AQUARIUS: The World's First Water-based Thruster Enabled 6U CubeSat to Complete Lunar Flyby

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ABSTRACT

This paper presents the outcomes of the initial operations and on-orbit performance of AQUARIUS (AQUA ResIstojet propulsion System), a micro-propulsion system. AQUARIUS utilizes water as a propellant and is designed for trajectory control and reaction wheel desaturation of a 6U CubeSat, EQUULEUS (EQUilibriUm Lunar-Earth point 6U Spacecraft). The spacecraft was launched in November 2022 by SLS, following which the initial operations commenced. Both the spacecraft and the propulsion system were confirmed to be in good health during the checkout process. Performance evaluation of the propulsion system confirmed that it met the requirement to execute the first delta-V maneuver scheduled 38 hours after separation from the launch vehicle. The delta-V maneuver was successfully completed, achieving a total delta-V of 6.48 m/s. The propulsion system demonstrated an average thrust of 5.94 ± 0.21 mN. Subsequently, precise trajectory control maneuvers were carried out, resulting in a successful lunar flyby. As a result of these initial operations, AQUARIUS became the world's first water propulsion system to successfully control its orbit in deep space.

INTRODUCTION

Small satellite launches have dramatically increased these years, and their missions have diversified.[1] Traditionally, deep space exploration was conducted only by large-scale, high-cost spacecraft. However, the innovations in communication devices, the increasing efficiency of solar panels, and the development of miniature propulsion systems have provided opportunities for small satellites to play an active role.[2] In 2014, a 50 kg-class spacecraft named PROCYON, developed by the University of Tokyo and JAXA (Japan Aerospace eXploration Agency), became the world's first microspacecraft to explore deep space.[3] Four years later, the MarCO CubeSats conducted an interplanetary voyage toward Mars.[4] On September 2022, an Italian CubeSat called LICIACube successfully imaged the DART impact on Dimorphos and showed the capability of CubeSat.[5] At the same time, 10 CubeSats were awaiting launch for their ambitious missions.

On November 16, 2022, NASA's Space Launch System successfully launched the Orion spacecraft and the 10 CubeSats. EQUULEUS (EQUilibriUm Lunar-Earth point 6U Spacecraft) is one of them, a 6U CubeSat —approximately 10 cm times 20 cm time 30 cm, weighing less than 11 kg— jointly developed by the University of Tokyo and JAXA. The spacecraft is intended for three scientific missions and a main engineering mission: demonstration of trajectory control by a CubeSat to reach the Earth-Moon L2 (EML2) point.[6] The key component of this mission is a miniature propulsion system, namely, AQUARIUS (AQUA ResIstojet propUlsion System).

AQUARIUS is a resistojet thruster that uses water as a propellant. Water can be stored as a liquid at room temperature, reducing the structural mass of the propulsion system. Moreover, its safety and availability led to shorter-period and lower-price development. The propulsion system is characterized by complete liquid-vapor separation and low-pressure, room-temperature vaporization. These features make it highly reliable and reasonable for a CubeSat.AQUARIUS plays a key role in orbit transfer and reaction control throughout the mission of EQUULEUS. This paper reports the result of initial AQUARIUS operations, including the world's first success in lunar-flyby using water propulsion, and its on-orbit performances.

AQUARIUS

System Hardware

AQUARIUS is a propulsion system designed for EQUULEUS and developed in-house by the University of Tokyo.[7] The system has a size of 2.5U and a structural mass of 1.3 kg. Figure 1 and 2 show the configuration and schematics of the hardware, respectively. AQUARIUS consists of three major components: a water tank, a vaporization chamber, and a thruster unit.

The tank is where liquid water is stored. Water is filled in a bladder installed in an aluminum body, and a space between the bladder and the body is purged by argon gas, initially pressurized up to 50 kPa. The tank has a heater to keep the propellant at room temperature to prevent it from freezing. In the event of freezing, the gap between the bladder and the wall prevents damage to the tank. Pressure and temperature inside the tank are monitored by the sensors.

