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

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Abstract: Steady-State MPD (Magneto-Plasma-Dynamic) thrusters for manned Mars exploration have been investigated at Osaka Institute of Technology. The MPD thruster is equipped with permanent magnets to make the system of the thruster easier. The water-cooled MPD thruster was experimented with a rod cathode. After the operation with rod cathodes, severe erosion was confirmed on the cathode tip. In order to decrease amount of erosion, single hollow cathode (SHC) and multi hollow cathode (MHC) were used for the water-cooled MPD thruster. Furthermore, before developing a fully radiation cooled MPD thruster, a anode radiation-cooled thruster was developed and experimented. The surface temperature of the anode was 825 degrees Celsius just after 10minutes operation. A fully radiation-cooled MPD thruster was been developing and analyzed with thermal analysis software. As a result, the temperature of the magnetic circuit, over 500 degrees Celsius, was higher than of the radiation panel, around 400 degrees Celsius. In order to lower temperature of permanent magnets, temperature of the radiation panel must be raised more.

I. Introduction

MPD (Magneto-Plasma-Dynamic) thrusters have been developed for manned Mars exploration at Osaka Institute of Technology. In this study, as one of the In-Space Propulsion project by JAXA (Japan Aerospace eXploration Agency), a practical MPD propulsion system was investigated. We planned to develop MPD thrusters as the main engines which have high thrust, high specific impulse and high thrust efficiency. In general, MPD thrusters are equipped with water-cooled coils to apply magnetic field. But the thruster system is complicated. In order to make the system easier, the MPD thruster we developed is equipped with permanent magnets.

We operated the thruster with rod cathodes. But the excessive erosion was confirmed on the cathode tip. Cathode damage is one of the most important problems for practical use. In order to solve this problem, we used two kinds of hollow cathode, Single Hollow cathode (SHC) and Multi Hollow cathode (MHC). The discharge of these cathodes isn't in spot mode but in diffusion mode. Reduction of the erosion amount is expected because the maximum cathode surface temperature doesn't approach to the melting point of the cathode material. We experimented with three kinds of cathode, rod cathode, single hollow cathode and multi hollow cathode, and compared these.

We are currently planning to develop a radiation-cooled MPD thruster. Heat analysis was carried out, and the temperatures of permanent magnets and a radiation panel were obtained. As a result, temperature of permanent

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magnets was higher than of the radiation panel. Therefore, we were improving the design of the radiation-cooled MPD thruster.

II. Experimental Equipment

A. Water-Cooled MPD Thruster

Figures 1 and 2 show the cross-section of the water-cooled MPD thruster and the 3D modeling of it. This thruster has magnet circuit which is formed by SS400 plates sandwiching permanent magnets around the anode for application of axial magnetic field[1, 2]. Figures 3 and 4 show analyzed magnetic lines of the water-cooled MPD thruster and the strength of magnetic flux density in axial of MPD thruster. The maximum magnetic field is about 0.16T.

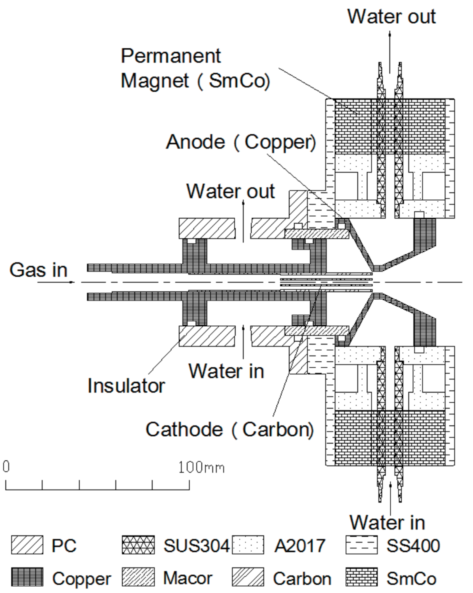


Figure 1. Cross-section of the water-cooled thruster.

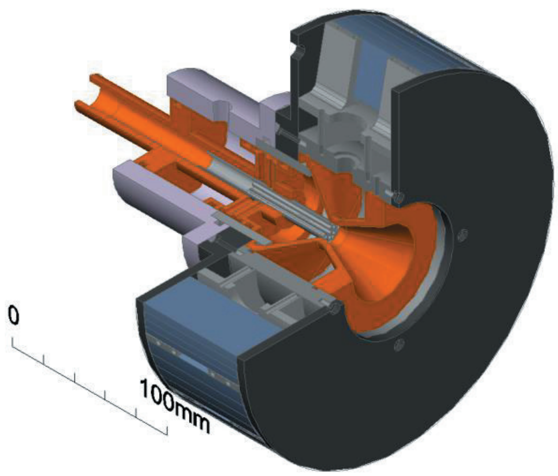


Figure 2. 3D modeling of the water-cooled MPD thruster.

