Performance Enhancement of a 1-kW Anode-layer Hall Thruster

IEPC-2005-020

Presented at the 29th International Electric Propulsion Conference, Princeton University, October 31 – November 4, 2005

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Abstract: Performance enhancement of a 1-kW class anode-layer Hall thruster was attempted in accordance with the hypothesis obtained from previous study. It has suggested that an improvement in thrust performance would be acquired by reducing magnetic field strength inside the hollow anode. In this study, an evolved version laboratory model 1-kW class anode-layer Hall thruster, TALT-2, which could change the axial distribution of radial magnetic field strength in the thruster by using magnetic shields and/or a radial trim coil was developed. The thruster was operated to confirm whether thrust performance could be improved with variation of magnetic field characteristics inside the hollow anode. The experimental results showed that a reduction in discharge current and an increase in thrust, i.e., an enhancement of thrust efficiency, were realized by using magnetic shields and the radial trim coil. Thrust efficiency was enhanced to 52 % with magnetic shields and the trim coil at a discharge voltage of 400 V and a xenon mass flow rate of 3.0 mg/s.

I. Introduction

THE Hall-effect thrusters are very advantageous electric propulsion device in space. The developments of this technology have been implemented mainly in former Soviet Union since 1960's[1], and, in the last decade, further progresses were achieved in United State, Europe, Russia and Japan[2-10]. Because the Hall thruster can achieve high thrust efficiency with specific impulse of 1000-3000 sec, they are used as device for orbit correction or as the main thruster in some space missions[11,12]. The Hall thrusters are classified into magnetic-layer type and anode-layer type. The anode-layer type Hall thrusters are one of promising electric propulsion systems. 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 electric propulsion device with longer lifetime and high thrust performance.

In our previous research, fundamental operational characteristics of a 1-kW class anode-layer Hall thruster have been investigated, and flowfield inside the thruster have been also modeled using a simple 1-D calculation model[13,14]. The obtained findings suggested a hypothesis which reduction in magnetic field strength inside the hollow anode might result in an improvement in the thrust performance.

In this study, performance enhancement is attempted in accordance with the hypothesis. An evolved version thruster, TALT-2, is developed. Axial distribution of radial magnetic field strength in the TALT-2 Hall thruster is changed by using magnetic shields and/or a radial trim coil. The operation is carried out to investigate an effect of

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variation of the magnetic field topography and anode front position on thrust performance. Discharge current and thrust are measured; specific impulse and thrust efficiency are estimated. Evaluation of this effort and discussion about further performance enhancement are made by obtained experimental results.

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[13,14]. This thruster, as shown in Fig.1, 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 anode is made of copper. The anode front position can be changed from 3.0 mm to 5.0 mm upstream from the channel exit. The width of hollow anode propellant path is fixed to 4.0 mm.

The 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 azimuthal coils is used as a radial trim coil[15, 16]. When the radial trim coil is energized, the axial distribution of radial magnetic filed strength inside the channel is altered. In operation, 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.

B. Vacuum facility

The experimental facility is shown in Fig. 3. The thruster is operated in a water-cooled stainless steel vacuum chamber that is 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.

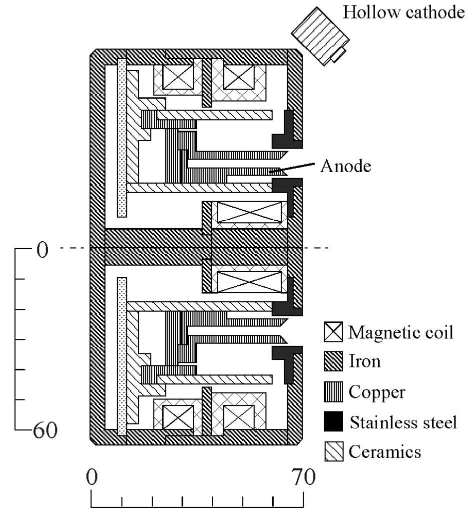


Figure 1 Cross-sectional view of TALT-2 Hall thruster without magnetic shields.

