On-orbit Demonstration of the Water Resistojet Propulsion System on Commercial 6U-Sat SPHERE-1 EYE

Yuichi Nakagawa, Akira Iwakawa, Shogo Kameyama, Takeo Kikuchi,
Kazuya Yaginuma, Jun Asakawa, and Hiroyuki Koizumi
Pale Blue Inc.
Tokatsu Techno Plaza 610, Kashiwanoha 5-4-6, Kashiwa, Chiba, Japan; +81-4-7115-1148
nakagawa@pale-blue.co.jp

ABSTRACT

SPHERE-1 EYE, a 6U CubeSat developed by Sony Group Corporation, was launched at the beginning of 2023. The satellite included a water resistojet propulsion system, which is designed for orbit raising after the initial checkout. The water resistojet propulsion system consists of a tank, a vaporizer, nozzles, a control board, and a power processing unit. The form factor of the propulsion system is 1.25 U, the wet mass is 1.4 kg, and the achievable total impulse of the system is 170 Ns or higher. A unique design of the water propulsion system is a vaporization chamber generating steam at room temperature and low pressure, under 10 kPa. The performance measured on the ground shows a thrust of 2.7 mN, and a specific impulse of 60 s. A qualification test campaign including vibration, shock, thermal, throughput, and system performance tests was conducted, followed by acceptance tests. On−orbit demonstration was conducted on March 3rd and 16th for all four nozzles and the thrust generation was confirmed. The estimated thrust on orbit was 6.1 – 7.2 mN. Comparison between the on-orbit results and the ground tests demonstrated the functionality of the system as anticipated.

INTRODUCTION

The number of CubeSats has been gradually increasing over the past decade, and their capabilities have also improved remarkably. In the early days, CubeSats were mainly developed by universities for educational purposes. Private companies started to utilize CubeSats later, such as the constellation of Planet's CubeSats for earth observation satellites [1]. SPHERE-1 EYE, the first commercial 6U CubeSat developed by Sony Group Corporation, demonstrates the continuous trend of private-sector-led development [2].

With the entry of private companies, we expect the trend toward diversification of CubeSat missions and requirements for higher added value. In this context, the role of the propulsion system should be to maximize mission duration and mission value of the upcoming demand, while serving the missions nowadays that inherently require propulsion.

Water has many advantages over other propellants because it is easy to handle and store as a liquid phase at room temperature and pressure. Research on water thrusters had been conducted since well before the rise of CubeSats. With the dawn of CubeSats, however, water as a propellant was focused again to meet the demand for miniaturization. Resistojet thrusters, ion thrusters, and pulsed plasma thrusters using water as a propellant have been researched and developed [3,4,5].

The resistojet thruster discussed in this paper was developed based on the AQUARIUS, which was developed at the University of Tokyo and installed on the EQUULEUS lunar exploration probe [6], and another resistojet thruster that was installed on a 3U CubeSat AQT-D and was deployed from International Space Station in 2019 [7]. The system architecture is simple because water evaporates at room temperature, and its envelope fits a 3U or 6U CubeSat. In addition, storing propellant under atmospheric pressure enables lightweight structure and leads to an increase propellant mass and total impulse. The small molecular weight of water can achieve a higher specific impulse than cold-gas thrusters of similar size [8].

This paper reports on the ground and on-orbit test results of the resistojet thruster installed on SPHERE-1 EYE. After describing the mission of SPHERE-1 EYE and its specifications, the propulsion system's ground test campaign is reported, which includes operation tests, environmental tests, throughput test, and system operation test. In addition, the results of the on-orbit tests are discussed and compared with the ground tests result.

SYSTEMS

Satellite: SPHERE-1 EYE

SPHERE-1 EYE, the first commercial 6U CubeSat developed by Sony Group Corporation, was launched on January 3rd of 2023 [2]. The satellite is equipped with a full-size Sony camera that allows a photographer to set the sensitivity, aperture, and shutter speed as desired. In addition, an attitude control system is installed to provide a high degree of freedom in camera work. Pale Blue's water propulsion system is installed for orbit raising and orbit maintenance to ensure a sufficient mission duration for this satellite.

