Preliminary Experimental Results of Surface Arc Thruster

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Abstract: Surface Arc Thruster is a micro thruster under development at Kyushu Institute of Technology, and it aims to be mounted on micro satellites. This thruster is electrothermal acceleration type, and sublimates Teflon which is a solid propellant by surface arc discharge, and thrust is generated by injecting the steam from the nozzle. As the main feature, a current regulative circuit is used to control the discharge current to several amperes. As a result, discharge current flows for several milliseconds, aiming at efficient propellant consumption. In this paper, I will explain the development of our Surface Arc Thruster and results of experiments.

Nomenclature

Q	=	flow rate
S	=	pumping speed
V_0	=	vacuum chamber capacity
$p(t)$	=	change amount of pressure
Δn	=	amount of substance
Δm	=	mass of vaporized gas
M	=	molecular weight
I_{bit}	=	impulse bit
M_{target}	=	target weight
g	=	gravitational acceleration
L	=	string length
x	=	target displacement

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I. Introduction

In recent years, the cost of micro satellites development is lower than that of large satellites, and it can be developed by universities and private companies, so the spread of micro satellites is progressing. As missions become more diverse in the future, attitude control and orbit change become necessary. Also, after missions, there is a possibility that micro satellites linger in the atmosphere and become debris. Therefore, to deal with these problems, it is necessary to develop thrusters that can be mounted on micro satellites.

At Kyushu Institute of Technology, A type of micro thruster called Surface Arc Thruster (SAT) has been developed in LaSEINE. This SAT is similar to pulsed plasma thruster (PPT), however, there are some differences. A current regulative circuit is employed in the system to control a surface arc discharge current constant. In the case of PPT, the discharge time duration is usually for several microseconds and the discharge current is several kilo amperes. On the other hand, the surface arc thruster has a discharge time of up to several tens of milliseconds and a discharge current of several amperes. By flowing current for a long time, generated vapor can be injected for a long time. In addition, since the discharge current is low, light and heat generated are reduced, and the loss of discharge energy can be reduced. Thus, it is considered that efficient propellant consumption and thrust improvement can be obtained. Surface Arc Thruster obtains thrust only by injecting sublimated vapor from the nozzle, so it is classified as electrothermal acceleration type. This thruster uses Teflon for solid propellant like PPT. This research purpose is a development of SAT that can be mounted on micro satellites.

II. Surface Arc Thruster

A. Principle of Surface Arc Thruster

The principle of thrust generation of Surface Arc Thruster is similar to PPT. A capacitor and a current regulative circuit are connected to the propulsion system. First, after charging the capacitor, discharge is caused by igniter, and a small amount of Teflon is vaporized (Fig 1(a)). As the gas spreads, short circuit between anode and cathode, and a surface arc discharge is formed. Thereafter, the discharge current flows through a current regulative circuit between the two electrodes, and Teflon is vaporized (Fig 1(b)). Then, thrust is obtained by injecting gas from a nozzle due to pressure increment in the plenum chamber (Fig 1(c)).

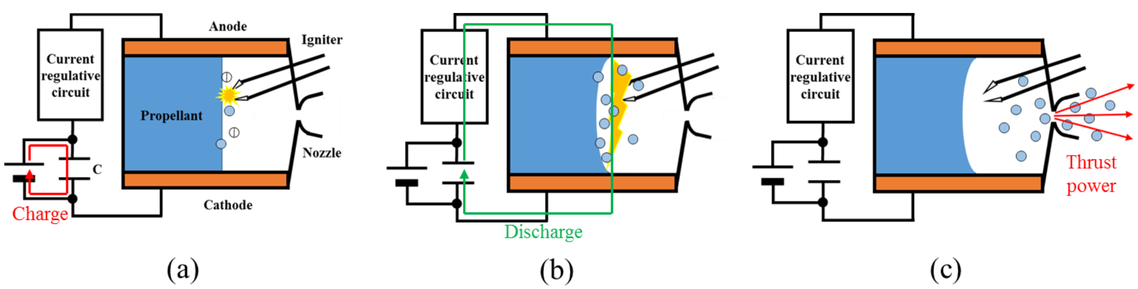


Figure 1. Principle of Surface Arc thruster

B. Current regulative circuit

The current regulative circuit to maintain constant discharge current is important to Surface Arc Thruster. There are two types of current regulative circuits. The first is a circuit using current regulative diodes(CRD) (Fig 2). In this circuit, more than one CRDs are connected in parallel (Fig 3) and it is possible to control the current from 1A to 5 A per 1A. This circuit was used for experiment of shooting discharge using a high-speed camera and measurement of impulse bit of thruster. However, there are problems with this circuit. The first problem is that withstanding voltage of the CRD is 100 V. Second problem is that the size of the circuit is large.

