Research and Development of High-Power Steady-State MPD Thrusters with Divergent and Cusp Magnetic Fields Using Permanent Magnets for In-Space Propulsion

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Abstract: A quasi-steady Magneto-Plasma-Dynamic (MPD) thruster doesn't fit for practical use in space, because of its heavy system and complicated system using solenoid-coil. In order to make the system easier, an MPD thruster was developed that doesn't have solenoidal coils but permanent magnets of Samarium Cobalt for applying magnetic field. Therefore, the thruster system was able to have simple structure, because the thruster system doesn't need cooling system and heater. Typical performance data using 60 mg/s of NH_3 at 6.75 kW were a thrust of 477.4 mN, a specific impulse of 811.4 s and a thrust efficiency of 19.0% with a magnetic field strength of 0.157 T. To acquire higher performances, an electrode shapes was changed to straight-divergent nozzle and cusp magnetic fields were applied to the MPD thruster in this research.

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 developed for In-space missions as one of the In-Space Propulsion project in collaboration with the Japan Aerospace eXploration Agency (JAXA). In order to achieve that mission, MPD thrusters are required with light and simple structure. In general, MPD thrusters are equipped with water-cooled coils to apply magnetic field. However, the thruster system is complicated. In order to make the system easier, the MPD thruster we developed is equipped with permanent magnets. In this research, shapes of a magnetic field were changed to cusp field. Therefore, the decrease in discharge voltage was anticipated and aimed at improvement of the thrust efficiency. And an electrode was changed to straight-divergent nozzle. Therefore, the drop of the speed loss of the propellant and the improvement of the thrust efficiency were anticipated. The final targets are to achieve thrust performances, a thrust of 0.5-2.0 N, a specific impulse of 1,000-3,000 s and a thrust efficiency of 40%.

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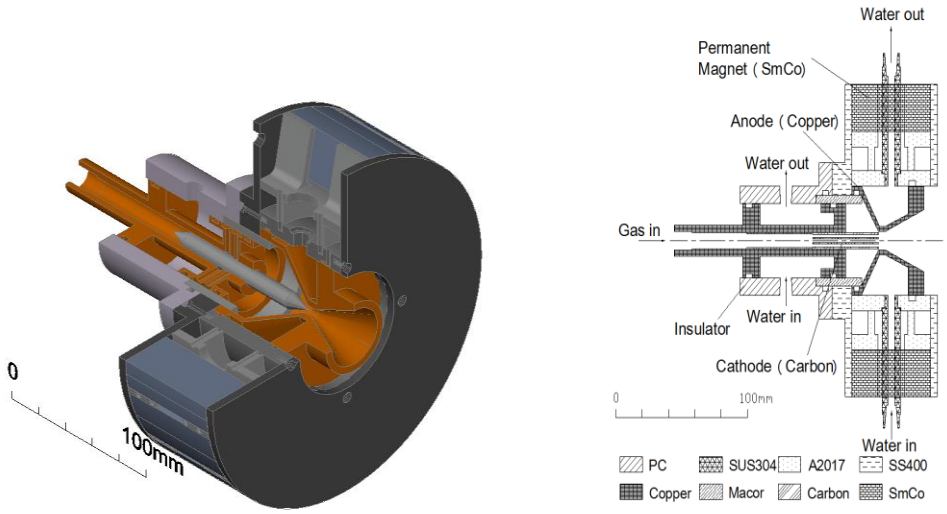
II.MPD thrusters

A. Water-cooled MPD thruster

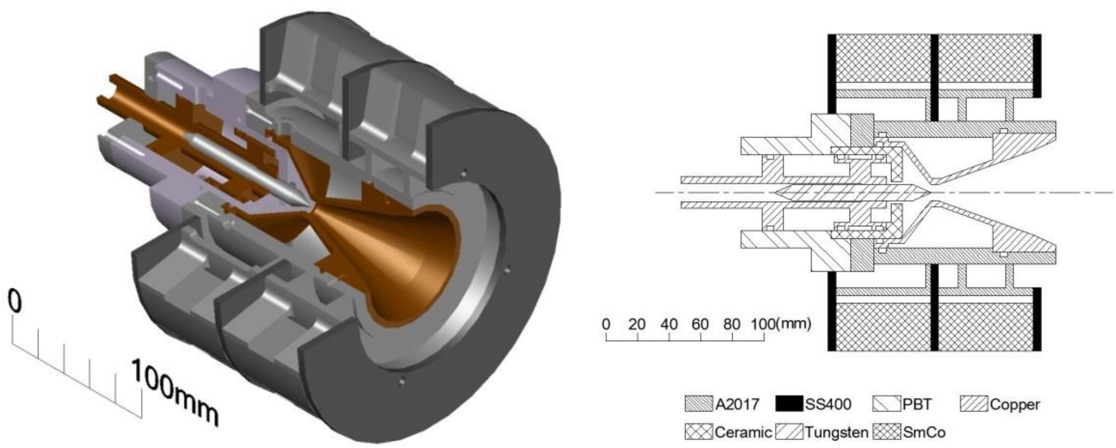
Figure 1 shows the 3D model and cross-sectional view of the MPD thruster with divergent field used for this study, respectively. The thruster was operated with an input power of 5-10 kW. And, Figure 2 shows the 3D model of the MPD thruster with cusp field used for this study.

