Performance Characteristics of High-Power, High-Specific-Impulse Anode-Layer-Type Hall Thrusters for In-Space Propulsion

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Abstract: **Hall thrusters are expected for future space exploration. In this study, we introduce the recent research and development of two kinds of anode-layer-type Hall thruster at Osaka Institute of Technology (OIT) in Japan. For Japan in-space propulsion, specially integrated, high-power and high-specific-impulse characteristics of Hall thruster are investigated. We measured performances of both the laboratory-model TAL-type TALT-2 and RAIJIN94 in order to obtain basic thruster characteristics with high discharge voltage and large mass flow rate and to understand practical problems under high power operations. With TALT-2 thruster, the input power and the specific impulse were above 3.5 kW and 2800 s, respectively. Both the thrust and the specific impulse linearly increased with discharge voltage. The thrust efficiency reached above 42 %. As for RAIJIN94 thruster, a typical thrust performance was a thrust of 59.1 mN and a thrust efficiency of 37.9 % at a specific impulse of 2008 s with an input power of 1.6 kW. At OIT, a new large-scale high-power TAL thruster was designed for Japan in-space propulsion, and it is under operation.**

I. Introduction

The permanent space development strongly requires high specific impulse, compact and simple structure electric thrusters. Many projects using electric propulsion for construction of large 1 GW-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 engines are 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 TAL (Thruster with Anode Layer) Hall Thruster for in-space propulsion. In this study, small TALT-2 Hall Thruster (discharge room outer-diameter is 60 mm) is used. TALT-2 which was developed at Osaka Institute of Technology. The operating condition is varied with discharge voltages of 300-1000 V (about two times of the conventional voltage). And we aimed at obtaining high specific impulse of 3000 s or more. Furthermore, we performed high voltage operations using a high-power prototype TAL thruster RAIJIN94 with 94 mm in discharge room diameter, developed by all Japan EP researchers.

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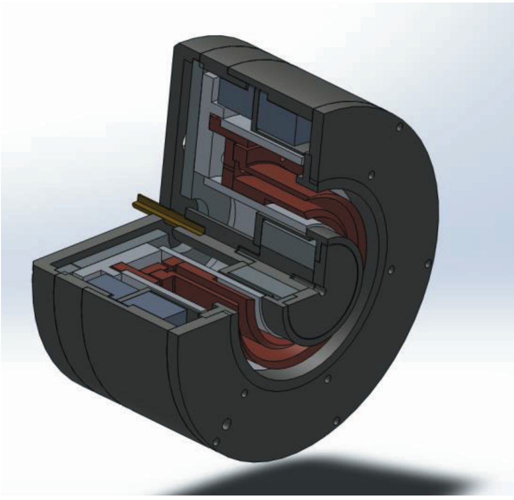
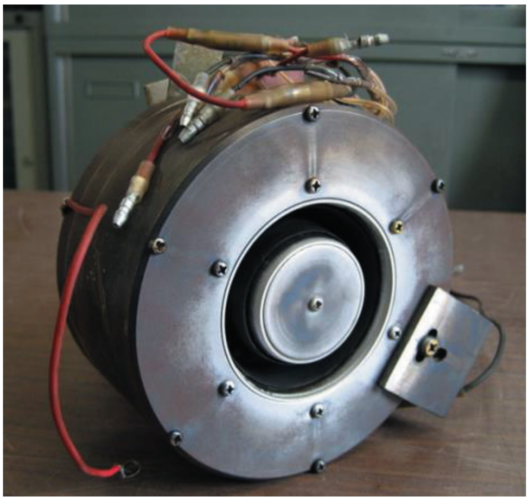
II. Experimental Apparatus

A. TALT-2

Figure 1 shows the schematic of the 1 kW laboratory-model TALT-2 thruster. Tables 1 and 2 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 65 mm and an inner diameter of 45 mm, i.e. with 10 mm in width, and the channel length is 35 mm. Figure 2 shows the calculated magnetic shapes.



(a) 3D model.



(b) Photo.

Figure 1. Schematic of TALT-2 Hall thruster.

Table 1. Specification of discharge channel.

Length	35 mm
Inner Diameter	45 mm
Outer Diameter	65 mm
Material	Copper(Cu)

Table 2. Detail of magnetic coils.

