

Initial Flight Operation of AQUARIUS: Water Resistojet Thruster on 6U EQUULEUS

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This paper presents the initial flight operations of the water resistojet propulsion system: AQUARIUS (AQUA Resistojet propulsion System). AQUARIUS was developed by the University of Tokyo and installed on a 6U spacecraft, EQUULEUS as a main propulsion system to achieve its primary engineering mission; trajectory control experiment within the Sun-Earth-Moon region. EQUULEUS was successfully launched on November 16, 2022, by NASA SLS, and is on its way to EML2. Until now, the water propulsion system has conducted multiple Delta-V maneuvers and trajectory correction maneuvers. It has been confirmed that AQUARIUS has achieved an average thrust of 6 mN and a total Delta-V of 17 m/s. AQUARIUS would be the first water propulsion system to successfully operate in deep space.

Key Words: Propulsion, Water, Resistojet, Deep Space, CubeSat

Nomenclature

F	:	thrust
g	:	gravity constant
I_{sp}	:	specific impulse
$\dot{m}$	:	mass flow rate
P	:	pressure
α	:	coefficient

Subscripts

DVT	:	Delta-V Thruster
RCT	:	Reaction Control Thruster
noz	:	nozzle
vap	:	vaporization chamber

1. Introduction

The development and utilization of small satellites have increased rapidly in recent years due to advances in technology and reduced launch costs.^{1),2)} The need for propulsion systems is also growing with the interest in drag recovery, orbit changes, and attitude control.³⁾ SpaceX has launched more than 1,000 Starlink constellation satellites, each equipped with Krypton or Argon Hall effect thrusters for lifetime extension.⁴⁾ In terms of deep space exploration, PROCYON (PROximate Object Close flyby with Optical Navigation) had the unified propulsion system of a xenon ion thruster and a cold gas jet, which demonstrated the capability of small satellites for deep space exploration.⁵⁾ MarCO (Mars Cube One), the first CubeSats to explore deep space, had cold gas jet thrusters to carry out fly-by to Mars. The UAE satellite Hope has a monopropellant hydrazine propulsion system for the Mars mission.⁷⁾ Although each propulsion system is successful, each has a high-pressure

gas system for propellant storage, leading to an increase in structural mass. A low pressure and easy-handling propellant is desired especially in small satellites, which often have restrictions on volume and mass. Furthermore, the accessibility and affordability of propellants are crucial factors to consider in the expanding market of small satellites.

Water is one of the promising propellants for small satellites because of its liquid state under standard conditions, which eliminates the need for a high-pressure gas system. In addition, its nontoxic nature, easy availability, and affordability make it convenient for developers to reduce costs and shorten the development time. Furthermore, the existence of water has the potential to be farmed and processed in situ in future missions. There has been some research on water propulsion systems including electric propulsion,⁸⁾⁻¹¹⁾ however, only a few have had the opportunity to operate in orbit. A water resistojet thruster, which was installed on UK-DMC, failed its thrust generation in orbit because of unsuccessful liquid-gas separation.¹²⁾ Another water resistojet thruster was installed on AeroCubes-OCSD-7B&-7C. It was assumed that frozen water blocked the nozzle, resulting in no thrust generation.¹³⁾ The water electrolysis propulsion system HYDROS, installed on 6U CubeSat PTD-1, demonstrated the orbit change by the thrusters in space.¹⁴⁾ Vapor-liquid separation as well as temperature management has been a significant challenge, especially for water resistojet thrusters, in the past due to the high latent heat. Moreover, there are no reports of water propulsion systems operating in deep space.

