as shown in Fig. 5(a). On the other hand, the RF transmission system, which consists of an RF generator and an impedance matching circuit, was connected to the RF plasma cathode to produce the RF plasma in the cathode, as shown in Fig. 5(b). The induction coil was energized at 13.56 MHz by the RF generator via the matching circuit. The incident RF power and the reflected RF power were measured by a directional coupler in the generator. The matching circuit consists of a series variable capacitor, a parallel variable capacitor, and a blocking capacitor. To reduce RF power loss and noise, the matching circuit was placed in the vacuum chamber. Because the circuit matched the impedance of the generator to that of the RF plasma cathode, there were no reflections of the RF power in the experiments. Therefore, in this paper, the term "RF power" refers to the net RF power into the cathode.

Third order LC low pass filters (LPFs) were inserted into the electrical leads to eliminate the RF noise from the RF plasma cathode, as shown in Fig. 5(b). These filters are not necessary for the combination of the Hall thruster and the hollow cathode. However, to compare the discharge and thrust characteristics between the RF plasma cathode and the hollow cathode, these filters were also inserted into the leads, as shown in Fig. 5(a).

A current probe (Tektronix, Inc., TCP-312 and TCPA-300) set between the thruster and the LPF to measure discharge current oscillations. To evaluate the discharge and thrust characteristics, the thrust, discharge current, discharge current oscillation, and cathode-to-ground voltage were measured as a function of the discharge voltage, anode mass flow rate, and magnetic flux.

III. Results and Discussion

Normal ion beam extraction and neutralization were experimentally confirmed for the combination of the Hall thruster and the RF plasma cathode. Figure 6 shows photographs of the thruster firing under the same conditions as that of the hollow cathode and the RF plasma cathode. The visual observation, shown in Fig. 6, reveals that the discharge phenomenon does not depend on differences in the types of cathode.

Figures 7-10 show the thrust, discharge current, amplitude of discharge current oscillation, and cathode-to-ground voltage for the two cathodes as a function of the discharge voltage at various anode mass flow rates,

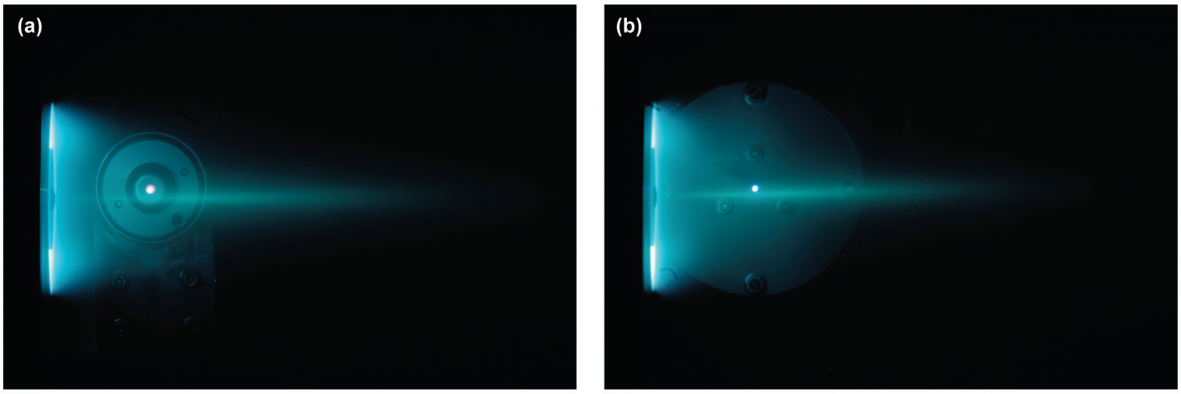

Figure 6. Photographs of the thruster firing at discharge voltage of 300 V, anode mass flow rate of 2.9 mg/s, and cathode mass flow rate of 0.3 mg/s with (a) the hollow cathode and (b) the outer coil-type RF plasma cathode.

