Performance Characteristics of Low-Power Cylindrical Hall Thrusters for Powered Flight of Micro/Nano-Satellites and Development of New Compact Electron Sources

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Mitsuyoshi Kobayashi[1], Tetsuo Kakuma[2], Yuya Takahata[3], Yusuke Furukubo[4], Kyohei Fujiwara[5], Tensei Kawakami[6], Hirokazu Tahara[7], and Kyoko Takada[8]
Osaka Institute of Technology, Asahi-ku, Osaka 535-8585, Japan

and

Tomoyuki Ikeda[9]
4-1-1, Kitakaname, Hiratsuka, Kanagawa 259-1292, Japan

Abstract: The number of lunching micro/nano-satellites has increased at university, institute and company all over the world. However, nano-satellites cannot choose orbital altitude for necessary mission for piggy pack launch. Therefore, it is necessary that nano-satellites are equipped with thrusters in order to move to orbital altitude appropriate to achieve a mission. Cylindrical Hall Thrusters (CHT) are suitable for thruster of nano-satellites because it is possible in miniaturization and low power. Osaka Institute of Technology (OIT) have been developed nano-satellites under "PROITERES (PRoject of Osaka Institute of Technology Electric Rocket Engine onboard Small Space Ship)". OIT plans to develop the 3rd PROITERES satellite for the purpose of moon exploration. Accordingly, A small CHT named TCHT-5 was developed. As a result, the TCHT-5 achieved the performance of a specific impulse of 1300 s with an input power of 84 W by a discharge room length of 12 mm and a magnetic poles position of 22 mm. In addition, Because a hollow cathode used now was not suitable for nano-satellites by heating and high power, a new electron sources is developed. The new cathode is named TaC-PI (Thrusters and Cathode with Piezoelectric Igniter). The TaC-PI is combination of a CHT thruster (magnetic field expansion plasma source) and ignition system. The ignition system consists of Piezoelectric Igniter and electrode. The goal of TaC-PI is steady-state operation of the Hall Thrusters for small exploration satellites.

[1] Graduate Student, Major in Mechanical Engineering, and Hirokazu.tahara@oit.ac.jp.
[2] Graduate Student, Major in Mechanical Engineering, and hirokazu.tahara@oit.ac.jp.
[3] Graduate Student, Major in Mechanical Engineering, and hirokazu.tahara@oit.ac.jp.
[4] Graduate Student, Major in Mechanical Engineering, and hirokazu.tahara@oit.ac.jp.
[5] Graduate Student, Major in Mechanical Engineering, and hirokazu.tahara@oit.ac.jp.
[6] Graduate Student, Major in Mechanical Engineering, and hirokazu.tahara@oit.ac.jp.
[7] Professor, Department of Mechanical Engineering, and hirokazu.tahara@oit.ac.jp.
[8] Associate Professor, Department of Intellectual Property, and hirokazu.tahara@oit.ac.jp.
[9] Assistant Professor, Department of Aerospace, and t-ikeda@tsc.u-tokai.ac.jp.

I.Introduction

The number of lunching Nano-Satellites has increased at university, institute and company in the world. The reason is because there has been an expectation for low-cost and low-risk satellites. However, Nano-Satellites can not choose orbital altitude for necessary mission. Therefore, it is necessary that Nano-Satellites are equipped with thrusters in order to move to orbital altitude appropriate to achieve a mission. Cylindrical Hall Thrusters (CHT) are suitable for thruster of Nano-Satellites because they are possible to miniaturization and low power. However, there is no achievement that Nano-Satellites are equipped with CHT. Also, CHT is required improvement to do mission.

Osaka Institute of Technology (OIT) have been developed Nano-Satellites under "PROITERES (PRoject of Osaka Institute of Technology Electric Rocket Engine onboard Small Space Ship)". [1, 2] OIT plans to develop 3rd PROITERES satellite for the purpose of moon exploration. Figure 1 shows the image of 3rd PROITERES satellite. If the 3rd PROITERES satellite is maximum weight 100kg,[3] the thruster is required a specific impulse from 1300 s or more with input power of 50 W. Accordingly, TCHT-5 in which the depth of discharge room and the length of magnetic pole can be changed, was developed as a new CHT.

In addition, hollow cathode is used now is not suitable for Nano-Satellites by heating and high power. Accordingly, new electron sources is developed. New cathode is named TaC-PI (Thrusters and Cathode with Piezoelectric Igniter). TaC-PI is combination of a CHT thruster (magnetic field expansion plasma source) and ignition system. Ignition system consists of Piezoelectric Igniter and electrode. The Goal of TaC-PI is steady-state operation of the Hall Thrusters for small exploration satellites.

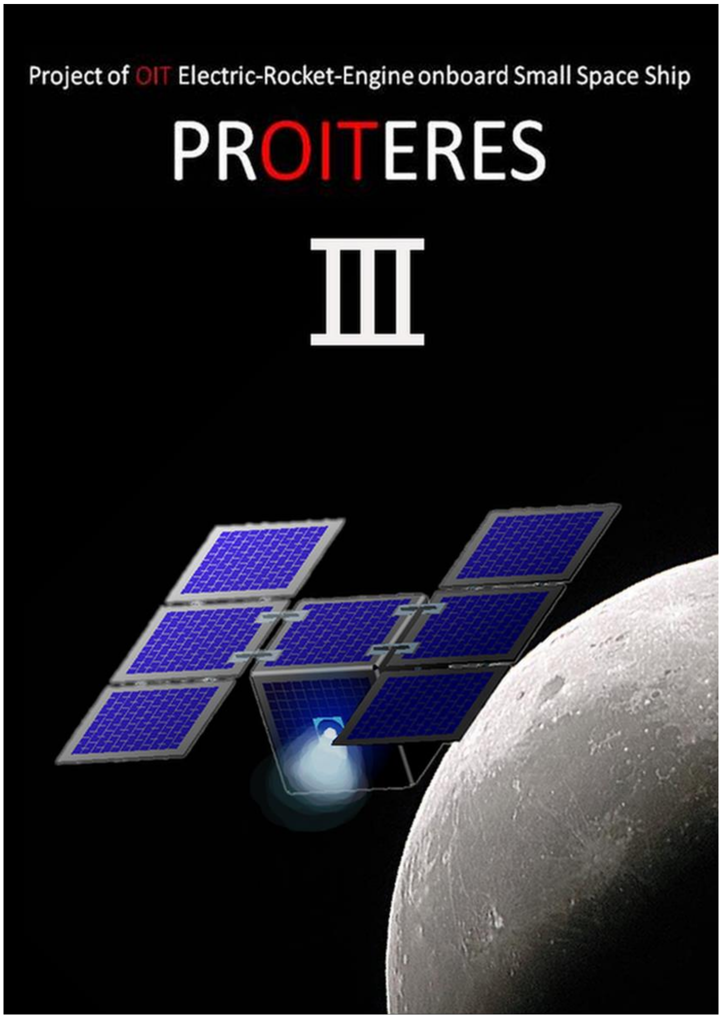


Figure 1. Image of 3rd PROITERES satellite.