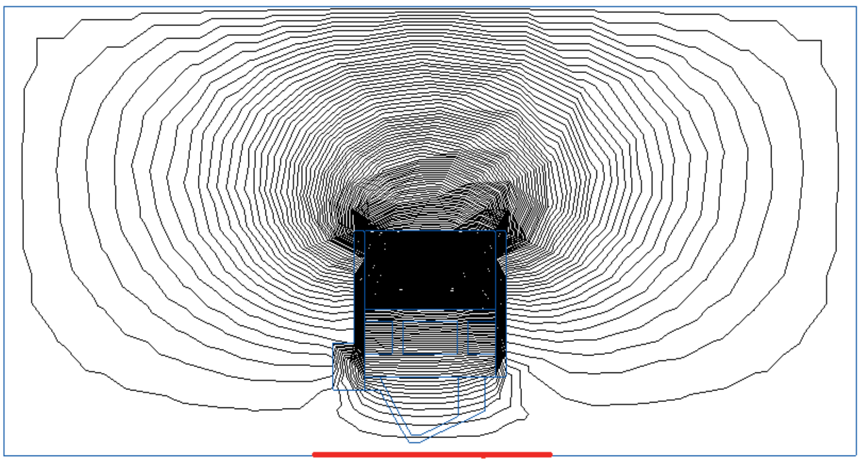


Figure 3. The analyzed magnetic line of the water-cooled MPD thruster.

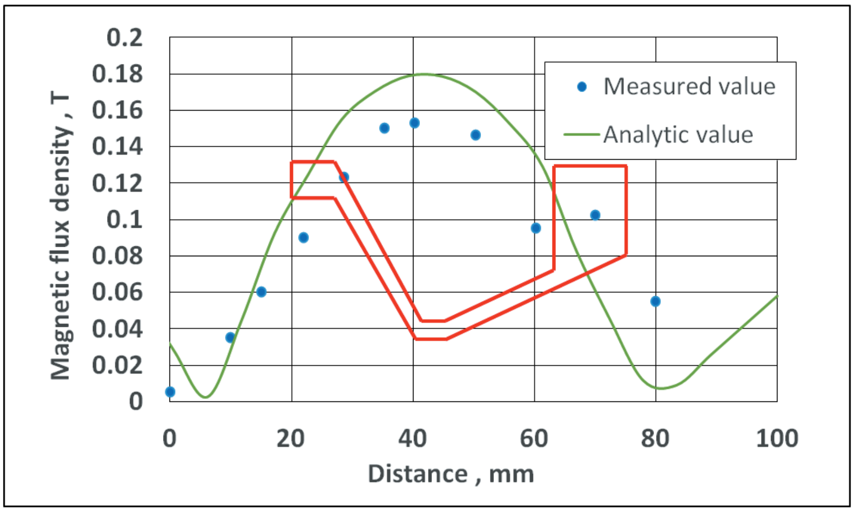


Figure 4. The strength of magnetic flux density in axial of the water-cooled MPD thruster.

B. Vacuum Chamber

We experimented with the vacuum chamber made of stainless steel with 1.2m in diameter and 2.0m in length. Figure 5 shows the schematic view of the vacuum chamber we used. The chamber is evacuated by using 2 pumps, which are called a rotary pump of $600m^3/h$ and a mechanical booster of $600m^3/h$. A pressure of the chamber can be kept about 20 Pa during experiments.

