

Performance Characteristics of Steady-State MPD Thrusters with Permanent Magnets and Multi Hollow Cathodes for Manned Mars Exploration

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Abstract: A quasi-steady MPD thruster does not fit for practical use in space because of its heavy weight and complicated system. Taking magnetic Curie temperature into consideration, we designed a steady-state water-cooled type MPD thruster. The MPD thruster doesn't have water-cooled coils but has permanent magnets of Samarium Cobalt for external magnetic field application. In this study, we aim at development of high-power MPD thrusters for a manned Mars exploration mission which needs a high specific impulse. We were investigated the changes of performance characteristics on applied magnetic field. We obtained a result of a thrust of 21.4 mN, a specific impulse of 2,907 s and a thrust efficiency of 4.9 % at 4.9 kW with hydrogen. Furthermore, we redesigned the shape of hollow cathodes, and we tested using a multi hollow cathode which is made of pure tungsten. Then, we obtained a high performance characteristics and a low erosion rate of the cathode.

I. Introduction

Steady state MPD (Magneto-Plasma-Dynamic) thrusters have been investigated at Osaka Institute of Technology. In this study, a practical MPD thruster system was investigated for manned Mars exploration mission as one of the In-space Propulsion project by collaborative research with JAXA (Japan aerospace eXploration Agency). In order to achieve that mission, MPD thrusters are needed with light and simple structure^{1,2)}. Therefore, we use the permanent magnets for applied magnetic field. Also, cathode erosion is one of important problems for practical use in MPD thruster. One of the solutions may is to use a hollow cathode because the current can attach in wider area than that of rod cathode. So, the maximum surface temperature of the hollow cathode is expected to be lower than the rod cathode. Thus, it can be lower than the melting point of the cathode material. Then, we designed and developed a single hollow cathode and a multi hollow cathode. The final target is to develop a steady-state radiation-cooled MPD thruster without water cooling for manned Mars explorations.

We performed basic experiments with propellant gases of hydrogen, ammonia, nitrogen, argon, and obtained their performance characteristics with rod cathodes. We also tested with hollow cathodes made of carbon and pure tungsten. Then, we compared their results. Furthermore, we were designing a radiation-cooled MPD thruster with thermal analysis.

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II. Experimental apparatus

An operating tests should be carried out in actual space because the thruster will be used in space. Therefore, the tests had carried out in vacuum tank because the earth is covered in an atmosphere. An experimental apparatus contains MPD thruster, vacuum system and thrust measurement and calibration system. In addition, a power supply system, propellant supply system and voltage and current measurement system are exists.

A. MPD thruster

Figure 1 shows the cross-sectional view and 3 dimensional model, respectively, of the water-cooled MPD thruster used for this study³⁻⁶. The MPD thruster is operated with input power of 5-10 kW. In order to compare performances between a conventional rod cathode and hollow cathodes, it is possible to replace them. The anode made of copper which has a good water-cooled effects. It has the constrictor of a convergent-divergent nozzle throat. Also, the cathodes made of pure tungsten or carbon. Both electrodes and body are water-cooled.

The MPD thruster has a magnetic circuit which is formed by SS400 plates sandwiched permanent magnets (SmCo) around the anode for application of axial magnetic field. Figure 2 shows magnetic field lines calculated by an analytic software (Quick field). As shown in the figure, they are parallel to the central axis in the constrictor. The maximum strength of magnetic field is about 0.157 T near the constrictor measured by Gauss meter. Also, the magnets can be attached individually, the strength of magnetic field can be changed, as shown in Fig. 3.