II.Experimental Apparatus

A. TCHT-5

The TCHT-5 is a cylindrical-type hall thruster. Figures 2 and 3 show the overview and cross- sectional view of the TCHT-5. Table 1 shows the details of TCHT-5. TCHT-5 can be changed the anode position and the discharge room length by screw mechanism. Figure 4 shows details of the discharge room length and the magnetic pole position. The discharge room length can be changed in a range of 7-17 mm. And also, the magnetic pole position can be changed of 11-22 mm.

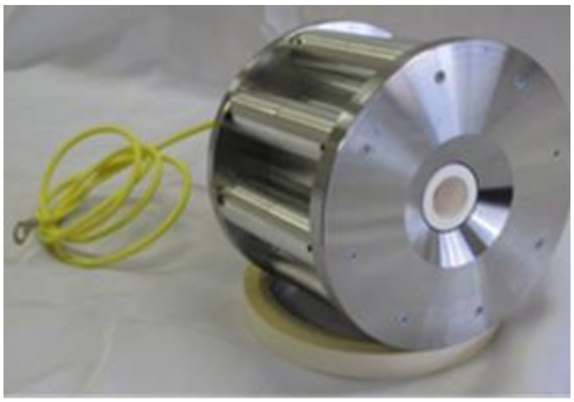


Figure 2. overview of the TCHT-5.

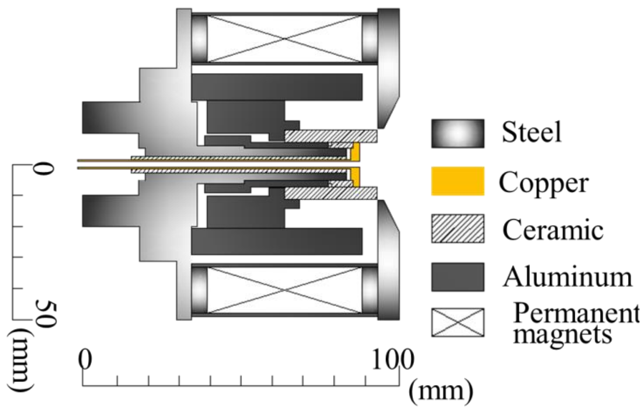


Figure 3. cross-sectional view of the TCHT-5.

Table 1. Details of the TCHT-5.

Discharge Channel Length [mm]	7-17
Discharge Channel Diameter [mm]	14
Discharge Channel Material	Boron Nitride (BN)
Magnetic Pole Position [mm]	11-22
Magnet Quantity	8
Magnet Material	Neodymium Magnet

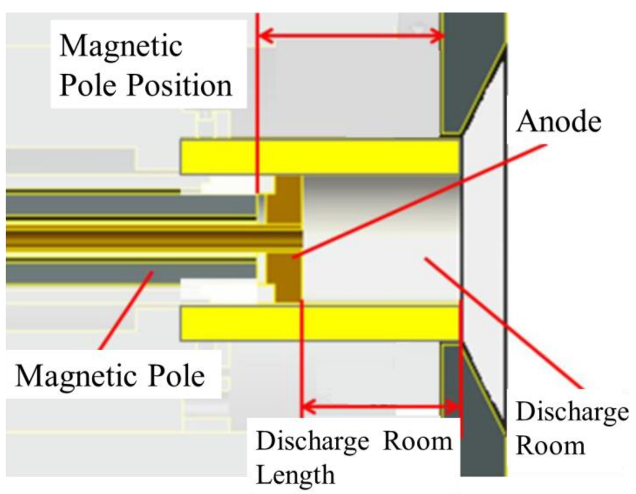


Figure 4. Details of variable mechanism.

B. Vacuum facility

Figure 5 shows the vacuum chamber and pumping system.[4)] 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. Table 2 shows the details of Vacuum facility.

Figure 6 shows schematic of experimental system, and Figure 7 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.[5)]

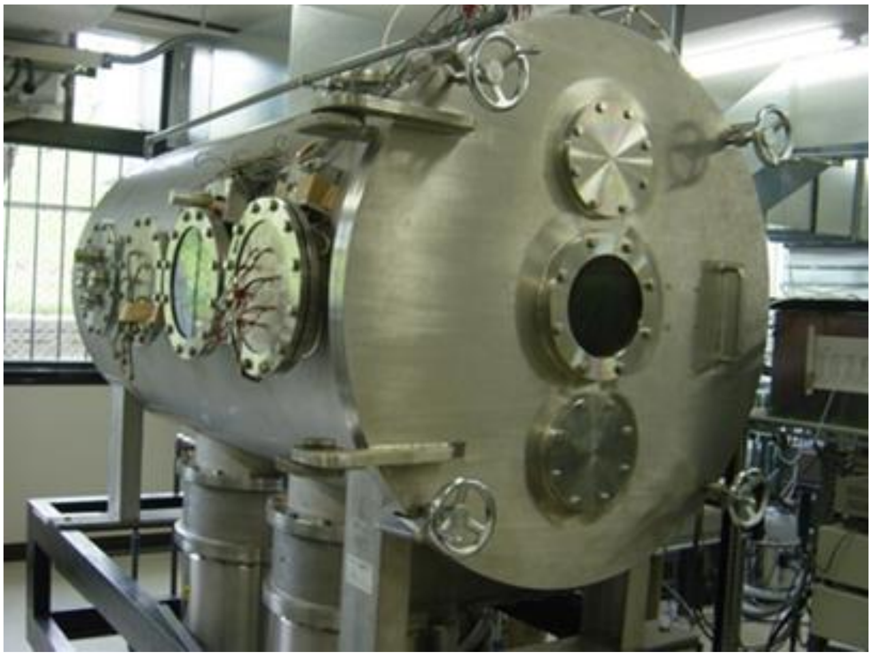


Figure 5. Vacuum chamber and pumping system.

Table 2. The details of Vacuum facility.

