Research and Development of Low-Power Cylindrical-Type Hall Thrusters for Nano/Micro-Satellites

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Abstract: The Osaka Institute of Technology (OIT) has been developing nano and micro satellites "PROITERES (in the Project of Osaka Institute of Technology Electric Rocket Engine onboard Small Space Ship)" which was started since 2007. Now a day, OIT is developing the 3rd PROITERES nano-satellite for moon exploration by powered-flight with electric thrusters. The Low-power Cylindrical-type Hall Thruster (CHT) will be mounted in the satellite. In this study, the TCHT-5 was developed as a new CHT, and the performance was measured. As a result, the TCHT-5 achieved the performance of a thrust of 1.1-5.5 mN, a specific impulse of 366-1853 s, and a thrust efficiency of 8.6-34.0% with an input power of 23-163 W.

I. Introduction

NANO and micro satellites can be generally developed with a cost of 1/20-1/50 of conventional satellites. Therefore, small laboratories such as universities have actively developed them in recent year. The University of Tokyo launched the micro-satellite "PROCYON" as piggybacking satellite of the "HAYABUSA2" in December 2014. Osaka Institute of Technology (OIT) also launched the 1st PROITERES (Project of Osaka Institute of Technology Electric Rocket Engine onboard Small Space Ship)-satellite in September 2012.[1-3] Furthermore, OIT has developed the 2nd PROITERES satellite will be launched in 2016. The 1st and 2nd PROITERES satellites have mounted a Pulsed Plasma Thruster (PPT) as an electric propulsion.[4-8] Moreover, OIT is planning to develop the 50 kg class micro satellite for the moon exploration as the 3rd PROITERES satellite. The 3rd PROITERES will be mounted the low-power Cylindrical-type Hall Thruster (CHT) for powered flight to Moon from low earth orbit. If the electric power is supplied with only sunlight, the specific impulse over 1300 s of the CHT is required at the input power of 50 W and a trip time of 3 years.

CHT with circular cross-sectional discharge room was developed by Dr. Raitses. Princeton Plasma Physics Laboratory (PPPL), Princeton University. PPPL's CHT achieved a thrust efficiency of 15-32% in the power range of 50-300 W.[9-10]

In order to develop further low-power thruster, OIT developed a special CHT which is named "TCHT-4". The TCHT-4 has permanent magnets in exchange for electromagnet. However, the TCHT-4 decreased performance at time of 170 s and did not operate because permanent magnet was degaussed by heating from plasma.[11-13]

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In this study, OIT developed a new CHT which is named "TCHT-5". In the TCHT-5 permanent magnets were arranged in consideration of degaussing by heating. In addition, discharge room length and magnetic poles position could be changed in order to determine an optimum magnetic field.[14] Then, performance characteristics of the TCHT-5 were measured and discussed.

II. General Guidelines

A. Cylindrical-type Hall thruster "TCHT-5"

Figures 1 and 2 show the appearance and cross-sectional view of the TCHT-5. The discharge chamber made of Boron Nitride (BN), and inner diameter is 14 mm. Xenon is used as the propellant. Furthermore, TCHT-5 can be changed the anode position and the discharge room length by screw mechanism. The anode position can be moved by changing magnetic pole position. Figure 3 shows details of the discharge room length (Xd) and the magnetic pole position (Xm). The discharge room length can be changed in a range of 7-17 mm. And also, the magnetic pole position can be changed in range of 11-22 mm.

Figures 4 and 5 show the calculated magnetic field shapes and strength of the TCHT-5. When the discharge room length is 7 mm, the maximum magnetic flux density of axis direction is 184 mT.

Figure 1. External appearance view of the TCHT-5.

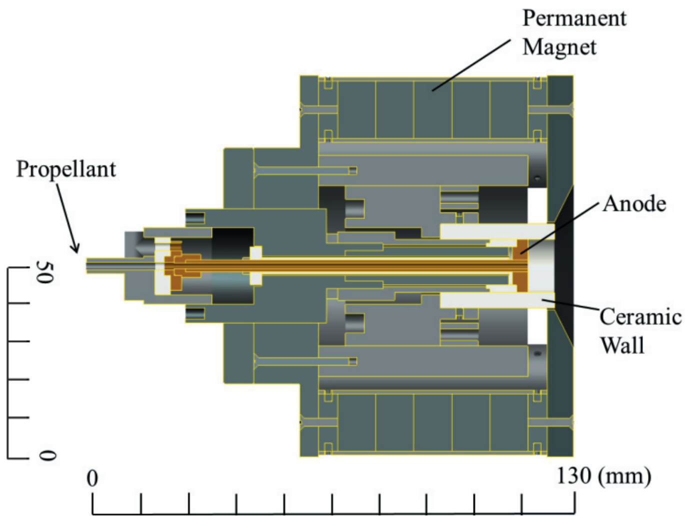


Figure 2. Cross-sectional view of the TCHT-5.

