Performance Characteristics and Interior Plasma Phenomena of High-Power and High-Specific-Impulse Hall Thrusters for Manned Mars Exploration

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Abstract: In Hall thruster R&D, high thrust, high thrust efficiency and long lifetime are required for In-Space missions such as manned Mars exploration and 1 GW-class solar power satellite construction. However, current situation does not satisfy these conditions. Therefore, the Hall thruster is required to improve the performance. In this study, the performance characteristics were measured with SPT-type and TAL-type Hall thrusters in the range of discharge voltage 300-1,000 V. In addition, in order to improve performance, it is necessary to understand plasma feature inside the discharge channel and to predict its performance. However, it is hard to make plasma diagnostics measurements inside the discharge channel. Therefore, numerical calculation using two-dimension Hybrid PIC model for the THT-VI was carried out. The validity of this model was verified by comparison between calculated and measured results.

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I. Introduction

Activities of Hall thruster R&D are required to space development in the future. This is because the Hall thruster is suitable for excellent propulsion performance, simple structure and small size. Future projects of electric propulsion for construction of large 1 GW-class solar power satellites and moon bases, and manned Mars exploration of in-space mission have been proposed. However, current Hall thrusters do not satisfy all performances, although when considering potentials of lifetime, efficiency, compact and performance, the improvement is required to meet it for achieving various future missions. The final goal of this study is development of high-power and high-specific-impulse SPT-type (Stationary Plasma Thruster) and TAL-type (Thruster with Anode Layer) Hall Thrusters. In this study, performance measurement was performed using the SPT-type and TAL-type Hall thrusters developed at Osaka Institute of Technology (OIT). The operations were carried out at a discharge voltage of 300-1000V. Then, the performance was aimed at achievement of specific impulse more than 3000 s. Also, in order to improve performance, it is necessary to understand plasma feature inside the discharge channel and predict its performance. However, it is hard to make plasma diagnostics measurements inside the discharge channel. Therefore, numerical calculation using two-dimension Hybrid PIC model for the THT-VI was carried out. The validity of this model was verified by comparison between calculated and measured results.

II. Experimental Apparatus

A. Vacuum Facility at OIT

Figure 1 shows the vacuum chamber and pumping system which is normally used in an experiment. The experimental apparatus consists of three subsystems: a vacuum exhaust system apparatus, a thruster operation system and a thrust force measurement apparatus. The used vacuum chamber is shown in Fig. 2. Table 1 also shows the specifications of the vacuum chamber and vacuum pump. The vacuum chamber is water cooling jacket type and can be used for long time experiments such as thruster durability tests. The vacuum pumping system consists of the vacuum chamber itself and two turbo molecular pumps and a rotary pump which are connected in series the chamber. In the rotary pump, a rotary pump "VD301" of Japan Aerospace Technology Co., Ltd. is used. If conditions of 15 Pa or less are required, a Turbo molecular pump "TG 5000" developed by Osaka Vacuum Equipment Manufacturing Co., Ltd. is used. By this procedure, the internal pressure can be reduced to a maximum of 3.3 x 10^{-3} Pa.

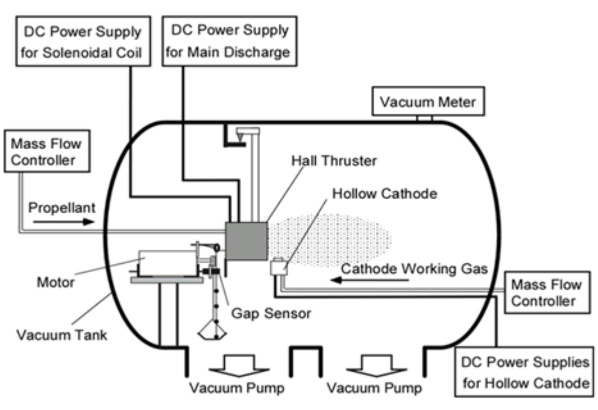


Figure 1. Experimental facility for Hall thruster at OIT.

Figure 2. Overview of vacuum chamber at OIT.

Table 1. Specifications of vacuum chamber and vacuum pump at OIT.

Chamber	
Length	2,250 mm
Diameter	1,200 mm
Pump	
Exhaust Velocity	10,000 L/s
Internal Pressure	3.3 x 10^{-3} Pa

B. Vacuum Facility at JAXA

In this study, some experiments were conducted by using a large vacuum chamber system with a high pumping performance in the Institute of Space and Astronautical Science (ISAS), Japan Aerospace eXploration Agency (JAXA), in which microwave ion engines onboard the HAYABUSA and HAYABUSA2 were operated and developed. The experimental conditions are the same as experiments performed in our university OIT. Figures 3 and 4 show the overview and the sub chamber A, respectively, of the vacuum chamber system. Figure 5 shows the experimental setup in the sub chamber A. The HAYABUSA vacuum chamber system is consisted of main chamber, sub chamber A, sub chamber B. Our experiments with THT-VI Hall thruster were carried out in the sub-chamber A directly connected to the main chamber. Table 2 shows the specifications of the vacuum chamber and vacuum pump.

Figure 3. Experimental facility for HAYABUSA and HAYABUSA2 microwave ion engines at ISAS, JAXA.

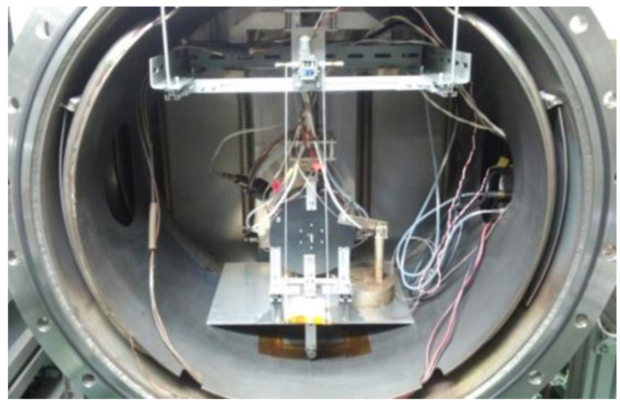


Figure 4. Overview of sub chamber A.

