

Performance Characteristics of Steady-State MPD Thrusters with Permanent Magnets and Multi Hollow Cathodes for In-Space Propulsion

IEPC-2013-094

*Presented at the 33rd International Electric Propulsion Conference,
The George Washington University • Washington, D.C. • USA
October 6 – 10, 2013*

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Abstract: A pulsed-operation MPD Thruster was not fit for practical use in space. In this study, the MPD thruster doesn't have coils for external magnetic field application but permanent magnets of Samarium cobalt. So, if magnetic Curie temperature is taken into consideration, a steady-state radiation-cooled MPD thruster without cooling water can be designed. The manned Mars explorations which are a final objective of this study are missions for which a high specific impulse is needed as in-space propulsion. Using hydrogen, we could obtain a result of thrust 41.9mN, specific impulse 2870s, and thrust efficiency 12.5%. Furthermore, we designed a multi-hollow cathode to decrease cathode damage. In a new water-cooled thruster with the multi-hollow cathode, anode geometry, distance between electrodes and magnet field strength can be changed.

I. Introduction

THIS study is one of In-space Propulsion Project which is unified by Japan Aerospace Exploration Agency (JAXA). The final target is manned Mars exploration. In order to achieve it, we planned to develop magneto-plasma-dynamic (MPD) thrusters as the main engines which have high thrust density and high specific impulse. In conventional steady-state MPD thrusters, axial magnetic fields are applied by external coils.^{1,2} However, because a permanent magnet with very high magnetic flux density like Samarium Cobalt had been developed, we planned to apply external magnetic field to MPD thrusters by using the permanent magnet. Therefore, the operation system becomes very simple, and a thruster with very light and compact can be designed.

And cathode damage is important problem for practical use of the MPD thruster. One of the solution may be to use a multi-hollow cathode. Because its discharge doesn't operate in spot mode but in diffusion mode, the maximum cathode surface temperature is expected to be less than the melting point of the cathode material compared with thermal conditions with conventional rod cathodes.

In this study, we redesigned a direct-current (DC) arcjet thruster used in previous experiments, so that it could attach permanent magnets. We carried out basic experiments with propellant gases of hydrogen, nitrogen, argon and ammonia, and obtained their performance characteristics. We also compared the results with those of conventional DC arcjet thrusters with nitrogen gas. Furthermore, we newly designed a water-cooled MPD thruster with a multi-hollow cathode, and stable operation could be confirmed.

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II. Experimental Apparatus

A. MPD thruster

Figure 1 shows the cross-sectional view of the water-cooled DC arcjet thruster used in previous studies.³ We changed only the anode side in order to attach permanent magnets.

Figures 2 and 3 show the configuration of the MPD thruster used for this study and its photo, respectively. It has a magnetic circuit which is formed by SS400 blocks sandwiching permanent magnets (samarium cobalt) at the anode side of the thruster, for application of axial magnetic field. As shown in the figures, the magnets are exposed outside. The propellant gas is injected as pivot flow from the upstream end of the discharge chamber. The MPD thruster is operated with input powers of 5-10kW.

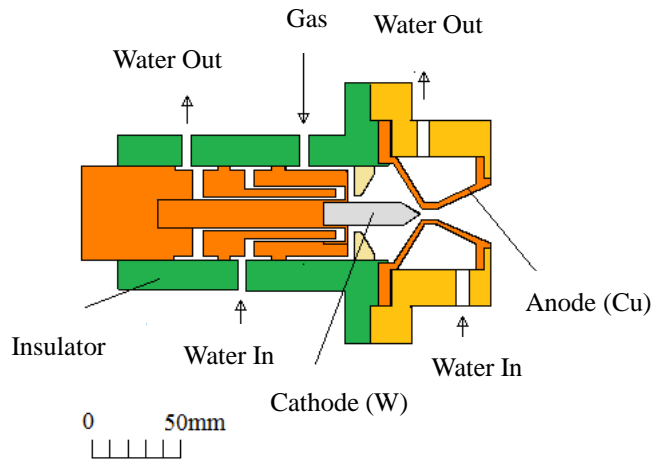


Figure 1. Configuration of water-cooled DC arcjet thruster in previous experiments.