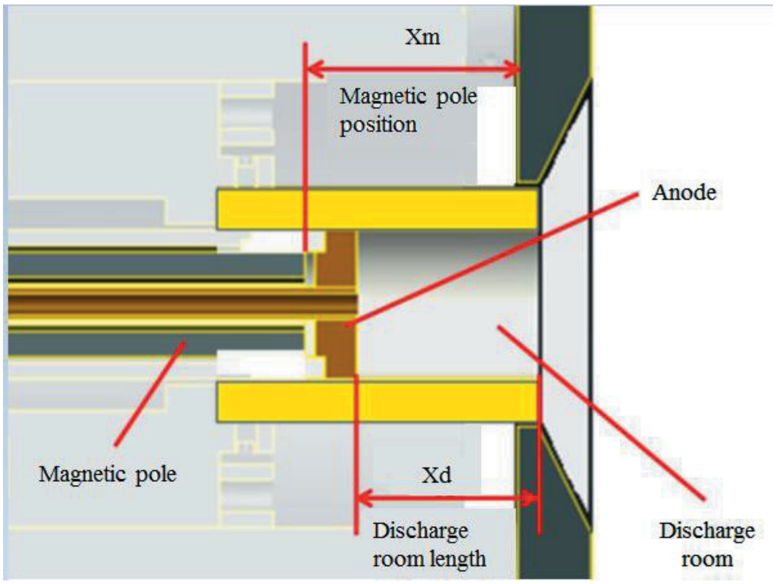


Figure 3. Discharge room length (Xd) and magnetic pole position (Xm).

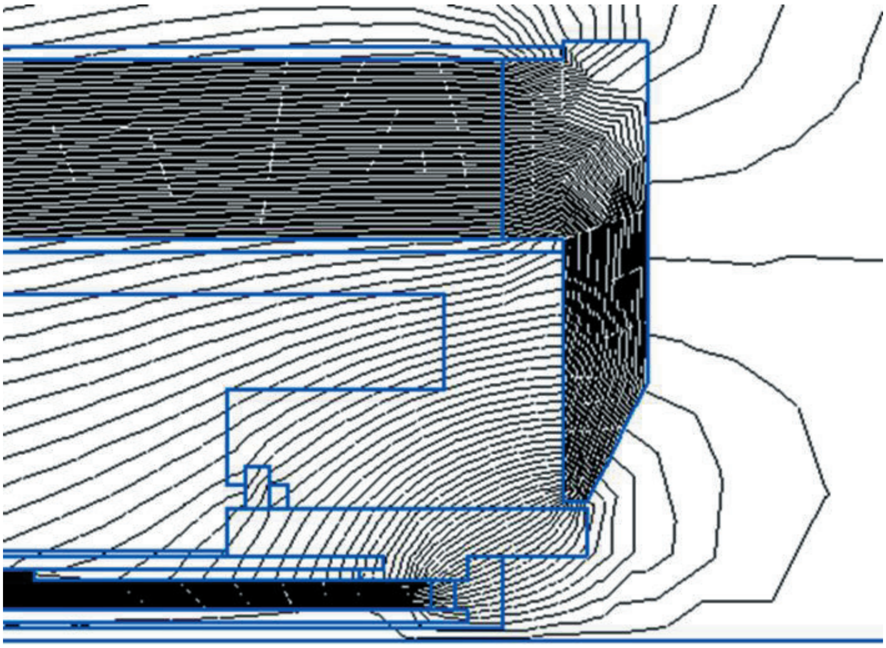


Figure 4. Magnetic field shape of the TCHT-5.

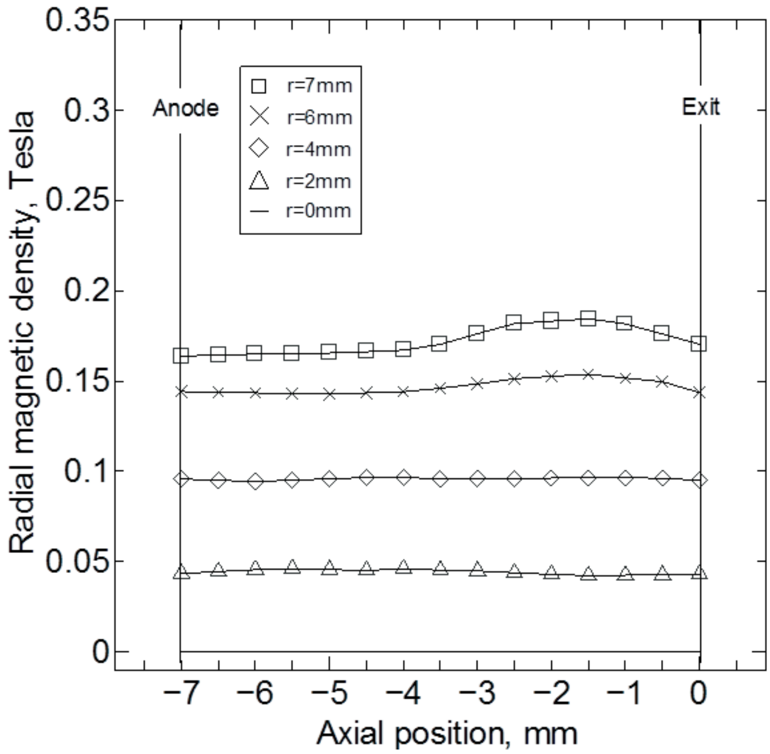


Figure 5. Magnetic flux density of the TCHT-5.