Table 1 Specification summary of SPHERE-1 EYE

Form factor	6U
Altitude	522 km
Camera	Full-size camera made by Sony
Lens	28 – 135 mm, F4

Resistojet Propulsion System

The water resistojet propulsion system consists of a tank, a vaporizer, nozzles, a control board, and a power processing unit (Figure 1). A unique design of our water propulsion system is a vaporization chamber generating steam at room temperature and low pressure, under 10 kPa. Liquid water propellant stored in the tank is injected into the vaporization chamber by actuating a solenoid valve, and the injected droplets then vaporize in the chamber, filling it with water vapor at saturated pressure. The saturated vapor flows by its own pressure difference with vacuum, and finally accelerates through nozzles, thus generating thrust. The performance measured on the ground shows a thrust of 2.7 mN, a specific impulse of 60 s, and a total system power consumption kept under 30 W.

The specification of the system is summarized in Table 2. The form factor of the propulsion system is 1.25 U, the wet mass is 1.4 kg, and the achievable total impulse of the system is higher than 170 Ns. Although the propulsion system is mainly used for orbit raising and keeping for the mission, the propulsion system has 4 nozzles to generate the angular momentum for unloading the satellite.

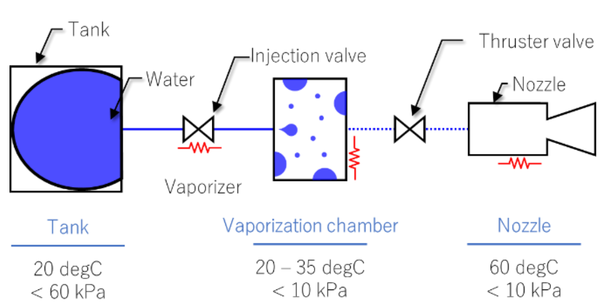

Figure 1 Simplified model of the water resistojet thruster with typical values

The control board installed in the system monitors the system status and can automatically prepare and fire depending on a simple command. The electrical interface is composed of regulated 5 V and unregulated voltage, which is directly supplied from the battery system of the satellite. Also, the combination of the system safety using water as propellant and simple control reduces development costs and time, making the water propellant propulsion system suitable for CubeSats.

Table 2 The ground qualified specification of the water resistojet propulsion system installed in SPHERE-1 EYE

Form factor	1.25 U
Mass (wet)	1.4 kg
Propellant mass	286 g
Power (Nominal)	< 30 W
Number of nozzles	4
Thrust (ave.)	2.7 mN
Specific Impulse	> 60 s
Total Impulse	> 170 Ns
Supply Voltage	5V and Unregulated
Communication interface	RS-422 UART

TEST ON THE GROUND

Equipment

The operation tests on the ground were conducted in the vacuum chamber at Pale Blue Inc. It is a cylindrical chamber with a diameter of 1 m and a length of 2.2 m. The inner pressure reaches the vacuum by two turbomolecular pumps with a pumping speed of 2400 L/s and one turbomolecular pump with a speed of 800L/s (N_2). The back pressure during the thruster operation tests was kept under 1 Pa, typically 0.5 Pa.

The thrust was directly measured using an inversed pendulum-type thrust stand. The detail of the thrust stand is described in [9]. This in-house thrust stand was developed to measure thrust force while mounted on a CubeSat and is capable of measuring thrust force at a several mN level with less than 10% of error when a 10 kg thruster or satellite is mounted on the stand.

Detailed operation tests and operation point analysis were performed using an engineering model that has an ideal design to the flight model except for minor modifications. The operation tests of the flight model were only performed around the designed operation point to verify its consistency with the engineering model. In this paper, we describe the result of the engineering model, which was tested in detail, in order to compare it with the on-orbit operation results.

Operation Test

The results of the operation test are shown from Figure 2 to Figure 4. Figure 2 shows the results when the injection valve was opened and closed only once, and the thrust was observed as one sequence from the start to the end. The injected water becomes vapor, then flows downstream passing the opened the thruster valve, and accelerates through the nozzle to generate thrust. The thrust continues until the water is depleted in the vaporization chamber. The thrust profile shows a sharp peak at the onset of vaporization and a gentle decrease. The vaporization chamber pressure time history is a similar decreasing trend during thrust generation. The temperature dropped while thrusting and recovered later, which is a clear indication of the vaporization process. This temperature variation was controlled within 4 ℃ and did not strongly impact the thrust.