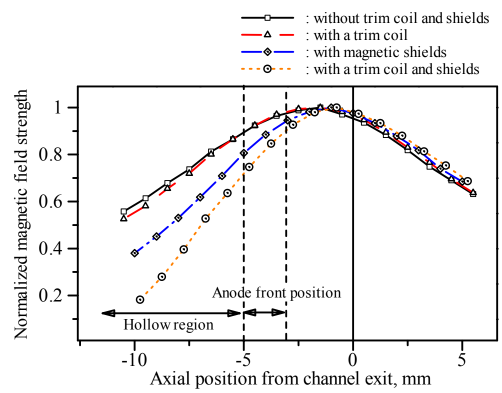


Figure 2 Axial distributions of normalized radial magnetic field strength.

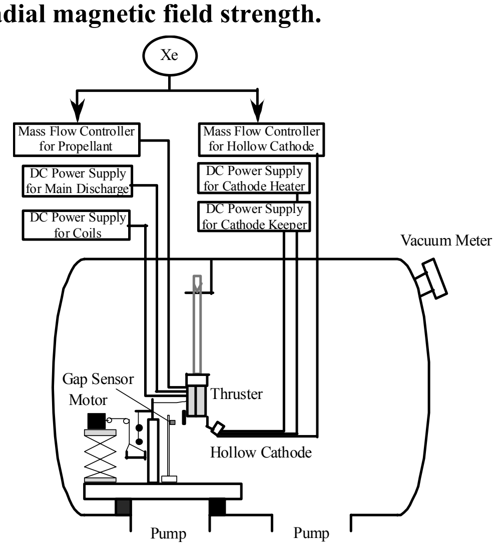


Figure 3 Schematic view of test facility.

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.

III. Results

A. Without magnetic shields operation

Firstly, the TALT-2 was operated under no magnetic shields configuration. Xenon mass flow rate is 3.0 mg/s and discharge voltage is varied from 200 V to 400 V. 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 optimum coil current that minimized the discharge current and current oscillation. Anode front position was -4.0 mm upstream from the channel exit; the hollow anode width was 4.0 mm.

Figure 4 (a) shows the discharge current characteristics. In figure legends, “TC” represents the trim coil. Discharge current gradually increases with discharge voltage. Increased fractions of multiply-charged ions might be cause of this discharge current increment. The current with the trim coil is slightly higher than that without the trim coil. This trend is attributed to the growth in electron temperature near the anode front with increase in magnetic field strength inside discharge channel. When the trim coil is energized, the magnetic field strength inside the channel increases slightly, as shown in Fig. 2.

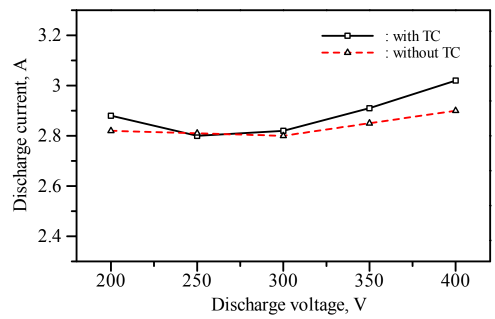
Figure 4 (b) shows the thrust and specific impulse. Thrust and specific impulse rise linearly with discharge voltage. The thrust decreases when the trim coil is energized. The comment about this trend is described later in this paper.

As shown in Fig. 4 (c), the efficiency is deteriorated when the thruster is operated with the trim coil. This is because of the increment in the discharge current and decrement in the thrust. Also, the thruster operation becomes inefficient in the voltage range of 300-400 V. This is due to the increment in discharge current accompanied by the production of multiply-charged ions.