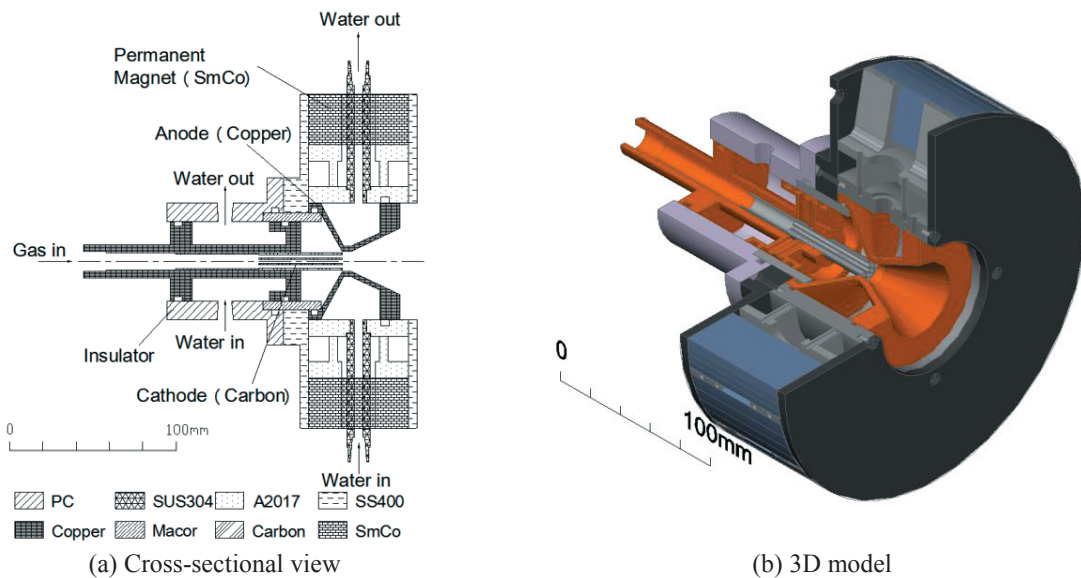


Figure 1. Steady state water-cooled MPD thruster.

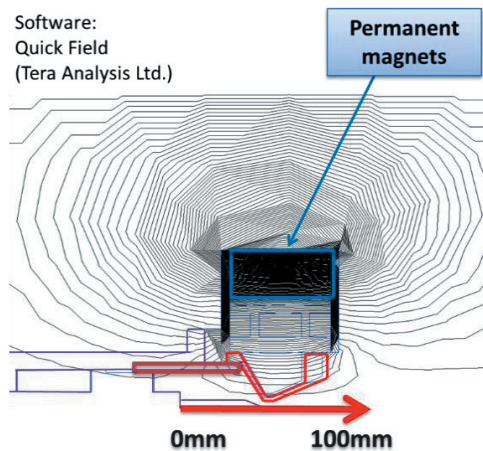


Figure 2. Magnetic field line.

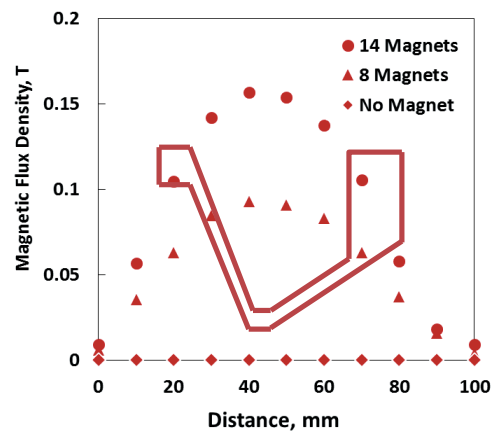


Figure 3. Magnetic flux density on the center axis.

B. Vacuum system

The experimental apparatus is shown in Fig. 4. The experiments were carried out in a stainless steel vacuum tank with 1.2m in diameter and 2.0 m in length as shown in Fig. 5. It has windows for observation. An atmosphere is evacuated by using a rotary pump of 600 m³/h and a mechanical booster of 6,000 m³/h. The pressure of the vacuum tank was measured by Pirani gauge. A tank pressure can fall down until 5 Pa by using the vacuum system as shown in Fig. 6. The tank pressure was kept around 10 Pa during firing.

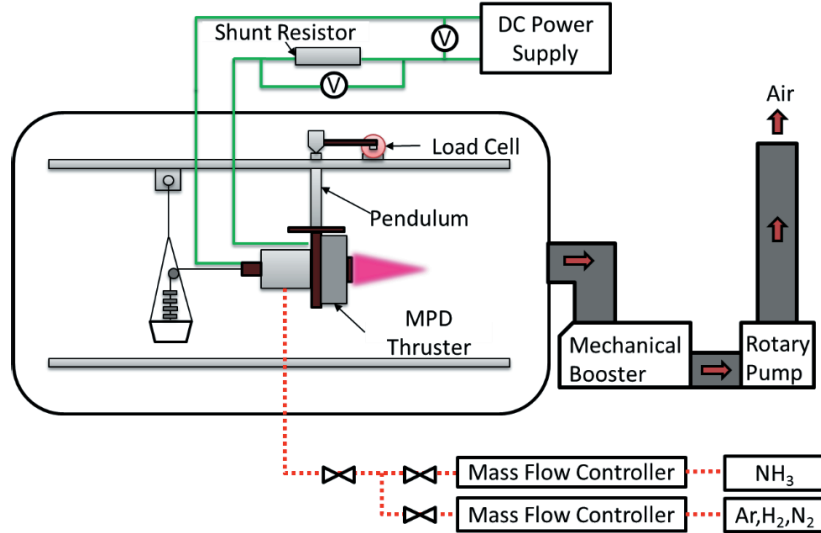


Figure 4. The schematic of experimental apparatus.



