Influences of Magnetic Field Topography and Discharge Channel Structure on Performance of Anode-Layer Hall Thrusters

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Abstract: Experimental studies were carried out to examine the effect of magnetic field topography and discharge channel structure on the performance of 1-kW class anode-layer Hall thruster TALT-2. The thruster was operated with a divergent-type hollow anode under various magnetic field topographies. The dependence of channel length was examined to find out the optimum anode front position. Performance enhancement was realized by using a divergent-type hollow anode under the optimum channel length and various magnetic field topographies. The results showed that some increment in thrust and thrust efficiency was obtained by using the divergent-type hollow anode. The thrust efficiency was enhanced to 57 % with the divergent-type hollow anode at a discharge voltage of 400 V and a xenon mass flow rate of 3.0 mg/s.

I. Introduction

The electric propulsion (EP) device can provide meaningful benefits that expand the application of spacecraft and that allow some attractive space missions.[1,2] The Hall-effect thrusters are very advantageous EP device. The developments of this technology have been carried out mainly in former Soviet Union since 1960's,[3] and in the last decade, further progresses were achieved in the United State, Europe, Russia and Japan.[4-12] Because the Hall thrusters can achieve high thrust efficiency with specific impulses of 1000-3000 sec, they are now used as devices for orbit correction or as the main thruster in some space missions.[1,4] Anode-layer Hall thrusters have a short discharge channel compared to the channel width, and the channel wall is made of electric conductor. In addition, the discharge channel is smaller than that of a magnetic-layer type with same power level. The anode-layer Hall thrusters, therefore, are expected to be accepted as compact EP device with longer lifetime and high thrust performance.

The enhancement of thrust performance of a 1-kW class anode-layer Hall thruster is our recent interest. In a previous investigation,[13] the role of magnetic field distribution in improving performance characteristics of anode-layer Hall thrusters was confirmed. This investigation showed that the thrust and the thrust efficiency increased while the discharge current decreased by increasing the axial gradient of the radial magnetic field inside the hollow anode. The thrust efficiency, however, did not reach our desired value.

In the present study, further enhancement of thrust performance is attempted, and the latest results are reported here. The thruster is operated with a divergent-type hollow anode and a cylindrical discharge channel with varying

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magnetic field topography. Discharge current and thrust are measured; specific impulse and thrust efficiency are estimated. Firstly, the effect of anode front position on performance is examined in different channel length. Then, the thruster which has a divergent-type hollow anode is operated under the optimum channel length to confirm whether the thrust performance can be improved. Evaluation and discussion about this effort and comparisons with thrust performances in our previous experiments, and with Russian SPT100 and TAL D-series are made.