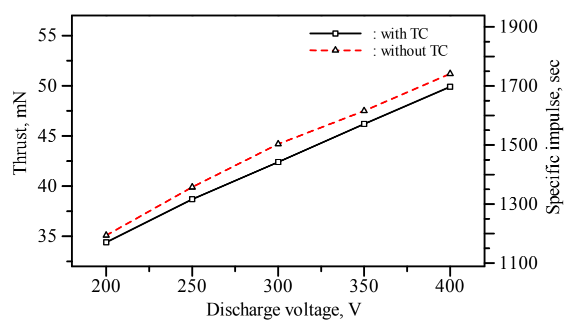
B. With magnetic shields operation

In second experiment, the thruster was operated using inner and outer magnetic shields. The discharge voltages and mass flow rate were the same as that of previous operation. The coil current ratio of 1.0 was also used, and the data acquisition was carried out under the optimum condition. The anode front position and hollow anode width were -4.0 mm and 4.0 mm, respectively.

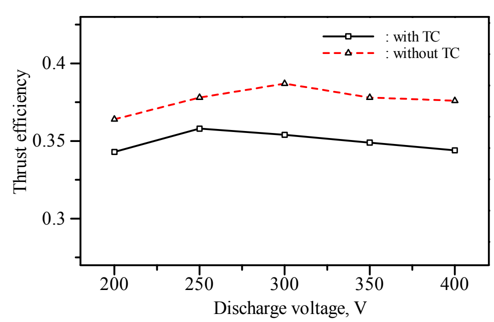
Figure 5 (a)-(c) present the discharge current, thrust and specific impulse, and thrust efficiency, respectively, versus discharge voltage. In this case, the discharge current also increases slightly with discharge voltage. Discharge current is suppressed by energizing the radial trim coil. The relative change in the discharge current is attributed to the change in the ion current or electron current. Because there is no significant change in the thrust, as shown in Fig.



a) Discharge current

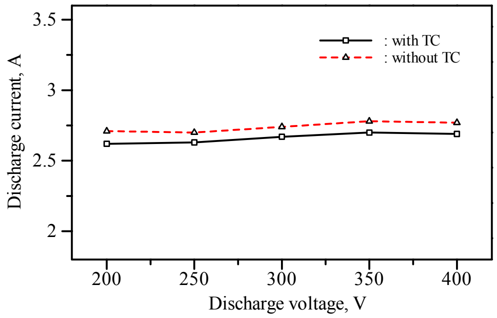


b) Thrust and specific impulse

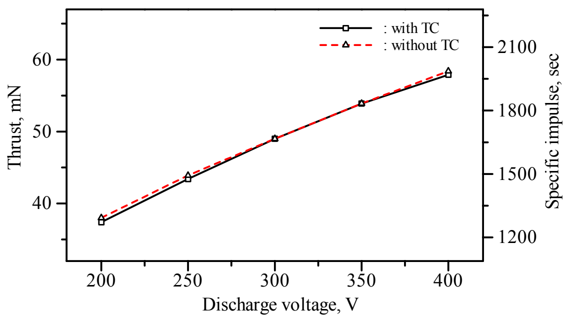


c) Thrust efficiency

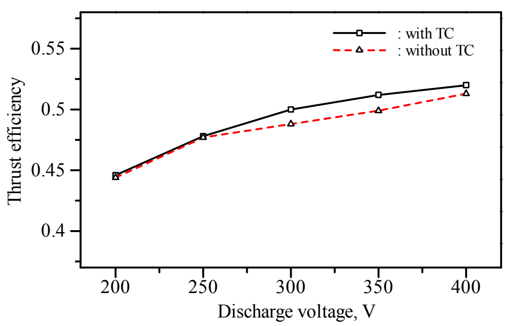
Figure 4 Thrust performances of TALT-2 Hall thruster without magnetic shields.