Figure 3 shows the relation between the thrust and the vaporization chamber pressure. These results have been obtained by changing the vaporization chamber temperature and the injected mass of the water. This figure demonstrates that the thrust generated by the resistojet thruster system has a strong correlation with the vaporization chamber pressure. Using the nozzle equation based on the quasi-one-dimensional compressible fluid dynamics, the thrust is uniquely determined by the stagnation pressure. The stagnation pressure can be determined by the vaporization chamber pressure and flow channel characteristics. Thereby, the result of Figure 3 implies the resistojet thruster system can be explained by the gas dynamics.

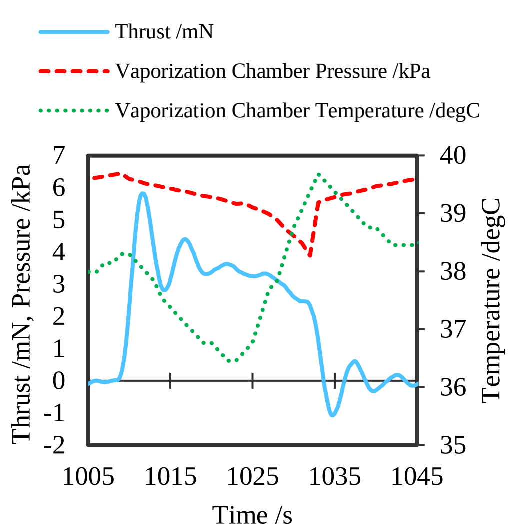

Figure 2 Operation test result: one shot result with once opening of the injection valve.

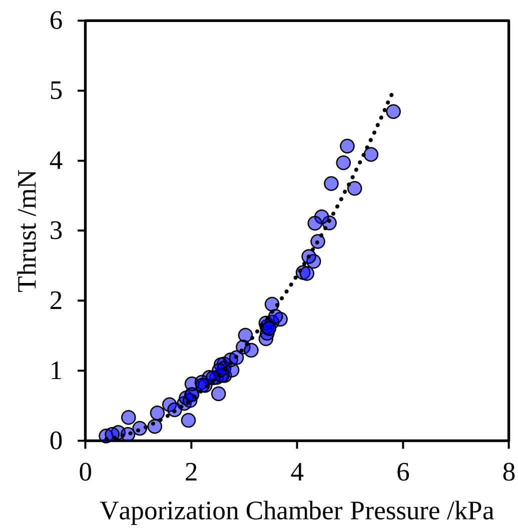

Figure 3 Operation test result: relation between vaporization chamber pressure and thrust.

The analysis of the optimal operating point for the satellite was conducted and the operating point was determined by using the operation test results and the satellite system requirement of the thrust, the specific impulse, and the available power.

Figure 4 shows a part of the results of continuous test at the determined operation point. During the operation, the

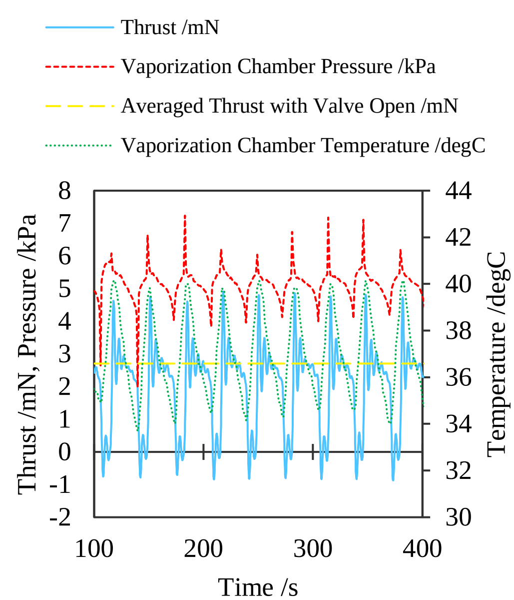

Figure 4 Operation test result: continuous operation with independent control

propulsion system automatically controlled the pressure and the temperature through an independent control system, and it generated thrust intermittently. The control system monitored the vaporization chamber pressure. When the pressure dropped a threshold, the thruster valves were automatically closed, and then water droplet was supplied to the vaporization chambers using the injection valve. After achieving the pressure beyond the threshold value, the thruster valve was automatically opened. This control was necessary to ensure the required specific impulse by keep operating at the optimum pressure. By continuously performing this control, the target thruster performance was achieved, resulting in an averaged thrust of 2.7 mN, a specific impulse of 60 seconds, and the required total impulse of 170 Ns.

