Flight Model Development and Ground Demonstration of Water Resistojet Propulsion System for CubeSats

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The University of Tokyo has proposed a water resistojet thruster with a high certainty of liquid–vapor separation and low power consumption. In this propulsion system, liquid water is periodically vaporized in a pulsating manner to generate thrust. A vaporization chamber with a labyrinth-shaped flow path catches droplets using their surface tension to separate the liquid and vapor, and the droplets vaporize under normal temperature to reduce the input power by reusing the heat from the surrounding components. In this study, we designed and fabricated a flight model of the proposed propulsion system for 6U CubeSat and evaluated the performance of this propulsion system, including the control method. The results confirm the concept of the proposed liquid–vapor separation method and its low power consumption. Moreover, we revealed the relationships between the vaporizing duty cycle, input power, and thrust.

Key Words: CubeSat, Micro-propulsion, Water, Resistojet Thruster

Nomenclature

| Symbol | Description |
|--------|-------------|
| \( A_{dc} \) | droplet surface area |
| \( C_D \) | discharge coefficient |
| \( C_F \) | thrust coefficient |
| \( C_{ev} \) | vaporization coefficient |
| \( C_n \) | gas conductance of nozzle |
| \( C_l \) | liquid conductance of valve |
| \( C_v \) | gas conductance of valve |
| \( c^* \) | characteristic velocity |
| \( F \) | thrust |
| \( g \) | gravity constant |
| \( I_sp \) | specific impulse |
| \( m \) | mass flow rate |
| \( m_l \) | mass flow rate of liquid water |
| \( p \) | pressure |
| \( p_{sat} \) | saturation pressure |
| \( Q \) | input power |
| \( R \) | gas constant |
| \( T \) | temperature |
| \( t \) | time |
| \( \Delta H \) | latent heat of water |
| \( \Delta M_{ijj} \) | injection mass |
| \( \eta_{i} \) | specific impulse efficiency |
| \( \sigma \) | condensation or vaporization coefficient |
| \( \tau \) | operation cycle period |
| \( \phi \) | duty cycle of each operation cycle |

Subscripts

ave: average value
c: stagnation point of nozzle
ev: vaporizationi: injectionideal: non-viscous ideal flowt: throattank: tankvc: vaporization chamber

1. Introduction

According to Space Works, the number of micro/nanosatellites that have been launched has doubled over the past several years. To date, micro/nanosatellites have frequently been used for technical demonstrations in low-earth orbits, without the use of a propulsion system. However, there is an increasing need for long-term orbit maintenance and deep space exploration using a propulsion system. Launched in 2014, PRoximate Object Close FYby with Optical Navigation (PROCYON) was the first deep space probe to be used as a microspacecraft weighing less than 100 kg. This spacecraft was launched for asteroid exploration and is equipped with the Ion thruster and COld-gas thruster Unified Propulsion System (I-COUPS), which consists of a miniature ion thruster with a total delta-V of 150 m/s and cold-gas jet thrusters for attitude control. Launch in 2018, Mars Cube One (MarCO) was launched as the first CubeSat for deep space exploration. MarCO has cold-gas jet thrusters with a total delta-V of 68.6 m/s to carry out fly-by missions to Mars. Because each of the previously launched deep space probes has a high-pressure gas system, an increase in the structural mass ratio could not be avoided, which is a significant disadvantage, particularly for CubeSats.
Water is a potential propellant and can reduce the structural mass ratio because it can be stored in a liquid state under normal temperature and pressure. Moreover, water has the advantages of non-combustibility and low toxicity. These advantages reduce development costs and increase the safety of the system, which is one of the most important issues when satellites are launched as a secondary payload. Therefore, water is considered to be a suitable propellant for micro/nanosatellites; hence, a large number of water propulsion systems have been investigated. Among these, resistojet thrusters are being developed owing to their simple structure. Figure 1 shows the water resistojet thrusters that have been developed and their technology readiness levels (TRLs). The TRL concept, which was introduced by NASA during the mid-1970s, is highly effective in communicating the status of new technologies among diverse organizations. Various vaporizing liquid microthrusters (VLMs) have also been developed. A VLM is an extremely small thruster employing micro-electro-mechanical system technology for micro/nanosatellites. However, the TRLs of such thrusters remain insufficient for practical use.

