Evaluation of Pulsed Plasma Thruster Performance by Increase of Electric Power

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Abstract: **Research and development on pulsed plasma thruster (PPT) for small satellites have been conducting in Tokyo Metropolitan University. In this study, improvement of propulsive performance of coaxial PPT was conducted in order to apply it to propulsion systems for small satellite for not only attitude control but also orbit control or formation flight. As a result of changing the thruster dimension and input energy, total impulse of 266Ns and specific impulse of 490s was achieved with single propellant at continuous operation by 468,000 shots. In addition, in order to achieve a stable operation, the inductance of entire circuit was evaluated, and it confirmed that the energy density is one of the main parameters for the stable operation, but the dimensions and other configurations of the discharge chamber may affect that.**

Nomenclature

ΔV	=	velocity increment
I_b	=	impulse bit
I_{sp}	=	specific impulse
Δm	=	mass shot
η_t	=	thrust efficiency
$m_{initial}$	=	initial mass of propellant
m_{end}	=	final mass of propellant
g	=	gravity acceleration
E_0	=	input energy
L_{cav}	=	cavity length
D_{cav}	=	cavity diameter
E/S	=	energy density; ratio of input energy to propellant ablation surface

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I. Introduction

SMALL satellites have been developing in the resent space activities because of its high cost performance, short development period and utilization of advanced technologies. For more development of small satellite, compact, lightweight and highly functional propulsion devices are required. Pulsed Plasma Thruster (PPT) is one of the electric propulsion devices, which is expected to be applied for small satellites because of the following three characteristics:

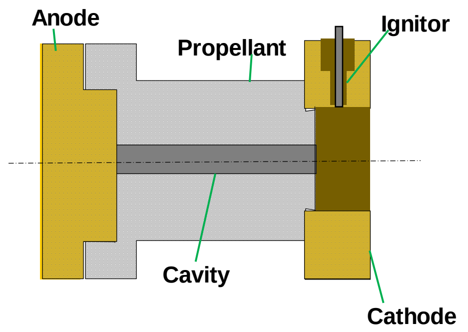
1) Simplicity; PPT system has a simple and lightweight structure, and high durability because it does not need any tanks, seals and mechanical valves by using a solid propellant such as poly-tetrafluoroethylene (PTFE).
2) Precise total impulse; PPT can offer the precise total impulse easily because it generates accurate and small pulse-thrust at optional time interval.
3) Low power consumption; PPT can operate at several watts.

In Tokyo Metropolitan University (TMU), research and development on two types of PPT for small satellites have been conducted. One is rectangular PPT, the other is coaxial PPT.

Rectangular PPT consists of parallel plate electrodes, rectangular propellant, and ignitor. The operation principle of rectangular PPT is as follows: first, the short-circuited between electrodes is created because the solid propellant PTFE is ablated by ignition energy. After that, ablated plasma is ejected by mainly an electromagnetic accelerating force which is induced by Lorentz force. This type of PPT has low impulse bit and high specific impulse. PPT-B20[1-4] (Engineering Model of parallel plate PPT in TMU) is a typical rectangular PPT. This model is passed many performance tests such as the thermal vacuum test and the vibration test, and it has achieved the small impulse bit of 22μNs with the high specific impulse of 960s. The power consumption of the system is only 4.2W at 0.75Hz operation frequency and it has achieved a million shot operations continuously. Recently, the missions for small satellites have a wide variety. PPT-B20 is appropriate to the missions that demand a precise total impulse with a long lifetime, such as attitude control and vibration control. However, its impulse bit is too small to comply with the missions that demand a high ΔV such as station keeping and an orbit transfer.

On the other hand, coaxial PPT with cylindrical cavity propellant has achieved larger impulse bit and lower specific impulse compared with the rectangular PPT such as PPT-B20 at the same stored energy. It will be required to comply with the missions that demand a high ΔV in time. Coaxial PPT consists of four parts as shown in Fig. 1: cylindrical anode, cylindrical cathode with orifice, ignitor, and hollow propellant. Main discharge current passes and evaporates the cylindrical cavity of the propellant and neutral propellant/plasma is ejected from an orifice of the cathode by electrothermal force mainly. One of the important characteristics of coaxial PPT is that the inner diameter of propellant will expand gradually through repetitive operation. Then thrust performances will vary with its diameter. The typical impulse bit history of coaxial PPT with single thruster head is shown in Fig. 2. Therefore, we developed the propellant feed mechanism named Disk Feed (DF) system[5,6] and attempted a repetitive operation test with eight propellants. As a result, approximately 480,000 shots was achieved and total impulse of 160Ns was obtained by input power of 10W.