At the downstream of the tank, two pairs of regulation valves and a vaporization chamber, where the vaporization of water takes place, are connected. Droplets of water are supplied intermittently into the chamber by opening and closing a series of regulation valves. Then, they receive heat from the chamber wall which is heated by three heaters, and start vaporizing. The vapor flow to thrusters, while the remaining liquid droplets are trapped by a labyrinth structure. This enables an appropriate liquid-vapor separation. The vaporization takes place at low-pressure and room-temperature, which leads to high thermal efficiency. This feature also allows for utilizing heat loss from other devices on the spacecraft. The chamber is sandwiched by communication devices to save heater power. The chamber has two sets of temperature and pressure sensors for redundancy since temperature control and pressure monitoring are the keys to AQUARIUS operation.

The thruster unit, placed at the minus-z plane of EQUULEUS, equips two delta-V thrusters (DVTs)

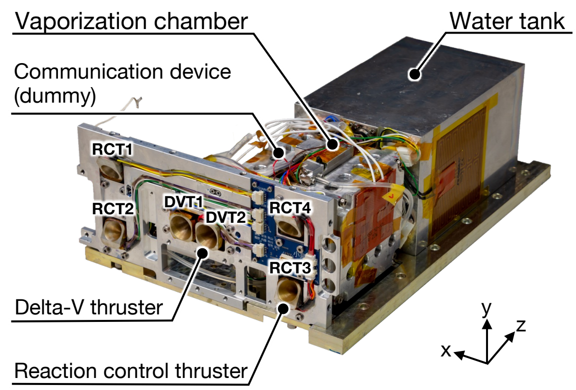

Figure 1: Configuration of AQUARIUS flight model. DVT stands for Delta-V Thruster, and RCT for Reaction Control Thruster. The dummy communication devices are replaced with the real ones when the propulsion system is loaded onto EQUULEUS.

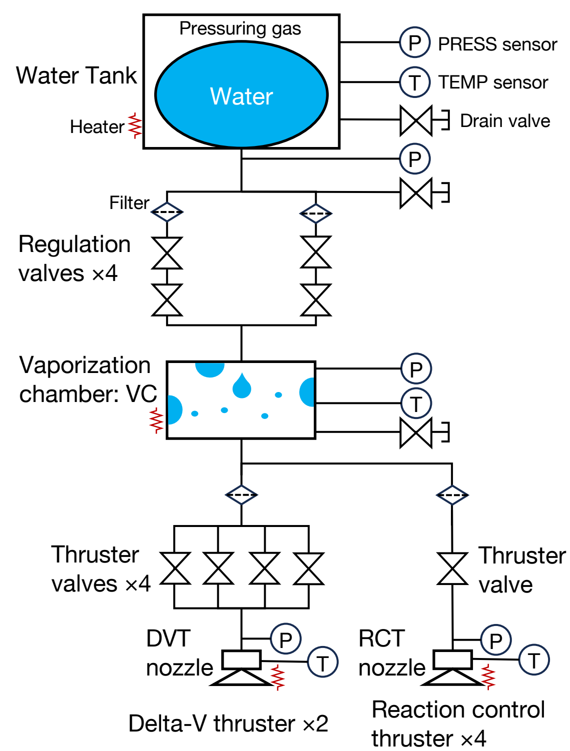

Figure 2: Schematic diagram of AQUARIUS. Two Delta-V thrusters and four Reaction control thrusters are equipped, but one of each is drawn. PRESS stands for pressure, and TEMP for temperature.

and four reaction control thrusters (RCTs). The numbering of each thruster is shown in Figure 1.

Each of the DVTs has four thruster valves, while each of the RCTs has one thruster valve. DVTs have a high-aperture-ratio nozzle to be used for delta-V maneuver. RCTs have a tilted, small nozzle, and a pair of RCTs are utilized to generate unloading torque around the three axes. The nozzles are heated by heaters, and the temperatures of each are monitored. The pressures just upstream of the nozzles are watched as well.