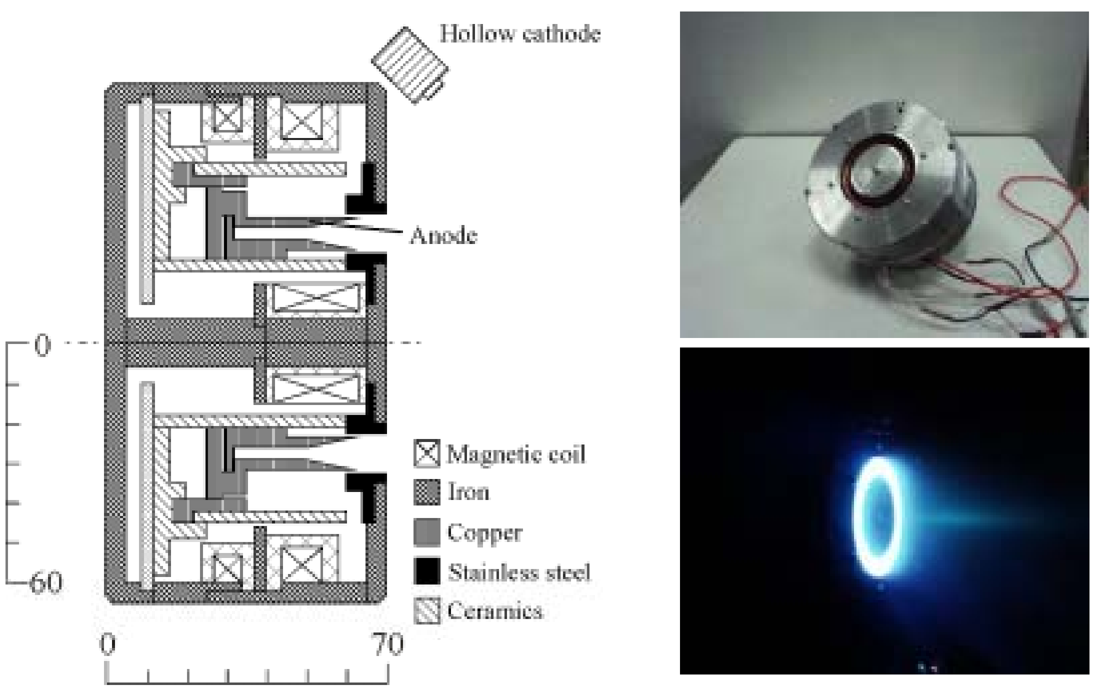
II. Experimental Apparatus

A. TALT-2 Hall Thruster

The TALT-2 Hall thruster is a laboratory-model 1-kW class anode-layer Hall thruster, and is an evolved version of TALT-1.[11,12] Figure 1 shows the thruster with a divergent-type hollow anode. The thruster with a normal-type hollow anode is shown in Ref.13. TALT-2 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. The discharge channel wall is made of stainless steel, and the hollow anode is made of copper. The front position of hollow anode can be changed from 3.0 to 5.0 mm upstream from the discharge channel exit. The obliquity of divergent part of the hollow anode is about 10 deg.

TALT-2 is equipped with three magnetic coils that produce a radial magnetic field inside the discharge channel. One is on the central axis and others are on the inner surface of the outer cylinder. One of the outer solenoidal coils is used as a radial trim coil.[14] When the radial trim coil is energized, the axial distribution of radial magnetic filed strength inside the channel is altered. In operations, a negative current is usually used for the trim coil. Moreover, TALT-2 can be equipped with two magnetic shields, and very sharp axial gradient of the radial magnetic field can be obtained by using both magnetic shields and a trim coil. Figure 2 shows the axial distribution of magnetic field strength on the channel median of TALT-2 without a trim coil and magnetic shields, with a trim coil, and with shields and with a trim coil and shields. As shown in Fig. 2, the axial gradient of magnetic field is changed, and the strength peak point shifts toward channel exit by using magnetic shields and a trim coil.

Xenon is used as the propellant. As the main cathode, a hollow cathode (Iontech HCN-252) is used.



(a) Cross-sectional view. **(b) Photos of thruster and plasma plume.**

Figure 1. Cross-sectional view and photos f TALT-2 Hall thruster with divergent-type hollow anode.

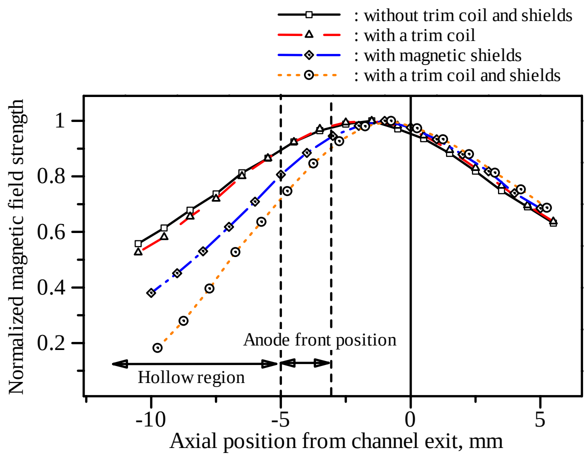


Figure 2. Axial distributions of normalized Radial magnetic field strength.