	Inner	Outer	trim
Quantity	1	1	1
Material	Copper Φ 0.5 mm		

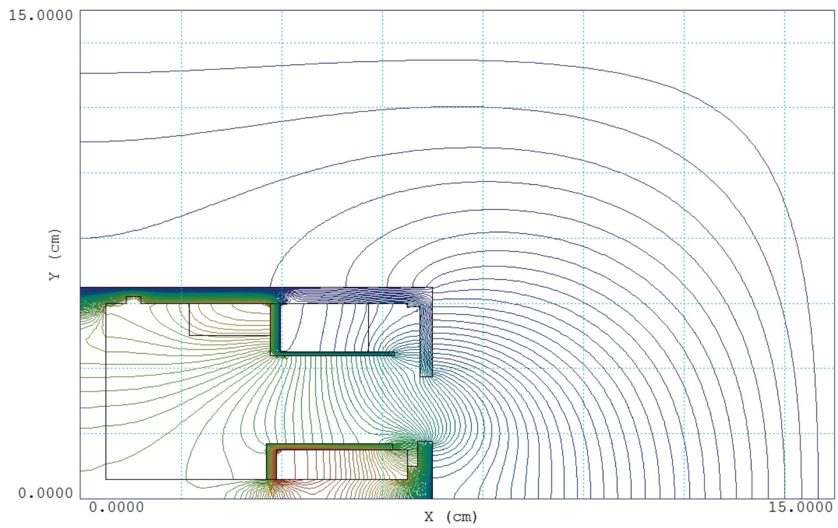
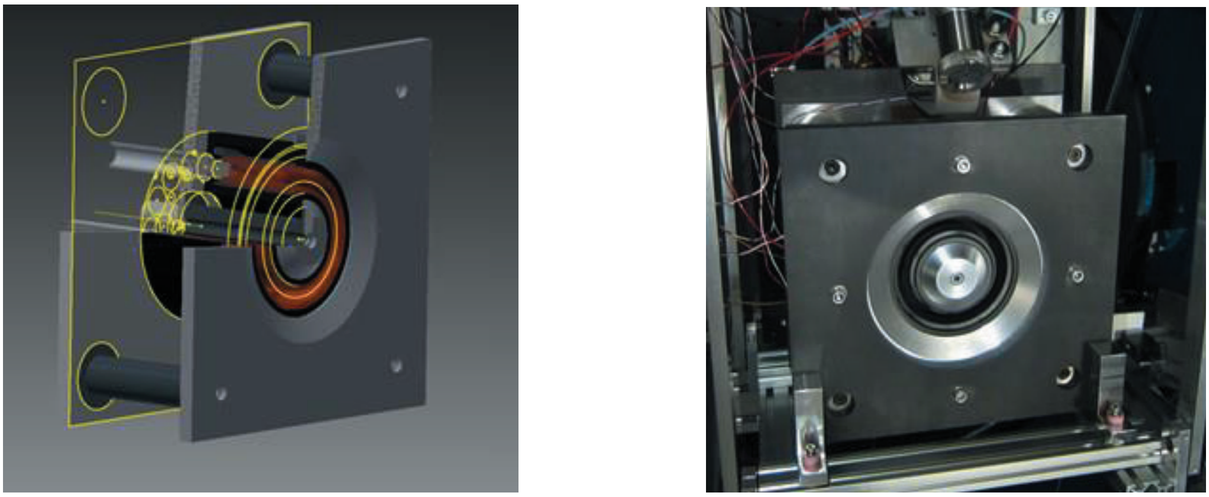


Figure 2. Magnetic field shape for TALT-2.

B. RAIJIN94

Figure 3 shows the schematic of the 5 kW RAIJIN94 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 94 mm and an inner diameter of 45 mm, i.e. with 24.5 mm in width, and the channel length is 55 mm. Figure 4 shows the calculated magnetic shapes.



(a) 3D model. **(b) Photo.**

Figure 3. Schematic of RAIJIN94.

Table 3. Specification of discharge channel.

Length	55 mm
Inner Diameter	45 mm
Outer Diameter	94 mm
Material	Copper(Cu)

Table 4. Detail of magnetic coils.

	Inner	Outer	trim
Quantity	1	4	1
Material	Copper Φ 0.5 mm		

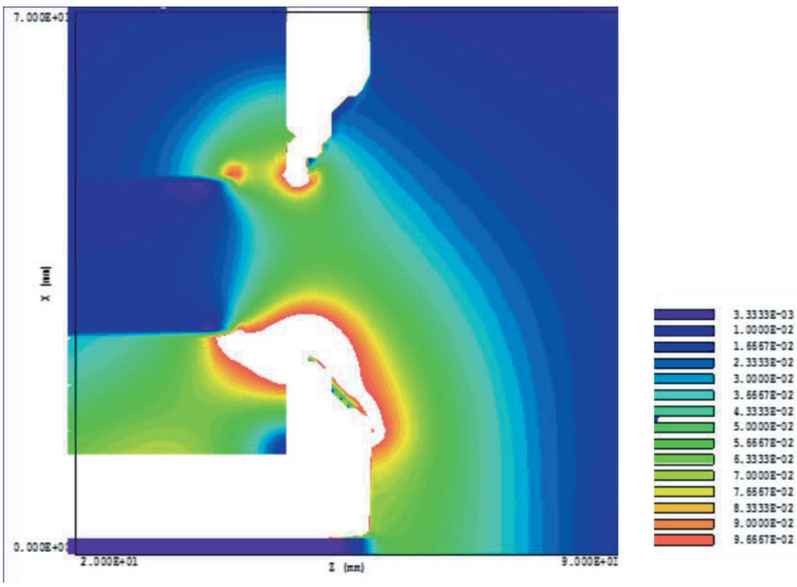


Figure 4. Magnetic field shape for RAIJIN94.