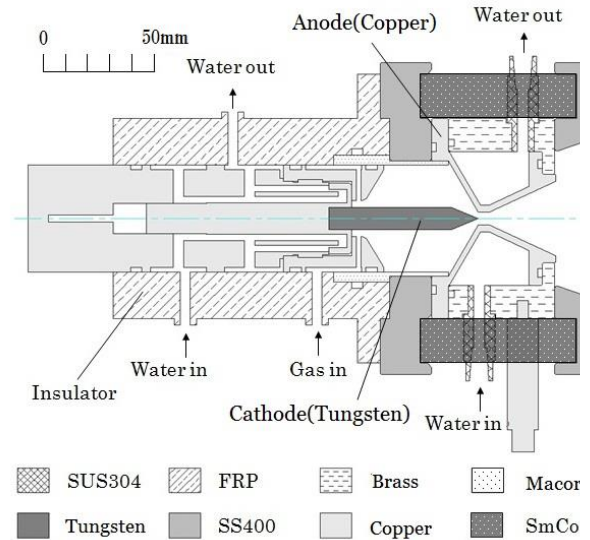


Figure 2. Configuration of water-cooled MPD thruster with permanent magnets.



Figure 3. Photo of MPD thruster.

A photo of the anode is shown in Fig.4. It is made of copper, which has a good thermal conductivity. The constrictor of a convergent-divergent nozzle throat has a diameter of 6 mm and a length of 5 mm, and a divergent nozzle angle is 50 deg.

The cathode is shown in Fig.5. A cylindrical cathode is made of pure tungsten, which is a heat resistant material. It has a diameter of 10 mm. The shape of the cathode tip is conical one, and the tip angle is 45 deg. In this study, the gap between the electrodes is set to 0 mm.

Figure 6 shows magnetic field lines. They are parallel to the central axis around the constrictor. As shown in Fig.7, the maximum value is about 0.15 T around the constrictor.



Figure 4. Photo of anode.



Figure 5. Photo of cathode.

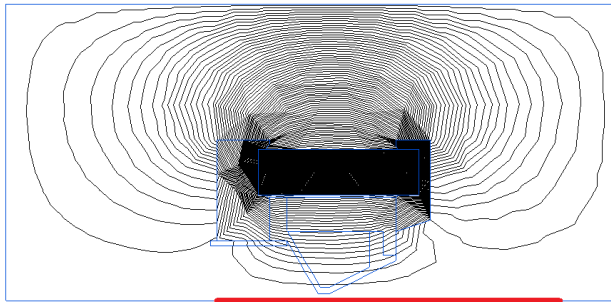


Figure 6. Magnetic field lines.

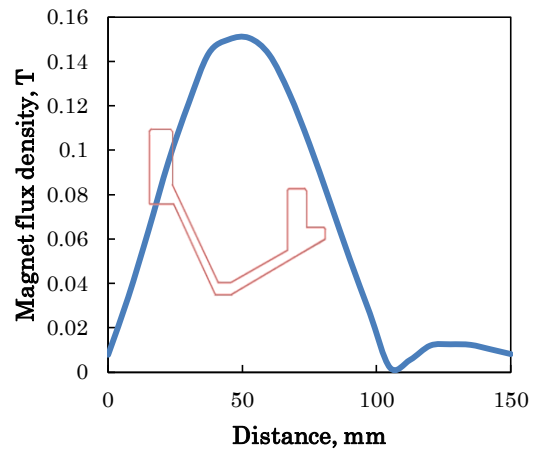


Figure 7. Magnet flux density vs axial distance on thruster axis.