B Vacuum facility

Figure 6 shows the vacuum chamber and pumping system. The TCHT-5 is operated in a water-cooled stainless steel vacuum chamber with 1.2 m in diameter and 2.25 m in length. The chamber is equipped with two compound turbo molecular pumps with a pumping speed of 10000 L/s on xenon, several DC power supply systems and a thrust measurement system. The vacuum chamber pressure is kept about 3.0×10^{-2} Pa under operations. A clean and high vacuum environment can be created by using the oil-free turbo molecular pump system.

Figure 7 shows schematic of experimental system, and Figure 8 shows the thrust measurement system. Thrust is measured by pendulum method; that is, the displacement of thruster is measured by an eddy-current type gap sensor.

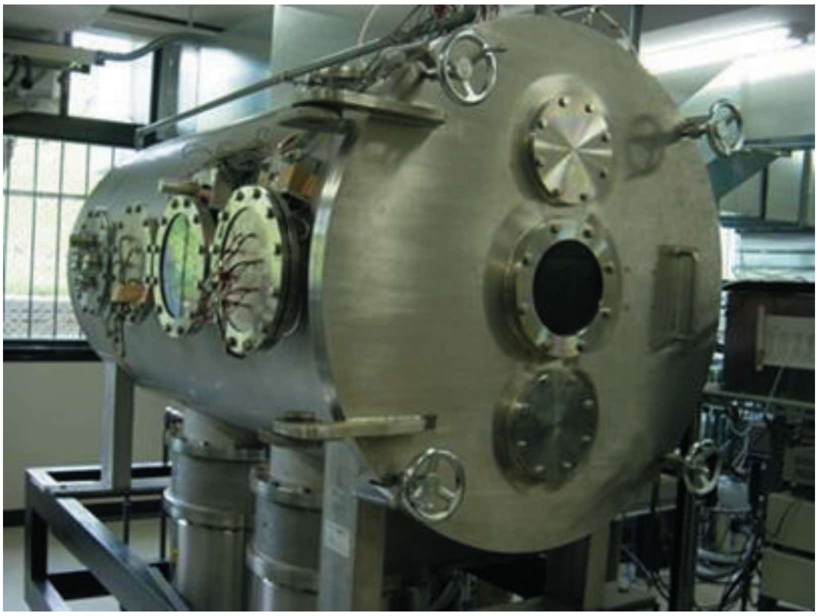


Figure 6. Vacuum chamber and pumping system.

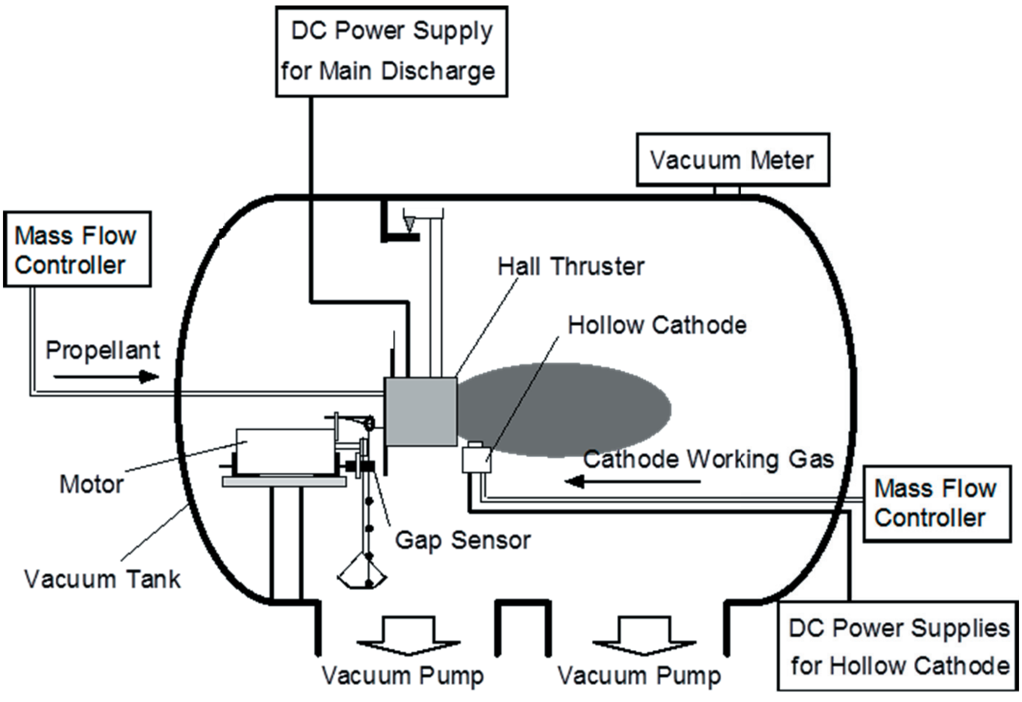


Figure 7. Schematic of experimental system.

