# Ten-Ampere-Level, Direct Current Operation of Applied-Field Magnetoplasmadynamics (MPD) Thruster using $LaB_6$ Hollow Cathode

**IEPC-2017-235**

*Presented at the 35th International Electric Propulsion Conference*
*Georgia Institute of Technology • Atlanta, Georgia • USA*
*October 8 – 12, 2017*

Hayato Kasuga,[1] Keisuke Mizutani,[2] Daisuke Ichihara,[3] Akira Iwakawa[4], and Akihiro Sasoh[5]
*Nagoya University, Nagoya, Aichi, 464-8603, Japan*

Kohei Kojima[6],
*Mitsubishi Heavy Industries Ltd, Komaki, Aichi, 485-8561, Japan*

Tatsuya Kimura[7],
*Mitsubishi Heavy Industries Ltd, Nagoya, Aichi, 455-8515, Japan*

Yoshihiro Kawamata[8], and Masaaki Yasui[9]
*Mitsubishi Heavy Industries Ltd, Komaki, Aichi, 485-8561, Japan*

**Abstract: Magnetoplasmadynamic thruster with a thermionic emission type hollow cathode using the $LaB_6$ emitter has been newly developed. The stable operation with the discharge current of ten-ampere level was able to be maintained by the thermionic emission type hollow cathode. From the results of the experiments conducted with the discharge current in range of 10 – 60 A, the discharge voltage and thrust were increased with the discharge current increasing. At the higher current condition more than 30 A, the rate of the discharge voltage increment become large, though the thrust was almost linear to the current. Because of this tendency, the thrust efficiency has a local maximum or the efficiency improving was saturated. After the series of the experiment, the severe damage of the hollow cathode has not been observed.**

## Nomenclature

| | | |
|---|---|---|
| $B$ | = | applied magnetic field, mT |
| $F$ | = | thrust, mN |
| $J_d$ | = | discharge current, A |
| $\dot{m}$ | = | mass flow rate, mg/s |

[1] Graduate student, Department of Aerospace Engineering.
[2] Graduate student, Department of Aerospace Engineering.
[3] Graduate student, Department of Aerospace Engineering.
[4] Lecturer, Department of Aerospace Engineering, iwakawa@nuae.nagoya-u.ac.jp.
[5] Professor, Department of Aerospace Engineering.
[6] Senior Engineer, Space Vehicle and Equipment Engineering Department
[7] Manager, Space Systems Engineering Department.
[8] Manager, Space Vehicle and Equipment Engineering Department.
[9] Manager, Space Vehicle and Equipment Engineering Department.

| | | |
|---|---|---|
| $V_d$ | = | discharge voltage, V |
| $z$ | = | coordinate |

## I.Introduction

FOR realizing the future in-space missions, the electric propulsion system with higher-thrust and higher-efficiency is necessary. For achieving these demands, the clustering has been suggested, but the clustering can not avoid the mass increment penalty. The electromagnetic acceleration type can be achieved these demands, especially higher thrust, with only single thruster head due to having higher thrust density.

Magnetoplasmadynamic (MPD) thruster is the electro-magnetic acceleration type thruster. Although the MPD thruster has been studied more than half century, a few space missions have been only conducted. The conventional MPD thruster composed a cylindrical anode and a lod cathode[1–3]. The critical issue of the conventional MPD thruster is the lifetime of the operation due to the severe cathode erosion[4]. This cathode erosion is caused by the operation condition with a large discharge current because the electrons for maintaining the plasmas is supplied from the cathode and the cathode is heated by the large discharge current. For preventing the cathode erosion, some studies have used a hollow cathode[5] or multi channel hollow cathode[6,7]. However, the discharge current level of these studies was still large and the erosion was observed. In past study, a 10 A level thruster operation was realized with a commercial-type thermionic electron emitter (LHC-03AE-1-01, Kaufman & Robinson Inc.)[8]. The MPD thruster operation with lower discharge density can be achieved using the hollow cathode with the thermionic electron emitter. From the analysis of variance method of the past results with the commercial-type cathode, discharge voltage increasing had a large dependence on the thrust efficiency. Though, the discharge current range of the commercial-type one was limited and the operation condition was also limited. Therefore, to improve the MPD thruster performance, a thermionic electron emitter type hollow cathode with $LaB_6$ emitter was newly developed and installed to the MPD thruster. The main objective of this study is extending and improving the operation range of the MPD thruster with a thermionic electron emitter type hollow cathode.