Operating Principle

AQUARIUS is operated in a pulsating manner, which means water is repeatedly supplied and emptied. In other words, the thrust is periodically generated and stopped. At the beginning of a cycle, a series of regulation valves are opened, and water droplets flow into the vaporization chamber. Then, water starts vaporizing and being injected from nozzles. During vaporization, latent heat causes a drop in the chamber temperature, which in turn causes the pressure and thrust to decrease. The latent heat of water is so large that the heaters cannot fully compensate for the limited power resource of the CubeSat. Therefore, a waiting time is needed after the end of the vaporization for temperature recovery to keep the temperature in a given range. During this time, thrust is not generated. This manner of operation contributes not only to maintaining the thrust but also to appropriate liquid-vapor separation. Because of the periodic thrust generation, with a fixed amount of water supply per cycle, the propulsion system has a minimum unit of impulse that can be generated, namely impulse bit.

As mentioned above, the lower the temperature of the vaporization chamber, the lower the thrust. Moreover, the low temperature of the flow path or nozzle may cause condensation or freezing of water. Thus, the temperature must be maintained above a given value. On the other hand, the valves have an upper limit in operating temperature, which must not be exceeded. Therefore, the temperature of the propulsion system is regulated by the bang-bang control of heaters. We also take care of the timing of the attitude adjustment before the propulsion operation. This is because the propulsion system is susceptible to spacecraft temperatures by the nature of the densely integrated CubeSats.

The Specifications of AQUARIUS are shown in table 1. The performance values were obtained in the ground test.[8] Thrust and specific impulse were averaged over a cycle.

Table 1: Specifications of AQUARIUS.

Parameters	Values
Size	2.5U
Propellant	Water (Storage pressure < 50 kPa)
Propellant mass	1.2 kg
Thrust*†	4.09 ± 0.38 mN (DVT) 0.64 ± 0.38 mN (RCT, single)
Specific impulse*†	68.5 ± 5.47 s (DVT) 59.8 ± 5.52 s (RCT, single)
Injection mass (setting, per cycle)	0.63 g (DVT) 0.17 g (RCT, pair)
Power consumption	< 20 W

* average during a cycle, including wait time.
† obtained from ground tests.[8]

INITIAL OPERATIONS

Requirements for a Successful Lunnar Flyby

After the separation from the launch vehicle, EQUULEUS took an orbit toward the moon. Before the closest approach, trajectory control by delta-V maneuver had to be completed. Otherwise, the CubeSat would no longer be able to reach EML2. The trajectory of EQUULEUS with and without the first delta-V maneuver (DV1) is shown in Figure 3. Considering the limitation of antenna assignments, it was required to commence the delta-V maneuver within 38 hours of the separation. Furthermore, to allow for adjustments in trajectory design and parameter tuning of the propulsion system, the feasibility assessment had to be conducted within a 20-hour timeframe following separation. In other words, the first AQUARIUS operation and evaluation of the performance needed to be carried out before this period. Given that other untested propulsion systems for deep space missions typically require over ten days for their initial operation in orbit, the AQUARIUS operation had to be conducted within an exceptionally brief timeframe.[4,9]

Checkouts and Performance Evaluation

EQUULEUS was successfully put into orbit on November 16, 2022, by NASA's SLS. In Figure 4, the sequence of operations following the launch is shown. The first antenna assignment started about an hour after the separation, and we established communication and proceeded with the checkouts of BUS components. The health of the CubeSat is confirmed, while the temperature was higher than expected. Following the checkouts, temperature control, and