Environmental Tests

The environmental tests have been conducted under the conditions required by the launch vehicle, Falcon 9, with the additional requirements from the satellite design structure. The QT-level tests, including the vibration, shock and thermal tests were conducted for the engineering model, and the AT-level tests were conducted for the flight model. Separately, the total ionization doze on the electrical board was conducted to confirm the radiation tolerance of the board. All tests have been completed without any issues and confirmed the thruster system to be an appropriate design.

The vibration and shock tests were conducted to verify the endurance to the launch vehicle environment. Before and after the vibration/shock tests, the propulsion system functionality was checked by repeating the operation test.

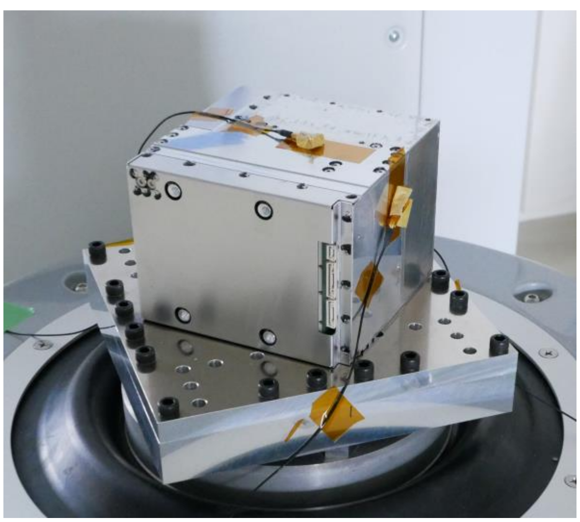

Figure 5 Vibration test setup with the flight model

The propulsion system successfully operated without any degradation in performance.

Thermal tests were conducted to verify the operational characteristics under the temperatures expected in orbit. The operating temperature range was specified as 4°C to 35°C. The tests were conducted at 4°C (the minimum value) and 35°C (the maximum value), and it was confirmed that the designed performance was

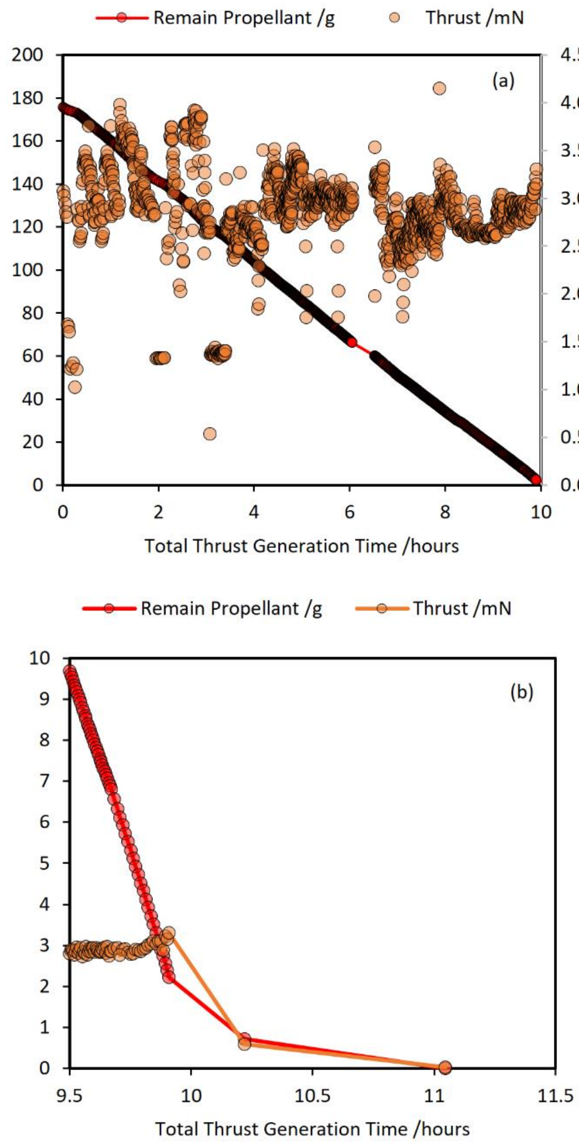

Figure 6 Results of throughput test: (a) all time result of throughput test, (b) result after less than 10 g of the remain propellant. Two plots after 10 hours were the operation after finishing the throughput test to check the remain propellant.

demonstrated. This data was also used to develop an on-orbit operation plan.