Chamber	
Length [mm]	2250
Diameter [mm]	1200
Pump	
Exhaust Velocity [L/s]	10000
Back Pressure [Pa]	3.3×10^{-3}

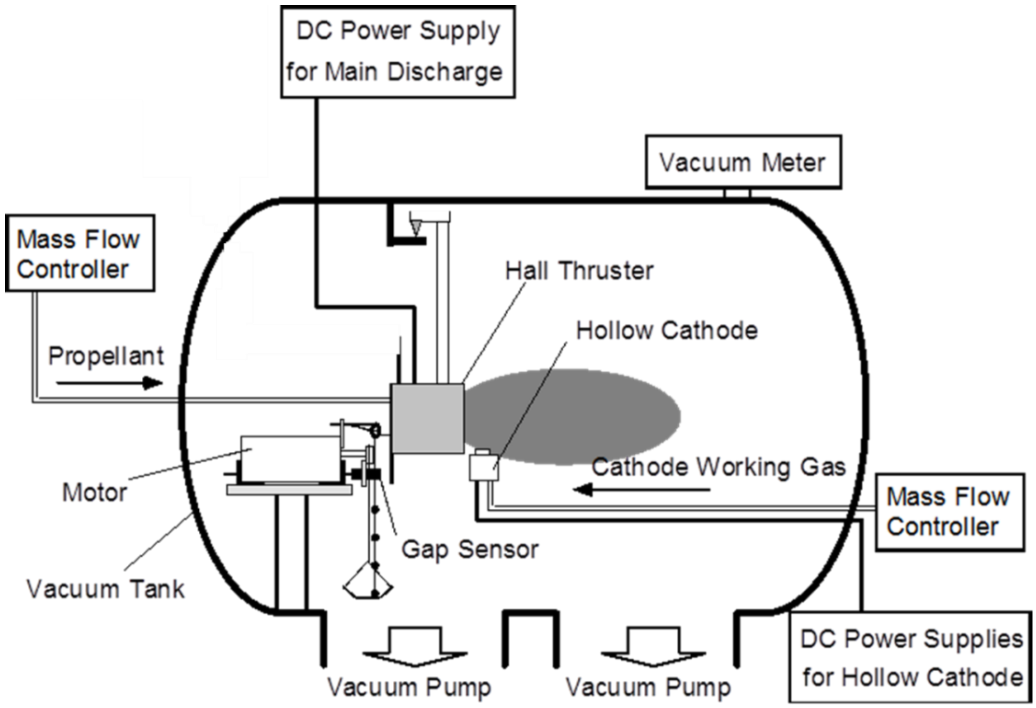


Figure 6. Schematic of experimental system.

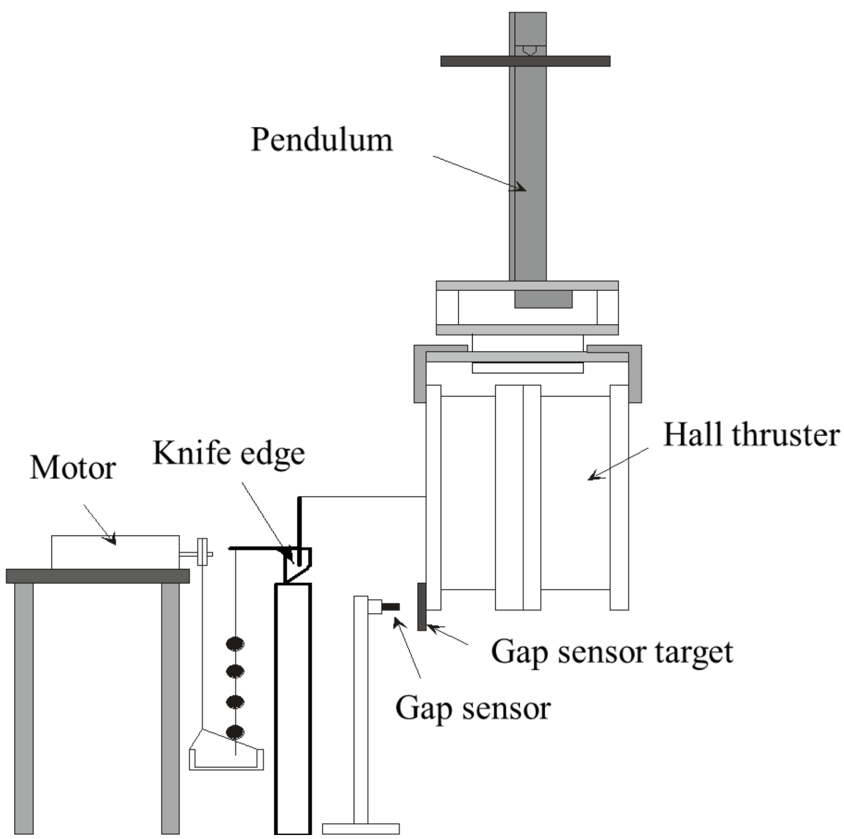


Figure 7. Thrust measurement system.

C. Hollow cathode

A hollow cathode (HCN-252 manufactured by Veeco-Ion-Tech) was used as a cathode for obtaining propulsive performance.[6] Figures 8 and 9 show the photograph and schematic of the hollow cathode. Figure 10 shows the internal structure of the hollow cathode.

Figure 8. Photo of the hollow cathode.

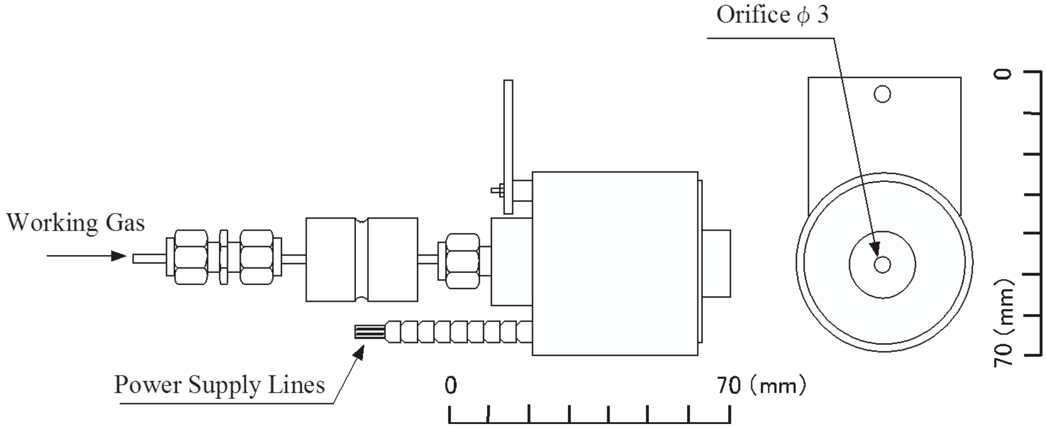


Figure 9. Schematic of the hollow cathode.