a) Discharge current

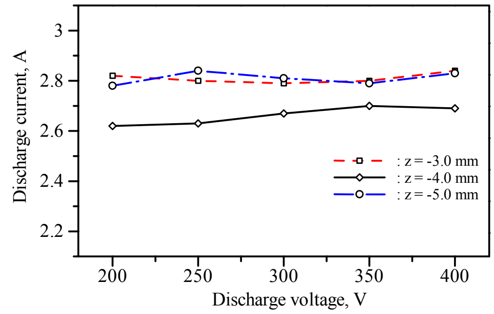


b) Thrust and specific impulse

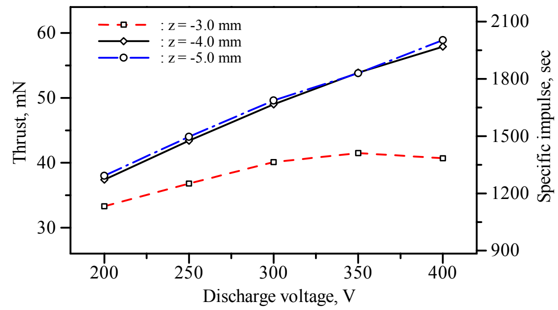


c) Thrust efficiency

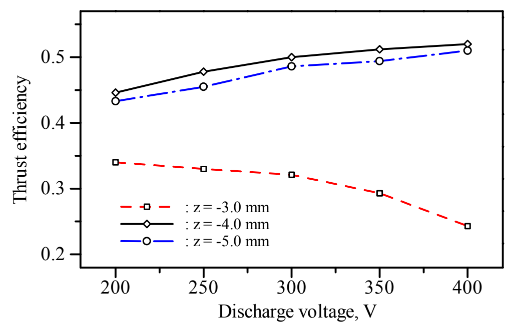
Figure 5 Thrust performances of TALT-2 Hall thruster with magnetic shields.



a) Discharge current



b) Thrust and specific impulse



c) Thrust efficiency

Figure 6 Thrust performances of TALT-2 Hall thruster dependent on anode front position.

5 (b), the decrement in ion current is likely to be quite small. Thus, the reduction in axial electron current seems to result in a suppression of discharge current. In Fig. 2, the radial magnetic field strength inside the hollow anode decreases by using the trim coil. It is considered that electron temperature and electric field inside the hollow anode declines owing to the reduction in the magnetic field strength, and that the decline in electron temperature and electric field results in a suppression of axial electron current.

C. Thrust performance dependent on the anode front position

Figure 6 (a)-(c) show the discharge current, thrust and specific impulse and thrust efficiency, respectively, dependent on anode front position (z). In Fig. 6, the mass flow rate is set to 3.0 mg/s, and magnetic shields and the trim coil are used.

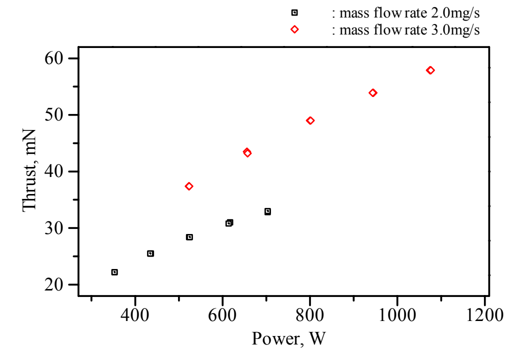
The discharge current, as shown in Fig. 6 (a), is the lowest with an anode front position of -4.0 mm. The discharge current of -5.0 mm and that of -3.0 mm are almost equal. Figure 6 (b) shows the thrust and specific impulse. The thrust of -3.0 mm is quite low compared to others. This might be because of a decline in propellant utilization accompanied by reduction in discharge channel length. Also, the thrust decreases in high voltage region when the anode front position is -3.0 mm. Ion acceleration length is expected to extend with increasing discharge voltage[1]. However, in short discharge channel length it is difficult to obtain sufficient acceleration length.