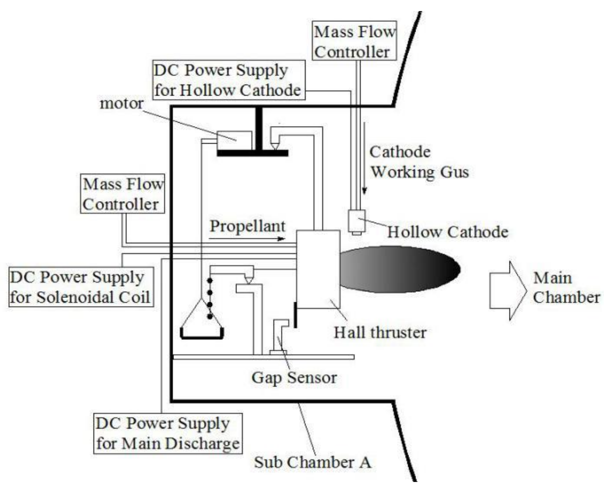


Figure 5. Experimental setup in sub chamber A.

Table 2. Specifications of vacuum chamber and vacuum pump at JAXA.

Main Chamber	
Length	5,000 mm
Diameter	2,000 mm
Sub Chamber A	
Length	600 mm
Diameter	800 mm
Pumps	
Turbo Molecular Pump	
Exhaust Velocity	140 L/a
Cryo Pump	
Exhaust Velocity	28,000 L/a
Internal Pressure	3.25 x 10^{-5} Pa

III. THT-VI

A. Outline of THT-VI

An external and a sectional view of the SPT type Hall thruster named THT-VI are shown in Fig. 6 and Fig. 7, and Fig. 8 shows the calculated magnetic shapes. Regarding the magnetic field shape, experiments were conducted under two kinds of conditions, so they are shown respectively. Furthermore, the specifications of the discharge channel and the coil are shown in Table 3, and Table 4.

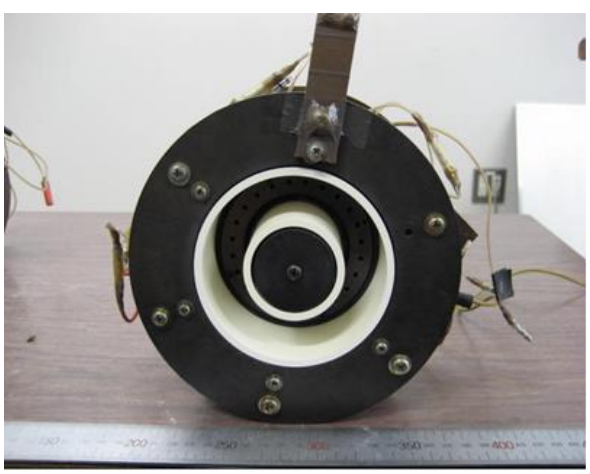


Figure 6. Overview of THT-VI.

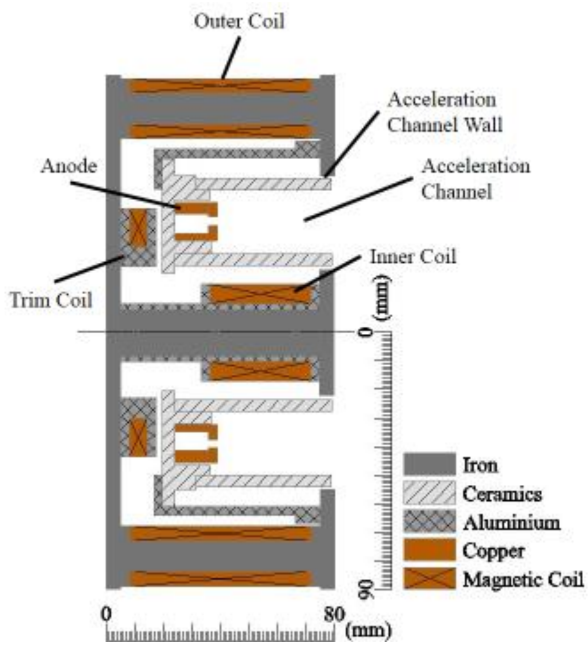
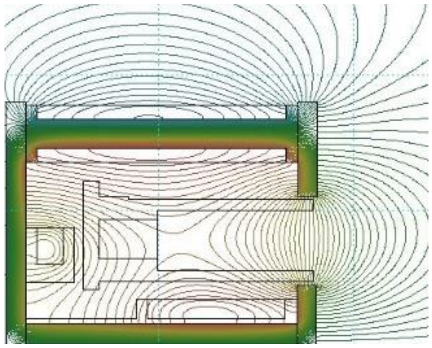
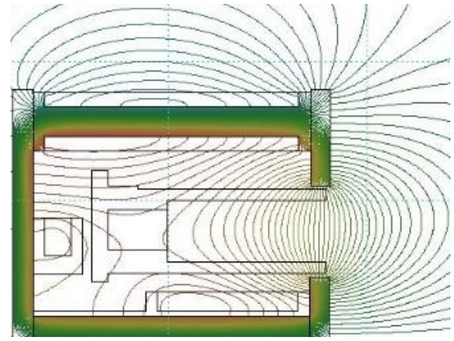


Figure 7. Cross-section view of THT-VI.



(a) Coil current 0.3, 0.3, 0.9 (Outer, Inner, Trim)



(b) Coil current 0.45, 0.45, 0.6 (Outer, Inner, Trim)

Figure 8. Magnetic field of THT-VI

Table 3. Specification of THT-VI discharge channel.

