Proposal for a Fully Integrated 1U Ion Thruster Using Water as Propellant

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***Abstract*—Space development by the private sector is flourishing, especially in the low-Earth orbit constellation market with small to medium-sized satellites. The demand for propulsion systems for small satellites is increasing and the system using alternative propellants is widely developed. In this paper, we describe the details of a water ion thruster developed in Pale Blue from the system's perspective, including its performance and interface.**

Keywords—water thruster, ion thruster, electric propulsion, CubeSat component

I. Introduction

Currently, space development by the private sector is flourishing, especially in the low-Earth orbit constellation market with small to medium-sized satellites weighing less than several hundred kilograms [1]. Satellites orbiting in low Earth orbit are subject to atmospheric drag and other disturbances, causing their orbits to shift with time. Orbit correction is essential to make observations at the same point on the earth and to operate the satellites without disrupting the formation between satellites. Since satellites for constellation are launched by the same rocket, orbit maneuvering from the same orbit to the constellation orbit is required. In addition, there is an international demand for de-orbiting to prevent satellites from becoming space debris by reducing the altitude of satellites at the end of their operations. An increasing number of satellites are equipped with propulsion systems for these various reasons [2].

The small electric propulsion systems currently on the market have two major characteristics. One is the use of alternative propellants, and the other is that the entire propulsion system is compact and fully integrated. Liquid or solid alternative propellants, such as iodine, indium, and water, do not require a high-pressure gas system, which makes the safety requirement simple [2]. Also, it does not need refueling propellant at the launch site, which makes the operation simple and reduces the cost. Krypton and argon are also regarded as alternative propellants of xenon, and these reduce the propellant cost dramatically [3]. Fully integrated systems have the advantage of not only facilitating its integration into satellites but also providing scalability that can meet a wide range of requirements from the satellites by clustering multiple units.

When talking about the size of subsystems on satellites, "U" is often used as a unit, which represents a Cube of 10 cm × 10 cm × 10 cm. It is because these components were developed in the CubeSat development at first, and still it is useful for considering the design of satellites. Especially, 1U is a standard size in the market, and propulsion systems using indium and iodine as propellants are already widely used. To make it safer, simpler, and lower in cost, we have now developed a 1U ion thruster "PBI" that uses water as the propellant. In this paper, we describe the details of PBI from the system's perspective, including its performance and interface.

II. System and Performance of PBI

PBI is a gridded ion thruster using water as a propellant. The whole schematic of PBI is shown in Figure 1. Water is fed to a discharge chamber as vapor by using a gas separation system and accumulator for controlling the mass flow rate of vapor. In the discharge chamber, water plasma is generated by microwave and static magnetic field. The chamber has two grids, which are a screen grid and an accelerating grid, and accelerates water ions to generate the thrust. The technique used in the ion source and the physics in the discharge chamber were mentioned in ref. [4] in detail.

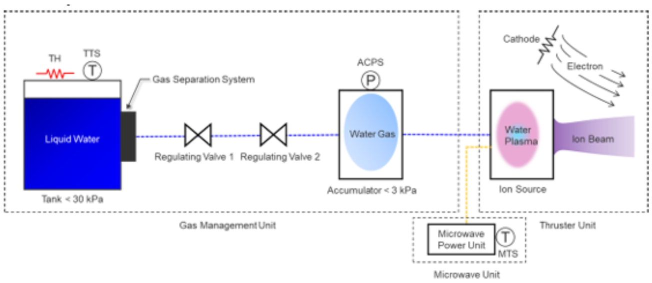

Figure 1 Schematic of PBI thruster

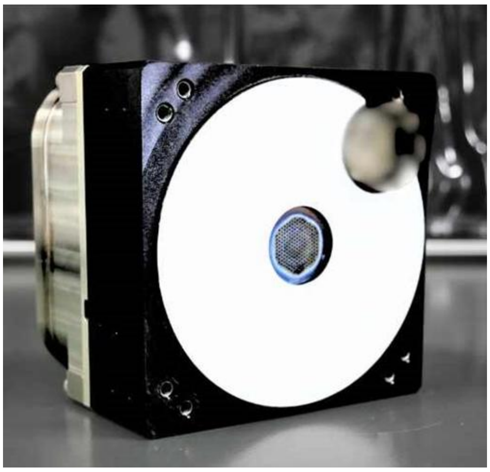

Figure 2 Picture of PBI thruster

The PBI has a thrust of 0.35 mN, a total impulse of 7000 Ns, and a power of 60 W. All components, including the tank, are contained within a 98 mm × 98 mm × 106 mm envelope. The appearance of PBI is shown in Figure 2. A notable feature is a large total impulse as a 1U propulsion system, which means that it can provide a larger ΔV to the satellite. The total impulse is determined by the propellant mass and specific impulse. We achieved this large value by expanding the tank volume, which led to a larger propellant mass, and by enhancing the specific impulse with the re-designing of the thruster head and the related components. Also, the increased efficiency of the microwave power source was contributed.

III. Interface of PBI

The mutual concept in the electric and software interface is “keep it simple.” The power supply and communication interface are all in a 9-pin MDM connector, which is a so-called “plug-and-play” system. The supply voltage is 24V-34V and the communication format is RS422. The maximum power consumption was defined for each mode shown in the following, and the 60 W is the largest value.

