Advance Publication by J-STAGE

Mechanical Engineering Journal

DOI:10.1299/mej.21-00347

Received date : 10 October, 2021

Accepted date : 22 February, 2022

J-STAGE Advance Publication date : 3 March, 2022

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Plume interference effects of the racetrack-shaped anode-layer Hall thruster system

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Abstract

Plume interference effects on the discharge characteristics and thruster performance for two heads system were investigated to evaluate the optimum design of the Hall thruster cluster system using the anode-layer head. An anode-layer head with a racetrack shape acceleration channel was designed in this study to better capture the interference effects. The racetrack-shaped head has straight parts and can certainly capture the plume interference effect. The system is termed a side by side (SBS) Hall thruster system because the two heads are positioned in a straight line to sandwich one hollow cathode. The SBS system's discharge characteristics and thruster performance were assessed. It was indicated that the thruster performance was better improved in SBS operations than the sum of the single operations. The thruster performance is also influenced by the interaction of the two heads' magnetic field directions. The effect of the plume interference on the amplitude increase point, which is the inner coil current when the discharge current oscillation amplitude increases rapidly, was evaluated to examine the stable operation range. The increased point also depends on the interaction of the magnetic field directions. These findings suggest that plume interference has an impact on the ionization through the backflow electron. Furthermore, a head susceptible to plume interference substantially impacts the behavior of the total discharge current due to individual head differences.

Keywords : Electric propulsion, Hall thruster, Cluster system, Plume interference, Anode layer

1. Introduction

The power of the electric propulsion system is proceeding with the full-scale implementation of all-electric satellites (Feuerborn et al., 2013; Funaki et al., 2019). Research and development of a 25 kW class Hall thruster cluster system with five 5 kW class anode-layer heads called RAIJIN and one neutralizer is ongoing in Japan (Miyasaka et al., 2013) (Fig. 1). The 5 kW class head employs a magnetic shielding (Hamada et al., 2017a, 2017b), and Yamamoto et al. realized efficiency of 0.53 when operating at a specific impulse of 2,200 s and the power of 4.5 kW when using a 5 kW class head with magnetic shielding (Hamada et al., 2017b).

The development of the head is also an important factor in the design of a Hall thruster cluster system, however, it is critical to investigate and evaluate the unique perspective to the cluster system, which is the interference between the plumes from each head. Research on several cluster systems have been ongoing so far (Beal et al., 2005; Lobbia et al., 2007; Walker et al., 2007; Zakharenkov et al., 2005; Tverdokhlebov et al., 2005). Beal et al. showed that the plume property was influence in multihead operation (Beal et al., 2005). Lobbia et al. showed thrust boost due to clustering (Lobbia et al., 2007). These results indicated that optimizing the arrangement and operating conditions can yield higher or lower performance than the sum of simple substances. A system with two Hall thruster heads and one neutralizer, which is the minimum number of clusters has been designed and investigated at Gifu University (Miyasaka et al., 2005, 2017, 2019). Two heads are positioned in a straight line to sandwich one hollow cathode in this arrangement, which is known

as a Side by side (SBS) system. Because two heads are used as in the SBS system, there are two combined magnetic field directions are applied by two heads, one in the same direction and the other in opposite directions, since two heads are utilized in the SBS system as shown in Fig. 2. The number of combinations increases when the number of groups increases further, such as 5 units. Therefore, it is necessary to evaluate the combination of 2 units in the magnetic field direction to acquire knowledge on their optimization. Anode-layer head types in addition to evaluations involving magnetic layer head types heads have been evaluated at Gifu University (Miyasaka et al., 2017). In the studies at Gifu University, there were differences in discharge current value, discharge oscillation amplitude increase condition, and thrust during single operation and SBS operation. In addition, difference was observed in the cases of difference combinations of magnetic field directions in SBS operations. These findings indicate that there is a plume interference effect in discharge characteristics and thruster performance, as well as the possibility of the influence of the magnetic field application directions being combined. The plume interference may affect the electric potential distribution. Therefore, the discharge characteristics and thruster performance may vary as a result of the effect of the ionization and acceleration reactions in the acceleration channel through the backflow electron characteristics to the head. However, a clearer finding has not been obtained since these tendencies depend on the operating conditions and it is difficult to increase the operating flow rate due to the use of two heads. Depending on the operating conditions, the interference effect was reduced and reproducibility problems occurred.