The University of Tokyo proposed and developed the water resistojet propulsion system AQUARIUS (AQUA Resistojet propulsion System) to overcome the challenges posed by previous studies and to conduct deep space exploration. AQUARIUS has unique features; its gas-liquid separation and power-saving

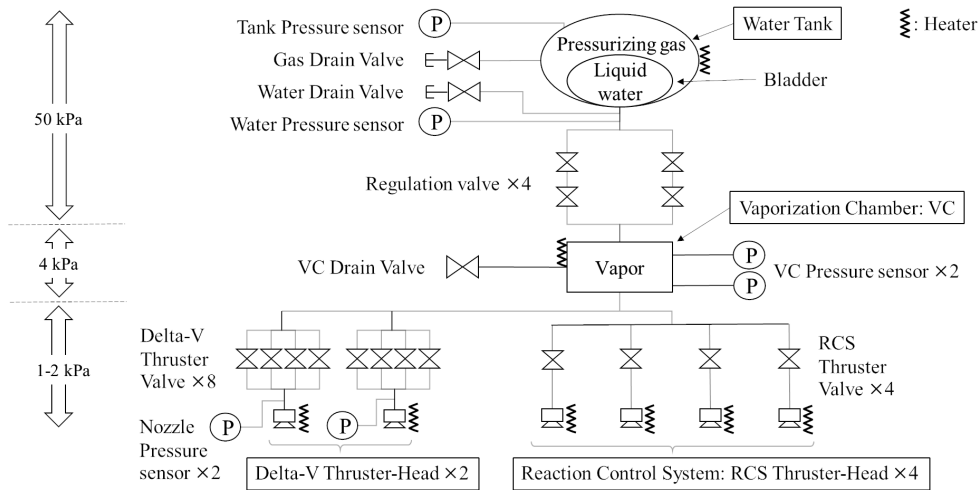


Fig. 1. System diagram of the water resistojet propulsion system.

strategy.¹⁵⁾ Its gas-liquid separation is achieved with a vaporization chamber. It consists of a room for vaporization and a flow path to achieve proper vapor-liquid separation. The chamber is maintained at a lower temperature than the surrounding components, making it possible to reduce heat loss by reusing the heat from the surroundings.

AQUARIUS is installed on a 6U CubeSat EQUULEUS (EQUilibriUm Lunar-Earth point 6U Spacecraft). The engineering mission of EQUULEUS is to demonstrate trajectory control in the Sun-Earth-Moon region where AQUARIUS plays an important role. EQUULEUS has three science missions which are described in the reference.¹⁶⁾ EQUULEUS was successfully launched on November 16th, 2022 as one of the secondary payloads by the NASA Space Launch System. It has been confirmed that AQUARIUS had been successfully operated in orbit after the initial checkout of the spacecraft. This paper reports the initial flight operation of AQUARIUS from November 2022 to April 2023. AQUARIUS has achieved an average thrust of 6 mN and a total Delta-V of 17 m/s, which makes it the first water propulsion system to successfully operate in deep space.

2. AQUARIUS

AQUARIUS, installed on EQUULEUS, mainly has two roles in the mission: 1) desaturation of wheel momentum as RCS (Reaction Control System), and 2) providing ΔV for major orbit change (Delta-V operation), and TCM (Trajectory Correction Maneuver). As of April 2023, AQUARIUS has completed three Delta-V operations and eleven TCMs.

2.1. Propulsion system configuration

Fig. 1 shows the system diagram of AQUARIUS. It mainly consists of three components; a water tank, a vaporization chamber, and thruster heads. The water tank stores liquid water inside a bladder. The bladder is initially pressurized to 50 kPa by Argon gas, which is the maximum operating pressure of the entire propulsion system. There are two pressure sensors in the water tank to measure the pressure of Argon gas and water. Four regulation valves are placed downstream of the tank to supply water droplets into the vaporization chamber. They

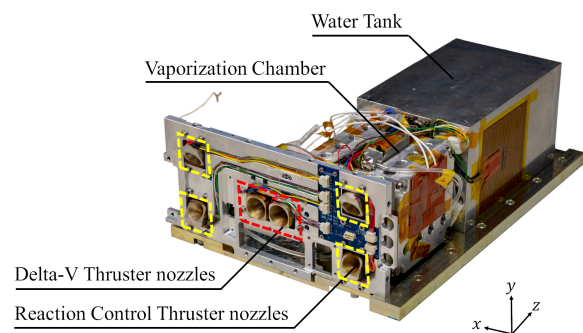


Fig. 2. AQUARIUS flight model. The red dotted square indicates Delta-V thruster nozzles while the yellow dotted squares indicate reaction control thruster nozzles.

are arranged in two series and two parallel to form a redundant system.

