Research and Development of Very Low Power Cylindrical Hall Thrusters for Nano-Satellites

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Abstract: Development of Hall thrusters for nano, small and low-power satellites below 100W is expected. In lowering Hall thruster power, the cylindrical-type Hall thruster is more advantage than conventional coaxial-type Hall thrusters. In this study, a very low power cylindrical Hall thruster was designed, and the thruster performance was measured. As a result, a stable operation was achieved even with 10W. The specific impulse and the thrust efficiency are 1570sec and 18.1%, respectively, with 66W. Also, the discharge current oscillation was lower compared SPT-type Hall thruster.

I. Introduction

THE Hall thruster is a promising propulsion device for small/nano satellites because of its high efficiency and thrust density. However, reducing Hall thruster dimension and input power results in significant decline of thrust performance. Accordingly, special design is required for low power Hall thruster. Raitses,Y proposed a cylindrical Hall thruster that has circular cross-sectional ceramic discharge chamber.[1] Because of large volume-to-surface ratio of the thruster, it suppresses an increase in ion flux to the wall accompanied by downsizing Hall thruster, and it prevents from overheating and erosion of thruster parts. Therefore, it will be preferable configuration as low power Hall thrusters. Smirnov designed and investigated miniature cylindrical Hall thruster, and their thruster achieved thrust efficiency of 15-32% in the power range of 50-300W.[2-3] Detailed effects of magnetic field configuration in cylindrical Hall thrusters are unknown, although it is much important to improve thrust performance. Hence, we investigated the effects with the cylindrical Hall thrusters named TCHT series in Osaka Institute of Technology. The discharge chamber consists of only a circular cross-sectional part with no coaxial parts. Although cylindrical Hall thrusters made by Raitses and Smirnov have short coaxial part, the coaxial part was excluded from TCHT-series. By applying strong radial magnetic field at the downstream region, Hall thruster TCHT-3B achieved higher thrust performance than TCHT-3A did at low power level because of a decrease in wall

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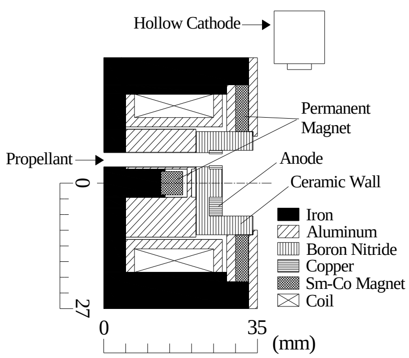
losses.[4-9] However, when the position applied strong magnetic field was far downstream, the thrust efficiency was declined because of a decrease in ionization utilization. The result indicates that the thrust efficiency is optimized by adjusting the region applied large magnetic field. The optimized TCHT-3B had a high efficiency of 18-39% in the power range of 35-140W.

In this study, we developed a lower-power and smaller-size cylindrical Hall thruster named TCHT-4 for small/nano satellites around 50W power. The performance characteristics are measured..

II. Experimental Apparatus

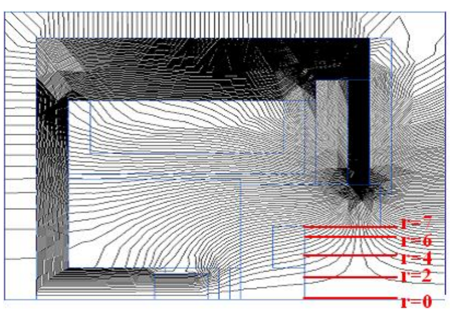
The Figure 1 shows the cross-sectional view of a very low power Hall thruster named TCHT-4. The anode located at the upstream end of the circular cross-sectional part is made of copper. As shown in Table 1, the length and radius of the discharge chamber are 7mm and 7mm, respectively. The wall materials of the discharge chamber are Boron Nitride (BN). The thruster has a permanent magnet on the central axis and a ring-like permanent magnet which is located at the downstream end of iron cylinder. Sm-Co permanent magnets were employed because the degradation of magnetic property by heating is relatively small. TCHT-4 also has a solenoidal coil on the inner surface of the outer cylinder. Figure 2 shows the calculated magnetic field shape and strength for TCHT-4.