Therefore, an anode-layer Hall thruster head with a racetrack-shaped acceleration channel to obtain a stronger interference effect based on suppressed operating flow rate has been developed in this study (Fig. 3). Pote et al. investigated a magnetic layer type thruster with a racetrack shape. Decreased performance due to the non-uniformity of the magnetic field was identified (Porte et al., 2000). However, the plume from the straight part of the racetrack-shaped head has higher plasma density and ion flux density compared with the circular-shaped head. In addition, the plume interference region between the straight parts is wider compared with the circular-shaped head. It is excellent for obtaining detailed knowledge of the interference effect since the racetrack-shaped head has a straight part, which projects it for a higher plume interference effect than the circular type even at the same flow rate. In addition, the anode-layer head has a shorter acceleration channel and longer lifetime owing to no ceramic wall. Thus, in this study, discharge characteristics and thruster performance of the SBS system comprising two anode layers with racetrack shape are evaluated in this study. In addition, to evaluate the effect of individual differences of the heads on SBS operation during cluster operation, we focused on the discharge characteristics of each head during SBS operation and evaluated them.

Fig. 1 Schematic of RAIJIN.

Fig. 2 Examples of combinations of directions of magnetic fields applied by two heads.

Fig. 3 Racetrack-shaped anode-layer Hall thruster head GRA-II.

2. Experimental setup

2.1 Anode-layer Hall thruster head with a racetrack shape “GRA-II”

Figures 4 (a) and 4 (b) show a cross-section map and a schematic of the newly designed anode-layer Hall thruster head “GRA-II” with a racetrack shape, respectively. The shape is such that a semicircular acceleration channel sandwiched a linear acceleration channel with a length of 31.4 mm from both sides. The inner and the outer coils applied the magnetic field. Figure 5 indicates the magnetic flux density vector diagram realized from the numerical analysis. The numerical analysis was performed for a similar geometry to GRA-II and typical experimental outer and inner coil currents of 5 and 0.2 A. Figure 5(a) illustrates the cross-section at the center of the straight part, whereas Figure 5(b) shows the cross-section at the apex of the semicircle. There was no clear difference in the magnetic flux density vector direction between the straight part and the semicircular part. The magnetic flux density distributions on the centerline of the acceleration channel shown in Figure 6 also indicate no clear difference in the peak position between the straight part and the semicircular part. However, the magnetic flux density of the straight part was higher than that of the semicircular part.

Fig. 4 Cross-section map and schematic of racetrack-shaped anode-layer Hall thruster head GRA-II.

Fig. 5 Magnetic flux vectors: center of the straight part and apex of a semicircle in head.

Fig. 6 Magnetic flux density distribution along the centerline of acceleration channel.

2.2 Electric circuit diagram

Figure 7 shows the circuit diagram of the SBS Hall thruster system. A common power supply was applied as the head power supply. In addition, one hollow cathode, HCN-252 was employed as the neutralizer. The tip of the HCN-252 was a RMtec HC-252. The coil current was configured so that the combination of the current directions of the inner and outer coils can be changed. Figure 8 indicates the magnetic flux density vector diagram realized from the numerical analysis. The outer and inner coil currents were 5 and 0.2 A, respectively. Figure 8(a) and (b) illustrate the cross-sections for the same and opposite directions. In the region downstream of the cathode, where the plume interference appears, the vector is oriented in the axial direction for the same direction. However, the vector is oriented in the radial direction for the opposite directions. This means the magnetic field lines are connected in the region. The electrons are strongly influenced by the directions of the magnetic field line. Thus, the difference in the magnetic vector distributions in the interference region for the two different combinations of the coil currents has a possibility of influences on the ionization through the backflow electrons from the interference region to the acceleration channel.

