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Miniature Water Ion Thruster; 1 km/s-class Delta-V for a 6U CubeSat

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ABSTRACT

A propulsion system gives CubeSats the capacity to change their orbit on their own, and in terms of achieving a large delta-V, electric propulsion has an advantage. Installing the electric propulsion on CubeSats has difficulties such as a high-pressure gas system, electrical components, and the drop of the efficiency because of the miniaturization. To clear these problems, the water ion thruster is proposed as a candidate for the CubeSats' electric propulsion. Water has an absolute advantage of applying for CubeSats' propulsion system in the point of safety. In addition, water is a liquid phase at room temperature and atmospheric pressure, and it makes easy to store and handle it. The thrust measurement and the improvement of the thruster based on experiments were conducted. The thrust and the specific impulse were estimated as 226 ± 19 μN and 384 ± 33 s at the highest performance point with 36.5 W power consumption of all system. It achieved a delta-V of 504 ± 43 m/s with the 1 kg of propellant for an 8 kg and 6U CubeSat.

INTRODUCTION

A propulsion system is one of the essential technologies for CubeSat. It gives CubeSats the capacity to change their orbit on their own, which extends a range of possibilities of advanced missions.[1,2] A deep space exploration is one example of the mission, which is inseparable from propulsion systems because it required the reaction control system not relying on the Earth's magnetic field and the ability of the orbit transfer in almost all cases.[3] One mission was already achieved, the twin CubeSats called Mars Cube One (MarCO) are the first and second CubeSat going to the deep space.[4] It had a propulsion system of cold-gas thrusters. It's more important because most of the CubeSats at Low-Earth Orbit (LEO) are launched at one time by a single rocket and cannot choose the initial orbit freely. The propulsion system gives the ability to change the orbit, and of course, it extends the lifetime of the satellite. These missions mainly require two functions of a propulsion system. One is the ability of a change of velocity to keep or change the orbit, and the other is the ability to change the angular momentum of the satellite. In this paper, we focused on a thruster to acquire a change of velocity.

In terms of achieving a large delta-V, electric propulsion has an advantage as a delta-V thruster for CubeSat compared with the cold-gas jet thrusters, which is commonly used for CubeSats because of its high specific impulse.[5] The limited volume makes the specific impulse more important. Therefore, Electric propulsion for CubeSats has been studied and developed in many universities and companies, and some of them were already launched.[5-7]

The difficult points of the electric propulsion for CubeSats are that the limited volume and other resources prevent from installing the high-pressure gas system, which many conventional electric propulsions use, and the electrical components to drive the thruster. In addition, the drop of the energy conversion efficiency due to miniaturizing the thruster is a problem to use an ion thruster and a Hall thruster, which is widely used as a thruster for large satellites.

Satisfying these requirements, we have proposed the miniature water ion thruster as a candidate of a high delta-V thruster for CubeSats.[8,9] Using water as a propellant has an absolute advantage of applying for CubeSats' propulsion system. It dramatically reduces the storage structure and makes handling of propellant relatively easy compared with using a high-pressure gas such as xenon, and the propellant feeding system becomes enough small to install on a 6U-class CubeSat. The system of separating the vapor from the water was an important issue of the feed system, and it was already developed as a part of the resist-jet thruster, AQUARIUS (AQUA ResIstojet propUlsion System) [10] installed on EQUULEUS (EQUilibriUm Lunar-Earth point 6U Spacecraft) and AQT-D (AQua Thruster-Demonstrator) [11].

In addition, when considering the deployment from ISS (International Space Station) and launch as a secondary payload, which is often the case in launching CubeSats, satisfying the safety requirements is much easier compared with using the other chemical propellants and the high-pressure gases. It is because the safety of water is regarded as the highest level among all materials. As a result, AQT-D, which has a water propulsion system, is planned to be deployed from ISS. [11]

In this paper, we show the experimental results of the water ion thruster and the current performance as a thruster. And the estimated performance as a module based on these experimental results with considering the efficiency of the components is discussed.

PRINCIPLE

The miniature water ion thruster is composed of the ion source and the neutralizer (Fig.1). The diameters of the ion source and the neutralizer are 20 mm. The propellant is fed to both the ion source and the neutralizer, and the mass flow rate is typically 30 µg/s for each in case of using water as a propellant. The microwave also inputs to both, and it heats up the electrons by Electron Cyclotron Resonance (ECR) heating with samarium-cobalt magnets. The heated electrons ionize the propellant and generate the plasma. [9,12]