The combination of rectangular PPT and coaxial PPT will enable to achieve various missions. However, total impulse is not enough to orbit control or station keeping. Then, in order to improve the total propulsive performance and to increase the total impulse of coaxial PPT, this study was carried out. One methods of increase the total impulse is the increase of the input energy and the ablation surface of propellant.



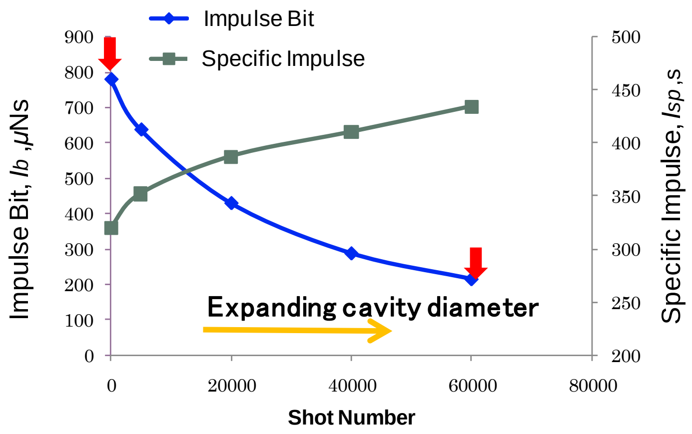


Figure 1. Conceptual diagram of coaxial PPT. **Figure 2. Impulse bit history of coaxial PPT with single thruster.**

Ⅱ. Objectives

The objective of this study is to evaluate and demonstrate the propulsive performance of PPT that can achieve the role for not only the reaction control but also the orbit control by the change of input energy. Therefore, four experiments, for the evaluation of the relation between input energy and thruster performance, were conducted.

Ⅲ. Experimental Apparatus

Figure 3 shows the experimental configuration of PPT operation. All experiments were conducted in a vacuum chamber, and its pressure was kept at approximately 6×10^{-3}Pa. The power supplies for main electrical discharge is attached to the capacitor bank out of the vacuum chamber, and a power-processing unit (PPU) and ground support equipment (GSE) are used as the power supply for ignitor. The measurement items are as follows: impulse bit, mass shot, specific impulse, current and voltage waveform, shot number, and propulsion efficiency. Impulse bit is measured by the target pendulum located at the exit of PPT plume. The slight displacement of the target was measured by the CCD laser displacement sensor, which is mounted backward of the pendulum, and the signal was monitored and recorded by the oscilloscope. Current and voltage waveform were measured by Rogowski coil and high voltage probe, respectively. Shot number is measured by photo diode shot counter (device that sense the optical radiation of the PPT plume). Mass shot is defined as the average of mass consumption by single operation. After that, specific impulse and propulsion efficiency are calculated by the following expressions[7].