2.3 Vacuum system

Figure 9 indicates the SBS system mounted on a pendulum thrust stand and installed in a space chamber with a diameter of 2.5 m and a total length of 5 m at the JAXA/ISAS. The thrust accuracy estimated from the linearity of a micro displacement meter Omron Z4D-F04A used for this thrust measurement is 2.4 mN. This corresponds to 7.5 % for the typical SBS thrust of 32 mN, and 16 % for the anode efficiency. However, the measured coefficient of determination of thrust calibration line R^2 was 0.99995. The actual linearity is high, which is considered to be sufficient for qualitative comparison. The primary pumps of this chamber were two cryopumps with an exhaust velocity of 28,000 l/s and the degree of vacuum in a single operation was 4×10^{-3} Pa and in SBS operation was $(7-8) \times 10^{-3}$ Pa. The vacuum chamber

was grounded. Figure 10 displays a snapshot in SBS operation. The propellant in this study was xenon. In Figure 10, the plume interference between the two heads can be observed.

2.4 Operational conditions

Table 1 shows the operating conditions for the single operation, which were the operation conditions of a single head, and for the SBS operation, which were the operation conditions of two heads. The distance between the head centers was fixed at 145 mm. The flow rate given to one head was unified to 15 sccm, and the neutralizer flow rates for the single and SBS operations were 1.5 sccm and 3 sccm, respectively. The ratio of the cathode flow rate to the flow rate of one head is set to 0.1 in both the single operation and the SBS operation. The discharge voltage and the outer coil current were fixed at 200 V and 5 A.

Fig. 7 Circuit diagram of Hall thruster SBS system.

Fig. 8 Magnetic flux vectors: center of the straight part for the same direction and opposite directions.

Fig. 9 SBS system mounted on a pendulum thrust stand and installed in JAXA/ISAS space chamber.

Fig. 10 A snapshot of racetrack-shaped anode-layer SBS system in operation.

Table 1 Operational conditions.

	Operation mode	
	Single	SBS (two-head)
Flow rate /Head	15 sccm	15 sccm/head
/ Cathode	1.5 sccm	3 sccm
Discharge voltage	200 V	
Outer coil current	5 A	

3. Results and discussion

3.1 Ion flux distribution

Figure 11 shows an example of ion flux distribution 150 mm downstream from the head when one racetrack-shaped anode-layer Hall thruster head is operated. The distribution was measured using an ion collector with a tungsten surface

with a diameter of 10 mm. The ion collector was swept two-dimensionally 150 mm downstream of the head. This distribution confirms that the plume disperses more in the straight part compared with the semicircular part.

Fig. 11 Ion current density distribution 150-mm downstream of the head.

3.2 Discharge characteristics and thruster performance

Figure 12 shows the total discharge currents $I_{SBS[s],tot}$ and $I_{SBS[o],tot}$ of head A and head B concerning the inner coil current in the SBS operations for the same direction of applied magnetic field directions and the opposite direction. In addition, the sum of the discharge currents $I_{sgl,sum}$ in the single operations of the two heads was also indicated as

$$I_{sgl,sum} = I_{sgl,A} + I_{sgl,B}. \quad (1)$$

These results indicate a typical discharge characteristic of the anode-layer Hall thruster head with electron diffusion mode transitions from Bohm diffusion to anomalous diffusion. Furthermore, the discharge current increases during SBS operation in the two modes compared with the case of a single operation. There was almost no variation between the two modes when the SBS operations were activated.