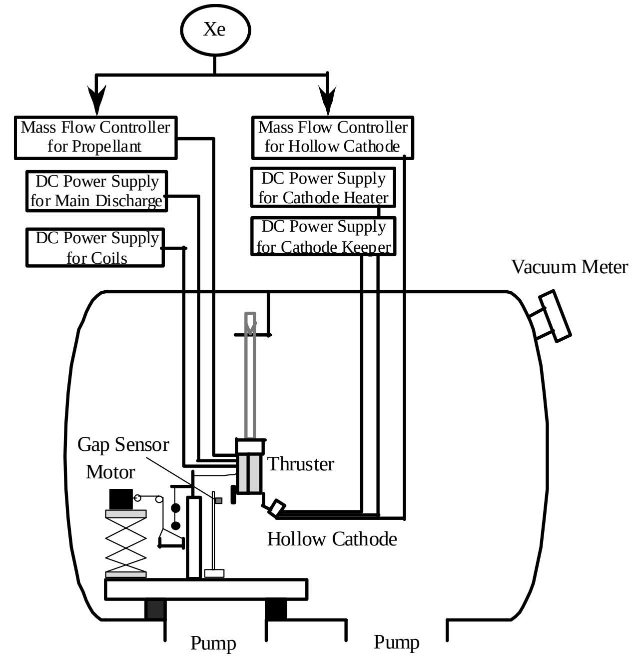


Figure 3. Schematic view of experimental facility.

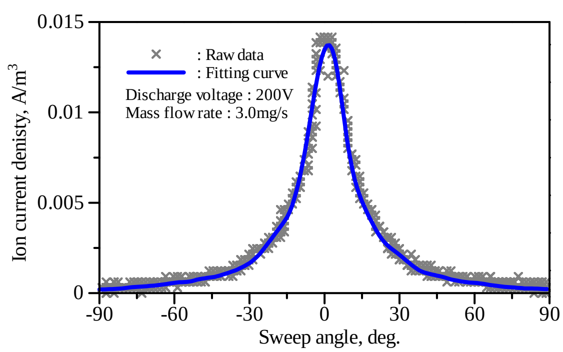


Figure 4. Typical spatial distribution of ion current density by Faraday cup.

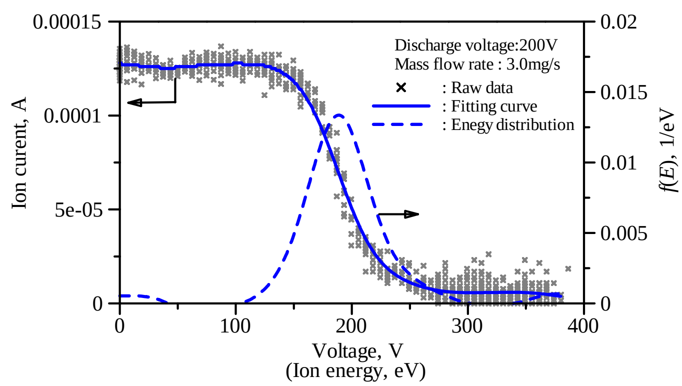


Figure 5. Typical ion current profile and its energy distribution function by retarding potential analyzer.

B. Vacuum Facility

The experimental facility is shown in Fig. 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.

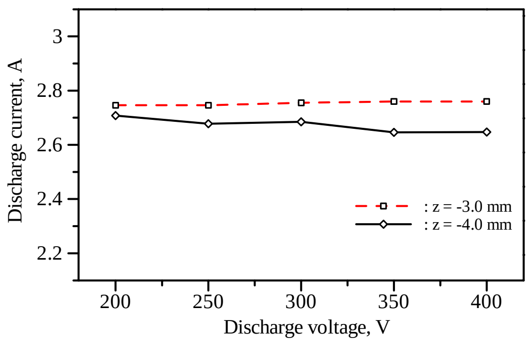
C. Thrust Measurement System

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. 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.