## II.Experimental Apparatus

A thermionic emission type hollow cathode with $LaB_6$ emitter was newly developed for MPD thruster. Figure 1 shows the schematic illustration of the developed cathode and Fig. 2 shows the photograph of the cathode. This cathode did not have any heater and the discharge was started with high-voltage ignition. The cathode has a $LaB_6$ emitter with inner radius of 1.5 or 2.0 mm and the length of the emitter is 8.0 mm. From the modified Rchardson-Dushman equation and the area of the inner surface, the temperature of the emitter during the operation was estimated to be 2150 K when maximum current of a series of these experiment with 60 A.

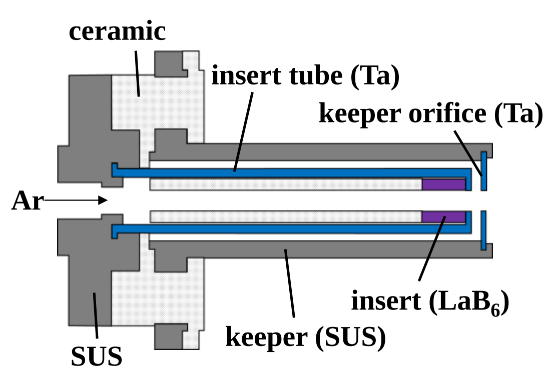


Fig. 1 Schematic illustration of developed thermionic emission type hollow cathode with $LaB_6$ emitter.

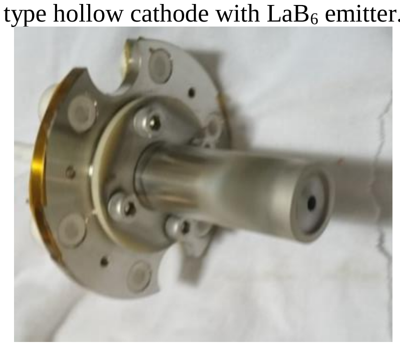


Fig. 2 Photo of developed thermionic emission type hollow cathode with $LaB_6$ emitter.

The developed cathode was installed in the applied-field MPD thruster as shown in Fig. 3. The anode radius is 40 mm, and the central axis of the hollow cathode corresponds to the central axis of the anode. The argon gas was used as propellant and the propellant is fed to the discharge channel through the hollow cathode. A magnetic field was able to be up to 265 mT at $z = 0$ mm on the central axis by the water-cooled solenoid coil. The magnetic field strength distribution was measured by a Gauss meter (GM-4000, Denshijiki Industry Co. Ltd.).

The experiment was conducted in the vacuum chamber with 2 m-dia. and 4 m-length. The ambient gas in the chamber was evacuated by a turbo molecular pump which was backed by a rotary pump. The back pressure was measured by a pirani gauge and an ionization gauge, and was kept less than $2.4\times10^{-2}$ Pa

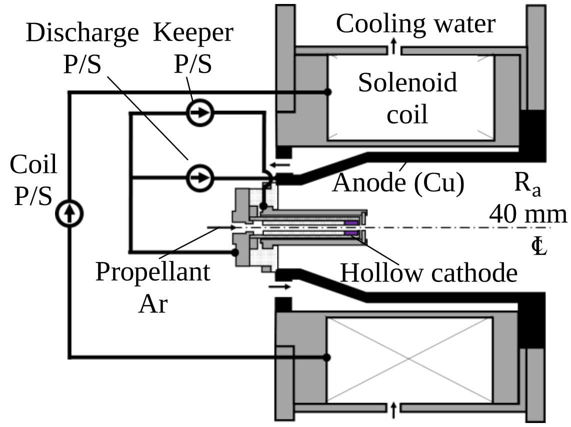


Fig. 3  Schematic illustration of an applied-field MPD thruster with developed cathode.

during the thruster operation. The mass flow rate of the propellant is controlled using a mass flow controller (KOFLOC Co. Ltd.). A pendulum type thrust stand was used for thrust measurement. The displacement of the stand was measured by a linear differential transfer. Before the experiments, the relation between the displacement of the stand and the force was calibrated.

## III.Experimental Results

Experiments were conducted by varying mass flow rate, discharge current, applied magnetic field and emitter inner diameter, these conditions are summarized in Table 1. The discharge current was extended from 20 to 60 A compared with the past study using commercial hollow cathode. The snapshot during an experiment with the discharge current of 60 A is shown in Fig. 4. The discharge voltage was almost steady during the higher-current experiment.