The MPD thruster has a magnetic circuit which is formed by iron plates sandwiched SmCo magnets around the anode for application of axial magnetic field. Figure 3 shows the MPD thruster with divergent field lines calculated by an analytic software (Tricomp). As shown in Fig. 3, they were parallel to the central axis in the constrictor. The maximum strength of magnetic field was approximately 0.157 T near the constrictor measured with a Gauss meter. Also, because the magnets can be equipped individually, the strength of magnetic field can be changed. And, Fig. 4 shows the water-cooled MPD thruster with cusp field lines calculated. As shows in Fig. 4, cusp shape is formed at the position of central iron plate made in SS400 put to the permanent magnets. Therefore, the performance acquisition by the change is possible at a cusp position.



(a) 3D model **(b) cross-sectional view**

Figure 1. MPD thruster with divergent field.



(a) 3D model **(b) cross-sectional view**

Figure 2. MPD thruster with cusp field.

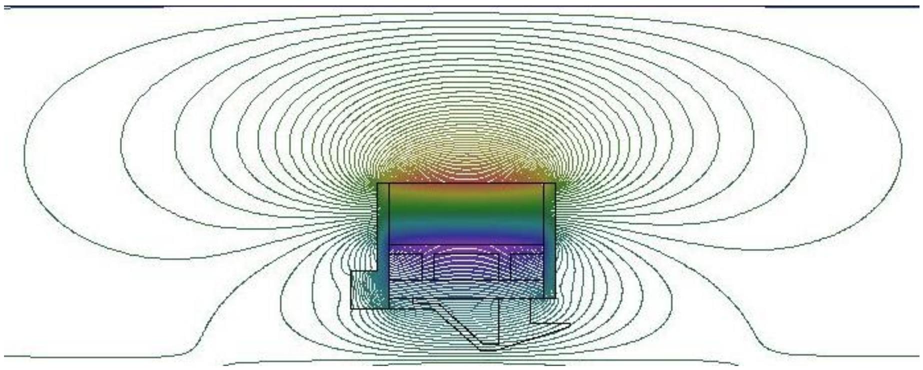


Figure 3. MPD thruster with divergent field lines.

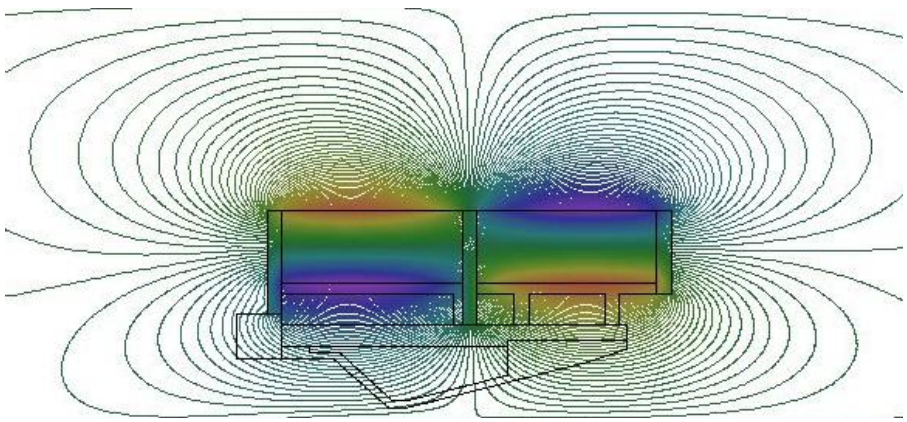


Figure 4. MPD thruster with cusp field lines.

B. Electrode

Table 1 represents electrode conditions. Figure 5 shows the schematic view of electrodes for MPD thruster using in these experiments. The nozzle shape of the MPD thruster with divergent field is convergent-divergent (CD) nozzle (see in Fig. 5 (a)). The constrictor diameters of 2 and 10 mm were used for one experiment.

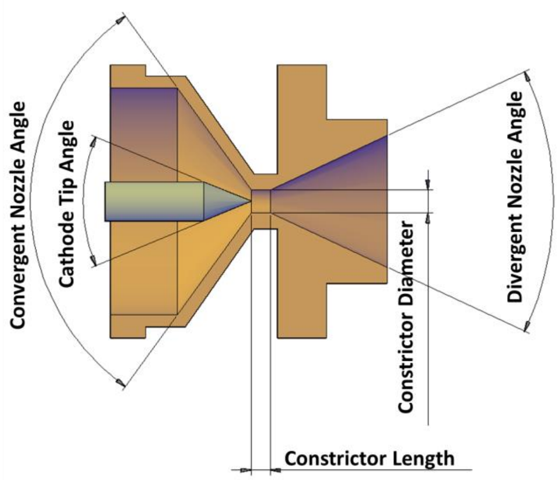
It was considered that propellant of supersonic speed was caused the wall-loss in convergent part with CD nozzle. Accordingly, a new anode which has no convergent part was developed. This anode had straight-divergent nozzle and it was called SD nozzle see in Fig. 5 (b). The SD nozzle was expected to decrease the wall-loss of propellant and to improve thrust.