Figure 13 shows the oscillation amplitudes of the total discharge currents in the SBS operations $I_{SBS[s],t}$ and $I_{SBS[o],t}$ and the sum of the discharge currents $I_{sgl,sum}$ in the single operations. The amplitude Δ of each discharge current I is defined by the following equation:

$$\Delta = \frac{1}{\bar{I}} \sqrt{\frac{\int_0^{t_d} (I - \bar{I})^2 dt}{t_d}} \quad (2)$$

$$\text{where } \bar{I} = \frac{\int_0^{t_d} I dt}{t_d} \quad (t_d: \text{time interval}). \quad (3)$$

From this figure, a sharp increase in the amplitude can be observed when the inner coil current was between 0.2 A and 0.4 A. The inner coil current at the time of the rapid increase in the amplitude relied on the operation mode. This rapid increase point of the oscillation amplitude in the SBS operations was lower compared with the single operation. In the SBS operations, the amplitude for the same direction of the combination of magnetic field directions was lower compared with the opposite directions. Lobbia et al. showed thrust boost in cluster operations and suggested localized propellant redigestion (Lobbia et al., 2007). However, the reason of lowering of the rapid increase point of the oscillation amplitude during SBS operations was regarded to be the increased backflow electron flux due to plume interference between the two heads in the SBS operations, which affected the ionization region. Therefore, in addition to the localized

propellant redigestion, a physical mechanism of the influence of the backflow electron flux on the ionization process also needs to be considered in cluster operations. Considering the effect of the combination of magnetic field directions, the difference in the magnetic field distribution in the plume region influenced the electronic characteristics of the plume region and its accompanying effect on the electric potential distribution, resulting in variations in the electron temperature and electron flux, which are the backflow electron characteristics. Fig. 14 illustrates a conceptual diagram of the difference between the assumed equipotential lines and the electron temperature. As can be seen from Fig. 8, the lines of magnetic force in the interference region are oriented in the axial direction for the same direction, however, are oriented in the radial direction for opposite directions. It is considered that the directions of the equipotential lines show the same tendency as the lines of magnetic force. That is, when the electrons emitted from the cathode have a large potential difference from the head end for the same direction, the electron temperature increases, however, for opposite directions, the potential difference becomes small and the electron temperature rise is small. That is, it can be predicted that when the electron temperature flowing into the head is high for the same direction, the ionized region shifts downstream with a lower applied magnetic field, and the discharge current vibration amplitude increases. However, to elucidate the physics, an extensive evaluation of plume characteristics and numerical analysis are likely to be necessary.

The results for the rapid increase point of the oscillation amplitude indicated that the stable operating conditions differ depending on the operating mode. To evaluate the effect of this variation in stable operating conditions on propulsion performance, the anode efficiency η_a was plotted as shown in Figure 15 in addition to the discharge current oscillation amplitude Δ . In general, stable operating conditions require that $\Delta < 0.2$, so we focused on the point that anode efficiency was maximized for $\Delta < 0.2$. The inner coil current that maximized the anode efficiency increased for the same direction of the combination of the magnetic field directions in SBS operations, for opposite directions, and in the single operation. The anode efficiency decreases in this order. Figure 16 illustrates plots of the discharge current I , thrust F , and anode efficiency η_a for the inner coil current that maximizes the anode efficiency. These values indicated the ratio with the value in the single operation. Compared with the sum of the thrust of the two heads in the single operation, the thrusts for the same direction and opposite directions in the SBS operations increased by 15% and 9%, respectively. However, the discharge current had a large increase rate of 20% and 14%, respectively. As a result, the increased rates of the anode efficiency were 10% and 3%, respectively. However, to compare the values between the single operation and SBS operations it is essential to consider the impact of backpressure. Therefore, to evaluate the effect of differences in the backpressure between the single and the SBS operations, discharge currents and the thrusts when one head operated and those when only the propellant was supplied to the other head during one head operation were plotted in Figure 17. The results were for circular heads, and the mass flow rate was 18 sccm, which varied from the 15 sccm in this study. However, the back pressures in the single operation and the single operation with propellant supply for the other head were 4×10^{-3} Pa and 7×10^{-3} Pa, respectively, showing the close values of this study with the racetrack-shaped head. Furthermore, in the comparison of the circular head with a larger flow rate than in this study, the discharge current increased by only 2%, and the thrust increased by 3% by supplying propellant to the other head, and these values are lower than the difference between the single and the SBS operations in Figure 16. These results showed the validity of the tendency obtained from Figure 16.