$$\Delta m = \frac{m_{initial} - m_{end}}{shotnumber} \quad \cdots (1)$$

$$I_{sp} = \frac{I_b}{\Delta m \cdot g} \quad \cdots (2)$$

$$\eta_t = \frac{{I_b}^2}{2\Delta m \cdot E_0} \quad \cdots (3)$$

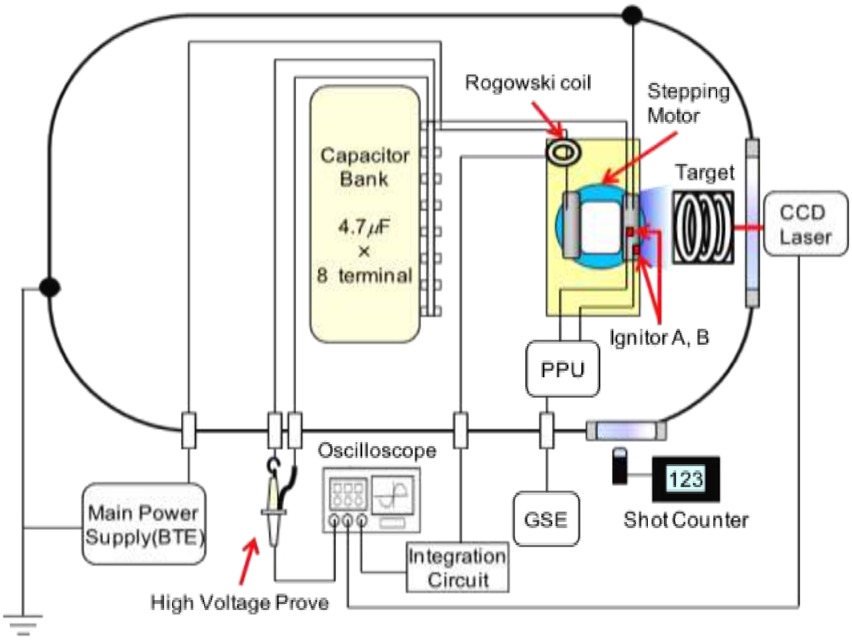


Figure 3. Experimental configuration of PPT.

Ⅳ. Experimental Methods

Each experiment is named from No.1 to No.4 as shown in Table 1, and the outline of experimental condition is shown in Table 2. Since operation frequency is 1 Hz, the value of input power is equal to that of input energy. In Tables 1 and 2, "high energy" indicates from 25J to 75J, and "ϕ" indicates the cathode inside diameter. In addition, the energy density is that the ratio of input energy to propellant ablation surface. Details of each experiment are described in the next section.

Table 1. The number corresponds to each experiment.

Number	Title of the experiment
No.1	High energy (25J, 50J, and 75J) at ϕ12mm coaxial PPT.
No.2	High energy (50J and 75J) at ϕ50mm coaxial PPT.
No.3	Continuous operation test at ϕ50mm coaxial PPT.
No.4	Effect of inductance in high energy (50J) at rectangular PPT.

Table 2. Outline of experimental conditions.

Number	Input Energy, J	Initial Cavity Diameter, mm	Cavity Length, mm	Energy Density, J/cm^2	Frequency, Hz
No.1	25, 50, 75	3, 5, 10	30, 50, 70	1.14～26.5	1
No.2	50, 75	15, 20, 25, 30, 35, 40, 45	50, 70	0.51～3.18	
No.3	75	3	50	26.5	
No.4	10, 50	-	-	1.25 , 6.25	

4-1. High energy at ϕ12mm coaxial PPT (No.1)

In order to evaluate the performance and confirm the tendency, input energy, cavity diameter D_{cav}, and the cavity length L_{cav} were changed respectively one by one and it evaluated. The experimental conditions and the schematic diagram of coaxial PPT are shown in Table 3 and Fig. 4, respectively. In each input energy, cavity diameter and cavity length are changed, and the propulsive performance was evaluated. The material of electrodes is molybdenum because it has high melting point and being about the low erosion and contamination.

Table 3. Experimental condition of high energy at ϕ12mm coaxial PPT.

Input Energy, J	25	50	75
Input Voltage, kV	1.88	1.88	2.15
Capacitance, μF	14.1	28.2	32.9
Ignition Voltage, kV	1.8		
Cavity Length, L_{cav} , mm	30, 50, 70		
Cavity Diameter, D_{cav} , mm	3, 5, 10		
Operation Frequency, Hz	1		
Shot Number, times	500		

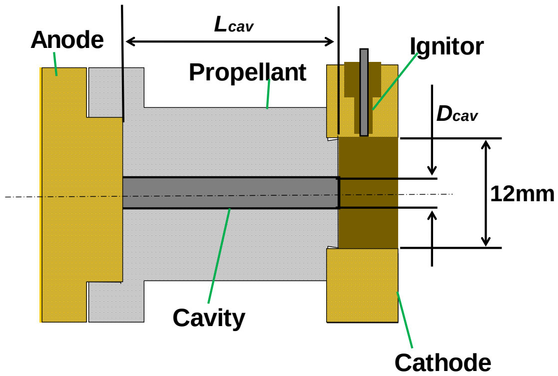


Figure4. Schematic diagram of ϕ12mm coaxial PPT.