Throughput Test

Figure 6 shows the result of the throughput test, which was conducted to verify whether the propulsion system could achieve the required total impulse. (a) shows the mass decrement time history, and (b) shows the closeup of the end-of-life. The initial propellant mass was set to 180 g at the test, and the real-time mass has been measured by installing the thruster system on the mass balance [9]. As can be seen here, there was no significant degradation in the thrust until the propellant was almost exhausted. The weight after the throughput test indicated that the amount of remaining propellant was less than 1%. The result was that the system met the specification of the designed total impulse.

System Operation Test

System operational test was conducted using the flight model installed on the satellite, the result is shown in Figure 7. The purpose of the test was to verify that the results obtained from the ground test using the engineering model were reproduced by the flight model in the satellite-installed condition. The test also included the verification of the electrical design including the noise it generates and the thermal design of the satellite. After the test, the weight of the water used was measured, and the difference was filled to ensure that the amount of propellant used at launch would not be reduced.

The test was conducted by using a vacuum chamber in the University of Tokyo. In the test, the propulsion system was controlled by simple commands and was verified in the continuous thrust generation mode under independent control. The results are shown in Figure 7. The control started at around 7700 s and ended at around 8450 s. The experimental results of the engineering model reproduced well, with some differences in terms of temperature control. The difference in temperature was expected because of the difference in the environment between the stand-alone and installed tests. In addition, since these data were obtained prior to launch, it became possible for us to smoothly estimate the on-orbit operating conditions and temperature rise time. It was remarked as one of the advantages of the propulsion system using water, which is easy to handle and has a refillable system on the satellite-installed condition.

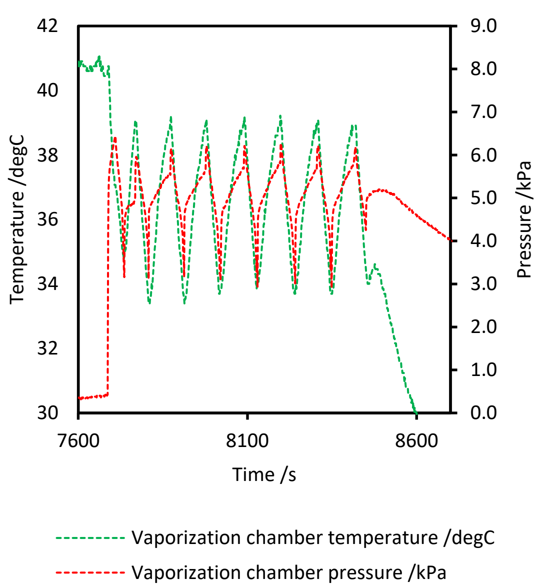

Figure 7 Result of system operation test

ON-ORBIT OPERATION

Result

On-orbit operation tests were conducted on March 3rd and 16th, and it was confirmed that all four nozzles generated thrust. The operation test was conducted under 3-axis attitude control by the satellite, and the change in total angular momentum of the satellite was calculated from the change in angular momentum of the reaction wheel and the angular velocity of the satellite. The results are shown in Figure 8, and this change in angular momentum confirmed the thrust generation. Also, from these results, the on-orbit thrust can be estimated by

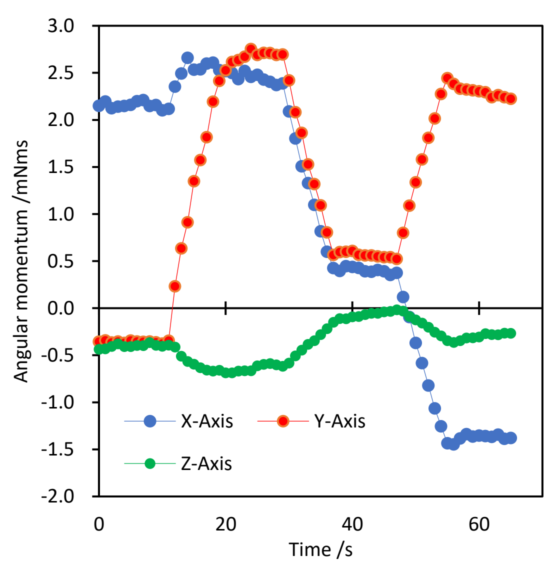

Figure 8 Total angular momentum of the satellite when operating the thruster. The thruster operated in 13-20 s, 31-38 s, and 49-56 s with the different nozzles.

assuming the position of the center of gravity and the direction of the thrust force. The results can be compared with the result on the ground.