B. Vacuum system

As shown in Figs.8 and 9, the MPD thruster is located in a vacuum tank made of aluminum and pyrex glass. The tank configuration is 0.6 m in diameter and 5.75 m long. We can clearly observe plasma plumes in the tank through the pyrex glass part. The propellant, cooling-water and electric power are supplied through some flanges. The vacuum tank is evacuated using an oil-diffusion pump of 13000 l/s, as shown in Fig.10, connected in series with a mechanical booster of 1630 m³/h and a rotary pump of 3000 m³/h. The tank pressure is measured by Pirani and ionization gauges. The vacuum pressure declines to 6.7×10^{-5} Pa.

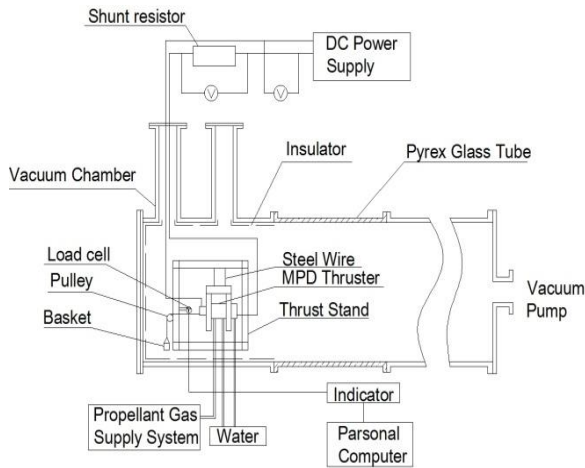


Figure 8. Schematic of experiment apparatus.

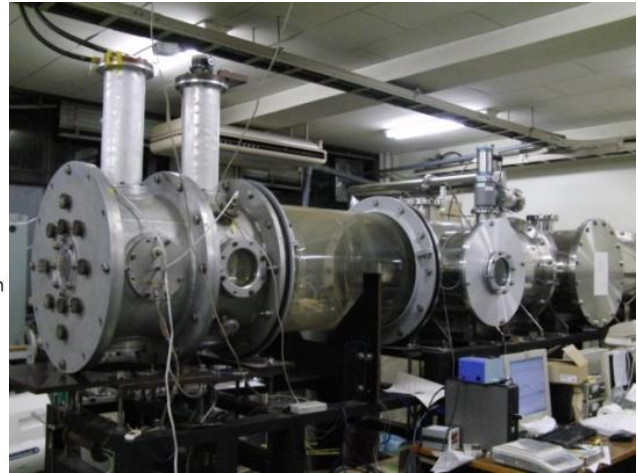


Figure 9. Vacuum tank.



Figure 10. Oil-diffusion pump.

C. Thrust measurement system

Figures 11-12 show the thrust measurement system. The MPD thruster is set on the thrust stand hanged using steel wires. Thrust is measured by a load cell. When the thruster operates, the load cell is pushed. Thrust calibration is carried out with a pulley and weight system, and a typical calibration curve, as shown in Fig.13, is almost linear.

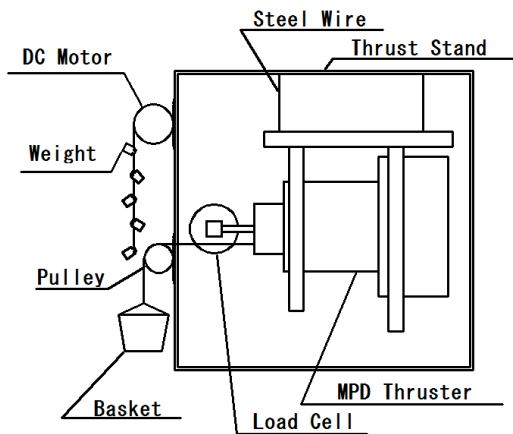


Figure 11. Thrust stand.