4-2. High energy at ϕ50mm coaxial PPT (No.2)

The thruster was enlarged to understand the operation limit (end of life) and to see the overall performance based on the result of the experiment of No.1. The thruster dimension was changed from ϕ12mm to ϕ50mm in the cathode inside diameter, and in order to clarify the influence of the cavity diameter D_{cav}, the initial cavity diameters are changed from 15 to 45 mm at 5mm intervals. This experimental condition and schematic diagram of ϕ50mm coaxial PPT are shown in Table 4 and Fig. 5, respectively.

Table 4. Experimental condition of ϕ50mm coaxial PPT.

Input Energy, J	50	75
Input Voltage , kV	1.65	2.05
Capacitance , μF	35.4	
Ignition Voltage , kV	1.8	
Cavity Length, L_{cav} , mm	50, 70	
Cavity Diameter , D_{cav} , mm	15, 20, 25, 30, 35, 40, 45	
Operation Frequency, Hz	1	
Shot Number, times	1,000	

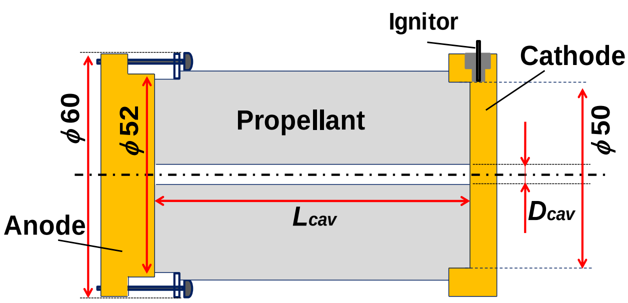


Figure 5. Schematic diagram of ϕ50mm coaxial PPT.

4-3. Continuous operation test at ϕ50mm coaxial PPT (No.3)

The propulsive performance of coaxial PPT in high energy was predicted from the results of an experiment of No.1 and No.2. The temporal variations of the impulse bit and the mass shot along the operation were estimated and calculated. However, because various factors are superposed in actual operation, it is necessary to conduct the actual continuous operation test. Experimental condition is shown in Table 5 and thruster configuration is the same as experiment of No.2 (Fig. 5). In this experiment, because the performance change was large, the first 100,000 shots measured the propulsive performance every 1000 shots, and measured the following every 10,000 shots.

Table 5. Experimental condition of continuous operation test at ϕ50mm coaxial PPT.

Input Energy, J	75
Capacitance, μF	34.1
Input Voltage, kV	2.1
Operation Frequency, Hz	1
Initial Cavity Diameter, D_{cav}, mm	3
Cavity Length, L_{cav}, mm	50
Shot Number, times	1,000,000 (Target)

4-4. Effect of inductance in high energy at rectangular PPT (No.4)

Experiment of coaxial PPT at high energy (No.1 to No.3) and experiment of rectangular PPT at high energy were conducted on parallel, and a large amount of charring was observed from the result of the rectangular PPT experiment. It is well known that one of the causes of the charring is the effect of inductance in the entire electrical circuit of the PPT system. Therefore, in order to establish the conditions that the PPT operates without charring at high energy, influence of the inductance was investigated at each experimental condition as shown in Table 6. There are the combination by the change of the capacitor and change of the electric wire (between PPT and capacitor), and the electric wire length kept the shortest in each experimental conditions. The thruster configuration is shown in Fig. 6. In each experiment, the amount of operation is 10,000 shots. Moreover, two kinds of electric wires are applied, which are a single core electric wire and a coaxial electric wire. The inductance of the entire circuit was evaluated including length of the electric wire and residual inductance of each capacitor, and the relation for the charring was examined.

Table 6. Experimental condition of rectangular PPT.

	Wire Length, mm	Wire shape	Capacitance, μF	Capacitor	Energy, J	Energy Density, E/S, J/cm^2
Case. 1	800*2	Single	28.2	Cap.A	50	6.25
Case. 2	300*2	Single	36.3	Cap.A	50	6.25
Case. 3	300*2	Single	5.1	Cap.B	10	1.25
Case. 4	400*2	Coaxial	36.3	Cap.A	50	6.25
Case. 5	400*2	Coaxial	5.1	Cap.B	10	1.25

Cap.A: Plastic Film Capacitor Bank (Inductance: 120nH)
Cap.B: Mica Paper Capacitor (Inductance: 30nH)

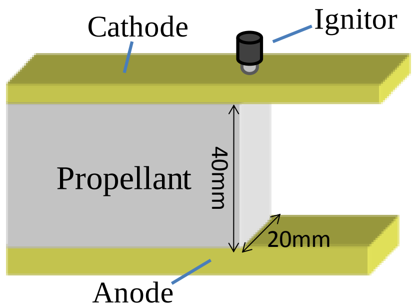


Figure 6. Schematic diagram of rectangular PPT.