Thus far, only two water resistojet thrusters have been demonstrated in orbit. One of these was installed on the 90-kg class UK-DMC satellite launched in 2003, and the other was installed on the 1.5U CubeSat AeroCube-OCSD-7B&-7C, launched in 2017. A greater decrease in the temperature and a higher thrust have been observed in UK-DMC operations as compared with the ground tests. This was attributed to the liquid water ejected from the nozzle without appropriate liquid–vapor separation. During the first in-orbit operation of AeroCube-OCSD-7B&-7C, a problem was encountered whereby thrust was not generated. As a similar phenomenon occurred during the ground tests, it was assumed that frozen water was blocking the nozzle.

From the two above-mentioned examples, it can be seen that liquid–vapor separation is a major problem in water resistojet thrusters. A majority of water resistojet thrusters vaporize the propellant by heating the two-layer liquid–vapor flow along their flow path. In this case, the liquid–vapor separation may be affected by the surrounding environment. The University of Tokyo has proposed a water resistojet thruster that solves this issue by incorporating a vaporization chamber, which contains the vaporizing room where droplets attach to the walls of the vaporizing room due to surface tension and a labyrinth shaped flow path to prevent liquid from flowing directly downstream. These structures were introduced to achieve proper liquid–vapor separation. Moreover, a normal temperature is maintained in the vaporization chamber to reduce the heat loss toward the surrounding components and to reuse the heat from the surrounding components that consume significant amounts of power. In water thrusters, the vaporization area requires a large amount of energy to vaporize the water with a large latent heat of 4.2 kJ/g. Therefore, reducing the energy consumption is important, particularly for micro/nanosatellites. Asakawa et al. tested an experimentally designed model of each component under several conditions. However, thus far, this propulsion system has not been tested with all of the components integrated under an actual control method. To demonstrate the concepts of liquid–vapor separation and power savings in a complete propulsion system, it is essential to test the assembled system using a flight model. In addition, because the design of the vaporization chamber and flow path affect the actual thermal conditions should be simulated owing to the sensitivity to the thermal conditions that occur as a result of the saturation pressure.

In this study, we designed a flight model of a water resistojet thruster with a vaporization chamber for the 6U CubeSat, and confirmed the liquid–vapor separation and power savings through experiments conducted under conditions close to those of orbital operations, which herein is called nominal operation. Subsequently, we investigated the relationships between the power input to the vaporization chamber, delta-V thruster (DVT) thrust, and duty cycle, which are important parameters during the pulsating operation.

2. Principle of the Propulsion System

2.1. Design concepts

This section describes the concept of the propulsion system proposed. As shown in Fig. 2, the propulsion system consists of three major parts: a tank for storing the liquid water, a vaporization chamber for vaporizing the liquid water, and thrusters for generating the thrust. The vaporization chamber separates vapor from liquid droplets and feeds only vapor to the thrusters.

The propulsion system is operated such that water is repeatedly and periodically filled and emptied in the vaporization chamber as schematically shown in Fig. 3. This pulsating operation is effective for separating the vapor from the liquid to prevent the specific impulse decreasing. Hence, we first evaluated performance during the thrusting period, and then evaluated the average performance during the pulsating operation.