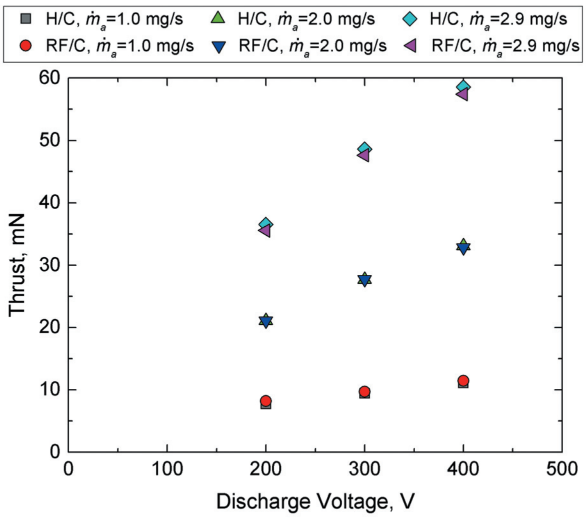

Figure 7. Thrust for the two cathodes as a function of discharge voltage at various anode mass flow rates. The error bars are smaller than the symbols.

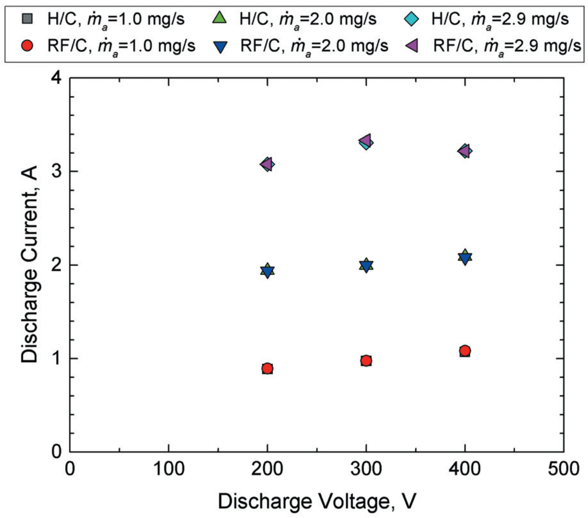

Figure 8. Discharge current for the two cathodes as a function of discharge voltage at various anode mass flow rates. The error bars are smaller than the symbols.

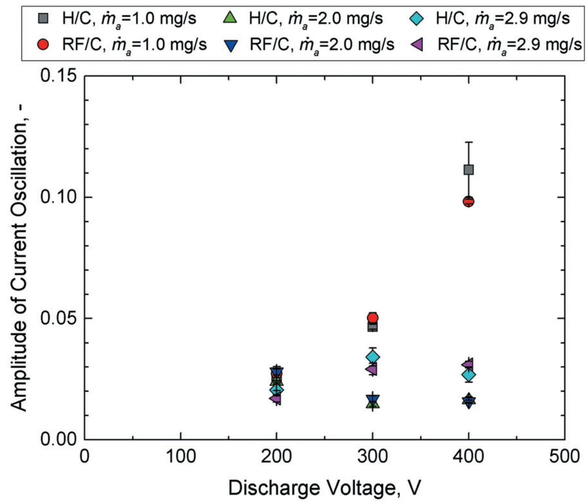

Figure 9. Amplitude of discharge current oscillation for the two cathodes as a function of discharge voltage at various anode mass flow rates.

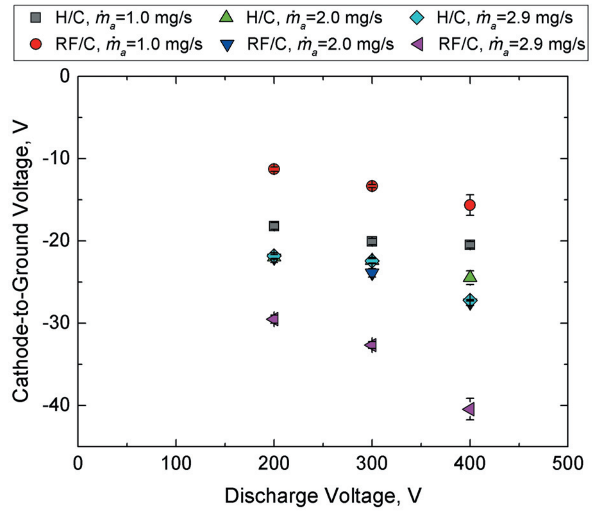

Figure 10. Cathode-to-ground voltage for the two cathodes as a function of discharge voltage at various anode mass flow rates.

respectively. The amplitude of the discharge current oscillation, Δ, is defined as

$$\Delta = \frac{\mathrm{R.M.S}}{\overline{I_d}} = \frac{1}{\overline{I_d}}\sqrt{\frac{\int_0^{\tau}\left(I_d - \overline{I_d}\right)^2 dt}{\tau}}, \qquad \left(\overline{I_d} = \frac{\int_0^{\tau} I_d\, dt}{\tau}\right) \tag{1}$$

where I_d and τ are the discharge current and measurement time, respectively[28]. In these figures, the cathode mass flow rate fraction was set to 10% of the anode mass flow rate. For the hollow cathode, the keeper current and the heater current were 0.3 A and 3.5 A, respectively. For the RF plasma cathode, the RF power was 45 W for an anode mass flow rate of 1.0 mg/s, 85 W for an anode mass flow rate of 2.0 mg/s, and 125 W for an anode mass flow rate of 2.9 mg/s. The symbols in these figures are the average values of three measurements and the error bars show the standard deviation.