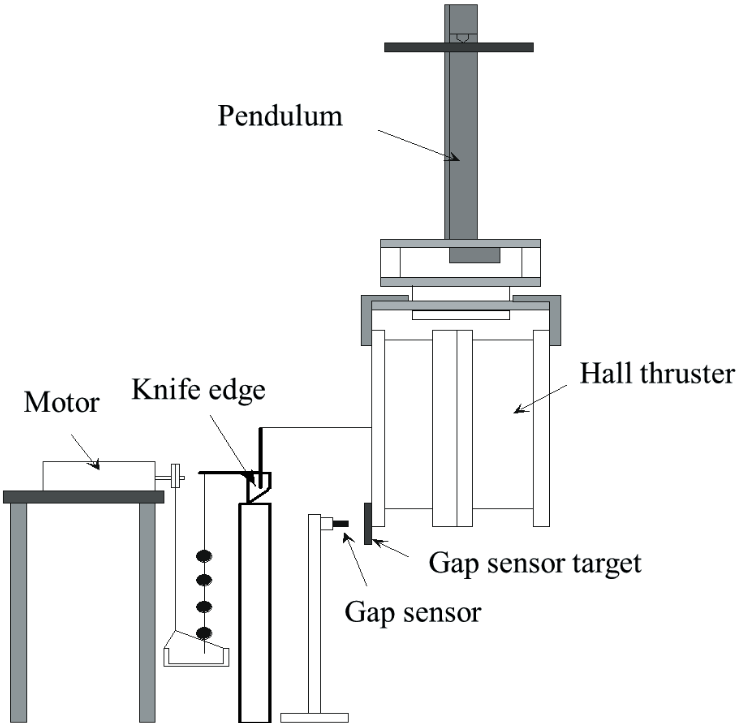


Figure 8. Thrust measurement system.

III. Experimental Condition

A. Experimental 1

Table 1 shows the experimental 1 conditions of the TCHT-5. In the experiment 1, the performance was compared when the magnetic pole positions was changed to Xm=19 mm and Xm=22 mm at a discharge room length of Xd=12 mm. Discharge voltage was changed every 50 V at applied voltages of 150-1000 V, and mass flow rate was changed every 0.05 mg/s in 0.3-0.4 mg/s. However, the TCHT-5 was not operated at discharge voltage above 950 V with Xm=22 mm and Xd=12 mm and the mass flow rate of 0.35 mg/s. Similarly, the TCHT-5 was not operated at discharge voltage above 850 V with the mass flow rate of 0.4 mg/s.

Table 1. Experimental 1 conditions.

Discharge Voltage	150-1000 V	
Magnetic Pole Position	19 mm	22 mm
Discharge Room Length	12 mm	
Propellant	Xenon	
Mass Flow Rate	TCHT-5	0.3-0.4 mg/s
	Hollow Cathode	0.1 mg/s
Back Pressure	4.0×10^{-2} Pa	

B. Experimental 2

Table 2 shows the experimental 2 conditions of the TCHT-5. In the experiment 2, the performance was compared when the discharge room length was changed to Xd=12 mm and Xd=15 mm at a magnetic pole position of Xm=22 mm. As with the experiment 1, discharge voltage was changed every 50 V at input voltages of 150-1000 V, and mass flow rate was changed every 0.05 mg/s in 0.3-0.4 mg/s.

Table 2. Experimental 2 conditions.

Discharge Voltage	150-1000 V	
Magnetic Pole Position	22 mm	
Discharge Room Length	15 mm	12 mm
Propellant	Xenon	
Mass Flow Rate	TCHT-5	0.3-0.4 mg/s
	Hollow Cathode	0.1 mg/s
Back Pressure	4.0×10^{-2} Pa	

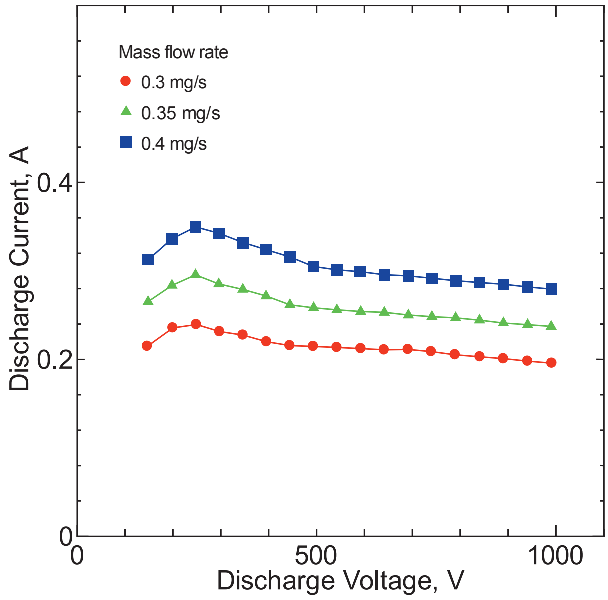
IV. Experimental Results and Discussion

Figure 9 shows a typical stable operation of the TCHT-5.

