Operation Characteristics of Applied-Field Magnetoplasmadynamics Thruster Using Hollow Cathode

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The thrust performance of a steady-state, applied-field magnetoplasmadynamics (MPD) thruster has been improved by increasing a discharge current was increased from 20 A to 60 A using a lanthanum hexaboride (LaB6) hollow cathode. The experimentally obtained thrust characteristics were consistent with that of electromagnetic acceleration. Using argon as the propellant, a thrust efficiency of 25.5% and a thrust/power ratio of 17.0 mN/kW were obtained with an applied magnetic field of 265 mT, discharge current of 30 A, propellant mass flow rate of 2.1 mg/s and discharge voltage was 121 V.

Key Words: Space Engineering, MPD Thruster, LaB6 Hollow Cathode

Nomenclature

A : Constant in Richrdson-Dushman equation
B : Magnetic field strength
C : Coefficient
F : Thrust
Ftare : Tare force
Isp : Specific impulse
Je : Emission current density
Jd : Solenoid coil current
Jd : Discharge current
Jk : Keeper current
k : Boltzman’s constant
m : Propellant mass flow rate
P : Discharge power
Ra : Anode inner radius
Rc : Effective cathode radius
RLaB6 : LaB6 inner radius
T : Insert surface temperature
Vo : Intercept in voltage-current characteristics
Vo : Discharge voltage
Vk : Keeper voltage
η : Thrust efficiency
φ : Work function

1. Introduction

For achieving future space missions such as manned Mars exploration or transportation between planets,1) high power electric propulsion thrusters need to be developed. Magnetoplasmadynamics (MPD) thruster, which is an electro-magnetic acceleration type thruster, is capable of generating high thrust density, thereby being a promising candidate that enables these types of missions.

MPD thruster can be classified into two types with respect to the magnetic field; self-field MPD (SF-MPD) and applied-field MPD (AF-MPD). A SF-MPD thruster uses a magnetic field self-induced by a discharge current Jd. The thrust produced is proportional to Jd. This type of thruster becomes functional only at a discharge currents of the order of 1 kA or higher. However, for such high discharge current, cathode erosion becomes a severe issue.2) An AF-MPD thruster utilizes an external magnetic field B, which is produced by a solenoid coil or permanent magnet. In this case, the produced thrust is proportional to JdB. Therefore, a large thrust can be obtained even with small discharge currents if a sufficiently strong magnetic field is applied. However, a conventional tungsten-based rod cathode is not capable of sustaining a steady-state discharge current level of 10 A because the Joule heating is not enough for maintaining the thermionic emission from the cathode. This problem can be solved by introducing a thermionic emission type hollow cathode to an MPD thruster.

In a previous study,3) a 10 A level thruster operation was realized with a commercial-type thermionic electron emitter (LHC-03AE-1-01, Kaufman & Robinson Inc.). In addition, to improve the thrust efficiency, the impact of Jd and B on η were investigated by the analysis of variance (ANOVA) method. In the ANOVA method, the observed variance in a particular variable is partitioned into components owing to different sources of variation. From the ANOVA results, it was concluded that increasing Jd could be the most effective method to increase η. However, the emitter current was limited to 20 A.

Therefore, the main objective of this study is to improve the thrust efficiency of AF-MPD thruster. To do so, a hollow cathode that is capable of supplying larger discharge currents, was developed and introduced to an AF-MPD. The modified AF-MPD thrust performance was examined experimentally.
2. Experimental Setup

2.1. Hollow cathode

In this study, a thermionic emission type hollow cathode for an MPD thruster was developed. The current magnitude strongly depends on the material of the thermionic emitter, (also known as "insert"), the temperature, and the inner surface area in contact with the plasma. This characteristic is well described by a modified Richardson-Dushman equation as follows.

\[ j_e = A T^2 e^{-\varphi/kT} \]  

Figure 1 shows the \( j_e \) values for different insert materials according to temperature. Among these insert materials, porous tungsten impregnated with barium oxide (BaO-W) has a low work function when compared to tantalum and tungsten. However, the reaction with impurities raises the BaO-W work function\(^3\) and a high feed-gas purity is needed in the BaO-W hollow cathode operation, which is one of its major disadvantages. In a commercial ion thruster using the BaO-W hollow cathode, a special "propulsion-grade" Xenon with overall >99.999% purity and \( \leq 0.1 \text{-ppm} \) oxygen and water impurities, is needed for avoiding reaction with these impurities.\(^5\) On the other hand, lanthanum hexaboride (LaB\(_6\)) has a higher current density when compared to tantalum and tungsten and low sensitivity to impurities. Thus, it can operate even in an environment where BaO-W is damaged. Further, it is possible to obtain a current density of 20 A/cm\(^2\) at about 2000 K. Previously, LaB\(_6\) hollow cathode emitter was studied, and the result has shown its capability for obtaining a discharge current higher than 100 A.\(^6\) For the above mentioned reasons, in this study, LaB\(_6\) was used as the thermionic emission material for increasing the current of the cathode.