Figure 5 shows the obtained results of the thruster performance of $\dot{m}$ = 2.1 mg/s. The discharge voltage, which is shown in Fig. 5 (b), has an increment tendency with the current increasing. The slope of the voltage is changed at 30 A, the slope of the higher current range more than 60 A is larger than that of the range less than 30 A. The thrust, which is shown in Fig. 5 (c), also has the increment tendency and the slope is almost linear. The thrust magnitude of the emitter with 3-mm-dia. is higher than that of the emitter with 4-mm-dia. The reason why this difference caused has been still not well understood. The thrust efficiency as shown in Fig. 5 (d) has a local maximum value at the current of 30 A. This tendency was mainly caused by the changing the slope of the discharge voltage.

Figure 6 shows the photograph of the developed hollow cathode after experiment. Although the experiments were conducted with the higher current of 60 A and the strong magnetic field of 265 mT, the severe damage has not been observed.

Table 1  Experimental Conditions

| control parameter | unit | |
|---|---|---|
| mass flow rate, $\dot{m}$ | mg/s | 1.5 – 2.7 |
| discharge current, $J_d$ | A | 10 – 60 |
| applied magnetic field, $B$ | mT | 133 – 265 |
| emitter inner diameter | mm | 3, 4 |

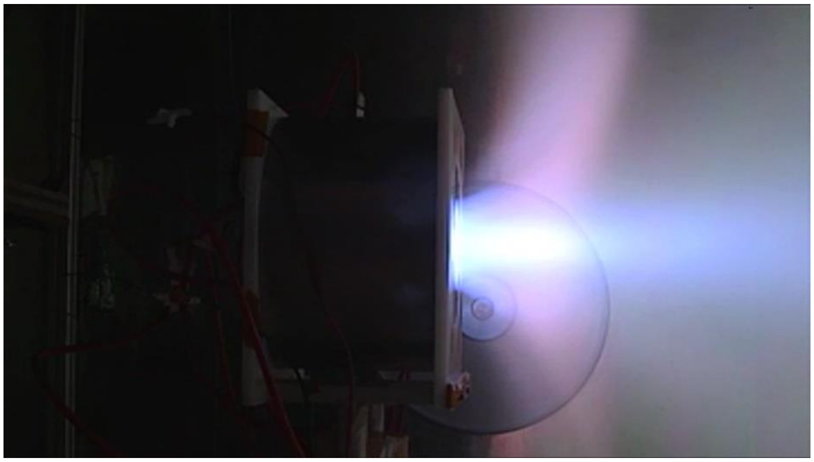
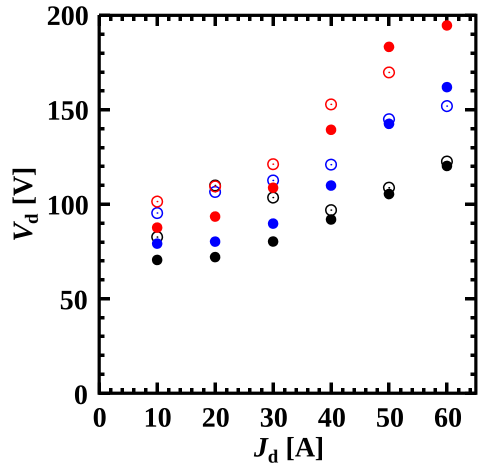


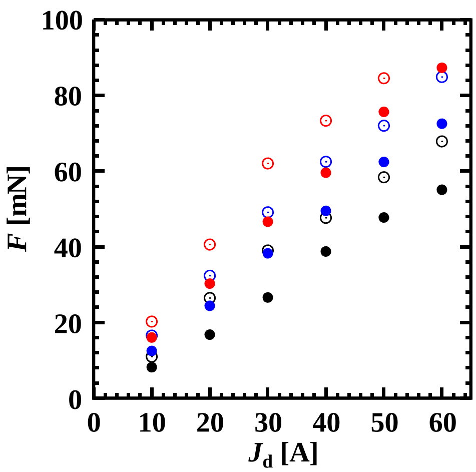
Fig. 4  Snapshot during operation: $\dot{m}$ = 2.7 mg/s, $J_d$ = 60 A, $B$ = 265 mT.

| | $\phi$ | |
|---|---|---|
| ***B*** | **3 mm** | **4 mm** |
| **133 mT** | ○ (black) | ● (black) |
| **199 mT** | ○ (blue) | ● (blue) |
| **265 mT** | ○ (red) | ● (red) |