As shown in Fig. 5 (c) the schematic view of electrodes for cusp field. In the anode used in a precedent study, jetted plasma heat a magnet holder directly from the nozzle exit and may cause a drop of the magnetic induction and the irreversibility demagnetization of magnets. Therefore, the angle of the anode nozzle was set to two stages of 40 deg. and 50 deg. .

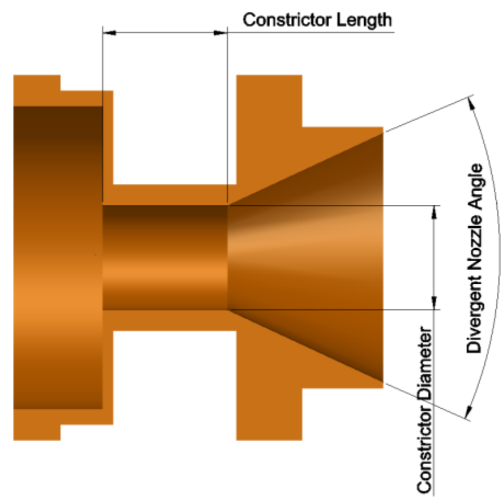
Figure 6 shows the rod cathode. The material of the cathode is pure tungsten which has high electric conductivity and high melting point. The rod cathode is a rod-shaped electrode with a diameter of 10 mm and a tip angle of 45 deg. .

Table 1. Electrode conditions.

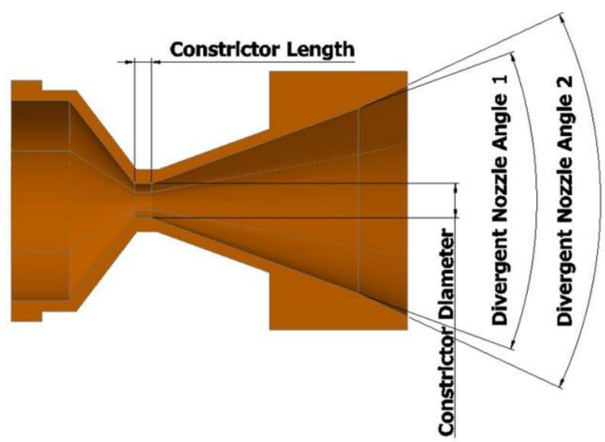
Cathode	Diameter	10 mm	
	Tip Angle	45 deg.	
Anode	Constrictor Diameter	2 mm	10 mm
	Constrictor Length	2 mm	5 mm
	Convergent Nozzle	120 deg.	
	Divergent Nozzle	50 deg.	
Electrode Distance		0 mm	



(a) Schematic view of CD nozzle anode



(b) Schematic view of SD nozzle anode



(c) Schematic view of CD nozzle anode with cusp field

Figure 5. Electrode of MPD thruster.

Figure 6. Rod cathode.

C. Experimental Facility

The schematic of experimental apparatus is shown in Fig.7. The experiments were carried out in a stainless steel vacuum tank with 1.2 m in diameter and 2.0 m in length. The experimental apparatus consists of MPD thruster, vacuum pumping system, the thrust measurement and calibration system. In addition, power supply system, propellant supply system and voltage and current measurement system are settled. An atmosphere was evacuated by using a rotary pump of 600 m^3/h and a mechanical booster of 6,000 m^3/h. The pressure of the vacuum tank was measured by a Pirani gauge. A tank pressure can fall down until 5 Pa by using the vacuum pumping system.

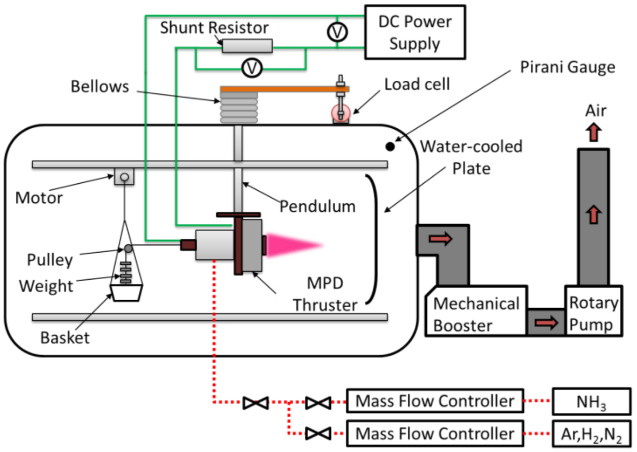


Figure 7. schematic view of experimental device.

