Performance Characteristics of High-Power, High-Specific-Impulse Hall Thrusters for Japanese In-Space Propulsion

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Abstract: The operational range of Hall thrusters will be hoped to be expanded for future orbital transfer vehicle and Mars exploration, i.e. for in-space propulsion. In this study, both small-size 1-kW-class SPT and TAL Hall thrusters were operated with higher discharge voltages, that is, with higher input powers and large specific impulses. The input powers and specific impulse for the SPT-type Hall thruster reached above 5kW and 3000sec, respectively. In the TAL Hall thruster, they were above 3.5kW and 2800sec, respectively. It was found that the both thrusters are promising for the future missions although the operations were thermally severe.

I. Introduction

The permanent space development requires high specific impulse, compact and simple structure Hall Thrusters. Projects of electric propulsion for construction of large 1GW-class solar power satellites and for manned Mars or other satellites exploration, i.e. in-space exploration, have been proposed[1-3]. High power, high thrust efficiency and long lifetime electric engine is required for these projects. However, current Hall thrusters do not satisfy all performances, although when considering potentials of lifetime, efficiency and compact, performance, improvement is possible to meet it.

The final goal of this study is development of high-power and high-specific-impulse SPT (Stationary Plasma Thruster) and TAL (Thruster with Anode Layer) Hall Thrusters for in-space propulsion. In this study, the relatively small THT-VI Hall Thruster (discharge room outer-diameter is 100mm) is used. The operating condition is varied with discharge voltages of 300-1000V (about two times of the conventional voltage). And we aimed at obtaining high specific impulse of 3000sec or more. Furthermore, we performed high voltage operations using a small TAL (TALT-2 which was developed at Osaka Institute of Technology) with 65mm in discharge room diameter.

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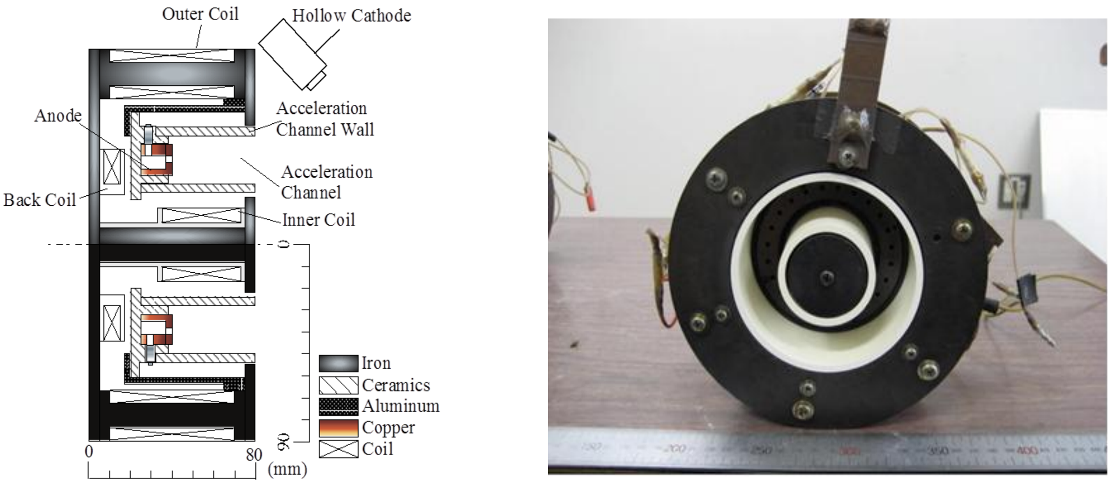
II. Experimental Apparatus

A. THT-VI

Figure 1 shows the schematic of the 1 kW laboratory model THT-VI thruster. Table 1 and Table 2 show the specifications of discharge channel and coil. This thruster is classified as the magnetic-layer thruster, i.e. stationary plasma thrusters. 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)[4].



(a) Cross-sectional view. **(b) Photo.**

Figure 1. Schematic of THT-VI Hall thruster.

Table 1. Specification of discharge channel.

