Two-Dimensional, Applied-Field MPD Thruster Using a Hollow Cathode

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Abstract: The cathode erosion of Magneto-Plasma-Dynamic (MPD) thrusters is one of the most serious problems to be overcome. In order to solve this problem, we have developed a new MPD thruster using a hollow cathode. To evaluate its thrust performance, the discharge voltage and thrust were measured with various operation parameters. As a result, the thrust, the specific impulse and thrust efficiency reach to 9 mN, 766 s and 2.8 %, respectively. After the thrust performance test, we could not find discharge crater on the electrodes.

Nomenclature

B	=	magnetic flux density
f	=	thrust
$\dot{m}_{BK}$	=	mass flow rate through the back plate of the channel
$\dot{m}_{HC}$	=	mass flow rate through the hollow cathode
H	=	thruster channel height
I_{sp}	=	specific impulse
J_c	=	coil current
J_D	=	discharge current
J_k	=	keeper current
t	=	time
V_s	=	gap sensor signal voltage
x	=	x component of the thruster discharge channel
y	=	x component of the thruster discharge channel
z	=	z component of the thruster discharge channel

I. Introduction

A Magneto-Plasma-Dynamics (MPD) thruster is one of the most hopeful promising candidates for space missions such as interplanetary flights because of its high thrust level in a specific impulse range of 1000 – 6000 s. [1,2] However, an MPD thruster has never been loaded on a satellite for practical use because of its poor operation performance and serious cathode erosion.

In our previous research,[3] we also found that a tungsten cathode was severely damages after only two-hour-operation. In order to solve this problem, we have developed a new MPD thruster using a hollow cathode instead of

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a tungsten cathode. In general, a hollow cathode has long lifetime; it can operate for several tens of thousands of hours.[4]

We adopted the rectangular configuration rather than an axisymmetric configuration. This is due to the following two reasons; first, the hollow cathode thruster performance is expected to be hampered by a radial pumping force[5]; second, the two-dimensional MPD thruster has the potential of good thrust performance.[6]

The purpose of this study is to evaluate the performance of the new steady-state, two-dimensional MPD thruster. Therefore, we measured the discharge voltage and the thrust with varying a discharge current, propellant mass flow rate and applied magnetic field. After that, we deduced the specific impulse and the thrust efficiency form these results.

II. Experimental Setup[7]

A. Thrust Head

The two-dimensional applied field MPD thruster which we have developed is illustrated in Fig. 1 and 2. A flat plate anode and a hollow cathode assembly (LHC1000, Kaufman Robinson, Inc.) are set on the top and bottom faces of the discharge channel. The other walls are made of ceramics. The distance between anode and cathode is varied from 20 to 40 mm. The thruster width and length are 56 mm and 75 mm, respectively.

Magnetic field is applied to the channel by solenoid coils which are connected in series and a steel yoke. Figure 3 shows magnetic field lines in the channel (*x*-*y* plane at *z*=37.5 mm), which is obtained from the data measured with a Gauss meter. As shown in this figure, the magnetic field is almost uniform in the channel. The spatial variation was within 9.4 %.

A part of the propellant is supplied through a port on the back plate of the thruster ($\dot{m}_{\mathrm{BK}}$). The other part is supplied through the hollow cathode, that is, the propellant for the hollow cathode is also used as a propellant for the main discharge ($\dot{m}_{\mathrm{HC}}$). Therefore, in low mass flow rate case, all of the propellant is supplied through the hollow cathode.

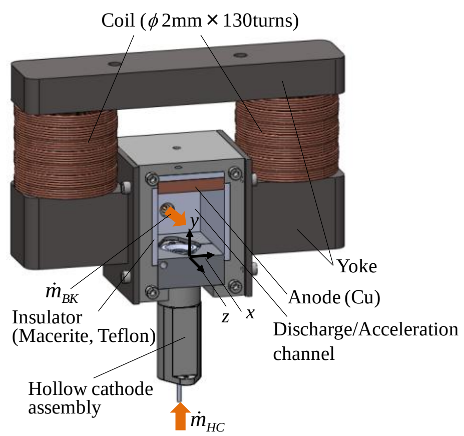

Figure 1. Schematic of the two dimensional applied field MPD thruster with a hollow cathode.