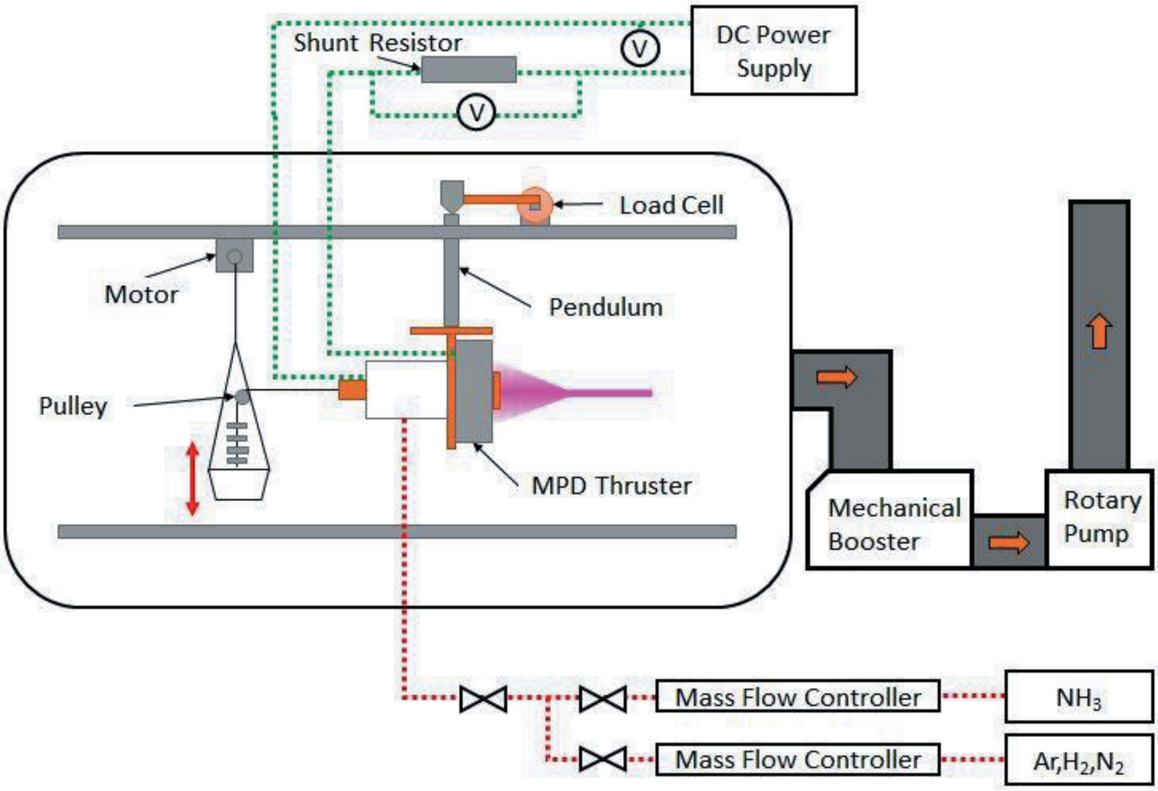


Figure 5. The schematic view of the space chamber.

C. Propellant Supply System

As the propellant, hydrogen (H_2), ammonia (NH_3), argon (Ar) and nitrogen (N_2) were used in this study. Propellants are injected into the thruster through a mass flow controller.

D. Thrust Measurement System

The pendulum method was used for thrust measurement. The thrust was measured by a load cell. In operation, the load cell is pushed by generated thrust. The thruster is mounted on the thrust stand which consists of an iron bar pendulum. Figure 6 shows the calibration line measured by using the thrust measurement system.

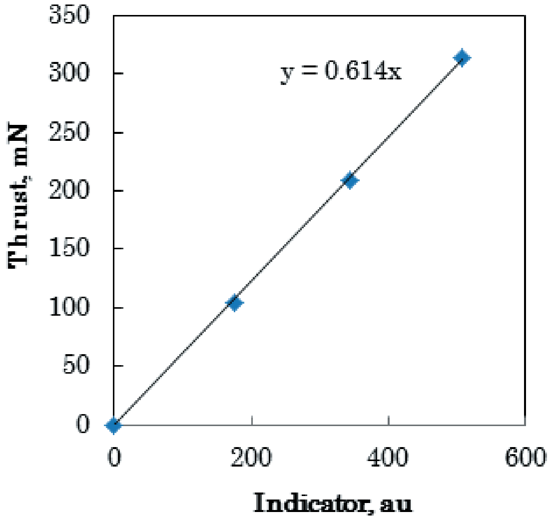


Figure 6. The calibration line.

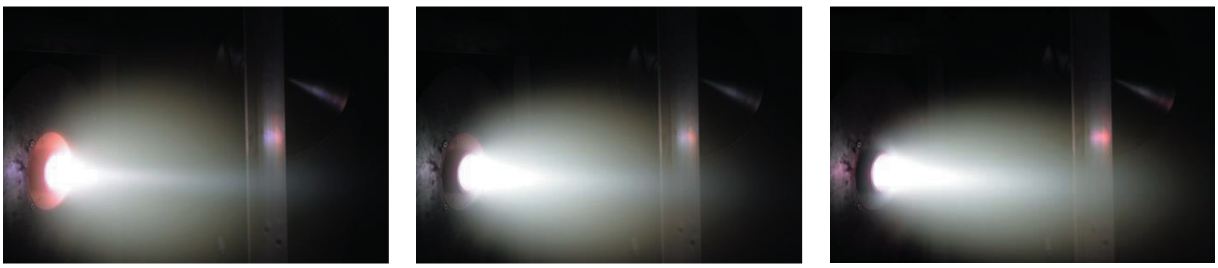
III. Result and Discussion

A. Application of Rod Cathode

At first, the operation with rod cathode was carried out. Table 1 shows the experiment condition. In this experiment, 4 propellants, H_2, NH_3, N_2, and Ar, were used. Figure 7 shows the operations with rod cathodes with NH_3 as a propellant. We could confirm the convergence of plume during operation. We could confirm convergence plume with lower mass flow rate.

Table 1. Experimental condition with a rod cathode.

prolpellant	H2	NH3	N2	Ar
Mass Flow Rate, mg/s	0.3 – 10	5 – 20	5 – 20	4 – 30
Magnetic Flux Density, T	0.157			
Discharge Current, A	70 - 150			



(a)5mg/s **(b)10mg/s** **(c)20mg/s**

Figure 7. The operation with rod cathode with NH_3.

Figures 8 and 9 show the discharge voltage versus discharge current characteristics and thrust versus discharge current with ammonia. The discharge voltage decreases with increasing discharge current. The thrust increases with increasing discharge current.