The vaporization chamber is formed by two components, the room for the water droplets to vaporize and the labyrinth-shaped flow paths. The injected water droplets are caught by the wall of the chamber by their surface tension. The flow paths are designed in such a way as to prevent water droplets from flowing directly into the nozzles. Two pressure sensors, which also form a redundant system, are located in the vaporization chamber to observe the behavior of the injected water and estimate the injected mass. There are three heaters attached to the chamber to compensate for the latent heat of the water. The communication device is also thermally connected to the chamber to reuse the waste heat from the device for water vaporization. The device consumes approximately 12 W. After vaporizing, the vapor flows into the thruster valves. Four parallel valves are connected to Delta-V thrusters (DVT) to improve flow conductance to generate the required thrust. On the other hand, one thruster valve is connected to each Reaction Control Thruster (RCT) nozzle.

The vapor that flows into the thruster valves is accelerated in the thruster heads. As shown in Fig. 2, two DVTs and four RCTs are placed on the -z panel of the spacecraft. The DVTs are facing toward -z, while the RCTs are tilted at 30° from the panel. When DVT or RCT firing is activated, an impulse is generated towards the z axis, and a set of two RCTs can also generate the angular momentum of each axis. A polyimide heater

Table 1. Specification of AQUARIUS. Performance values were obtained from the ground experiment.¹⁷⁾

Propellant	Water
Volume	2.5U
Propellant mass	1.22 kg
Thrust (DVT)	4.10 ± 0.56 mN
Thrust (RCT)	1.79 ± 0.35 mN
Specific impulse (DVT)	73.1 ± 9.21 s
Vaporization temperature	28.8 ± 0.48 °C
Total power consumption	<22 W

is wrapped around each nozzle to keep the temperature around 70 °C to prevent condensation of water.

2.2. Working principle

The propulsion system is operated in a pulsating manner where water is supplied and emptied periodically. Each cycle includes the thrusting time, where water droplets are injected and vaporized, and the waiting time for the recovery of the vaporization chamber temperature. The performance acquired in orbit as well as in the ground experiment is averaged in each cycle. The vaporization chamber's temperature and nozzles' temperature are regulated by a bang-bang controller, which involves turning on and off the heaters based on whether the temperatures exceed certain thresholds. The control of heaters and valves is conducted by the On-Board Computer (OBC).

It has been revealed from the ground experiment that the thrust force F towards the z-axis can be described as

$$\begin{cases} F = \alpha_{DVT} P_{noz} \\ F = \alpha_{RCT} P_{vap}, \end{cases} \quad (1)$$

where α_{DVT} and α_{RCT} are constant, P_{noz} is the pressure of the thruster nozzle and P_{vap} is the pressure of the vaporization chamber. Performance results from the ground test as well as the specification of the propulsion system are summarized in Table 1. Since thrust cannot be measured directly in orbit, α_{DVT} and α_{RCT} are updated in orbit by correlating the Doppler shift of the communication waves and the pressure in AQUARIUS. Similarly, the mass flow rate of the thrusters is estimated in three different methods; using the setting value, the purge gas profile, and the integral value of the pressure. In the setting value method, the mass injected into the vaporization chamber is determined by the opening time of the regulation valve, which was correlated with the pressure of the tank and the temperature of the stored water. In the purge gas profile method, the amount of water that is injected is estimated by the changes in pressure and temperature of the purge gas using the gas equation of state. In the third method, the integral of the nozzle and vaporization chamber pressure is used for the estimation. Pressure integral and mass differences were correlated in the ground-based test. Finally, the specific impulse I_{sp} is written as

$$I_{sp} = \frac{F}{\dot{m}g}, \quad (2)$$

where $\dot{m}$ is the mass flow rate, and g is the gravitational constant.