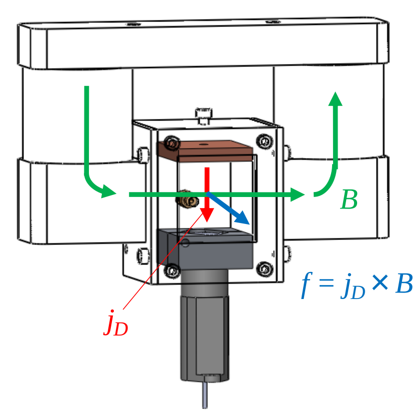

Figure 2. Primary Lorentz force component.

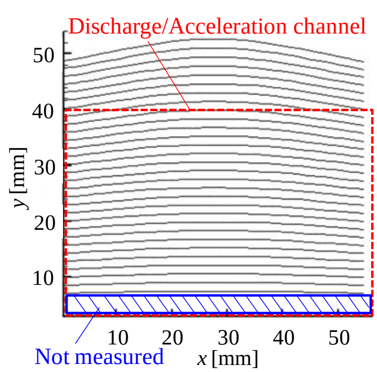

Figure 3. Experimentally-measured magnetic field lines in the acceleration channel (*B*=25 mT, *z*=27.5 mm).

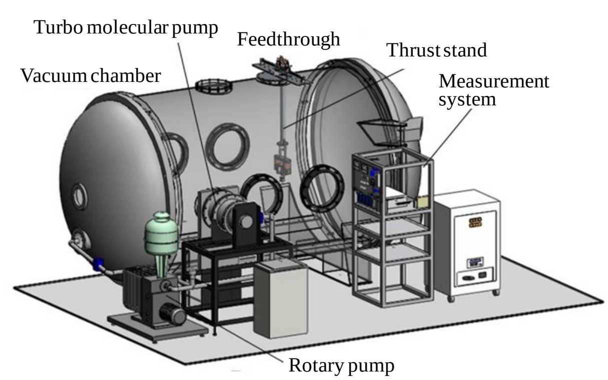

Figure 4. Vacuum system.

B. Vacuum System

The thruster was operated in the stainless-steel vacuum chamber which diameter and length are 2 m and 4 m respectively (Fig. 4). The chamber was evacuated by a turbo-molecular pump (3200 l/s) and a rotary pump (33.3 l/s). The ambient pressure in the vacuum chamber is measured by an ionization vacuum gauge and a Pirani gauge. The ambient pressure of 10^{-3} Pa was maintained. At the mass flow rate of 0.42 mg/s, the ambient pressure was 2.8×10^{-2} Pa.

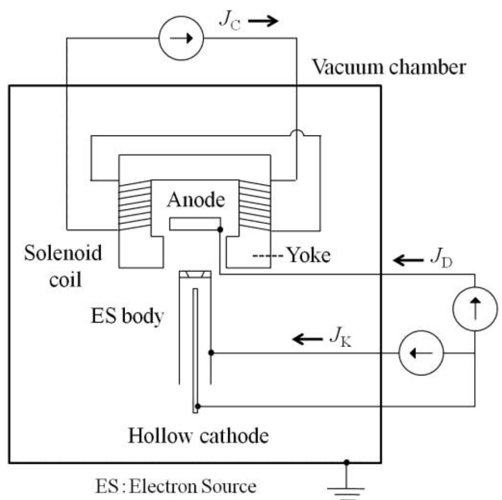

Figure 5. Electrical circuit.

C. Electrical Circuit and Propellant Feeding System

The electrical circuit is shown in Fig. 5. Electrical current to discharge, the hollow cathode and the coils were fed through the arm of the thrust stand. The propellant, also fed through the arm, was supplied using two mass flow controllers (MODEL3660, F.S 1.0 slm (standard litter per minute) and 0.2 slm, respectively, KOFLOC); one from the back plate, the other through the hollow cathode. All of the currents and voltages are monitored by a data logger.

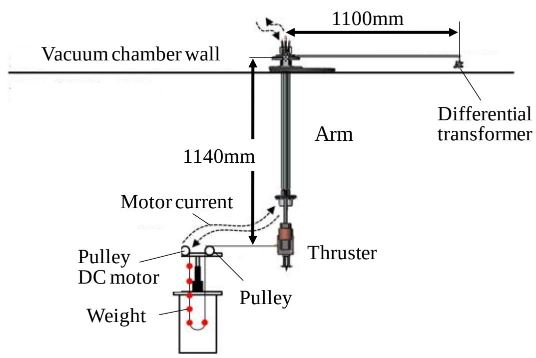

Figure 6. Pendulum type thrust stand.