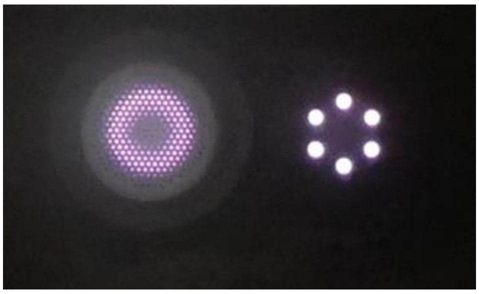

Figure 1: Front view of the water ion thruster

The ion source generates the thrust by accelerating the ions. In the ion source, the ionized propellants are accelerated by two grids; the screen grid and the accelerating grid. The screen grid is typically applied more than 1 kV, and the ions achieve the momentum from this electrical potential difference. Therefore, the thrust is a function of the beam current and the screen voltage, and it estimated as below;

$$F = \alpha \sqrt{\frac{2M_{\mathrm{i}}V_{\mathrm{S}}}{e}} I_{\mathrm{b}} \qquad (1)$$

where α = thrust correction factor; e = elementary charge; V_s = screen voltage; M_i = mass of the ion; I_b = beam current. The thrust correction factor represents the negative effect of the beam divergence, the multiply charged ions, and the dissociated ions such as H^+, OH^+, and so on. In other words, if the thrust correction factor was one, it means that all ions are exhausted as the straight beam and these are all H_2O^+.

The neutralizer emits the electrons from the plasma to neutralize the ion beam in order not to drop the electrical potential of the satellites. The wall of the neutralizer is negatively biased and the electron emitted by using the potential difference between the neutralizer and space. The negative biased voltage was controlled to emit enough electrons to neutralize the ion beam, and the typical value is 40-50 V.

PERFORMANCE

In this section, we focused on the current performance of the water ion thruster. The results of the thrust measurement and some experiments to improve the performance of the water ion thruster are shown.

Thrust measurement

The direct thrust measurement using the pendulum-type thrust stand shown in fig. 2 was conducted to determine the thrust correction factor. The factor of this miniature ion thruster with xenon propellant was already validated by comparing the beam current and the measured thrust in space operation. However, in the case of water, the effect of the beam divergent is expected to be worse, and the dissociation, which never happens in the xenon case, should have a bad effect.

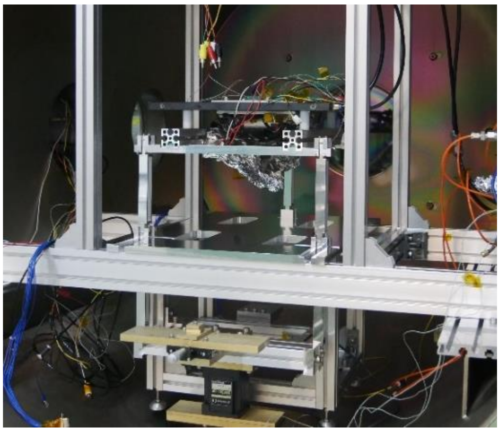

Figure 2: Pendulum-type thrust stand

The results are summarized in Table. 1. The microwave power input was 2.0 ± 0.050 W and the mass flow rate was 86 ± 10.8 µg/s. The thrust correction factor was over 0.9 when the screen voltage was over 1.0 kV. It means that the effect of the beam divergent and the dissociation did not affect the thrust seriously, and the thruster could generate the thrust as well as other gridded ion thrusters. The further detail of the thrust measurement was in Ref. 9 and 13.

Table 1: Measured thrust correction factors with changing the screen voltage

Screen voltage /kV	Thrust correction factor
0.60	0.81 ± 0.088
0.80	0.91 ± 0.079
1.0	0.92 ± 0.075
1.2	0.93 ± 0.073
1.4	0.92 ± 0.074

Dependence on the microwave power input

Firstly, the performance dependence of the ion source on the microwave input power was evaluated. In this experiment, the mass flow rate and the screen voltage was fixed at 30 ± 2 µg/s and 1.0 kV, and the frequency of the microwave was 4.25 GHz. The performance was evaluated by two values, the beam current, which indicates the thrust directly, and the ion production cost, which is defined as below;

$$C_\mathrm{i} = \frac{P_\mathrm{in}}{I_\mathrm{s}} \tag{2}$$

where C_i = ion production cost; P_in = microwave input power; I_s = screen current. The ion production cost presents how much microwave power is needed to achieve 1 A of the screen current, and the lower it is, the better.

The results are shown in fig. 3. The microwave input power was changed from 0.7 W to 2.5 W, and the beam current was clearly increased with microwave power. The ion production cost was almost constant from 0.9 to 2.5 W, and it means that the thrust-power ratio was almost the same in this range. Since the mass flow rate is constant, the higher beam current means the higher specific impulse at this condition. Therefore, the operation point should be chosen as the power consumption of the ion thruster module did not exceed the power budget required from a satellite and a mission.