III.Experiment of MPD thruster with divergent field

The basic performances with rod cathodes were investigated by using MPD thruster with divergent field. And, performance characteristics were obtained by changing the nozzle diameter, the propellant flow rate, and the magnetic field strength.

A. Experimental condition of influence of anode constrictor diameter on thrust performance

Table 2 shows experimental conditions. Anodes with diameters of 2 mm and 10 mm were used for this experiment. As the propellant, ammonium was used.

Table 2. Experimental conditions.

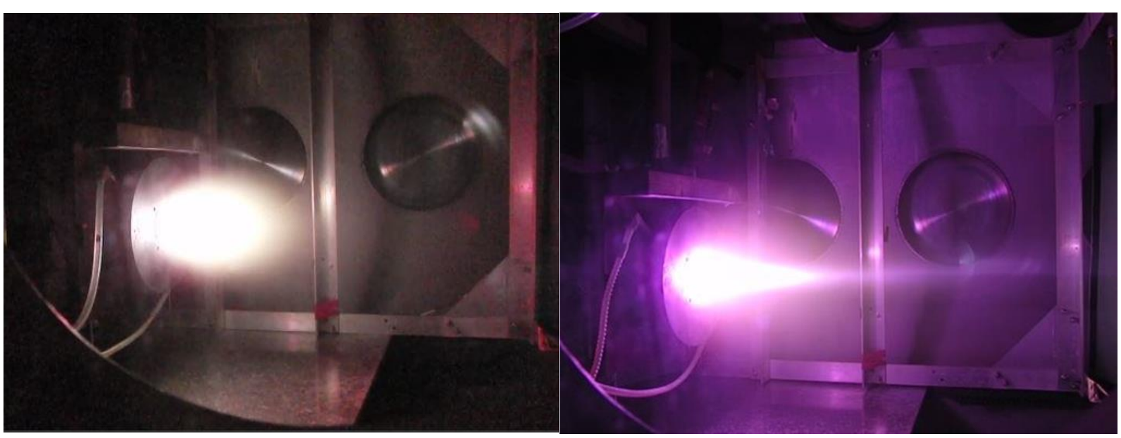
Propellant	NH_3
Constrictor Diameter, mm	2, 10
Mass Flow Rate, mg/s	5, 60, 150
Magnetic Flux Density, T	0.157
Discharge Current, A	70-150

B. Experimental result of influence of anode constrictor diameter on thrust performance

The performance characteristics were examined by the difference of anode constrictor diameter and propellant mass flow rate. Figure 8 shows operations using the anodes which have constrictor diameters of 2 and 10 mm, respectively. In the case of operation using the anodes which have constrictor diameters of 10 mm, the plasma plume was converged on the center axis. It was considered that electromagnetic acceleration was main acceleration. The electromagnetic acceleration was characteristics of MPD thruster. On the other hand, in the case of operation using the anodes which have constrictor diameter of 2 mm, the plasma plume was expanded. As the reason, it was considered that electrothermal acceleration was main acceleration.

