AQT-D: Demonstration of the Water Resistojet Propulsion System by the ISS-Deployed CubeSat

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ABSTRACT

AQT-D (AQua Thruster-Demonstrator) is a 3U CubeSat for a demonstration of a water resistojet propulsion system developed by The University of Tokyo. AQT-D installed the 1U propulsion system using water as a propellant, named AQUARIUS-1U (AQUA ResIstojet propUlsion System 1U). We completed the design and assembly of the AQT-D flight model. AQUARIUS-1U was fired on a pendulum-type thrust balance, and its performance was directly characterized in both a stand-alone test and an integrated test using an entire spacecraft system. AQT-D is currently scheduled to be delivered to JAXA in July 2019 and launched to the International Space Station (ISS) in the middle of 2019 by the H-IIB rocket. AQT-D will be deployed from the Japanese Experiment Module (JEM), known as Kibo, and demonstrate water propulsion technology.

INTRODUCTION

A propulsion system is a key technology in the satellite utilization because of its capability of orbit transfer, station-keeping, or attitude control.[1] A lot of development and research efforts in past studies have enabled a wide range option of propulsion systems depending on missions or design specifications for satellites over 100 kg.[2, 3] It has been accelerating space industry using large satellites. In recent years, CubeSats, nano-satellites, and micro-satellites have been arousing interest as a rapidly growing niche in the space industry. The number of CubeSats or such small satellites launched has been drastically increasing since 2010.[4] In many cases, a propulsion system was not installed because the mission did not require it. Especially, CubeSats deployed from the International Space Station (ISS) never have a propulsion system because of very strict requirements for safety.[5] In addition, a conventional propulsion system cannot be applicable for CubeSats in terms of volumetric or cost restriction because it uses high pressure or toxic propellants such as Nitrogen, Xenon or hydrazine. Even though cold gas thruster which used Nitrogen or sulfur hexafluoride was installed on small satellites, its performance was not enough for actual missions. [6]

Water has been arousing interest as an ultra-green propellant because of its storability, non-flammability, and non-toxicity. [7] Water can be stored in a liquid phase, which allows for the design of all propulsion system below 100 kPa, reduction of dry mass ratio, and simplification of feed line routing by using soft tubes. The safety also makes possible short period and low-cost development compared to conventional propellant. In addition, water can be obtained anywhere or filled at a launch site or an orbital habitation module in the future. Moreover, water has been arousing interest as a potential resource for future deep space exploration. In the future, the use of water collected in space is likely to be promoted.

Water micro-resistojet (or called electrothermal thruster) has been widely researched and developed. Two types of water micro-resistojet were launched. [8, 9] Both propulsion systems experienced anomaly operation such as liquid water exhausting from the nozzle or ice plug forming at a nozzle. In addition, they have only a small amount of water less than 26 g. Further research and on-orbit demonstration are necessary to establish a water micro-propulsion technology including not only resistojet but also advanced electric propulsion such as ion thruster for sustainable CubeSats utilization. [10]

AQUARIUS (AQUA ResIstojet propUlsion System) was proposed as the water propulsion system using a room temperature evaporation system. [11] AQUARIUS consists of a tank, a vaporizer, and two types of thrusters, designed within 2.5U and storing 1.2 kg of water. It is to be installed on the 6U deep space exploration CubeSat: EQUULEUS (EQUilibriUm Lunar-Earth point 6U Spacecraft) and launched by SLS (Space Launch System) EM-1 in 2020.[12]

AQT-D (AQua Thruster-Demonstrator) is a 3U CubeSat for a demonstration of 1U-size water-micro propulsion system, named AQUARIUS-1U. The propulsion concept and fundamental design were based on proposed AQUARIUS. [11] AQT-D will be launched to the ISS (International Space Station) in the middle of 2019. This spacecraft will also be the world's first ISS-deployed CubeSat installing the propulsion system. The safety of water enables for ISS-deployed CubeSat to install a propulsion system. Deployment of CubeSats from the ISS is quite attractive because of the constant launch opportunity, low-cost, and user-friendly launch environment. However, ISS-deployed CubeSats have short lifetime due to the low altitude and air drag force. Installing a water micro-propulsion system on CubeSats can overcome this crucial issue. In addition, AQT-D has a role as a pre-cursor of EQUULEUS in terms of propulsion technology demonstration.

