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A 100 W-class Water-vapor Hall Thruster for Constellations and Space Explorations by SmallSats

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ABSTRACT

The laboratory models of a water-vapor Hall thruster and LaB6 thermionic cathode were developed and tested. To optimize the thruster design to water-vapor propellant, the geometrical investigation was conducted. After testing six different models, the smallest thruster, with an outer diameter of 20 mm, was found to be the most suitable for 100-W class operation. This thruster was able to be operated less than 100 W at 200 V. In addition, the discharge power was suppressed to 200 W even at 300 V. Based on the plume diagnostics, the thrust force of 2.9 mN, specific impulse of 650 s, and anode efficiency of 4.6 % were obtained as a representative performance of this 300 V operating point. After the thruster operation was achieved, the cathode coupling test was conducted to demonstrate electron emission under water-vapor plasma existence. As a result of this experiment, the effective increase in electron current compared to the previous stand-alone tests was confirmed as well as the compatibility to the water-vapor plasma plume. On the other hand, the electron emission current has not achieved 100 mA-class yet and the required heating power was predicted over 100 W; thus, further improvement is progressing.

INTRODUCTION

Recently, small satellites are attracting attention for the use in satellite constellations.[1)] The concept of satellite constellation is to offer high-speed, large- capacity communications by linking a large number of satellites, which is expected to bring innovation in the field of information technology. Small satellites have also been used for space explorations including deep space. In November 2022, 10 CubeSats were launched by Space Launch System and headed for their missions around the Moon.[2)] As those large-scale utilization of small satellites increases, the importance of small propulsions is further growing. In the constellations, communication satellites should have their own propulsion systems for station keeping, attitude control, and final deorbiting. In the case of deep-space probes, the propulsions also play a critical role for orbit transfer. A low-power Hall thruster is considered to be one of the suitable propulsion systems because of its high specific impulse and moderate thrust force.[3)] However, since conventional Hall thrusters need expensive rare-gas propellant such as xenon and krypton, it is not easy especially for new challengers to use them. This situation renders the search for more inexpensive propel- lant alternatives highly relevant. Now, we expected water as a candidate because of its overwhelming availability and other unique properties with regard to small satellites; it is storable as a liquid and thus eliminates a high-pressure system, is easy to handle in regular test facilities, and is less hazardous. It has already been proven that water propellants can be used with variety of environment in space. For instance, a 6U CubeSat EQUULEUS achieved active orbit transfer using a water resistojet thruster even in deep space.[4)]

Our proposal is a Hall thruster system that directly generates plasma from water vapor and accelerates it in the same way as a conventional one. As a different approach, a Hall thruster combined with water electrolysis has been proposed.[5)] Compared to the water electrolysis Hall thruster, the direct use of water vapor can make the entire system simple and compact. From this point of view, the water-vapor Hall thruster that we proposed is suitable to be installed in small satellites. We are aiming to provide a 100 W-class propulsion system for upcoming power trends of small satellites. In the previous study, a prototype thruster was developed and successfully operated with water vapor in stable.[6)] In addition, the performance characteristics were evaluated from the results of the plume diagnostics.[6)] A water-compatible cathode is another key component in our development. Conventional Hall thrusters have commonly been using hollow cathodes which consume a propellant. However, operating a hollow cathode with water propellant is difficult because the electron-emitting insert is vulnerable to oxidization. To solve this problem, we are pioneering a 100 mA-class thermionic cathode which does not need any propellant.[7)]

This paper described the development status and achievement of two essential elements for a water-vapor Hall thruster: discharge channel and cathode. Regarding the discharge channel, we have developed several scale models to figure out the appropriate design for 100 W-class operations with water propellant. We also have developed a cathode model to demonstrate the concept of propellant-free electron emission. The latest results of ongoing Hall thruster stand-alone performance tests and cathode coupling tests are presented, as well as the design details and ground-test systems.