D. Thrust Measurement System

The thrust is measured using a pendulum type thrust stand using a bellows (Fig.6). [8] The displacement of the arm was measured by a differential transformer.

Thrust stand is calibrated with weights driven with a system composed of a DC motor, pulleys and a string. A typical signal of the calibration and a calibration result is shown in Fig. 7 and 8. As shown in these figure, the differential transformer signal is almost proportional to the thrust; the coefficient of determination R^2=0.99925.

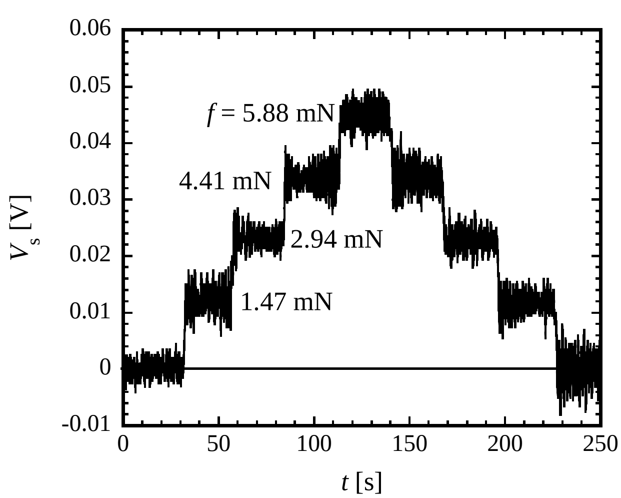

Figure 7. Typical calibration signal.

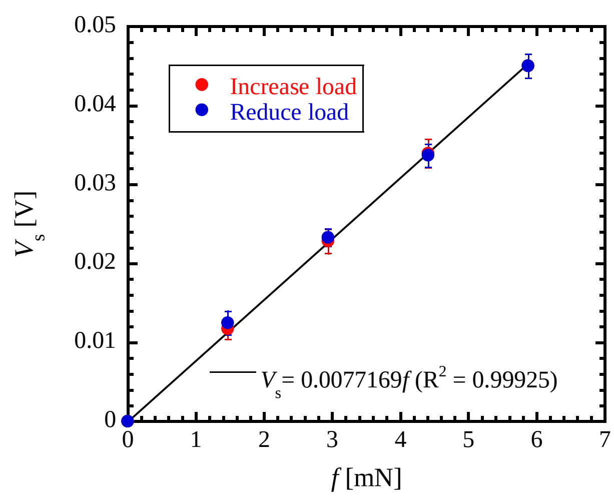

Figure 8. Calibration result. *The error bar denotes the amplitude of the noise shown in Fig. 7.*

III. Result and Discussion

A. Discharge Voltage

Figure 9, 10, and 11 show the discharge voltage as a function of the propellant mass flow rate, the magnetic field, and the discharge voltage, respectively.

As shown in Fig. 9, the discharge voltage decreases with the mass flow rate. This means that the plasma resistivity is small in the large mass flow rate case. This is because the plasma density in the channel increases with the mass flow rate. The discharge voltage also decreases with the height of the discharge channel *H*. This result can be explained by the same discussion.

As shown in Fig. 10, the discharge voltage increase with the magnetic flux density. This is also because of the decrease of the charge carrier with increase of the magnetic flux density.

Unlike these two results, the variation in the discharge voltage with the discharge current is small (Fig.11). A back electromotive force (EMF) $u_x BH$ scales with u_x where u_x denotes an effective exhaust velocity given by $F/\dot{m}$. Figure 12 shows the relationship between the back EMF and the discharge voltage. As shown in this figure, the back EMF is 12 V at most, being much smaller than the difference in discharge voltage shown in Fig. 9. This implies that the contribution of back EMF is small in the discharge voltage.

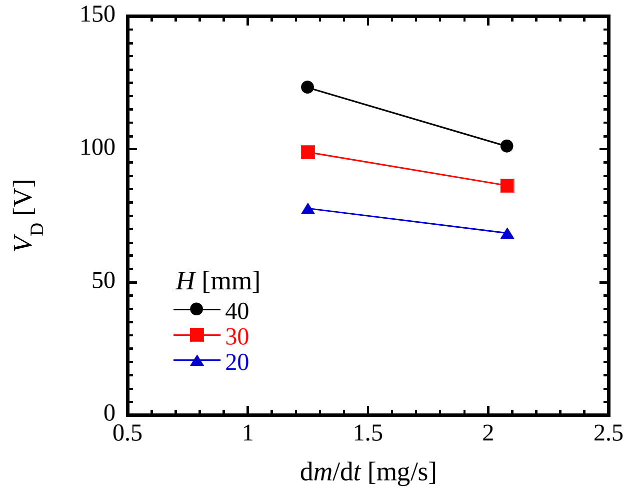

Figure 9. Discharge voltage as a function of $\dot{m}$ (J_D=10 A, *B* = 38 mT).