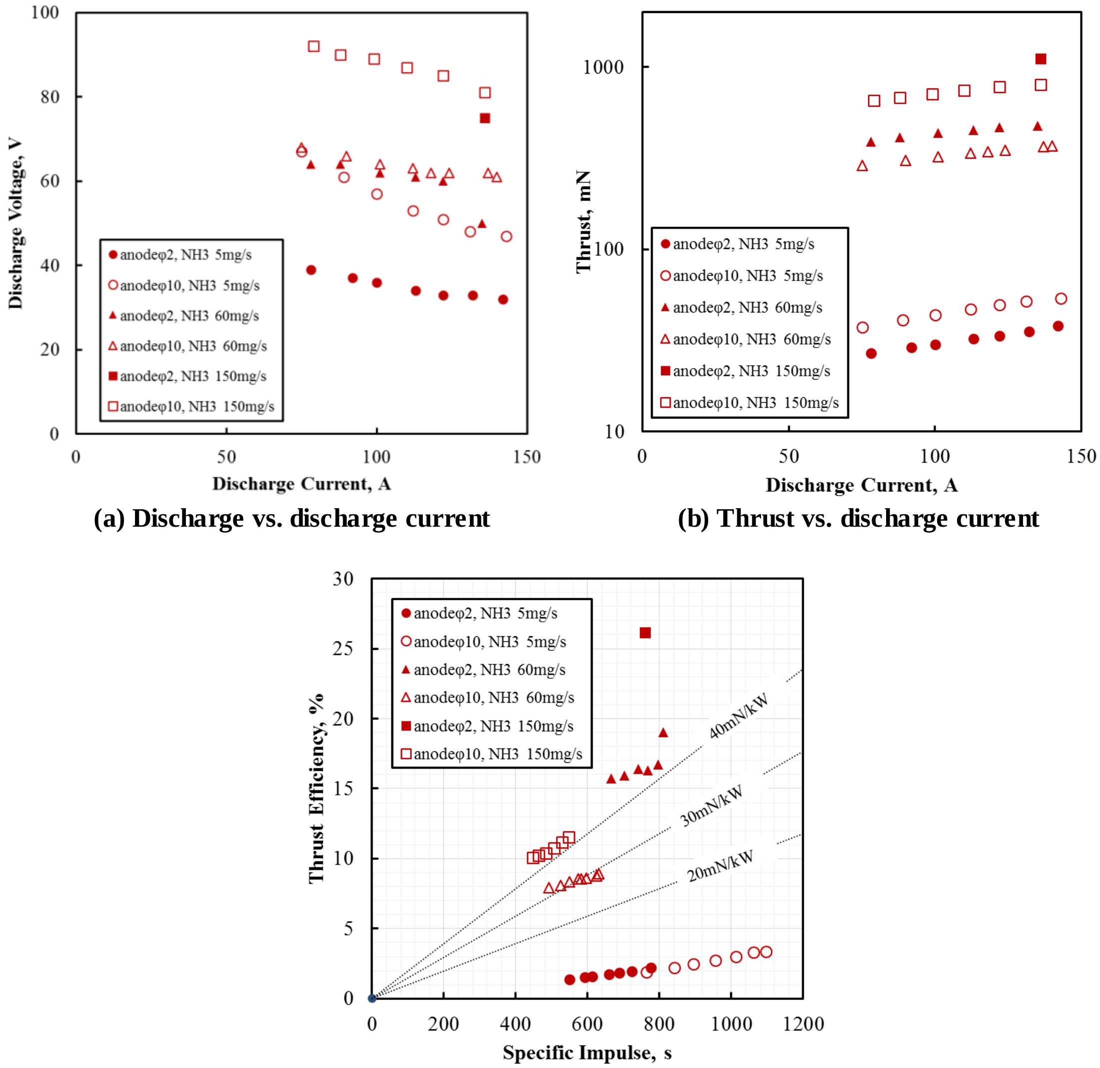
The performance characteristics were shown in Fig. 9. As shown in Fig. 9 (a), the discharge voltage decreased with increasing the discharge current. In this result, the operation of MPD thruster in this experiment was considered normal. As shown in Fig. 9 (b), the thrust increased with increasing the discharge current. In addition, it was compared about anode constrictor diameter. In the case of small flow rate, the thrust with anode which had constrictor diameter of 10mm was higher than that with anode which had constrictor diameter of 2mm. As the reason, it was considered that electromagnetic acceleration was main acceleration because the pressure in the discharge room was low. On the other hand, in the case of large flow rate, the thrust with anode which had constrictor diameter of 2mm was higher than that with anode which had constrictor diameter of 10mm. It was considered that electrothermal acceleration was main acceleration because the pressure in the discharge room was high from this result. As shown in Fig. 9 (c), the thrust efficiency in large flow rate was higher than that in small flow rate. In the case of large flow rate, it was confirmed the thrust and discharge voltage was high. The thrust efficiency was known to be proportional to the square of the thrust value and to be inversely proportional to discharge voltage. Therefore, the thrust efficiency was higher in large flow rate.

Typical performance with NH_3, a thrust of 477.4 mN, a specific impulse of 811.4 s and a thrust efficiency of 19.0%, were obtained at 0.157 T. And, the input power was 6.75 kW in this typical performance data.



(a) anode constrictor diameter of 2 mm **(b) anode constrictor diameter of 10 mm**

Figure 8. Plasma plume.



(a) Discharge vs. discharge current **(b) Thrust vs. discharge current**

(c) Thrust efficiency vs. specific impulse

Figure 9. Experimental results.

C. Experimental condition of influence of nozzle shape on thrust performance

MPD thrusters were considered the propellant speed have already reached the supersonic speed when the propellant was invested. The propellant speed had been increased by as increasing the cross-sectional area of flow channel in speed of supersonic zone. And, it was confirmed cross-sectional area of convergent part was decreasing toward the constrictor part. For this reason, it was considered that propellant of supersonic speed was caused the wall-loss in convergent part. The SD nozzle was expected to decrease the wall-loss of propellant and to improve thrust. Therefore, the comparative experiments of CD nozzle and SD nozzle was performed for examination of as to whether the thrust was improved by SD nozzle.

In this experiment, an MPD thruster with divergent field was used. Table 3 shows experimental condition.

Table 3. Experimental conditions.

Propellant	NH_3
Constrictor Diameter, mm	20
Mass Flow Rate, mg/s	10, 60, 150
Magnetic Flux Density, T	0.157
Discharge Current, A	70-150

D. Experimental result of influence of nozzle shape on thrust performance

Figure 10 shows plasma plumes of NH_3 60 mg/s using the CD and SD nozzle anodes, respectively. It can be confirmed that the plume converges under the condition of 60 mg/s. And, the same tendency was also observed under other conditions. This is probably because the anode's constrictor diameter was 20 mm and the discharge chamber pressure was not kept high.