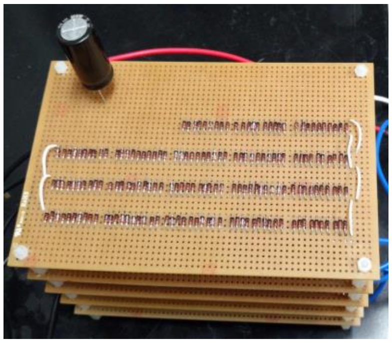


Figure 2. CRD current regulative circuit

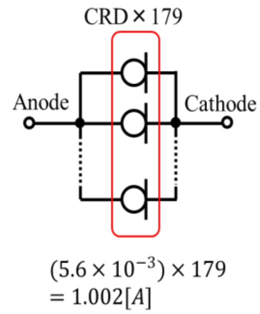


Figure 3. Parallel connecting of CRDs on 1 board

The second is a circuit using MOSFET (Fig 4). MOSFET is generally used for switching operation and the like, but by applying MOSFET, current regulative operation can be performed. This circuit can overcome two problems of current regulative circuit using CRD. The withstanding voltage of the employed MOSFET is 800 V. It is possible to finely set the current by adjusting a variable resistance in the circuit. Also, the circuit size can be reduced.

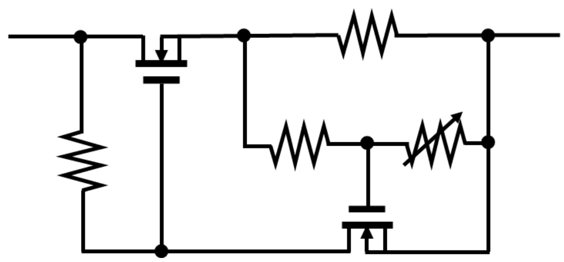


Figure 4. MOSFET current regulative circuit

III. Surface arc discharge generation condition

A CRD current regulative circuit and a thruster sample were used to investigate conditions of surface arc discharge generation. If current is smaller for maintaining surface arc discharge, the discharge duration will be longer, however it is considered that discharge cannot be sustained if the current is too small. Therefore, it is necessary to investigate the threshold at which the current is sustained. In this experiment, the thruster sample shown in Fig 5 was used. The discharge current was changed from 2 to 4 A, and the discharge duration was measured for each current value. Capacitor capacity, charging voltage and current values were set as Table 1. The experimental system is shown in Fig 6, and circuit configurations are basically same in each experiment.

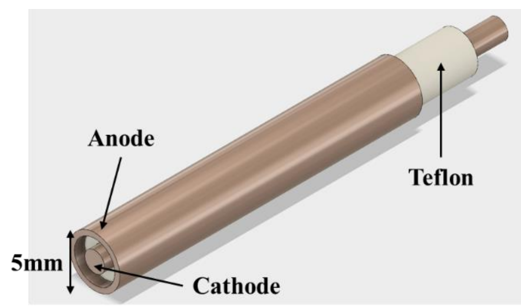


Figure 5. Thruster sample

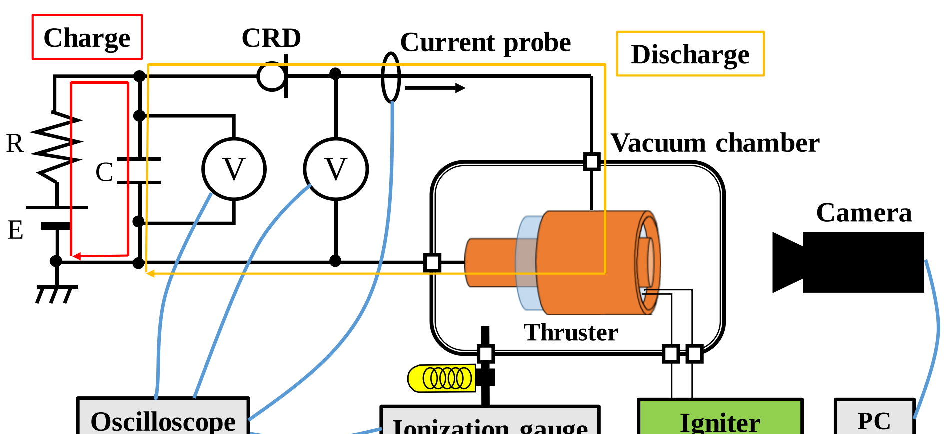
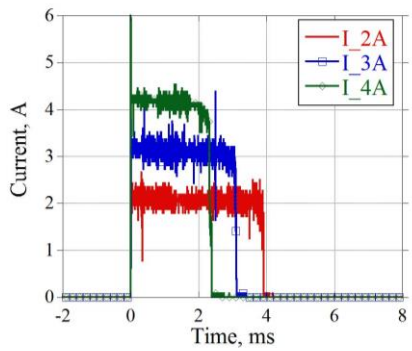