LABORATORY MODEL

Thruster Design

Figure 1 shows the system schematic of a water-vapor Hall thruster. The operating principle is same as that of conventional Hall thrusters; propellants are converted to plasma in the discharge channel and only ions are accelerated downstream near the channel exit by the effect of magnetic screen. The propellants, water-vapor, are supplied by the dedicated feeding system. In this system, the mass flow rate of water-vapor is controlled by the accumulator pressure, which is kept in constant by bang-bang control of regulation valve. Vapor-liquid separation is now performed by gravity, but in the future, we plan to incorporate other gravity-free methods such as proposed by Asakawa et al.[8)]

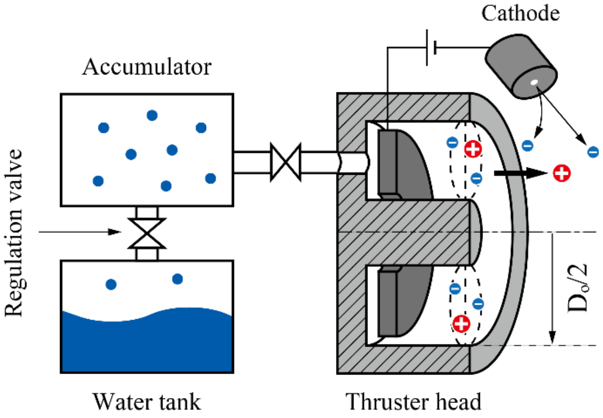

Figure 1: System schematic of a water-vapor Hall thruster.

To the best of our knowledge, we are the first to try a 100 W-class Hall thruster with water-vapor propellant. Thus, the design criteria have not been established yet. To figure out the appropriate geometry, we developed several patterns of discharge channel. Some of them are shown in Figure 2. Tested models and their representative dimension (outer diameter D_o) are summarized in Table 1. No.0 is the prototype model, which was developed in reference to a 100 W-class xenon Hall thruster. In spite of their size difference, the geometry of the magnetic screen is designed to be as similar as possible.

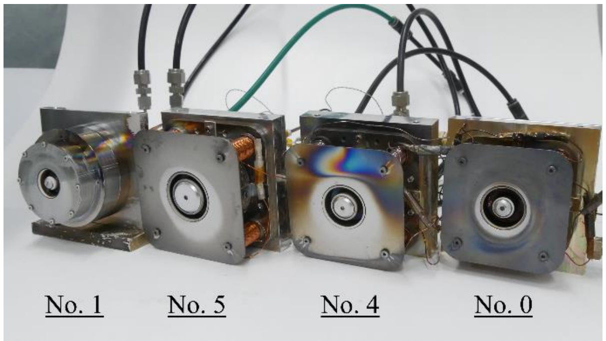

Figure 2: Hall thrusters that we developed.

Table 1: Scale and status of the Hall thrusters

No.	D_o	Status
0	26 mm	Stable operation at 200–240 V
1	20 mm	Stable operation at 200–300 V
2	24.5 mm	Stable operation at 200–240 V
3	27.5 mm	Stable operation at 200 V
4	29 mm	Stable operation at 200–220 V
5	34 mm	No stable operation

Cathode Design

The basic mechanism of electron supply is same as that of a classical filament cathode; the well-heated emitter emits thermionic electrons of the current density J given by the Richardson-Dushman equation:

$$J = AT^2 \exp\left(-\frac{e\phi}{k_\mathrm{B}T}\right), \qquad (1)$$

where A : Richardson coefficient, T: emitter temperature, e: elementary charge, k_B: Boltzmann coefficient, and ϕ: work function. The cathode we designed has two unique characteristics. One is the use of a LaB_6 tip as an electron emitter. Although this cathode does not use any working gas, it can be exposed to the exhausted propellants downstream from the thruster. According to the previous study, it is known that LaB_6 has low work function and more durability to oxidation[9)]; thus, LaB_6 was expected to work well under the water-vapor plume. The other is the adoption of a multi-layer insulation (MLI) to achieve sufficiently high temperature with low heating power. The LaB_6 tip is heated up by an attached graphite heater, but effective thermal insulation is necessary to preferentially conduct the heat to the tip. MLI is a structure with excellent thermal insulation and has been used in satellite's surface and hollow cathode. By applying this technology, we attempt to reduce the power consumption to less than half of the thruster discharge power. The structural detail and actual appearance are shown in Figure 3 and Figure 4, respectively.

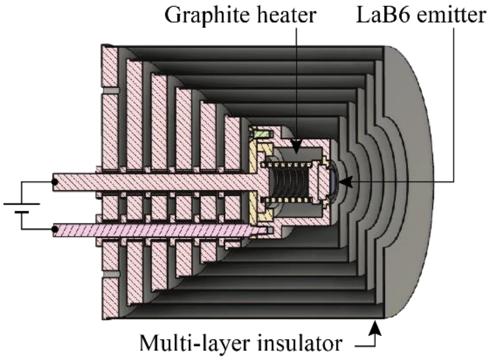

Figure 3: Structural schematic of a LaB_6 thermionic cathode.