2.2. Instantaneous performance

First, we considered the vaporization process from the
droplets in the vaporization chamber. Hertz and Knudsen proposed the equation for vaporization from the liquid surface.\(^{29}\) Assuming that the vaporization coefficient and condensation coefficient are \(\sigma\) and the temperature of the liquid and vapor are \(T\), the mass flow rate of vaporization \(\dot{m}_{ev}\) is given as follows:

\[
\dot{m}_{ev} = \frac{\sigma A_{sfc}}{\sqrt{2\pi RT}} (p_{sat} - p_{vc}).
\]  

(1)

Here, \(p_{sat}\) is the saturation pressure obtained from the measured data,\(^{30}\) and \(A_{sfc}\) is the liquid surface area. Assuming that droplets attach to all walls of the vaporizing room in the vaporization chamber, \(A_{sfc}\) is considered the surface of the wall area.

Next, the thrust generation process is considered. The thrust in a general rocket nozzle is expressed as follows:

\[
F_{\text{ideal}} = p_{c}A_{c}C_{F_{\text{ideal}}},
\]  

(2)

where, \(C_{F_{\text{ideal}}}\) is the ideal thrust coefficient given by Eqs. (3)–(30) in a previous study.\(^{31}\) The ideal mass flow rate of the propellant is determined by the choke flow rate, as follows:

\[
\dot{m}_{\text{ideal}} = \frac{p_{c}A_{1}}{c^{*}},
\]  

(3)

where, \(c^{*}\) is the characteristic velocity given by Eq. (3-32) in the same study mentioned above.\(^{31}\) With this propulsion system, the nozzle stagnation pressure \(p_{c}\) reaches a few kilopascals or less owing to the vaporization chamber temperature corresponding to the saturated vapor temperature, which has a value similar to the normal temperature. It is known that the actual mass flow rate and exhaust velocity are both smaller than those calculated using a general nozzle formula (Eq. (2)). This is particularly true in a flow with a low Reynolds number, which is due to the development of the boundary layer in the nozzle.\(^{32,33}\) The specific impulse efficiency and discharge coefficient are defined as the ratio of the value measured to the ideal value in the following equations.

\[
C_{D} \equiv \frac{\dot{m}}{\dot{m}_{\text{ideal}}}
\]  

(4)

\[
\eta_{I_{sp}} = \frac{I_{sp}}{I_{sp,\text{ideal}}} = \frac{F}{\dot{m}g} = \frac{F_{\text{ideal}}}{\dot{m}_{\text{ideal}}g}
\]  

(5)

The actual thrust and specific impulse can thus be expressed as follows:

\[
F = \eta_{I_{sp}}^{\text{ideal}} \dot{m} c^{*} C_{F_{\text{ideal}}},
\]  

(6)

\[
I_{sp} = \eta_{I_{sp}}^{\text{ideal}} \dot{m} c^{*} C_{F_{\text{ideal}}} g.
\]  

(7)

Next, the mass flow rate is calculated by considering the flow conductance of each part used in the propulsion system. Thruster valves are placed between the vaporization chamber and the nozzle, and the gas conductance of the valve with an orifice is typically expressed as follows:\(^{34}\)

\[
C_{v} \equiv \frac{\dot{m}}{\sqrt{(p_{vc} - p_{c}) p_{c}}}
\]  

(8)

The conductance of the valve should be as large in volume as possible such that the temperature does not decrease to the boiling point owing to rapid expansion. Because the feeding lines are connected in series, the mass flow rate of the vaporization is thus the same as that through the nozzle. In this case, the mass flow rate can be calculated as follows:

\[
\dot{m} = C_{v}C_{v'}C_{n} C_{n'}^{\frac{c_{*}^{2}}{C_{n}^{2} + C_{v}^{2} + C_{v'}^{2} + C_{n}^{2}}} p_{sat},
\]  

(9)

where, \(C_{n}\) and \(C_{v}\) are defined as follows:

\[
C_{n} \equiv \frac{\dot{m}}{p_{c}} = \frac{C_{D} A_{1}}{c^{*}},
\]  

(10)

\[
C_{v} \equiv \frac{\sigma A_{sfc}}{\sqrt{2\pi RT}}.
\]  