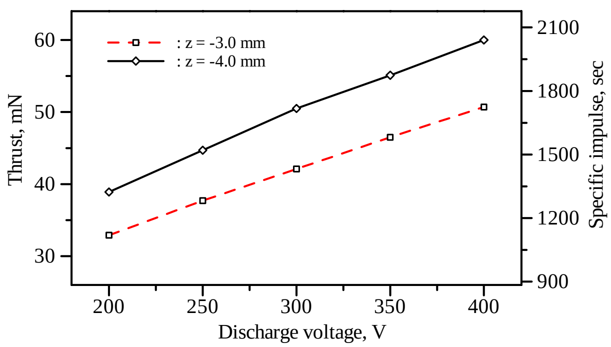
D. Plasma Plume Diagnostic Measurement System

Exhaust plasma diagnostic measurement is also carried out to evaluate plume divergent angles and voltage utilization efficiencies, as shown in Figs. 4 and 5. Ion current spatial profiles are measured with a Faraday cup, and ion energy distribution functions are estimated from data with a retarding potential analyzer (RPA). The Faraday cup and the RPA are located at 20 cm downstream from the thruster exit, and a motor rapidly, semi-circularly moves them.

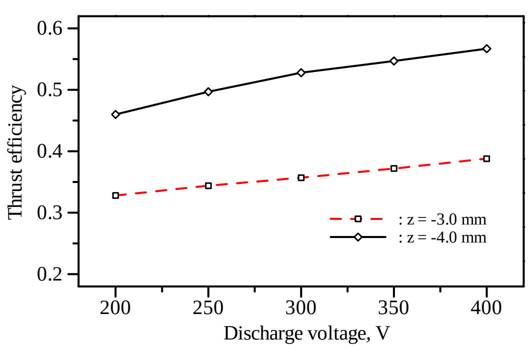
III. Experimental Results



(a) Discharge current.

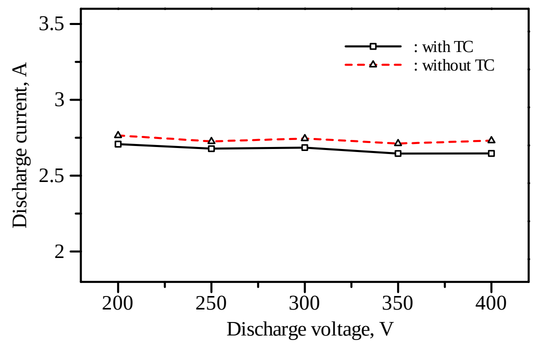


(b) Thrust and specific impulse.

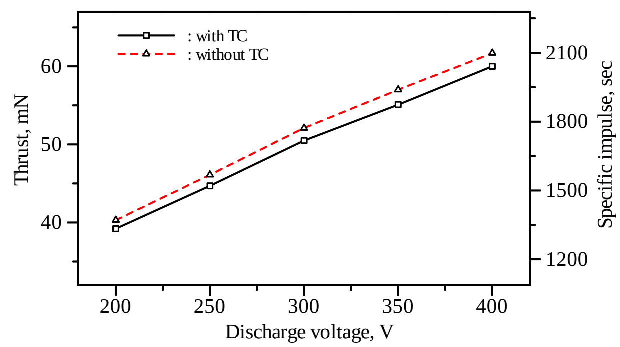


(c) Thrust efficiency.

