Research and Development of Hall Thruster Series at Osaka Institute of Technology

IEPC-2013-101

Presented at the 33rd International Electric Propulsion Conference,
The George Washington University • Washington, D.C. • USA
October 6 – 10, 2013

Masato Nishida[1], Yohei Mito[2], Taisuke Kagota[3], Tsuyoshi Kawamura[4], Tomoyuki Ikeda [5],
and Hirokazu Tahara [6]
Osaka Institute of Technology
5-16-1, Omiya, Asahi-Ku, Osaka 535-8585, Japan

Abstract: The Hall thrusters are expected for future space missions. In this paper, we introduce the recent research and development of three kinds of Hall thruster, that is, CHT, SPT and TAL, at Osaka Institute of Technology. Very-low-power cylindrical Hall thruster (CHT) is being developed for nano/small satellites in recent application. The thrust efficiency of CHT-type named TCHT-4 was 18.1% at a specific impulse of 1570 sec with an input power of 66W. Both SPT and TAL are also being developed for in-space propulsion, that is, for future high-power and high-specific-impulse operations. Typical thrust performance of SPT-type named THT-VI reached a thrust of 110mN and a thrust efficiency of 61% at a specific impulse of 3200sec with an input power of 2.8kW. As for TAL-type TALT-2, a stable operation was kept at 2800sec with above 3.5kW.

I. Introduction

The permanent space development requires high specific impulse, compact and simple structure Hall Thrusters. Electric propulsion for construction of large 1GW-class solar power satellites and main engines for manned Mars exploration ships have been proposed. High power, high thrust efficiency and long-lifetime rocket engine is required for these projects. Although current Hall thrusters do not satisfy all performances, when considering potentials of lifetime, efficiency and compact, performance improvement is possible to meet it. At Osaka Institute of Technology (OIT), Osaka, Japan, the development of high-power and high-specific-impulse Stationary Plasma Thruster (SPT)[1-7] and Thruster with Anode Layer (TAL)[8-10] are being carried out. Also, the low-power Cylindrical Hall Thruster (CHT) is promising for small/nano satellites[11-14]. At OIT, the 3rd PROITERES nano-satellite is being developed for powered flight to moon by a special CHT.

In this study, three kinds of Hall thruster are introduced under research and development at OIT. The first is CHT. The second is SPT which is classified into magnetic-layer-type Hall thruster[3-7]. The third is TAL which is classified into anode-layer-type Hall thruster.

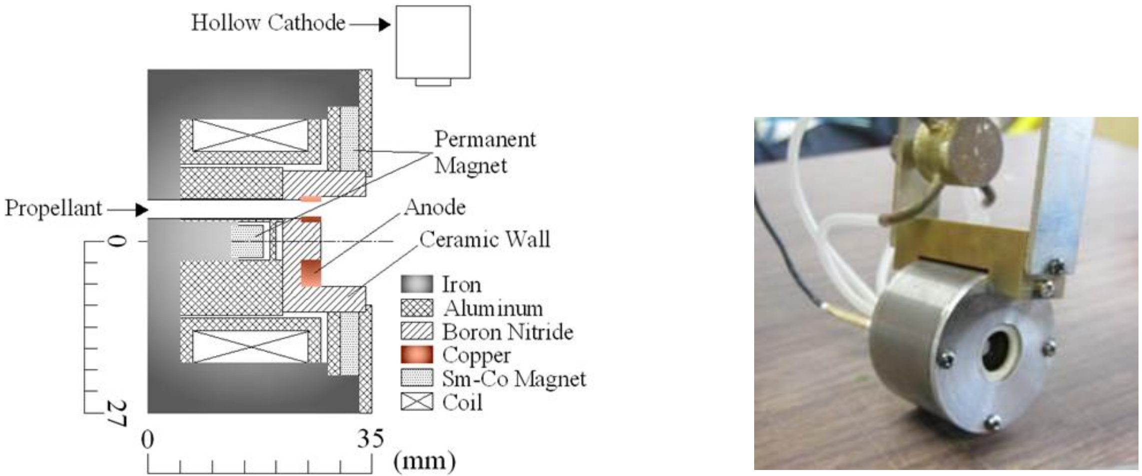
---

[1] Graduate Student, Graduate School Major in Mechanical Engineering, and tahara@med.oit.ac.jp.
[2] Graduate Student, Graduate School Major in Mechanical Engineering, and tahara@med.oit.ac.jp.
[3] Undergraduate Student, Department of Mechanical Engineering, and tahara@med.oit.ac.jp.
[4] Undergraduate Student, Department of Mechanical Engineering, and tahara@med.oit.ac.jp.
[5] Graduate Student, Graduate School Major in Mechanical Engineering, and tahara@med.oit.ac.jp.
[6] Professor, Department of Mechanical Engineering, and tahara@med.oit.ac.jp.