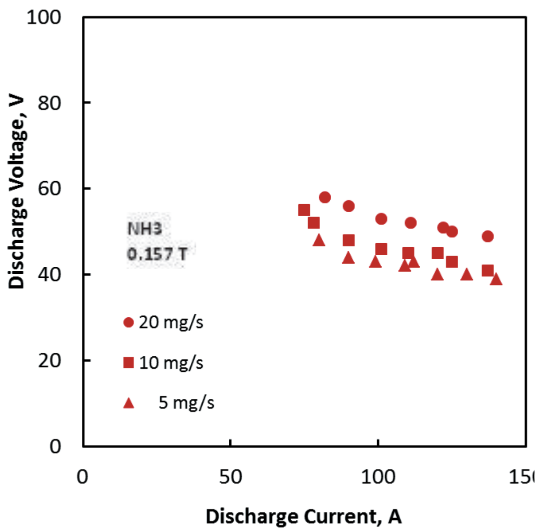


Figure 8. Characteristic of discharge voltage versus discharge.

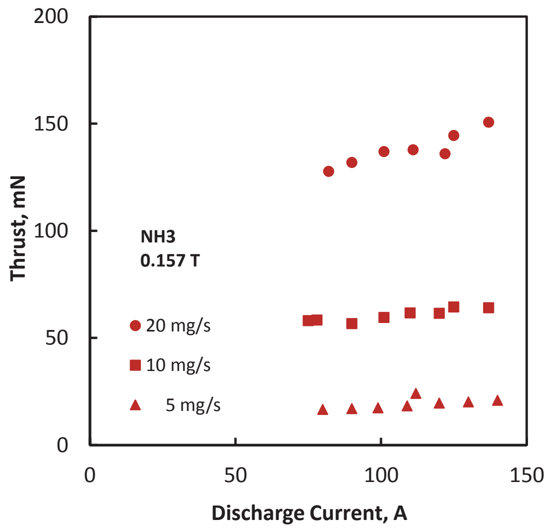


Figure 9. Characteristic of thrust versus discharge current.

After the operation, the severe erosion was confirmed in the cathode tip. Figure 10 shows the damage in the cathode tip. In order to operate longer, this problem should be solved. One of the solutions is to use hollow cathode. The discharge of hollow cathodes isn't in spot mode but in diffusion mode[3)]. For the reason the maximum temperature of a cathode in diffusion mode is lower than that in spot mode because the current flux is lower.


Figure 10. The damage in cathode tip.

B. Application of Hollow Cathodes

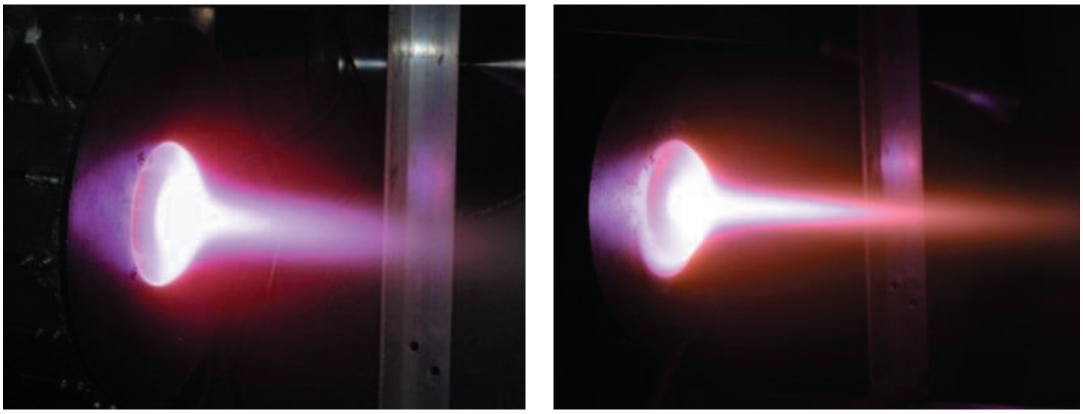
Hollow cathodes which made of tungsten, SHC and MHC, were used in this experiment. Figure 11 shows hollow cathodes we used. Table 2 shows the experiment condition.

Figure 11. Hollow cathodes.

Table 2. Experimental condition.

Propellant	H2	NH3	Ar
Mass Flow Rate, mg/s	0.15 – 0.60	2.5 – 15	5 – 20
Magnetic Flux Density, T	0.157		
Discharge Current, A	70 – 150		130

Figure 12 shows the operation with SHC and MHC. The stable operations were confirmed with both of cathodes.



(a)Single hollow cathode **(b)Multi hollow cathode**

Figure 12. Operations with each cathode.

Figures 13 and 14 show the characteristics of discharge voltage versus discharge current and the characteristics of thrust versus discharge current compared with rod cathode (RC) and MHC. The discharge voltage decreases with increasing discharge current with both cathodes. On the other hand, the thrust with MHC depended on discharge current but the thrust with rod cathode didn't. One of reasons for this may be concerned with pumping force in thrust.