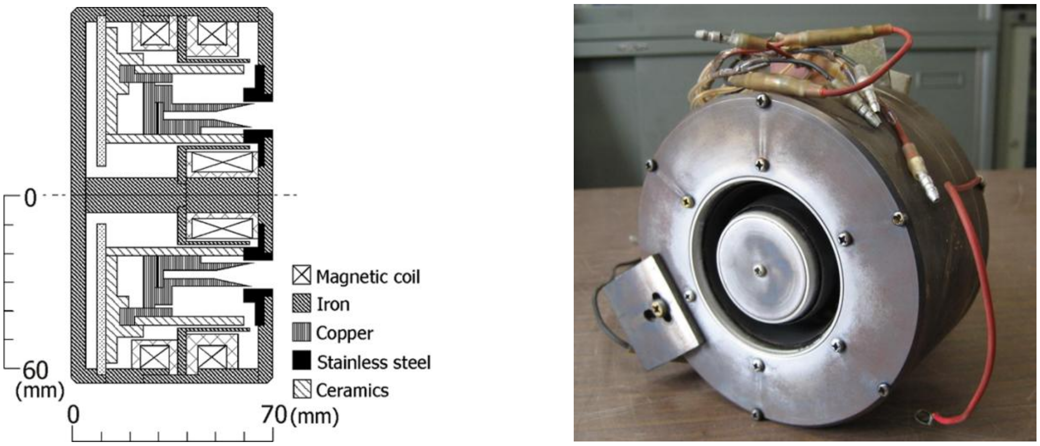
Discharge channel	
Length	40mm
Inner diameter	56mm
Outer diameter	100mm
Material	Boron nitride（BN）

Table 2. Details of THT-VI coil.

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

B. TALT-2

Figure 2 shows the schematic of TALT-2 thruster. Tables 3 and 4 show the specifications of discharge channel and coil. This thruster is classified as the anode-layer-type thrusters. 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 2. Schematic of TALT-2 Hall thruster.

Table 3. Specification of discharge channel.

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

Table 4. Details of TALT-2 coil.

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

C. Vacuum facility

The experimental facility is shown in Fig.3[1-6]. 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.

As thrust measurement system shown in Fig.4, 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.5, 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).

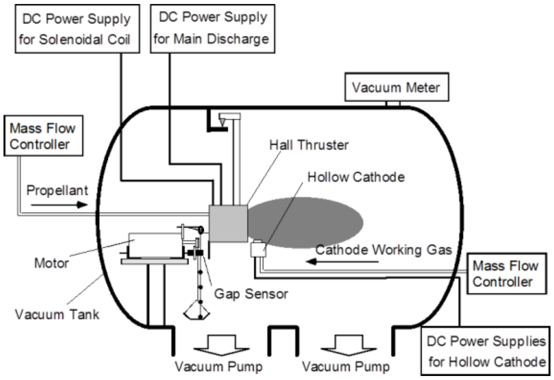


Figure 3. Experimental facility for Hall thruster.

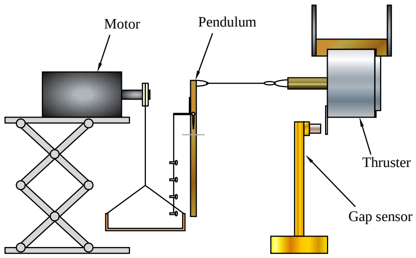


Figure 4. Thrust measurement system.

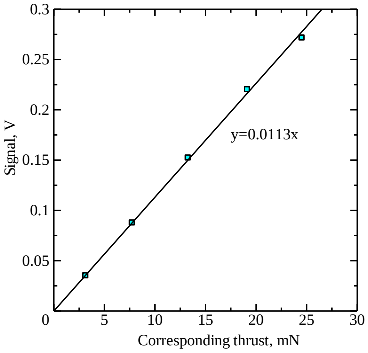


Figure 5. Thrust calibration plotting.

III. Experimental Conditions

A. THT-VI

Table 5 shows the experimental condition for THT-VI thruster[6].

