Pulsed Plasma Acceleration Using Powdered Propellant

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Pulsed plasma thrusters (PPTs) are the simplest electric acceleration devices with solid propellant on satellites. In order to make their thrust performance higher and to feed propellant more effectively, we have been developing a new type PPT using powdered propellant. To estimate its thrust performance, we have made a test model thruster for comparing the thrust performances of PPTs with solid propellant and powdered propellant. And we measured their impulse bits and propellant consumptions using "Thrust Mass Balance" we made. As a result, it was revealed that a PPT using powdered propellant showed as high thrust performance as a PPT using solid propellant in the case that propellant surface was formed enough uniformly.

Keywords: Electric Propulsion, Pulsed Plasma Thruster, Powdered Propellant, Thrust Measurement, Thrust Mass Balance.

1. Introduction

Pulsed plasma thrusters (PPTs) have been studied for long years. Because of their simplicity, solid propellants are used popularly on satellites. Figure 1 shows the schematic diagram of a parallel-plate PPT with solid propellant. PTFE (Poly-Tetra-Fluoro-Ethylene) is known as the most adequate solid material for the propellant of PPTs with which the highest thrust efficiency can be obtained.

In these years, many researchers are studying about propellant feed system. The simplest is shown in Fig. 1, pushing propellant with springs. This system is simple and robust, but includes a certain restriction of thruster configuration. Another feed system is called "side-fed," with which two or more propellant bars are pushed from all sides. Even when using this feed system, some restriction on thruster configuration exists.

In order to overcome such propellant feed problems, other researchers have researched about PPTs with fluid (liquid or gas) propellants [1] [2]. Some of them showed very high thrust efficiency, but very high repetition frequency was needed for high performance because of influence of exhausted gas without ionization. So there remained a problem of high power consumption. Another problem is complexity of the systems. All of them need pressure control system or temperature control system. As simplicity is one of the advantages of PPTs with solid propellant, mechanical complexity is not good.

Another type of PPT is coaxial type. Figure 2 shows the electrode configuration of a coaxial PPT. As you see in this figure, this type of PPT is not an electromagnetic accelerator. So this type shows different thrust performance from parallel-plate PPTs, low specific impulse and high

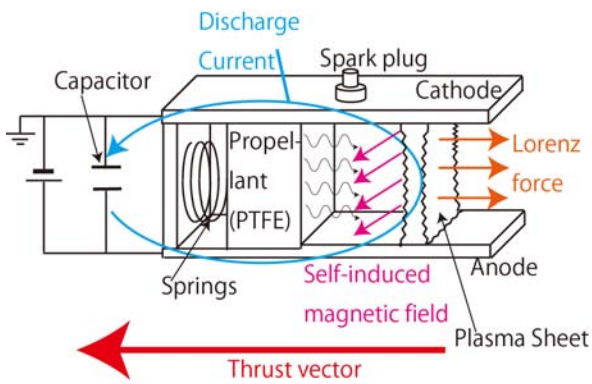

Fig.1 Schematic diagram of a parallel-plate pulsed plasma thruster with solid propellant.

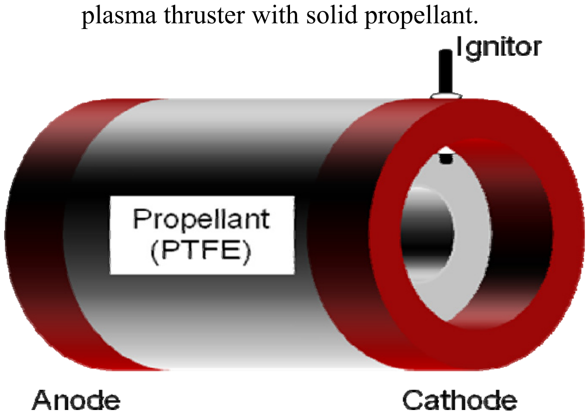

Fig.2 Electrode configuration of a coaxial PPT.

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thrust. The most significant character of this type PPT is that thrust performance changes as propellant is consumed gradually. With this type of thruster, Mukai et al. have developed propellant feed system that changes propellant block to increase the total impulse [3].