Figure 5. Vacuum tank.

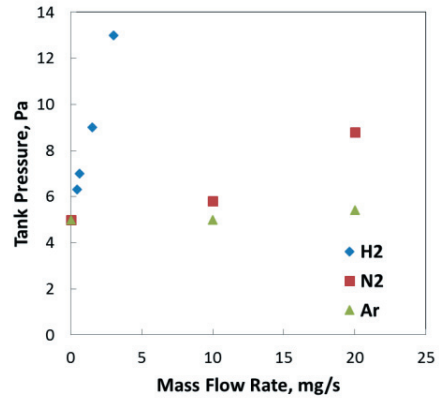


Figure 6. Tank pressure at idle time.

C. Thrust measurement and calibration system

The MPD thruster is mounted on pendulum type thrust measurement system as shown in Fig. 7. The thrust is measured by a load cell. The thruster is connected with a load cell through a pendulum. The load cell is pushed when the thruster was operated. As shown in Fig. 8, the calibration line has a high sensitivity and good linearity. The thrust was calibrated with a motor, pulley and weight arrangement which moved for an up-and-down motion.

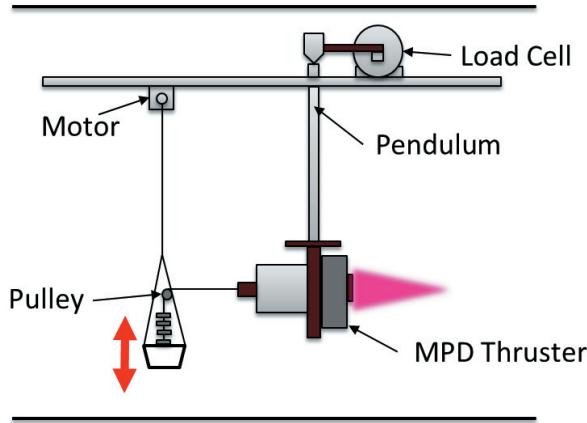


Figure 7. Thrust measurement system.

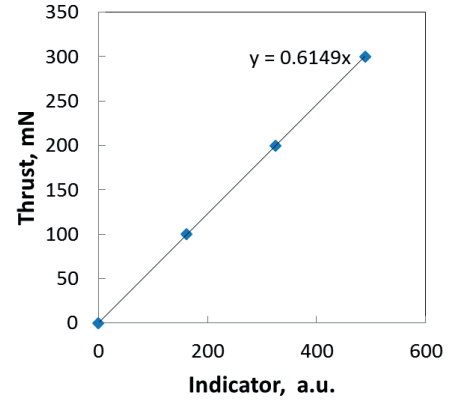


Figure 8. Calibration line.

III. Results

A. Application of rod cathode

We investigated the performance characteristics by changing the strength of magnetic field. The electrode condition and the operating condition are shown in Tables 1 and 2.

Table 1. Electrode condition with rod cathode.

Cathode	Cathode Diameter, mm	10
	Cathode Tip Angle, deg	45
Anode	Constrictor Diameter, mm	10
	Constrictor Length, mm	5
	Convergent Nozzle Angle, deg	120
	Divergent Nozzle Angle, deg	50
Electrode Distance, mm		0

Table 2. Operating condition with rod cathode.

Propellant	Mass Flow Rate, mg/s	Applied Field, T	Discharge Current, A
H ₂	0.5-10	0, 0.093, 0.157	70-150
NH ₃	5-30	0, 0.093, 0.157	70-150
N ₂	5-30	0, 0.093, 0.157	70-150
Ar	10-80	0, 0.093, 0.157	70-150

In this condition, the plasma plumes are shown in Fig. 9. They differed in color and shape. Specially, we focused on the operation with ammonia. The shape of plasma plume depends on strength of applied magnetic field with ammonia as shown in Fig. 10. As shown in Fig. 10, we could not observe cathode jets without magnets. As the number of magnets increase, the cathode jet is obviously brighten. Therefore, we could find that the cathode jet depends on the strength of applied magnetic field. Also, as the discharge current increases, the brightness of cathode jet is darken, and the outline of the plume is expand. Furthermore, as the strength of applied magnetic field is strengthen, the radius of the cathode jet increases because the position of the current attachment might moves from the cathode tip to the cathode bottom. Therefore, applied magnetic field is expected to improve erosion rate of the cathode because of the reduction of the current density^{7,8)}.