C. Vacuum facility

The experimental facility is shown in Fig. 5[4-10]. The thruster is operated in a water-cooled stainless steel vacuum chamber with 1.2 m in diameter and 2.25 m in length as shown in Fig. 6. The chamber is equipped with two compound turbo molecular pumps with 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 5.4×10^{-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. 7, 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. 8, 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).

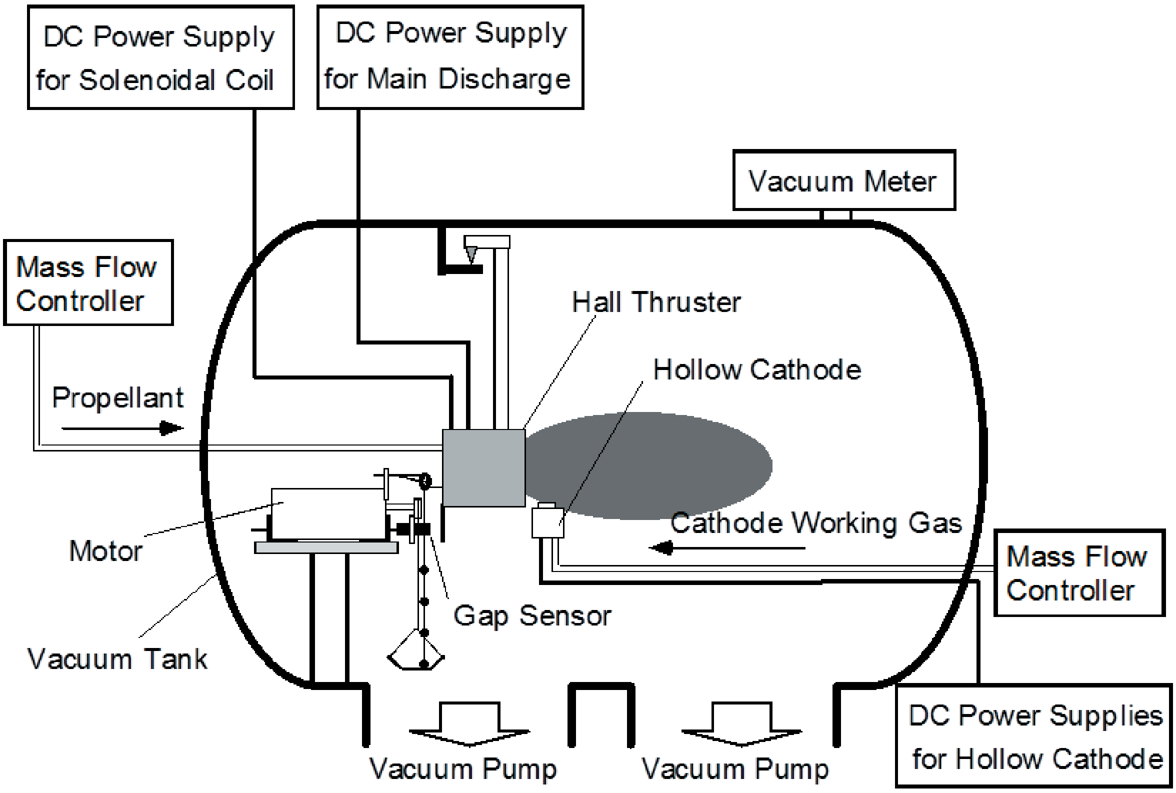


Figure 5. Experimental facility for Hall thruster.