The thrust for the hollow cathode is slightly lower than that for the RF plasma cathode for an anode mass flow rate of 1.0 mg/s, as shown in Fig. 7. For an anode mass flow rate of 2.0 mg/s, the thrust for the hollow cathode is approximately the same to that for the RF plasma cathode. For an the anode mass flow rate of 2.9 mg/s, the thrust for the hollow cathode is 1 mN higher than that for the RF plasma cathode. In contrast to the relationship between the thrust and the cathode type, the data presented in Figs. 8 and 9 show that the discharge current and the amplitude of the discharge current oscillation are not affected by the difference of the cathode type. Compared to the hollow cathode, the cathode-to-ground voltage for the RF plasma cathode is strongly affected by the anode mass flow rate, as shown in Fig. 10. The cathode-to-ground voltage for the RF plasma cathode is approximately 6 V higher than that for the hollow cathode for an anode mass flow rate of 1.0 mg/s. On the other hand, for an anode mass flow rate of 2.0 mg/s, the voltage for the RF plasma cathode is approximately 2 V lower than that for the hollow cathode. Moreover, for an anode mass flow rate of 2.9 mg/s, the voltage for the RF plasma cathode is approximately 10 V lower than that for the hollow cathode.

The data presented in Figs. 8 and 9 indicate that the plasma produced in the acceleration channel and the quantity of ions leaving the thruster are the same for the hollow cathode and the RF plasma cathode. However, the thrust slightly depends on the difference in the cathode type, as shown in Fig. 7. The thrust, T, for a single charged propellant is

$$T = \sqrt{\frac{2M}{e}} I_b \sqrt{V_b} \tag{2}$$

where M, e, I_b, and V_b are the ion mass, elementary charge, ion beam current, and average beam voltage, respectively. The thrust is proportional to the ion beam current times the square root of the average beam voltage. If the potential of the ion beam plasma is not changed and the discharge voltage which is the potential difference between the anode and the cathode, remains constant, as the cathode-to-ground voltage decreased, the average beam voltage through which ion was accelerated also decreased[29]. The thrust that was calculated using Eq. (2) is 57.2 mN for an anode mass flow rate of 2.9 mg/s, an average beam voltage of 360 V, and a propellant utilization efficiency of 0.85. As the average beam voltage varies from 360 V to 350 V, the thrust varies from 57.2 mN to 56.4 mN. This result indicates that the 10 V drop in the cathode-to-ground voltage leads to a 0.8 mN decrease in the thrust. The value of the thrust reduction is comparable to the difference in the thrust between the hollow cathode and the RF plasma cathode for an anode mass flow rate of 2.9 mg/s, as shown in Fig. 7. Therefore, the changes in the cathode-to-ground voltage that are due to the differences in the cathode type are the reasons for which the thrust slightly depends on the differences in the cathode type.

Figure 11 shows the discharge current and amplitude of the discharge current oscillation for the two cathodes as a function of the maximum magnetic flux on the channel center line for a discharge voltage of 300 V, anode mass flow rate of 2.9 mg/s, and cathode mass flow rate of 0.3 mg/s. For the hollow cathode, the discharge current increased as the magnetic flux decreased, and the discharge in the acceleration channel disappeared for a magnetic flux below 9 mT. On the other hand, for the RF plasma cathode with an RF power of 125 W, the discharge current also increased as the magnetic flux decreased, and the discharge in the acceleration channel was unstable below a magnetic flux of 14 mT. In the unstable discharge, the luminescence of the discharge plasma was observed, but the thrust drastically decreased. The absolute value of the cathode-to-ground voltage was equal to the discharge voltage obtained for the unstable discharge, which means that the acceleration voltage is 0 V. Therefore, the ions are not accelerated by electrostatic forces during the unstable discharge, and the thrust is then very low. Because the unstable discharge operation is not normal for the operation of the Hall thruster, the range of magnetic flux values for normal operation with the combination of the Hall thruster and the RF plasma cathode at an RF power of 125 W is from 14 mT to 16 mT. The range increased as the RF power increased, as shown in Fig. 11. The maximum electron-emission current from the RF plasma cathode proportionally increased as the RF power increased, and the maximum emission current values were 2.9 A and 3.3 A for an RF power of 120 W and 140 W[25], respectively. The increase in the RF power with the increased emission current is the reason for the enlargement of the operation range. Compared to the hollow cathode, the normal operation range for the RF plasma cathode is narrow because of the lack of the electron emission at a constant RF power.