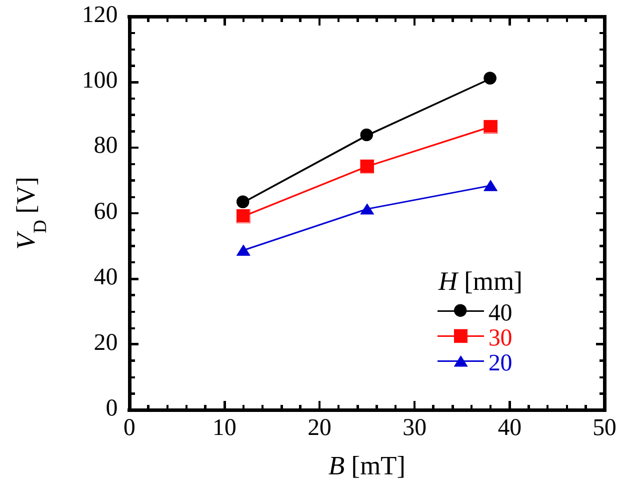

Figure 10. Discharge voltage as a function of *B* (J_D = 10 A, $\dot{m}$ = 2.1 mg/s).

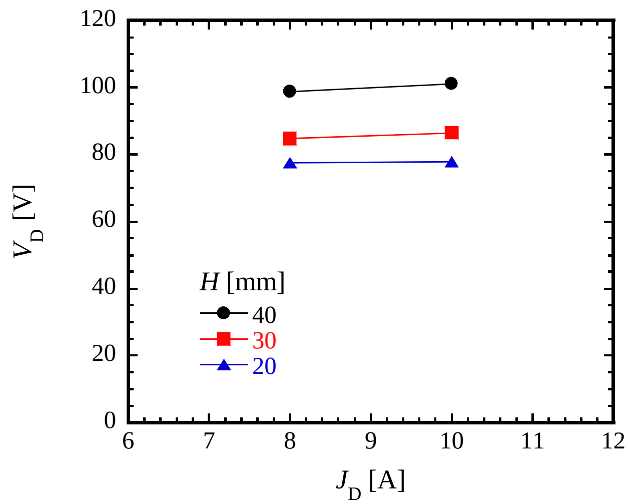

Figure 11. Discharge voltage as a function of J_D (*B* =38 mT, $\dot{m}$ = 2.1 mg/s).

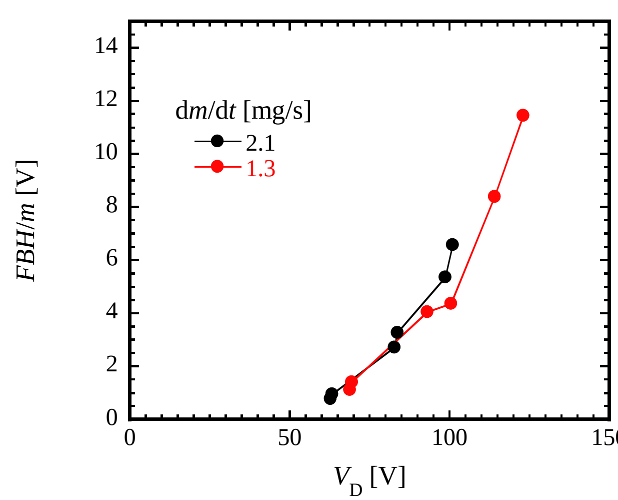

Figure 12. Discharge voltage as a function of J_D (*B* =38 mT, $\dot{m}$ = 2.1 mg/s).