II. Experimental Apparatus

A. CHT Hall thruster TCHT-4

Figure 1 shows the cross-sectional view of a very low-power Hall thruster named TCHT-4. Table 1 and Table 2 show the specifications of a discharge channel and an internal solenoidal coil, respectively. The anode located at the upstream end of the circular cross-sectional part is made of copper. The length and radius of the discharge chamber are 7mm and 7mm, respectively. The wall materials of the discharge chamber are Boron Nitride (BN). TCHT-4 a has a solenoidal coil on the inner surface of the outer cylinder. The thruster also 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.



(a) Cross-sectional view.

(b) Photo.

Figure 1. Schematic of TCHT-4 Hall thruster.

Table 1. Specification of discharge channel.

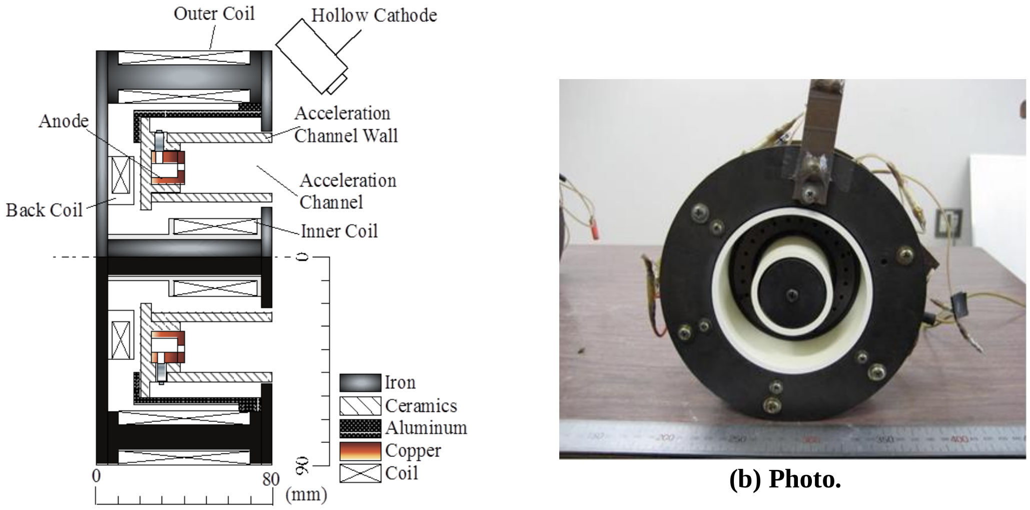
Discharge channel	
Length	7 mm
Diameter	14 mm
Material	Boron nitride (BN)

Table 2. Coil detail of TCHT-4.

Coil	
Material	Copper ϕ 0.5 mm
Number of turns	250

B. SPT Hall thruster THT-VI

Figure 2 shows the schematic of the 1kW-class laboratory-model THT-VI thruster. Table 3 and Table 4 show the specifications of a discharge channel and an internal solenoidal coil, respectively. This thruster is classified as the magnetic layer type, i.e. stationary plasma thruster. The thruster has a discharge channel with an outer diameter of 100mm and an inner diameter of 56mm, i.e. with 22 mm in width, and the channel length is 40mm. The channel dimensions are the same as those of SPT100 in Russia. The discharge channel wall is made of boron nitride (BN) [7].



(a) Cross-sectional view.

(b) Photo.

Figure 2. Schematic of THT-VI Hall thruster.

able 4. Coil detail of THT-VI.