Discharge Channel	
Length	40 mm
Outer Diameter	100 mm
Inner Diameter	56 mm
Material	Boron Nitride

Table 4. Specification of THT-VI magnetic coils.

	Outer Coil	Inner Coil	Trim Coil
Quantity	6	1	1
Number of Turns	1,400	1,200	350
Material	Copper φ0.5 mm		

B. Experimental Conditions

The experiments were conducted under two kinds of experimental conditions. Table 5 shows the experimental conditions conducted at JAXA, and Table 6 shows the experimental conditions conducted at OIT.

Table 5. Experimental conditions of THT-VI (JAXA).

Discharge Voltage	300-1,000 V	
Propellant	Xenon	
Mass Flow Rate	THT-VI	3.0 mg/s
	Hollow Cathode	0.1-0.2 mg/s
Coil Current	0.3A, 0.3A, 0.9A (Outer, Inner, Trim)	
Back Pressure	3.55 x 10^{-3} Pa	
Vacuum Facility	JAXA Chamber	

Table 6. Experimental conditions of THT-VI (OIT).

Discharge Voltage	300-1,000 V	
Propellant	Xenon	
Mass Flow Rate	THT-VI	3.0, 4.0 mg/s
	Hollow Cathode	0.1 mg/s
Coil Current	0.45A, 0.45A, 0.6A (Outer, Inner, Trim)	
Back Pressure	6.0 x 10^{-2} Pa	
Vacuum Facility	OIT Chamber	

C. Experimental Results

Figures 9-12 show the characteristics of discharge current, thrust, specific impulse and thrust efficiency as a function of discharge voltage. Furthermore, a photo of the successful operation of the thruster at the discharge voltage of 1,000 V is shown in Fig.13.

In these experiments, both propellant mass flow rates were successfully tested up to discharge voltage of 1,000 V.

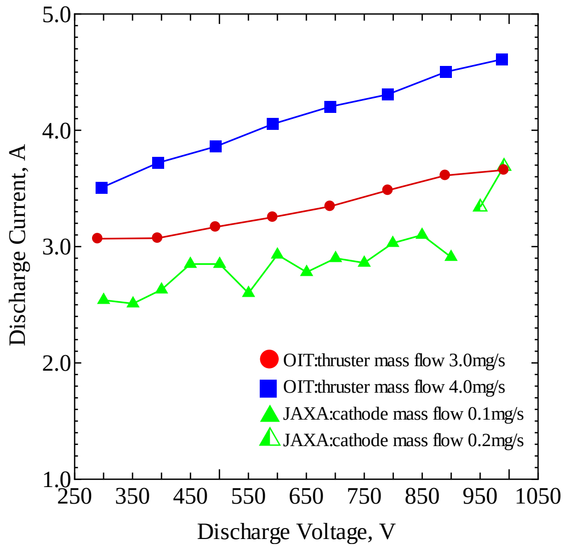


Figure 9. Discharge current vs discharge voltage.

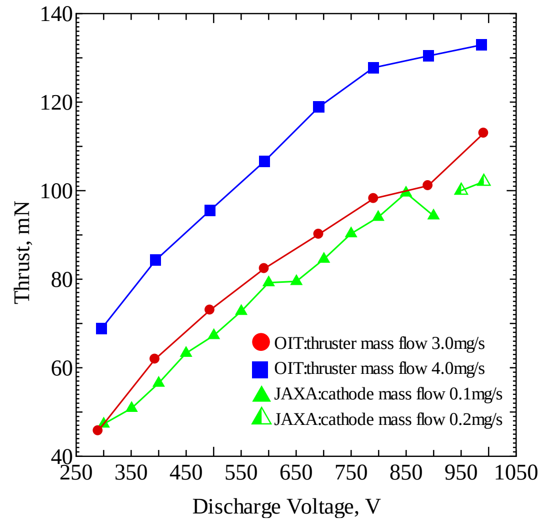


Figure 10. Thrust vs discharge voltage.

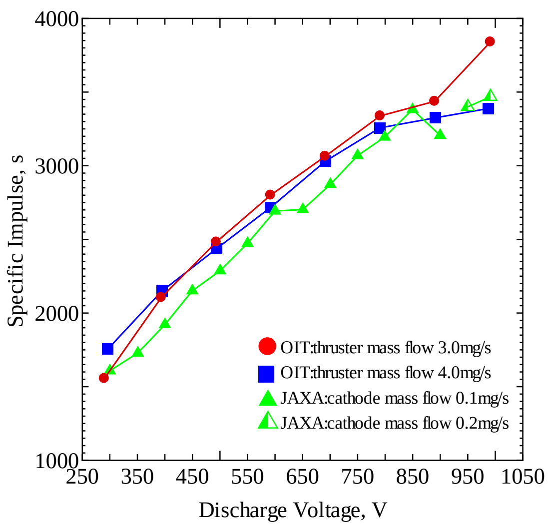


Figure 11. Specific Impulse vs discharge voltage.

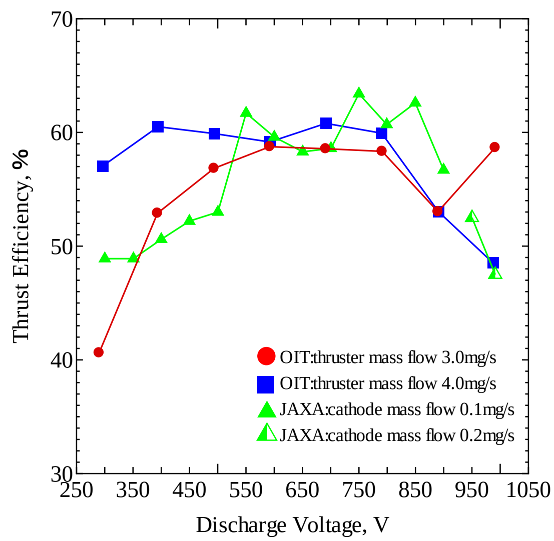


Figure 12. Thrust efficiency vs discharge voltage.