Fig. 12 Discharge currents for two combinations of magnetic field directions and the sum of discharge currents in single operations of two heads.

Fig. 13 Discharge current oscillation amplitude for two combinations of magnetic field directions and the sum of discharge currents in single operations of two heads.

Fig. 14 Conceptual diagram of the difference between the assumed equipotential lines and the electron temperature for the same direction and opposite directions

Fig. 15 Discharge current oscillation amplitude and anode efficiency for two combinations of magnetic field directions and the sum of single operations of two heads.

Fig. 16 Discharge current, thrust, and anode efficiency for inner coil current that maximizes anode efficiency.

Fig. 17 Discharge current and the thrust when one head was operated and the only propellant was supplied to the other head during one head operated.

3.3. Investigation of plume interference effects on discharge characteristics by each head

Figures 18 (a) and (b) indicate the discharge currents $I_{SBS,A}$ and $I_{SBS,B}$ of each head for the same direction and opposite directions in SBS operations. The black line in Figs. 18(a) and (b) shows the average value $I_{SBS,avg}$ of head A and head B. In both Figures 18(a) and (b), there is a difference in the discharge current due to the individual difference between head A and head B, with head B giving a higher discharge current. Figure 19 shows the discharge current of each head in single operation. In Figure 19, the individual difference was observed. The discharge current of head B is higher than that of head A similar to Figure 18. Furthermore, in Figure 18, this difference in discharge current was suppressed as shown in Figure 18(b) for opposite directions. This also indicates that the combination of magnetic field application directions influenced the backflow electron characteristics into the acceleration channel.

Figures 20(a) and (b) display the discharge current oscillation amplitude $\Delta_{SBS,A}$ and $\Delta_{SBS,B}$ for each head for the same and opposite directions in the SBS operations, respectively. The black line shows $\Delta_{SBS,tot}$ of the total discharge current of the two heads. The increased point of the oscillation amplitude, which is the inner coil current in which the vibration amplitude increases rapidly, existed between 0.2 A and 0.4 A. In either combination of magnetic field directions, the increase point of the oscillation amplitude of head A was lower than that of the total discharge current, whereas the value of head B was higher. For opposite directions, the increase point becomes higher and the difference between the three increase points was smaller than that for the same direction. Figures 21(a) and (b) show the discharge current

amplitude Δ for the two modes in the SBS operations and the single operation for head A and head B, respectively. In each head, the rapid increase points of the oscillation amplitude for the two modes in the SBS operations were lower than that in the single operation. The low shift of the increase point for the same direction was larger than that for opposite directions. The tendencies were the same for the comparison between the total discharge current of the two heads in the SBS operations and the single operation shown in Figure 13. This shift of the increase point to the low inner coil current side indicated some effects of plume interference on the ionization process. When the findings of the two heads were compared, the shifts of head A were larger than those of head B. It suggests that the plume interference effect on head A is stronger owing to individual differences.