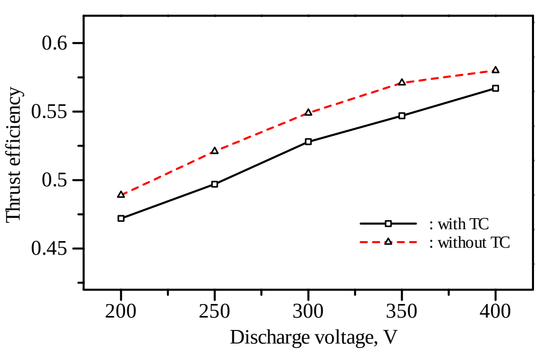
Figure 6. Performance characteristics dependent on discharge channel length.



(a) Discharge current.



(b) Thrust and specific impulse.



(c) Thrust efficiency.

Figure 7. Performance characteristics dependent on magnetic field topography.

A. Dependence of Discharge Channel Length

Firstly, the dependence of discharge channel length was examined. In a previous study, high performance was obtained when the magnetic shields were used.[13] Thus, in this study, the thruster was operated with inner and outer magnetic shields in all operations. The xenon mass flow rate is 3.0 mg/s, and the discharge voltage is varied from 200 to 400 V in increment of 50 V. The anode front position was set to 3.0 and 4.0 mm upstream from the channel exit. The current ratio of inner-coil/outer-coil was set to 1.0, and the ratio of trim-coil/other-coils was also set to 1.0. At each voltage, data was acquired under the optimum coil current that minimized the discharge current and current oscillation.

Figure 6(a) shows the discharge current characteristics. The current in the case of -4.0 mm is lower than that of -3.0 mm, especially in the high voltage region. The current characteristic of -3.0 mm is more stable compared to that with the normal-type hollow anode.[13] The thrust and the specific impulse, as shown in Fig. 6(b), are increased with shifting the anode to upstream of the channel. The inclement is about 8.0 mN over the operated range. As a result, the thrust efficiency, as shown in Fig. 6(c), is improved about 20 % by extending the channel length.

The decline in thrust and the increment in discharge current is probably due to the deterioration of propellant utilization and increment in axial electron current accomplished by insufficient ionization, respectively. The stabilization of operation in the case of -3.0 mm with using a divergent-type hollow anode is probably attributed to an enlargement of surface inside the hollow anode at which the electron is collected.

B. Effect of Magnetic Field Topography

The effect of magnetic field topography on performance characteristics with the divergent-type hollow anode is the next issue. The thruster was operated with using an auxiliary trim coil. The discharge voltage range and the mass flow rate were the same as that of the previous operation. The anode front position was set to -4.0 mm upstream from the channel exit in accordance with the results in section III-A.

The discharge current is slightly suppressed by energizing the trim coil, as shown in Fig. 7(a). In figure legends, “TC” represents the auxiliary trim coil. Figure 7(b) shows the thrust and specific impulse. The thrust and the specific impulse are declined, and that is opposite to the characteristic of the operation with the normal-type hollow anode in which there was no change in thrust and specific impulse by using the trim coil.[13,14] The discussion about the cause of this trend is described later in this paper. Consequently, as shown in Fig. 7(c) the thrust efficiency decreases with using the trim coil.

IV. Discussion

A. Thrust Performances with Divergent-Type Hollow Anode

As shown in Fig. 6(b), the thrust and the specific impulse with the anode front position of -3.0 mm increases monotonically with discharge voltage. In operation with the normal-type hollow anode, the thrust declined in the