(11)

Finally, the thrust is obtained from Eqs. (6) and (9), as follows:

\[
F = \frac{C_{v}C_{n}C_{v'}^{\frac{c_{*}^{2}}{C_{n}^{2} + C_{v}^{2} + C_{v'}^{2} + C_{n}^{2}}} \eta_{I_{sp}} p_{sat} c^{*} C_{F_{\text{ideal}}}}{\eta_{I_{sp}}^{\text{ideal}}},
\]  

(12)

2.3. Average performance of pulsating operation

The pulsating operation can be divided into two phases (Fig. 3). The first phase is the thrust generating period and the second phase is the draining period during which the vaporization chamber recovers the heat lost during vaporization. Here, \(\tau\) denotes the cycle time, which is the time from the first water injection to the second water injection. The time ratio of thrusting to operating (duty cycle \(\phi\)) is determined from the temperature recovery time and satisfies the

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Fig. 2. Diagram of the resistojet thruster proposed.

Fig. 3. Time history of simplified operation.
energy conservation in the following equation.

\[ \Delta H \dot{n} \phi \tau = \dot{Q}_{vc} \tau \]  \hspace{2cm} (13)

Here, \( \dot{Q}_{vc} \) is the average heater power input into the vaporization chamber and \( \Delta H \) is the latent heat of the water. Therefore, the duty cycle can be expressed as follows:

\[ \phi = \frac{\dot{Q}_{vc}}{\Delta H \dot{n}} < 1. \]  \hspace{2cm} (14)

For the drain, the number of duty cycles must be less than one.

The cycle time \( \tau \) is determined by the number of droplets injected. The tank and vaporization chamber are connected with a regulation valve. During a brief opening of the regulation valve, a small number of droplets are injected into the vaporization chamber owing to the pressure difference. Here, the number is determined by the valve opening time and the mass flow rate inside the regulation valve. Typically, the mass flow rate of a liquid flow is given using the liquid conductance as follows:

\[ m_{l} = C_{l} \sqrt{p_{tank} - p_{vc}}. \]  \hspace{2cm} (15)

This equation is also applied in the industry.\( ^{34} \)

The average thrust \( F_{ave} \) is the product of the instantaneous thrust \( F \) and the duty cycle \( \phi \). Hence, the average thrust is given by Eqs. (9), (12), and (14) as follows:

\[ F_{ave} = \phi F = \frac{\dot{Q}_{vc}}{\Delta H} \eta_{sp} C_{sp} C_{F,ideal}. \]  \hspace{2cm} (16)

This equation demonstrates that the average thrust does not depend on the valve conductance or the structure of the vaporization chamber. From Eqs. (7), (14), and (16), the flow conductance must be designed to achieve a certain thrust as follows:

\[ \frac{C_{ev} C_{n} C_{\tau}^{2}}{C_{ev} C_{n}^{2} + C_{ev} C_{\tau}^{2} + C_{ev} C_{\tau}^{2}} \geq \frac{F_{ave}}{\eta_{sp} \eta_{ff} C_{sp} C_{F,ideal}}. \]  \hspace{2cm} (17)

3. Flight Model Design of the Propulsion System

3.1. Requirements of the propulsion system

The propulsion system used in this study was developed for the deep space probe EQUilibrIUm Lunar-Earth point 6U Spacecraft (EQUULEUS), which is scheduled to be launched as part of NASA’s Space Launch System Exploration Mission-1.\(^{35} \) EQUULEUS will fly to the Earth-Moon L2 point (EML2) to complete several scientific objectives. In addition, EQUULEUS requires a propulsion system, the performance of which is presented in Table 1.\(^{35} \) A total delta-V budget of 61.0 m/s is required to arrive at EML2 and stay for one year. An average thrust of 3.3 mN is required for a period over 10 h for the first delta-V operation immediately after launch. This propulsion system, called the AQUA ResIstojet propUlision System (AQUARIUS) has two delta-V thrusters (DVTs) for trajectory control and four reaction control thrusters (RCTs) for attitude control.\(^{23} \)

The AQUARIUS specifications when considering the actual operational plan are presented in Table 2. The operating temperature and power consumption can be determined by conducting thermal and power generation simulations.