3. Flight operation results

Figure 3 shows the schedule of events during the initial operation of the spacecraft after separation from the launch vehi-

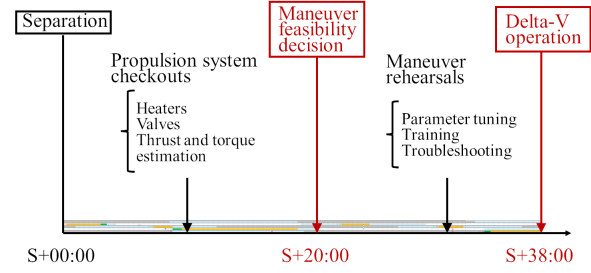


Fig. 3. The schedule of events related to the propulsion system after the separation of the spacecraft from the launch vehicle. The horizontal axis shows the time (hh:mm) after separation.

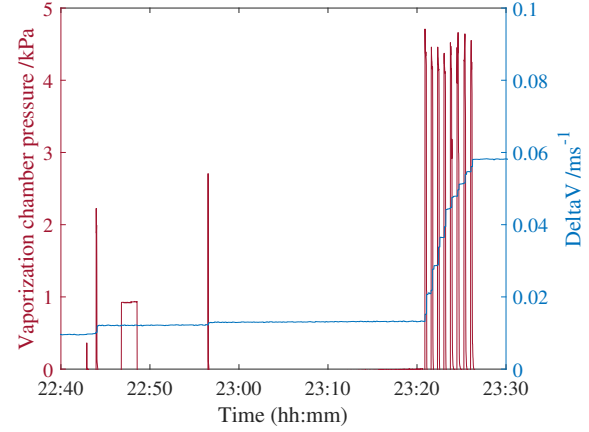


Fig. 4. The first injection of water into the vaporization chamber during the checkout. Delta-V generation was also confirmed by the two-way Doppler shift of the communication waves. The horizontal axis is in UTC, November 16th.

cle. AQUARIUS operation started with the initial checkout of the propulsion system along with other BUS systems. Initial checkout was followed by the thrust and torque estimation of AQUARIUS. After a few maneuver rehearsals, the Delta-V operation began. All checkouts, preparations, and rehearsals had to be completed within 38 hours after separation, otherwise, the spacecraft would not be able to remain in the Earth-Moon region.

3.1. Initial Checkout of the propulsion system

AQUARIUS-related checkout started with the heaters. Here, the tank heater, the vaporization chamber heaters, the nozzle heaters, and the water heater were turned on and checked out consecutively. All of the heaters were confirmed to be problem-free. Each heater was turned on for several seconds and a temperature increase was observed.

After the checks of other components, such as the attitude control system, the checks of the valves were performed, which was also completed. Fig. 4 shows the increase in the vaporization chamber pressure with Delta-V, by opening the regulation valves. Here the water was injected into the vaporization chamber for the first time, followed by the confirmation of consecutive water injections. The vaporization chamber pressure of the very first water injection did not rise as expected. The cause of this is believed to be that a gas had been injected from the regulation valve. The generation of thrust was also confirmed by observing the two-way Doppler shift during the propulsion system checkout as shown in Fig. 4.