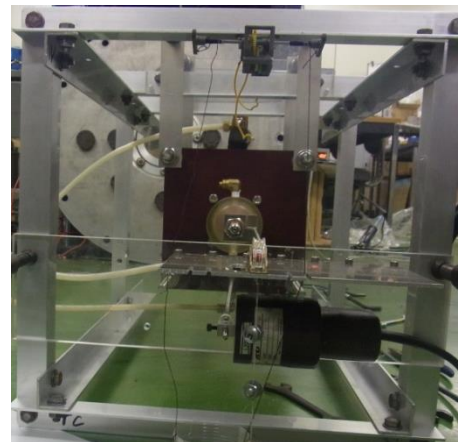


Figure 12. Photo of thrust stand.

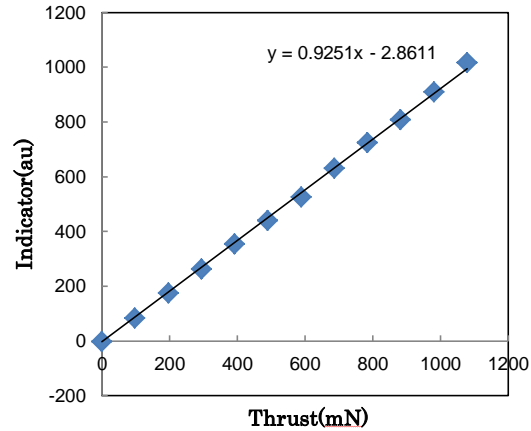


Figure 13. Thrust calibration curve.

III. Results and Discussion

In this study, at first we verified whether stable operations with nitrogen and argon gases were achieved. Table 1 shows the mass flow rates and results. The result of nitrogen gas is 402.9 mN, 281 s and 10.4 % at 5.36 kW. That of argon gas is 82.9 mN, 56.3 s and 0.71 % at 3.20 kW. As shown in Fig.14, the discharges with both gases were very stable. The plasma plume of nitrogen is expanded radially compared with that of argon.

Table 1. Performance data with N₂ and Ar.

	N ₂ :0.15g/s	Ar:0.17g/s
Thrust[mN]	402.9	82.0
Input Power[kW]	5.36	3.20
Specific Impulse[s]	281	56.3
Thrust Efficiency[%]	10.4	0.71

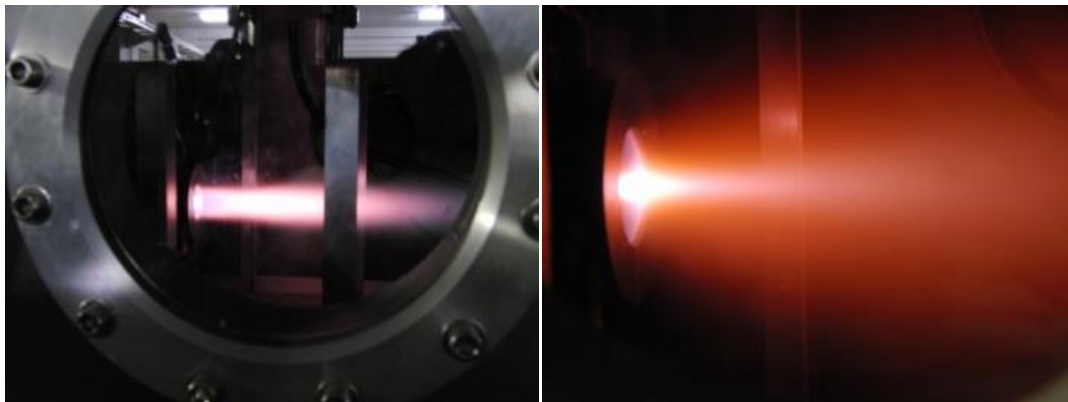


Figure 14. Photos of N₂ (left) and Ar (right).

The result with hydrogen gas is shown in Table 2. The input power is 4.7 kW. The specific impulse is 2870 s, and the thrust efficiency is 12.5 %. These values are higher than those with nitrogen and argon gases. As shown in Fig.15, we can observe long plasma beam with hydrogen. It is expected because the operation is in electromagnetic acceleration mode. With ammonia gas, as shown in Fig.16, it is slightly difficult to stably keep discharge. This is expected because of the higher binding energy of NH_3 molecule than those of other gases.