Figure 6. Experimental system

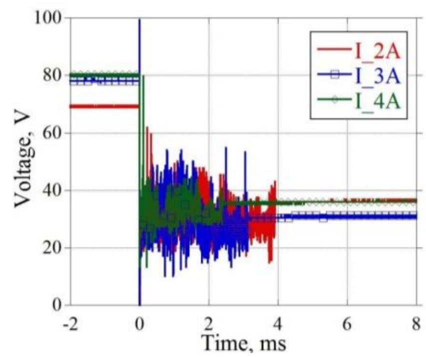
Table 1. Experiment setting of discharge generation condition

Capacitor capacity	Charging voltage	Current value
$220\mu F$	$84V$	$2 \sim 4A$

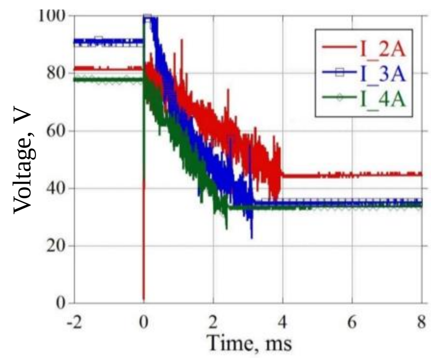
The measurement results are shown in Figs 7 and 8.



(a) Discharge current



(b) Discharge voltage



(c) Capacitor voltage

Figure 7. Discharge current and voltage and capacitor voltage

From Fig 7, as the discharge currents become larger, the duration of discharge becomes shorter. This is because a discharge time of capacitor becomes shorter by increasing current. So, maximum durations of discharge current are largely related to the discharge time of capacitor.

From the Fig 8, it can be confirmed that the durations are distributed around the average value when the discharge currents are 3A and 4A, but when it is 2A, the duration was greatly varied. Therefore, from this experiment, it is considered that the surface arc discharge persists relatively stably when the current is 3 A or more.

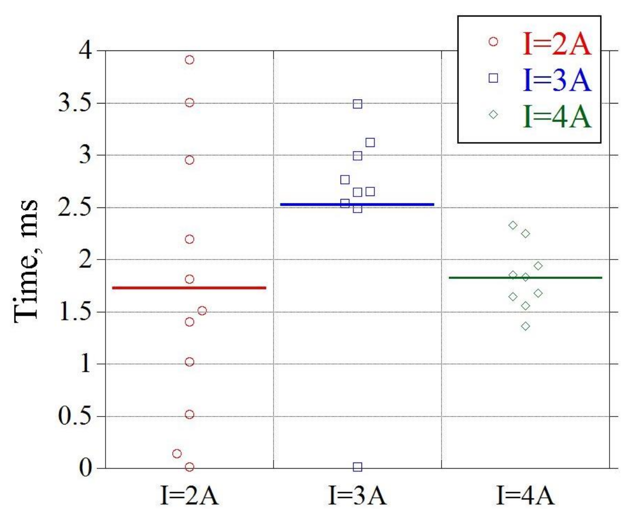


Figure 8. Discharge time

IV. Measurement of propellant mass vaporized by discharge

A mass of propellant vaporized by surface arc discharge was measured. The amount of the vaporized propellant can be obtained from the following calculation.

When gas flow rate is generated in the vacuum chamber and evacuated by a vacuum pump,

$$Q = V\frac{dp}{dt} + pS \quad (1)$$

The total amount of generated gas is

$$\int Qdt = (V_0 + St)p(t) \quad (2)$$

When the ideal gas state equation is applied, the amount of substance of the gas is