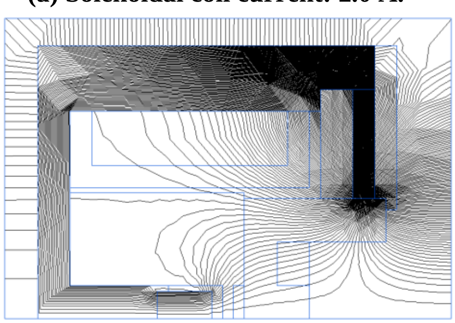
(a) Cross-sectional view.

(b) Photo.

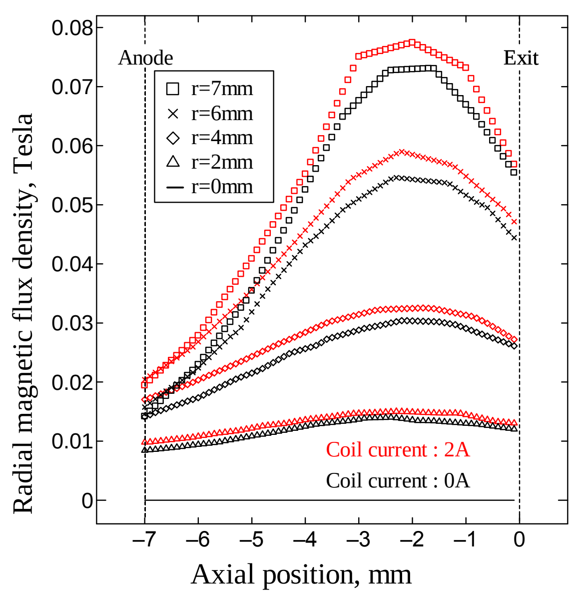
Figure 1. Configuration of very low power cylindrical Hall Thruster TCHT-4.



(a) Solenoidal coil current: 2.0 A.



(b) Solenoidal coil current: 0 A.



(c) Strengths of radial magnetic field.

Figure 2. Shape and strength of magnetic field for TCHT-4 Hall thruster.

The magnetic field has an axial component, and the strength is the highest near the anode located at the upstream region. The maximum magnetic flux density is 770Gauss (0.077Tesla). The hollow cathode (Iontech HCN-252) is employed as the electron emission source. Propellant gas is injected into the discharge chamber through four lines behind the anode. Xenon is used as the propellant and the working gas of the cathode. The experimental facility is shown in Figure 3.The thruster 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 that have a pumping speed of 10000 l/s on xenon, several DC power supplies, and a thrust measurement system. The vacuum chamber pressure is kept about 3.0 x 10^{-2} Pa under operation. A clean and high vacuum environment can be created by using the oil-free turbo molecular pump system. Thrusts are measured by a pendulum method. The thruster is mounted on a thrust stand suspended with an aluminum bar, and the position of thruster is detected by an eddy-current-type gap sensor (non-contacting micro-displacement meter). As shown in Figure4, it has a high sensitivity and good linearity. Thrust calibration is conducted with a weight and knife-edge arrangement which can apply a known force to the thruster under vacuum condition. Discharge current oscillation is also measured with a current probe (Iwatsu SS-250).

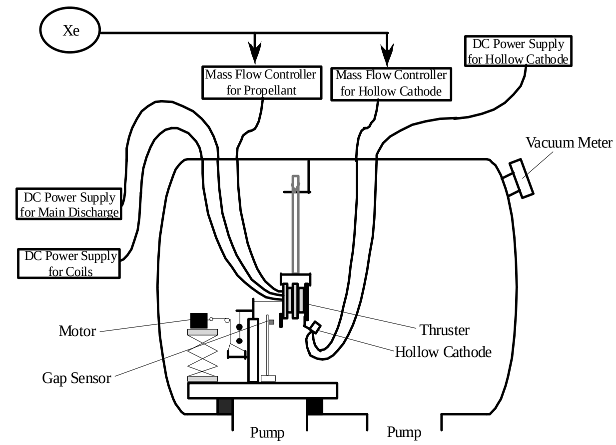


Figure 3. Experimental system for Hall Thruster.