Table 2. Performance data with H_2 .

	H_2 :0.0015g/s
Thrust[mN]	41.9
Input Power[kW]	4.7
Specific Impulse[s]	2870
Thrust Efficiency[%]	12.5

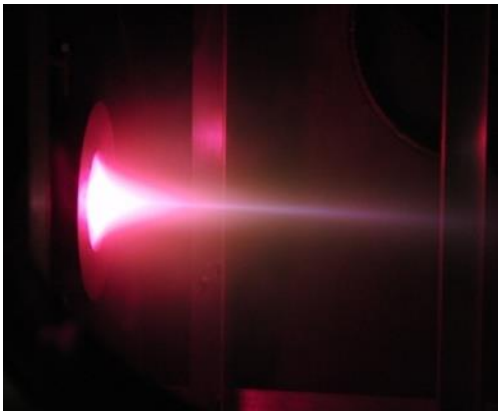


Figure 15. Photo of H_2 .

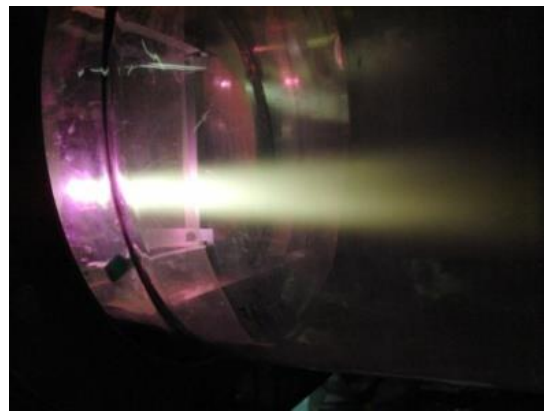


Figure 16. Photo of NH_3 .

The discharge voltage vs current characteristics of four gases are shown in Fig.17. The discharge voltage decreases with increasing discharge current. This is dropping characteristics which are seen in electrothermal acceleration mode. With ammonia gas, the discharge voltage is higher than those with other gases.^{1,2} Figure 18 shows the thrust vs discharge current characteristics with four gases. The thrust increases with increasing discharge current.

As shown in Table 3, we compared the MPD thruster with the conventional DC arcjet thruster. With nitrogen gas, the discharge voltage, thrust, specific impulse and thrust efficiency with the MPD thruster are higher than those with the DC arcjet thruster. In the MPD thruster, it is considered because of efficient electromagnetic acceleration by strong axial magnetic field with permanent magnets.

Figure 19 shows a photo of a cathode after experiments. Severe cathode damage is observed.

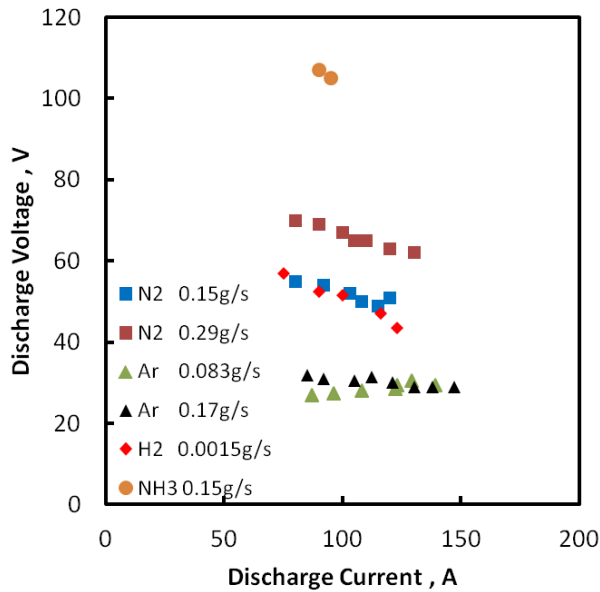


Figure 17. Discharge voltage vs current characteristics.