The designed performances of the DVT and RCT operations are as presented in Table 3. These values can be calculated from the equations given in Sections 2.2 and 2.3 under certain assumptions. To calculate the designed performance, the coefficients were assumed based on previous studies, and the e = 0.08^36 \ C_{D} = 0.8 and \ \eta_{sp} = 0.7^33,34). In this calculation, \( \dot{Q}_{vc} \) power levels of 16 W for DVT and 4 W for RCT are assumed. The droplet temperature was assumed to be the same as that of the vaporization chamber.

To achieve this performance, the structure of the propulsion system was properly designed and certain components were selected. Figure 4 shows a schematic diagram and an image of the propulsion system components. Moreover, the specifications of the components are presented in Table 4. The following sections describe the design of each component in detail.

3.2. Tank and regulation valves

The tank is made of aluminum, except for the part in con-
tact with water, which is made of stainless steel to avoid corrosion. Inside the tank, 1,224 cm$^3$ of liquid water is stored in the bladder, which is pressurized to 50 kPa absolute by argon gas. The volume was determined from the total delta-V of 61.0 m/s required for the EQUULEUS mission. Two pressure sensors (Model 85, Measurement Specialties, Inc.) are used for measuring the water pressure and ullage pressure of the gas inside the tank. Four regulation valves (IEPA Series, Lee Co.) periodically inject water droplets into the vaporization chamber. For redundancy, these valves are serially and parallelly connected.

3.3. Vaporization chamber

The vaporization chamber was composed of aluminum and manufactured using 3D printing to create the vaporizing room and inner labyrinth-shaped flow paths. Figure 5 shows the computer-aided design model of the vaporization chamber. The vaporizing room, the volume and surface area of which were designed to be 8.6 cm$^3$ and 11.2 cm$^2$, respectively, is explicitly larger than the flow path cross-section of 27 mm$^2$ to catch droplets using the droplet surface tension. Moreover, the flow paths have multiple corners to capture the droplets. Because a flow path is generated inside the vaporization chamber, the heat input into the vaporization chamber can be to evaporate the droplets that attach to the walls inside the flow path. Outside the vaporization chamber, ceramic heaters are mounted to keep the temperature constant. Two pressure sensors (010KD, Honeywell, Inc.) were installed for redundancy, and were used to calculate the RCT thrust and mass of the remaining droplets.

3.4. Thruster valves and thrusters

For the six thrusters, there are 12 thruster valves applied (LHD Series, Lee Co.) just after the vaporization chamber. Four valves are used in parallel for each DVT, as shown in Fig. 4, to maximize the flow conductance in a limited volume. Although the probability of failure increases due to the parallel arrangement, the higher thrust is needed to achieve the EQUULEUS mission. For the RCT, each thruster has a single thruster valve because the RCT does not require a large amount of thrust.

Figure 4 shows the six thrusters in the spacecraft panel. Each thruster is connected to the vaporization chamber through a soft tube made of a fluoro resin. The thruster consists of a thermal insulator made of polyamide-imide, a nozzle made of anodized aluminum, a polyimide film heater, and...
a temperature sensor. Because the polyamide-imide has a low thermal conductivity of 0.29 W/K, the exhaust heat from the nozzle to the satellite can be suppressed. The throat diameters of the DVT nozzles are larger than those of the RCT nozzles because delta-V operation requires larger thrust than a reaction control operation. The RCTs are tilted at 30° from the mounting surface, and a set of two thrusters are operated simultaneously when the reaction wheel needs to be unloaded. The nozzle conductance designed for DVTs and RCTs is calculated as $2.76 \times 10^{-9} \text{kg/sPa}$ and $1.55 \times 10^{-9} \text{kg/sPa}$, respectively. Such conductance satisfies Eq. (17).