The performance characteristics were shown in Fig. 11. Figure 11 (a) shows discharge voltage vs. discharge current. As shown in Fig. 11 (a), the discharge voltage decreased with increased the discharge current. However, voltage drop became more significant when using CD nozzle than SD nozzle. And, as the mass flow rate increased, the discharge voltage value increased.

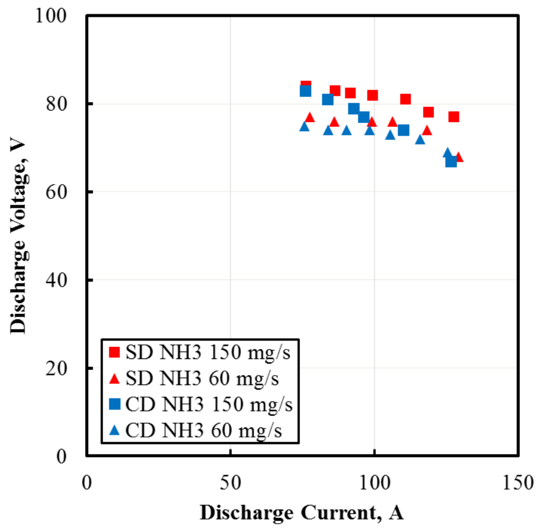
Figure 11 (b) shows thrust vs. discharge current. Improvement of thrust was confirmed by using SD nozzle. As described above, it is considered that thrust was improved because the speed loss of the propellant became small and the speed of the plasma discharged from the nozzle increased. Table 4 shows gas thrust. Gas thrust was meant thrust before power supply. Propellant speed was compared by comparing gas thrust on the same mass flow rate with the same size of cross-sectional area. It was confirmed gas thrust using SD nozzle is higher than CD nozzle. Therefore, it could be confirmed that wall-loss were caused at a convergent part of the CD nozzle.

As shown in Fig. 11 (c), thrust efficiency vs. specific impulse. The thrust increased with the SD nozzle, but the decrease in the voltage was better when using the CD nozzle. Therefore, the thrust efficiency was not much different when compared by two nozzles. However, when the SD nozzle was used, it was possible confirm the improvement of specific impulse because the thrust was improved.

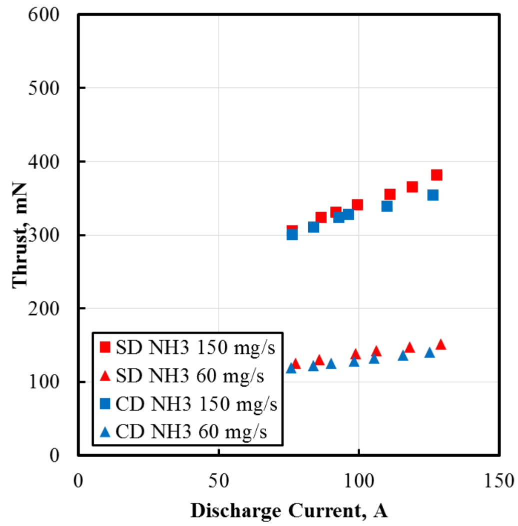
In this experiment, the anode with a constrictor diameter of 20 mm was used. Therefore, the discharge chamber pressure was not kept high and the discharge voltage became high. In the future, it is necessary to reduce the constrictor diameter of the SD anode and acquire the operating characteristics, in order to keep the discharge chamber pressure high and to improve the thrust efficiency.

(a) CD nozzle anode **(b) SD nozzle anode**

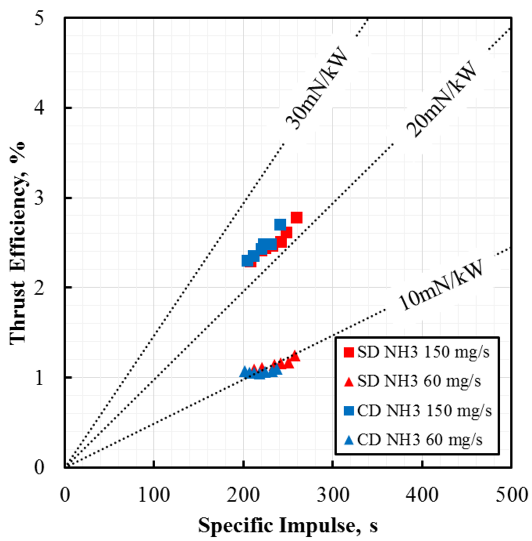
Figure 10. Plasma plume.



(a) Discharge vs. discharge current



(b) Thrust vs. discharge current



(c) Thrust efficiency vs. specific impulse

Figure 11. Experimental results.

Table 4. Thrust performance.