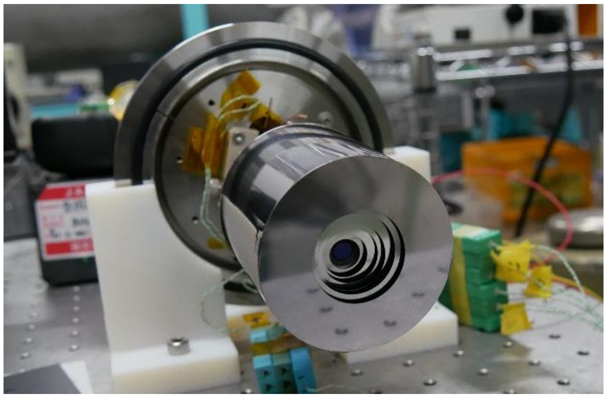

Figure 4: Front view of the cathode.

The main technical challenge is to provide relatively large number of electrons (~1 A) without plasma bridge. If there is dense plasma between the emission point and thruster plume like a hollow cathode, a lot of electrons can easily be induced outside with low potential difference. However, since this cathode did not produce plasma, electron transportation is expected to be limited by the negative space charge of itself. One of the ways to mitigate the potential barrier is to place the cathode so that the emitter interferes with ions in the plume.

GROUND-TEST FACILITY

All the operating tests of the Hall thrusters was conducted with the main discharge chamber shown in Figure 5, whose diameter and length are 1.0 m and 2.6 m, respectively. This chamber has two high-vacuum pumps: a turbo molecular pump and cryopump. The typical background pressure was $1–3\times10^{-2}$ Pa during thruster firing. In the chamber, two types of plasma instruments are equipped for the performance evaluation: a Faraday probe and retarding potential analyzer (RPA). The Faraday probe can measure the ion beam current and its divergence while the RPA can measure the acceleration potential. Both probes were located on the thrust axis as shown in Figure 6 and only Faraday probe can be moved in an arc around the thruster. The analysis details and performance estimation method can be seen in Ref. 6).

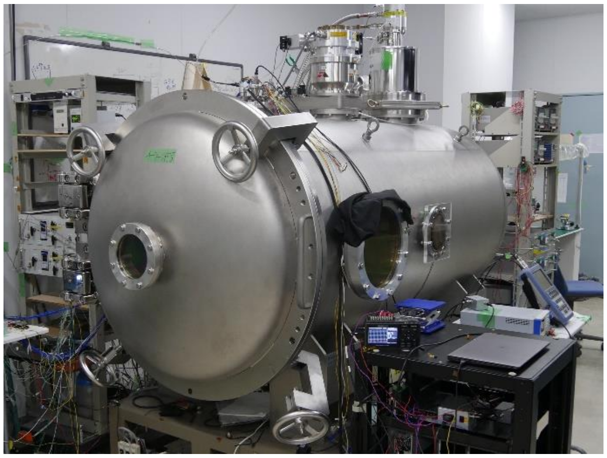

Figure 5: Main discharge chamber.

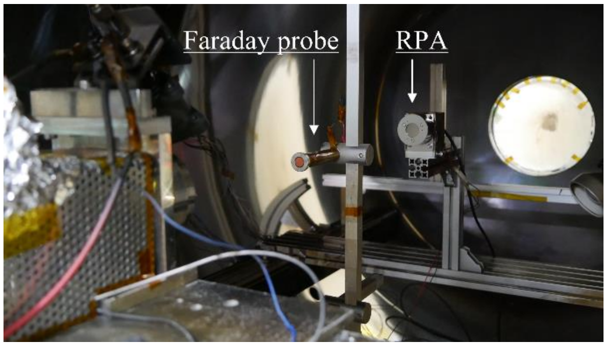

Figure 6: Faraday probe and RPA.