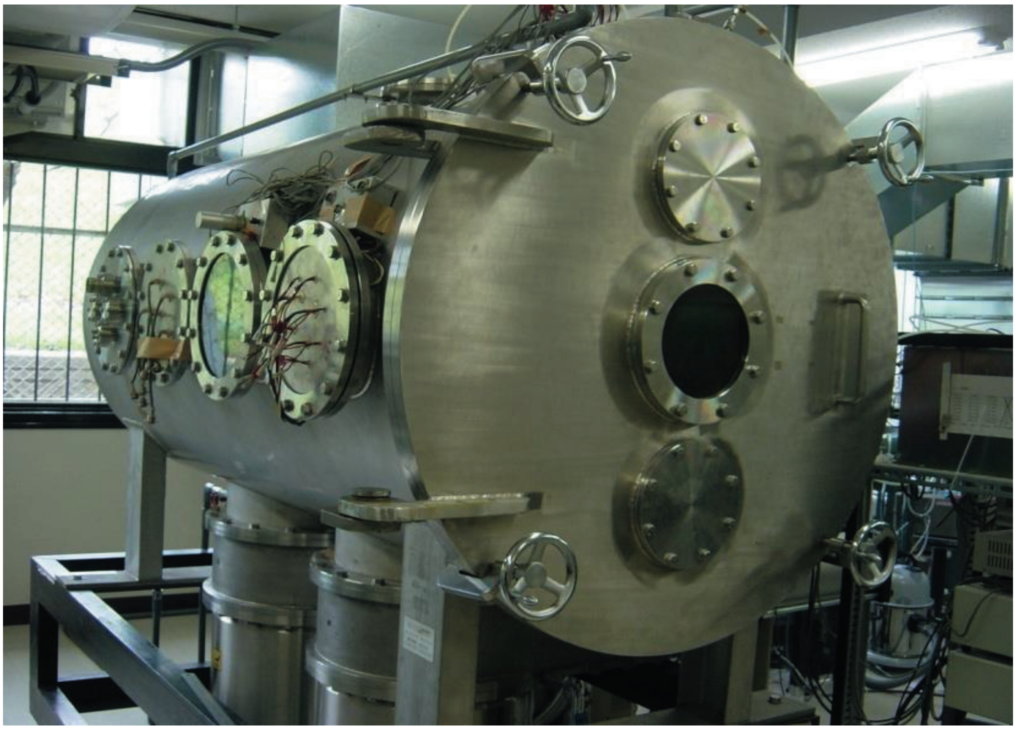


Figure 6. Vacuum facility.

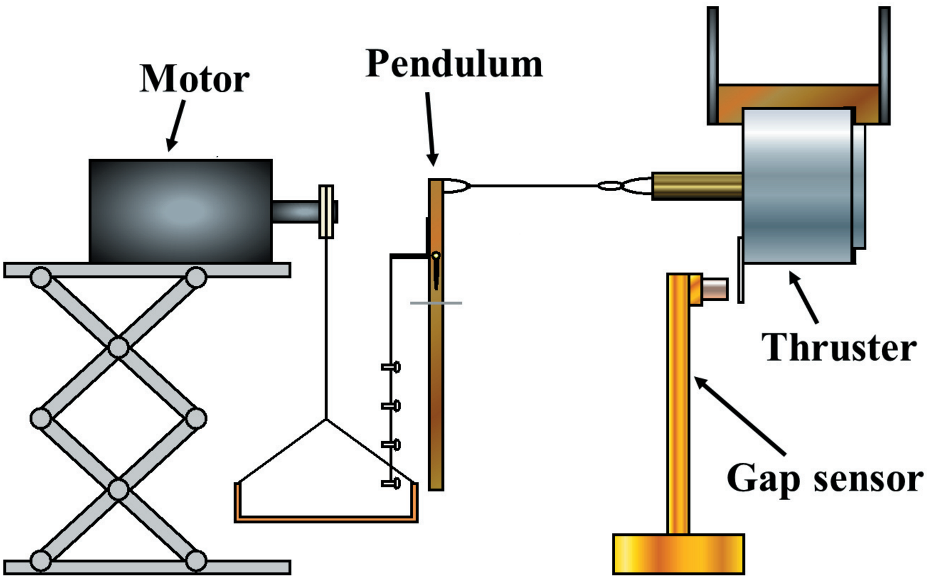


Figure 7. Thrust measurement system.

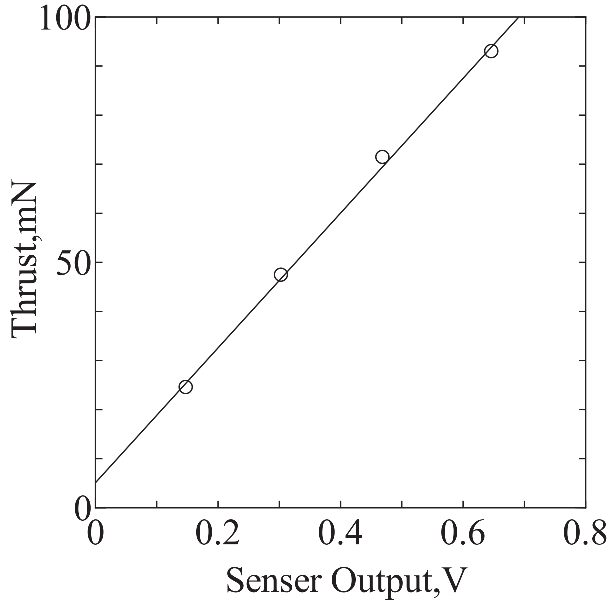


Figure 8. Thrust calibration plotting.

III. Experimental Results

A. TALT-2

Table 5 shows the experimental condition for TALT-2 thruster. The operating condition is varied with discharge voltages of 300-800 V. Xenon is used as the propellant. The main mass flow rate is 3.0 mg/s.

Table 5. Operational conditions of TALT-2.