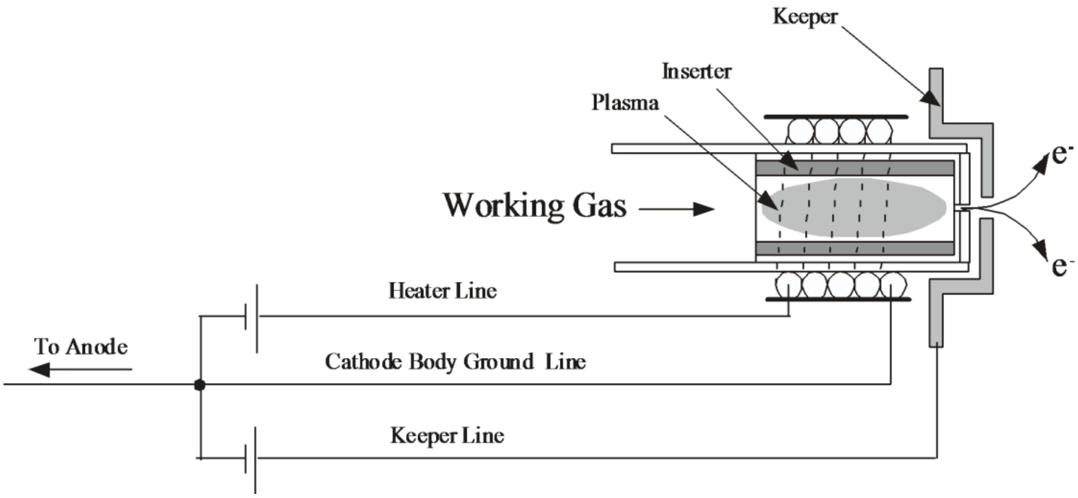


Figure 10. Internal structure of the hollow cathode.

D. TaC-PI

Figure 11 shows the overview of the TaC-PI(CHT Thruster (magnetic field expansion plasma source) and Cathode with Piezoelectric igniter). TaC-PI is the TCHT-5 attached to a device to Figure 12. TaC-PI ionizes xenon gas flowing in from the thruster with a piezoelectric igniter[7)] and supplies electrons by releasing electrons with keeper. TAC-PI is planned not only to act as a cathode but also as a thruster by arranging the same type device one more time.

Figure 11. Overview of the TaC-PI.

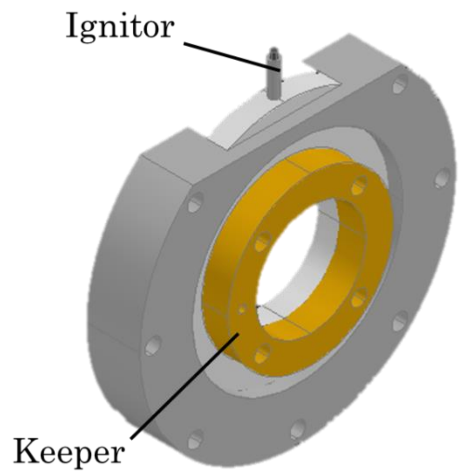


Figure 12. The device of TaC-PI.

III.Experimental Condition of the propulsive performance

A. Experimental Condition 1

Table 3 shows the experimental condition 1 of TCHT-5. The experiment 1 was compared the performance when the magnetic pole positions were changed 19 mm and 22 mm. Also, the discharge room length was12 mm. Discharge voltage was changed every 50 V in 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 operating at the discharge voltage above 950 V with the magnetic pole position 22 mm, the discharge room length 12 mm, and the mass flow rate of 0.35 mg/s. Similarly, the TCHT-5 was not operating at the discharge voltage above 850 V with the mass flow rate of 0.4 mg/s.

Table 3. Experimental condition 1

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 Condition 2

Table 4 shows the experimental condition 2 of the TCHT-5. In the experiment B, the performance was compared when the discharge room length was changed to12 mm and 15 mm at a magnetic pole position of 22 mm. As with the experimental condition 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 4. Experimental condition 2

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	

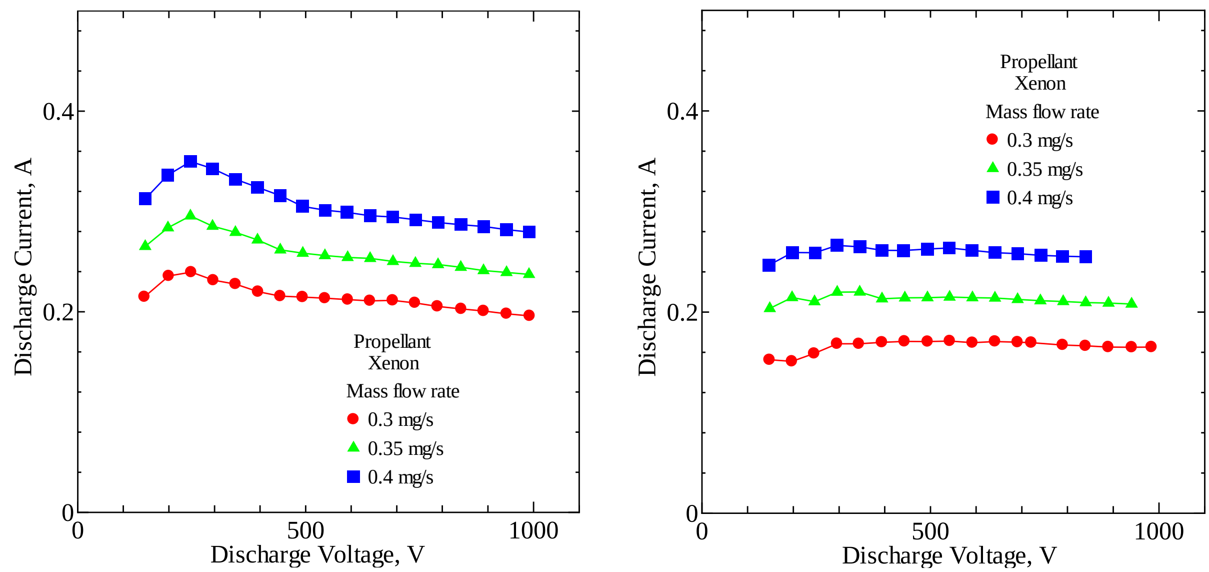
IV.Experimental Results of the propulsive performance

Figure 13 shows a typical stable operation of the TCHT-5.

Figure 13. Operation of the TCHT-5.