EXPERIMENTAL DEMONSTRATION

Hall thruster performance tests

For stand-alone performance tests of the Hall thrusters, we used a commercial plasma-bridge cathode (LFN2000, Kaufman & Robinson) worked with tungsten filament and xenon gas because the proposed thermionic cathode was not technically matured. We tried 6 patterns of thruster listed in Table 1, and the stable operation was performed with five of them. Figure 7 shows the plasma plume appearance during firing with water-vapor propellant. The search for operability was conducted above 200 V of discharge voltage. Among the tested thruster models, No.1 (the most miniature one) had the widest operating region around 100 W. Figure 8 shows the estimated performances for every thruster model. In the case of No. 0 or 2–4, the typical minimum discharge current was 1 A; thus, operation less than 200 W was difficult to achieve. On the other hand, only No. 1 performed continuous discharge with around 0.5 A of discharge current. Owing to that, No. 1 could be operated from 200 to 300 V with 70–200 W of discharge power. Looking at the thrust trend in Figure 8 (a), the thrust force of No. 1 seemed to be smaller than that of the others. Instead, the specific impulse was improved by increasing the discharge voltage as shown in Figure 8 (b). As a result, we could achieve a thrust force of 2.9 mN, specific impulse of 650 s, and anode efficiency of 4.6 % at 200 W with the most miniature thruster.

From the perspective of operational stability, No. 1 was also superior to the others. In some thrusters, the discharge frequently stopped and had to be re-ignited many times. However, No. 1 had well discharge stability and rarely need re-ignition process. Figure 9 shows the typical time history of discharge current. While the flow rate was changed after the beginning, the thruster operated continuously for more than 45 minutes until it was manually stopped. In conventional Hall thrusters, high-frequency oscillations of the discharge current are also a common problem. As for the water-vapor Hall thrusters, the oscillation amplitude at stable operating points was sufficiently small.

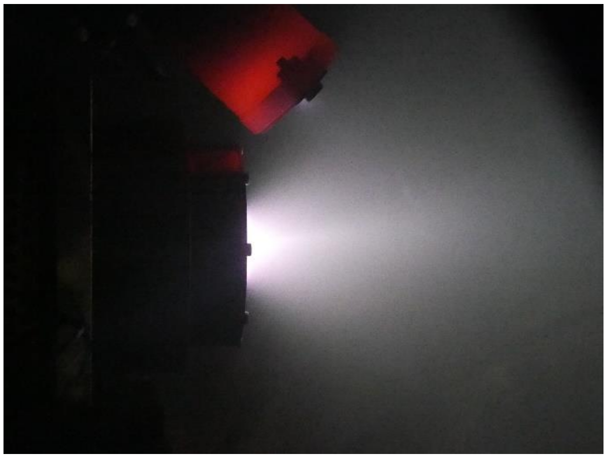

Figure 7: Plume appearance of the water-vapor Hall thruster. This photograph is No. 1.

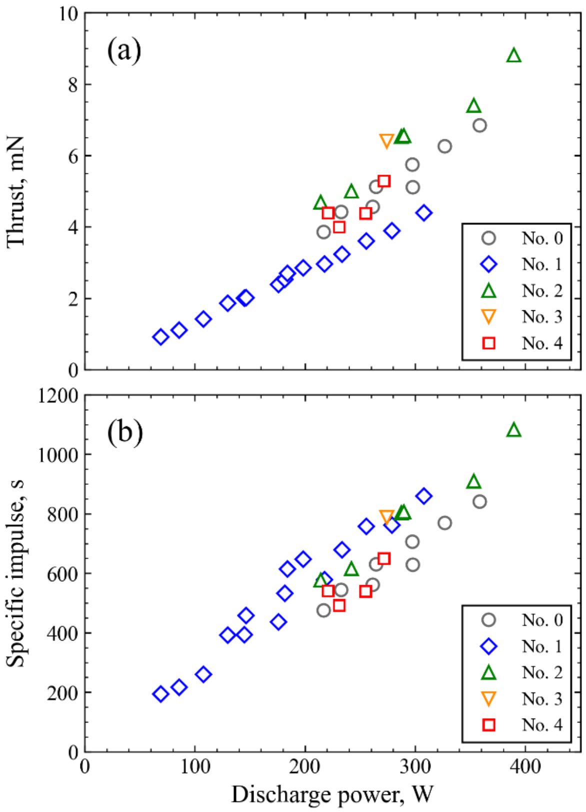

Figure 8: (a) Thrust and (b) specific impulse of each thruster model as a function of discharge power.