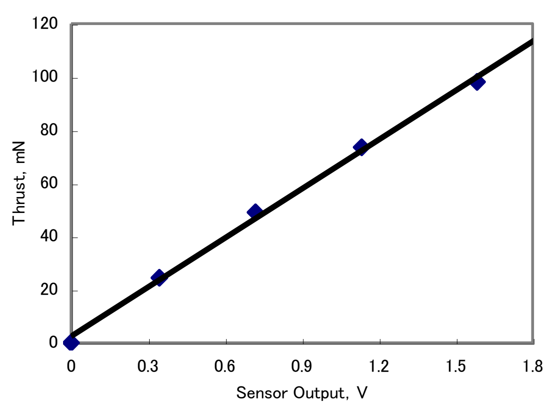


Figure 4. Typical thrust calibration line.

Table 1. Specifications of TCHT-4.

Anode	
Material	copper
Discharge channel	
Length	7mm
Diameter	14mm
Material	Boron Nitride（BN）
Cathode	
Hollow Cathode Neutralizer Iontech HCN-252	
Magnet	
Sm-Co Magnet Nirokuseisakusho YK-20	
Coil	
Material	copper φ0.5mm
Number of turns	250

III. Experimental Results and Discussion

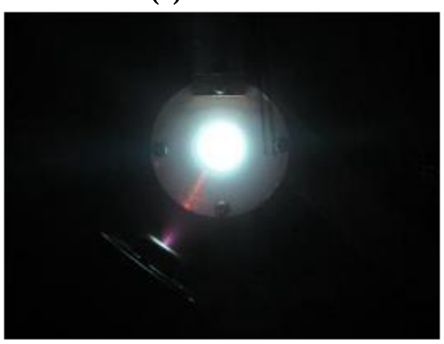
Figure 5 shows typical photographs of plasma plume for TCHT-4. The stable and azimuthally-uniform plume is slightly expanded radially compared with that with conventional SPT-type Hall thrusters. This is expected because there exists an axial component of magnetic field as shown in Figure 2.

Figure 6 shows the discharge current vs discharge voltage characteristics at xenon mass flow rates of 0.1, 0.2 and 0.3 g/s with and without a solenoidal coil current of 2.0 A. The discharge currents increase with increasing discharge voltage with all operational conditions. At a constant discharge voltage, an increase in mass flow rate increases discharge current. The discharge current without the solenoidal coil is lower than that with the solenoidal coil. This is expected because the magnetic field with both the solenoidal coil and the magnet is not optimized with this thruster.

As shown in Figure 7, both the thrust and the specific impulse almost linearly increase with the discharge voltage with all operational conditions. At a mass flow rate of 0.2 mg/s, the thrust and the specific impulse without the solinoidal coil are almost equal to those with the solenoidal coil. The thrust ranges from 0.3 to 3.5 mN and the specific impulse from 400 to 1400 s.

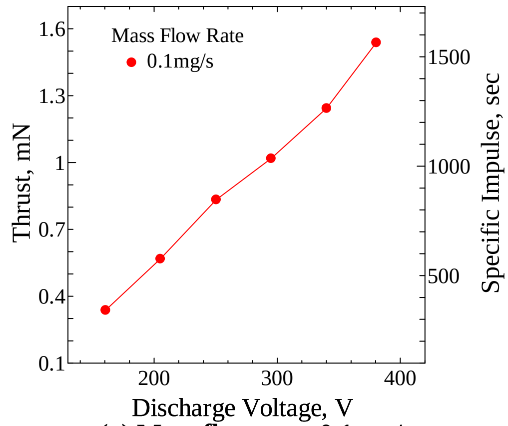
Figure 8 shows the thrust efficiency vs discharge voltage characteristics. The thrust efficiency slightly increases or is constant with increasing discharge voltage. It is around 10 %, and the maximum is about 18 % with a discharge voltage of 400 V.

(a) Side view

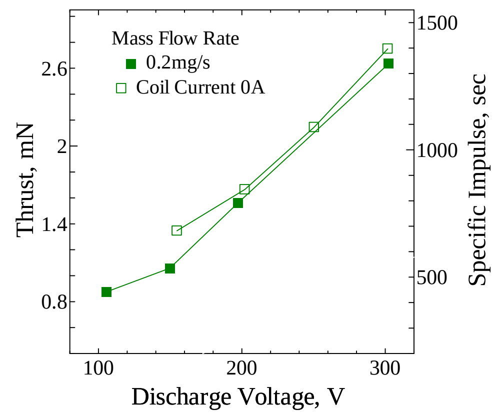


(b) Front view.