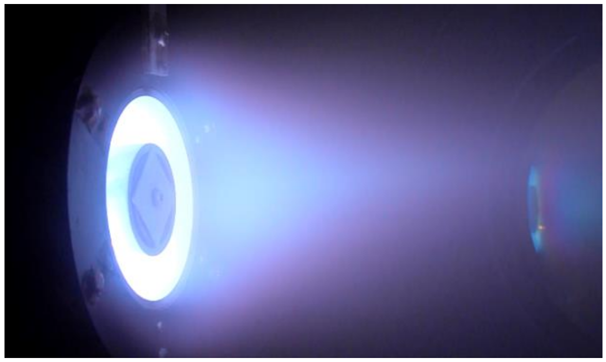


Figure13. Photo of operation at discharge voltage of 1,000 V.

In the experiment in the JAXA, red heat was confirmed in the discharge channel when operating at a discharge voltage of 850 V. In the previous experiments, thruster was broken by overheating during operation at a discharge voltage of 1,000 V. Thus, temporarily interrupted the experiment, cooled the thruster Therefore, ionization was not promoted more than at a discharge voltage before 850 V and affects the parameters after at a discharge voltage of 900 V. Also, the shape of magnetic field was not optimum at a discharge voltage of 950 V to 1,000 V, so it is expected that it was reached the anode without being able to capture electrons well.

Therefore, we carried out measure the performance with new magnetic field shape in OIT. As a result, stable operation was successful with discharge voltage of 300 V to 1,000 V. Moreover, the performance improvement was seen even compared with the experimental result of JAXA. Regarding the discharge current, the experiment conducted by JAXA was lower than the experimental result, because it is considered difference in the back pressure of chamber.

IV. TALT-2B

A. Outline of TALT-2B

Figure 14 shows an external view of the improved TAL type Hall thruster "TALT - 2B", Fig. 15 shows a cross-section view of the same thruster, and Fig. 16 shows the calculated magnetic shapes. Furthermore, the specifications of the discharge channel and the coil are shown in Table 7, and Table 8.

In previous operation tests, it was found out that the operation in the high voltage region is difficult due to the burnout of the outer coil, the melting of the anode, and the breakage of the ceramics which are the result of the thermal expansion of the anode. Therefore, OIT developed a TALT-2B which improved the thruster head while preserving the shape of the discharge channel. The first point of improvement is that the outer coil was changed from a one ring - shaped air core coil to six cored coils. The idea behind this change was that the burnout can be avoided by the separation of the outer coil from the discharge channel. Therefore, the shape of THT-VI was adopted. The second point is that gaps are formed in the ceramics around the anode. The damage of the ceramics was caused by the absence of gaps. In detail, a large gap was added by fitting the ceramics together.

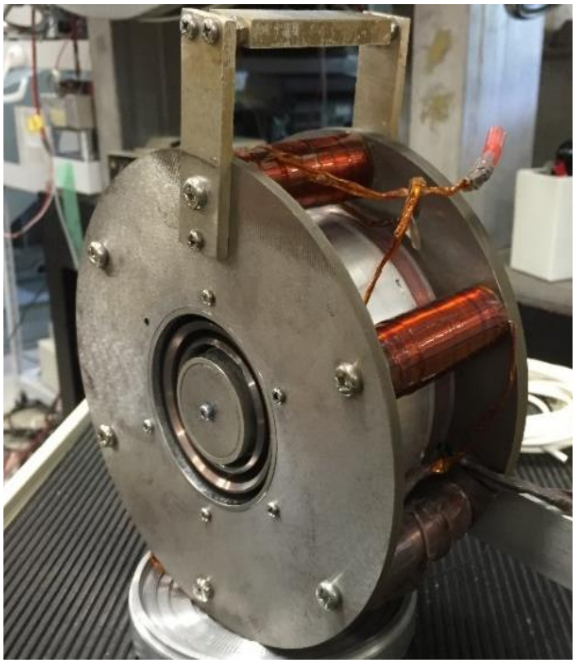


Figure 14. Overview of TALT-2B.