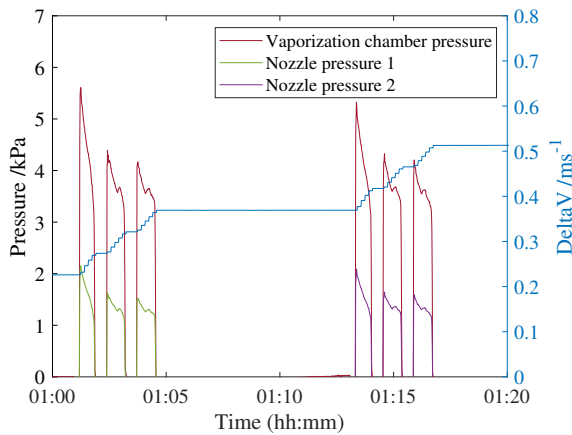


Fig. 5. The thrust estimation operation. The coefficients from Eq.(1) were determined by the pressure increase and Delta-V. The horizontal axis is in UTC, November 17th.

Table 2. Performance of AQUARIUS in the first Delta-V operation in orbit.

Thrust (DVT)	5.94 ± 0.21 mN
Thrust (RCT)	1.22 ± 0.07 mN
Specific impulse (DVT)	86.6 ± 12.3 s
Vaporization temperature	32.8 ± 1.47 °C

3.2. Torque and thrust estimation

Torque and thrust generated by the propulsion system were evaluated using reaction wheels and a two-way Doppler shift. Thrust vector misalignment was confirmed, which directly affects the frequency of desaturation of the reaction wheels. Fig. 5 shows the pressure of the vaporization chamber and the nozzles, and Delta-V derived from the Doppler shift. α_{DVT} and α_{RCT} from Eq. (1) were determined in this estimate. Parameters of conducting FDIR (Fault Detection, Isolation, and Recovery), an on-board system to autonomously recover during Delta-V operation, were also tuned. The evaluated result of time-averaged thrust including unloading of the reaction wheels had been considered to be adequate for Delta-V operation.

3.3. Delta-V maneuver rehearsals and its operation

The first Delta-V operation was scheduled after 38 hours from separation requiring Delta-V of 6.4 m/s in total. A few rehearsals were conducted to verify the operation sequence, FDIR parameters, and feasibility beforehand. After multiple rehearsals were performed, a 'Go' decision for the Delta-V operation was determined. Part of the propulsion system operation during the Delta-V operation is shown in Fig. 8. Pressure, temperature, and heater power input in the propulsion system is indicated. The pressure in the vaporization chamber followed a specific pattern in each cycle, where it initially decreased during the first 30 seconds and subsequently increased due to the heaters. The nozzle pressures were proportional to the pressure of the vaporization chamber, and the temperature of the vaporization chamber and the nozzles were controlled stably.

Table 2 is the summary of average performance during the Delta-V operation. Thrust and specific impulse of DVT were about 5.9 mN and 87 s where they had increased almost 20 % from the ground test. The vaporization chamber temperature was about 27.2 °C during the ground test, while it is 33.8 °C in orbit due to the equilibrium temperature of the spacecraft. The higher temperature in orbit, as well as the facility effect, can be