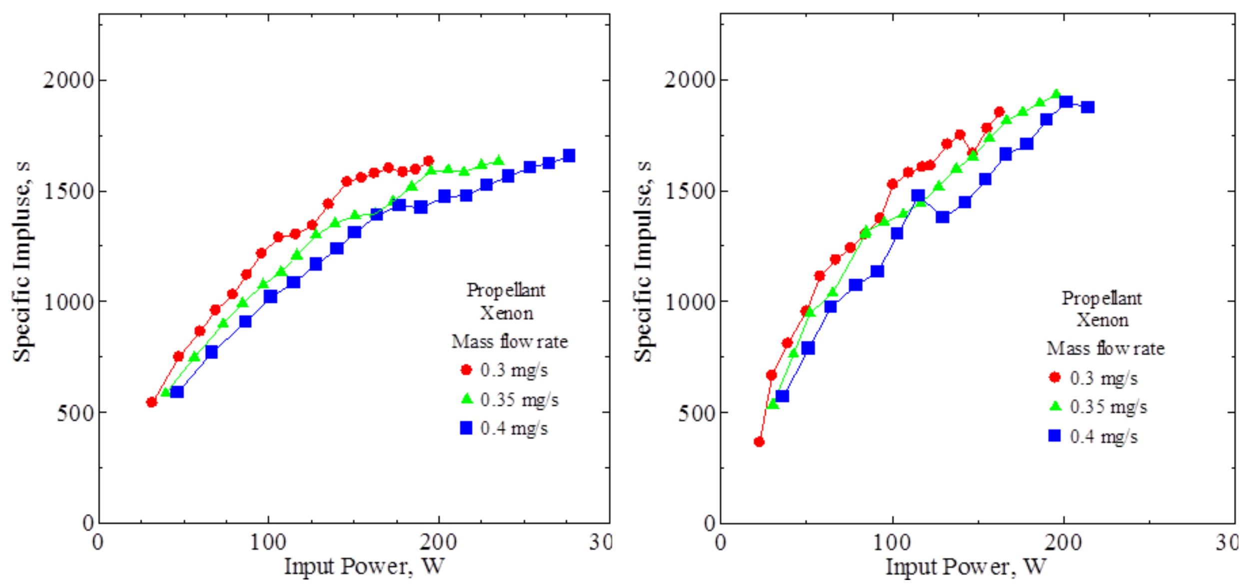
A. Experimental result 1

Figure 14 shows the discharge current as a function of discharge voltage at the cases of the magnetic pole positions 19 mm and 22 mm. The discharge current in the magnetic pole position 19 mm was decreased at a discharge voltage of 350 V. In contrast, the discharge current in the magnetic pole position 22 mm became constant at the discharge voltage of 350 V. Figures 15 and 16 show specific impulse and thrust efficiency as a function of input power at the cases of the magnetic pole positions 19 and 22 mm. The TCHT-5 achieved the specific impulse of 1300 s and the thrust efficiency of 21% with the magnetic pole position 19 mm at a mass flow rate of 0.3mg/s and an input power 115 W. With the magnetic pole position 22 mm the specific impulse and the thrust efficiency reached 1300 s and 30%, respectively, with an input power of 84 W. As a result, the performance with the magnetic pole position 22 mm was higher than that with 19 mm.



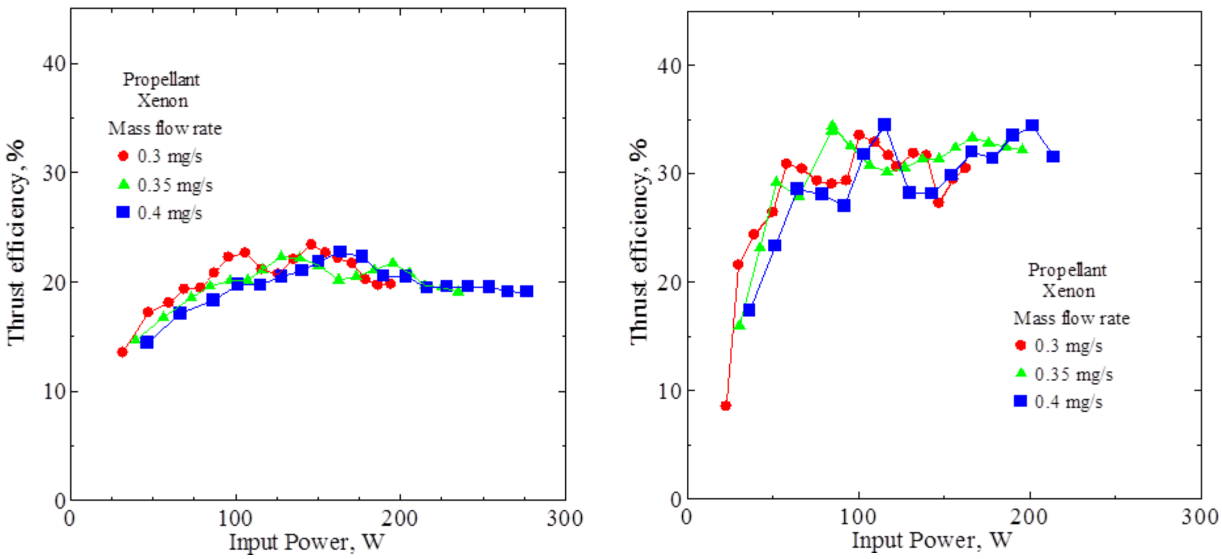
(a) Magnetic Pole Position 19 mm. **(b) Magnetic Pole Position 22 mm.**

Figure 14. Discharge current (A) - Discharge voltage (V).



(a) Magnetic Pole Position 19 mm. **(b) Magnetic Pole Position 22 mm.**

Figure 15. Specific impulse (s) - Input power (W).

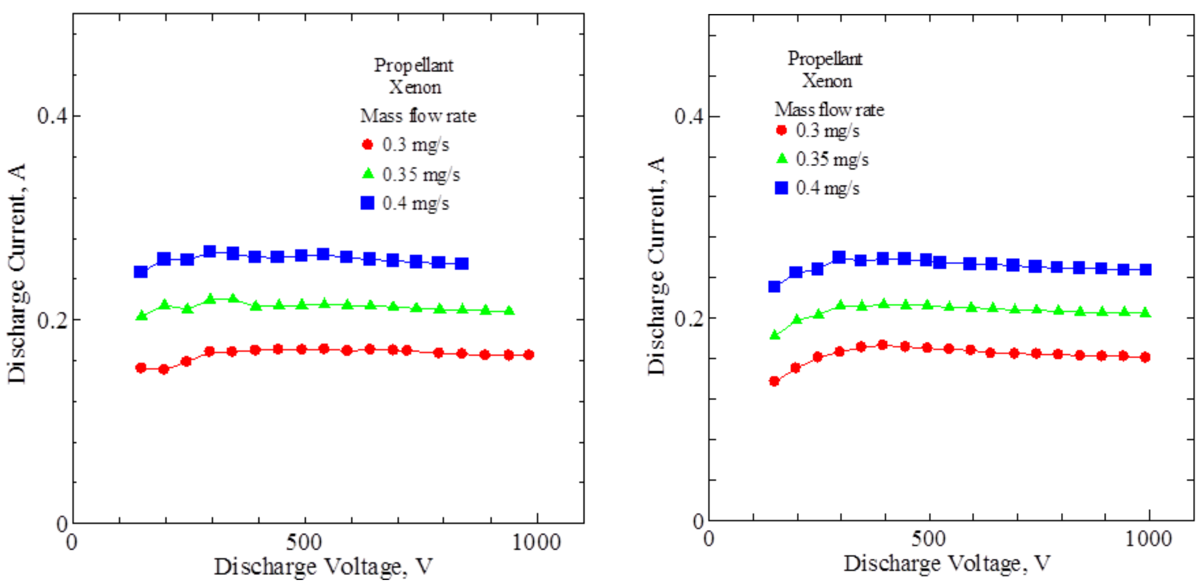


(a) Magnetic Pole Position 19 mm. **(b) Magnetic Pole Position 22 mm.**

Figure 16. Thruster efficiency (%) - Input power (W).