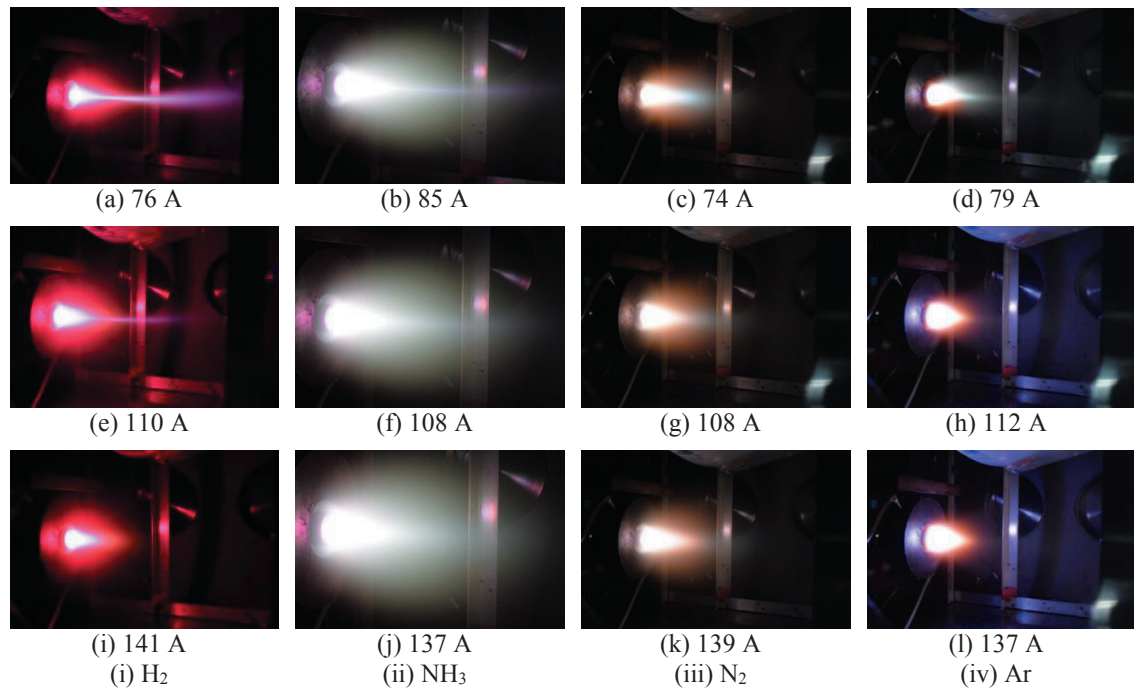


Figure 9. Plasma plumes with each discharge current.