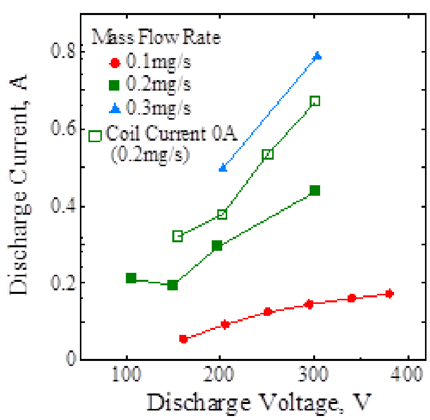
Figure 5. Typical photo of plasma plume for TCHT-4.

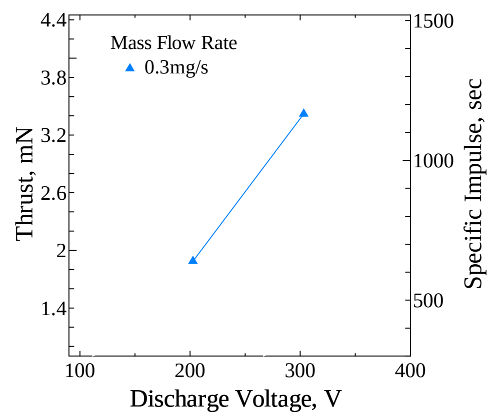


(a) Mass flow rate: 0.1 mg/s.



(b) Mass flow rate: 0.2 mg/s.





(c) Mass flow rate: 0.3 mg/s.

Figure 6. Discharge current vs discharge voltage.

Figure 7. Thrust and specific impulse vs dischage voltage.

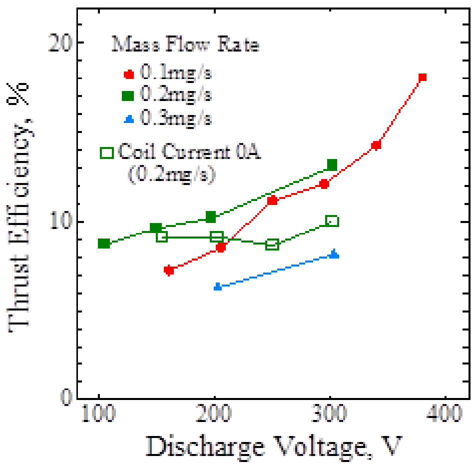


Figure 8. Thrust efficiency vs discharge voltage.

Figures 9 and 10 shows the characteristics of the specific impulse and the thrust efficiency, respectively, as a function of input power. Both the specific impulse and the thrust efficiency almost linearly increase with the input power. They ranges from 350 s and 7 % at 10 W to 1600 s and 18.1 % at 66 W with 0.1 mg/s; from 450 s and 9 % at 20 W to 1350 s and 13 % at 130 W with 0.2 mg/s and from 600 s and 6 % at 100 W to 1200 s and 8 % at 240 W with 0.3 mg/s. The thruster operated stably even with very low powers.

Figures 11-13 show characteristics of discharge current oscillation with a mass flow rate of 0.2mg/s. Current oscillation becomes larger with increasing discharge voltage although the amplitude is low compared with SPT-type Hall thruster. Peaks in the power spectra are observed around about 10kHz with 100V and around 32 and 67kHz with 250V. As shown in Figure 13, the dominant frequency increases with the discharge voltage.

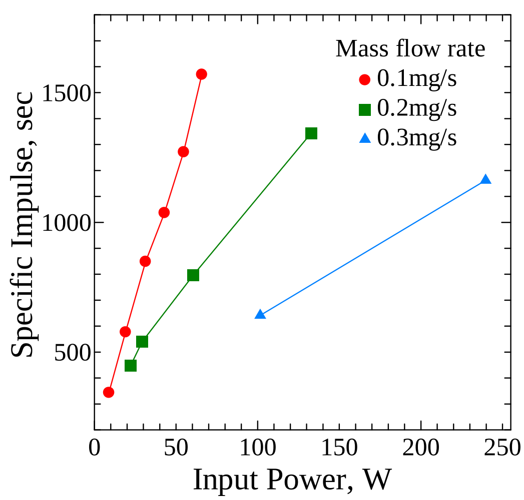


Figure 9. Specific impulse vs input power.