Discharge Voltage	300-800 V	
Propellant	Xenon	
Mass Flow Rate	TALT-2	3.0 mg/s
	Hollow Cathode	0.1-0.5 mg/s
Coil Current	1.5, 0.3, 0.9A (inner, outer, trim)	
Backpressure	$5.4\text{x}10^{-2}$ Pa	

Figures 9-11 show the discharge current, thrust, specific impulse and thrust efficiency as a function of discharge voltage. Figure 12 show the operation photograph of TALT-2. The discharge current is almost flat with a constant mass flow rate. Both the thrust and the specific impulse linearly increase with discharge voltage. The thrust ranges from 40-90 mN at specific impulses of 1000-3000 s. Typical thrust performance, as shown in Table 6, is a thrust of 82.5 mN and a thrust efficiency of 38.1 % at a specific impulse of 2803 s with an input power of 2.9 kW. There are not data with high discharge voltages above 850 V. This is because of unstable operation with the anode melted during operation at 850 V. With an orange-color portion seen in Fig. 13, we could observe the melting location of the anode. This is inferred because TALT-2 has too small electrodes for high voltages and high powers.

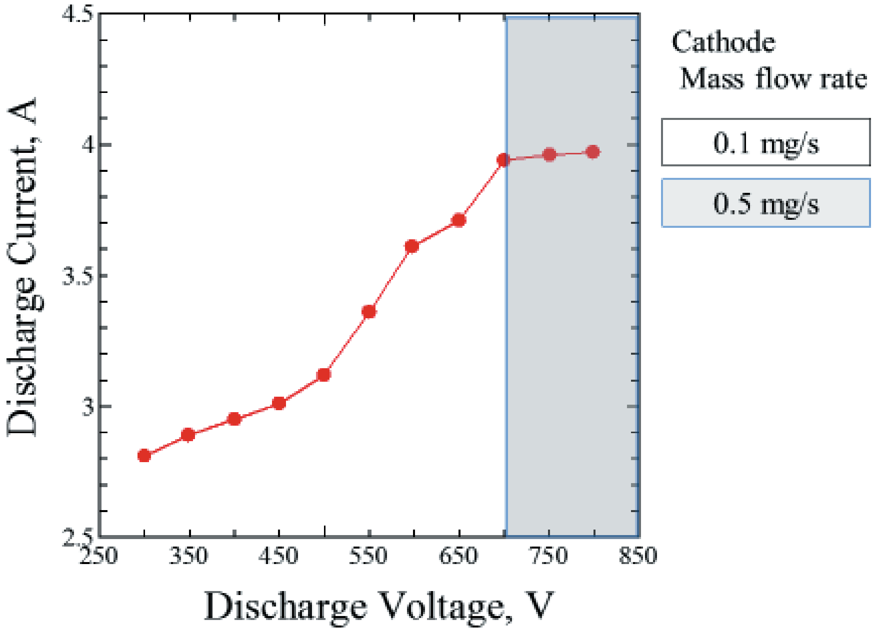


Figure 9. Discharge current vs voltage.

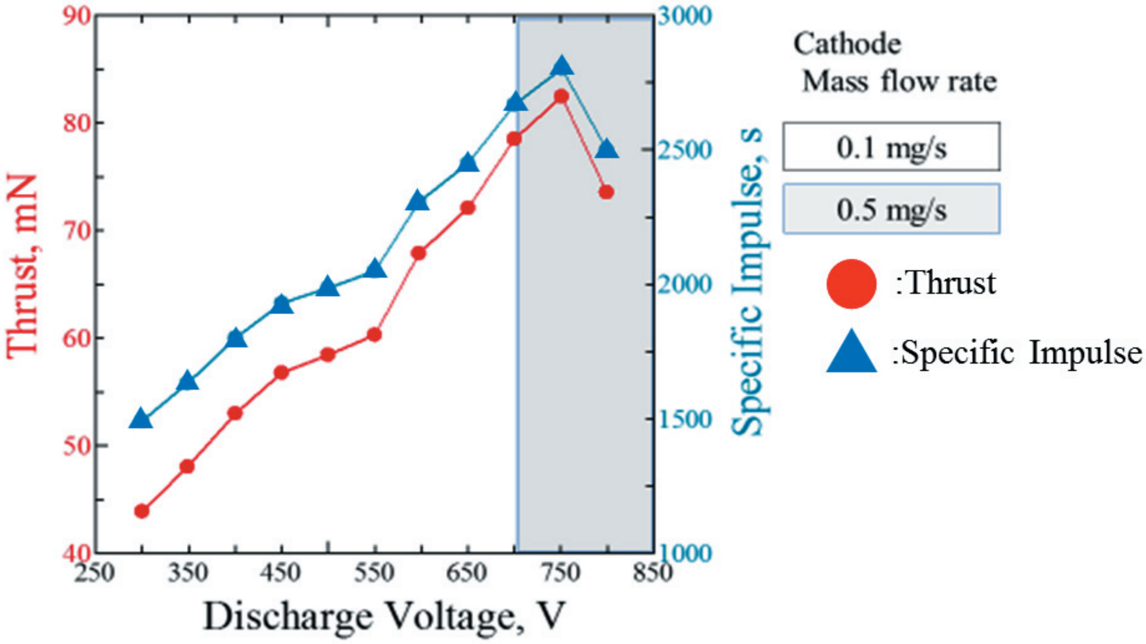


Figure 10. Thrust and specific impulse vs discharge voltage.