2. Powdered Propellant Pulsed Plasma Thruster

To solve both of above problems, we are developing a PPT with powdered propellant (PTFE powder). Powder sometimes behaves as fluid material with sufficiently small particle diameter, but it does not need any pressure control system or temperature control system. Our purpose is to make propellant feed easier with the least complexity.

Figure 3 shows a conceptual diagram of a PPT with powdered propellant. In this figure, powdered propellant is provided from left side and fed to the acceleration position (between electrodes) uniformly by rotating the insulator roller.

Although in this figure parallel plate electrodes are drawn, there is some possibility of applying this technology to coaxial-like one. If this is achieved, it should be a coaxial-like PPT without performance change.

3. Test Model Thruster

We made a test model thruster for examining the characteristics of a powdered propellant PPT and comparing with a solid propellant PPT. The test model thruster is shown in Fig.4. The capacitance of the capacitor bank is 6.0μF. The anode and cathode are made of copper and the spark plug is tungsten. Solid PTFE or powdered PTFE was used as propellant.

The configuration of the test model thruster is shown in Fig.5. Experimenting as a solid propellant PPT, we put a rectangular solid PTFE between the electrodes (Fig. 5-a). Experimenting as a powdered propellant PPT, we put a rectangular solid ceramic between the electrodes in the same configuration as the above solid PTFE, and spread PTFE powder (the particle diameter is around 0.25 μm) on the ceramics with a uniform thickness (Fig.5-b).

The operation of the thruster was conducted in a 1-m-diam, 2-m-long vacuum chamber. The background pressure was maintained under 5 mPa.

4. Thrust Mass Balance

Usually measurement of propellant mass loss of solid propellant PPT is conducted with electric balance at the atmospheric pressure. But particularly with powdered propellant PPT, we have to consider mass loss derived from vacuum drawing if powdered propellant does not completely adsorb into the surface of feeding roller. Therefore, some method for precise mass loss measurement in vacuum is necessary. We designed a thrust mass balance to measure impulse bit and mass loss

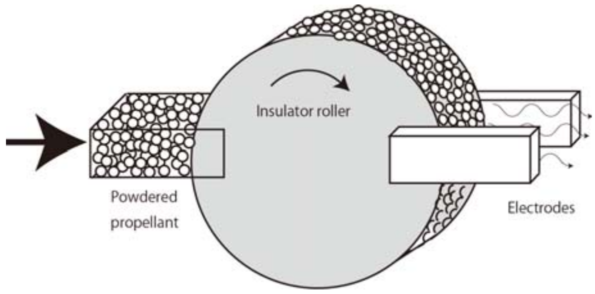

Fig.3 Conceptual diagram of a powdered propellant pulsed plasma thruster.

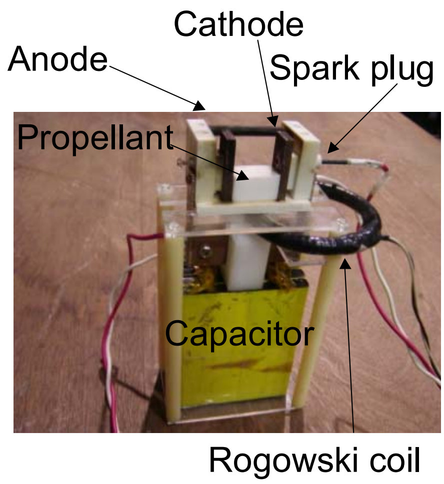

Fig.4 Test model thruster.

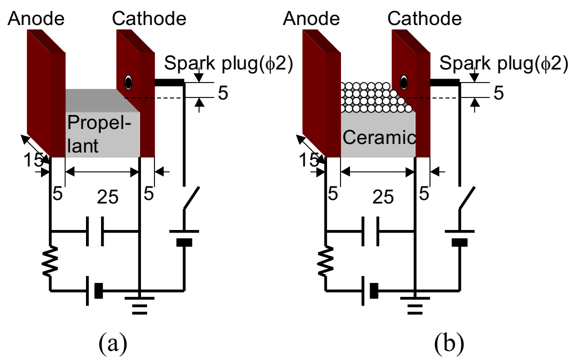

Fig.5 Configuration of the test model thruster.