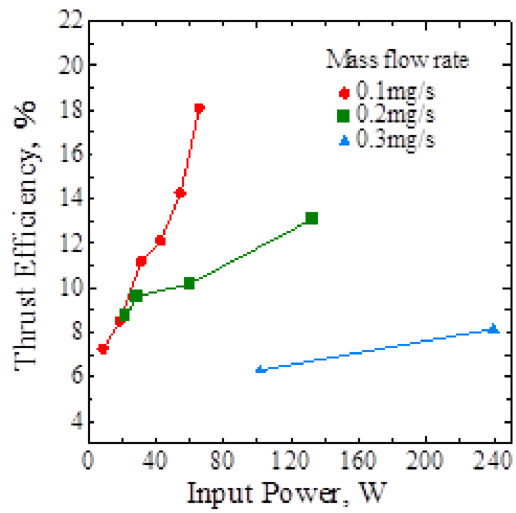
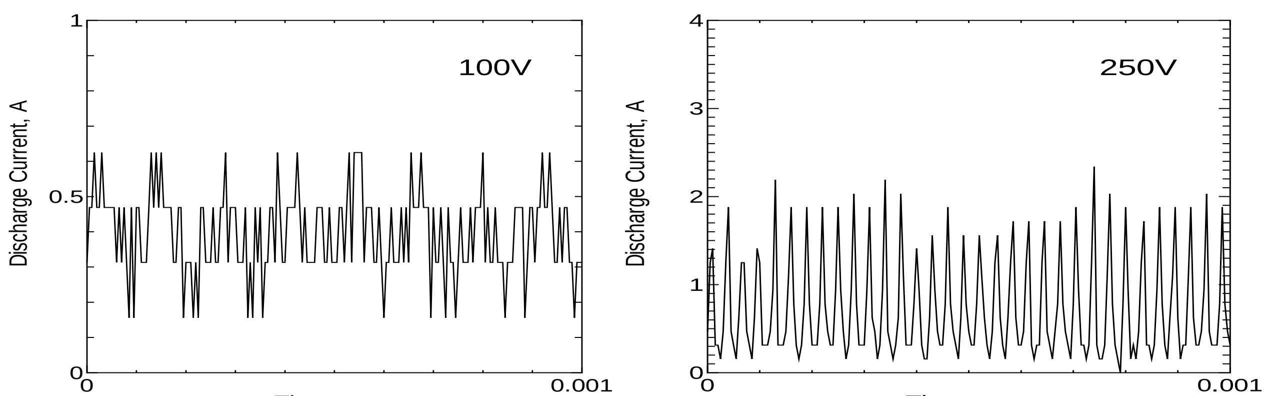
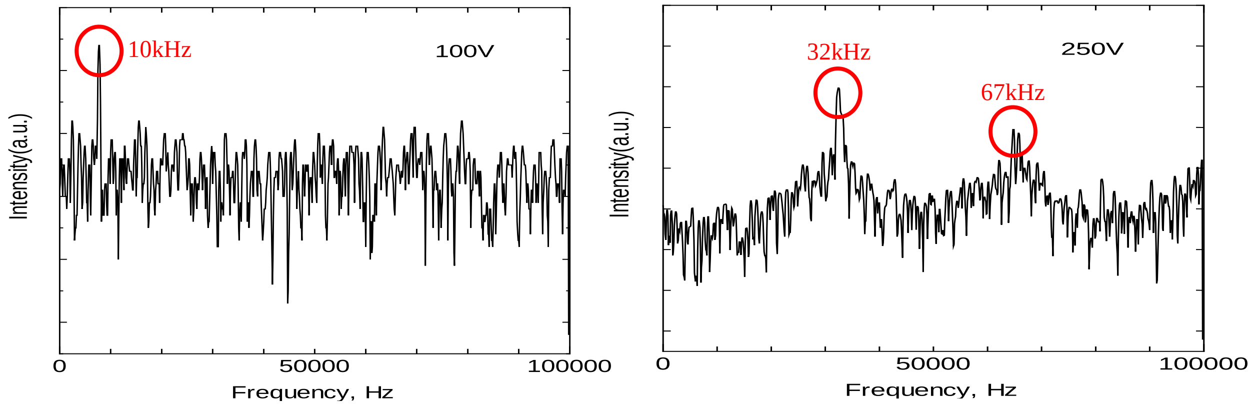


Figure 10. Thrust efficiency vs input power.