The software interface is highly automated so that thrust generation can be performed with simple commands. The mode transition diagram is shown in Figure 3. The modes are defined as “OFF,” “Standby,” “Warm-up,” “Pre-Thrusting Ignition,” and “Thrusting.” The transition between these modes can be done by one command and automatic failure detections and mode transition are installed. “System Check Out” is a mode for diagnosing the health of the propulsion system and is provided as a means to verify that there are no anomalies before the propulsion system is put into operation. The telemetry packet is allowed to CCSDS (Consultative Committee for Space Data System), which is commonly used as a packet for satellite components.

For the mechanical interface, eight screw holes for M4 are prepared for fixing it on the satellite. The screws are on the front panel (the exposed panel) or side of the thruster unit. The thruster is to be fixed with isolated washers not to connect to the satellite’s chassis electrically.

For the thermal interface, storage and operating temperatures are defined. The storage temperature includes the on-orbit power-off state and ranges from -20 deg C to 60 deg C. The tanks are designed to be freeze-resistant. The operating temperature range is 10 deg C to 50 deg C, which represents the range in which the propulsion system can proceed to the “Pre-Thrusting Ignition” sequence and beyond. The ability to generate thrust at these relatively low temperatures is a benefit of the high vapor pressure of water at these temperatures. This means that the user saves time and power to heat the propellant to a high temperature by “Warm-up”.

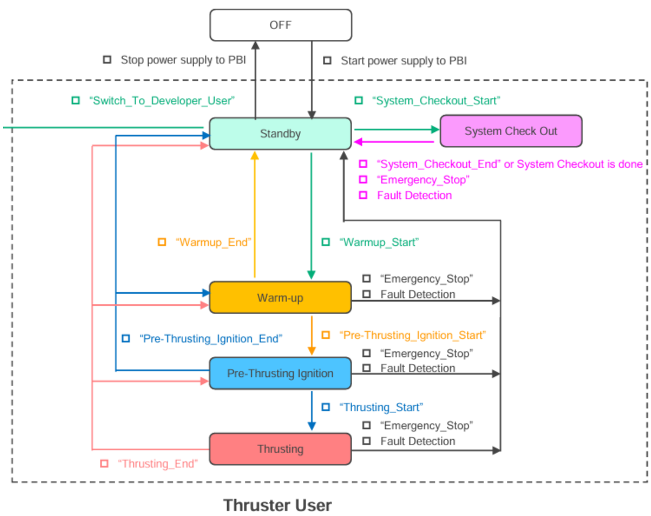

Figure 3 Mode transition diagram of PBI

IV. Operation and Environmental Test

Operation tests are conducted in a vacuum chamber in a fully integrated configuration. Ion beam measurements and other tests are being conducted to evaluate specifications. The example of the result is shown in Figure 4. Until 110 s, the thruster was “Pre-Thrusting Ignition” mode, which is to generate the plasma but not to generate the thrust. The performances at the nominal operation point, which was 45 deg C, were 360 μN of thrust, 2100 s of specific impulse, and 58 W of power. It shows the thrust was higher than that in the specification, and the power was lower than that in the specification. Also, the specific impulse was enough high to satisfy the total impulse of 7000 Ns.

These tests are conducted for the flight model of PBI. The first space demonstration of PBI is scheduled for 2025 and plans to conduct in-orbit thrust measurement and other experiments. The thrust was calculated from the beam current of the ions in the ground tests, but it would be able to be estimated more precisely from the satellite attitude and the change of its internal angular momentum.

The environmental tests for PBI were conducted. For launching, the vibration test and shock test were conducted to verify that it matched the requirements from the rocket. For the space environment, a thermal vacuum test was conducted. The operation of generating plasma was conducted in a thermal vacuum chamber. Also, the radiation tolerances of the electrical components were verified for total ionic dozes and single-event effects. In PBI, a lot of COTS (Commercial Off-The-Shelf) products are used for reducing a cost, but we checked enough resistivity to the radiation for all electrical parts.

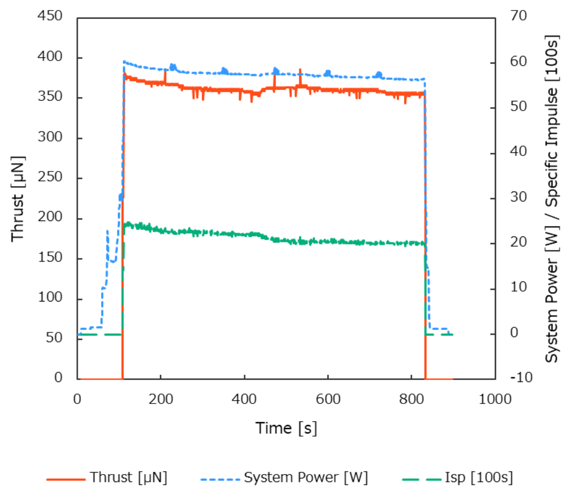

Figure 4 PBI operation test result on the ground. The temperature at the start point was 27 degrees of Celsius.

V. Conclusion

The 1U water ion thruster was developed and tested. It works using water as a propellant, and it has a thrust of 0.35 mN, a total impulse of 7000 Ns, and a power of 60 W. All components, including the tank, are contained within a 98 mm × 98 mm × 106 mm envelope. The electrical and software interfaces were kept simple, and the mechanical and thermal interfaces were well-defined for system design. The first flight model is to be demonstrated in 2025.

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