$$\Delta n = \frac{\int Qdt}{RT} = \frac{1}{RT}\{(V_0 + St)\,p(t)\} \quad (3)$$

When the molecular weight M is used, the mass of the vaporized gas is

$$\Delta m = \Delta n \times M \quad (4)$$

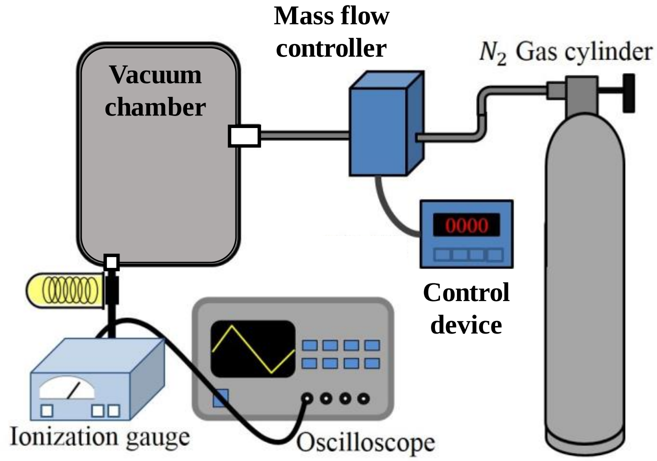


Figure 9. Measurement of vacuum chamber pumping speed

Before measurement of propellant mass, a pumping speed of vacuum chamber was measured (Fig 9). In the experiment, nitrogen was introduced into the vacuum chamber, and increasing amounts of flow rate and pressure at that time were measured to calculate the effective pumping speed. Experiments showed the effective pumping speed to be $S = 0.016[m^3/s]$. Next, an amount of vaporized propellant was measured. In the experiment, the current was measured at 3A and 4A, and a thruster sample in Fig 5 was used. A graph of Teflon vaporized amount is shown in Fig 10.

From Fig 10, an average amount of vaporized propellant was larger when the discharge current was 4A. However, in both cases there was a variation in the amount.

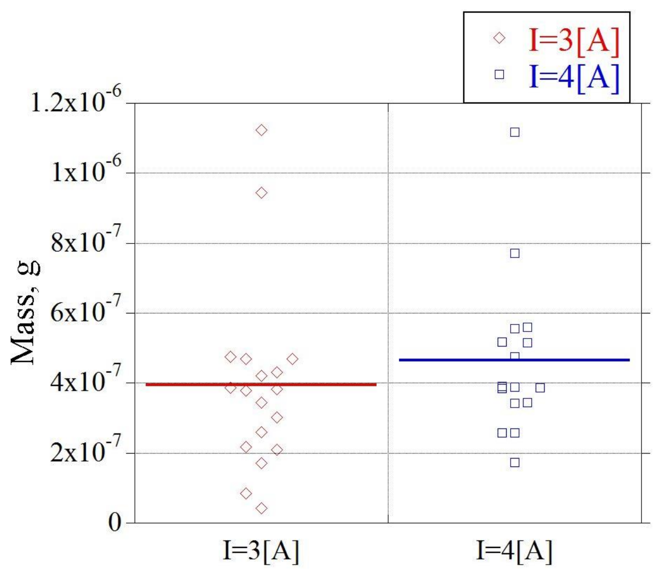


Figure 10. Amount of vaporized propellant

V. Capturing arc discharges with high-speed camera

In this experiment, two thruster samples of Figs. 5 and 11 were used, and a surface arc discharge occurring on each propellant surface was taken with a high-speed camera. Also, a CRD current regulative circuit was used.

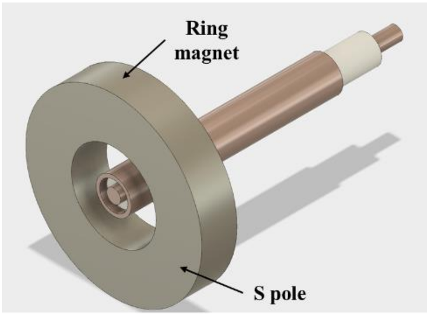


Figure 11. Thruster sample with ring magnet

For shooting discharge, the experiment was conducted with a nozzle of the thruster removed. The purpose of this experiment is to confirm the usefulness of ring magnet. A ring type magnet has a magnetic field as shown in Fig 12. When the ring magnet is installed around the thruster, a magnetic field is applied to the surface of the thruster in a certain direction because that is in the center of the magnet. If a surface arc discharge occurs between Anode and Cathode, a Lorentz force is applied to the discharge current and moves so as to rotate the propellant surface (Fig 13). As a result, energy can be uniformly applied to the entire propellant, so it is considered that the loss of one propellant can be eliminated and the efficiency of consumption can be raised.

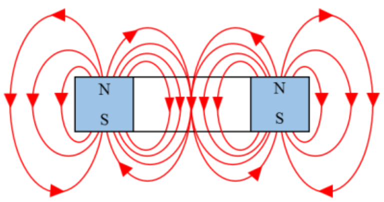


Figure 12. Magnetic field of ring magnet

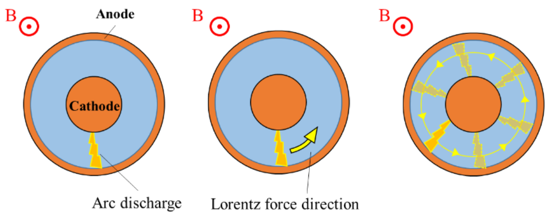


Figure 13. Arc discharge moving in magnetic field

In this experiment, voltage of a capacitor, discharge voltage, and discharge current were measured, and discharge image was acquired. Capacitor capacity, charging voltage and current values were set as follows (Table 2).