Mass Flow Rate, mg/s	60		150	
Nozzle Type	SD	CD	SD	CD
Gas Thrust, mN	36.8	33.1	95.6	92.6
Maximum thrust, mN	151.5	139.8	381.7	354.6

IV.Experiment of MPD thruster with cusp field

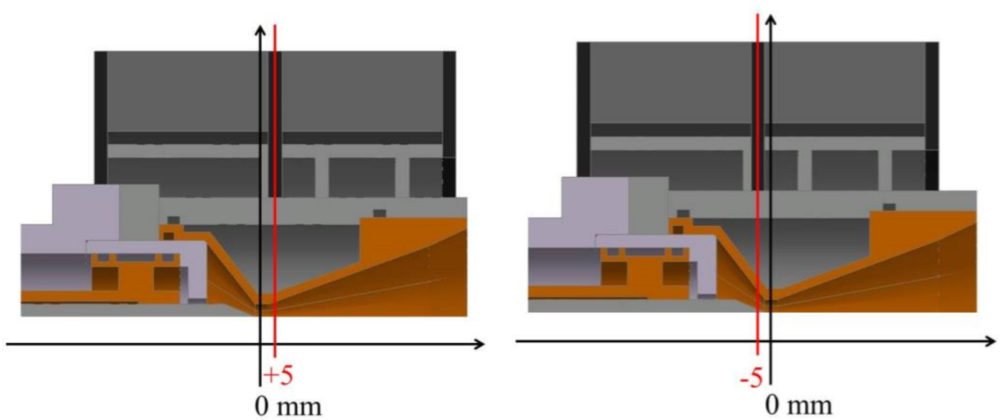
A. Experimental objective and conditions

The MPD thruster with cusp field was developed, applied experiment, and acquired performance. And, the performance of MPD thruster with cusp field and MPD thruster with divergent field was compared.

Table 5 shows experimental conditions. In order to compare the performance with the water-cooled MPD thruster with divergent field, experience conditions were not change. In addition, the cusp position can be changed freely by moving the magnetic circuit in the axial direction. The cusp position was on the constrictor, and its position was defined as 0 mm which is the reference position. The thruster downstream direction was set to a positive value from the reference. Experiments were conducted at three places of -5, 0, +5 mm and performance characteristics were acquired. Fig. 12 represents the schematic view of the cusp position.

Table 5. Experimental conditions.

Propellant	NH_3
Mass Flow Rate, mg/s	10, 60, 150
Cusp position, mm	-5, 0, +5
Discharge Current, A	70-150



(a) +5 mm **(b) -5 mm**

Figure 12. Cusp position.

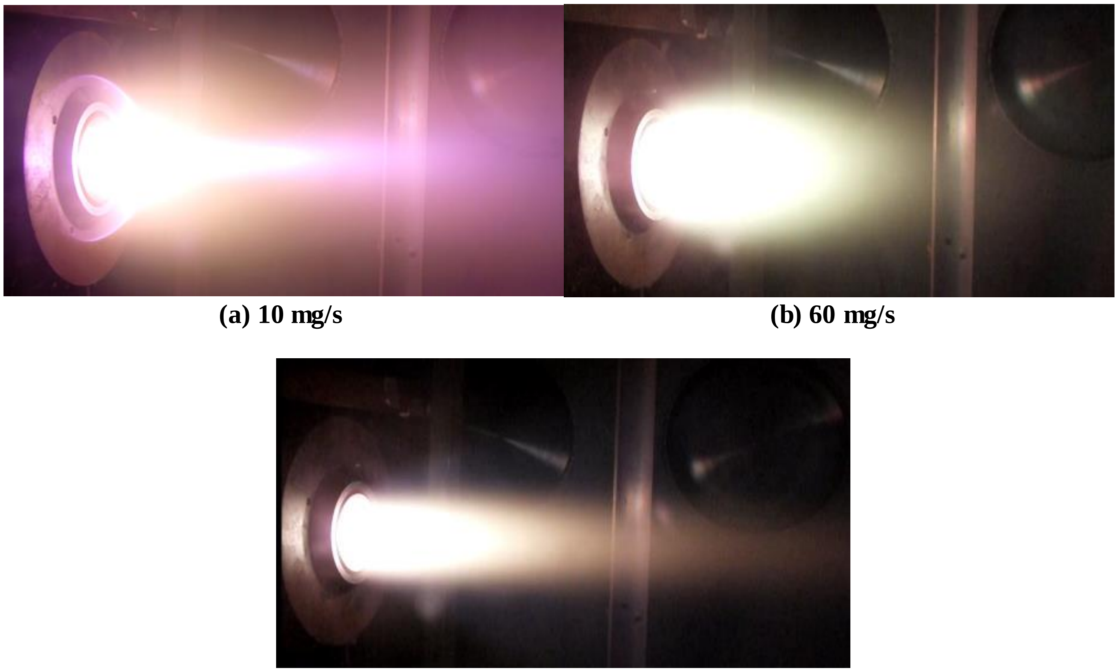
B. Experimental result

4shown in Fig. 13(a), it was confirmed the plume was converged. As the reason, it was considered electromagnetic acceleration was main acceleration. On the other hand, it was confirmed the plume was diverged in Figs. 13(b) and (c). As the reason, it was considered electrothermal acceleration was main acceleration. This is a trend also seen in operation with a MPD thruster with divergent field.