3.5. Thermal connection to the vaporization chamber

The vaporization chamber is cooled by the evaporation of water droplets. Therefore, if a hot device is thermally connected to the vaporizing chamber, the heat can be used to warm the vaporizing chamber and compensate for the vaporization heater power. In the actual EQUULEUS spacecraft, the communication device, which is the device that consumes the largest amount of power, is mounted next to the vaporization chamber. This communication device consumes approximately 12 W and its temperature is calculated to reach approximately 30°C in-orbit based on a thermal simulation. In this study, instead of the communication device, an aluminum block with a heater (dummy communication device) was thermally attached to the vaporization chamber and heat was input at 12 W.

4. Experiment Conditions

4.1. Experiment apparatus

The test operation of the AQUARIUS flight model was conducted in a vacuum chamber. During the operation, the background pressure was below $1 \times 10^{-4} \text{Pa}$. Figure 6 shows the experiment setup. A gravity pendulum-type thrust balance was used for the thrust measurements, and the thrust balance was calibrated before and after each operation. AQUARIUS was connected to the on-board computer (OBC) of the EQUULEUS engineering model. AQUARIUS was mounted onto a mass scale with a resolution of 0.01 g. The mass scale measured the mass flowing out of the initial state, and the mass flow rate was calculated as the difference.

4.2. Control method used for the propulsion system

The electric circuit board of the propulsion system was controlled by the OBC in this study. The propulsion system can be activated automatically by sending commands to the OBC through a personal computer. To operate this propulsion system, it is necessary to determine the proper methods for maintaining the temperature of the vaporization chamber, determining the droplet injection time, and adjusting the amount of water injected. These can be achieved using a feedback control based on the actual propulsion system quantities measured. Figure 7 shows a flow chart of the control method for the heaters and valves.

First, to maintain the temperature of the vaporization chamber and the nozzles, the heater was controlled using a bang-bang control method with reference to the temperature sensors. During actual operation, the heater was turned off when the temperature exceeded the upper threshold and turned on when the temperature dropped below the lower threshold. Using this control method, the heater input power was obtained from the results of the bang-bang control.

Next, droplet injection was automatically conducted after the vaporization chamber pressure dropped below the threshold. For proper gas–liquid separation, it is desirable for injection to be applied with all droplets being regularly vaporized. This is because liquid–vapor separation performance will be significantly reduced if the volume of non-vaporized droplets exceeds that of the vaporization chamber. Moreover, to recover the temperature of the vaporization chamber, a waiting period is required after the pressure is reduced to the threshold. For draining, the thruster valves are kept open throughout the entire operation.

Next, to maintain a constant amount of water injection, the opening time of the regulation valve was controlled based on the tank pressure measured. Since the pressure of the vaporization chamber was approximately zero just before injection (Fig. 3), the amount of water injected $M_{\text{inj}}$ was determined using only $\sqrt{p_{\text{tank}}}$ from Eq. (15).

4.3. Operational parameters

There are two types of operation. The nominal operation...
conditions are listed in Table 5. The order of thrusters used was DVT1, DVT2, both RCT1 and RCT4, DVT1, DVT2, and both RCT2 and RCT3. This operation was repeated twice. The thruster used was determined based on the valves opened, which was controlled by the OBC as programmed in advance. To simulate the thermal environment during spacecraft operation, the dummy communication device was sufficiently warmed to approximately 30°C to reach a steady state.

The other experiment is the duty-cycle dependent experiment. During this experiment, the mass of droplets injected and the waiting time were changed to modify the duty cycle. The duty cycle is calculated as the ratio of thrusting time to propulsion system operating time (Fig. 3). The conditions of this experiment are listed in Table 6. The vaporization time is defined as the time until the pressure drops below the threshold after injection. Because the dummy communication device was heated immediately before operation and reached approximately 29°C, waste heat from the dummy heater was not used for vaporization during this experiment. We conducted 16 tests by changing the injection mass and waiting time. During each experiment, the vaporization cycle was repeated approximately 10 times while the same thruster (DVT2) was used and the operating parameter was fixed.