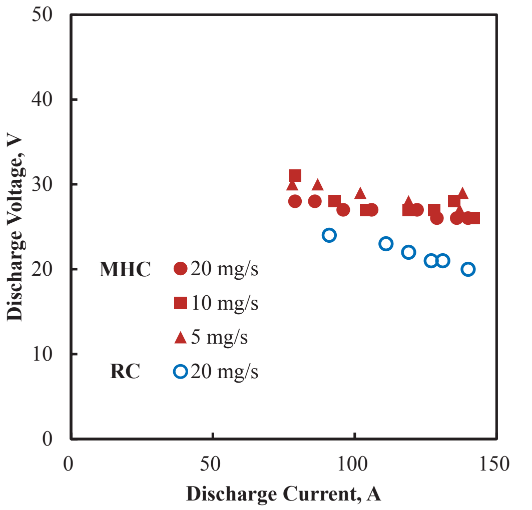


Figure 13. Characteristic of discharge voltage versus discharge current.

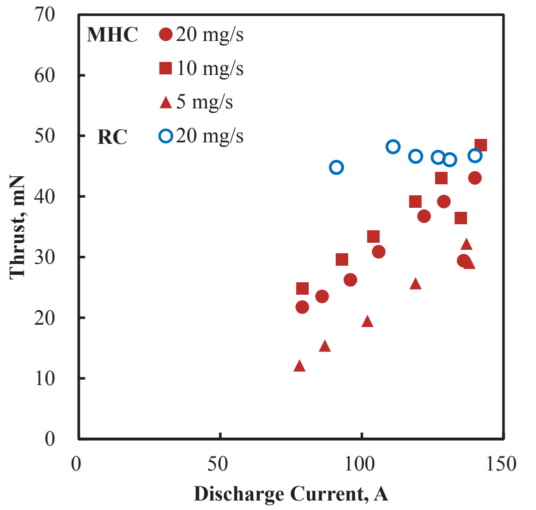


Figure 14. Characteristic of thrust versus discharge current.

IV. Anode Radiation-cooled Thruster

A. Anode Radiation-cooled Thruster

Before designing a fully radiation-cooled MPD thruster, an anode-radiation-cooled thruster was developed to examine all effects of heat and determination of optimum material for components[4,5]. Figures 15 and 16 show the schematic view of anode radiation-cooled thruster and its 3D modeling. This thruster does not have any permanent magnet. So it is arcjet thruster shape. Carbon was used for anode, and tungsten was used for cathode. The cathode holder was water-cooled.

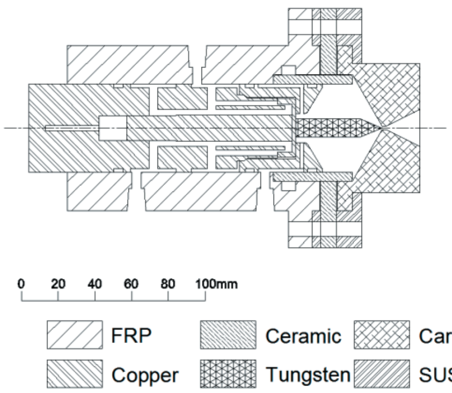


Figure 15. Cross-section of the anode radiation- cooled thruster.

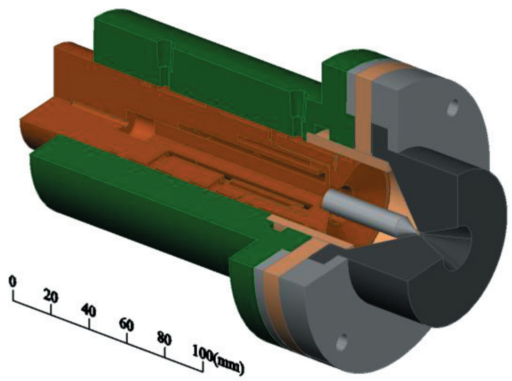


Figure 16. 3D modeling of the anode radiation- cooled thruster.

B. Experimental condition

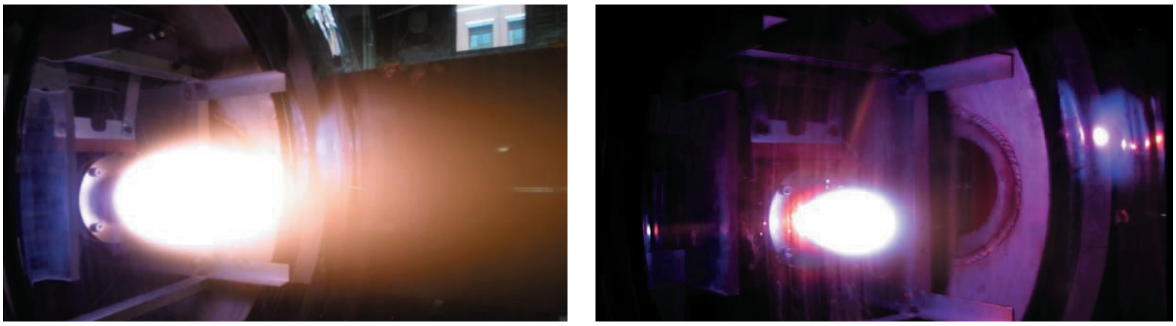
Table 3 shows the experimental condition with anode radiation-cooled thruster. This thruster was experimented with H_2 and N_2 as a propellant.