Figure 14 shows the performance characteristics of this experiment. As shown in Fig. 14(a), the discharge voltage decreased with increased the discharge current. In addition, it was confirmed that the discharge voltage decreased by applying the cusp field.

Figure 14 (b) shows thrust vs. discharge current. It compared to the MPD thruster with cusp field and the MPD thruster with divergent field. It is considered that the Lorentz force due to the applied cusp field became an obstacle to acceleration.

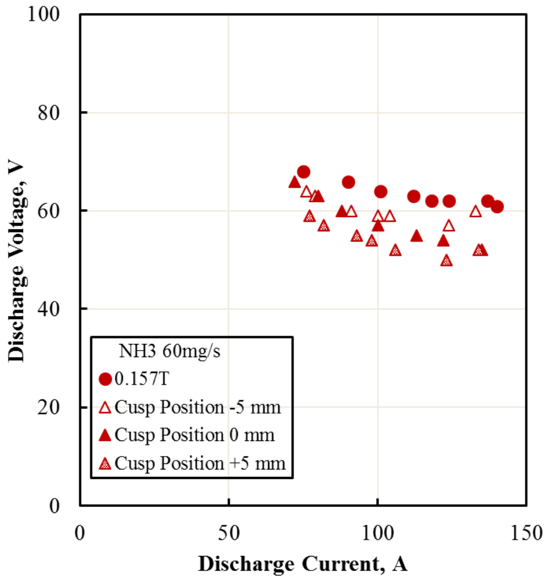
As shown in Fig. 14 (c), thrust efficiency vs. specific impulse. By using the cusp field, the discharge voltage decreased, but the thrust became small. Therefore, the MPD thruster with divergent field resulted in higher thrust efficiency. In the future, it is necessary to change the cusp position and find the condition that the thrust is difficult to decrease.



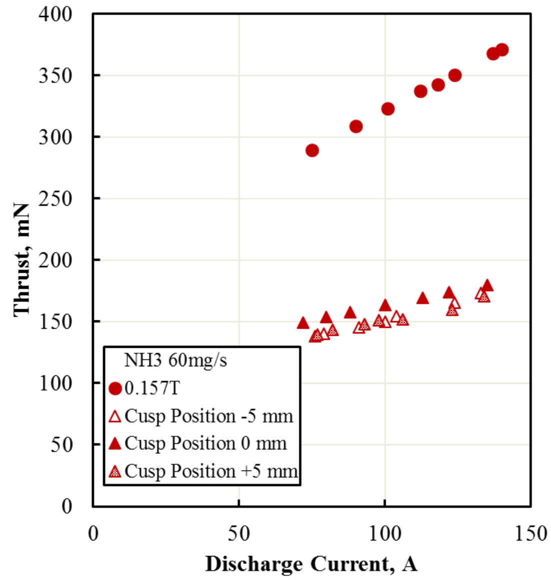
(a) 10 mg/s **(b) 60 mg/s**

(c) 150 mg/s

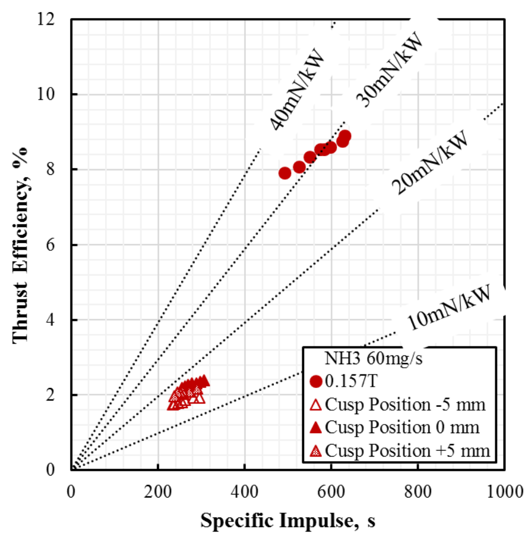
Figure 13. Plasma plume.



(a) Discharge vs. discharge current



(b) Thrust vs. discharge current



(c) Thrust efficiency vs. specific impulse

Figure 14. Experimental results.

V.Conclusion

The following results were obtained.

A) A MPD thruster with permanent magnets was developed and tested with NH_3. The characteristics of a thrust of 477.4 mN, a specific impulse of 811.4 s and a thrust efficiency of 19.0% were obtained at 0.157 T.

B) In the water-cooled MPD thruster with divergent field, the nozzle shape of the anode was changed and the performance characteristics were obtained. By changing from CD nozzle to SD nozzle, the propellant speed deceleration was suppressed and thrust improved. In this experiment, thrust efficiency was the same as that of the CD nozzle. However, propulsion performance was improved by improving specific impulse.

C) By changing from the divergent field to the cusp field, the discharge voltage decreased. However, the Lorentz force due to the applied cusp field became an obstacle to acceleration. Therefore, it is necessary to change the cusp position and find the condition that the thrust is difficult to decrease.

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