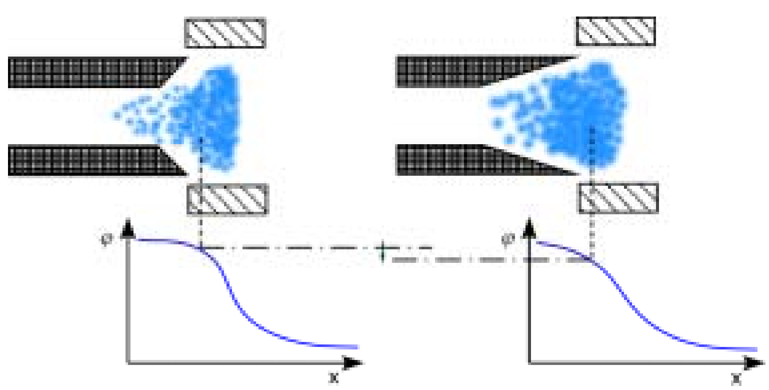
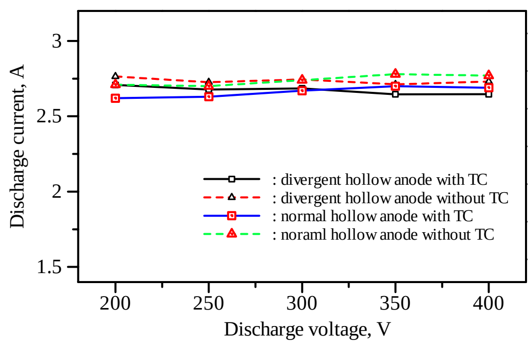


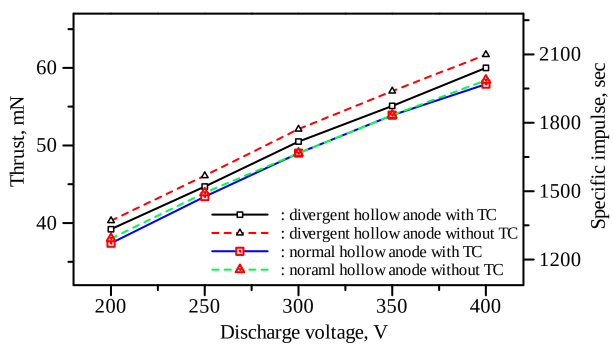
Figure 8. Difference of ionization and ion acceleration between normal-type and divergent-type hollow anodes.

high-voltage region (300-400 V).[13] The characteristic length of ionization and ion accelerating layer is expected to extend with increasing discharge voltage.[4] As shown in Fig. 8, a divergent-type hollow anode seems to enable the ionization and acceleration region to expand smoothly toward the upstream of the hollow region. Thus, a sufficient length of such layer is obtained in the high voltage region. Also the discharge becomes more stable by using the divergent-type hollow anode. It is expected to be attributed to smooth expansion of plasma into the hollow region and an increment in electron collecting surface inside the hollow anode.

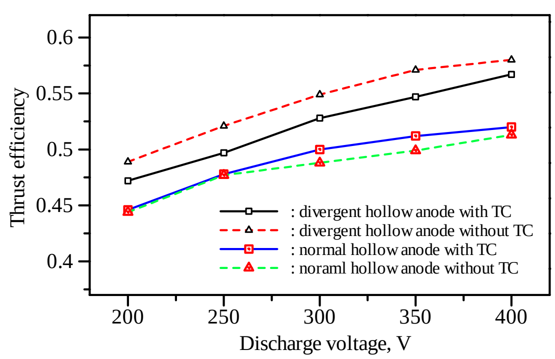
Figure 7(b) reveals that the thrust and the specific impulse decreased with the trim coil. A reduction of propellant utilization efficiency is possible explanation. The temperature of electron in upstream of the hollow anode decreases, and the ionization region is considered to be shrunk due to the decrement in magnetic field intensity.



(a) Discharge current.



(b) Thrust and specific impulse.



(c) Thrust efficiency.

Figure 9. Performance comparisons between operations with normal-type and divergent-type hollow anodes.