The operating condition is varied with discharge voltages of 300-1000V. Xenon is used as the propellant. The main mass flow rate is 3.0-4.5mg/s.

Table 5. Operational conditions of THT-VI.

Discharge Voltage	300~1000V	
Propellant	Xenon	
Mass Flow Rate	THT-VI	3.0~4.5mg/s
	Hollow Cathode	0.1~0.75mg/s
Coil Current	0.3, 0.3, 0.9A (inner, outer, trim)	
Cathode Distance	200mm	
Backpressure	3.0×10^{-2}Pa	

B. TALT-2

Table 6 shows the experimental condition for TALT-2 thruster[6]. The operating condition is varied with discharge voltages of 300-550V. Xenon is used as the propellant. The main mass flow rate is 3.0mg/s.

Table 6. Operational conditions of TALT-2.

Discharge Voltage	300~550V	
Propellant	Xenon	
Mass Flow Rate	TALT-2	3.0mg/s
	Hollow Cathode	0.1mg/s
Coil Current	0.8,0.8,2.0A (inner, outer, trim)	
Cathode Distance	133mm	
Backpressure	1.0×10^{-2}Pa	

IV. Experimental Results and Discussion

A. THT-VI

Figures 6-8 show the discharge current, thrust, specific impulse and thrust efficiency as a function of discharge voltage. Figures 9 and 10 show the operation photograph 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.

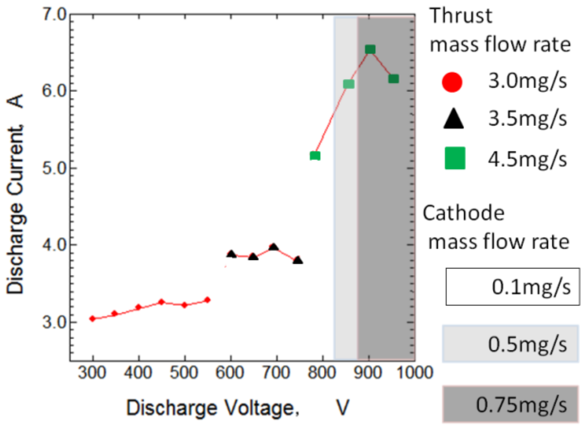


Figure 6. Discharge current vs voltage.

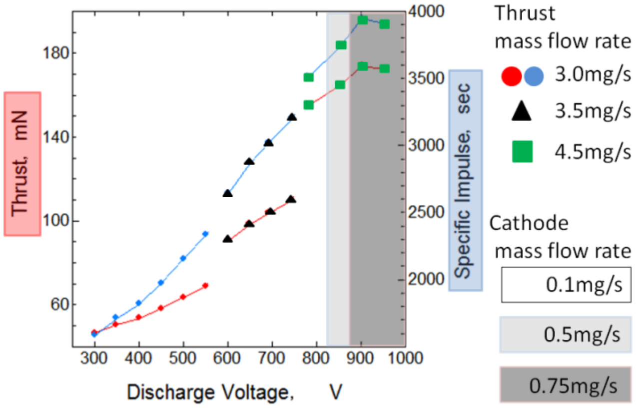


Figure 7. Thrust and specific impulse vs discharge voltage.

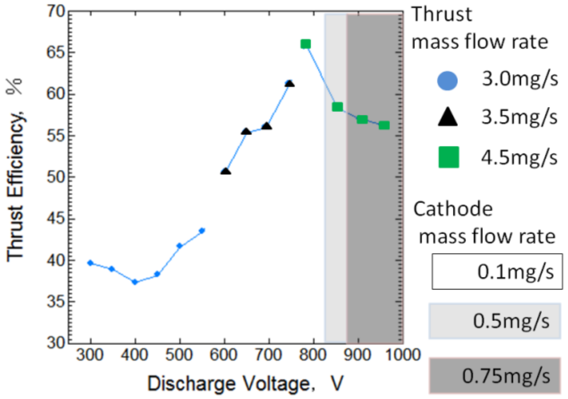


Figure 8. Thrust efficiency vs discharge voltage.