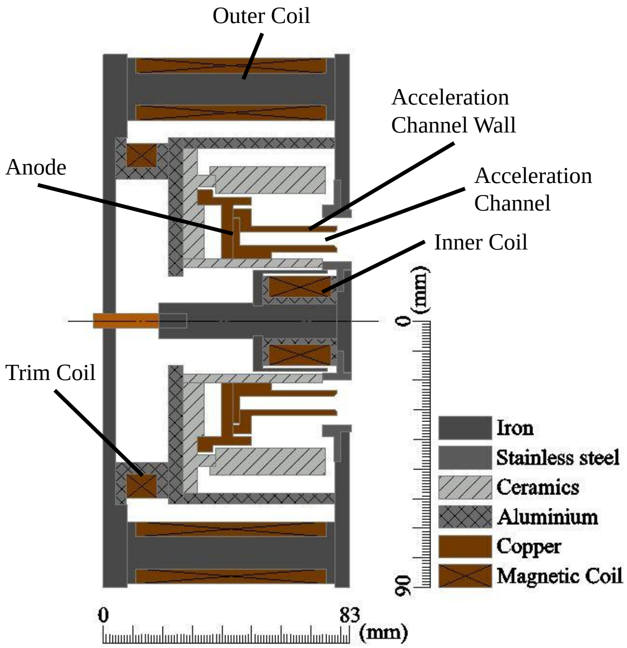


Fig 15. Cross-section view of TALT-2B

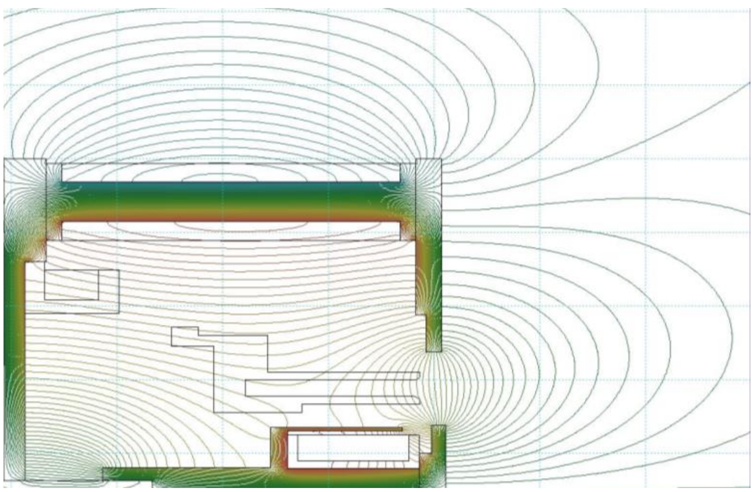


Figure 16. Magnetic Field of TALT-2B

Table 7. Specification of TALT-2B discharge channel.

Discharge Channel	
Length	35 mm
Outer Diameter	65 mm
Inner Diameter	45 mm
Material	Copper

Table 8. Specification of TALT-2B coil.

	Outer Coil	Inner Coil	Trim Coil
Quantity	6	1	1
Number of Turns	1,400	480	240
Material	Copper φ0.5 mm		

B. Experimental Conditions

The experimental conditions of TALT-2B are shown in Table 9. To confirm the stability of the operation the discharge voltage was increased successfully from 300 V to 500 V.

Table 9. Experimental conditions of TALT-2B.

Discharge Voltage	300-500 V	
Propellant	Xenon	
Mass Flow Rate	TALT-2B	3.0 mg/s
	Hollow Cathode	0.1 mg/s
Coil Current	1.2 A, 2.0 A, 2.0 A (Outer, Inner, Trim)	
Back Pressure	6.0 x 10^{-2} Pa	
Vacuum Facility	OIT Chamber	

C. Experimental Results

The experimental results like discharge voltage, discharge current, thrust, specific impulse and thrust efficiency are presented in Table 10.

This experiment was planned to operate up to the discharge voltage of 1,000 V. The experiment was stopped because operation of thruster became unstable at 600 V. After the experiment, melting of the anode and burnout of the inner coil were confirmed.

Table 10. Experimental results of TALT-2B.

Discharge Voltage	300 V	400 V	500 V
Discharge Current	4.6 A	5.4 A	6.2 A
Thrust	37 mN	44 mN	50 mN
Specific Impulse	1,260 s	1,490 s	1,690 s
Thrust Efficiency	16%	15%	13%

V. RAIJIN94

A. Outline of RAIJIN94

The external view and 3D model of the TAL type Hall thruster “RAIJIN94” is shown in Fig. 17 and Fig. 18, and Fig.19 shows the calculated magnetic field. Furthermore, the specifications of the discharge channel and the coil are shown in Table 11, and Table 12.

RAIJIN 94 was produced at the "Department of Advanced Energy Engineering Science, Graduate School of Engineering Sciences, Kyushu University", with the aim of developing a 10 kW class Anode-Layer type Hall thruster. The previous stage of the thruster was 5 kW.

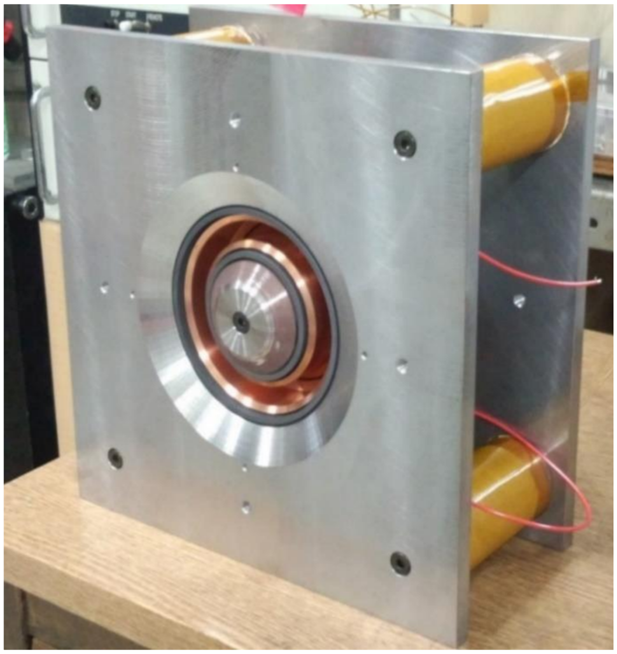


Figure 17. Overview of RAIJIN94

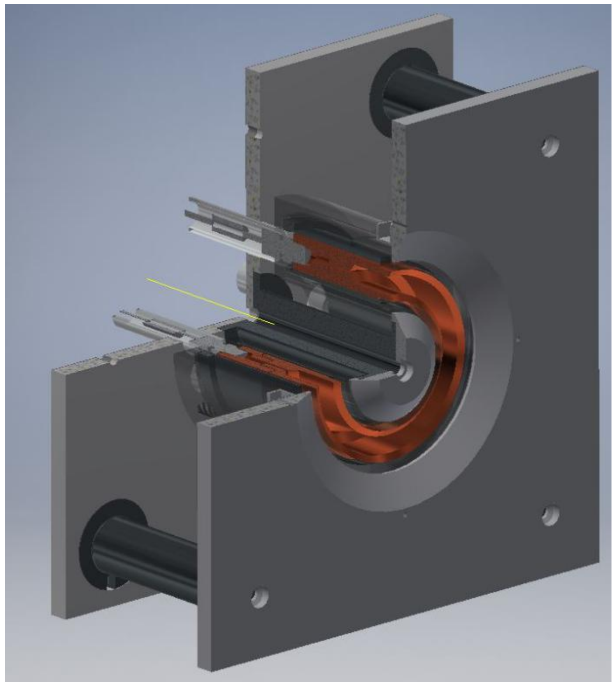


Figure 18. 3D model of RAIJIN94.