To better examine these results, the inner coil current I_i^* when the increase in discharge current oscillation amplitude was maximized is shown in Figure 22. The red, blue, and black circles indicate I_i^* of each head for the same and opposite directions in the SBS and single operations, respectively. The solid red and blue lines indicate I_i^* of the total discharge current for the same and opposite directions in the SBS operations. From these results, I_i^* of head A decreased by 23% and 45% for opposite and the same directions in the SBS operations, respectively as compared with the single operation. However, in head B, the decrease was only 2% and 13% for opposite directions and the same direction, respectively compared with the single operation. The results showed that head A had a significantly strong plume interference effect. This is due to the individual differences between head A and head B, and it is considered that head A was more strongly affected by the properties of electrons in the interference region due to the slight variation in the shape of the magnetic field between the two heads. Next, the difference in I_i^* between the total discharge current of the two heads and the discharge current of each head were examined. The differences for opposite directions and the same direction between the discharge current of head A and the total discharge current of the two heads were only 1% and 17%, respectively. However, in the case of head B, the differences were 10% and 32%, respectively. These results imply that the oscillation characteristic of the total discharge current of the two heads does not show the average of the characteristics of the two heads, but the characteristic of the head that is more susceptible to the interference effect.

Fig. 18 Discharge currents for head A and head B and averaged discharge current of two heads for the same direction and opposite directions in SBS operations.

Fig. 19 Discharge currents for head A and head B in single operations.

Fig. 20 Discharge current oscillation amplitudes for heads A and B and averaged discharge current of two heads for the same direction and opposite directions in SBS operations.

Fig. 21 Oscillation amplitudes of individual current of (a) head A and (b) head B for the same direction and opposite directions in SBS operations and single operation.

Fig. 22 Inner coil current when the increase in discharge current oscillation amplitude is maximized.

4. Conclusions

An anode-layer Hall thruster head with a racetrack shape acceleration channel that can more clearly capture the plume interference effect between heads has been developed to obtain knowledge of the optimum design of the cluster system by the anode-layer head. An SBS system comprising heads A and B as well as a common hollow cathode were designed. The discharge characteristics and thruster performances were evaluated.

As a result, it was shown that the thruster performance was improved in SBS operations than in the sum of the single operations. The thruster performance was improved based on the combination of the magnetic field directions applied by the two heads and was improved when the two magnetic fields were applied in the same direction. The discharge voltage of this investigation was 200 V. Furthermore, the tendency of performance improvement for the combination correlates to the increasing tendency of the discharge current. As a result, chances are that the increase in the backflow electron flux due to plume interference in the SBS operations promoted the ionization in the acceleration channel. Therefore, it is suggested that this difference will be compressed during high specific impulse operation, which is under higher discharge voltages. In the future, It will be vital to analyze under a wide range of operating conditions and to understand how this performance improvement impact is dependent on the operating conditions.

Furthermore, considering the stable operating range, the effect of the plume interference on the amplitude increase point, which is the inner coil current value when the discharge current oscillation amplitude increases rapidly, was analyzed. As a result, it was shown that the increase point of the total current of the two heads in the SBS operations is lower than in every single operation. This amplitude increase point also relies on the combination of the two magnetic field application directions and shifts to a lower value when the two magnetic fields are applied in the same direction. It is considered that this is because of the shift in the ionization zone due to an increase in the backflow electron flux by plume interference. The larger shift was observed when it was applied in the same direction because of the difference in the magnetic flux density distribution in the plume interference field, however, numerical analysis and detailed diagnosis of the plume interference field are considered essential for this. Increase point characteristics yielded interesting results concerning the individual differences of the head. A difference in the susceptibility to plume interference appears due to individual differences in the individual head. The increased point of the head susceptible to plume interference behaved close to the total current of the two heads. This means that when there is an individual difference between the heads, the total current of the two heads may not reflect the average behavior of each of the two heads in the SBS operation, however, one of the heads is strongly influenced by the plume interference effect, which has a strong impact on the total current behavior.

Acknowledgement

The authors would like to thank N. Yamamoto, Hiroki Watanabe, and I. Funaki for technical assistance with the experiments at ISAS/JAXA. This work was supported by JSPS KAKENHI Grant Number 19H02343.