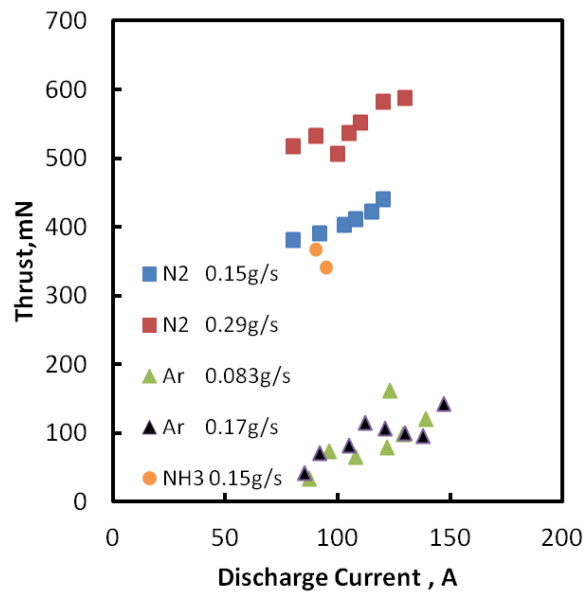


Figure 18. Thrust vs discharge current characteristics.

Table 3. Comparison between DC arcjet and MPD thruster.

	DC Arcjet	MPD thruster
Mass flow rate[g/s]	0.146	0.146
Discharge current[A]	75.5	80
Discharge voltage[V]	40.5	55
Input power[kW]	3.06	4.4
Thrust[mN]	180.4	381
Specific impulse[s]	126	267
Thrust efficiency[%]	3.7	11.3



Figure 19. Cathode damage.

IV. New MPD Thruster with Multi-Hollow Cathode

A. Multi-hollow cathode

We plan to use a multi-hollow cathode in order to decrease cathode damages. Because the discharge with the multi-hollow cathode isn't in spot mode, but in diffuse mode with a lower surface temperature around 2500K.^{4,5,6}

Figure 20 shows the configuration of a multi-hollow cathode designed for the MPD thruster. It has seven small-diameter pipes inserted in a large-diameter pipe. The material is carbon which is lower cost than tungsten. Figure 21 shows the photo of conical-shaped solid cathodes made of tungsten and carbon, a multi-hollow cathode and a single hollow cathode.

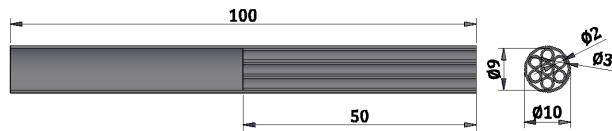


Figure 20. Configuration of multi-hollow cathode.

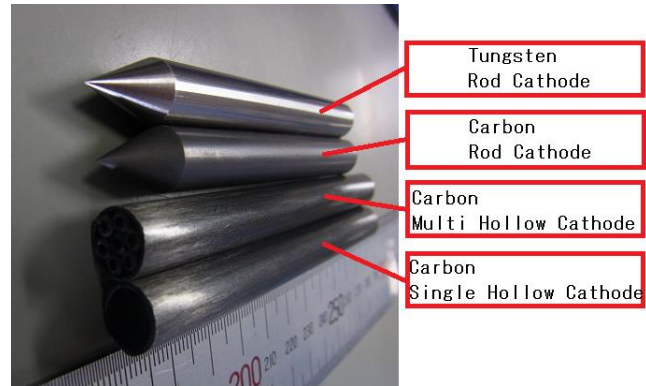


Figure 21. Photo of all cathodes.

B. MPD thruster with multi-hollow cathode

Figure 22 shows a new MPD thruster with the multi-hollow cathode. In order to compare performances with a conventional solid cathode and the multi-hollow cathode, it is possible to replace cathode. The configuration of the anode is the same to previous ones. By taking into account design of radiation-cooled thruster, permanent magnets are attached to a little far radially from the center axis. The number of permanent magnets can change easily.