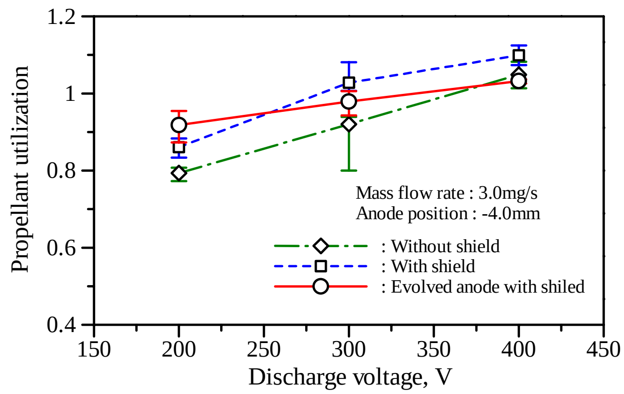
B. Comparisons of Thrust Performance

Figure 9 shows the performance comparisons between the operation with the normal-type hollow anode and that with the divergent-type hollow anode. Figure 9(a) shows the comparison of discharge current. There is no significant change in current characteristics. As shown in Fig. 9(b), the thrust enlarges when the divergent-type hollow anode is used. In the case of the divergent-type hollow anode, it is expected that the wide region for ion production is secured inside the discharge channel; i.e., the propellant utilization efficiency, as shown in Fig. 10(a), is higher than that of the normal-type hollow anode, although the beam divergent half-angle shown in Fig. 10(b) is not changed and the voltage utilization efficiency shown in Table 1 is slightly decreased. Because of this improvement in propellant utilization, the electron temperature inside the hollow anode diminishes, and an axial electron current becomes small. Therefore, the discharge current does not change in spite of an increment in the axial ion current accompanied by an improvement in ion production process.

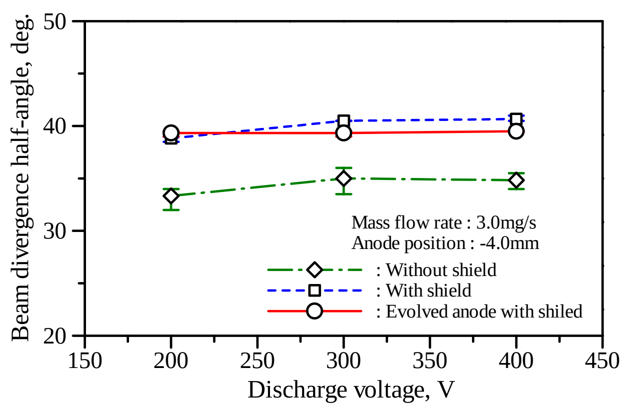
Consequently, the thrust efficiency, as shown in Fig. 9(c), is enhanced by about 3.0 - 6.0 %, and the efficiency reached 57 % at a discharge voltage of 400 V and a xenon mass flow rate of 3.0 mg/s.

C. Comparisons between TALT Series in Japan, and SPT100 and TAL D-Series in Russia

Figure 11 shows the performance comparisons between TALT series in our study, and SPT100 and TAL D-series in Russia. TALT-2 and TALT-2A represent our Hall thruster with the normal-type hollow anode and the divergent-type one, respectively. The thrust efficiencies with TALT-2 and TALT-2A, as shown in Fig 11(a), are higher than those with TAL D-38 and TAL D-55 at all specific impulses. In comparison with SPT100 shown in Fig. 11(b), stable operations with TALT-2 and TALT-2A are achieved in the wide specific impulse region, and the thrust efficiencies with TALT-2 and TALT-2A are higher than those with SPT100 at specific impulses of 1200-1600 sec. Consequently, the TALT-2A thruster, as shown in Fig 12, can be kept

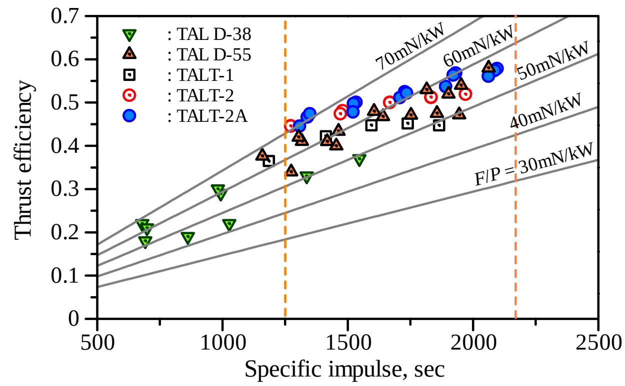


(a) Propellant utilization.