![Fig. 1. Emission current density versus temperature for different materials.](image1)

![Fig. 2. The schematic of the hollow cathode.](image2)

2.2. AF-MPD thruster

Figure 3 shows the schematic of the coaxial type AF-MPD thruster used in this study. The discharge channel is composed of a water-cooled anode made of copper and a hollow cathode.

![Fig. 3. Schematic of the AF-MPD thruster.](image3)
The anode radius \( R_a \) is 40 mm, and the central axis of the hollow cathode coincides with the axis of the anode. The propellant is supplied to the discharge channel through the hollow cathode. A magnetic field up to 265 mT was applied by the water-cooled solenoid coil at \( z=0 \) mm in the center axis of the thruster. The magnetic field strength distribution was measured by a Gauss meter (GM-4000, Denshijiki Industry Co. Ltd.)

### 2.3. Vacuum system

Figure 4 shows the schematic of the vacuum system, which are composed of vacuum pump, thrust stand, feed through, and thrust calibration system. The vacuum chamber diameter and length are 2 m and 4 m, respectively. Ambient gas in the chamber was exhausted by a turbo molecular pump that is backed by a rotary pump. The back pressure was measured by a pirani gauge and an ionization gauge, and was kept less than \( 2.4 \times 10^{-5} \) Pa during the thruster operation. The mass flow rate of the propellant is controlled using a mass flow controller (KOFLOC Co. Ltd.).

Thrust was measured using a pendulum type thrust stand. The displacement of the stand arm was measured by a linear differential transfer. Before the experiments, the relation between the displacement of the stand and the force was calibrated using weights. The mass of the weights was measured using an electronic balance. The weights were connected to the strings and the number of the weight was changed by a motor in a step operation. Data was measured by oscilloscope (YOKOGAWA Instruments) and using a LabView program (National Instruments).

### 3. Operation Characteristics

#### 3.1. Operation conditions

The operation conditions are given in Table 1. The thrust and discharge voltage were measured by varying the four operation parameters.

<table>
<thead>
<tr>
<th>Control parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>LaB6 inner radius, mm</td>
<td>( R_{LaB6} )</td>
<td>1.5 or 2.0</td>
</tr>
<tr>
<td>Discharge current, A</td>
<td>( J_d )</td>
<td>10-60</td>
</tr>
<tr>
<td>Magnetic field strength, mT</td>
<td>( B )</td>
<td>133-265</td>
</tr>
<tr>
<td>Mass flow rate, mg/s</td>
<td>( \dot{m} )</td>
<td>1.5-2.1</td>
</tr>
<tr>
<td>Keeper current, A</td>
<td>( J_k )</td>
<td>2</td>
</tr>
</tbody>
</table>

Figure 5 shows the time histories of the current, voltage, thrust and electromagnet actuator signal recorded in a typical run. Before the thruster operation, the hollow cathode experiences breakdown; the discharge between the keeper and the emitter was maintained during a series of experiments. Next, the external magnetic field was supplied by the solenoid coil and right after the discharge current was supplied. By using the solenoid actuator shown in Fig. 4, a feedback control was carried out; the thrust was measured from the force to the actuator. The actuator was used to suppress the displacement of the thrust stand. From Fig. 5 (c), it can be observed that even during the thruster operation, the center of displacement signal (LVDT) vibration does not change, and the current value of the actuator used at that time is converted to the thrust. The average value of each signal for 1 second from the end of the main discharge was used and it was treated as measurement data.

In this system, \( J_d \) and \( J_k \) were supplied from outside the vacuum chamber through the pendulum arm using a vacuum feed-through. Between the electromagnetic circuits outside the vacuum chamber and those fixed on the pendulum arm, Lorentz forces were produced and acted as a “tare” force, \( F_{tare} \). In this study, even the influence of the geomagnetic field was considered in the correction of a measured thrust value.

During the operation of the hollow cathode, the insert wear occurs because of sputtering. In this experiment, after a main discharge for 43 minutes using the insert with 1.5 mm inner radius, the insert mass decreased by 0.07 mg. Assuming that the insert erosion occurred only during the main discharge, this value corresponded to a mass flow rate of 0.027 mg/s, which was two orders in magnitude smaller than that of the propellant, 1.5-2.7 mg/s. Here, the influence of the insert erosion on the thrust performance will be neglected.
3.2. Influence of cathode configuration

Figure 6 shows $V_d$ and $F$ as a function of $J_d$ for three cathode configurations. The operations under the same conditions were conducted at least two times, and the average value of them was plotted. Each error-bar corresponds to a standard deviation. The operating area was expanded to 60 A using the hollow cathodes developed in this study.