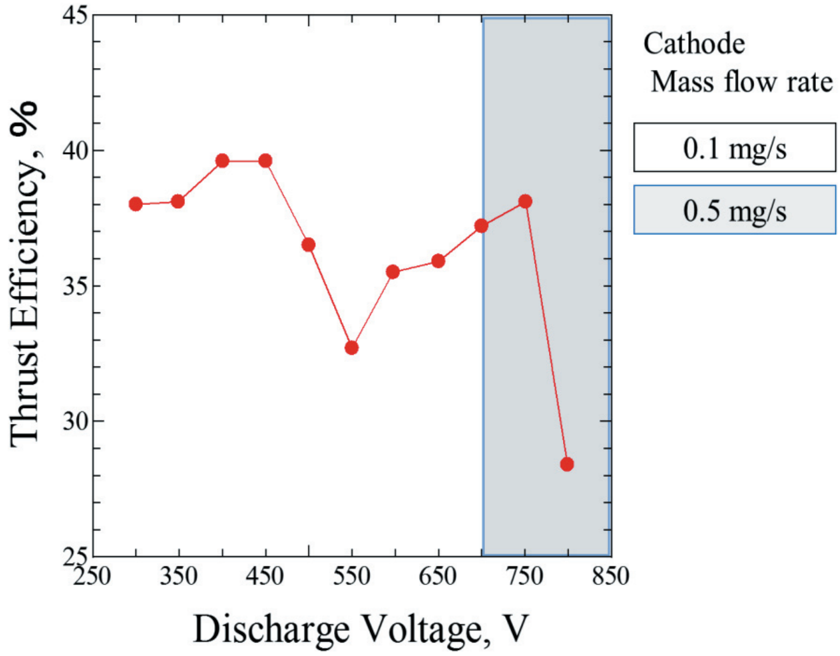


Figure 11. Thrust Efficiency vs discharge voltage.

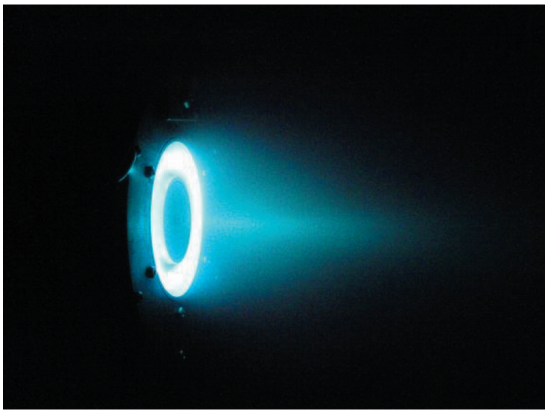


Figure 12. Operation photograph of TALT-2 (450 V).

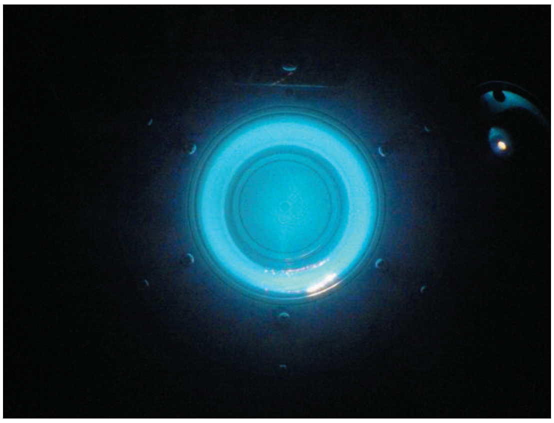


Figure 13. Operation photograph of TALT-2 (850 V).

Table 6. Typical thrust performance of TALT-2

Discharge Voltage	750 V
Discharge Current	3.96 A
Thrust	82.5 mN
Specific Impulse	2802 s
Thrust Efficiency	38.1 %
Power	2.9 kW

B. RAIJIN94

Table 7 shows the experimental condition for RAIJIN94 thruster. The operating condition is varied with discharge voltages of 300-450 V. Xenon is used as the propellant. The main mass flow rate is 3.0 mg/s.

Table 7. Operational conditions of RAIJIN 94.