Discharge channel	
Length	40mm
Inner diameter	56mm
Outer diameter	100mm
Material	Boron nitride（BN）

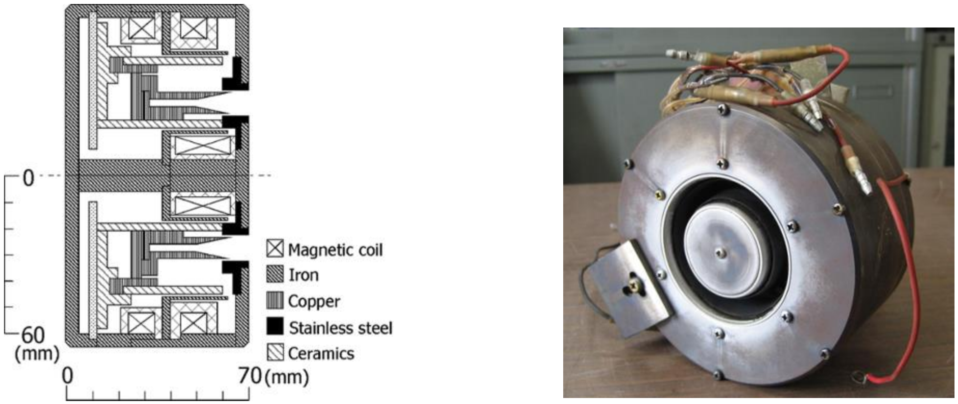
Table 3. Specification of discharge channel.

T

Coils	
Material	Copper φ0.5mm
Inner coil	
Number of turns	1200
Quantity	1
Outer coils	
Number of turns	1400
Quantity	6
Trim coil	
Number of turns	350
Quantity	1

C. TAL Hall thruster TALT-2

Figure 3 shows the schematic of TALT-2 thruster. Table 5 and Table 6 show the specifications of a discharge channel and an internal solenoidal coil, respectively. This thruster is classified as the anode-layer-type thruster. The thruster has a discharge channel with an outer diameter of 65mm and an inner diameter of 45mm, i.e. with 10mm in width, and the channel length is 35mm.



(a)Cross-sectional view.

(b) Photo.

Figure 3. Schematic of TALT-2 Hall thruster.

Table 5. Specification of discharge channel.

Discharge channel	
Length	35mm
Inner diameter	45mm
Outer diameter	65mm
Material	Copper（Cu）

Table 6. Coil detail of TALT-2.

Coils	
Material	Copper φ0.5mm
Inner coil	
Number of turns	480
Quantity	1
Outer coil	
Number of turns	240
Quantity	1
Trim coil	
Number of turns	200
Quantity	1

D. Vacuum facility

The experimental facility is shown in Fig.4[1-10]. The thruster is operated in a water-cooled stainless steel vacuum chamber with 1.2m in diameter and 2.25m in length. The chamber is equipped with two compound turbo molecular pumps with a pumping speed of 10000l/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.

In thrust measurement system shown in Fig.5, pendulum method is used in order to accurately measure thrusts. The thruster is mounted on a thrust stand suspended with an aluminum bar, and the displacement of the thruster is detected by an eddy-current-type gap sensor. As shown in Fig.6, 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. Plasma plume is also observed with a high speed camera (Photron: FASTCAM APX RS).

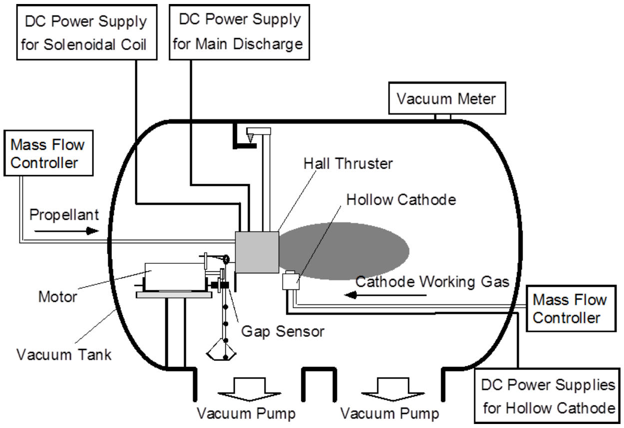


Figure 4. Experimental factory for Hall thruster.