The discharge current of -3.0 mm is higher than that of -4.0mm, however the ion current decreases with reduction of propellant utilization. The increment in axial electron current is a possible explanation of this phenomenon. It is expected that high-energy electrons flow into the anode without losing those energy because of the insufficient ionization. The discharge current of -5.0 mm is also higher than that of -4.0 mm. This is probably due to the increase in electron temperature near the anode front. It is considered that the electron comes to travel longer distance before leaving the anode, i.e., the energy gained from electric field increases with increasing discharge channel length.

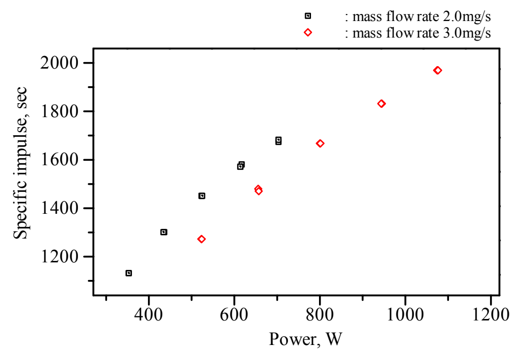
D. Thrust performance dependent on discharge power

To examine the performance characteristics dependent on discharge power, the thruster was operated under xenon mass flow rates of 2.0 and 3.0 mg/s at discharge voltages of 200-400V. Both the trim coil and magnetic shields were used, and the anode front position and hollow anode width were set to -4.0 mm and 4.0 mm, respectively.

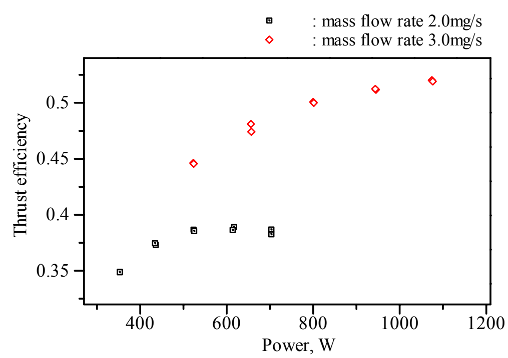
Figure 7(a)-(c) show the thrust, specific impulse and thrust efficiency, respectively, versus discharge power. The thrust and specific impulse increase with discharge power, as shown in Fig. 7 (a) and (b). At the same discharge power, the thrust rises with increasing mass flow rate. This is probably attributed to an improvement in propellant utilization efficiency. Similarly, the thrust efficiency is enhanced with increase of mass flow rate by propellant utilization enhancement. On the other hand, the specific impulse decreases with increasing mass flow rate. This is due to the discharge voltage reduction.



a) Thrust



b) Specific impulse



c) Thrust efficiency

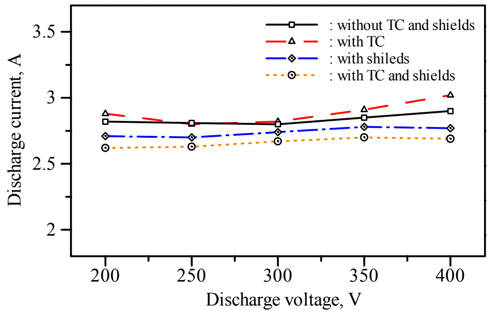
Figure 7 Thrust performances of TALT-2 Hall thruster dependent on discharge power.

IV. Discussion

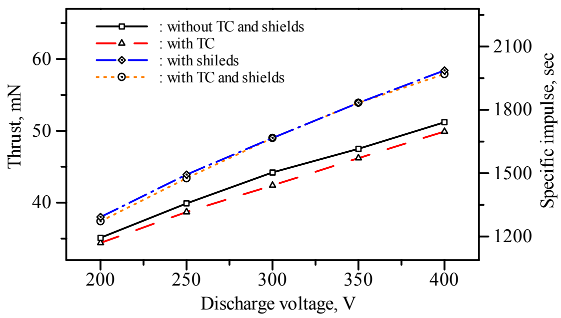
In this section, the discussion about this effort is made by comparing experimental results under no magnetic shields configuration with that under magnetic shields configuration, and comparing thrust performances of TALT-1 with that of TALT-2.