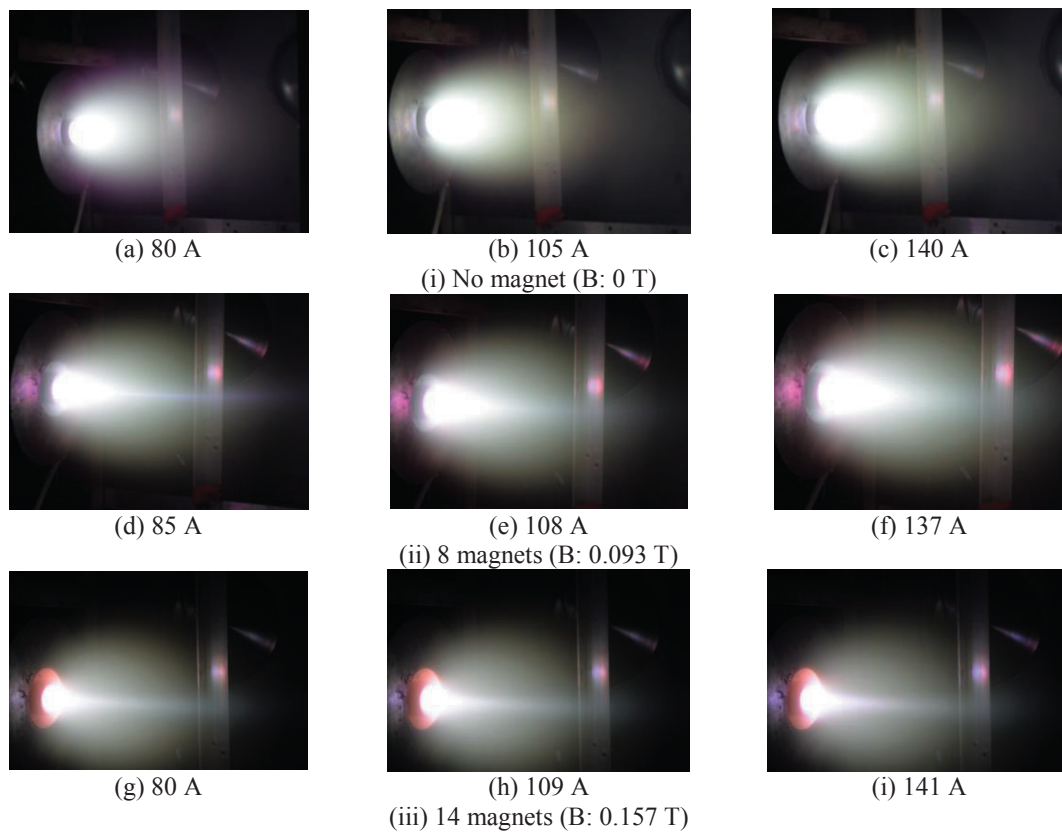


Figure 10. Plasma plumes with each applied field (NH₃ : 5 mg/s).

We obtained performance characteristics of hydrogen, ammonia, nitrogen and argon. The performance characteristics of ammonia are shown in Fig. 11. With a typical value at 0.157 T, we could obtain the results of a thrust of 21.4 mN, a specific impulse of 2,907 s and a thrust efficiency of 4.92 % at 5.18 kW with hydrogen. Also, the performance of a thrust of 151 mN, a specific impulse of 768 s and a thrust efficiency of 5.73 % are obtained at 6.71 kW with ammonia. In Fig. 11 (a), dropping characteristic was slightly found. Also, we could find that the thrust increases with increasing discharge current. However, we guessed that the plasma is not sufficiently accelerated by swirl acceleration because the discharge voltage and the thrust increases with increasing mass flow rate. Therefore, we consider that the contribution of electromagnetic acceleration for plasma must become stronger.

The thrust efficiency vs specific impulse characteristics are shown in Fig. 12. As shown in Fig. 12, improvement of thrust performance by applied magnetic field is needed.

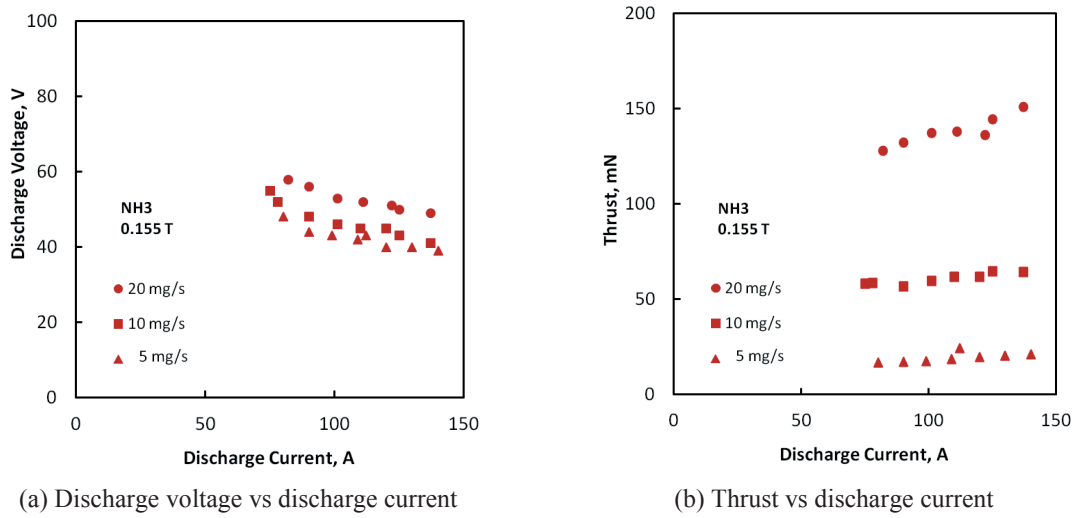


Figure 11. Performance characteristics of NH₃.