This paper describes the AQT-D mission overview, specifications of the spacecraft and propulsion system, and test results of the propulsion system.

MISSION OVERVIEW

In this section, the mission overview of AQT-D is described. The objective of AQT-D mission is the on-orbit demonstration of AQUARIUS-1U. The mission scenario is composed of three sections as shown in Figure 1.

At first, spacecraft health is expected to be checked out after deployment from ISS. Then, we will conduct 3-axis attitude control of the spacecraft by using its AOCS for the characterization of thruster performance. The implementation period of the first section is expected to be within one month.

The second, thruster operation and performance characterization are planned to be performed. Both DVT and RCT is to be fired and their performance data will be analyzed by profiles of pressure, temperature, angular velocity, and angular momentum during the firing. The results are expected to be compared with ground test results. The implementation period of the second section is supposed to be two months.

Finally, the long-time firing test, totally 15 hours, is expected to be conducted to confirm the orbit transfer capability of the thruster. In this test, Delta-V thruster will provide a thrust towards the tangential direction to change the orbit. Then, the orbit transfer is to be measured by using the GNSS (Global Navigation Satellite System) sensor. The total firing time of 15 hours will be achieved by conducting 10 minutes firing for 90 times. The long-time operation is expected to provide delta-V of 54 m/s for the 4 kg spacecraft.

SPACECRAFT

In this section, details of the spacecraft system are described. AQT-D is a 3U CubeSat, which has the 3-axis attitude control and the propulsion system. The design and development of its bus-system are based on TRICOM-1R. [13] TRICOM-1R was already launched by the smallest orbital rocket SS-520 and operated in 2017 – 2018.[14] The bus-system newly installed Reaction wheels, 3-axis control software, and S-band communication transceivers. Specifications of AQT-D were listed in Table 1.

Structure

The size of AQT-D is 100 mm × 100 mm × 340.5 mm designed based on requirements for ISS-deployment CubeSat. AQT-D has a deployment system of store and forward antenna. Therefore, the size becomes 260 mm × 260 mm × 340.5 mm after antenna deployment. The propulsion system is mounted on the PZ side and the store and forward antenna is mounted on the MZ side. Figure 1 shows a CAD model of AQT-D spacecraft and Figure 2 shows a photograph of AQT-D spacecraft.

AOCS (Attitude Orbit Control System)

3-axis attitude control is expected to be conducted on AQT-D. The geo-magnetic sensor and the sun sensors are used for an attitude determination. AQT-D does not install a start tracker due to volumetric restriction. Especially, the gyro sensor was calibrated before the spacecraft integration to evaluate a dependency on temperature and output drift. It was cleared from the calibration results that the attitude determination accuracy can be estimated less than 30 deg. This value is enough to characterize the performance of the Delta-V thruster.

Table 1: Specifications of AQT-D spacecraft

Item	Values
Size	100 mm × 100 mm × 340.5 mm
Wet mass	< 3.78 kg
AOCS	3-axis attitude control
Acceleration sensors	3-axis
Gyro sensors	3-axis
Geomagnetic sensor	3-axis
Sun sensors	3-axis
Reaction wheels	3-axis
Magnetic torques	3-axis
GNSS-R	1
Power system	
Power	< 8.6 W
Solar cells	24
Battery capacity	< 7600 mAh, 8.4 V (charged)

Battery cells	4
Propulsion system	Water micro-resistojet thruster
S&F antennas	4
Cameras	2

EPS (Electric Power System)

Four solar panels are mounted on MX. PX, MY, and PY side. The maximum energy power obtained from the solar panels is estimated at 8.6 W in the sunshine. The battery capacity is designed within a range from 4940 mAh to 7600 mAh. The maximum battery capacity is limited depending on the battery temperature and the voltage control circuit.