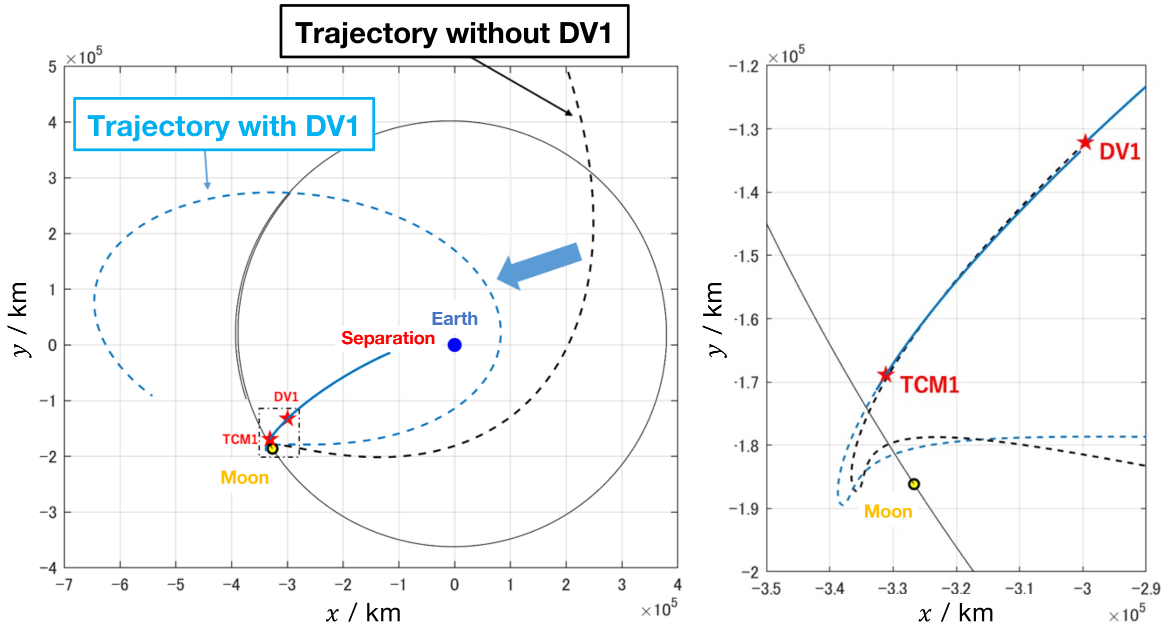

Figure 3: The trajectory of EQUULEUS during the initial operations plotted in a Sun-Earth fixed coordinate. The graph on the right is the enlarged view around the Moon. The solid line represents the trajectory of the Moon, while the dashed lines represent the trajectories of the spacecraft with DV1 (blue) and without DV1 (black). Star plots indicate locations where the propulsion system was operated. Conducting DV1 allows the spacecraft to reapproach the Moon.

three-axis attitude control were established, and we were ready for the first operation of the AQUARIUS. Approximately 11 hours after separation, we confirmed the health of the propulsion system and successfully conducted the first injection in space. We also evaluated the thrust from the two-way Doppler shift and confirmed that AQUARIUS met the requirements on performance.

Delta-V Maneuver

The first delta-V maneuver was scheduled 38 hours after the separation. Before this, we conducted several operations to adjust FDIR thresholds, address the issue of high spacecraft temperature, and confirm the sequence of the maneuver. Finally, we were fully prepared and started DV1 at the scheduled time. The time history of the first quarter of the operation is shown in Figure 5. A graph on the top shows the telemetry data of pressure and temperature of the vaporization chamber and delta-V thruster nozzles. As can be seen in the nozzle pressures, the selection of DVTs switched from time to time. This is to avoid saturation of reaction wheels since DVTs generate torque around the Y-axis (see Figure 1). The switching was conducted