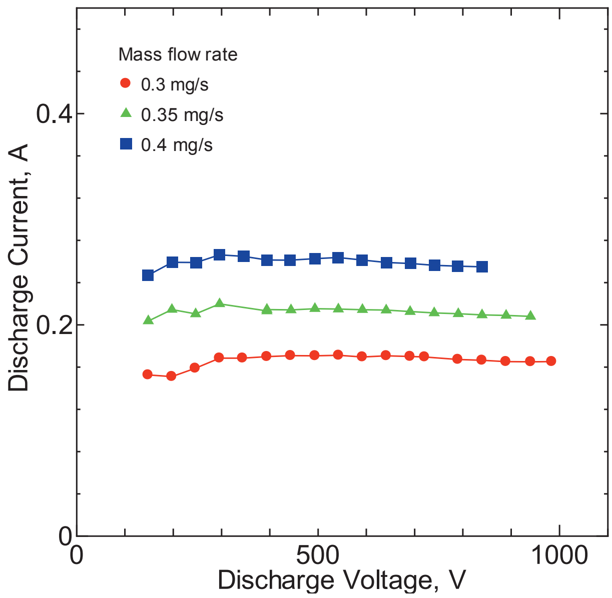
Figure 9. Operation of the TCHT-5.

A. Experiment 1

Figure 10 shows the discharge current as a function of discharge voltage at the cases of Xm=19 and 22 mm. The discharge current in Xm=19 mm was decreased at a discharge voltage of 350 V. In contrast, the discharge current in Xm=22 mm became constant at the discharge voltage of 350 V. Figures 11 and 12 show specific impulse and thrust efficiency as a function of input power at the cases of Xm=19 and 22 mm. The TCHT-5 achieved the specific impulse of 1303 s and the thrust efficiency of 21.2% with Xm=19 mm at a mass flow rate of 0.3 mg/s and an input power 115 W. With Xm=22 mm the specific impulse and the thrust efficiency reached 1303 s and 29.8%, respectively, with an input power of 84 W. As a result, the performance with Xm=22 mm was higher than that with Xm=19 mm.

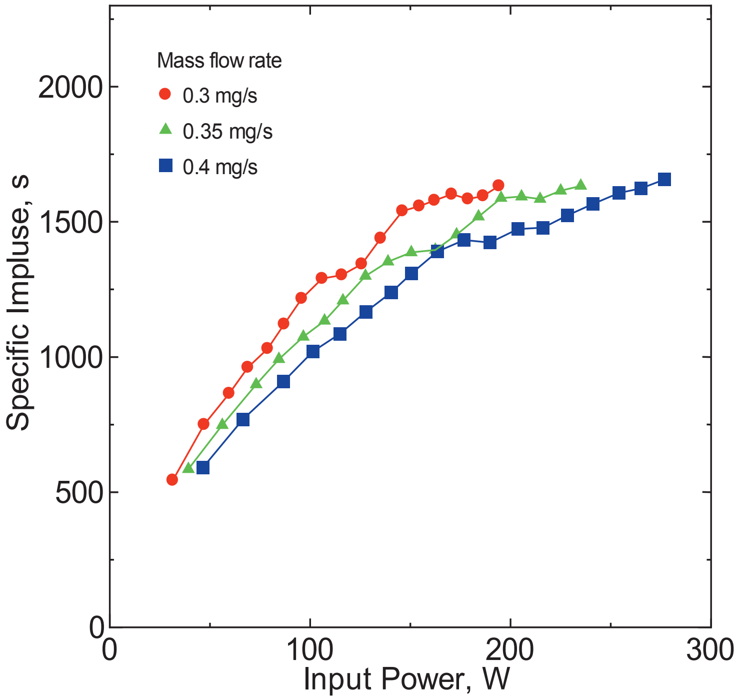


(a) Xm=19 mm

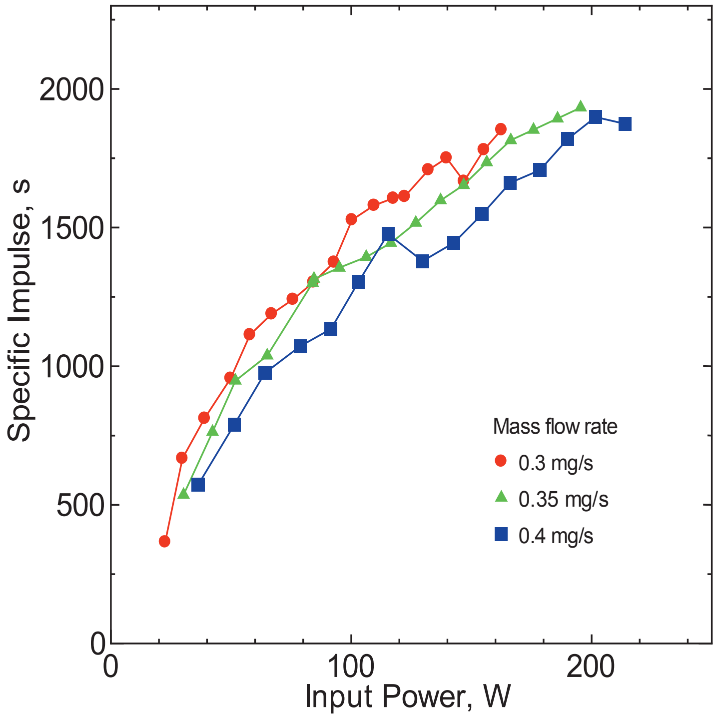


(b) Xm=22 mm

Figure 10. Discharge current vs discharge voltage.