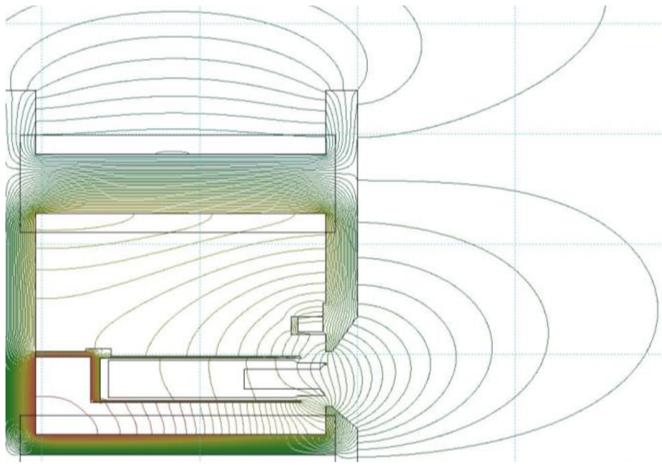


Figure 19. Magnetic field of RAIJIN94.

Table 11. Specification of RAIJIN94 discharge channel

Discharge Channel	
Length	55 mm
Outer Diameter	94 mm
Inner Diameter	60 mm
Material	Copper

Table 12. Specification of RAIJIN94 coil

	Outer Coil	Inner Coil	Trim Coil
Quantity	4	1	1
Number of Turns	736	736	100
Material	Copper φ1.0 mm		

B. Experimental Conditions

The experimental conditions for "RAIJIN94" are shown in Table 13.
We could confirm the operation in increments of 50 V from a discharge voltage of 300 V to 1,000 V. Experiments were carried out with two different propellant: Xenon, Krypton. This experiment was conducted with JAXA's experimental facility.

Table 13. Experimental conditions of RAIJIN94.

Discharge Voltage	300-1,000 V	
Propellant	Xenon, Krypton	
Mass Flow Rate	RAIJIN94	3.0 mg/s
	Hollow Cathode	0.1 mg/s
Coil Current	0.8 A, 0.8 A, 2.0 A (Outer, Inner, Trim)	
Back Pressure	3.55×10^{-3} Pa	
Vacuum Facility	JAXA Chamber	

C. Experimental Results

Figures 20-23 show the characteristics of discharge current, thrust, specific impulse and thrust efficiency as a function of discharge voltage.

During krypton operation, red heat was observed at the anode at a discharge voltage of 850 V. Thus, the experiment was stopped. Essentially, thrust, specific impulse and thrust efficiency should all increase proportional to the input voltage in case of Hall thrusters. But in the experiments only the thrust and specific impulse showed a linear increase, the thrust efficiency had a decreasing behavior.

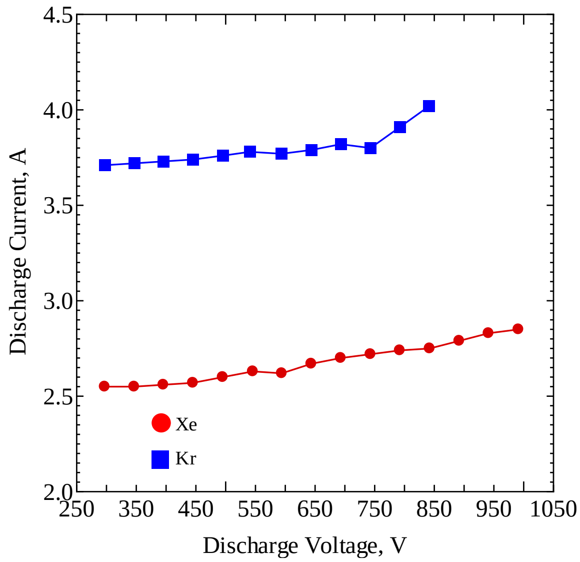


Figure 20. Discharge current vs discharge voltage.

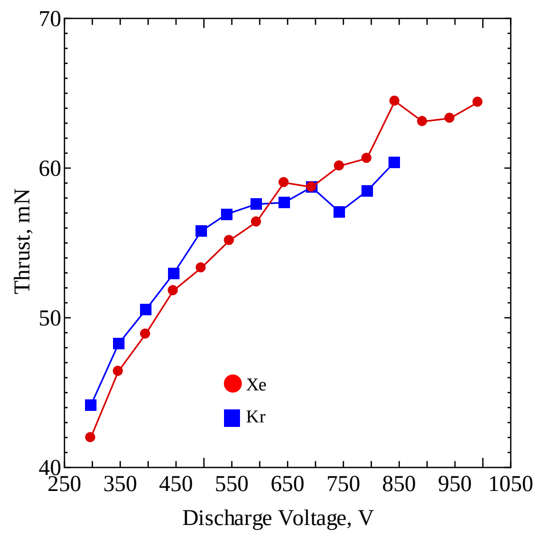


Figure 21. Thrust vs discharge voltage.