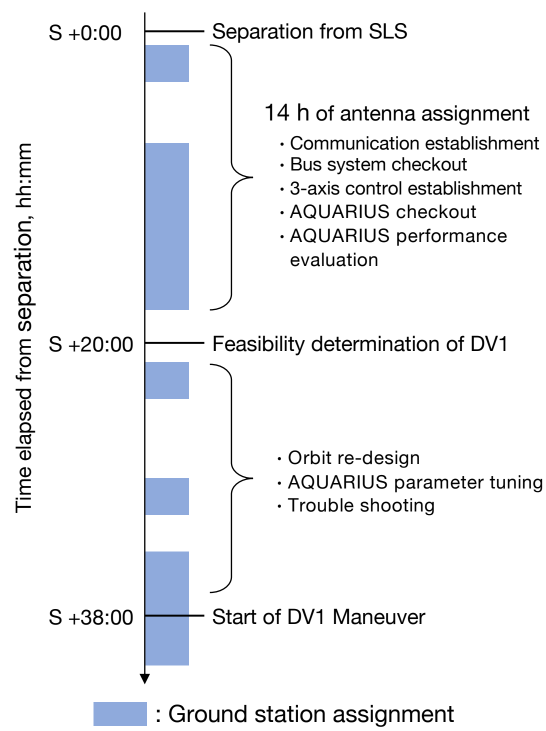

Figure 4: The sequence of operations after separation from the launch vehicle.