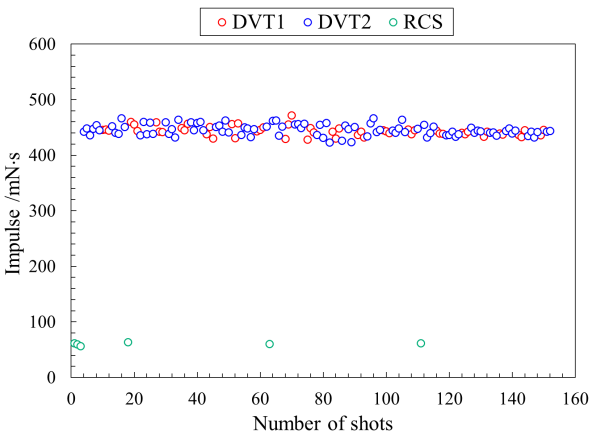


Fig. 6. Summary of the first Delta-V operation

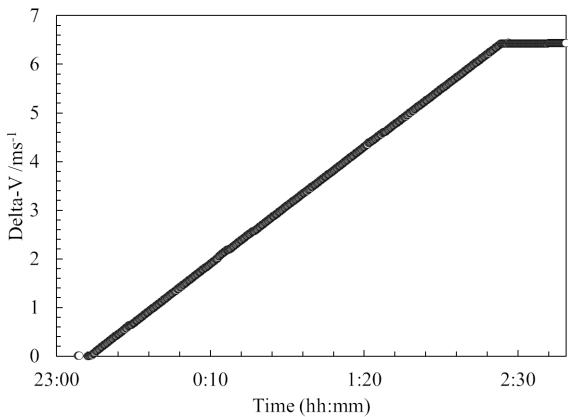


Fig. 7. Total delta-V achieved in the first Delta-V operation.

responsible for the increase in thrust and specific impulse compared to the ground experiment. The summary of the thrust and the cycle time in the first Delta-V operation is indicated in Fig. 6. A total of 154 injections including 6 RCT injections were conducted with high reproducibility. Finally, the total Delta-V of 6.48 m/s was achieved in three hours, which is shown in Fig. 7. Overall, the first Delta-V operation was completed.

3.4. Trajectory Correction Maneuvers

TCMs (Trajectory Correction Maneuvers) were performed twice, before and after the first lunar flyby. Compared to the Delta-V operation, TCM requires less Delta-V, for example, 0.84 m/s for TCM1. The RCT, which has lower impulse bits, is used for more precise Delta-V management. The RCT was selected to manage the angular momentum of the spacecraft simultaneously. TCM1 and TCM2 were also successfully completed.

The equilibrium temperature of TCM1 was lower compared to the first Delta-V operation. Even so, the time average thrust was almost the same (approximately 6 mN). Fig. 9 shows the thrust-to-power ratio of the first Delta-V operation (DV1) and TCM1. It implies that the higher the vaporization chamber temperature is, the higher the thrust-to-power ratio. This means that the required heater power input to achieve the certain time-averaged thrust was less in DV1. The heaters were only controlled by the temperatures, so there was more power input from the surrounding environment to the vaporization chamber in DV1.

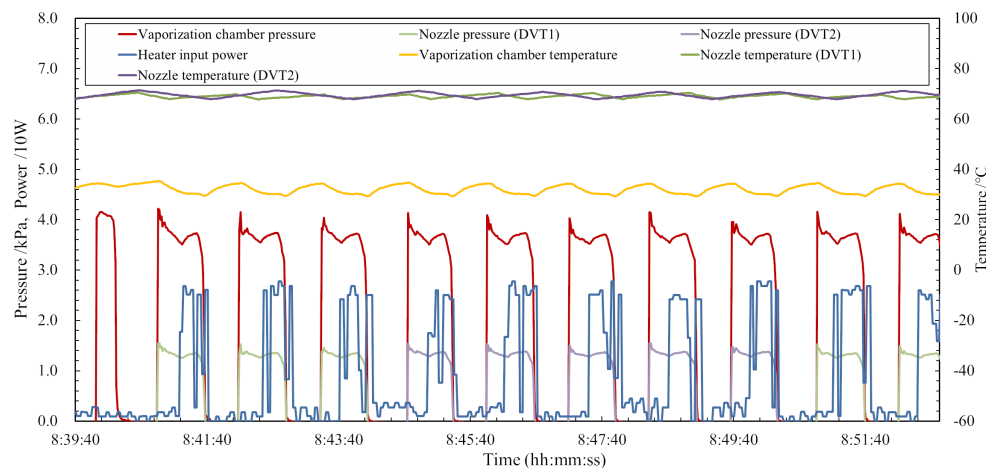


Fig. 8. Time history of AQUARIUS's pressure, temperature, and heater input power during Delta-V operation. The horizontal axis is in JST, November 18th.