Figure 23 shows the experimental apparatus. A new MPD thruster is hanged with four leaf springs.

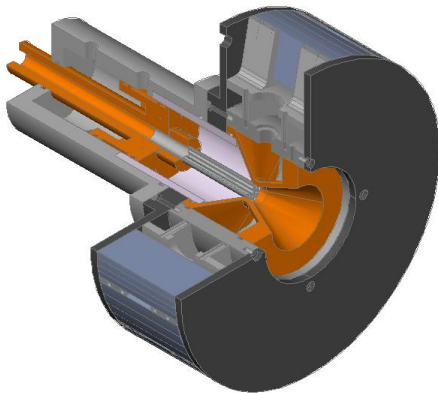


Figure 22. New MPD thruster with multi-hollow cathode.

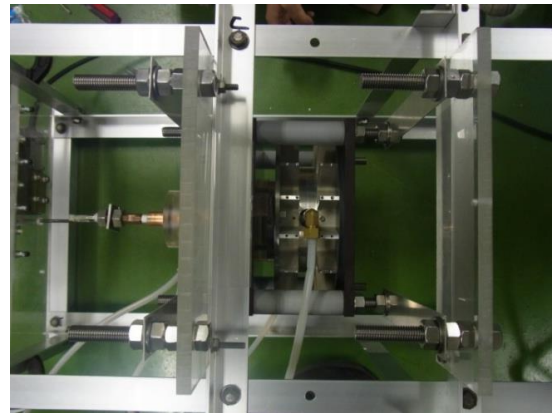


Figure 23. Experimental apparatus.

Figure 24 shows magnetic field lines. They are parallel to the central axis around the constrictor. As shown in Fig.25, the calculated value is corresponding to the measurement value. Around the constrictor, the calculated value and the measurement value are about 1.8T and 1.5T, respectively.

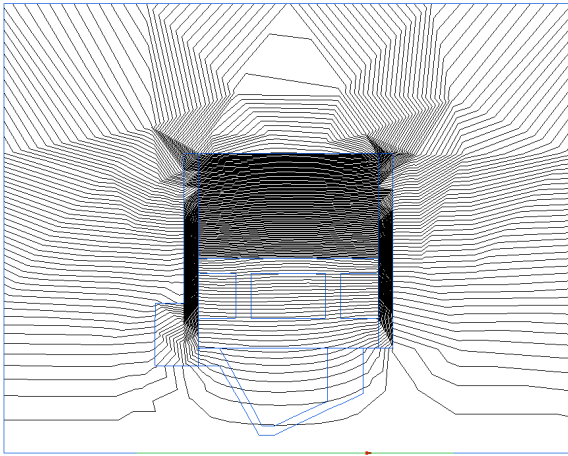


Figure 24. Magnetic field lines.

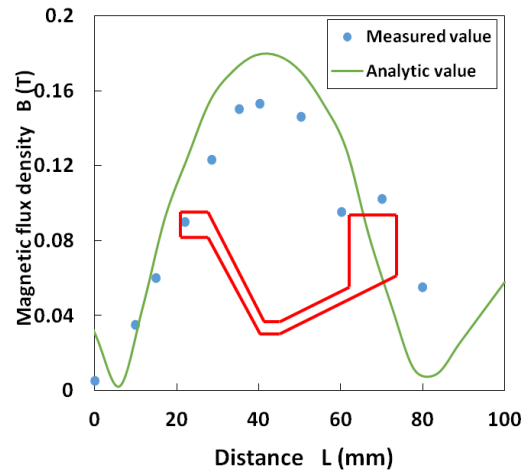


Figure 25. Magnet flux density vs axial distance on thruster axis.

C. Basic experiment with new MPD thruster

Figures 26 and 27 show the hydrogen plumes without and with applied magnetic field, respectively, using a tungsten solid cathode. When the axial magnetic field is applied by permanent magnets, the plume converged to the central axis. Figure 28 shows the discharge voltage vs current characteristics.^{7,8} Both the discharge voltages without and with applied magnetic field are almost equal.