3.3. Influence of magnetic field strength

Figure 7 shows $V_d$ and $F$ as a function of $B$ for constant $J_d$. $V_d$ and $F$ increase with increasing $B$. The slope in $V_d$ and $F$ variation increases as $J_d$ increases.

3.4. Influence of mass flow rate

Figure 8 shows $V_d$ and $F$ as a function of $\dot{m}$ for $B$. $V_d$ decreases with increasing $\dot{m}$. On the other hand, thrust is almost independent of $\dot{m}$. This behavior is consistent to electro-magnetic acceleration.

3.5. Application of swirl acceleration model

In the thruster operation of this study, the discharge current level is so low that a self-field thrust and an electro-thermal thrust are neglected. The scaling of the electro-magnetic thrust can be described by a swirl acceleration model, that is, the rigid rotator model suggested by Fradkin. The ionized flow acts as a rigid rotator, experiencing a torque due to a Lorentz force produced by a discharge current and the applied magnetic field. The kinetic energy of the rotating plasma column is converted to a kinetic energy of the axial motion, which yield a thrust. The Fradkin et al.’s thrust formula is as follows.

$$F_{\text{swirl}} = \frac{1}{\sqrt{2}} J_d B R_c \left[ 1 - \frac{3}{2} \left( \frac{R_c}{R_a} \right)^2 \right]$$  \hspace{1cm} (2)

In this study, $R_c$, which equals to an orifice radius of 2.0 mm, is much smaller than $R_a$ of 40 mm. Hence, Eq. (2) can be simplified to

$$F_{\text{swirl}} \approx \frac{1}{\sqrt{2}} J_d B R_c$$  \hspace{1cm} (3)
Figure 9 shows the thrust $F$ versus Lorentz force $JdBR_a$. Roughly speaking, $F$ increases linearly with $JdBR_a$.

\[ F = \frac{F_{sw}}{mN} \]

\[ J \cdot B \cdot R_a^2 / m \]

\[ V_d = V_0 + C \cdot \frac{J \cdot B \cdot R_a^2}{m} \]

3.6. Thrust performance

Figure 11 shows the thrust efficiency versus the specific impulse. We can observe that $\eta$ increases with increasing $B$ owing to an increase in the thrust. On the other hand, $\eta$ decreases with an increase in $R_{LaB6}$. This is caused by the thrust decrement with the increase in $R_{LaB6}$, see Fig. 9. The decrement in $V_d$ with $R_{LaB6}$ does not have a significant impact on increasing $\eta$.

The discharge current has an optimum value to maximize $\eta$ for any combination of $B$ and $\dot{m}$. At higher discharge current, as seen in Fig. 6, $\eta$ decreased due to the sharp increment in $V_d$.

In this experiment, $R_{LaB6}$ of 1.5 mm showed better efficiency than $R_{LaB6}$ of 2.0 mm. Two possible reasons are as follows: One reason is that a higher-density plasma is generated when $R_{LaB6}$ is small. This has a positive influence on the overall current distribution. The second is related to the insert orifice radius. In this study, the final plasma flow passage is determined by $R_{LaB6}$. The orifice radius, 2.0 mm, was equal to or larger than $R_{LaB6}$. The confirmation of the above points warrants further investigations including plasma diagnostics.

In this experiment, as the best performance using argon as the propellant, a thrust efficiency of 25.5% and a thrust/power ratio of 17.0 mN/kW were obtained with a magnetic field of 265 mT, a discharge current of 30 A, a propellant mass flow rate of 2.1 mg/s, a discharge voltage of 121 V, and a LaB$_6$.
inner radius of 1.5 mm.

4. Conclusion

In this study, for improving the thrust efficiency of the AF-MPD thruster, a LaB$_6$ hollow cathode, capable of increasing the discharge current, was developed. The operation characteristics of the AF-MPD thruster with the developed LaB$_6$ hollow cathode were experimentally measured. The operation range was expanded from 20 A to 60 A. The thrust and discharge voltage increased with increasing the discharge current and magnetic field strength. The highest thrust efficiency of 25.5% was achieved with a discharge current of 30 A. With discharge currents larger than 30 A, improvement in thrust efficiency was not observed because the discharge voltage was sharply increased with increasing the discharge current. This suggests that the insert inner radius needs to be increased to increase the discharge current without being accompanied by a sharp increase in the discharge voltage. Therefore, the design of a hollow cathode with an even larger insert inner radius should be further investigated.

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References