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 9. Operation photograph of THT-VI (300V).

Figure 10. Operation photograph of THT-VI (1000V).

B. TALT-2

Figures 11-13 show the discharge current, thrust, specific impulse and thrust efficiency as a function of discharge voltage. Figures 14 show the operation photograph of TALT-2 at 600V. The mass flow rate (TALT-2 and hollow cathode) is constant unlike SPT. 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 with high discharge voltages above 600V. This is because the anode melted during operation at 600V. With orange-color portion in Fig.14, we could observe the melting location of the anode. This is expected because TALT-2 has too small electrodes for high voltages and high powers.

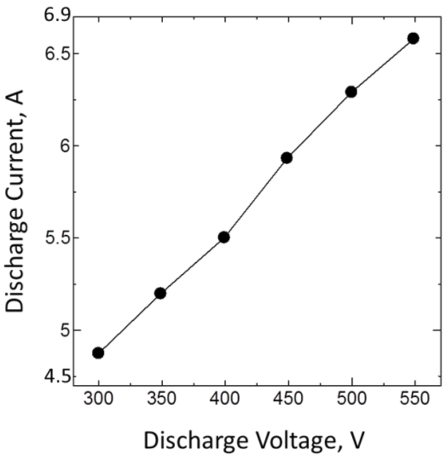


Figure 11. Discharge current vs voltage.

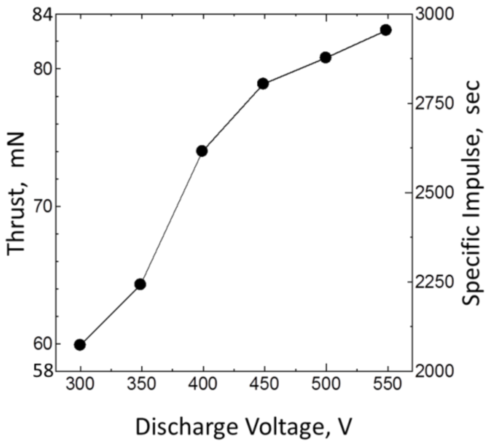


Figure 12. Thrust and specific impulse vs discharge voltage.

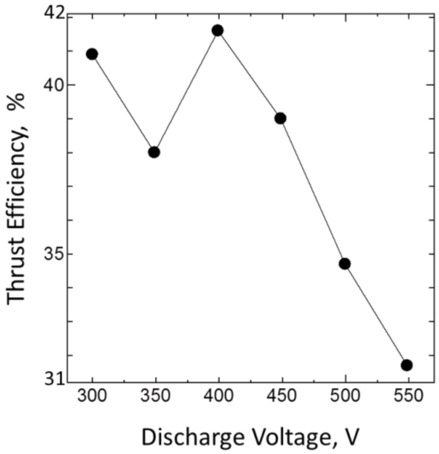


Figure 13. Thrust efficiency vs discharge voltage.

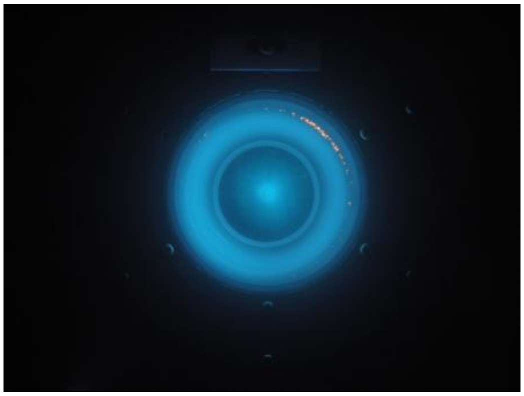


Figure 14. Operation photograph of TALT-2 (600V).

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

V. Comparisons with Another High-Power Hall Thrusters

Although we could establish high-specific-impulse operations above 3000sec, the dimensions and specifications of the both thrusters, the vacuum chamber, the vacuum pumps, the thrust measurement system, that is, all experimental systems have some problems for stable operations. We compare our data of THT-VI with data of international conventional Hall thrusters such as SPT-140, 173Mv2, and NASA-400M. Figures 15 and 16 show the comparisions[7].