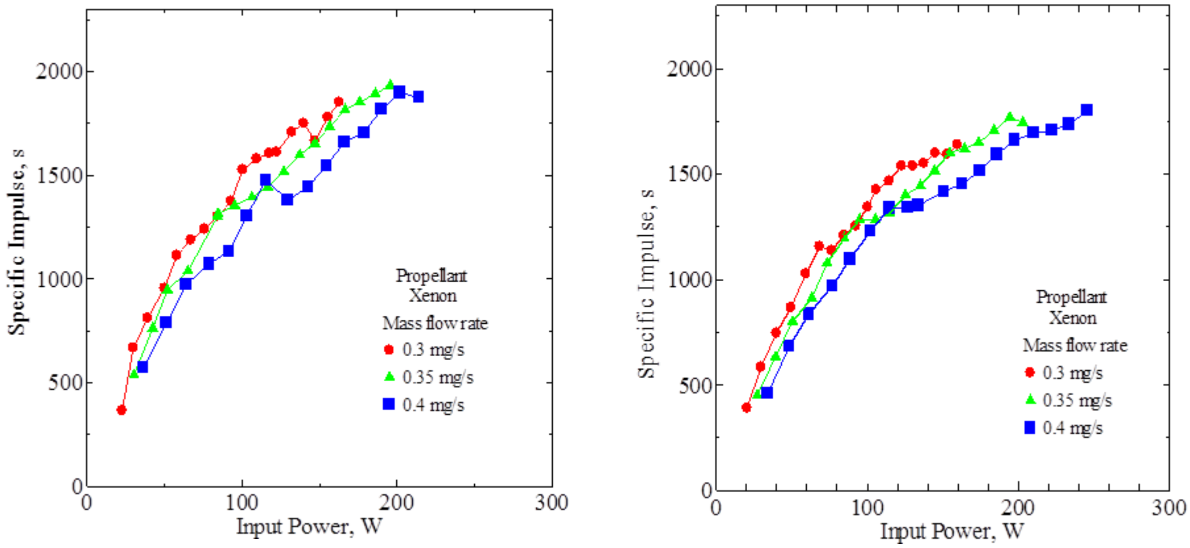
B. Experimental result 2

Figure 17 show the discharge current as a function of discharge voltage at the cases of the discharge room length 12 mm and 15 mm. The discharge current resulted in value close to both discharge room length. Figures 18 and 19 show specific impulse and thrust efficiency as a function of input power at the cases of the discharge room length 12 and 15 mm. TCHT-5 achieved the specific impulse of 1344 s and the thrust efficiency of 26% with the discharge room length15 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 the discharge room length15 mm. Accordingly, the performance with the discharge room length 15mm was lower than that with 12 mm.



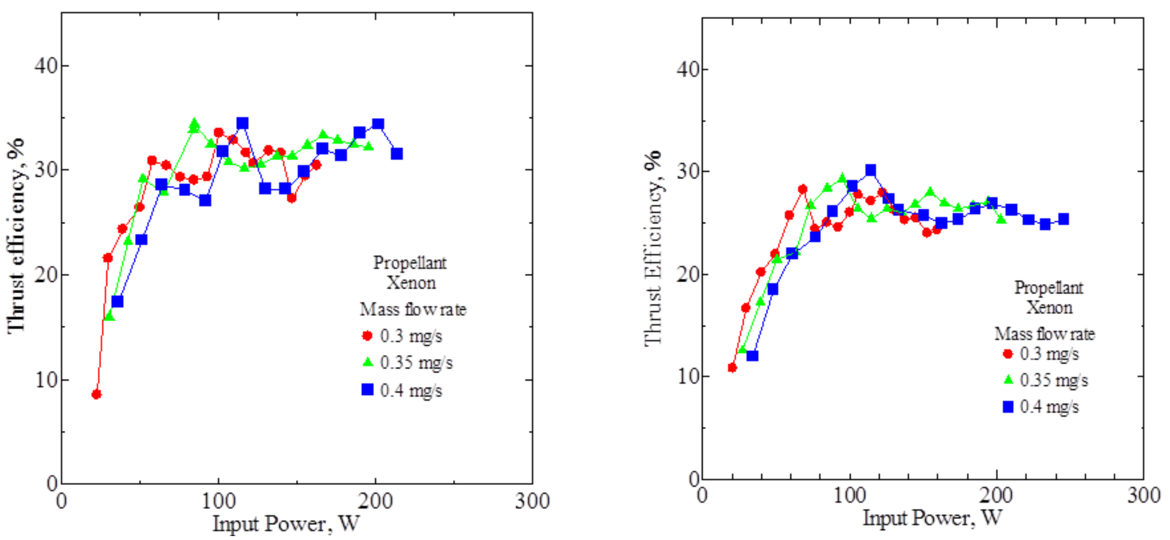
(a) Discharge room length 12 mm. **(b) Discharge room length Xd = 15 mm.**

Figure 17. Discharge current (A) - Discharge voltage (V).



(a) Discharge room length 12 mm. **(b) Discharge room length Xd = 15 mm.**

Figure 18.Specific impulse (s) - Input power (W).



(a) Discharge room length 12 mm. **(b) Discharge room length Xd = 15 mm.**

Figure 19.Thruster efficiency (%) - Input power (W).

V.Igniter-type electron source "TaC-PI"

The hollow cathode HCN-252 is unsuitable for micro satellite. For this reason HCN-252 requires power of 90 W or more.[8)] And to operate the hollow cathode, heating with a heater for more than 16 minutes is required. At the satellite's orbit altitude 400 km point, it can be seen from Figure 20 the sunlight time that electric power can be supplied is about 56 minutes. Therefore, the thruster operation time in the low Earth orbit is less than 40 minutes. In this research, a new type of electron sources by a piezoelectric igniter[9)] was devised and examined which can generate electrons by instantaneous discharge and operate thrusters. A New type of electron sources is named TaC-PI (CHT Thruster (magnetic field expansion plasma source) and Cathode with Piezoelectric Igniter). TaC-PI is planned not only to act as a cathode but also as a thruster by arranging the same type device one more time. TaC-PI ionizes xenon gas flowing in from the thruster with a piezoelectric igniter and supplies electrons by releasing electrons with keeper.