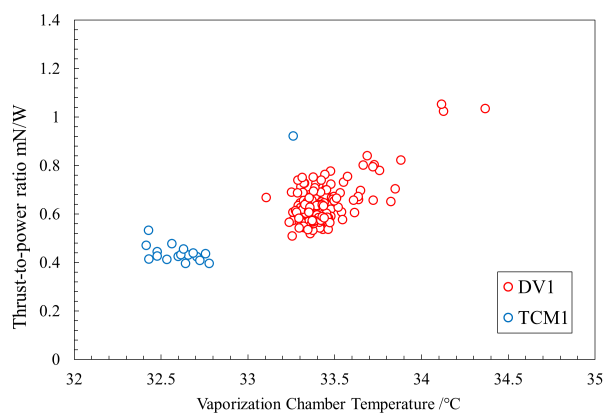


Fig. 9. Thrust-to-power ratio in different vaporization temperature conditions.

4. Lessons learned

The initial operation of the EQUULEUS was highly time-critical, especially until the first Delta-V operation when the operation had to be performed quickly and accurately. A lot of training in advance including the checkouts were conducted. In the AQUARIUS team, the operation to estimate thrust from Doppler shift data was critical, and it took many people to train and double-check to get through the actual operation. A lot of training and preparation for the whole team contributed to this success.

Temperature management of the spacecraft in orbit was also important for AQUARIUS. The whole propulsion system including flow paths needed to be maintained at the right temperature for operation while the temperature conditions were affected by the attitude of the spacecraft. As this was not easy to prepare beforehand, it was necessary to find a way to manage the temperature in orbit. The most probable location for the water to freeze was at the tubes between the vaporization chamber and the nozzles due to the absence of a heater. Thus, the tubes should be heated by the input from the vaporization chamber and nozzles. Fig. 10 shows the sequence to maintain tube temperature at around vaporization chamber temperature. The tubes are at a lower temperature initially, and the tubes and the vaporization chamber temperature would increase

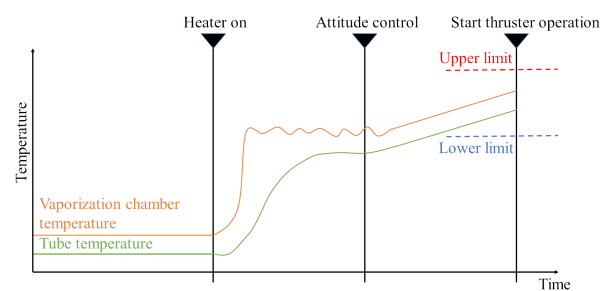


Fig. 10. The temperature management strategy for the second trajectory correction maneuvers.

at a similar level after turning on the heaters. By the attitude change, the vaporization chamber temperature and tube temperature would increase due to changes in equilibrium temperature. Finally, the tube temperature would surpass the minimum temperature to freeze. There is also an upper limit for the vaporization chamber, that is, the operating guaranteed temperature of thruster valves since they are located in a similar spot. Thus far, AQUARIUS has been successfully operating with this heating method.

5. Conclusion

The water resitojet thruster AQUARIUS was developed and integrated into 6U CubeSat EQUULEUS. Since its launch on November 2022, it has continued its operations to reach EML2. Until now, AQUARIUS has achieved a total Delta-V of 17 m/s by multiple Delta-V operations and TCMs. This makes AQUARIUS to be the first water propulsion system to operate in deep space successfully.

- In the initial checkout operation, the heaters, valves, and all the propulsion systems were checked. No issues were confirmed.
- The torque and thrust generated by AQUARIUS were evaluated after the checkout of the propulsion system. Torque around each axis thrust misalignment and thrust itself were estimated, and they were considered to be adequate for the Delta-V operation.
- The first Delta-V operation was successful as AQUARIUS achieved 6.48 m/s delta-V in total. The thrust and spe-

cific impulse in orbit were higher than the results from the ground experiment.

- TCMs were also completed successfully using RCT as a lower impulse-bit generator.

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