5. Experiments

5.1. Nominal operation

The time history of this experiment is shown in Fig. 8. The pulsating operation was confirmed within approximately 1,000 s of operation. Immediately after the first injection (time = 0), the vaporization chamber pressure and thrust suddenly increased, whereas the vaporization chamber temperature decreased. Within approximately 60 s, the vaporization chamber pressure and thrust gradually decreased because the saturation pressure of the water in the vaporization chamber decreased with the temperature of the vaporization chamber. After the droplets fully vaporized, the vaporization chamber pressure and thrust dropped to zero and the vaporization temperature started to recover.

During the subsequent cycles, the thrust, pressure, and temperature exhibited the same behavior. Once every three cycles, the RCTs were used, as shown in Table 5. Because the flow conductance of a RCT is smaller than that of a DVT, the RCT thrust was also smaller than the DVT thrust. During the vaporization phase, the flow-out mass measured by the mass scale increased at high pressure. Particularly during RCT operation, it was observed that the value measured by the mass scale increased approximately 0.2 g immediately after the thrust was generated. This was caused by the vertical thrust of the RCT nozzles, which formed at an angle of 30° with the z-axis. When RCTs were used, it is considered that the plume from each nozzle experienced interference. However, this influence should be relatively smaller than the thrust measured because the distance between nozzles is 100 times or more larger than the nozzle throat diameter.

From this result, it was proven that the propulsion system operated with proper liquid–vapor separation. This occurred because, first, the thrust and vaporization chamber pressure decreased simultaneously to zero. Secondly, there was no mass decrease after the vaporization chamber pressure reached zero. Therefore, it is assumed that liquid water did not flow out of the vaporization chamber. Moreover, no liquid or ice was observed after passing through the nozzles during propulsion system operation.

Table 7 shows the performance results of nominal operation. These parameters were averaged based on the operation time, including the waiting time when the pressure and thrust were approximately zero. The value of the error was half the width of the maximum and minimum average values for each cycle. Compared with the designed performance, the duty cycle was larger; however, the average mass flow rate and average thrust were smaller. First, the duty cycle increased because the saturation pressure was smaller than that as-

| Conditions | Order of operation for nozzles |
|------------|-------------------------------|
|            | DVT1⇒DVT2                    |
|            | ⇒RCT1&4                      |
|            | ⇒DVT1⇒DVT2                   |
|            | ⇒RCT2&3…                     |
| Vaporization chamber temperature | 28°C                        |
| Nozzle temperature | 60°C                        |
| Injection mass | 0.63 g (DVT)                 |
|                  | 0.17 g (RCT)                 |
| Pressure threshold | 0.10 kPa                    |
| Injection waiting time | 20 s                        |

Table 6. Duty cycle test conditions.

| Conditions | Nozzle used |
|------------|-------------|
|            | DVT2        |
| Vaporization chamber temperature | 28°C        |
| Nozzle temperature | 70°C        |
| Injection mass range | 0.1–1.0 g   |
| Pressure threshold | 0.10 kPa    |
| Injection waiting time range | 8.7–57 s    |

cause the saturation pressure of the water in the vaporization chamber decreased with the temperature of the vaporization chamber. After the droplets fully vaporized, the vaporization chamber pressure and thrust dropped to zero and the vaporization temperature started to recover.