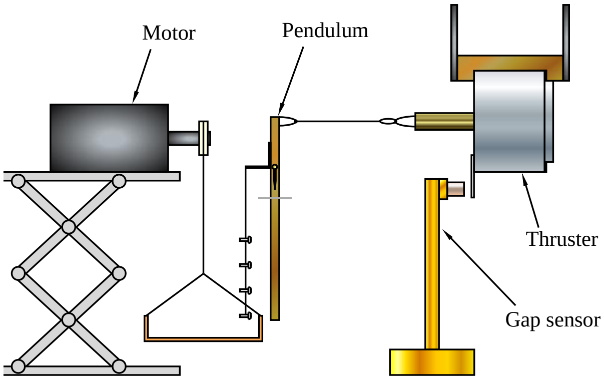


Figure 5. Thrust measurement system.

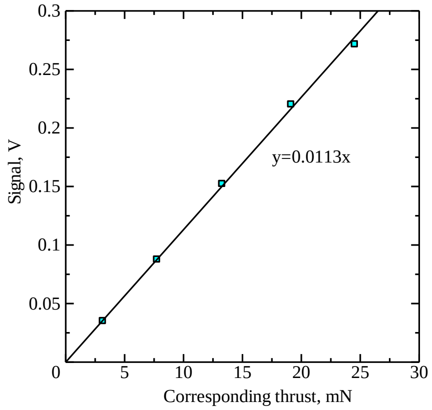


Figure 6. Thrust calibration plotting.

III. Experimental Results and Discussion

A. CHT Hall thruster TCHT-4

At OIT, the CHT Hall thruster is being developed for the 3rd PROITERES nano-satellite, i.e. moon-exploration university-satellite with electric thrusters for powered flight from the low-earth orbit to moon. Figures 7 and 8 show the characteristics of specific impulse and thrust efficiency, respectively, as a function of input power at xenon mass flow rates of 0.1, 0.2 and 0.3g/s with and without a solenoidal coil current of 2.0 A. Figure 9 show the operation photograph of CHT. Both the specific impulse and the thrust efficiency almost linearly increase with the input power. They ranges from 350sec and 7% at 10W to 1600sec and 18.1% at 66W with 0.1mg/s; from 450sec and 9% at 20W to 1350sec and 13 % at 130W with 0.2mg/s and from 600sec and 6% at 100W to 1200sec and 8% at 240W with 0.3mg/s. The thruster operated stably even with very low powers. Also, the discharge current oscillation was lower compared with SPT-type Hall thruster.

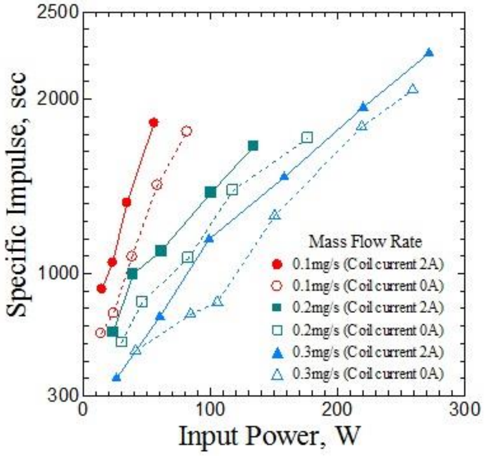


Figure 7. Specific impulse vs input power.

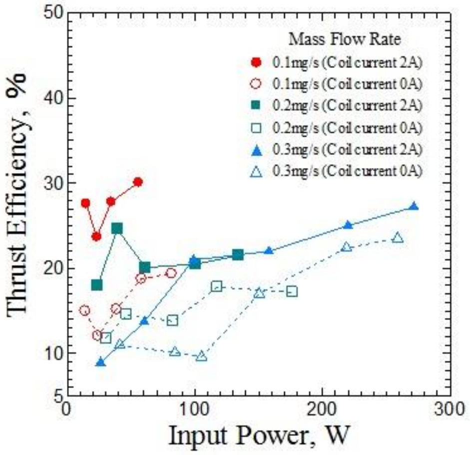


Figure 8. Thrust efficiency vs input power.

Figure 9. Operation photograph of TCHT-4.