Table 3. Experimental condition.

Propellant	N2	H2
Mass Flow Rate, mg/s	20	4.0
Discharge Current, A	55 - 150	

C. Result and Discussion

Figure 17 shows the operation of anode radiation-cooled thruster with each propellant. The stable operations were confirmed with both of propellants. The operation time was about 10 minutes.



(a)N_2 20 mg/s (b)H_2 4.0mg/s

Figure 17. Operations of anode radiation-cooled thruster.

Figures 18 and 19 show the characteristic of discharge voltage versus discharge current and the characteristic of input power versus discharge current. Figure 18 shows that discharge voltage decrease with increasing discharge current same as water-cooled MPD thruster. The maximum input power was 6.1 kW with H_2

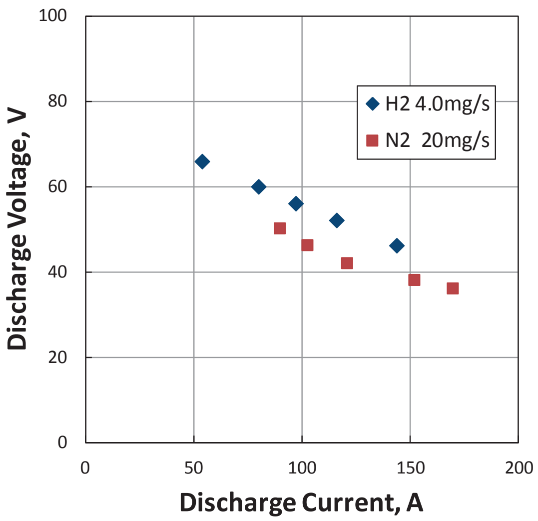


Figure 18. Characteristic of discharge voltage versus discharge current.

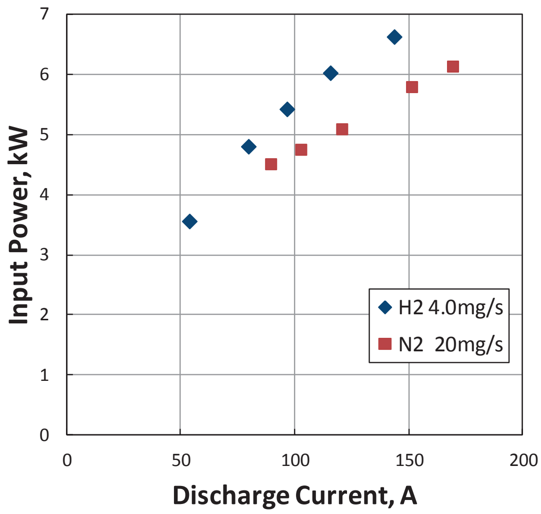


Figure 19. Characteristic of input power versus discharge current.

Just after the operation, a red heat was confirmed at the carbon anode. This red heat had lasted for about 2 minutes. The temperature of the radiation anode was measured, and obtained the result of a temperature of about 850 degrees Celsius. Figure 20 shows the red heat of the carbon anode just after the operation.

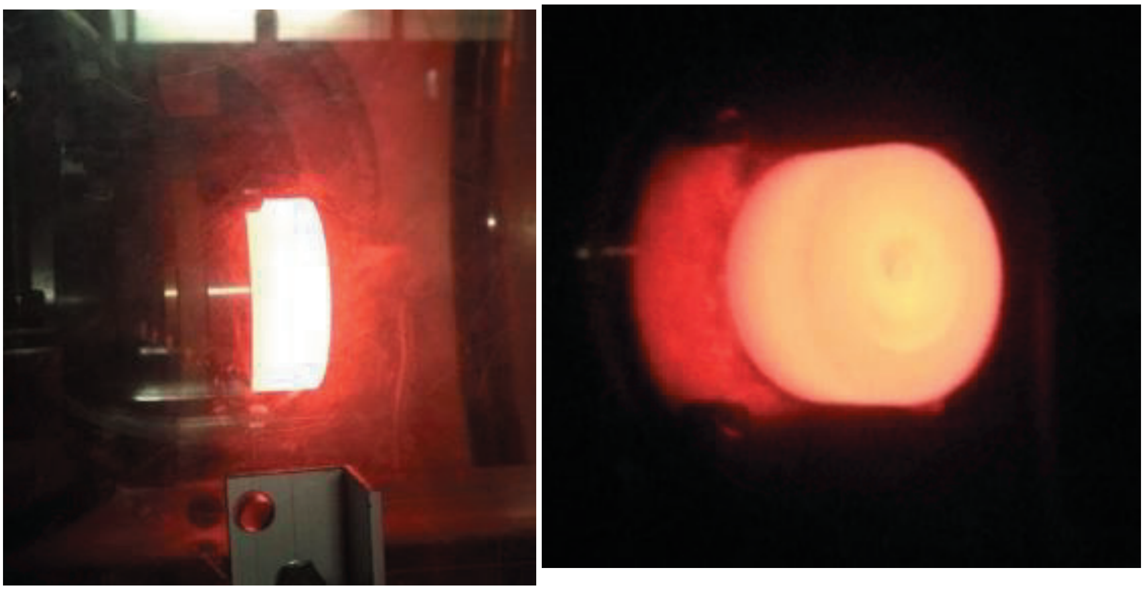


Figure 20. The red heat of the carbon anode.