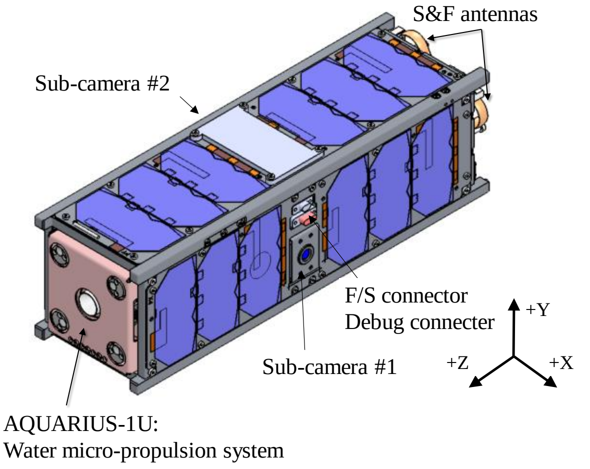

Figure 1: CAD model of AQT-D spacecraft

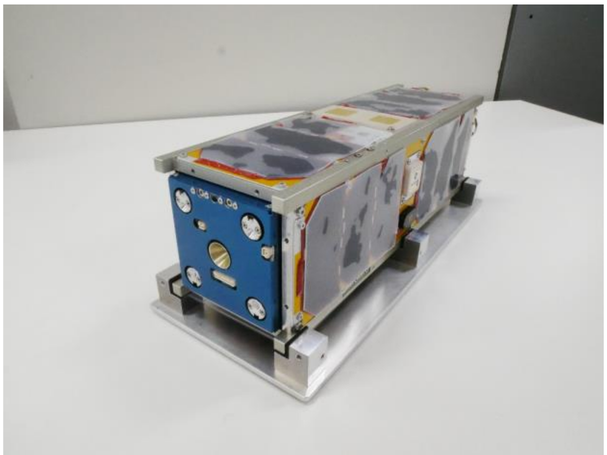

Figure 2: Photograph of AQT-D spacecraft

PROPULSION SYSTEM

In this section, details of the propulsion system are described. The propulsion system, named AQUARIUS-1U (AQUA Resistojet propulsion System-1U), uses water as a propellant. Water has no toxicity, flammability, or carcinogenic issues, and no explosion hazards. Therefore, the propulsion system does not require a pressure vessel for propellant storage. The safety of this system makes possible low-cost development, and also propellant filling at launch site or an orbital habitation module such as ISS or the Lunar Orbital Platform-Gateway (LOP-G) in the future. The ultimate green propellant "water" enables ISS-deployed CubeSats to install a propulsion system.

Figure 3 shows a system diagram of the propulsion system. Figure 4 shows a photograph of the propulsion system. The propulsion system consists of a tank, a vaporizer, Delta-V thruster, and RCS thrusters. Total wet mass and dry mass are approximately 1.20 kg and 0.80 kg. Inside the tank, a bladder is inserted, which is a kind of rubber balloon, storing less than 0.40 kg water. Pressurized gas and water are separated by the bladder. The vaporizer was manufactured by using additive manufacturing, which allows for a flexible design of inner feed lines. Water droplets are injected into the vaporizer by opening the regulating valves downstream of the tank and evaporates at room-temperature (290 – 310 K). the vaporizer is filled with water vapor with a saturated pressure (< 5 kPa). The saturated vapor flows under its own pressure to the thrusters, which are pre-heated to approximately 343 K. finally, the steam is expelled from the thruster. Table 2 listed specifications of the propulsion system.