References

- Beal, B. E. and Gallimore, A. D., The Effects of Cathode Configuration on Hall Thruster Cluster Plume Properties, AIAA Paper 2005-3678 (2005).
- Feuerborn, S. A., Neary, D. A., and Perkins, J. M., Finding a Way: Boeing's "All Electric Propulsion Satellite", AIAA-2013-4126(2013).
- Funaki, I., Sano, T., Fukatsu, T., Tashiro, Y., Shiiki, T., Cho, S., Matsunaga, Y., and Goto, D., Development Status of 6-kW-Class Hall Thrusters at JAXA, International Electric Propulsion Conference, IEPC-2019-441 (2019).
- Hamada, Y., Kawashima, R., Komurasaki, K., Yamamoto, N., and Tahara, H., Development Status of 5 kW Class Anode-Layer Type Hall Thruster: RAIJIN94, International Electric Propulsion Conference, IEPC-2017-412 (2017).
- Hamada, Y., Bak, J., Kawashima, R., Koizumi, H., Komurasaki, K., Yamamoto, N., Egawa, Y., Funaki, I., Iihara, S., Cho, S., Kubota, K., Watanabe, H., Fuchigami, K., Tashiro, Y., Takahata, Y., Kakuma, T., Furukubo, Y., and Tahara, H., Hall Thruster Development for Japanese Space Propulsion Programs, Transactions of the Japan Society for Aeronautical and Space Sciences, Vol. 60, No. 5 (2017), pp.320-326.
- Lobbia, R. B. and Gallimore, A. D., Performance Measurements from a Cluster of Four Hall Thrusters, International Electric Propulsion Conference, IEPC-2007-177 (2007).
- Miyasaka, T., Komurasaki, K., Koizumi, H., Schönherr, T., Yamamoto, N., Tahara, H., Takegahara, H., Nakano, M., Aoyagi, J., Funaki, I., Watanabe, H., Okawa, Y., Kakami, A., Takao, Y., Yokota, S., Oazaki, T., and Osuga, H., Overview on Developments of High-Power Anode Layer Thruster in Japan, International Symposium on Space Technology and Science, o-1-01 (2013).
- Miyasaka, T., Asato, K., Furuta, D., Uyama, Y., Goto, R., Shimizu, D., Yoshida, M., Sakoda, M., and Miyake, Y., Characteristics of Side by Side Operation of Hall Thruster, International Electric Propulsion Conference, IEPC-2015-70(2015).
- Miyasaka, T., Uyama, Y., Yoshida, M., Miyake, Y., Shimizu, D., Goto, R., and Sakoda, M., Interference Effects of Multi-Head Operation of Anode Layer Side by Side (SBS) System, Vacuum, Vol. 136(2017), pp.184-189.
- Miyasaka, T., Kita, T., Asahara, M., Oishi, K., Sakoda, M., Mamiya, Y., and Kanie, H., Influences of Cathode Position on Operations and Thrust Performance of Side by Side Hall Thruster System, Vacuum, Vol. 167(2019), pp.524-529.
- Porte, B., Hruby, V., and Tedrake, R., "Performance of a Multi-Kilowatt Non-Circular Discharge Hall Thruster," AIAA-2000-3249(2000).
- Tverdokhlebov, S. O., Semenkin, A. V., Shoumkin, B. V., Kochergin, A. V., Butler, B., Yuen, J. L., Shoji, J. M., and Mason, L., Evaluation of TAL technology applicability to high power (10 kW and above) electric propulsion system Paper, AIAA-2001-3892(2001).
- Walker, M. L. R. and Gallimore, A. D., Hall Thruster Cluster Operation with a Shared Cathode, Journal of Propulsion and Power, Vol. 23, No. 3 (2007), pp.528-536.
- Zakharenkov, L. E., Semenkin, A. V., Garkusha, V. I., and Lebedev, Y. V., Study of the 3-TAL Thruster Assembly Operation, International Electric Propulsion Conference, IEPC-2005-185 (2005).