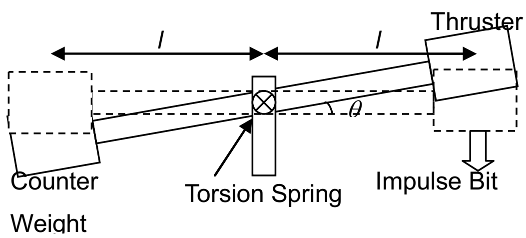

Fig.6 Side view of the thrust mass balance. Gravity force acts downwards in this figure.

simultaneously. This system enables precise history of specific impulse.

Figure 6 shows the schematic diagram of the thrust mass balance. A balance arm mounting the thruster and a counter weight can rotate around torsion springs. If an impulse is given at the point of the thruster, the balance arm starts rotational oscillation. By measuring amplitudes of this oscillation, impulse bits can be measured. On the other hand, if propellant mass decreases at the point of the thruster, the inclination of the arm after damping changes. By measuring this change, mass losses can be measured.

5. Thrust Performance Measurement

We measured impulse bits and propellant consumptions of the test model thruster in vacuum by above thrust mass balance. In addition, we measured pressure rise of the vacuum chamber after each pulse discharge by an ionization gauge. We conducted the measurements comparing following three cases of propellant type.

A) Solid rectangular PTFE.
B) 0.25-μm-diam PTFE powder simply put on the smooth rectangular ceramics with the thickness of 1mm.
C) 0.25-μm-diam PTFE powder rubbed into the surface of rectangular porous ceramics with average pore size of 10μm, 40% of porosity.

Experimental condition was following; charging voltage is 1kV; stored energy was 3J. In order to measure both history of impulse bits and propellant consumptions, we conducted the measurement by following procedure.

1. Measured impulse bit during 5 shots with the frequency of 0.5 shots per minute.
2. Operated the thruster with the frequency of 0.5 Hz during 95 shots. Propellant consumption was measured in this step.
3. Repeat step 1 and step 2. The measurement was finished when total shot number reaches to 505.

In step 1, the interval of operation was 2 minutes. This long interval was for waiting sufficient damping of oscillation of the pendulum. In step 2, the interval time was much shorter than the oscillation cycle and the operation continues during 95 shots because propellant consumption per shot was too small to measure precisely.

Figure 7 shows the displacement of the measuring point of the pendulum. In the step of impulse bit measurement (step 1), an impulse was given to the pendulum once every 2 minutes and the pendulum oscillated damping. Figure 8 shows step 1, extended figure from a part of Fig.7. Each impulse bit was found by the

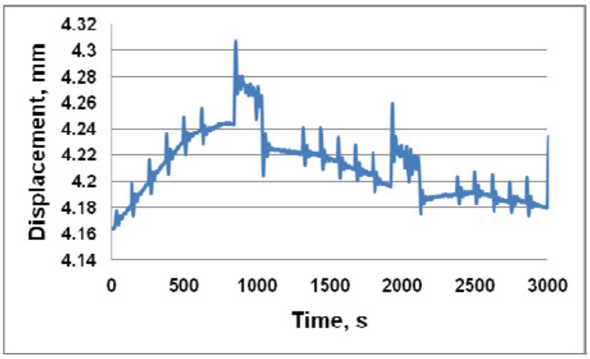

Fig.7 History of displacement of measured point.

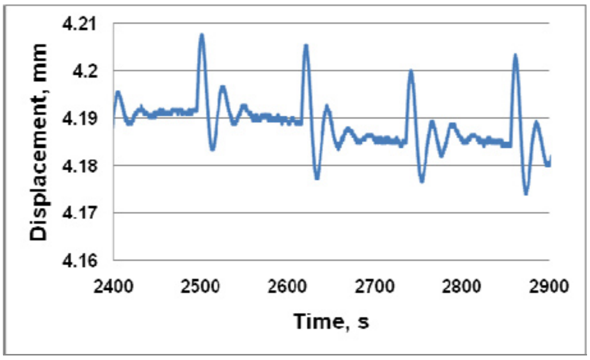

Fig.8 Extended figure of Fig.7.