The anode efficiency and the total efficiency are introduced in order to evaluate the thrust performance with the hollow cathode and the RF plasma cathode[30]. The anode efficiency, η_a, describes the basic thruster performance without considering the effects of the cathode power, cathode mass flow rate, and power used to generate the magnetic field. Thus, it is defined as follows:

$$\eta_a = \frac{1}{2}\frac{T^2}{\dot{m}_a P_d} \tag{3}$$

where $\dot{m}_a$ and P_d are the anode mass flow rate and the discharge power (which is the discharge current times the discharge voltage), respectively. The total efficiency, η_t, is defined as the jet power divided by the total electric

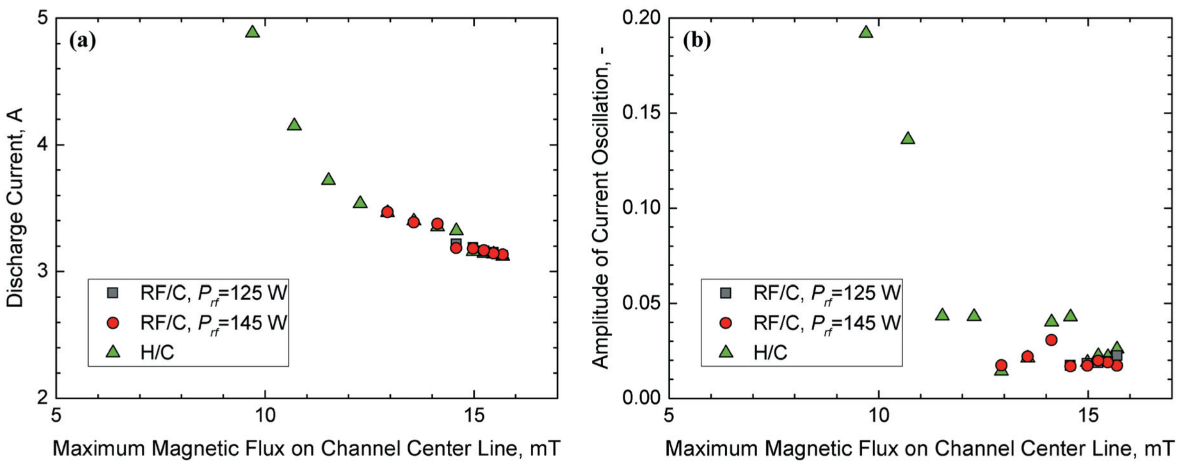

Figure 11. Data for the two cathodes as a function of maximum magnetic flux on the channel center line at discharge voltage of 300 V, anode mass flow rate of 2.9 mg/s, and cathode mass low rate of 0.3 mg/s: (a) discharge current, and (b) amplitude of discharge current oscillation.