Discharge Voltage	300-450 V	
Propellant	Xenon	
Mass Flow Rate	RAIJIN94	3.0 mg/s
	Hollow Cathode	0.1 mg/s
Coil Current	0.3, 0.3, 0.9A (inner, outer, trim)	
Backpressure	5.4×10^{-2} Pa	

Figures 14-16 show the discharge current, thrust, specific impulse and thrust efficiency as a function of discharge voltage with applying a constant magnetic field strength. Figure 17 show the operation photograph of RAIJIN94 thruster. The discharge current and both the thrust and the specific impulse linearly increase with increasing discharge voltage. However, the thrust efficiency linearly decreases with discharge voltage. The thrust ranges from 50-62 mN at specific impulses of 1750-2150 s. Typical thrust performance, as shown in Table 8, is a thrust of 59.1 mN and a thrust efficiency of 37.9 % at a specific impulse of 2008 s with an input power of 1.6 kW. There are not data with discharge voltages above 500 V. This is because of unstable operation with the anode glowed at 500 V. This is inferred because the radial magnetic field isn't optimal.

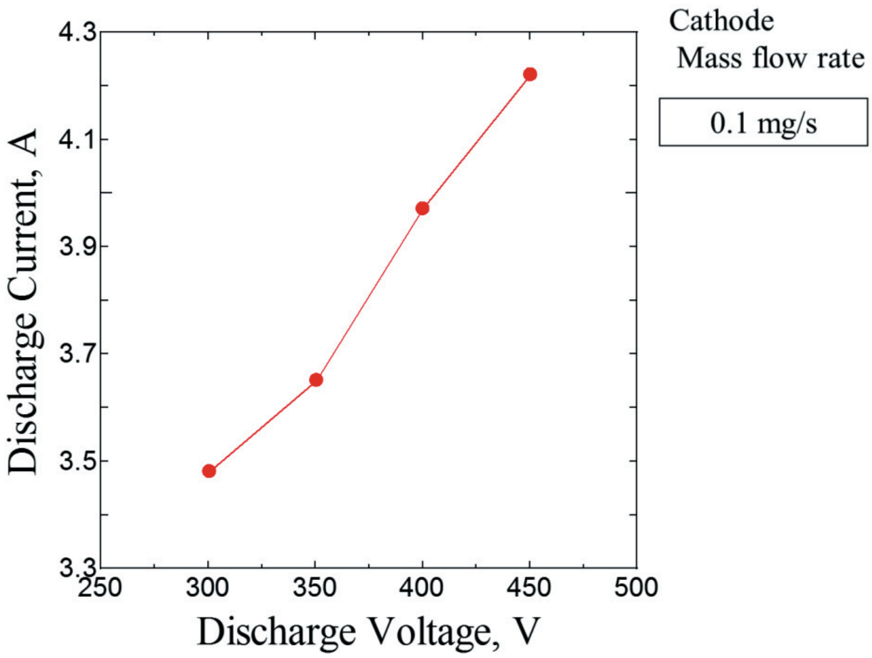


Figure 14. Discharge current vs discharge voltage.

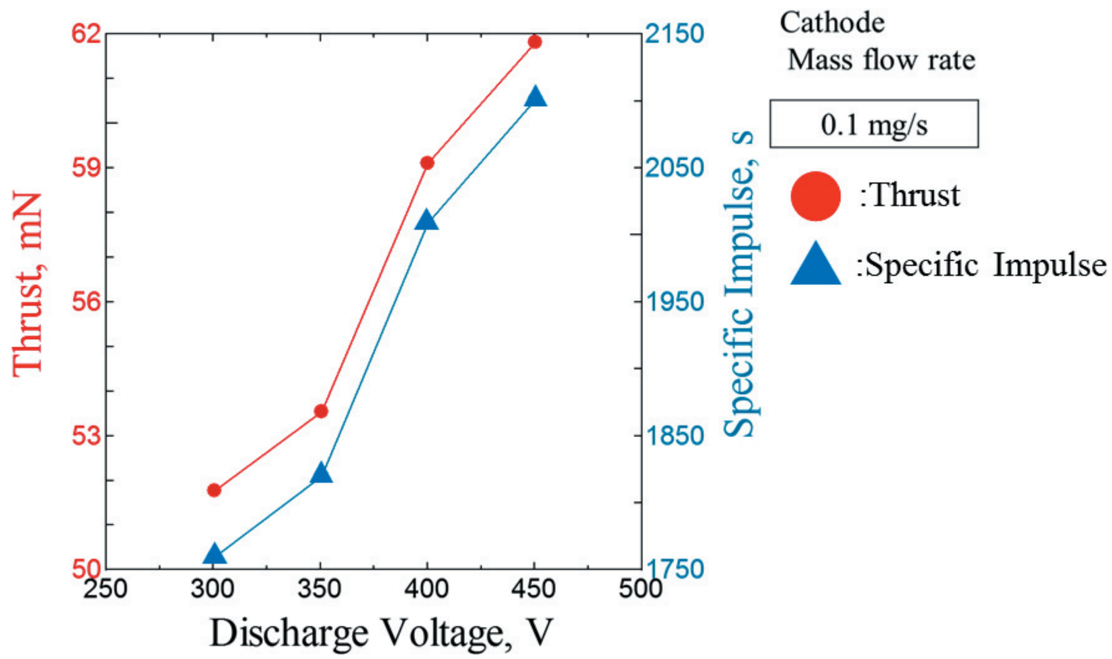


Figure 15. Thrust and specific impulse vs discharge voltage.