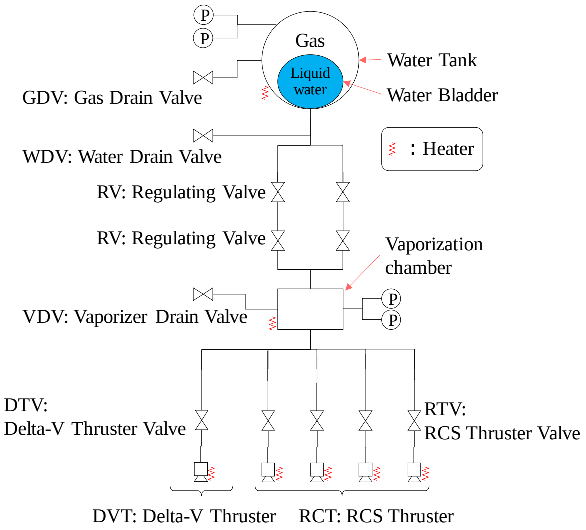

Figure 3: System diagram of the water micro-propulsion system

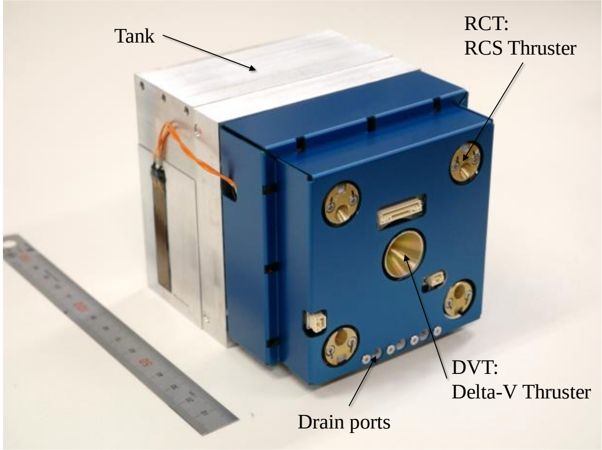

Figure 4: Photograph of the water micro-propulsion system

Table 2: Specifications of the propulsion system

Item	Value
Size	92 mm × 92 mm × 105 mm
Propulsion type	Resistojet (Electrothermal)
Propellant	Water
Wet mass	< 1.20 kg
Dry mass	< 0.80 kg
Total impulse	< 250 Ns
Number of thruster	1 × Delta-V thruster 4 × Reaction control thruster
Typical pressure	
Tank	< 100 kPa (303 K)
Vaporizer	< 5 kPa (290 - 310 K)
Nozzle (plenum)	< 5 kPa (343 K)
Delta-V Thruster	
Thrust	4 mN (depends on power)
Specific impulse	70 s
Thrust to power ratio	0.22 mN/W
Reaction control thruster	
Thrust	< 1 mN (depends on power)
Specific impulse	70 s
Thrust to power ratio	0.22 mN/W
Minimum impulse bit	> 0.5 mNs

DIRECT THRUST MEASUREMENT: STAND-ALONE AND INTEGRATED FIRING TEST -

Thrust performance of the propulsion system was directly measured by using the pendulum-type thrust stand developed by the authors. In addition, both stand-alone firing using the propulsion module and integrated firing using the entire spacecraft system were conducted

Stand-alone firing test

Figure 5 shows a photograph of the experimental setup of the stand-alone firing test. The propulsion module was mounted on a mass balance to measure mass profile during firing. Both components were mounted on the pendulum-type thrust stand designed base on the proposed one.[15] 10 minutes firing was conducted by using in-house developed software. Figure 6 shows an example of firing profile of the Delta-V thruster. Water droplets were injected intermittently by opening the regulating valve for 2.7s at a cycle time of 60 s. Vaporizer pressure and thrust had peak value just after injection. Then, vaporizer temperature decreased because of the heat of evaporating water droplets. Figure 7 shows firing profile of RCS thrusters.

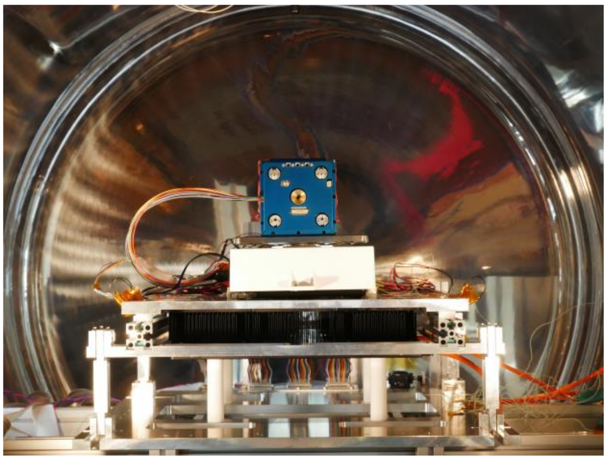

Figure 5: Experimental setup of the stand-alone firing test. Thrust and mass profiles during the firing were directly measured by using the thrust stand and the mass balance.