As shown in Fig. 8 (a), the discharge current decreases when the magnetic shields are installed. This is probably due to the reduction in axial electron current. In Fig. 2, the axial distribution of radial magnetic field is altered fairly, and the magnetic field strength inside the hollow anode is decreased by using magnetic shields. Owing to the decrement in magnetic field intensity, the electric field declines and the electron heating by electric field become less effective inside the hollow anode. This results in a reduction in electron temperature, i.e., a reduction in axial electron current. However, a measurement of ion current is needed to ensure this consideration.

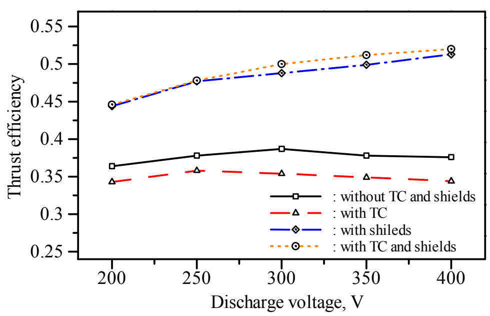
The comparison of thrust and specific impulse is presented in Fig. 8 (b). The thrust and specific impulse are increased by using the magnetic shields. This is likely to be caused by a suppression of ion losses inside the hollow anode and an improvement in ion production and acceleration process. With decreasing the electron temperature, excessive ion production inside hollow anode is restrained and most ion acceleration comes to occur in the discharge



a) Discharge current

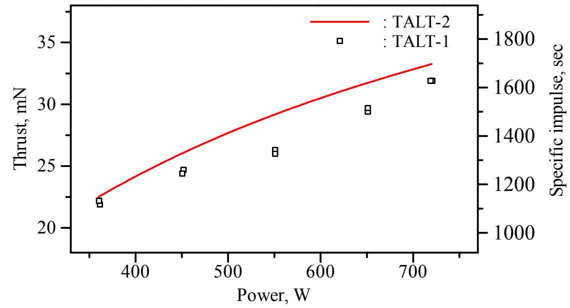


b) Thrust and specific impulse

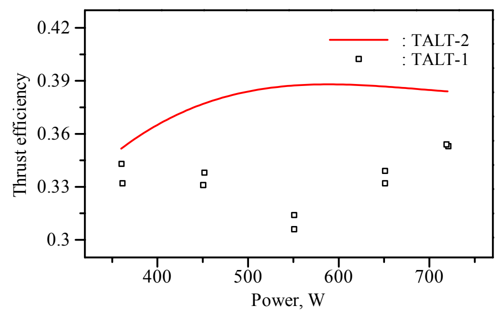


c) Thrust efficiency

Figure 8 Thrust performances comparison between without magnetic shields and with shields one.



a) Thrust



b) Thrust efficiency

Figure 9 Performance comparisons with TALT-1 Hall thruster.

channel. Thus, ion losses inside the hollow anode reduces, effectual ionization and ion acceleration are expected to be realized under magnetic shields configuration.

In the no magnetic shields case, the thrust slightly decreases when the trim coil is energized. The axial distribution of magnetic field strength does not change so much with using a trim coil. Thus, it is considered that propellant utilization efficiency and ion production process are almost the same as the case of no trim coil operation. Therefore, the decrease in thrust may be attributed to reduction in the focusing of ion beam, but measurement of exhaust ion beam is needed to conclude it.

Thrust efficiency is enhanced significantly by using magnetic shields and a radial trim coil, as shown in Fig. 8 (c). The efficiency reached 52% at a discharge voltage of 400V under magnetic shields and a trim coil configuration.