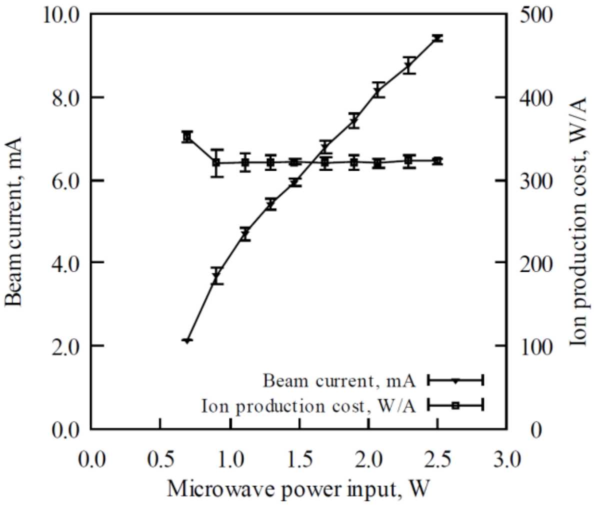

Figure 3: Beam current and the ion production cost while changing the microwave power input.

Performance dependence on the microwave frequency

To improve the performance, some parameters and geometries were changed and these effects were tested. In this paper, we focused on the two parameters; the frequency of the microwave and the bias voltage of the antenna in the ion source.

The frequency of the microwave determines where the electron is mainly heated and the plasma is mainly generated. The electrons are heated by ECR heating, and its resonance frequency is determined only the strength of the magnetic field as below;

$$\omega_\mathrm{c} = \frac{\mathrm{e}B}{m_\mathrm{e}} \tag{3}$$

where B = magnetic flux density; m_e = mass of an electron. Since the magnetic field in the ion source has a gradient in the axial direction as shown in fig. 4, the ECR heating area moves to correspond with the frequency in the axial direction. These affect the plasma density, the plasma distribution, and the beam extraction from the plasma.

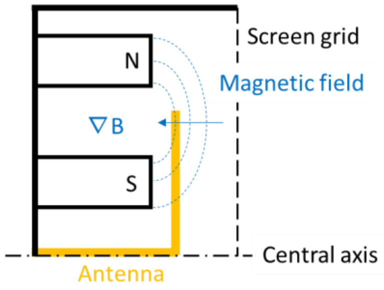

Figure 4: Schematic of the inside of the ion source

The results are shown in fig. 5. The other parameters were fixed as 31.3 ± 0.8 µg/s of the mass flow rate, 1.0 kV of the screen voltage, and 1.5W of the microwave input power. At the point which the beam current is zero, the plasma was not kept and the ion thruster did not work. The range of the operation was from 3.4 GHz to 4.9 GHz, and these results suggested that the ECR heating area be too near to the screen grid to keep the plasma at less than 3.4 GHz and that it be too near to the antenna or the magnet at more than 5.0 GHz.

The beam current was relatively constant at 4.0 GHz to 4.9 GHz, and the fluctuation from the average is within 10 %. It also suggests the possibility of changing the frequency, not because of the performance of the thruster itself, but the efficiency or other performance of the component which supplies the microwave to the ion thruster.

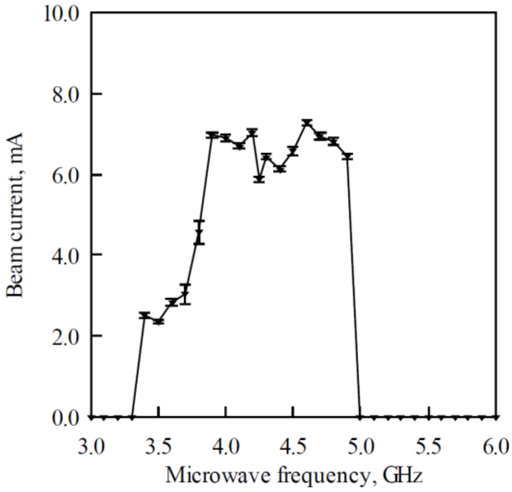

Figure 5: Beam current with the microwave frequency. The mass flow rate is 31.3±0.8 µg/s, the screen voltage is 1.0 kV, and the microwave input power is 1.5 W.

Performance improvement with the antenna bias voltage

The antenna is a part of the ion source and the neutralizer, which provides the microwave to the plasma (fig. 4). Since the electrical field of the microwave is strong near the antenna, and the magnetic flux density around the antenna is strong, the plasma density near the antenna is relatively high. It means the loss of the plasma to the antenna is a severe problem to increase the beam current. In this experiment, the antenna was biased by DC voltage to reduce the loss and change the plasma property.

The results are shown in fig. 6. The beam current increased almost twice at the highest point, and the ion production cost was reduced in spite of increasing the power consumption because of the bias voltage. The highest beam current was 12.7±0.36 mA with the antenna bias voltage of 38.2 V.