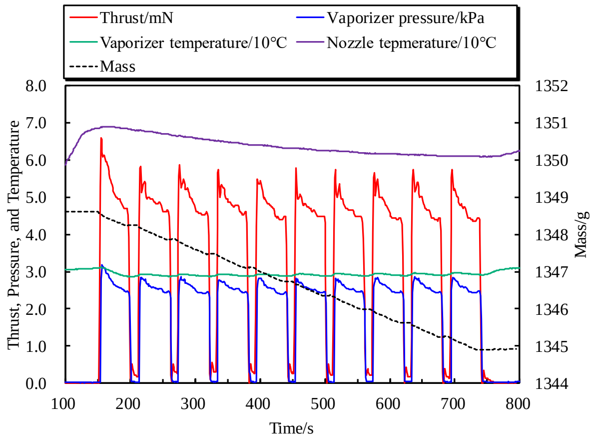

Figure 6: Performance profile of the stand-alone firing test of the Delta-V thruster

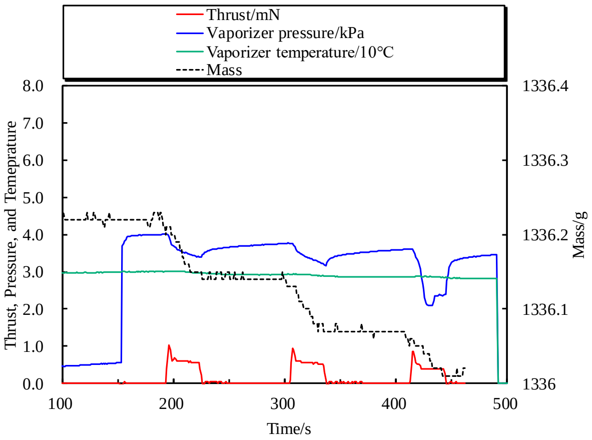

Figure 7: Performance profile of the stand-alone firing test of the RCS thrusters

Integrated firing test

Figure 8 shows a photograph of the experimental setup of the integrated firing test. The spacecraft installed the propulsion system was mounted on the thrust stand which was similar to the stand-alone test. The mass balance was not used in the integration test because the maximum load of the mass balance was lower than the spacecraft mass. Therefore, mass consumption was calculated based on the results of the stand-alone test. Power was supplied from the battery to keep the same firing condition between ground and on-orbit. Firing tests of both the delta-V thruster and RCS thrusters were conducted by using actual flight command and data handling system.

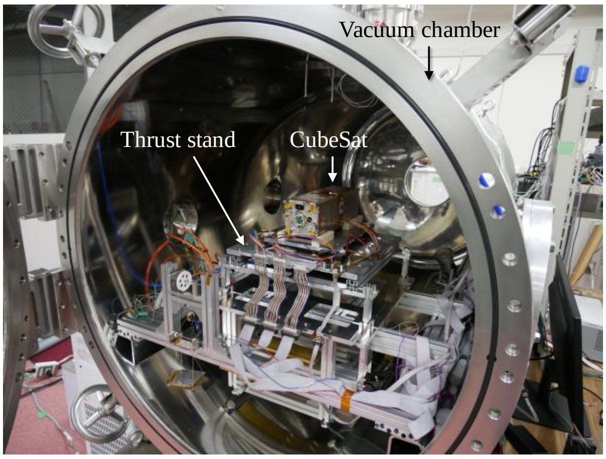

Figure 8: Experimental setup of the integrated firing test. Thrust profile during the firing was directly measured by using the thrust stand.

DEVELOPMENT STATUS

AQT-D will be launched to the ISS in fall 2019. The development of the spacecraft engineering model (EM) started in April 2018. Environmental tests of EM were completed at the end of 2018. Thrust performance of the propulsion system was directly measured by using a pendulum-type thrust stand developed by the authors. The first safety review was also completed in November 2018. The flight model (FM) was improved based on the EM test results. All tests of FM including electrical, thermal cycle, vibration, and thrust measurement were completed at the end of May 2019. The safety review phase III is expected to be held in July 2019. The spacecraft will be delivered to JAXA in July.

Acknowledgments

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