Table 2. shooting discharge experiment setting

Capacitor capacity	Charging voltage	Current value
$220\mu F$	$90V$	$3A$

The measurement result and the discharge image are shown below.

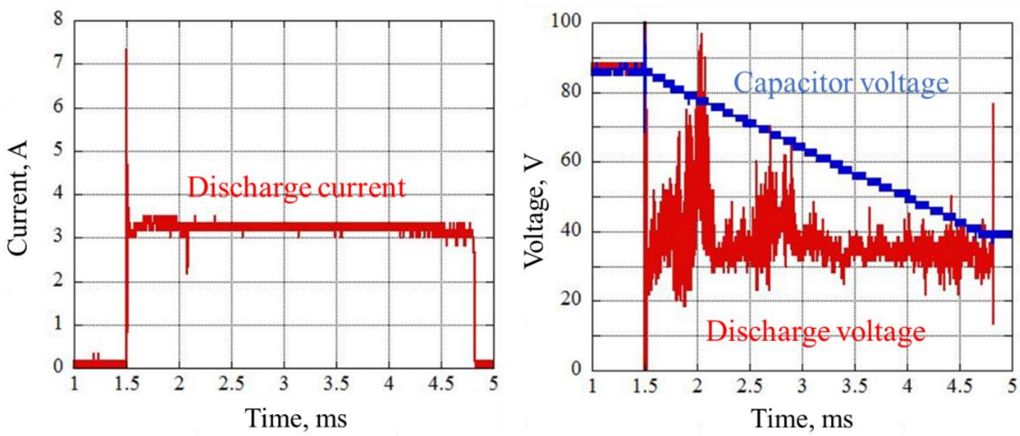


Figure 14. Discharge current and voltage and capacitor voltage in case of no magnet