B. SPT Hall thruster THT-VI

Figures 10-12 show the discharge current, thrust, specific impulse and thrust efficiency as a function of discharge voltage. Figures 13 and 14 show the operation photographs of THT-VI. The discharge current is almost flat with a constant mass flow rate although not so good with high discharge voltages of 800-1000V. Both the thrust and the specific impulse linearly increase with discharge voltage. The thrust ranges from 50 to 200mN at specific impulses of 1500-4000sec. The thrust efficiency reaches above 60%. Typical thrust performance, as shown in Table 7, is a thrust of 110mN and a thrust efficiency of 61% at a specific impulse of 3200sec with an input power of 2.8kW.

Although the thrust increases with increasing discharge voltage up to 950V, above 950V the thrust almost is almost flat. This is expected because propellant is under highly-ionized state with increasing input power and because the high-power operation is slightly unstable.

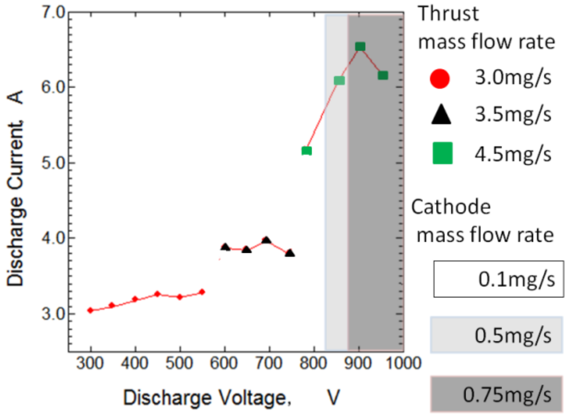


Figure 10. Discharge current vs voltage.

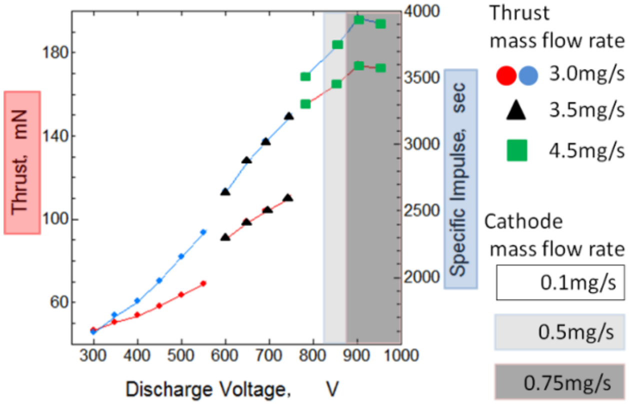


Figure 11. Thrust and specific impulse vs discharge voltage.

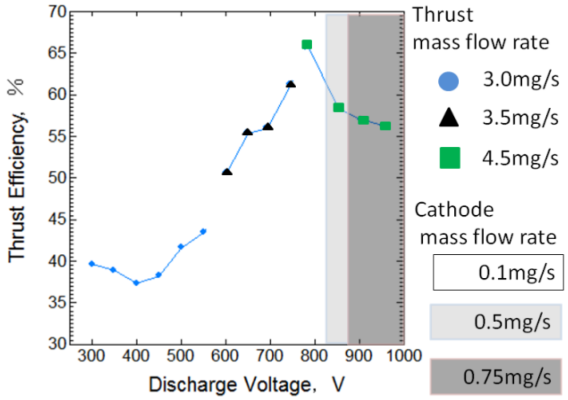


Figure 12. Thrust efficiency vs discharge voltage.

Table 7. Typical thrust performance of THT-VI.

Discharge Voltage	744V
Discharge Current	3.8A
Thrust	110mN
Specific Impulse	320sec
Trust efficiency	61%
Power	2.8kW

Figure 13. Operation photograph of THT-VI (300V).

Figure 14. Operation photograph of THT-VI (1000V).

C. TAL Hall thruster TALT-2

Figures 15-17 show the discharge current, thrust, specific impulse and thrust efficiency as a function of discharge voltage. Figure 18 shows the operation photograph of TALT-2 at 600V. The thrust ranges from 60 to 82mN at specific impulses of 2000-2800sec. The thrust efficiency reaches above 60%. Typical thrust performance, as shown in Table 8, is a thrust of 74mN and a thrust efficiency of 42% at a specific impulse of 2625sec with an input power of 2.2kW. There are not data more than 600V. This is because the anode melted during operation at 600V. The mass flow rate (TALT-2 and hollow cathode) was constant unlike SPT. With orange-color portion in Fig.16, we could observe the melting location of the anode. This is expected because TALT-2 had too small electrodes for high voltages and high powers.