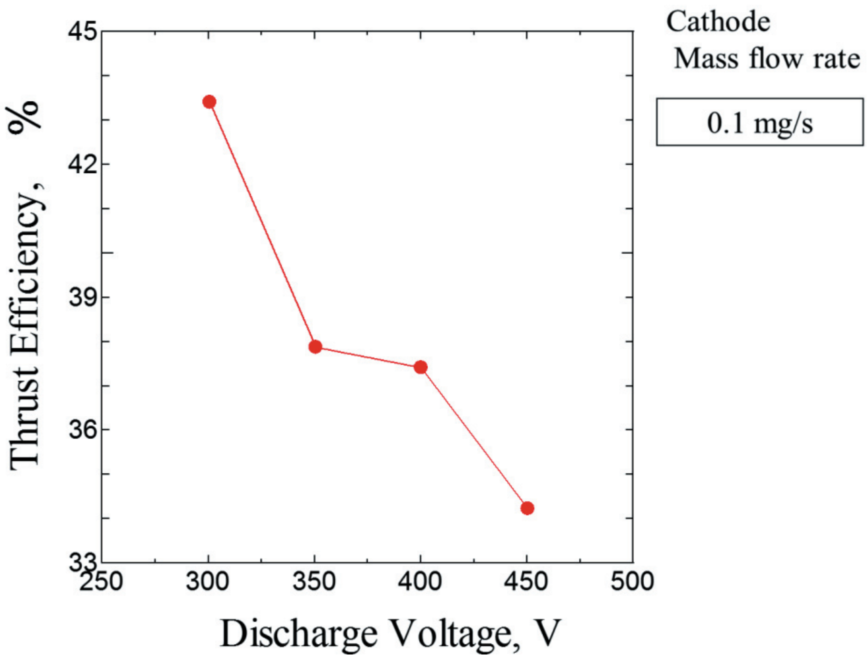


Figure 16. Thrust Efficiency vs discharge voltage.

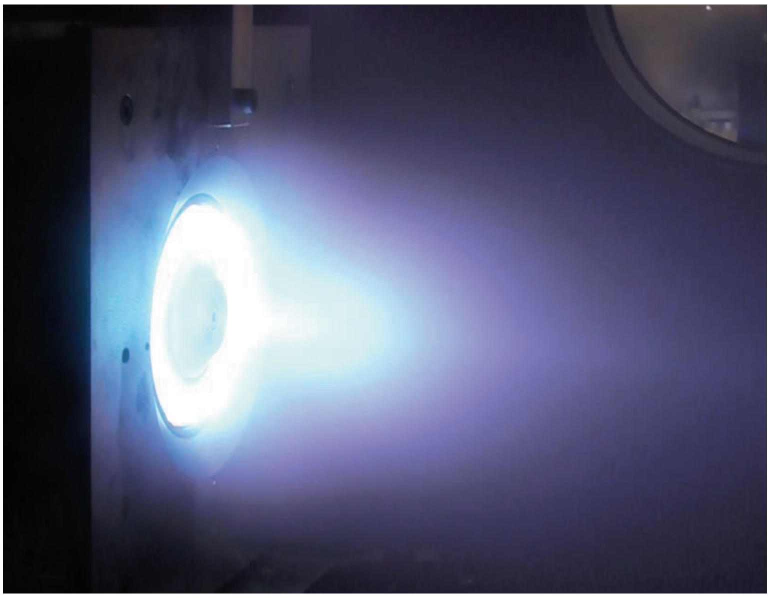


Figure 17. Operation photograph of RAIJIN94 (450 V).

Table 8. Typical thrust performance of RAIJIN94

Discharge Voltage	400 V
Discharge Current	3.97 A
Thrust	59.1 mN
Specific Impulse	2008 s
Thrust Efficiency	37.9 %
Power	1.6 kW

IV. Conclusion

At Osaka Institute of Technology (OIT), high-power and high-specific-impulse characteristics of two Hall thrusters of the 1-kW-class laboratory-model TALT-2 and the 5-kW-class prototype RAIJIN94 were measured in order to obtain basic thruster performances with high discharge voltages and large mass flow rates, i.e. with high power operations and to understand practical problems for in-space propulsion.

With TALT-2 thruster, typical thrust performance is a thrust of 82.5 mN and a thrust efficiency of 38.1 % at a specific impulse of 2803 s with an input power of 2.9 kW. As for RAIJIN94 thruster, typical thrust performance is a thrust of 59.1 mN and a thrust efficiency of 37.9 % at a specific impulse of 2008 s with an input power of 1.6 kW. There are not data with discharge voltages above 500 V. It was found that the TALT-2 thruster is promising for the future missions although the operations were thermally severe. As RAIJIN94 thruster we must find an optimal magnetic field condition. At OIT, a new large-scale high-power TAL thruster is under design.

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