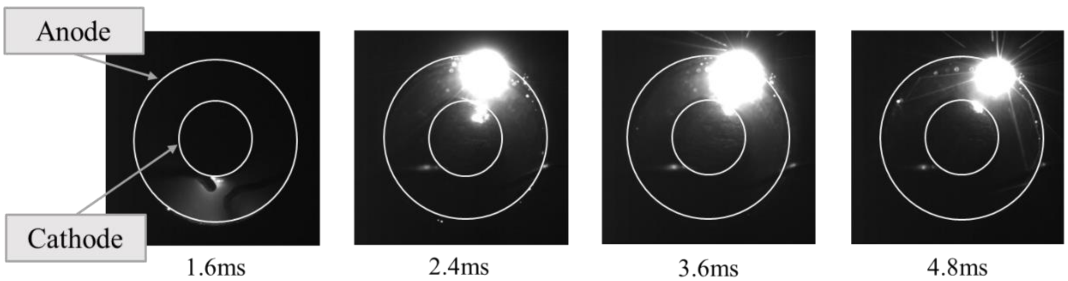


Figure 15. Discharge image in case of no magnet

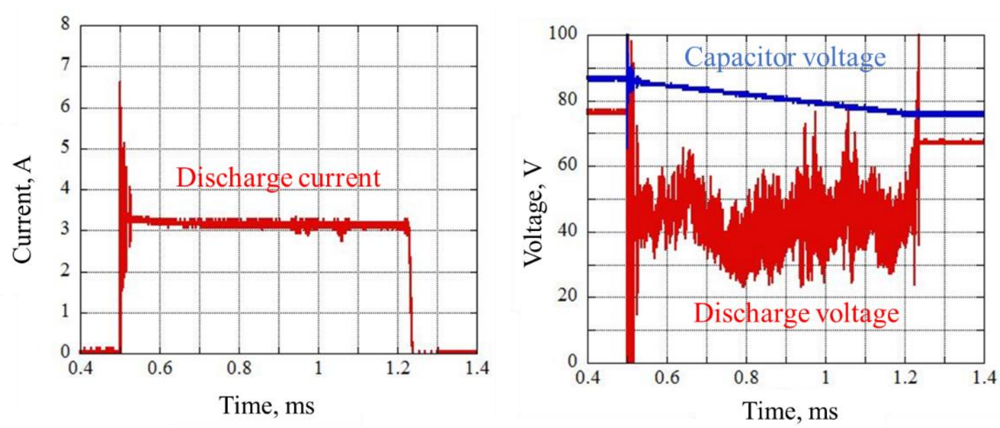


Figure 16. Discharge current and voltage with magnet

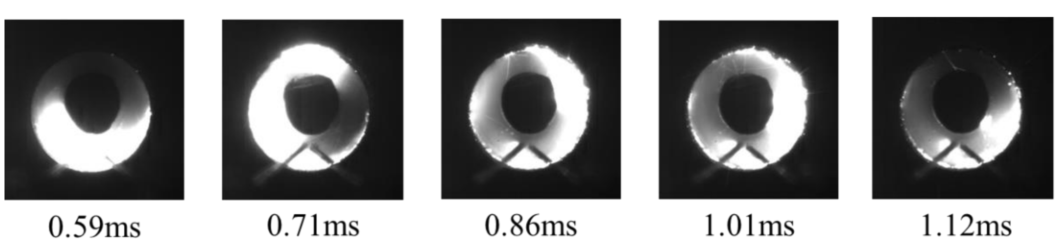


Figure 17. Discharge image with magnet

From Fig 17, it can be confirmed that the discharge is rotating and moving on a surface of propellant when a ring magnet is used. On the other hand, from Fig 15, the discharge did not move when the magnet was not used. Comparing the discharge duration, it was 3.2 ms when there was no magnet, and it was 0.6 ms when there was a magnet. Therefore, when a ring magnet was used, the duration was 1/5 as compared with that without a magnet. The cause is considered as follows. In the case of no magnet, it is thought that discharge continues at the shortest distance between anode and cathode, but in the case of setting a magnet, a force is applied in the rotating direction by the Lorentz force, so that the discharges are sustained while rotating between both electrodes. As a result, it is considered that it becomes difficult to sustain the discharge for a long time because the discharge path length becomes too long.

VI. Measurement of impulse bit

It is necessary to measure a impulse bit in order to confirm whether the surface arc thruster generates thrust power and operates as a thruster. To measure the thruster impulse bit, a measuring system was employed (Fig 18). This system measures the impulse bit by placing a thruster in front of a target of polyimide film suspended from the thread and measures the impulse bit by examining how much the target moved by thruster injection. The calculation method is as follows.

$$I_{bit} = M_{target}\sqrt{2g(L-\sqrt{L^2-x^2})} \quad (5)$$

The target specifications are as follows.

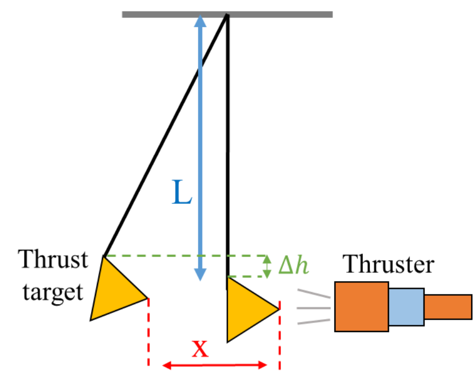


Fig 18. Measurement system of impulse bit

Table 3. Target specifications

Material	Polyimide
Weight [kg]	3.4×10^{-5}
Size D × H [mm]	25×12.5
L [mm]	110

For impulse bit measurement, the thruster sample of Fig 19 was used. It was attached to a thruster of Fig 5 with a nozzle. The nozzle diameter is 0.7 mm, and igniter was inserted with a minute hole in the surface of the nozzle cover. In this case, the impulse bit was measured only when there was no magnet.

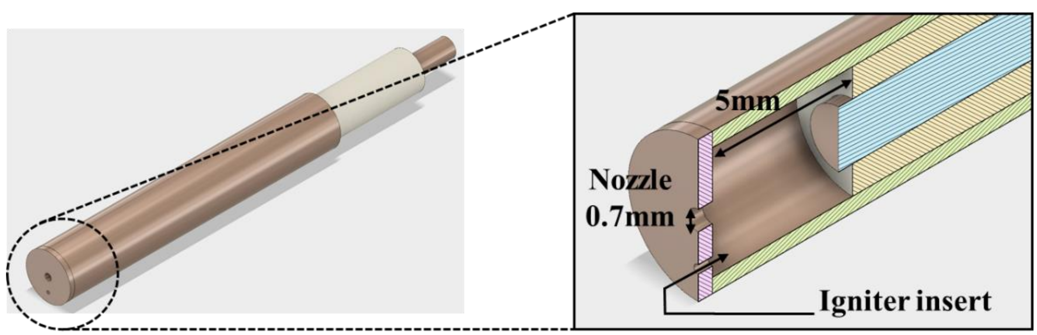


Figure 19. Thruster with nozzle

Capacitor capacity, charging voltage and current values were set as follows.