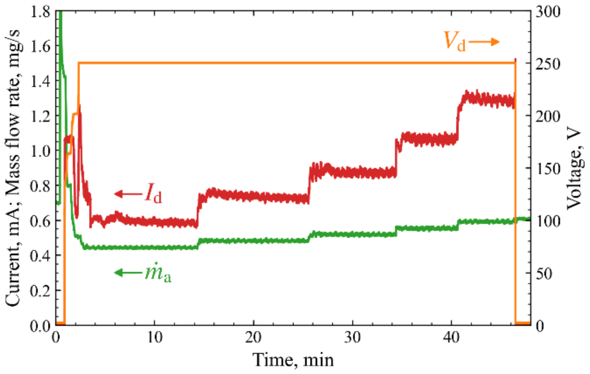

Figure 9: Typical time history of discharge current I_d of No. 1. The discharge voltage V_d and mass flow rate $\dot{m}_a$ were manually set during operation.

Cathode coupling test

After the thruster operation achieved, we worked the thermionic cathode near the plasma plume and evaluated the electron emission from it. The objective of this experiment is to demonstrate the effective increase in electron emission current by the existence of ion beam and usability of the LaB_6 emitter in water-vapor plasma plume. Because the electrons from the thermionic cathode were predicted to be insufficient for thruster ignition and discharge maintenance, the commercial cathode used in the thruster stand-alone tests was also worked together in this experiment. The coupled thruster was the prototype model (No. 0). Each placement is shown in Figure 10. During the cathode heating, the discharge current was almost 1.2 A, which was corresponding to the ion beam current of 0.6–0.7 A. Figure 11 (b) shows the measured electron emission current with the previous results of the cathode stand-alone working tests7) and Figure 11 (a) shows the minimum heating power to achieve each surface temperature as a reference. In both no-plasma case and near-plume case, electron emission current was increased along the curve of Richardson-Dushman equation at low temperature region; however, it was saturated above certain temperatures. We attribute this saturation to the space-charge limit. Comparing the saturated current values between no-plasma case and near-plume case, the achieved electron current in near-plasma case is about 100 times higher than that in no-plasma case. This result suggests that even the existence of low-density ions has great positive effect on mitigation of space-charge limit. However, the electron current did still not reach the discharge current by around an order. In order to operate the thruster only with the thermionic cathode, further investigation of plume-emitter inference or other additional ideas to enhance the electron emission is necessary. In addition, since the heating power is predicted over 100 W, we should also improve the thermal design in the future. Regarding the compatibility of LaB$_6$ emitter to the water-vapor plasma plume, significant negative effect on electron emission was not observed in this test. However, clear change in the LaB$_6$ surface appearance was confirmed. The appearances before and after the coupling test are shown in Figure 12. In future study, we will analyze the cause and effect by microscopic observation.

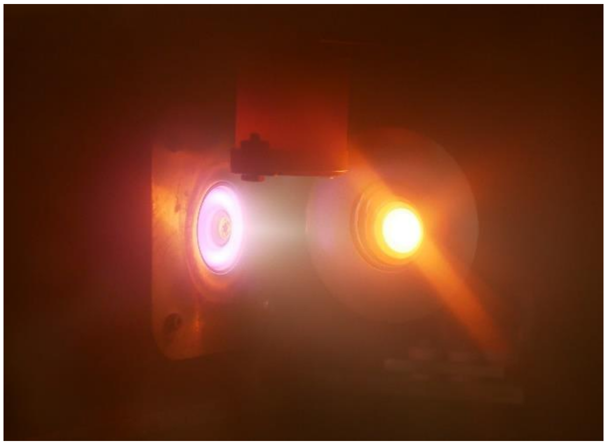

Figure 10: Thermionic cathode worked near the plume of the water-vapor Hall thruster.

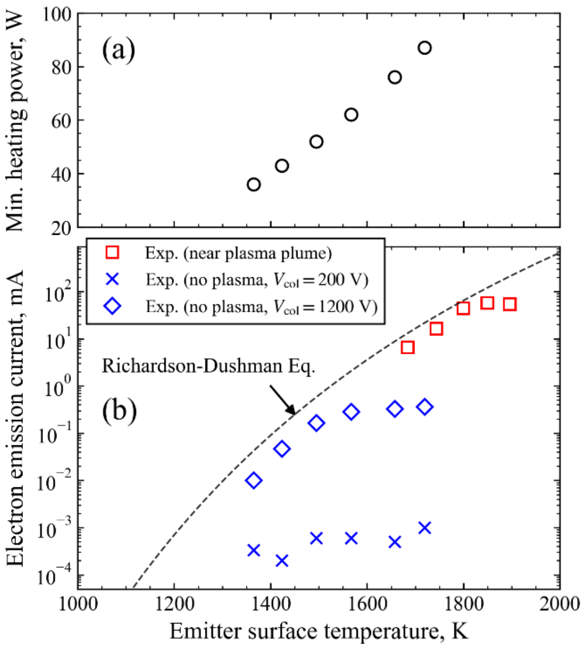

Figure 11: (a) Minimum cathode heating power corresponding to the emitter surface temperature7). (b) Theoretical and experimental electron emission current as a function of the surface temperature. The theoretical curve of Richardson-Dushman eq. was calculated with the work function of 3.3 eV.