(a) 100V. **(b) 250V.**

Figure 11. Oscillations of discharge current.



(a) 100V. **(b) 250V.**

Figure 12. FFT analysis of discharge current oscillation.

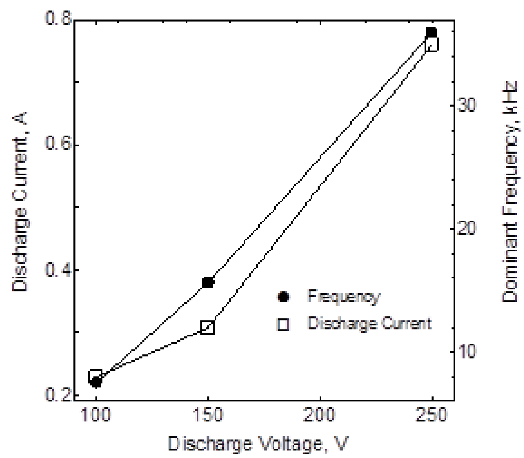


Figure 13. Discharge voltage dependence of discharge oscillation.

IV. Introduction of "PROITERES" series satellites

Currently, Osaka Institute of Technology is being developed nano-satellite "PROITERES 1" (The Project of Osaka Institute of Technology Electric-Rocket-Engine onboard Small Space Ship) with electrothermal pulsed plasma thrusters (PPTs) and high resolution camera. The missions of this satellite are powered flight of nano-satellite by PPTs in orbital and observation of Kansai district in Japan with a high-resolution camera. PROITERES will be launched from Satish Dhawan Space Centre (India) to the sun-synchronous orbit of 670 km in the end of 2012. Figure 14 shows an illustration of PROITERES 1.

Additionally, we have started to develop the "PROITERES 2" and "PROITERES 3" satellites since Oct. 2010. The PROITERES 2, as illustrated in Figure 15, is a 50-kg earth-observation satellite with high-power and large-total-impulse pulsed plasma thruster system for practical use. The PPT system with 10-15 kg is provided with four thruster heads with Teflon feeding mechanisms, and the total impulse per one thruster head is 2500 Ns at an input power of 25 W. As a result, we can change totally the altitude of the satellite up to 400 km, and on the lower orbit of 200 km we can keep the altitude up to one month.

The PROITERES 3 is a 50-kg moon-exploration satellite with cylindrical-type Hall thruster system for powered flight from the low earth orbit to the moon orbit. The Hall thruster system will produce specific impulses of 1500-2000 sec at xenon mass flow rates of 0.1-0.3 mg/s with an input power of 30 W. The trip time to the moon is within 3 years.

The 2nd and 3rd PROITERES satellites are under development.

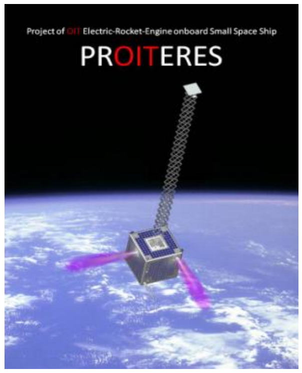


Figure 14. PROITERES 1 in orbit (image).

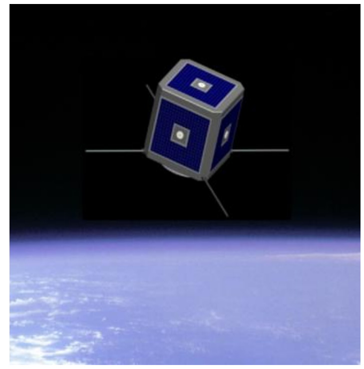


Figure 15. PROITERES 2 in orbit (image).