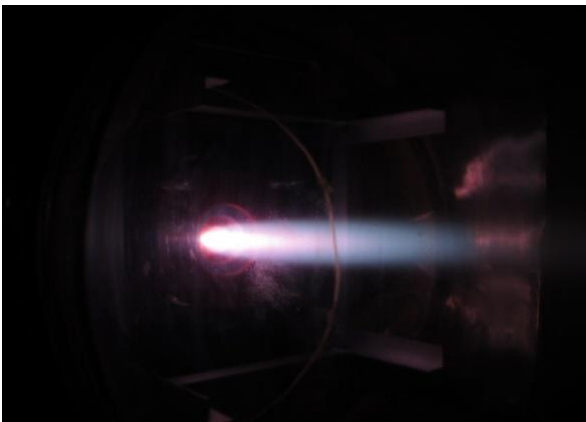


Figure 26. Without applied magnetic field.

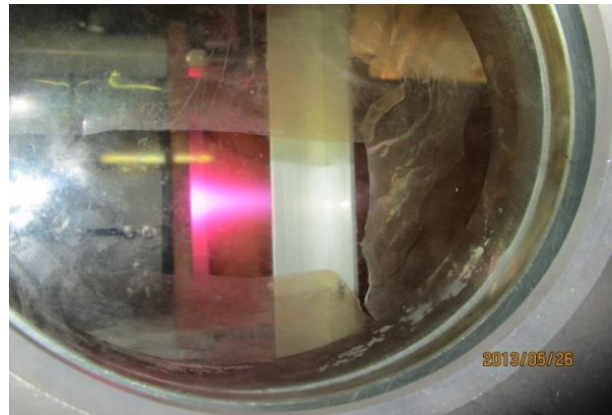


Figure 27. With applied magnetic field.

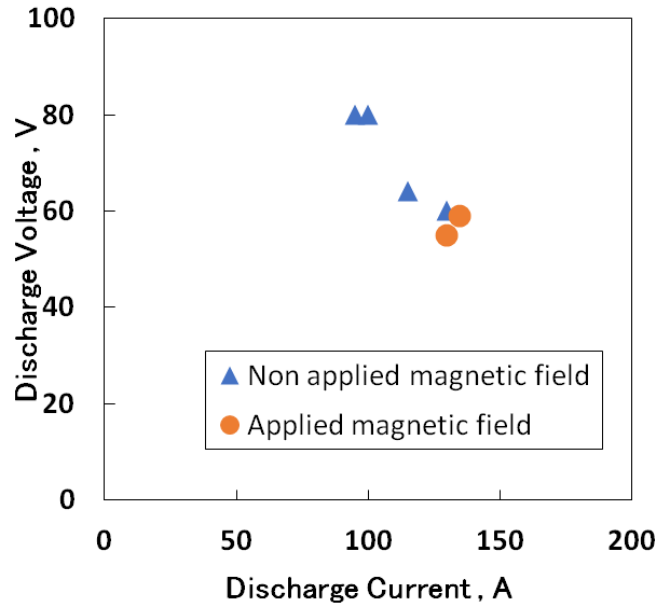


Figure 28. Discharge voltage vs current characteristics.

V. Conclusion

The water-cooled steady-state MPD thrusters with permanent magnets were developed, and the thruster performances were measured.

- (1) The dropping characteristics were seen in the discharge voltage vs current characteristics.
- (2) Using hydrogen, we could obtain a result of thrust 41.9 mN, specific impulse 2870 s, and thrust efficiency 12.5 %.
- (3) Compared with the conventional DC arcjet thruster, the discharge voltage, thrust, specific impulse and thrust efficiency increased.
- (4) The MPD thruster with the multi-hollow cathode was newly designed, and we carried out the basic experiment.

References

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