B. Thrust

Figures 13 ~ 15 show the thrust as a function of the mass flow rate, the magnetic field, the discharge current and the channel height. As shown in these figures, the thrust is independent of the mass flow rate, while the thrust increase with the magnetic field, the discharge current and the channel height. This result indicates that the electromagnetic acceleration rather than the electro thermal acceleration is dominant in this operation range. Figure 16 shows the relation between the measured thrust and ideal electromagnetic force $J_D BH$. As shown in this figure, the thrust is almost proportional to $J_D BH$. This result also sustains that the thruster operates under the electromagnetic acceleration mode. However, measured thrust is only 50 ~ 70 % of the $J_D BH$. This tendency is probably caused by the magnetic field because the relation between F and B is very similar to that between F and $J_D BH$. Currently, the difference between the volume integration of z-component of an electromagnetic force and the value estimated using representative value is not accurately.

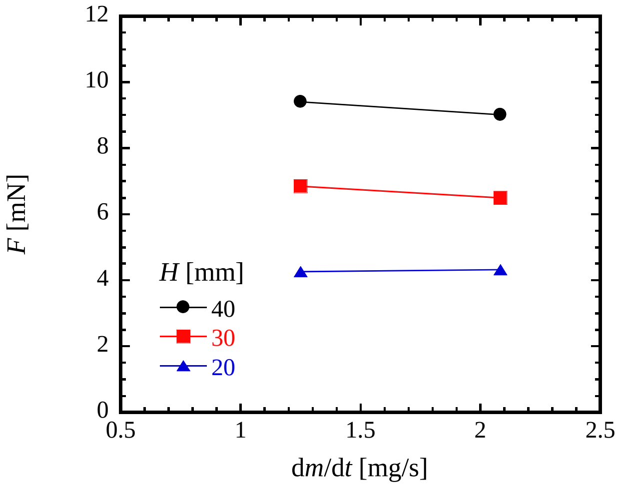

Figure 13. Thrust as a function of $\dot{m}$ (J_D = 10 A, B = 38 mT).

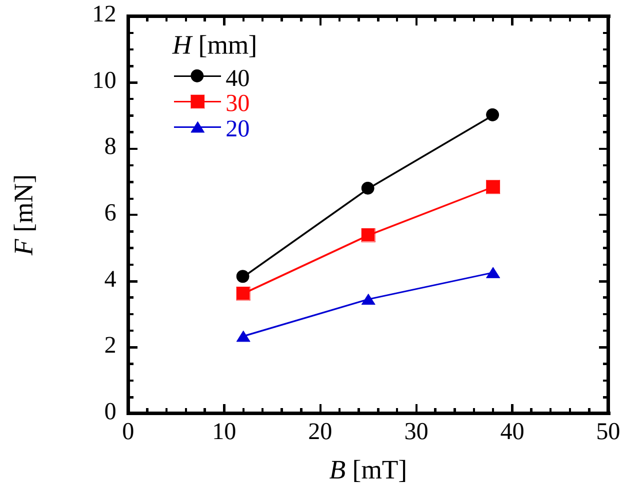

Figure 14. Thrust as a function of B (J_D =10 A, $\dot{m}$ = 2.1 mg/s).

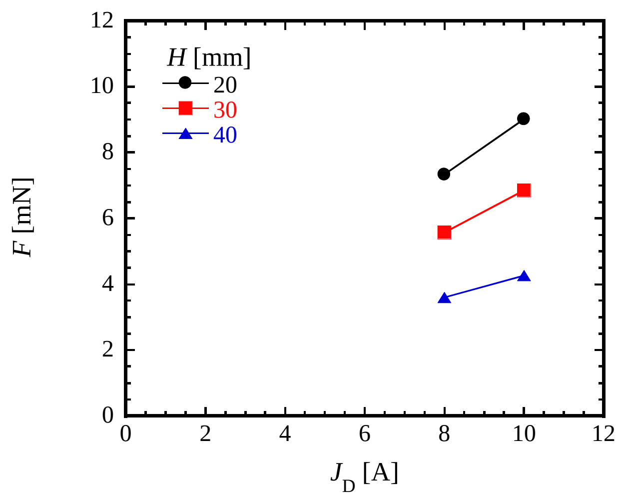

Figure 15. Thrust as a function of J_D (B = 38 mT, $\dot{m}$ = 2.1 mg/s).