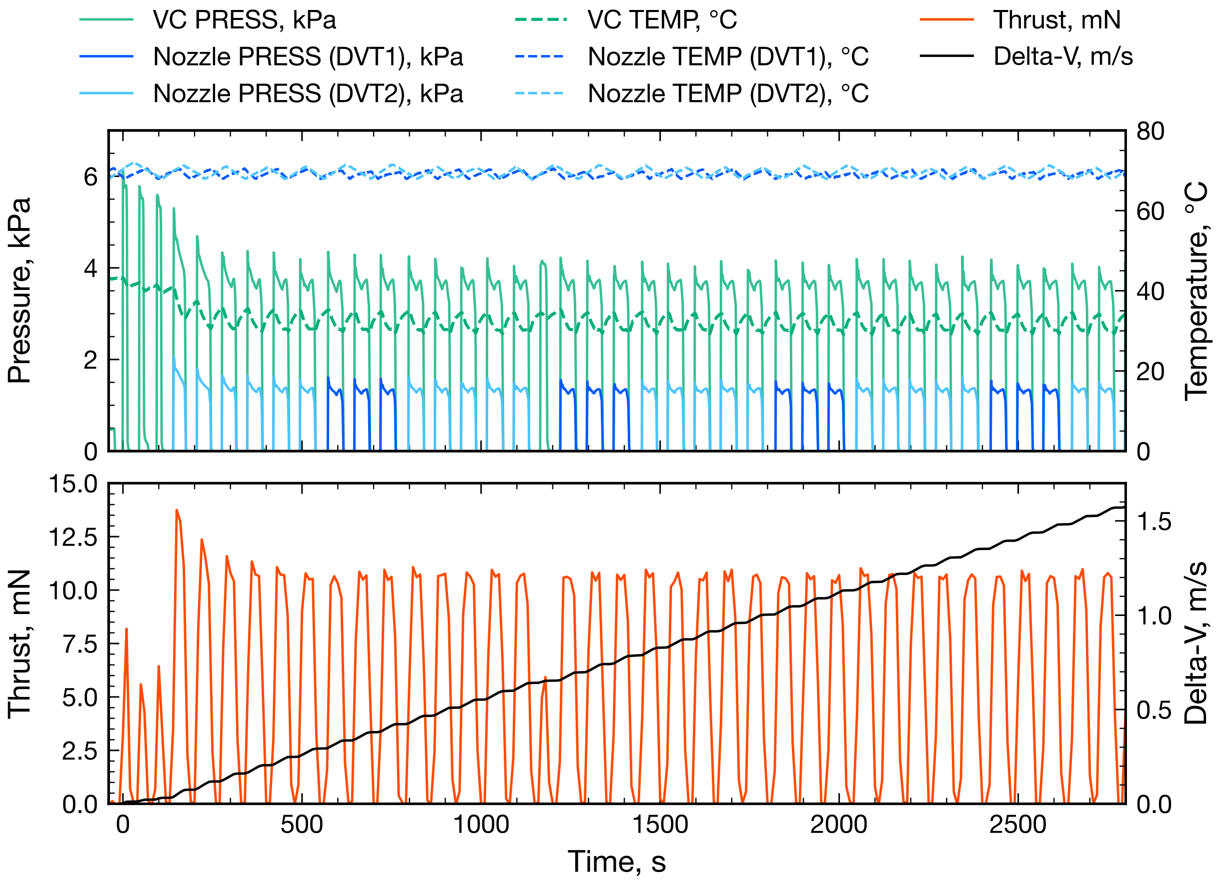

Figure 5: Time history of the propulsion system operation during the first quarter of DV1 maneuver. The start time of the first injection is set to $t = 0\,\mathrm{s}$. Thrust and Delta-V shown in the lower graph are calculated by the two-way Doppler shift.

autonomously by an On-Board Computer (OBC). The bottom graph shows the instantaneous thrust and total delta-V calculated from the two-way Doppler shift. Delta-V increased in a staircase fashion, and one of each step corresponds to a velocity increment per cycle. Throughout 3 hours of continuous operation, the performance of AQUARIUS was stable and highly reproducible. In summary, a total delta-V of 6.48 m/s was achieved with 154 injections.

TCMs and Lunar Flyby

Before and after the lunar flyby, trajectory correction maneuvers (TCMs) were performed. In TCMs, the planned delta-V is lower than DV1, but the focus is placed on achieving higher accuracy. To achieve precise control of delta-V, we utilized the RCT, which has a smaller impulse bit. Figure 6 shows the outcome of the AQUARIUS operation during the TCM conducted after lunar flyby (TCM2).

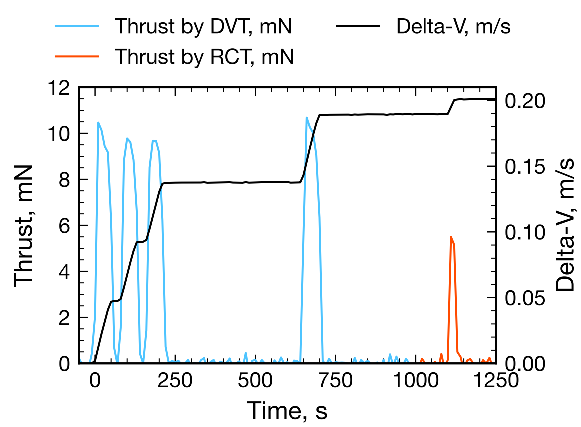

Figure 6: Result of the propulsion system operation during TCM2. The start time of the first injection is set to $t = 0\,\mathrm{s}$. The first four injections shown in blue are from a DVT. The final one, shown in red, is from an RCT with a smaller impulse.