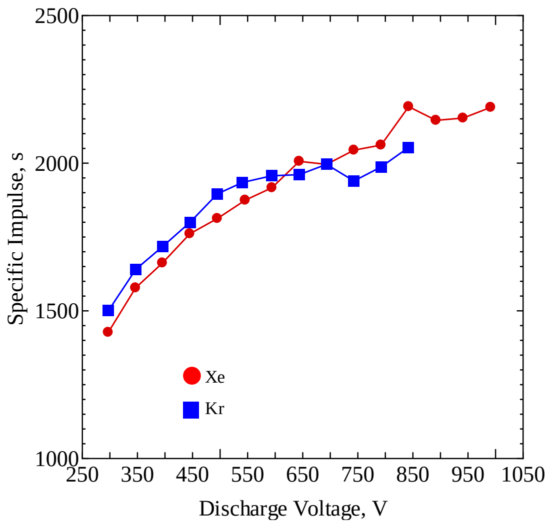


Figure 22. Specific Impulse vs discharge voltage.

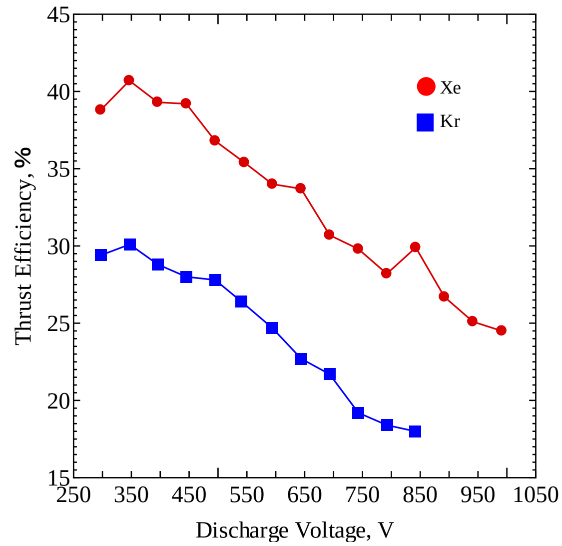


Figure 23. Thrust efficiency vs discharge voltage.

VI. Numerical Calculation

A. Method of Calculation

As a calculation method, the Hybrid-PIC model which calculates heavy particles (ions, neutral particles) by using the particle method and calculates the electrons as a fluid model was adopted. A flowchart of the calculation is shown in Fig.24. First, set initial conditions. Next, ionization collision determination of neutral particles is performed to calculate the density and velocity of heavy particles. Next, calculate the electron temperature and electric potential by computing with the fluid model of electrons and finish the calculation after the values converge.

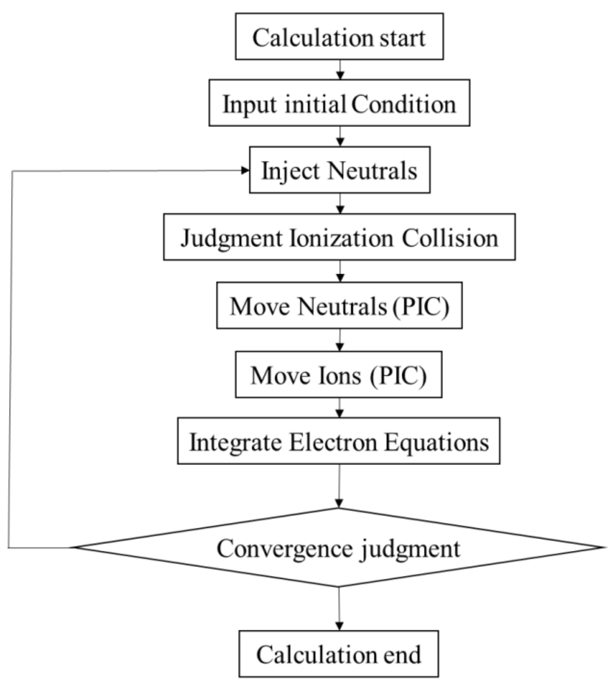


Figure 24. Flowchart for calculation.

B. Calculation Region

The calculation model is shown in the Fig. 25. As shown in the figure, the calculation area is inside the discharge channel and 10 mm downstream.

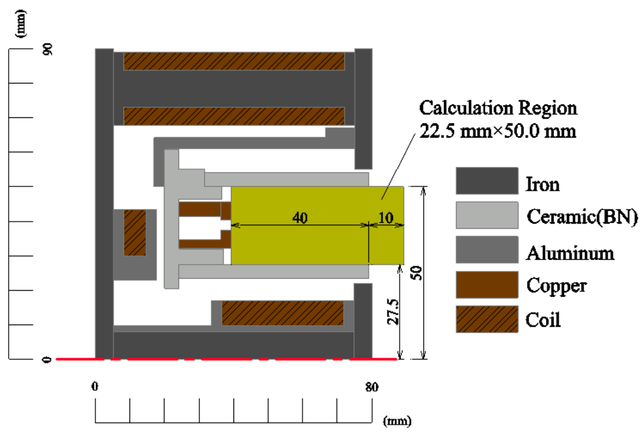


Figure 25. Hybrid-PIC model for the THT-VI.

C. Calculation Conditions and Results

In order to verify the validity of this model, calculations were performed under the same conditions as Table 5. The calculation conditions are shown in Table 14. Figures 26-29 show the characteristics of discharge current, thrust, specific impulse and thrust efficiency as a function of discharge voltage.

Table 14. Calculation conditions

Discharge Voltage	300-1,000 V
Propellant	Xenon
Mass Flow Rate[mg/s]	3.0 mg/s
Maximum Magnetic Field Strength[T]	0.013 T

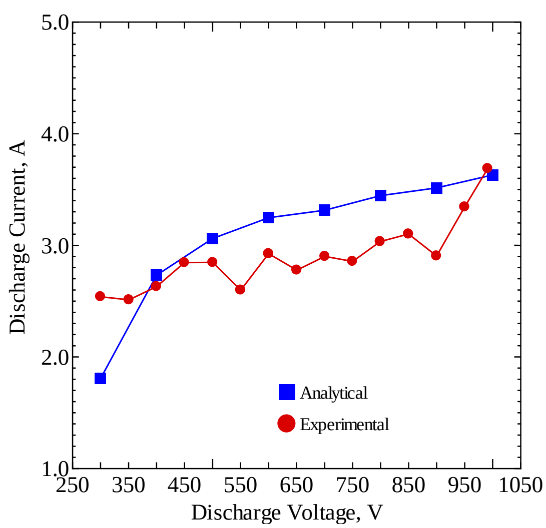


Figure 26. Discharge current vs discharge voltage.