A. Fully Radiation-Cooled MPD Thruster

We are developing a fully radiation-cooled MPD thruster[6)]. Figures 21 and 22 show the cross-section of the fully radiation-cooled MPD thruster and its 3D modeling. From all results of experiment with anode radiation-cooled thruster, the temperature around heat source was 825 degrees Celsius. Thus high-melting point material, tungsten, molybdenum, and so on, should be used around there. In order not to transmit heat to magnetic circuit, some insulator will be set between magnetic circuit and the heat source, and heat generated from heat sources must be thrown away through a radiation panel to prevent heat transmit to a spacecraft.

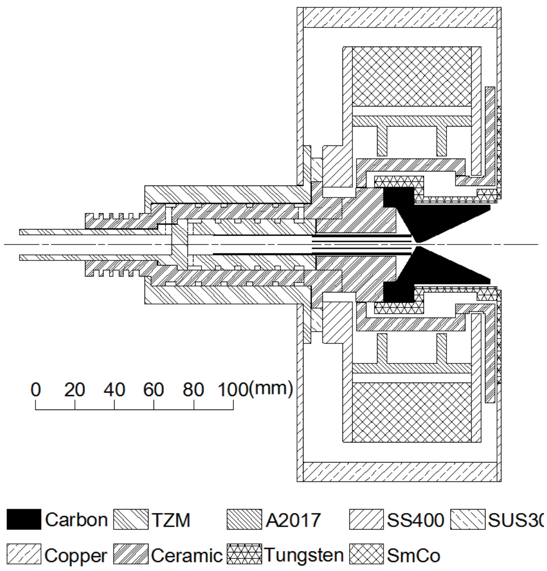


Figure 21. Cross-section of fully radiation-cooled MPD thruster.

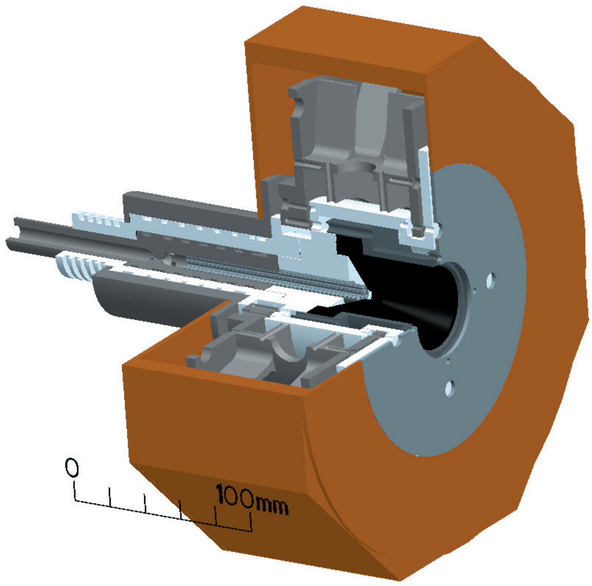


Figure 22. 3D modeling of fully radiation-cooled MPD thruster.

B. Thermal Analysis

In order to examine the temperature of magnetic circuit in operation, thermal analysis was carried out. Figure 23 shows the analytical model of the fully radiation-cooled MPD thruster. The simplest model of the thruster was used to make analysis time shorter. Also, table 4 shows the analysis condition with fully radiation-cooled MPD thruster. Analysis time was 3000s with a standard personal computer, and applied heat was 5kW, Figures 24 and 25 show the results of thermal analysis. According to the results, while the temperature of permanent magnets was about 500 degrees Celsius, the temperature of the radiation panel was around 400 degrees Celsius. The temperature of 500 degrees Celsius is more than the irreversible demagnetization temperature of a SmCo magnet, 350 degrees Celsius. In order to lower the temperature of permanent magnets and throw away heat generated from heat sources, the temperature of the radiation panel must be raised more.