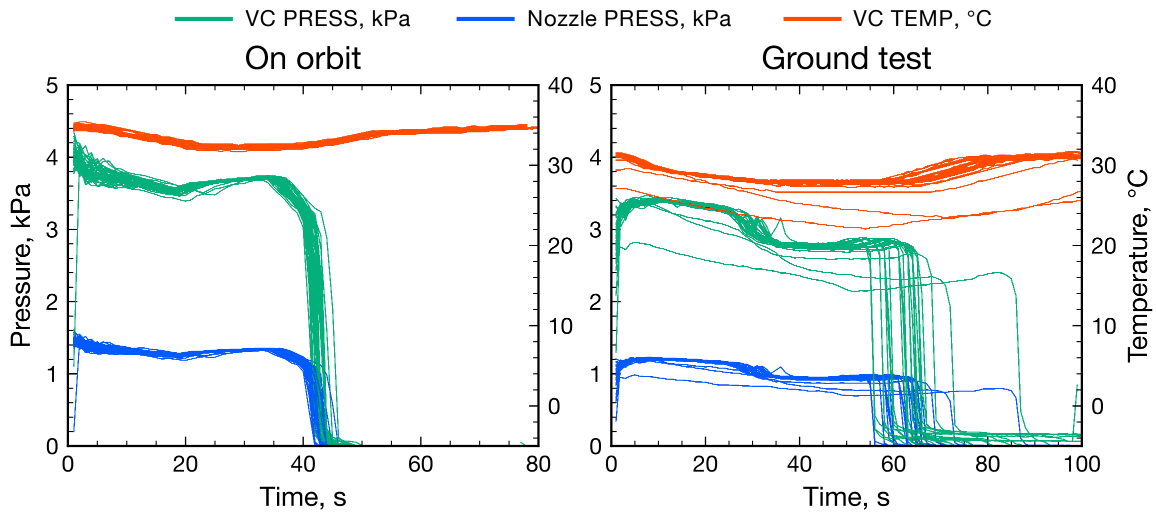

Figure 7: Overlapping view of pressure and temperature profiles in each cycle. The graph on the left shows the result during DV1, and on the right is the result of a ground test.

The first four injections were carried out using a DVT, resulting in a delta-V of approximately 5 cm/s per injection. The final injection was performed by the RCT, providing a velocity increment of about 1 cm/s. TCM2 yielded a delta-V of 20.11 cm/s (), closely matching the scheduled value of 20.09 cm/s. With precise trajectory correction executed during TCMs, EQUULEUS successfully conducted a lunar flyby and was placed on a trajectory toward EML2. With the success of DV1, TCMs, and the lunar flyby, AQUARIUS became the world's first water propulsion system to succeed in changing orbit in deep space.

Summary of On-Orbit Performace

The results and thruster performances during the DV1 are summarized in Table 2. AQUARIUS exhibits higher thrust and specific impulse comparing those observed in the ground test (see Table 1). A comparison of the pressure and temperature profiles during the operation in DV1 and the ground test is presented in Figure 4. The figure shows that the operating temperature and pressure are higher in DV1. On the other side, the relationships between the temperature of the chamber and its pressure stay the same as in the ground experiment, as well as the association of the chamber pressure and the nozzle pressure. This suggests that the increase in spacecraft temperature led to higher pressure in the vaporization chamber, increasing nozzle pressure. Therefore, the higher thrust in DV1 is the result of higher operating temperature. Additionally, the cycle time is shorter for DV1. Given that the injection mass setting remains the same, this indicates an increase in mass flow rate.

Table 2: Summary of the performance during the DV1 maneuver.

Parameters	Values
Delta-V	6.48 m/s
Total consumption of propellant†	94.09 g
Number of injections	153 (total) 147 (DVT) 6 (RCT)
Thrust*	5.94 ± 0.21 mN (DVT) 0.61 ± 0.04 mN (RCT, single)
Specific impulse*	86.6 ± 12.3 s

* averaged over a cycle, including wait time.
† sum of setting values.

CONCLUSION

AQUARIUS is a water resistojet thruster developed for a 6U CubeSat, EQUULEUS. The spacecraft was launched in November, 2022 into the trajectory toward Moon. We conducted checkouts of the spacecraft and evaluation of the on-orbit performance of the thruster in a remarkably short time to confirm that the trajectory control mission is feasible. Delta-V maneuver, trajectory correction maneuvers, and lunar flyby were successfully completed, which makes AQUARIUS the world's first water propulsion system to successfully change an orbit in deep space.

During the initial operations, AQUARIUS shows the capability of generating delta-V of several m/s and orbit controlling with an accuracy of less than 1 cm/s with a single propulsion system. The on-orbit thrust and specific impulse of Delta-V Thruster are 5.94 ± 0.21 cm/s and 86.6 ± 12.3 s, respectively. To date, AQUARIUS has performed two additional DV maneuvers and several TCMs, with a total delta-V of approximately 17 m/s and more than 440 shots.