V. Conclusion

The laboratory-model very low-power cylindrical Hall thruster TCHT-4 was developed, and the thruster performance was measured. Both the thrust and the specific impulse almost linearly increased with the discharge voltage with all operational conditions. The thrust, the specific impulse and the thrust efficiency almost linearly increased with the the discharge voltage and input power. The thrust ranged from 0.3 to 3.5 mN and the specific impulse from 400 to 1400 s. The thrust efficiency ranged from 7 % at 350 s and 10 W to 18.1 % at 1600 s and 66 W with 0.1 mg/s; from 9 % at 450 s and 20 W to 13 % at 1350 s and 130 W with 0.2 mg/s and from 6 % at 600 s and 100 W to 8 % at 1200 s and 240 W with 0.3 mg/s. The thruster operated stably even with very low powers. Current oscillation became larger with increasing discharge voltage although the amplitude was low compared with SPT-type Hall thruster. Peaks in the power spectra were observed around about 10kHz with 100V and around 32 and 67kHz with 250V, and the dominant frequency increased with the discharge voltage.

The Project of Osaka Institute of Technology Electric-Rocket-Engine onboard Small Space Ship (PROITERES) was started at Osaka Institute of Technology in 2007. In PROITERES 1, a nano satellite with electrothermal PPTs will be launched in 2012. The main mission is to achieve powered flight of nano-satellite by an electric thruster and to observe Kansai district in Japan with a high-resolution camera.

In addition, we started the research and development of the “PROITERES 2” and “PROITERES 3” satellites in Oct. 2010. The 2nd satellite of PROITERES series, it is a 50-kg earth-observation satellite with high-power and large-total-impulse PPT system for practical use. The 3rd satellite of PROITERES series is a 50-kg moon-exploration satellite with cylindrical-type Hall thruster system for powered flight from the low earth orbit to the moon orbit. The Hall thruster system will produce specific impulses of 1500-2000 sec at xenon mass flow rates of 0.1-0.3 mg/s with an input power of 30 W. The 2nd and 3rd PROITERES satellites are under development.

References

[1]Raitses, Y., and Fisch, N. J., “Parametric Investigations of a Nonconventional Hall Thruster,” Physics of Plasmas, Vol.8, 2001, pp.2579-2586.

[2]Smirnov, A., Raitses, Y., and Fisch, N. J., “Parametric Investigation of Miniaturized Cylindrical and Annular Hall Thrusters,” Journal of Applied Physics, Vol.92, 2002, pp.5673-5679.

[3]Smirnov, A., Raitses, Y., and Fisch, N. J., “ Plasma Measurements in a 100W Cylindrical Hall thruster,” Journal of Applied Physics, Vol.95, 2004, pp.2283-2292.

[4]Shirasaki, A., Tahara, H., and Yoshikawa, T., “Performance Characteristics of Low Power Hall Thrusters with Circular Cross-sectional Discharge Chambers,” Proceedings of the 24th International Symposium on Space Technology and Science, ISTS 2004-b-35, 2004, pp. 203-208.

[5]Shirasaki, A., Tahara, H., and Yoshikawa, T.,”Operational Characteristics of Cylindrical Hall Thrusters,” 28th International Electric Propulsion Conference, Toulouse, France, Paper No. IEPC-03-051, 2003.

[6]Shirasaki, A. and Tahara, H., ”Plume Measurement and Miniaturization of the Hall Thrusters with Circular Cross-sectional Discharge Chambers,” 29th International Electric Propulsion Conference, Princeton, USA, Paper No. IEPC-05-051, 2005.

[7]Tahara, H. and Tonari, T., ”Performance Characteristics of Very Low Power Cylindrical Hall Thrusters,” 31st International Electric Propulsion Conference, University of Michigan, Michigan, USA, Paper No. IEPC-2009-272, 2009.

[8]Togawa, K. and Nose,M., Sugimoto,N. Nishida, T., Ikeda, T., Fujita T., Tahara, H., “Performance Characteristics of Very Low Power Cylindrical Hall Thrusters for Nano-Satellites”, Symposium on Space Ttransportation, Paper No. STEP-2010-004, JAXA, Japan (2011)(in Japanese)

[9]Togawa, K. and Nose,M., Sugimoto,N. Nishida, T., Ikeda, T., Tahara, H,. and Watanabe, Y., “Performance Characteristics of Very Low Power Cylindrical Hall Thrusters for Nano-Satellites”, 28th International Symposium on Space Technology and Science, Paper No. ISTS 2011-b-22 , Okinawa, Japan (2011)