Ⅴ. Results and Discussions

5-1. High energy at ϕ12mm coaxial PPT (No.1)

The result of impulse bit vs. energy density is shown in Fig. 7. The white plot is result of previous study at 28J. It is considered that the impulse bit and the energy density are in the proportion. It was confirmed that this is similar to the tendency of low energy PPT from 3J to 10J.[8] In addition, when the cavity length L_{cav} increased, the increasing rate of the impulse bit to the energy density also grows. Moreover, the impulse bit of 6.4mNs was achieved, which is four times or more compared with the maximum value in the previous study[8]. Furthermore, the change of the specific impulse is little, the maximum value is 591s and this is almost the same in the previous study at low energy.[8]

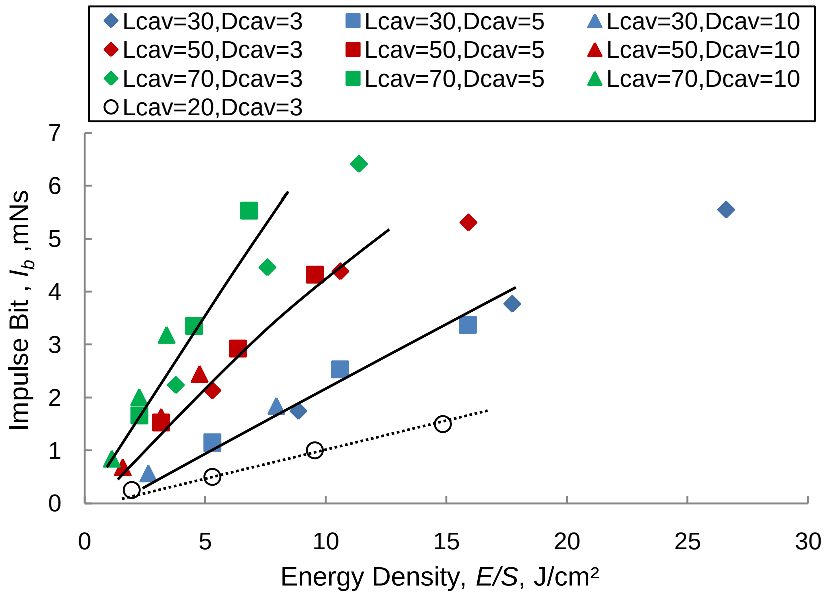


Figure 7. Impulse bit vs. Ratio of input energy to propellant ablation surface.

5-2. High energy at ϕ50mm coaxial PPT (No.2)

Figure 8 shows the relation between the impulse bit and the cavity diameter D_{cav}. Both impulse bits which cavity length L_{cav} is 50mm or 70mm, are nearly same. Thus, it is confirmed that the impulse bit does not depend on the cavity length and it is constant during the mid-term operation (the cavity diameter is 15mm or more), though the impulse bit had the relation with the cavity diameter in the beginning of the operation (the cavity diameter is from 3mm to 10mm). Moreover, Fig. 9 shows the relation between the specific impulse and the cavity diameter, and it is confirmed that the specific impulse increases as the cavity diameter increases though there were a few gaps because of expansion of the cavity diameter. It is difficult to ablate equally when the propellant ablation surface is expanded.

In our previous study, it was considered that energy density of 0.93J/cm^2 or more is the threshold value for its stable operation[9]. On the other hand, in the case of coaxial PPT, repetitive operation was succeeded with the energy density of 0.51J/cm^2 or less (the case of E_0=50J, D_{cav}=45mm, L_{cav}=70mm at ϕ50mm coaxial PPT, as shown in Table 2), in this study. It is clear that the boundary of the stable operation changed according to the thruster configuration, and did not take a constant value of the energy density obtained from the previous research.