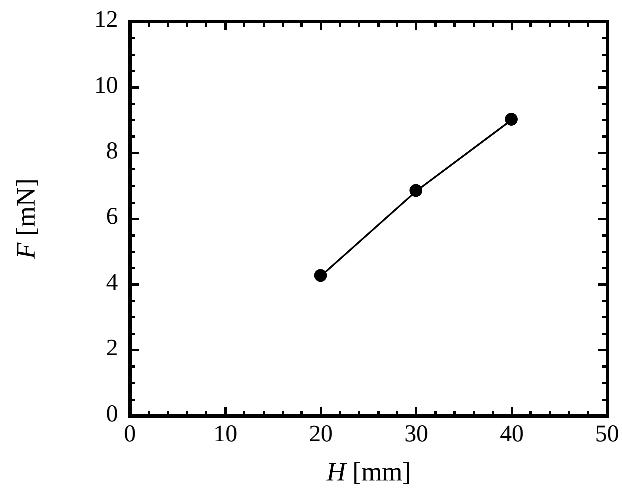

Figure 16. Thrust as a function of H (B = 38 mT, $\dot{m}$ = 2.1 mg/s, J_D = 10 A).

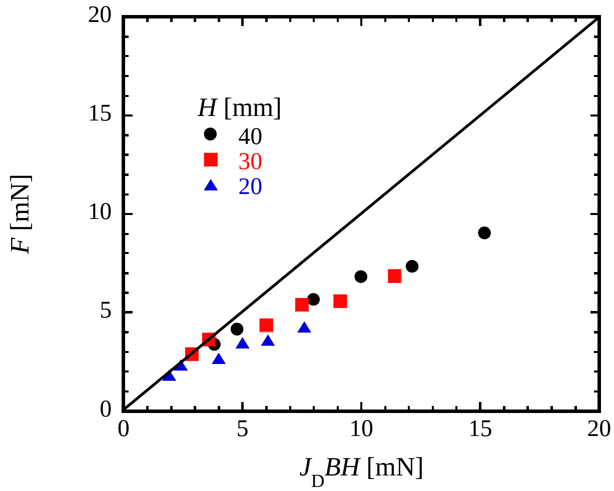

Figure 16. Relationship between measured thrust and ideal electromagnetic force.

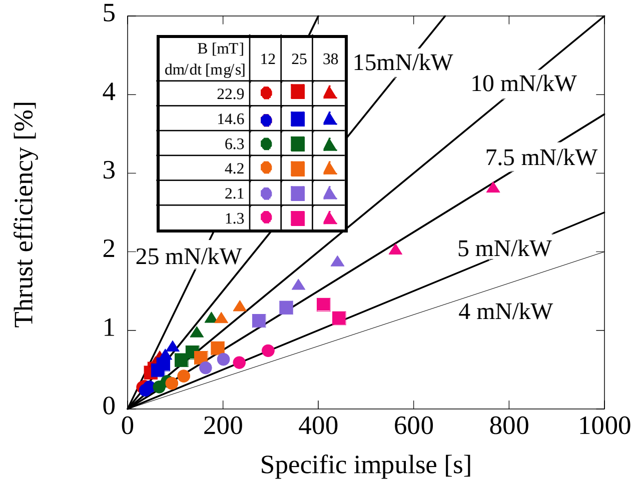

Figure 17. Relationship between thrust efficiency and specific impulse.

C. Propulsion Performances

The relationship between specific impulse and thrust efficiency is shown in Fig. 17. The solid line represents the thrust-to-power ratio. As shown in this figure, the highest thrust efficiency reaches at 2.8 % with the specific impulse of 766 s in this operating range.

The specific impulse, thrust efficiency and thrust-to-power ratio increase with the magnetic flux density. This means that the optimum operation point of the thruster is in the higher I_{sp} range. In order to realize the high I_{sp} operation, more magnetic flux density or less mass flow rate is needed. This is our future works.

In addition, during more than three-hour thrust performance test, the hollow cathode worked without any problem; there are little discharge crater on the electrodes after the test. Therefore, a hollow cathode can be a good candidate for a MPD cathode.

IV. Conclusion

A steady state, applied-field, two-dimensional MPD thruster using a hollow cathode was designed and manufactured. To evaluate the thrust performance, discharge voltage and thrust with varying discharge current, magnetic flux density, propellant mass flow rate and channel height were measured. As a result, the maximum thrust was 9 mN in the current operation condition. In this operation condition, the electromagnetic acceleration was dominant.

The specific impulse and thrust efficiency were deduced from the experimental data. The thrust efficiency reaches at 2.8 % with the specific impulse of 766 s. These thrust performance is expected to be improved by the higher magnetic flux density.

During the more than three-hour thrust measurement test, the hollow cathode worked without any problem; after the test we could not find discharge crater. Hence, a hollow cathode is a hopeful candidate for a MPD thruster cathode.

Acknowledgments

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