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tion chamber should not a value. The input power cannot be actively changed using the cause the power consumption was smaller than the assumed the average mass
lux caused by the latent heat. In addition, among the thrust and vaporization chamber heater during this experi-
steam rate and average thrust decreased be-
cussing owing to the lower surface temperature of the dro-
sumed owing to the lower surface temperature of the drop-
lets. In theory, the liquid temperature is assumed to be the same as that of the vaporization chamber. However, in ac-
tuality the surface temperature should decrease based on the local heat flux caused by the latent heat. In addition, the average mass flow rate and average thrust decreased because the power consumption was smaller than the assumed value. The input power cannot be actively changed using the above-mentioned control method.

Although the duty cycle and input power for the vaporiza-
tion chamber should not affect the specific impulse, the spec-
ic impulse was smaller than the designed performance, particularly during RCT operation. According to Eq. (7), this is considered to be caused by the small specific impulse efficiency because the viscosity effect was larger than expected. In this experiment, the specific impulse efficiencies measured were 0.65 for the DVT and 0.55 for the RCT. Previous studies have shown that the background pressure affects the nozzle performance.38,39) Compared with this result obtained at approximately 0.01–0.1 Pa, the orbital performance may increase.

This experiment demonstrated the concept of energy sav-
ings. The average latent heat calculated from the mass flow rate was 14.8 W. Compared with this latent heat, the exper-
imental power consumption was smaller. The latent heat was collected by the exhaust heat from the device, which was thermally coupled with the vaporization chamber. During this experiment, the thermal conditions inside the vacuum chamber were different than those in space. Because there is more heat loss from radiation in space compared with that during the ground experiments, the dummy communication device was heated more in comparison with the orbital conditions.

5.2. Duty cycle dependency experiment

Figure 9 shows the dependence of the duty cycle on the thrust and vaporization chamber heater during this experi-
ment. Sixteen results are shown, and the values are the aver-
eges of all cycles under each condition. As the result of changing the injection mass and waiting time, the duty cycle changed from 0.25 to 0.80. There is a positive correlation among the thrust, power, and duty cycle. As shown in Eqs. (13) and (16), assuming that the flow conductance and temperature are constant, the thrust and vaporization chamber power should be linear to the duty cycle. The results agree with the theory to a certain extent. However, in fact, the flow conductance changes slightly depending on the Reynolds number of the flow when the propellant mass flow rate is low, as in this experiment. Furthermore, the temperature is not constant based on the results of bang-bang control. For this reason, there is small variation in linearity.

Despite the small variation, this result suggests that the thrust and power can be controlled by changing the duty cycle. The slope of this relationship can be changed by the operation temperature or flow conductance. Thus, a control method based on duty cycle can be adapted to other thrusters.

6. Conclusion

This study investigated a water resistojet propulsion sys-
tem for use in CubeSats. To achieve a certain liquid–vapor separation, this propulsion system has three main separate components: a tank, a vaporization chamber, and nozzles. This propulsion system has a unique vaporization system for solving the problems inherent to a traditional water thrusters. To achieve the separation of vapor from liquids, a vaporization room and labyrinth-shaped flow path are used to catch the droplets, preventing them from flowing out downstream, and all droplets are periodically vaporized to avoid an overflow. Moreover, to save energy and compensate for latent heat, hot devices are thermally connected to the vaporization chamber at room temperature.

Because the thermal environment and flow conductance between components are important for performance, a flight model was developed and tested. To maintain the temperature and control the amount of droplet injection, a control method was implemented in the spacecraft control units.
and applied in this study. We carried out two types of experiments, namely, an experiment under nominal operation conditions in space and a duty cycle dependency test.

The former experiment was carried out to demonstrate the concept of this propulsion system. From the results of the thrust, pressure, and change in mass, proper liquid–vapor separation was confirmed. Comparing the experimental power consumption with the latent heat calculated, the concept of power savings was by collecting the exhaust heat from other device was demonstrated.

During a later experiment, we measured performance dependency on the duty cycle, which is the ratio of thrust and waiting times. From this experiment, it is believed that thrust and power can be controlled by changing the duty cycle. This control method can be applied to other vaporizing thrusters.

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