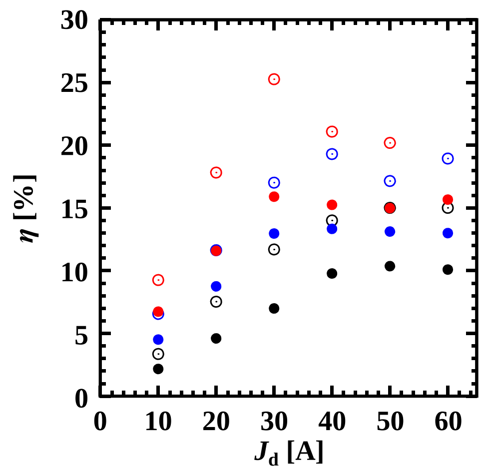
(a) Symbols




(b) Discharge voltage




(c) Thrust




(d) Thrust efficiency

Fig. 5  Experimental results: $\dot{m}$ = 2.1 mg/s.

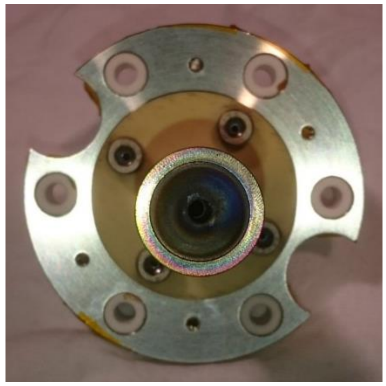


Fig. 6 Appearance of hollow cathode after operation.

## IV.Conclusion

An applied-field MPD thruster with the thermionic emission type hollow cathode with $LaB_6$ emitter has been newly developed and experiments were conducted by varying mass flow rate, discharge current, applied magnetic field and emitter inner diameter. From the results, the discharge voltage and the thrust were increased with the discharge current increasing, however, the thrust efficiency was not monotonically improved with the current. The discharge voltage increasing at the higher current range more than 30 A became steep, and this caused the degrading the efficiency. The efficiency more than 25% has been achieved under this series of the experiment. The hollow cathode did not have the severe damage after the experiment, though the discharge current was 60 A maximum.

## Acknowledgments

The authors thanks to K. Tachibana of the Technical Division, Nagoya University, for his support to the LaB6 processing.

## References

[1] Myers, R. M., Mantenieks, M., and Sovey, J., *Geometric effects in applied-field MPD thrusters*, 1990.

[2] Sasoh, A., and Arakawa, Y., “Thrust Formula for Applied-Field Magnetoplasmadynamic Thrusters Derived from Energy Conservation Equation,” *Journal of Propulsion and Power*, vol. 11, 1995, pp. 351–356.

[3] Kodys, A. D., and Choueiri, E. Y., “A Critical Review of the State-of-the-Art in the Performance of Applied-field Magnetoplasmadynamic Thrusters,” *Joint Propulsion Conference and Exhibit*, 2005, pp. 1–23.

[4] Schrade, H. O., Auweter-Kurtzt, M., and Kurtz, H. L., “Cathode erosion studies on MPD thrusters,” *AIAA Journal*, vol. 25, 1987, pp. 1105–1112.

[5] Fradkin, D. B., Blackstock, A. W., Roehling, D. J., Stratton, T. F., Williams, M., and Liewer, K. W., “Experiments using a 25-kw hollow cathode lithium vapor mpd arcjet,” *AIAA Journal*, vol. 8, 1970, pp. 886–894.

[6] Lev, D. R., and Choueiri, E. Y., “Scaling of Efficiency with Applied Magnetic Field in Magnetoplasmadynamic Thrusters,” *Journal of Propulsion and Power*, vol. 28, May 2012, pp. 609–616.

[7] Albertoni, R., Paganucci, F., Rossetti, P., and Andrenucci, M., “Experimental Study of a Hundred-Kilowatt-Class Applied-Field Magnetoplasmadynamic Thruster,” *Journal of Propulsion and Power*, vol. 29, Sep. 2013, pp. 1138--1145.

[8] Ichihara, D., Uno, T., Kataoka, H., Jeong, J., and Iwakawa, A., “Ten-Ampere-Level, Applied-Field-Dominant Operation in Magnetoplasmadynamic Thrusters,” *Journal of Propulsion and Power*, vol. 33, 2017, pp. 360–369.