Table 4. Impulse bit measurement setting

Capacitor capacity	Charging voltage	Current value
$660\mu F$	$100V$	$5A$

The measurement results of discharge current, discharge voltage, capacitor voltage and thruster injection are shown below.

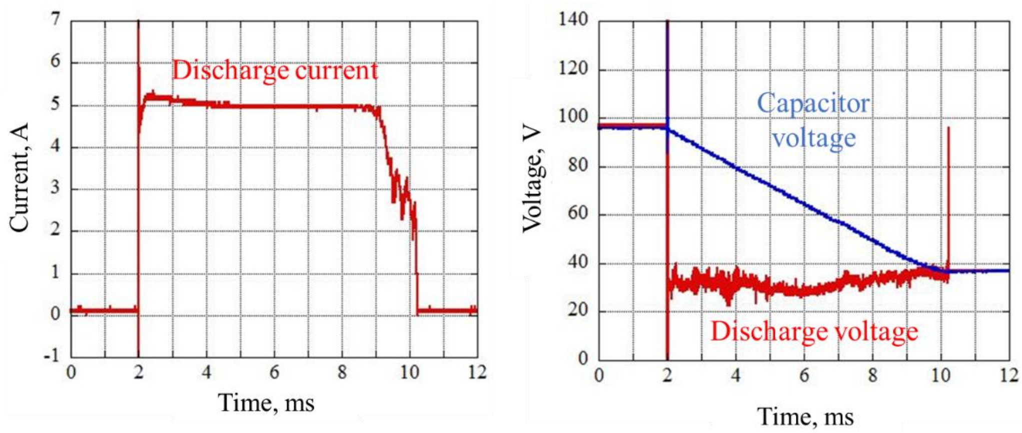


Figure 20. Discharge current and voltage and capacitor voltage on impulse bit measurement

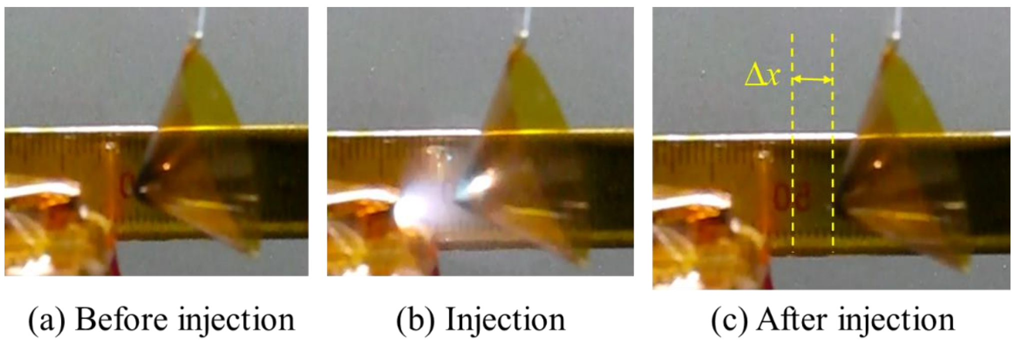


Figure 21. Thruster injection

From the experimental results, the moving distance of the target was $\Delta x = 5mm$. Therefore, from the above calculation equation, impulse bit of the thruster is

$$I_{bit} = M\sqrt{2g(L-\sqrt{L^2-x^2})} = 1.6\mu Ns \quad (2)$$

VII. Development of Surface Arc Thruster model

A model of Surface Arc Thruster assumed to be mounted on micro satellites was created as shown in Fig 22. There are two main points in this creation. The first is to reduce leak from the vapor generation space. Since Surface Arc Thruster obtains thrust by gas dynamic acceleration, leakage of the generated steam from a part other than a nozzle leads to a decrease in thrust. The second is to have a propellant supply mechanism. When the propellant is consumed, a steam generation space expands, so the internal pressure decreases and the thrust decreases. A model of Surface Arc Thruster created considering these problems is shown in Fig 22.