Acknowdedgments

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References

[1] B. Tech, "Smallsat by the numbers 2023," 2023.

[2] N. Chahat, E. Decrossas, D. Gonzalez-Ovejero, O. Yurduseven, M. J. Radway, R. E. Hodges, P. Estabrook, J. D. Baker, D. J. Bell, T. A. Cwik, and G. Chattopadhyay, "Advanced cubesat antennas for deep space and earth science missions: A review," *IEEE Antennas and Propagation Magazine*, vol. 61, no. 5, pp. 37–46, 2019.

[3] R. Funase, T. Inamori, S. Ikari, N. Ozaki, H. Koizumi, A. Tomiki, Y. Kobayashi, and Y. Kawakatsu, "Initial operation results of a 50kg-class deep space exploration microspacecraft procyon."

[4] A. Klesh, B. Clement, C. Colley, J. Essmiller, D. Forgette, J. Krajewski, A. Marinan, T. Martin-Mur, J. Steinkraus, D. Sternberg, T. Werne, and B. Young, "Marco: Early operations of the first cubesats to mars."

[5] D. Elisabetta and Z. Angelo, "Impact observations of asteroid dimorphos via light italian cubesat for imaging of asteroids (liciacube)," *Nature Communications*, vol. 14, no. 4, p. 3055, 2023.

[6] R. Funase, S. Ikari, K. Miyoshi, Y. Kawabata, S. Nakajima, S. Nomura, N. Funabiki, A. Ishikawa, K. Kakihara, S. Matsushita, R. Takahashi, K. Yanagida, D. Mori, Y. Murata, T. Shibukawa, R. Suzumoto, M. Fujiwara, K. Tomita, H. Aohama, K. Iiyama, S. Ishiwata, H. Kondo, W. Mikuriya, H. Seki, H. Koizumi, J. Asakawa, K. Nishii, A. Hattori, Y. Saito, K. Kikuchi, Y. Kobayashi, A. Tomiki, W. Torii, T. Ito, S. Campagnola, N. Ozaki, N. Baresi, I. Yoshikawa, K. Yoshioka, M. Kuwabara, R. Hikida, S. Arao, S. Abe, M. Yanagisawa, R. Fuse, Y. Masuda, H. Yano, T. Hirai, K. Arai, R. Jitsukawa, E. Ishioka, H. Nakano, T. Ikenaga, and T. Hashimoto, "Mission to earth – moon lagrange point by a 6u cubesat: Equuleus," *IEEE Aerospace and Electronic Systems Magazine*, vol. 35, no. 3, pp. 30–44, 2020.

[7] A. Jun, K. Hiroyuki, N. Keita, T. Naoki, M. Masaya, F. Ryu, and K. Kimiya, "Fundamental ground experiment of a water resistojet propulsion system: Aquarius installed on a 6u cubesat: Equuleus," *TRANSACTIONS OF THE JAPAN SOCIETY FOR AERONAUTICAL AND SPACE SCIENCES, AEROSPACE TECHNOLOGY JAPAN*, vol. 16, no. 5, pp. 427–431, 2018.

[8] N. Keita, A. Jun, K. Kosei, A. Mariko, W. Qihang, M. Masaya, A. Yasuho, K. Hiroyuki, F. Ryu, and K. Kimiya, "Flight model development and ground demonstration of water resistojet propulsion system for cubesats," *TRANSACTIONS OF THE JAPAN SOCIETY FOR AERONAUTICAL AND SPACE SCIENCES*, vol. 63, no. 4, pp. 141–150, 2020.

[9] J. R. Brophy, C. E. Garner, and S. C. Mikes, "Dawn ion propulsion system: Initial checkout after launch," *Journal of Propulsion and Power*, vol. 25, no. 6, pp. 1189–1202, 2009.