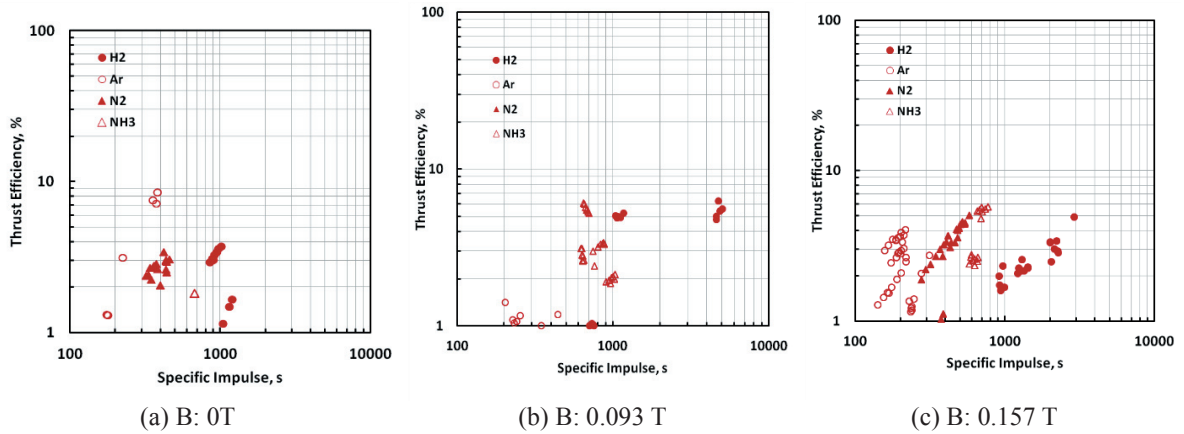


Figure 12. Thrust efficiency vs specific impulse characteristic.

B. Application of hollow cathodes

We used tungsten or carbon that has a high melting point as a material of cathode^{5,6)}. First, a hollow cathode which is made of carbon was used because the cost of pure tungsten is expensive for bad workability. We aimed to optimize the shape of hollow cathodes by many experiments with various shapes.

We manufactured a multi hollow cathode and a single hollow cathode as shown in Fig. 13. Also, the cross-sectional view of the multi hollow cathode is shown in Fig. 14. The cathode outer diameter is 10 mm, and the inner diameter is 9 mm. Seven small pipes are inserted in the main pipe for the multi hollow cathode. The electrode condition and the operating condition are shown in Tables 3 and 4. After short operation, the constrictor diameter of the anode was expanded from 10 mm to 12 mm.



Figure 13. Hollow cathodes
(Left: multi hollow cathode; Right: single hollow cathode).

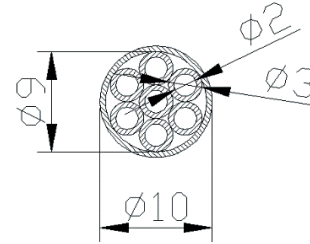


Figure 14. Cross-sectional view of multi hollow cathode.

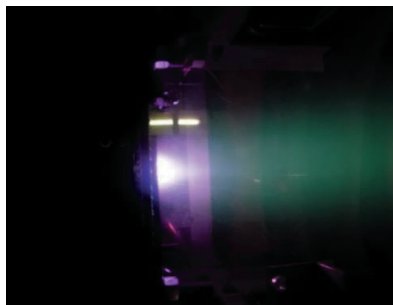
Table 3. Electrode condition with hollow cathodes.

Cathode	Cathode Diameter, mm	10
Anode	Constrictor Diameter, mm	12
	Constrictor Length, mm	7.72
	Convergent Nozzle Angle, deg	120
	Divergent Nozzle Angle, deg	50
Electrode Distance, mm		-7.72

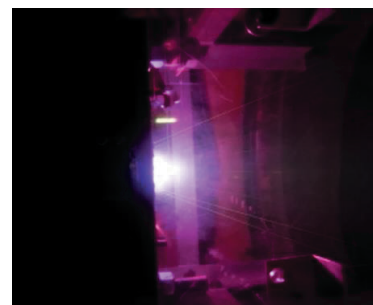
Table 4. Operating condition with hollow cathodes.