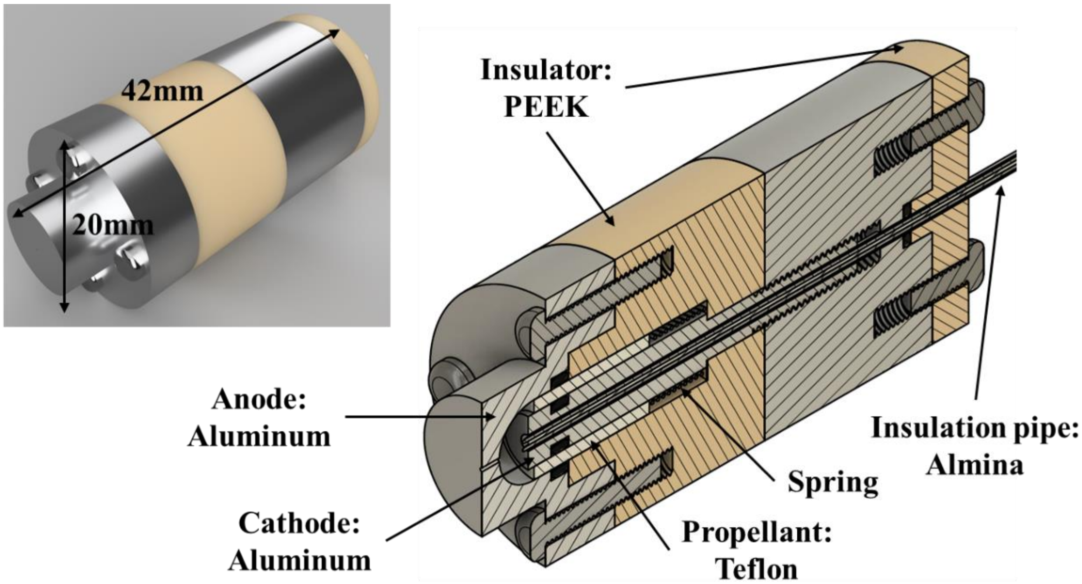


Figure 22. Model of Surface Arc Thruster

Fig 23 shows an enlarged view of the vicinity of the vapor generation space.

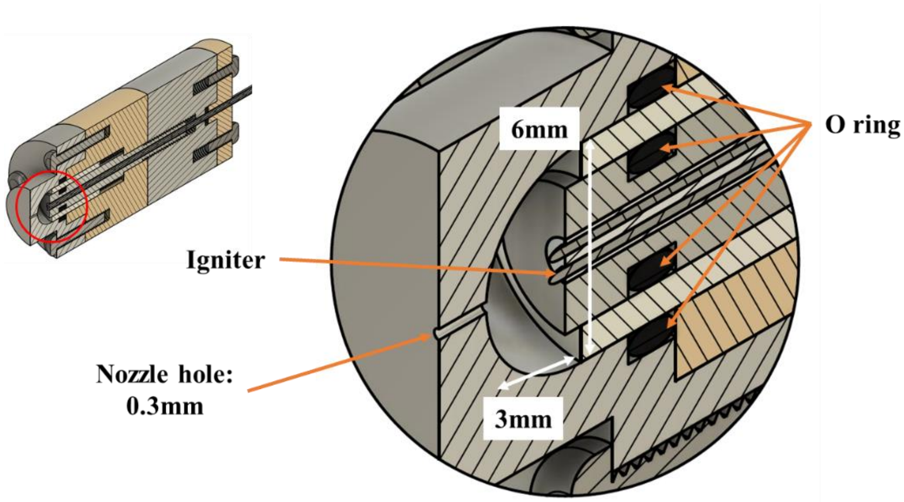


Figure 23. Enlarged view of vapor generation space

As shown in Fig 23, this thruster has a coaxial structure, and a cylindrical Teflon is sandwiched between anode and cathode. Also, inside of the cathode is inserted a two-hole type alumina insulation pipe through an igniter, and an initial discharge is generated here. By inserting O-rings between the cathode and the Teflon and between the anode and the Teflon, the generated steam does not leak backward. A spring is inserted in the rear part of the Teflon, and the spring can push Teflon to a predetermined position according to consumption of the propellant. Since the steam generation space has a structure like a hemisphere, the propellant is designed not to be extruded beyond curve portion. Since thruster has a length of 42 mm and a diameter of 20 mm, I think that it can be mounted on micro satellites.

VIII. Conclusion

As first experiments of Surface Arc Thruster development, discharge generation condition and amount of vaporized propellant by surface arc discharge were measured. From these experiments, it was confirmed that the propellant is vaporized even at a low current and the threshold of the current required for sustaining a discharge.

In an experiment of capturing discharges with a high-speed camera, we could confirm the appearance of surface arc discharge rotating and moving by a ring type magnet. From this, it seems that using a ring magnet is useful, so I would like to conduct an experiment on the operation of thruster with the magnet attached as the next step. In addition, although the thrust of Surface Arc Thruster could be confirmed by impulse bit measurement experiment, it was extremely small, so improvement is necessary. In the future, we will create Surface Arc Thruster and will conduct the injection experiment using MOSFET current regulative circuit explained at the beginning.

Reference

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