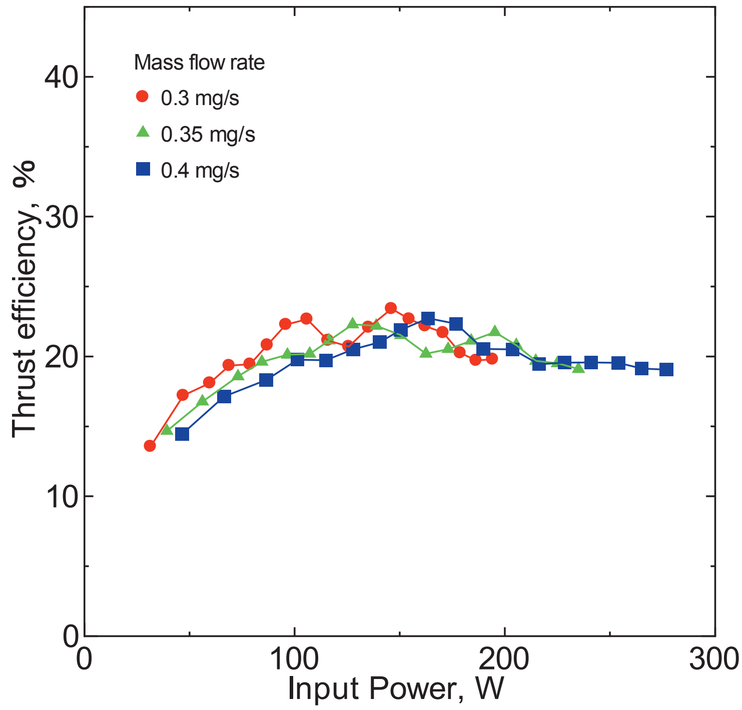


(a) Xm=19 mm

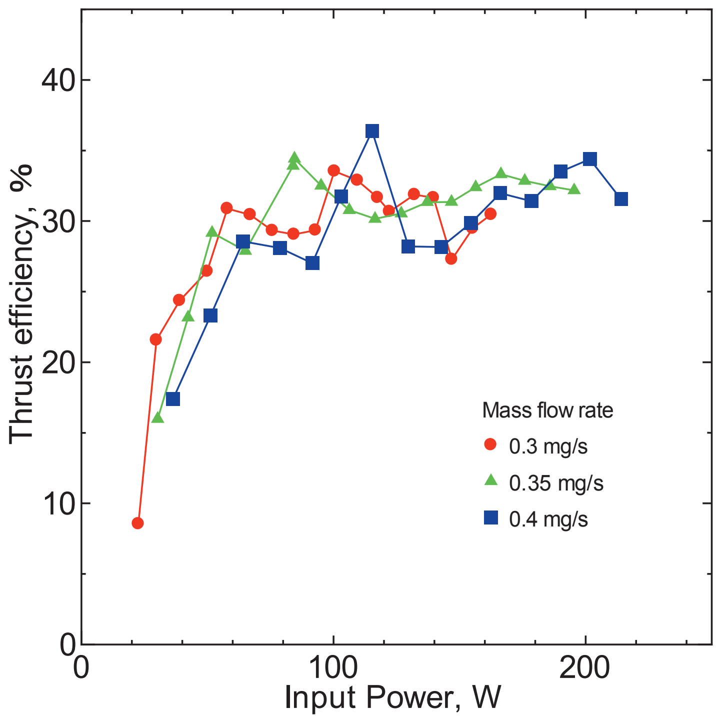


(b) Xm=22 mm

Figure 11. Specific impulse vs input power.