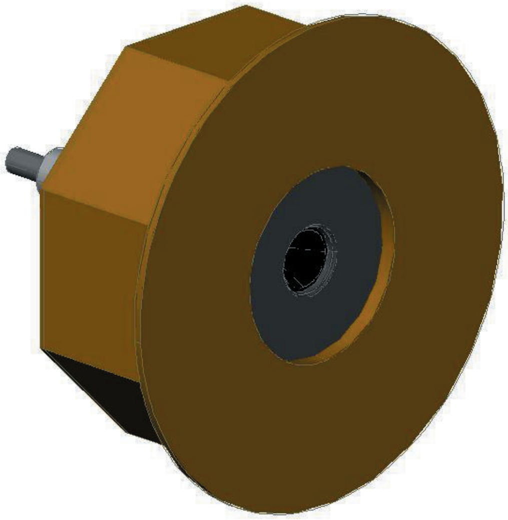


Figure 23. The analytical model.

Table 4. Analysis condition with the fully radiation-cooled MPD thruster.

Analytical model	Figure 23
Analysis time, s	3000
Applied heat, W	300
Software	Thermal desktop

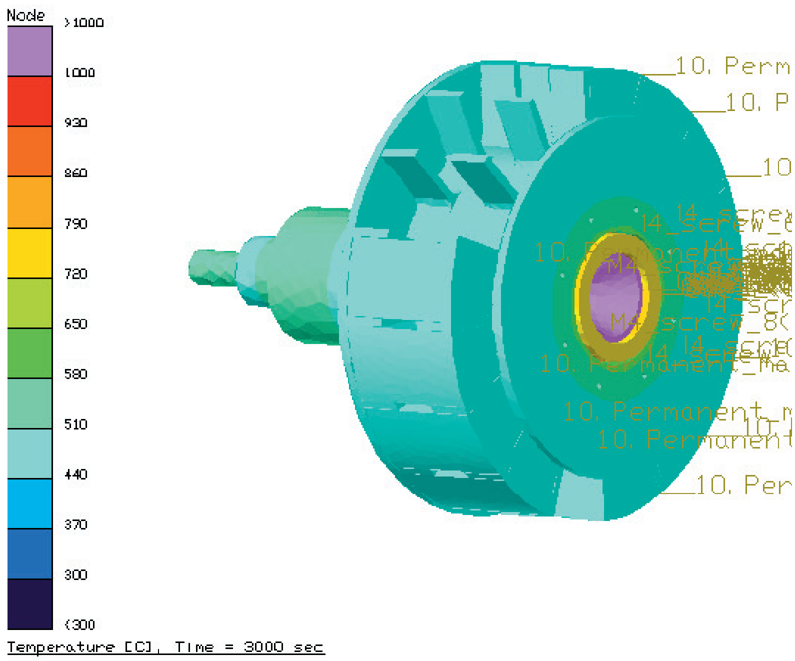


Figure 24. The analyzed temperature of the magnetic circuit.

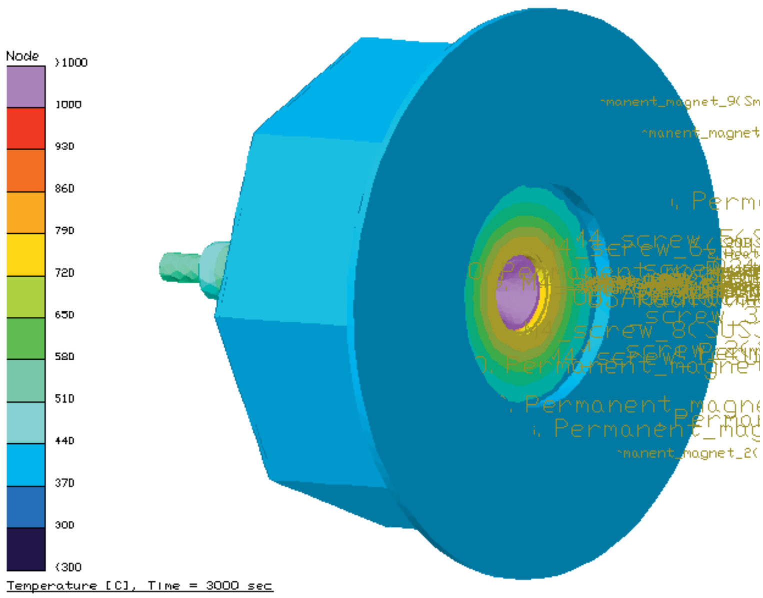


Figure 25. The analyzed temperature of the entire thruster.

V. Conclusion

The following results were obtained.

1) The water-cooled MPD thruster was developed and experimented. As a result, the result of a specific impulse of 2,907s and a thrust efficiency of 4.92% were obtained with H_2 0.75mg/s as a propellant.
2) The stable operations were confirmed both of multi hollow cathode and single hollow cathode.

3) The stable operations were confirmed with both of H_2 and N_2 as a propellant with the anode radiation-cooled thruster.
4) With the anode radiation-cooled thruster, the red heat was confirmed in the carbon anode, and the temperature of it was 825 degrees Celsius.
5) Heat analysis was carried out with the fully radiation-cooled MPD thruster and the temperature of the magnetic circuit was over 500 degrees Celsius and the temperature of the radiation panel was around 400 degrees Celsius. Therefore the temperature of the radiation panel should be raise and generated heat is thrown away from the panel more.

References

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