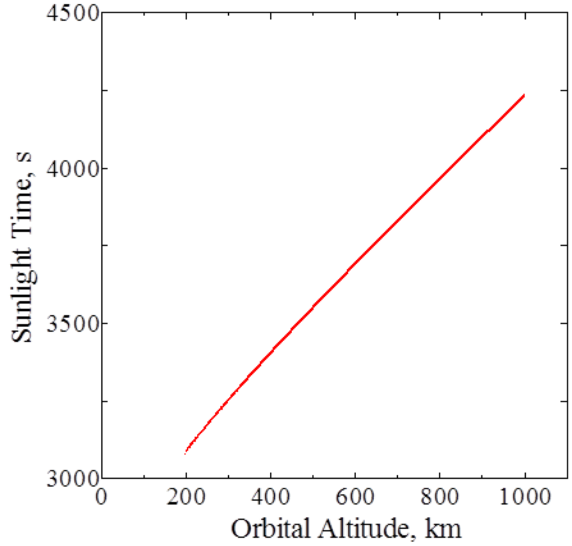


Figure 20. Sunlight time (s) - Orbital altitude (km).

A. The operation experiment

By using the TaC-PI introduced in the previous section, the SPT type hall thruster "THT-VI"[10] and the Cylindrical type Hall thruster "SCHT-1" were tried to operate. These thrusters were adopted for operation experiment because they can operate stably. Figure 21 shows Schematic diagram of operation experiment with TaC-PI. Figure 22 and 23 show the overview of the THT-VI and the SCHT-1.

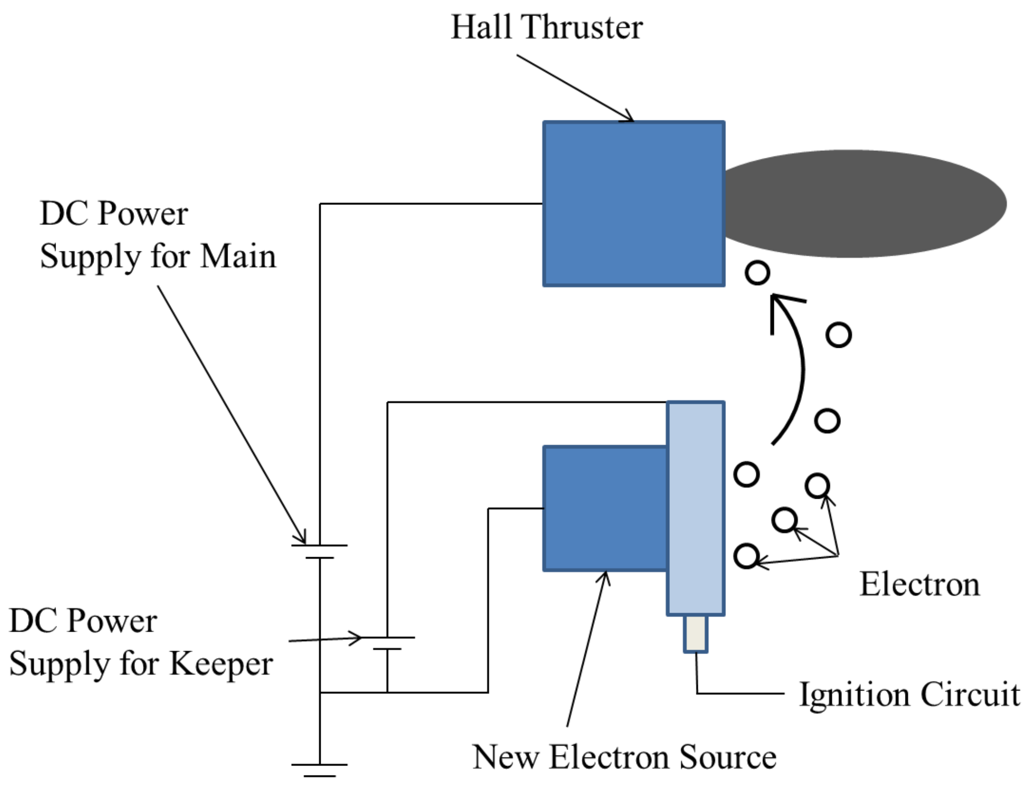


Figure 21. Schematic diagram of operation experiment with TaC-PI.

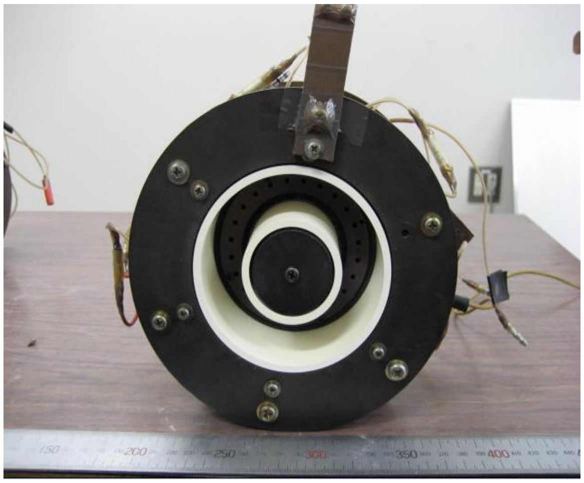


Figure 22. Overview of the THT-VI.

Figure 23. Overview of the SCHT-1

B. Conditions and results of THT-VI

As a result, steady operation could not be confirmed when THT-VI flow rate was 1.0 - 3.0 mg/s. On the other hand, when the flow rate was 4.0 mg/s, the injection could be confirmed, although it was about 10 seconds (Figure 24). Figures 25 and 26 show graphs of voltage and current obtained at this time. The part surrounded by circle is in operation. As can be seen from Figure 21, the discharge current at this time was 10 A. 10 A is the upper limit of the DC power supply device. In addition, the discharge voltage was stepped down to 80 V or 120 V instead of 400 V applied. This is because the circuit was short-circuited, and the discharge current tried to flow more than 10 A, it is considered that the DC power supply device was limited and the voltage was also stepped down. Table 5 shows experimental conditions of THT-VI.

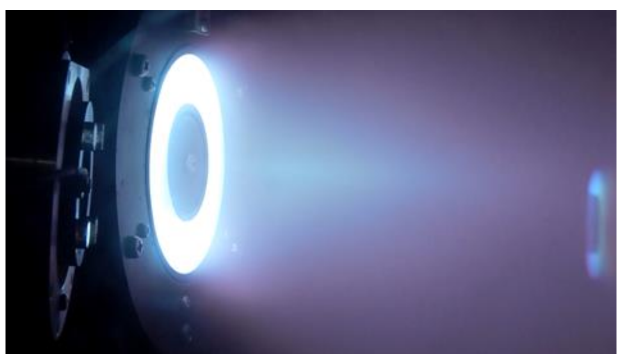


Figure 24. Operating state of THT-VI with TaC-PI.

Table 5. Experimental conditions of THT-VI.