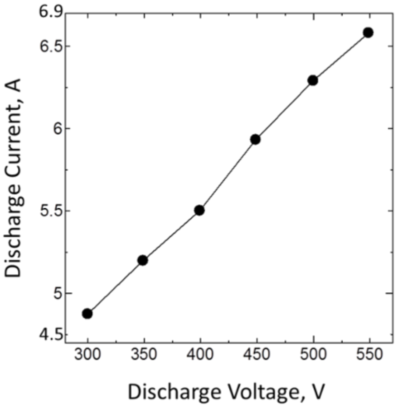


Figure 15. Discharge current vs voltage.

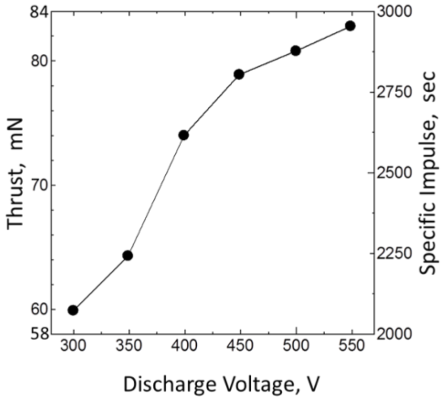


Figure 16. Thrust and specific impulse vs discharge voltage.

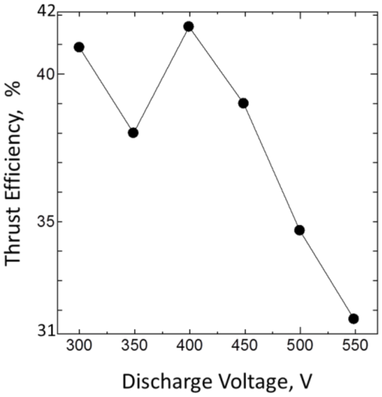


Figure 17. Thrust efficiency vs discharge voltage.

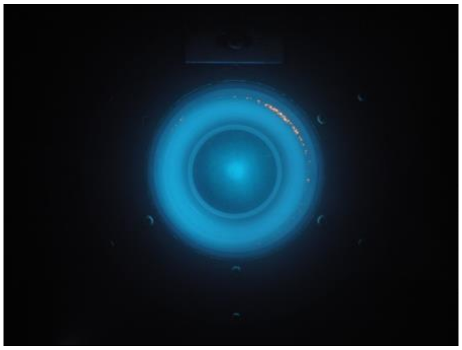


Figure 18. Operation photograph of TALT-2 (600V).

Table 8. Typical thrust performance of TALT-2.

Discharge Voltage	744V
Discharge Current	3.8A
Thrust	110mN
Specific Impulse	320sec
Trust efficiency	61%
Power	2.8kW

IV. Conclusion

We introduced the recent research and development of three kinds of Hall thruster at OIT.

The low-power cylindrical Hall thruster is being developed for small/nano satellites. At OIT, the 3rd PROITERES nano-satellite for powered flight to moon by a special CHT is under development. As a result, a stable operation was achieved even with 10W. The specific impulse and the thrust efficiency were 1570 secand 18.1%, respectively, with 66W. Also, the discharge current oscillation was lower compared with SPT-type Hall thruster.

At OIT, high-power and high-specific-impulse characteristics of Hall thrusters were measured with both the laboratory-model SPT-type THT-VI and TAL-type TALT-2 in order to obtain basic thruster performances with high discharge voltage and large mass flow rate and to understand practical problems under high power operations.

With THT-VI the discharge current was almost flat with a constant mass flow rate although not so good with high discharge voltages of 800-1000V. The input power reached above 5kW. Both the thrust and the specific impulse linearly increased with discharge voltage. The thrust ranged from 50 to 200mN at specific impulse of 1500-

4000sec. The thrust efficiency reached above 60%. Typical thrust performance was a thrust of 110mN and a thrust efficiency of 61% at a specific impulse of 3200sec with an input power of 2.8kW. As for TALT-2 thruster, the input power and the specific impulse were above 3.5kW and, 2800sec, respectively. It was found that the both thrusters are promising for the future in-space missions although the operations were thermally severe. At OIT, a new large-scale high-power TAL thruster is under design.