A wide propulsive performance achieved from a result of No.1 experiment and No.2 experiment are shown in Fig. 10, and this includes the results of the previous study in TMU[4,8,10-11]. The triangle mark plots are the result of this study.

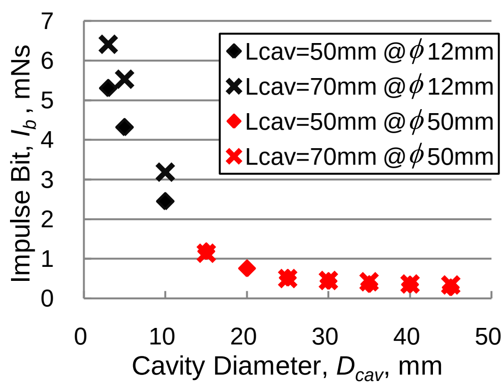


Figure 8. Impulse bit vs. cavity diameter.

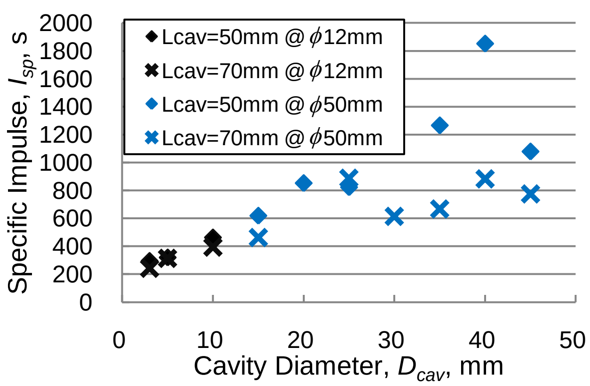


Figure 9. Specific impulse vs. cavity diameter.

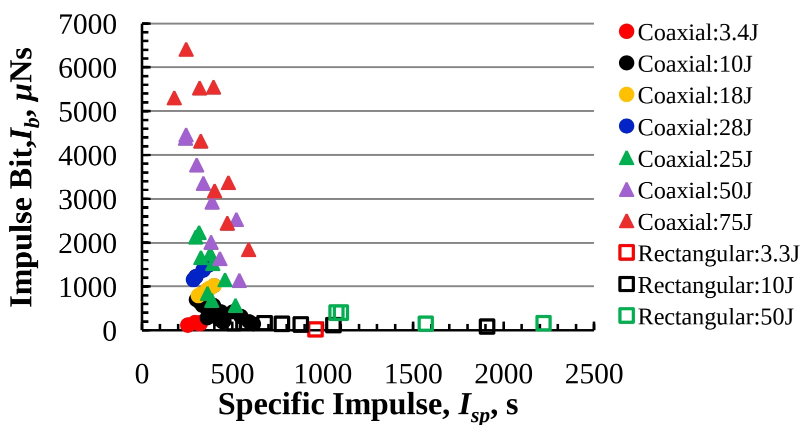


Figure 10. Thrust performances on PPT in TMU.

5-3. Continuous operation test at ϕ50mm coaxial PPT (No.3)

A history of impulse bit measured during the experiment of No.3 is plotted in Fig. 11 with the predictive curve. At the beginning, 4.66mNs of the impulse bit was obtained, and at the 468,000 pulse operations, 0.57mNs of the average impulse bit, and during the whole experiment, 266Ns of the total impulse and 490 s of the average specific impulse were obtained. Compared with the predictive curve, 67 % of the average impulse bit and total impulse, and 54 % of the specific impulse had been achieved. Through the propulsive performance of 80 % or more of the predictive value was achieved up to 120,000 shots, it became 60 % or less of the predictive value since 130,000 shots, and the operation terminated at 468,000 shot.