THT-VI	
Discharge voltage	400 V
Mass flow rate	4.0 mg/s
Propellant	Xenon
TaC-PI	
Keeper voltage	200 V
Mass flow rate	0.5 mg/s
Propellant	Xenon

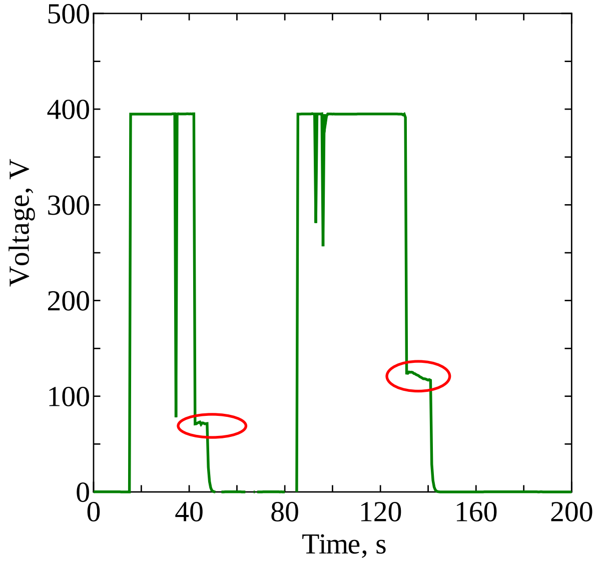


Figure 25. Voltage(V) - time(s) at condition of THT-VI.

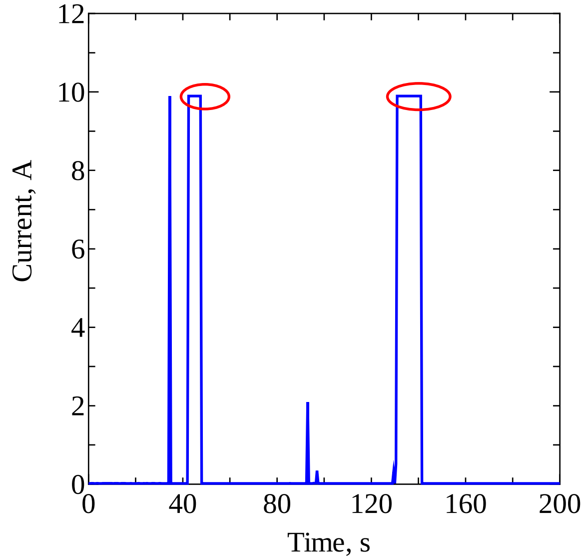


Figure 26. Current(A) - time(s) at condition of THT-VI.

C. Conditions and results of SCHT-1

As a result, steady operation could not be confirmed when SCHT-1 input voltage was 200 - 650 V and mass flow rate was 0.3 - 0.45 mg/s. On the other hand, when the discharge voltage was 700 V and the flow rate was 4.0 mg/s, the injection could be confirmed although it was about 30 seconds (Figure 27). Figures 28 and 29 show graphs of voltage and current obtained at this time. The part surrounded by the red circle is in operation. As can be seen from Figure 23, the discharge current at this time was 0.3 A. This is because the circuit was not short-circuited.

Furthermore, 0.3 A is a reasonable value commensurate with the experimental conditions at this time. Table 6 shows experimental conditions of SCHT-1. In this experiment the keeper used in the previous section was not used. Back pressure during the experiment was 2.7 × 10-2 Pa.

Figure 27. Operating state of SCHT-1 with TaC-PI.

Table 6. Experimental conditions of SCHT-1.

SCHT-1	
Discharge voltage	700 V
Mass flow rate	0.5 mg/s
Propellant	Xenon
TaC-PI	
Keeper	Not use
Mass flow rate	0.5 mg/s
Propellant	Xenon

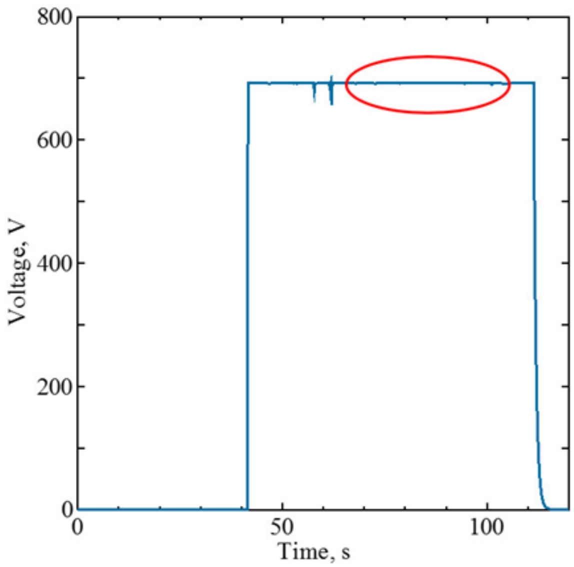


Figure 28. Voltage(V) - time(s) at conditions of SCHT-1.

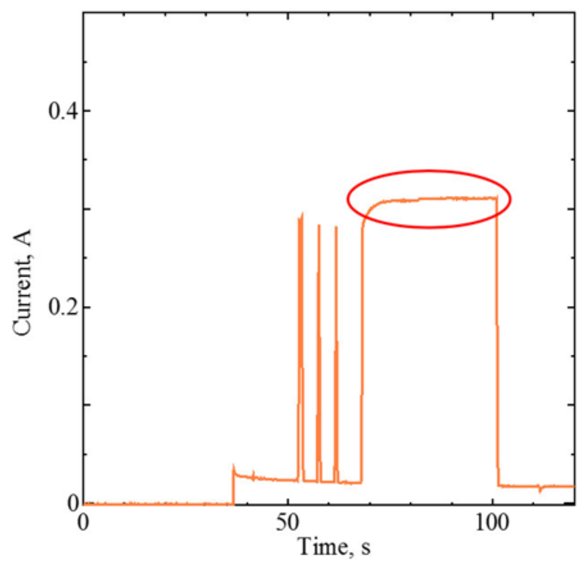


Figure 29. Current(A) - time(s) at conditions of SCHT-1.

VI.Conclusion

A. Propulsive performance

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 (the specific impulse over 1300 s with the input power of 50 W.), although the input power was over 50 W.

The TCHT-5 thruster achieved the highest performance in experimental conditions with the magnetic pole position 22 mm and the discharge channel length 12 mm. The performance is the thrust of 3.8 mN, the specific impulse of 1300 s and the thrust efficiency of 30% with an input power of 84 W and a mass flow rate of 0.3 mg/s.

B. Cathode development

TaC-PI was used as an electron source instead of a hollow cathode and succeeded in operating SPT type and CHT type Hall thrusters. However, with only the instantaneous discharge by the igniter, generation of plasma was not sustained, and it was impossible to completely supply electrons stably.

In the future ignition discharge is performed in the discharge room on the TaC-PI side. Furthermore, change the mirror magnetic field of Tac-PAC to the cusp magnetic field. Expecting confinement of plasma by setting the cusp magnetic field, aim for stable supply of electrons.

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