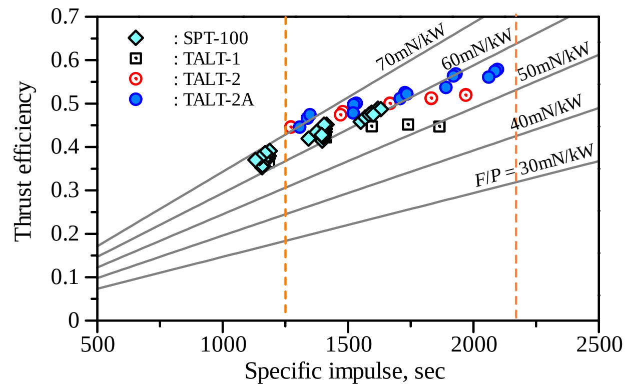


(b) Beam divergent half-angle.

Figure 10. Propellant utilization and beam divergent half-angle dependent on discharge voltage.



(a) Performance comparisons between TALT series and TAL D-series.



(b) Performance comparisons between TALT series and SPT-100.

Figure 11. Performance comparisons between our TALT series, and TAL D-series and SPT100.

Table 1. Voltage utilization and average ion energy.

Configuration	η_E	E_{ave}
Without shield	0.802	160.4eV
With shield	0.892	178.4eV
Evolved anode with shield	0.857	171.5eV

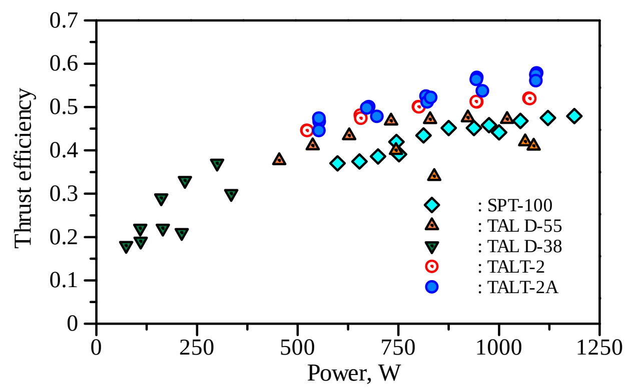


Figure 12. Thrust efficiency vs input power with our TALT series, and TAL D-series and SPT100.

higher thrust efficiencies of 45-57 % with the wide input power of 550-1100 W.

V. Conclusions

The effect of magnetic field topography and discharge channel structure on the performance of 1-kW class anode-layer Hall thruster TALT-2 was investigated. The thruster was operated with a divergent-type hollow anode and a cylindrical discharge channel under various magnetic field topographies. The main results are as follows:

1) The thrust efficiency was improved by extending the channel length. Also the discharge in a short discharge channel operation became stable compared to the operation with the normal-type hollow anode. This is considered to be because of the increment in plasma collecting surface of the anode.

2) In operation with the divergent-type hollow anode, the thrust and the thrust efficiency were declined when the auxiliary trim coil was energized as opposed to the operation with the normal-type hollow anode. This is because of a reduction of propellant utilization efficiency.

It was revealed that the divergent-type hollow anode enhanced the thrust efficiency by about 3.0 - 6.0 %. The maximum efficiency reached 57 % at a discharge voltage of 400 V and a xenon mass flow rate of 3.0 mg/s. In comparisons between our TALT series, and SPT100 and TAL D-series in Russia, the TALT-2 or -2A thrusters can be kept higher thrust efficiencies of 45-57 % in the wide specific impulse of 1200-2200 sec with the wide input power of 550-1100 W.

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