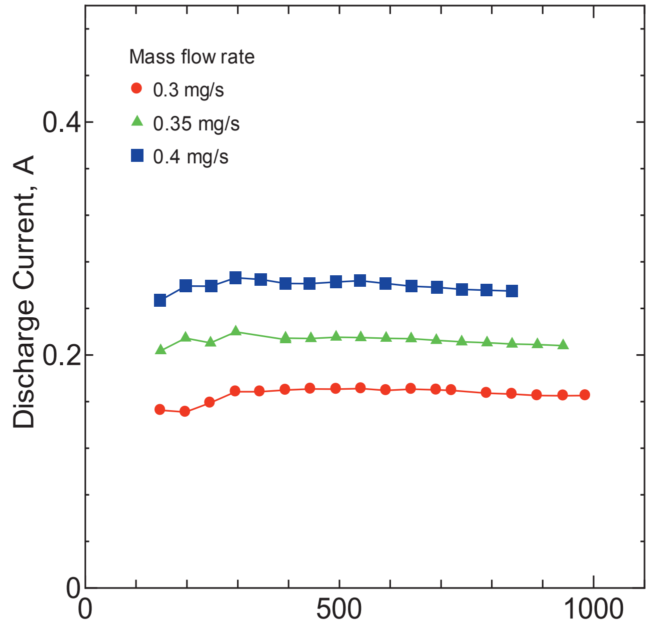


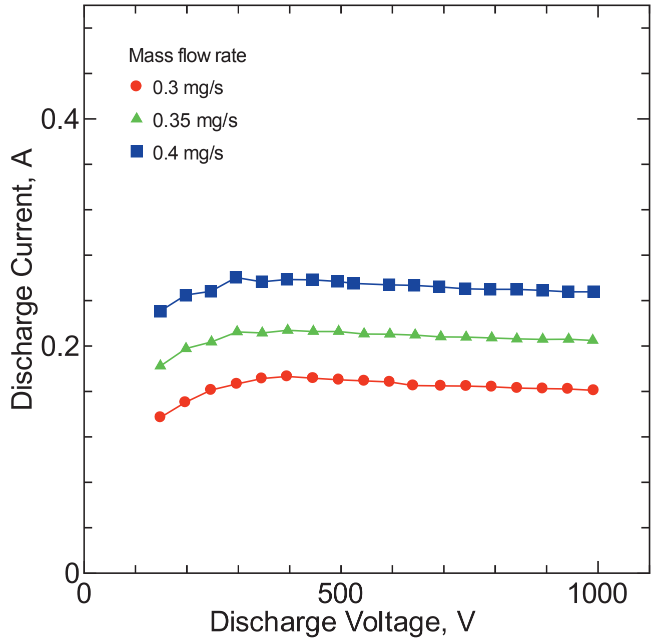
(a) Xm=19 mm



(b) Xm=22 mm

Figure 12. Thrust efficiency vs input power.



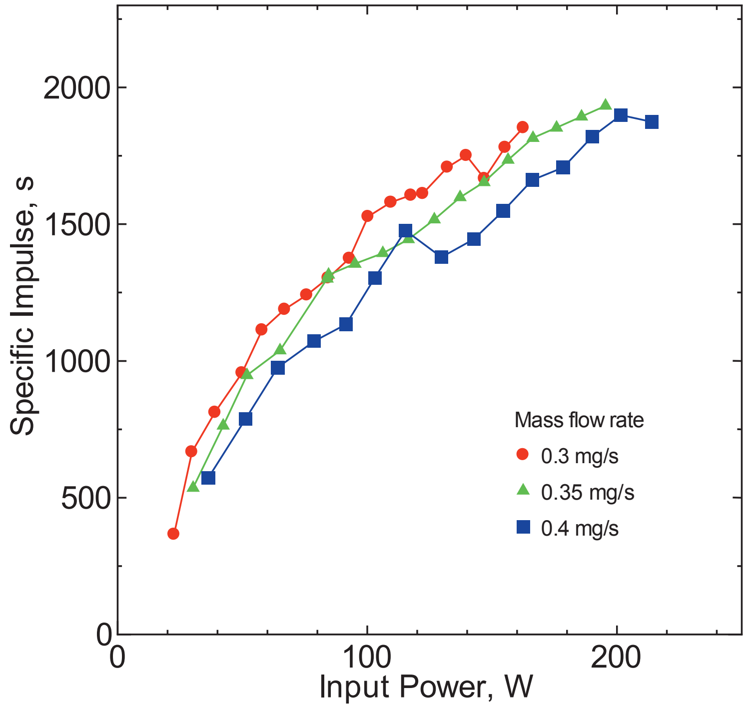


(b) Xd=15 mm

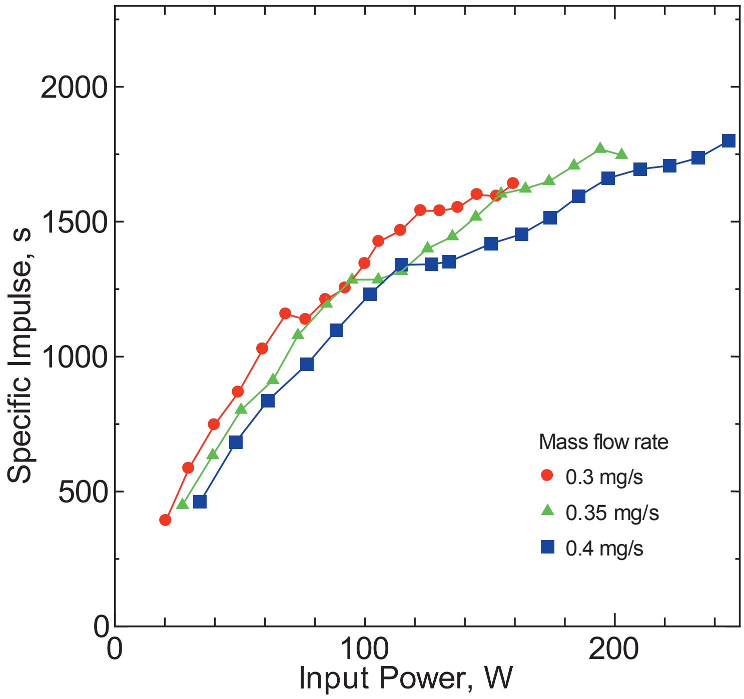
Figure 13. Discharge current vs discharge voltage.