Propellant	Mass Flow Rate, mg/s	Applied Field, T	Discharge Current, A
H ₂	3.0	0.157	70-150

The plasma plume with hollow cathodes is shown in Fig. 15. We couldn't observe cathode jet, but the plasma plume was slightly converged to the central axis. In spite of operation, we have seen some sparks during firing. The cathode after firing is shown in Fig. 16. The cathode had severe erosion in a few minutes operation. The cathode was cut to the place of 15 mm from the cathode tip. Therefore, the maximum wall temperature may be highest than the melting point of carbon although thermionic emission is expected to be efficiently carried out at low discharge voltages. Accordingly, even using hollow cathodes, the cathode erosion could not be reduced. We considered that this is a problem with cathode material. We determined to carry out experiments with the cathode made of pure tungsten.



(a) Single hollow cathode



(b) Multi hollow cathode

Figure 15. Plasma plume with hollow cathodes of H₂.



(a) Single hollow cathode



(b) Multi hollow cathode

Figure 16. Cathode damage after firing.

We redesigned the shape of hollow cathodes to manufacture those made of pure tungsten. The conventional carbon multi hollow cathode consists of 8 pipes, but the redesigned tungsten cathode, as shown in Fig.17, is 1 rod with 7 holes of diameter of 2.4 mm. Accordingly, we succeeded in reduction of costs of 75%. The operating condition is shown in Table 5.



Figure 17. Pure tungsten hollow cathodes.

Table 5. Operating condition with hollow cathodes.

Propellant	Mass Flow Rate, mg/s	Applied Field, T	Discharge Current, A
H ₂	0.15-0.60	0.157	70-150
NH ₃	2.5-15	0.157	70-150
Ar	5-20	0.157	130

The plasma plumes with hollow cathodes of hydrogen are shown in Fig. 18. The operation was stable, and the plasma was converged to the center axis with a high brightness. At high mass flow rates, the operation was unstable accompanied by green light. This phenomena is inferred to be in the spoke mode operation. Therefore, we need to optimize the strength of applied magnetic field.

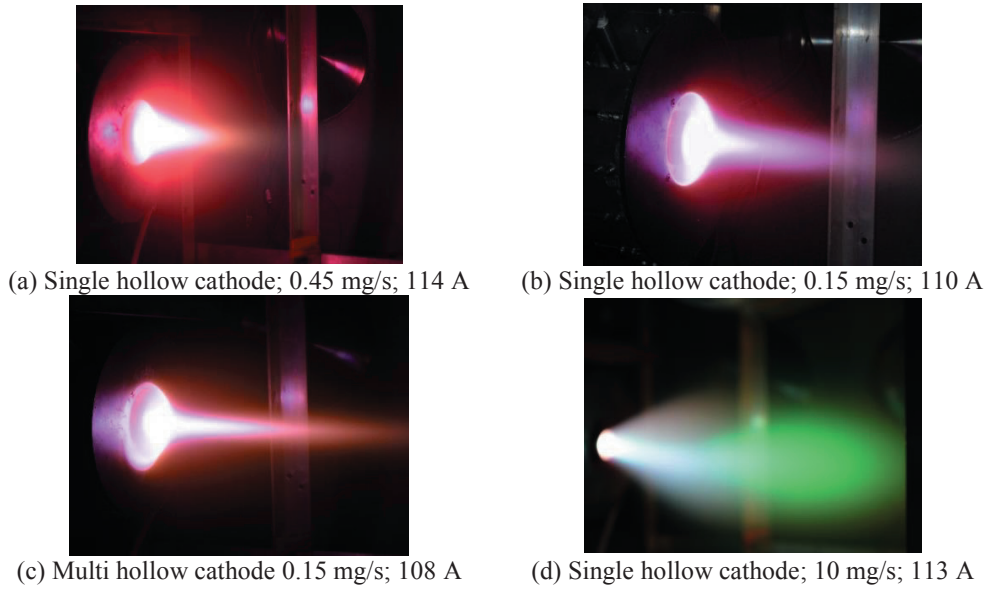


Figure 18. The plasma plume with hollow cathodes of H_2 .

IV. Discussion

In this experiment, we could confirm stable operations with rod cathode and hollow cathodes. We aimed to reduce cathode erosion, we developed hollow cathodes. The cathode before and after 10 minutes firing is shown in Figs. 19 and 20. As shown in Figs. 19 and 20, hollow cathodes had severe erosions for short time operation. Although all over the cathode around the tip had severe erosion, we could especially find the severe erosion on the cathode of outer surface. It showed that the current attached to the inner and outer surface of the cathode. The operation is stable, but we might not set optimum condition. We must find for it.