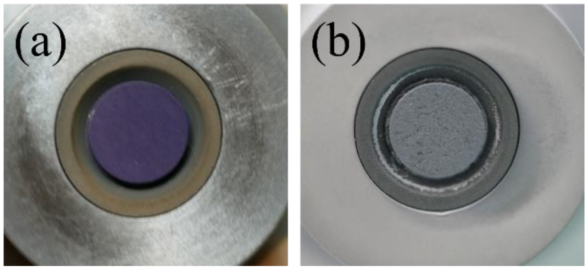

Figure 12: LaB$_6$ surface appearance (a) before and (a) after the cathode coupling test.

CONCLUSION

The development of 100 W-class water-vapor Hall thruster is progressing for the future use in satellite constellations and space explorations. The laboratory models of the thruster and cathode has been developed and tested. The investigation of thruster geometry revealed that the most miniature design ($D_o = 20$ mm) was the most suitable for 100 W-class operation. This thruster achieved both 200 V stable operation at 70 W and 300 V stable operation at 200 W. The cathode-compatibility testing under the existence of water-vapor plasma plume was also conducted. From this experiment, not only the usability of LaB_6 was indicated, but also the positive effect of ion beam existence on mitigation of space-charge limit was demonstrated. For the practical application of the water-vapor Hall thruster, the development of a 100 mA-class compatible cathode and modularization of the thruster integrated system will be continued.

Acknowledgments

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References

1. Curzi, G., Modenini, D., and Tortora, P., "Large Constellations of Small Satellites: A Survey of Near Future Challenges and Missions," Aerospace, Vol. 7, No. 9, 2020, p. 133.
2. Creech, S. D., Robinson, K. F., and Cox, R., "NASA's Space Launch System: Deep Space Access for CubeSats," Proceedings of the 70th International Astronautical Congress, Washington D.C., October 2019.
3. Conversano, R. W., Lobbia, R. B., Arestie, S. M., Lopez-Ortega, A., Chaplin, V. H., Reilly, S. W., and Goebel, D. M., "Demonstration of One Hundred Kilogram Xenon Throughput by a Low-Power Hall Thruster," Journal of Propulsion and Power, Vol. 39, No. 2, 2023, pp. 217–231.
4. Moriai, I., et al., "Initial Flight Operation of AQUARIUS: Water Resistojet Thruster on 6U EQUULEUS," Proceedings of the 34th International Symposium on Space Technology and Science, Kurume, Japan, June 2023.
5. Schwertheim, A., and Knoll, A., "Experimental Investigation of a Water Electrolysis Hall Effect Thruster," Acta astronautica, Vol. 193, 2022, pp. 607–618.
6. Shirasu, K., Kuwabara, H., Matsuura, M., Koizumi, H., Nakagawa, Y., Watanabe, H., Sekine, H., and Komurasaki, K., "Demonstration and Experimental Characteristics of a Water-Vapor Hall Thruster," Journal of Electric Propulsion, Vol. 2, No. 1, 2023, p. 11.
7. Takasaki, D., Fujimori, A., Sekine, H., Koizumi, H., Watanabe, H., Nakagawa, Y., Komurasaki, K., "Performance Measurements of a Propellant-Free LaB6 Thermionic Cathode," Proceedings of the 37th International Electric Propulsion Conference, Cambridge, MA, June 2022.
8. Asakawa, J., Koizumi, H., Yaginuma, K., Nakagawa, Y., "Pre-Flight Testing Results of Multiple Water Propulsion Systems – Resistojet and Ion Thruster for SmallSats," Proceedings of the 36th Annual Small Spacecraft Conference, Logan, Utah, August 2022.
9. Goebel, D. M., Watkins, R. M., and Jameson, K. K., "LaB6 Hollow Cathodes for Ion and Hall Thrusters," Journal of Propulsion and Power, Vol. 23, No. 3, 2007, pp. 552–558.