The cause of this propulsive performance deterioration is chiefly due to the capacitor malfunction, and details are described as follows. Figure 12 shows the history of accumulated shot number in the experiment of No.3. There are some periods when the operation is interrupted intentionally (red plots) in order to check the on-off cycle. There were some troubles around 100,000 shots because the insulation countermeasure was insufficient and electrical short-circuit was occurred in the PPT circuit. For this reason, more secure insulation management was applied and after that, it brought successive operation without any trouble after 100,000 shots. In addition, the capacitance of the capacitor had decreased from 34.1 μF to 23.4 μF when the capacitance was measured when the experiment of No.3 was finished. Then, it is thought that the impulse bit decreased because the capacitance of the capacitor decreases by the short-circuit of the capacitor twice or more times, and the input energy also decreases along with it. Figure 13 shows the photos of the propellant surface before and after the operation. Charring had appeared gradually from the early period and spread to the propellant surface. There were mainly two reasons of operation termination at 468,000 shots. One is the shortage of the energy density due to low input energy, and the other is a remarkable charring at the propellant surface which interrupts the electrical discharge. One of the solutions for the reduction of the charring is to adapt lower inductance of electric circuit. Then, higher average thrust performance will be obtained when the performance of the capacitor bank would be preserved without incident.

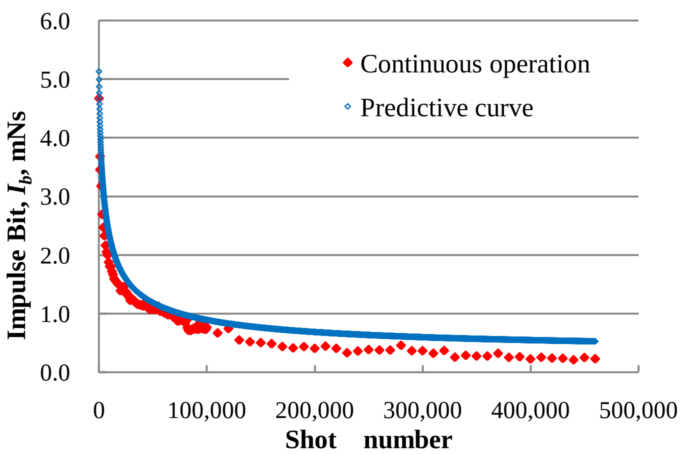


Figure11. A history of impulse bit and predictive curve calculated by the result of No.1 and No.2 experiments.

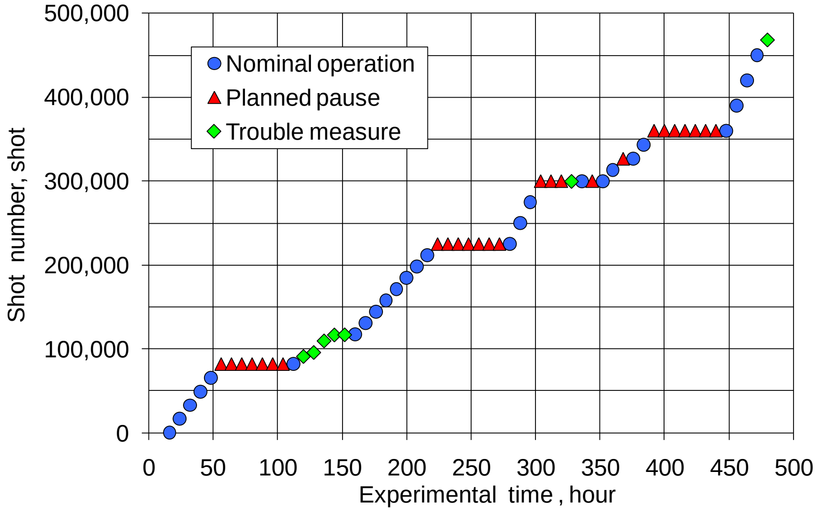


Figure 12. A history of accumulated shot number.

(a) Before operation **(b) After 468,000 shots**

Figure 13. Photograph of propellant surfaces before and after No.3 experiment.