The cathode erosion rate is shown in Table 6. In Table 6, the erosion rate of hollow cathodes is too much than that of rod cathode. Bad ignitionability and discharge at the outer surface can be considered a cause.

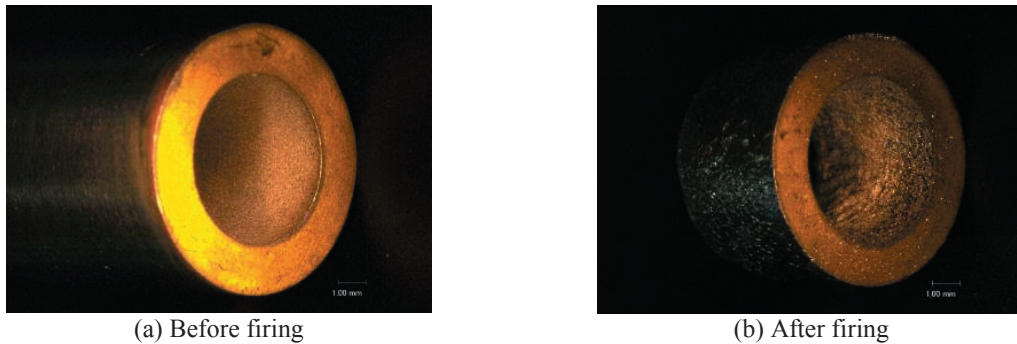


Figure 19. Damage of the single hollow cathode.

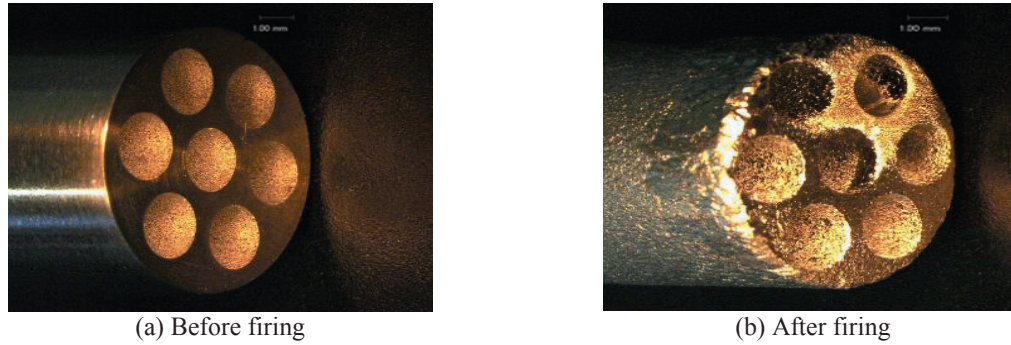


Figure 20. Damage of the multi hollow cathode.

Table 6. The results of cathode erosion.

Cathode types	Single	Single	Multi	Multi	Rod
Propellant	H ₂	H ₂	H ₂	NH ₃	H ₂
Mass Flow Rate, mg/s	0.3	0.15	0.15	2.5	0.15
Discharge Current, A	113	110	108	115	110
Discharge Voltage, V	35	52	36	37	47
Erosion rate, mg/min	149	212	73.6	-	0.1193

Conclusion

The steady state water-cooled MPD thrusters with permanent magnets was developed, and the thrust performance was measured. Also, the erosion rate was compared with hollow cathodes and the rod cathode. We obtained the following results.

- (1) We could obtain a typical performance of a thrust of 21.4 mN, a specific impulse of 2,907 s and a thrust efficiency of 4.92 % at 5.18 kW with hydrogen. Also, a performance with ammonia reached a thrust of 151 mN, a specific impulse of 768 s and a thrust efficiency of 5.73 % at 6.71 kW.
- (2) We could establish the improvement of thrust performance with each propellant by applied magnetic field.
- (3) Carbon isn't suitable as cathode material using hydrogen.
- (4) Although pure-tungsten multi hollow cathodes had large erosion rates with a short-time operation in this study because of poor design, we have already found designing of preferable hollow cathodes with very low erosion. So, we must also find for optimum operating condition which is the mass flow rate, the strength of applied field, the shape of electrodes and so on.

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