References

[1] Fukushima, K., Omori, S., Agata, H. and Tahara, H.: Performance Change Prediction in Long Operation for Magnetic-Layer-Type Hall Thrusters, 26th International Symposium on Space Technology and Science, Hamamatsu City, Japan, ISTS 2008-b-56p, 2008.

[2] Fujita, T., Tonari, T., Shimizu, Y. and Tahara, H.: Performance Prediction in Long Operation for Magnetic-Layer-Type Hall Thrusters, 27th International Symposium on Space Technology and Science, Tsukuba Convention Center, Tsukuba City, Japan, ISTS 2009-b-10p, 2009.

[3] Sugimoto, N., Nose, M., Togawa, K., Nishida, T., Ikeda, T., Tahara, H. and Watanabe, Y.: Optimization of Acceleration Channel Structure and Material for Magnetic-Layer-Type Hall Thrusters, 28th International Symposium on Space Technology and Science, Okinawa Convention Center, Ginowan City, Okinawa, Japan, ISTS 2011-b-18p, 2011.

[4] Tahara, H., Fujita, T. and Shimizu, Y.: Performance Prediction in Long Operation for Magnetic-Layer-Type Hall Thrusters, 31st International Electric Propulsion Conference, University of Michigan, Michigan, USA, IEPC-2009-140, 2009.

[5] Ikeda, T., Fujita, T., Sugimoto, N., Ozaki, J., Tahara, H. and Watanabe, Y.: Optimization of Acceleration Channel Structure and Material for Magnetic-Layer-Type Hall Thrusters, 32nd International Electric Propulsion Conference, Kurhaus, Wiesbaden, Germany, IEPC-2011-038, 2011.

[6] Shimizu, Y., Shinya, T., Fujita, T., Tonari, T. and Tahara, H.: Influence of Hollow Anode Configuration on Performance of Anode-Layer Hall Thrusters, 27th International Symposium on Space Technology and Science, Tsukuba Convention Center, Tsukuba City, Japan, ISTS 2009-b-12, 2009.

[7] Yuge, S., Kuwamura, Y. and Tahara, H.: Influences of Magnetic Field Topography and Discharge Channel Structure on Performance of Anode-Layer Hall Thrusters, 30th International Electric Propulsion Conference, Florence, Italy, IEPC-2007-336, 2007.

[8] Mito. Y., Nishida. M., Kagota. T., Kawamura. T., Ikeda. T., and Tahara. H.: Performance Characteristics of High-Power, High-Specific-Impulse Hall Thrusters for Japanese In-Space Propulsion, 33rd International Electric Propulsion Conference, George Washington University, Washington, D.C., USA, IEPC-2013-096, 2013.

[9] Mito, Y., Ikeda, T., Sugimoto, N., Togawa, T. and Tahara, H.: Research and Development of High-Power High-Efficiency Hall-Type Ion Engines for Space Exploration, International Conference on Renewable Energy Research and Applications 2012, Best Western Premier Hotel Nagasaki, Nagasaki City, Nagasaki, Japan, 2012.

[10] Mito. Y., Sugimoto. N., Kato. Y., Ikeda. T. and Tahara. H.: Research and Development of High-Power and High-Specific-Impulse Hall Thrusters at Osaka Institute of Technology, 29th International Symposium on Space Technology and Science, Nagoya Congress Center, Nagoya City, Aichi, Japan, ISTS 2013-o-1-02, 2013.

[11] 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 University, Princeton, USA, IEPC-05-051, 2005.

[12] Tahara, H.: Research and Development of Hall-Effect Thrusters at Osaka Institute of Technology, 44th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, Connecticut Convention Center, Connecticut, USA, AIAA-2008-5086, 2008.

[13] Tahara, H. and Tonari, T.: Performance Characteristics of Very Low Power Cylindrical Hall Thrusters, 31st International Electric Propulsion Conference, University of Michigan, Michigan, IEPC-2009-272, 2009.

[14] Ikeda. T., Mito. Y., Nishida. M., Kagota. T., Kawamura. T. and Tahara. H.: Development of Low-Power Cylindrical Hall Thrusters for Nano Satellites, 33rd International Electric Propulsion Conference, George Washington University, Washington, D.C., USA, IEPC-2013-109, 2013.