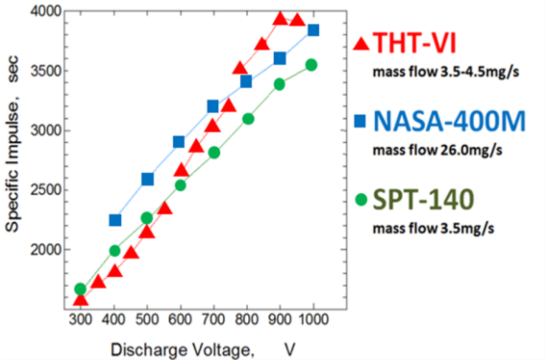


Figure 15. Specific impulse vs discharge voltage comparison.

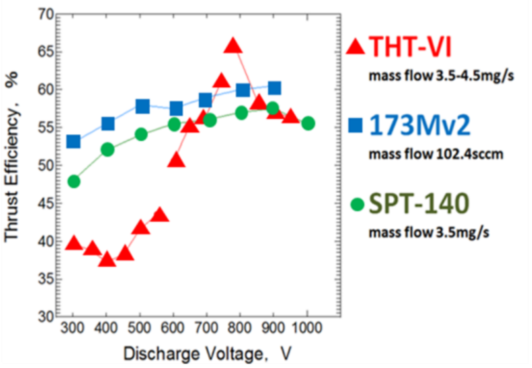


Figure 16. Thrust efficiency vs discharge voltage comparison.

The performances of THT-VI are slightly higher than those of SPT-140, 173Mv2 and NASA-400M in high voltage ranges, specially with higher voltages above 800V. This is considered because of large errors of thrust measurement under unstable operations with high voltages. Also, the TALT-2 thruster could not operate with high voltages. We need to improve thrust measurement system and to establish stable operations with high voltages by intensively changing thruster design.

At Osaka Institute of Technology, a new large-scale high-power TAL thruster is under design.

VI. Conclusion

At Osaka Institute of Technology (OIT), high-power and high-specific-impulse characteristics of Hall thrusters were measured with both the 1-kW-class laboratory-model SPT-type THT-VI and TAL-type TALT-2 in order to obtain basic thruster performances with high discharge voltages and large mass flow rates and to understand practical problems under high power operations for in-space propulsion.

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 impulses 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 missions although the operations were thermally severe. At OIT, a new large-scale high-power TAL thruster is under design.

References

[1] 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 (29th ISTS), Nagoya Congress Center, Nagoya City, Aichi, Japan, ISTS 2013-o-1-02, 2013.

[2] Kagota. T., Kawamura. T., Mito. Y., Sugimoto. N., Togawa. K.., Kato. Y., Yamamoto. R., Ikeda. T., and Tahara. H., “Research and Development of Three Kinds of Hall Thruster at Osaka Institute of Technology,” 29th International Symposium on Space Technology and Science (29th ISTS), Nagoya Congress Center, Nagoya City, Aichi, Japan, ISTS 2013-b-54p, 2013.

[3] Nishida. M., Mito. Y., Kagota. T., Kawamura. T., Ikeda. T., and Tahara. H., “Development of the Hall thrusters in Osaka Institute of Technology,” 33rd International Electric Propulsion Conference (33rd IEPC), George Washington University, Washington, D.C., USA, IEPC-2013-101, 2013.

[4] 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, (28th ISTS), Okinawa Convention Center, Ginowan City, Okinawa, Japan, ISTS 2011-b-18p, 2011.

[5] Mito, Y., Ikeda, T., Sugimoto, N., Togawa, K., 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 (ICRERA), Best Western Premier Hotel Nagasaki, Nagasaki City, Nagasaki Japan, 2012.

[6] 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.

[7] Jacobson, D., Manzella, D., Richard, R.,and Peter, Y.," NASA's 2004 Hall Thruster Program," 40th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, Broward County Center, Fort Lauderdale, USA, AIAA-2004-3600, 2004.