Analysis

A comparison of the results from the on-orbit tests with those estimated based on Figure 3 from the ground tests, is shown in Table 3, with the error for each being within 10 - 15%. Note the error in the measured thrust values include multiple error sources, such as thrust measurement, center-of-gravity estimation, nozzle installation direction. In addition, the effect of back pressure during the ground test should be considered. Although the operation test on the ground was conducted with a back pressure of about 1 Pa or lower, the result suggests that a stronger vacuum is required for accurate performance measurements [10]. For the present satellite mission, the precise thrust estimation was not required because the mission was designed and confirmed achievable with the lower, more conservative thrust and specific impulse obtained during the ground test. For a mission that requires precise thrust estimation, it is important to conduct a test with an improved method that takes these facility effects into account, or to conduct a test with a lower back pressure.

Table 3 Comparison of estimated thrust between from ground test and from on-orbit test

Nozzle ID	Estimated thrust from ground test	Estimated thrust from on-orbit test
A	6.4 mN	6.6 mN
B	6.1 mN	7.0 mN
C	5.9 mN	6.1 mN
D	6.2 mN	7.2 mN

CONCLUSION

The water resistojet propulsion system was developed for a 6U CubeSat: SPHERE-1 EYE and operated on orbit successfully. The ground tests confirm the required performance was satisfied and all the environmental tests passed. The performance on orbit has well reproduced the ground test results considering the factors of possible errors. It also shows the feasibility of the application of the water resistojet propulsion system on CubeSats not only from the viewpoint of performance and interface, but also the ease of handling and safety requirements.

ACKNOWLEGEMENT

We would like to thank all those involved in the development of the water resistojet propulsion system leading up to on-orbit demonstration, as well as engineers at Pale Blue Inc. who were involved in the development of the thruster system. Also, we would like to thank all the project members who have developed and operated the SPHERE-1 EYE.

References

1. O'Donnell, K., and Richardson, G., "Small Satellite Trending & Reliability 2009-2018," Proceedings of the small satellite conference 2020, Logan, UT, August 2020, SSC20-S2-01.
2. STAR SPHERE space inspection project, https://starsphere.sony.com/en/, accessed on 6/5/2023.
3. Koizumi, H., Asakawa, J., Nakagawa, Y., Nishii, K., Takao, Y., Nakano, M., and Funase, R., "Assessment of Micropropulsion System Unifying Water Ion Thrusters and Water Resistojet Thrusters," Journal of Spacecraft and Rockets, April 2019.
4. Nakagawa, Y., Koizumi, H., Naito, Y., and Komurasaki, K., "Water and xenon ECR ion thruster—comparison in global model and experiment," Plasma Sources Science and Technology, Vol. 29, 2020, 105003.
5. Scharlemann C. A., and York, T. M., "Pulsed plasma thrsuter using water propellant, part I; design and investigation of thrust behavior," AIAA 2003-5022, 2003.
6. Nishii K., et al, "Flight Model Development and Ground Demonstration of Water Resistojet Propulsion System for CubeSats," Transaction of Japan Society for Aeronautical and Space Sciences, Vol. 14, No. 2, 2018, pp. 1-10.
7. Yaginuma, K., et al, "AQT-D: CubeSat Demonstration of a Water Propulsion System Deployed from ISS," Transaction of Japan Society for Aeronautical and Space Sciences, Vol. 17, No. 20, 2020, pp. 1-8.
8. Ames Research Center, "State-of-the-Art Small Spacecraft Technology," NASA/TP-2022-0018058.
9. Asakawa, J., Nishii, K., Nakagawa, Y., Koizumi, H., Komurasaki, K., "Direct measurement of 1-mN-class thrust and 100-s-class specific impulse for a CubeSat propulsion system," Vol. 91, Issue 3, March 2020.
10. Nishii, K., Koizumi, H., and Komurasaki, K., "Experimental Characterization of Nozzle Performance at Low Reynolds Numbers for Water Microthrusters," Journal of Propulsion and Power, January 2021.