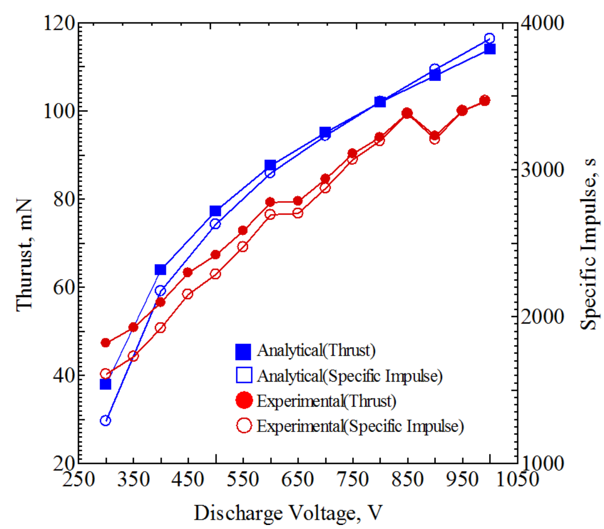


Figure 27. Thrust・specific impulse vs discharge voltage.

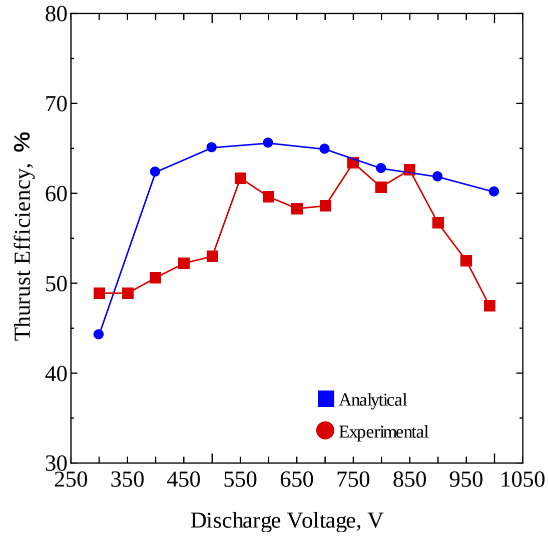


Figure 28. Thrust efficiency vs discharge voltage.

From Fig. 24 - 26, it was possible to approximate the experimental value to an average error of about 13% in all graphs.

VII. Conclusion

A. THT-VI

In the SPT type Hall thruster "THT-VI", stable operation from a discharge voltage of 300 V to 1,000 V was confirmed under both conditions. In the experiment at JAXA, the thrusts between 47 and 110 mN, specific impulses between 1,600 and 3,400 s, thrust efficiencies between 48 and 61% could be achieved. In the experiment at OIT, for a propellant mass flow rate of 3.0 mg/s, thrusts between 46 and 112 mN, specific impulses between 1,550 and 3,840 s, thrust efficiencies between 40 and 59% could be achieved. For a propellant mass flow rate of 4.0 mg/s, thrusts between 68 and 133 mN, specific impulses between 1,750 and 3,400 s, thrust efficiencies between 48 and 61% could be achieved. In the future, we plan to conduct to raise the reliability of the data and perform performance measurements with other propellants.

B. TALT-2B

In response to previous study results, we have developed a TAL type Hall thruster "TALT-2B" with improved ceramics in the area of the outer coil and the anode contact part.

In TALT-2B, stable operation from a discharge voltage of 300 V to 500 V was confirmed. For this thruster thrusts between 37 and 50 mN, specific impulses between 1,260 and 1,690 s and thrust efficiency between 13 and 16% were recorded. However, at a discharge voltage of 600 V, the experiment had to be stopped because extreme red heat was observed on the outer peripheral part of the anode. After the experiment, the melting of the anode and the burnout of the inner coil were confirmed. It is thought that the magnetic forces of the six modified outer coils are excessively strengthened, excessively converging to the inside, the heat is burned in the inner coil and burned out. It is considered that the burning of the inner coil caused the magnetic field shape to be disturbed which made the plume diverge. As a result of the diverging plume the anode melted. On the other hand, improvement of this research is considered reasonable, in that no abnormality was found in ceramics of outer coil and anode contact part. From now on, by improving the inner coil of the TALT-2B, we aim to develop thrusters that can be operated successfully in the high voltage region.

C. RAIJIN94

In the TAL type Hall thruster "RAIJIN 94", stable operation from a discharge voltage of 300 V to 1,000 V was confirmed. In this discharge voltage range thrusts of 42 - 64 mN, specific impulses of 1,430 - 2, 200 s and thrust efficiency of 24 - 41% were recorded. Although the discharge current was relatively constant, the propulsive efficiency showed a decreasing behavior. A too strong magnetic field was considered to be the reason for this decreasing behavior because the plume converged inwards and thus a part of it collided with the discharge chamber walls. Therefore, in the future, we aim for higher thrust efficiencies especially in the high voltage region by optimizing the magnetic field shape.

D. Numerical Calculation

For THT-VI, we verified the validity of this model by carrying out numerical calculation by two-dimensional Hybrid-PIC model. Comparing the calculation result with the experimental result, the average error was about 13%. In the future, we plan to perform performance prediction, in-channel plasma parameters, and simulation of wear of the discharge chamber wall using this model.

References

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