Figure 9 (a) and (b) present the performance comparison with old version anode-layer Hall thruster, TALT-1. The data of TALT-1[12] and TALT-2 shown in Fig. 9 are in the case of an anode front position of -4.0 mm, a hollow anode width of 4.0 mm and a mass flow rate of 2.0 mg/s. These figures show thrust performance versus discharge power, and each solid line indicates the data of TALT-2.

Figure 9 (a) shows the comparison of thrust and specific impulse. As shown in this figure, the thrust and specific impulse of TALT-2 are higher by about 2.0-3.0 mN and 100-150 sec, respectively. The thrust efficiency is enhanced by about 2.0-7.0 %, as shown in Fig. 9 (b).

These results suggest that some enhancement of thrust performance is realized by changing the magnetic field topography. It is expected that reduction in magnetic field strength inside the hollow anode results in an improvement in ion lose inside the hollow anode and ion acceleration inside the discharge channel as the previous study suggests.

V. Future Works

In this study, some improvement in thrust performance was achieved, but it has not been reached to our target yet. To realize more enhancement of thrust performance, more structural improvement in the thruster is probably needed. For this aim, an enhancement of propellant utilization efficiency, i.e., an increment in thrust, must be accomplished. In this study, we succeeded in reducing the ion loss inside the hollow anode and improving the ion acceleration process in the discharge channel. To increase the thrust more, further enhancement of ionization is required. Now we prepare a new hollow anode that has a unique structure. Figure 10 shows the cross-sectional view of new TALT-2 which has a unique hollow anode. The hollow anode has a divergent part, and more enhancements of propellant utilization and reduction in ion losses are expected. In the near future, the new thruster will be operated under various conditions.

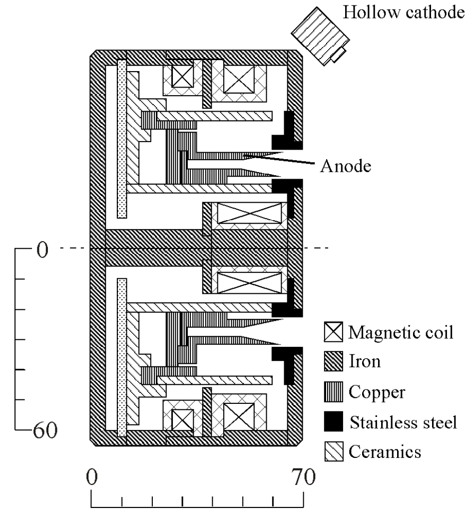


Figure 10 Cross-sectional view of new TALT-2 Hall thruster with unique hollow anode.

VI. Conclusions

The performance enhancement of a 1-kW class anode-layer Hall thruster was attempted in accordance with the hypothesis obtained from previous study. An evolved version laboratory model anode-layer Hall thruster, TALT-2, was developed. The thruster has a radial trim coil and can be equipped with two magnetic shields. By using the trim coil and/or magnetic shields, the axial distribution of radial magnetic field in the thruster was altered. The thruster was operated under various magnetic field topography and anode front position. The following results were obtained.

1) The optimum anode front position was obtained. The optimum position was considered to be determined by the balance between propellant utilization efficiency and a fraction of axial electron current.
2) The thrust efficiency was enhanced when the radial trim coil was energized and magnetic shields were used. It was considered that this enhancement was due to the reduction in ion loss inside the hollow anode and improvement in ion production and acceleration process accompanied by decrease in magnetic field strength inside the hollow anode.
3) The performance of TALT-2 was higher than that of old version anode-layer Hall thruster, TALT-1. Thus, the performance enhancement was succeeded.
4) The maximum thrust efficiency of 52 % was obtained with a discharge voltage of 400 V and a mass flow rate of 3.0mg/s under using both the magnetic shields and trim coil.

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