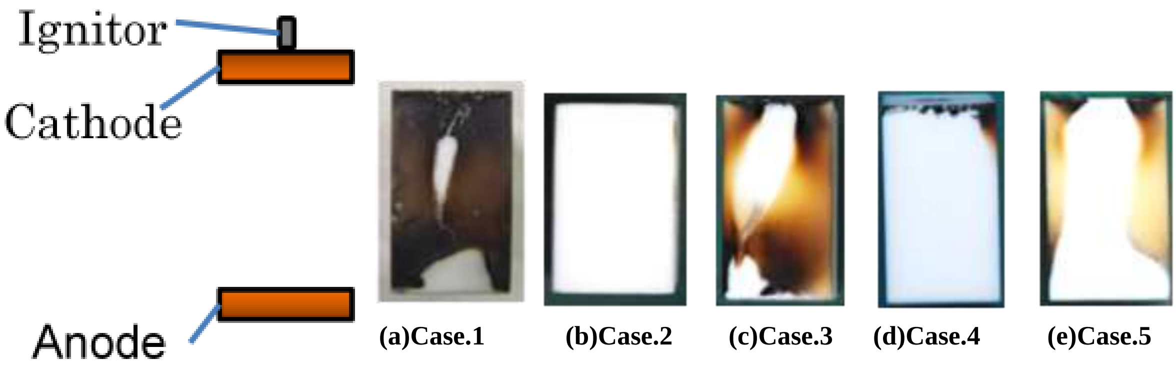
5-4. Effect of inductance in high energy at rectangular PPT (No.4)

Table.7 and Fig. 14 shows the result of No.4 experiment and the photographs of each propellant ablation surface. The inductance of a coaxial wire is 54nH/m, and that of the single core wire is 146nH/m, so total inductance is decreased by use of a coaxial wire, and this is confirmed in the result of Case.2 and Case.4 experiment. Moreover, it becomes more remarkable difference in the low energy region compared with Case.3 and Case.5. In addition, the energy density of Case.3 and Case.5 was the lowest in this experiment, but the energy density is 1.25J/cm^2 and it is more than 0.93J/cm^2 that was the threshold value for the stable operation. However, charring was generated as a result in Case.3 and Case.5, and the stable operation that does not generate the charring was not carried out. On the other hand, all experiments were operated without suspension, and at the Case.2 and Case.4 experiment, the stable operation was accomplished without the generation of a lot of charring. Therefore, it confirmed that the energy density is one of the main parameters for the stable operation, but the dimensions and other configurations of the discharge chamber may affect that.

Table 7. Experimental results of No.4 experiment.

	Case.1	Case.2	Case.3	Case.4	Case.5
Input Energy, J	50	50	10	50	10
Capacitor	Cap. A	Cap. A	Cap. B	Cap. A	Cap. B
Wire Configuration	Single	Single	Single	Coaxial	Coaxial
Wire Length, mm	800*2	300*2	300*2	400*2	400*2
Energy Density, E/S, J/cm^2	6.25	6.25	1.25	6.25	1.25
Impulse Bit, I_b, μNs	283	406	161	402	151
Specific Impulse, I_{sp}, s	2645	1076	2221	1101	1570
Mass shot, μg/shot	10.9	38.5	7.39	37.3	9.78
Total Inductance, nH	1060	340	510	310	330

Cap.A: Plastic Film Capacitor Bank (Inductance: 120nH)
Cap.B: Mica Paper Capacitor (Inductance: 30nH)



(a)Case.1 (b)Case.2 (c)Case.3 (d)Case.4 (e)Case.5

Figure 14. Photographs of propellant ablation surfaces after 10,000shots viewed from the front.

Conclusions

Performance evaluation of the PPT of high input energy was investigated. The influence of the cavity diameter was clarified and new insights on the relationship between the energy density and performance were found as follows.

(1) The impulse bit and the energy density tend to the definite proportion as well as the case of low energy. Moreover, when the cavity length increases, the increasing rate of the impulse bit to the increase of the energy density also grows.

(2) Impulse bit of 6.4mNs was achieved with single thruster of coaxial PPT with 75J, and this is four times or more compared with the maximum value in the previous study.

(3) When the cavity diameter enlarges over 15mm, it was confirmed that the impulse bit kept nearly constant regardless of the cavity length increase, although the specific impulse increased in proportion with the cavity diameter by ϕ50mm coaxial PPT.

(4) Through the 468,000 shots of pulse operations, 0.57mNs of average impulse bit, 266Ns of the total impulse and 490s of the average specific impulse were obtained by ϕ50mm coaxial PPT with 75J.

(5) Because of a capacitor's trouble and a remarkable charring of the propellant ablation surface, continuous operation test of coaxial PPT with 75J was suspended at 468,000 shots.

(6) Both a coaxial PPT and a rectangular PPT, the threshold value of the energy density for the steady operation, varies by the conditions such as the thruster dimensions and the whole PPT system.

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