B. Experiment 2

Figure 13 shows the discharge current as a function of discharge voltage at the cases of Xd=12 and 15 mm. The discharge current resulted in value close to both discharge room length. Figures 14 and 15 show specific impulse and thrust efficiency as a function of input power at the cases of Xd=12 and 15 mm. TCHT-5 achieved the specific impulse of 1344 s and the thrust efficiency of 26.0% with Xd=15 mm at a mass flow rate of 0.3mg/s, and an input power of 100 W. Therefore, we obtained the same specific impulse range with a rise of input power of 16 W at Xd=15 mm. Accordingly, the performance with Xd=15mm was lower than that with Xd=12 mm.

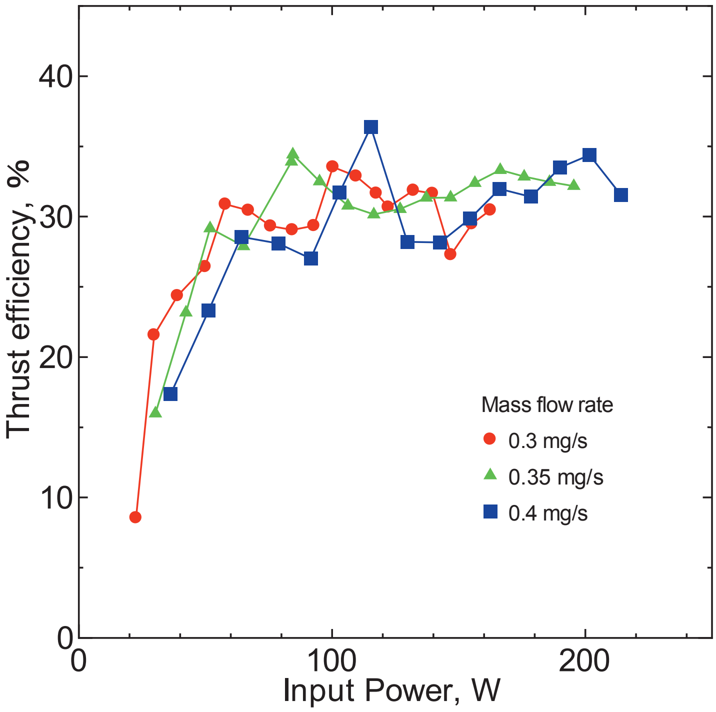


(a) Xd=12 mm

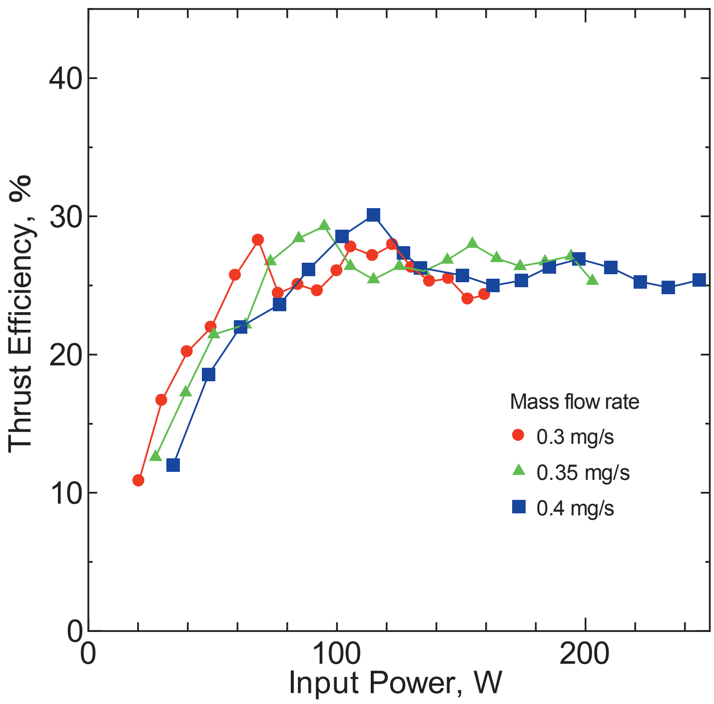


(b) Xd=15 mm

Figure 14. Specific impulse vs input power.



(a) Xd=12 mm



(b) Xd=15 mm

Figure 15. Thrust efficiency vs input power.

V. Conclusion

TCHT-5 was developed as a new low-power CHT, and the thruster performance was measured.

As experimental conditions, the magnet pole position and the discharge room length were changed, and the performance was compared. Consequently, TCHT-5 achieved the performance of specific impulses over 1300 s which satisfies thruster performance for the 3rd PROITERES satellite, although the input power was over 50 W.

The TCHT-5 thruster achieved the highest performance in experimental conditions with Xm=22 mm and Xd=12 mm. The performance is the thrust of 3.8 mN, the specific impulse of 1302 s and the thrust efficiency of 29.0% with an input power of 84 W and a mass flow rate of 0.3 mg/s.

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