MODULE OF THE WATER ION THRUSTER

Components of the module

The system schematic of the module is shown in fig. 7. The module is composed of the water feed system, the High Voltage Power Supply (HVPS), Microwave Power Supply (MPS), DC Block, the control unit, and the water ion thruster itself. DC Block is a unique and important part of the module. It passes the microwave and isolates MPS form the ion source, which is biased by over 1.0 kV, to protect it.

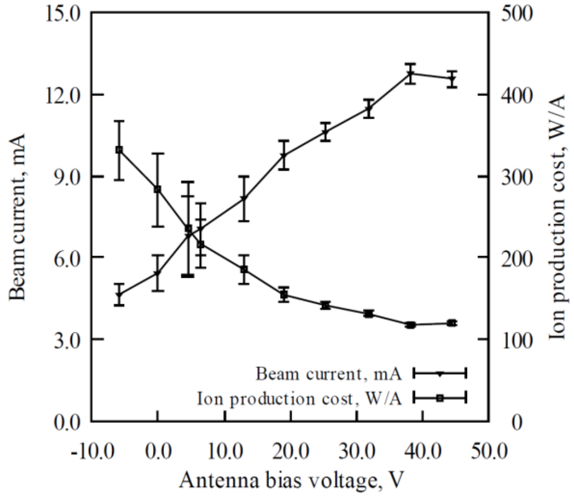

Figure 6: Beam current and the ion production cost while changing the antenna bias voltage. The mass flow rate is 30.3±1.0 µg/s, the screen voltage is 1.0 kV, and the microwave input power is 1.5 W.

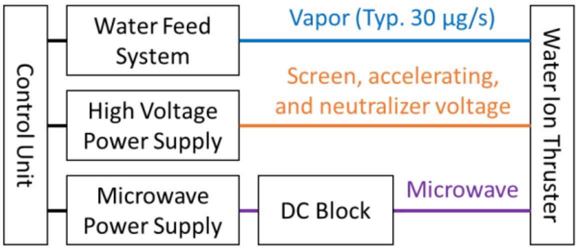

Figure 7: System schematic of the water ion thruster module

The water feed system was based on the resist-jet thruster installed on AQT-D. However, the fine mass flow control system is required to operate the ion thruster, which differs from the case of the resist jet thruster. It has to feed the water to the thruster at 30 µg/s typically within 10 % fluctuation at least. The test model was already developed for the ground experiment, and it achieved the accuracy of around 1.0 µg/s for feeding the water at 30 µg/s with less than 2 W power consumption. Currently, the next model is being developed to miniaturize it to enough size to install as a part of the module.

HVPS and MPS are also being developed for miniaturization and higher efficiency. Although these for 50 kg-class satellites were already developed and launched in 2014 with PROCYON (PRoximate Object Close flYby with Optical Navigation), the size is not small enough and the efficiency has a room of improvement. Currently, these sizes became enough small, and we focused on increasing the efficiency of these components.

Performance estimation as a module

The estimated performance of the water ion thruster is shown in Table 2. The performance of the ion source was determined from the experiment of applying the bias voltage to the antenna. The microwave input power and the mass flow rate of the neutralizer were regarded as the same value as that of the ion source.

Table 2: Estimated performance of the thruster

Items	Value
Microwave input power	1.5 W (2 port)
Mass flow rate	30 µg/s (both)
Screen voltage	1.0 kV
Antenna bias voltage	38 V
Beam current	12.7 ± 0.36 mA
Thrust	226 ± 19 µN
Specific impulse	384 ± 33 s

Based on this estimated performance of the ion thruster, the performance as a module was estimated. The efficiencies and losses were from the previous components which were equipped with the launched satellite. In case of some components which were already developed, the measured or designed values were used. Table 3 shows the power consumption of the module. Assuming that the module was installed in 6 U CubeSat, the achieved delta-V was 504 ± 43 m/s using 1 kg propellant for a CubeSat whose wet-mass was 8 kg. It can extend the lifetime of a CubeSat in LEO by several years.

Table 3: Power consumption of the module

Items	Value	Comments
Total power consumption	36.5 W	
MPS	13 W	Including the loss of DC Block From previous components
HVPS	19.5 W	Designed
Antenna bias	1 W	From experiment
Feed system	2 W	From experiment
Control Unit	1 W	From experiment

Conclusion

The water ion thruster is a strong candidate as a delta-V thruster for CubeSat, since the safety of water has a big advantage as a CubeSat's component, and the high specific impulse is attractive especially for the deep space missions or the life extension in LEO. The ability to achieve the delta-V of several hundred m/s was expected from the experimental results. The total power consumption would be less than 40 W, and it was enough low to install a 6U CubeSat when considering that the solar array panel deploys. However, the specific impulse is still low as an ion thruster and there is a lot of room of improvement. And almost all components are also under developing, and these should be completed and integrated to evaluate as a whole module for the CubeSat.

Acknowledgments

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