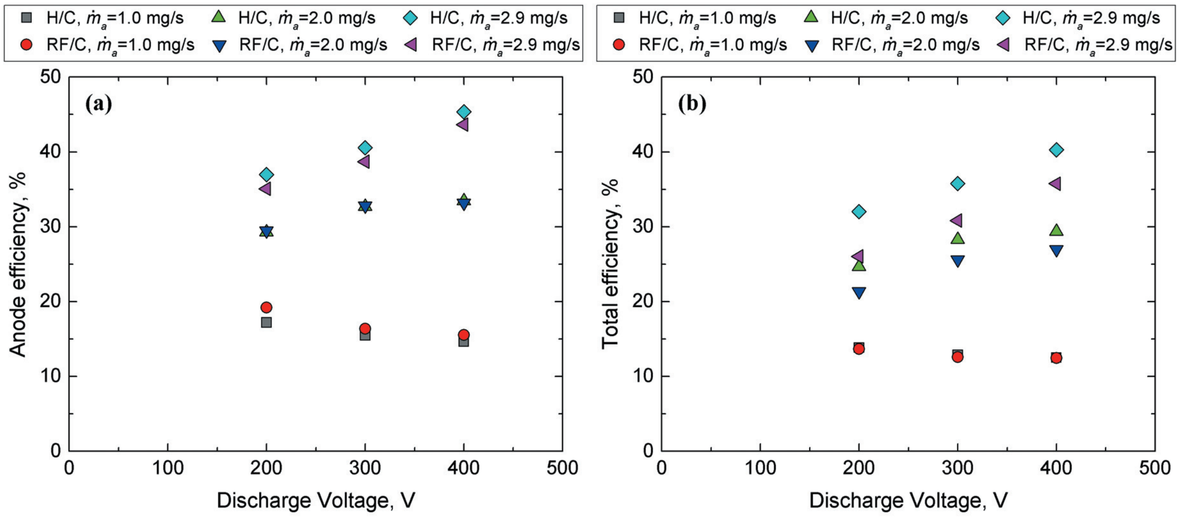

Figure 12. Data for the two cathodes as a function of discharge voltage at various anode mass flow rates: (a) anode efficiency, and (b) total efficiency.

power into the thruster, as given in the following equations.

$$\eta_t = \frac{1}{2}\frac{T^2}{(\dot{m}_a + \dot{m}_c)(P_d + P_m + P_k + P_h)} \quad \text{(for hollow cathode).} \tag{4}$$

$$\eta_t = \frac{1}{2}\frac{T^2}{(\dot{m}_a + \dot{m}_c)(P_d + P_m + P_{rf})} \quad \text{(for RF plasma cathode).} \tag{5}$$

In Eqs. (4) and (5), $\dot{m}_c$, P_m, P_k, P_h, and P_{rf} are the cathode mass flow rate, coil power, keeper power for the hollow cathode, heater power for the hollow cathode, and the RF power for the RF plasma cathode, respectively.

Figure 12 shows the anode efficiency and the thrust efficiency for the two cathodes as a function of the discharge voltage at various anode mass flow rates. The anode efficiency of the RF plasma cathode is comparable to that of the hollow cathode, as shown in Fig. 12(a). From this result, the feasibility of the RF plasma cathode as the electron source for the Hall thruster in ground tests was confirmed. However, the total efficiency of the RF plasma cathode is lower than that of the hollow cathode at anode mass flow rate of 2.0 mg/s and 2.9 mg/s, whereas the total efficiency of the RF plasma cathode is comparable to that of the hollow cathode at an anode mass flow rate of 1.0 mg/s, as shown in Fig. 12(b). While the keeper power and the heater power for the hollow cathode were nearly-constant as the anode mass flow rate increased, the RF power for the RF plasma cathode increased as the anode mass flow rate increased. The additional power consumption led to a difference in the total efficiency between the hollow cathode and the RF plasma cathode. This result confirms that for space-related applications, it is important to improve the power consumption of RF plasma cathodes.

IV. Conclusion

To prevent the Hall thrusters from experiencing the drawbacks of the dispenser hollow cathode, we evaluated the discharge conditions and thrust characteristics using a combination of an anode-layer-type Hall thruster and an outer coil-type RF plasma cathode. The results can be summarized as follows:

(1) Normal ion beam extraction and neutralization were experimentally confirmed for the combination of a Hall thruster and an RF plasma cathode. From the data obtained for the discharge current and the amplitude of the discharge current oscillation, the discharge phenomenon is not affected by differences in the cathode type (hollow cathode and RF plasma cathode). On the other hand, the thrust depends to a small extent on the difference in the cathode type because of the increase and decrease in the cathode-to-ground voltage.

(2) The discharge current for both two cathodes increased as the maximum magnetic flux on the channel center line decreased. However, compared to the hollow cathode, the normal operation range for the RF plasma cathode is narrow because of the lack of the electron emission from the RF plasma cathode at a constant RF power.

(3) The anode efficiency of the RF plasma cathode was found to be comparable to that of the hollow cathode. Based on this result, the feasibility of the RF plasma cathode as an electron source for Hall thrusters in ground tests was confirmed.

(4) Because of the high RF power consumption, the total efficiency of RF plasma cathodes is lower than that of hollow cathodes for anode mass flow rate of 2.0 mg/s and 2.9 mg/s, whereas the total efficiency of the RF plasma cathode is comparable to that of the hollow cathode at an anode mass flow rate of 1.0 mg/s. This result confirms that for space-related applications, it is important to improve the power consumption of RF plasma cathodes.

Acknowledgments

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