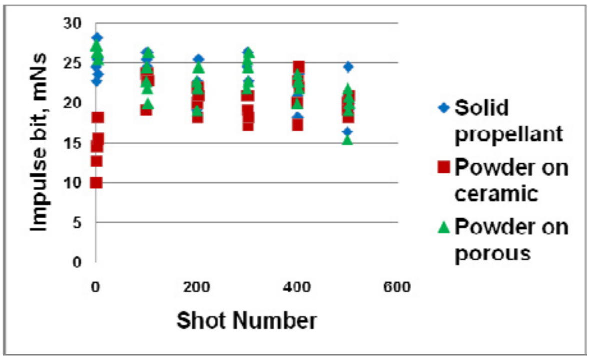

Fig.9 History of impulse bit.

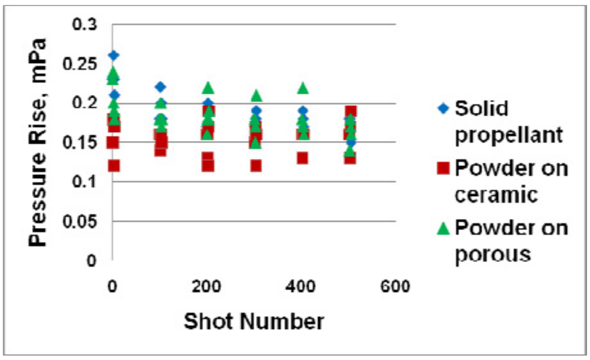

Fig.10 History of pressure rise.

maximum amplitude of each oscillation.

In the step of propellant consumption measurement (step 2), the behavior of the displacement seems similar to response to steady thrust. However, it is clear that there is a difference between the displacement in equilibrium of moment before and after series of shots. The propellant consumption is found by this difference.

Although there is a kind of drift, the reasons of this drift are not clear so far.

Figure 9 shows history of impulse bits during 505 shots comparing case A, B, and C. Figure 10 shows history of pressure rises in the vacuum chamber.

From Fig.9 and Fig.10, both impulse bit and pressure rise tend to reduce gradually. And it is also sure that there is no clear difference between the solid propellant and powdered propellant excepting an initial inefficiency in case B.

Table 1 shows the comparison of the mass shot measured with this thrust mass balance and the mass shot calculated from sum total mass change measured by an electric balance between before and after series of experiment.

Table.1 Comparison of mass shot measurement

Case		A	B	C
In-vacuum measurement by thrust mass balance				
Total change	mg	1.0	4.0	1.1
Mass shot	μg	2.1	8.4	2.3
Out-of-vacuum measurement by electronic balance				
Total change	mg	0.78	41.29	0.95
Mass shot	μg	1.5	81.8	1.9

In order to evaluate the accuracy of this measurement in vacuum, the values of case A (solid propellant) was compared first. As a result, we can believe this measurement roughly although there is 20-30% of deference.

From table 1, we found that about 90% of mass change occurred at time other than operating, such as drawing vacuum, leaking air into the vacuum chamber, and so on, in case B. On the other hand, in case C, such mass loss was not appeared.

Table 2 shows thrust performance of case A, B, and C. Mass shot was calculated from in-vacuum measurement using the thrust mass balance.

Table.2 Comparison of thrust performance

Case		A	B	C
Impulse bit	μNs	23	20	23
Mass shot	μg	2.1	8.4	2.3
Specific impulse	s	1100	240	1040
Thrust-power ratio	μNs/J	7.6	6.5	7.6
Thrust efficiency	%	4.1	0.75	3.9

In case B (powdered propellant simply put on the smooth rectangular ceramics), the specific impulse was much lower, about 20% of that of case A (solid propellant). However, in case B, the amount of vaporized propellant was almost the same as that of case A. So we can say that most part of propellant loss was without vaporization in case B.

This problem of poor specific impulse can be solved by using porous ceramic. In fact, the thrust performance of case C (powdered propellant rubbed into the surface of rectangular porous ceramics) was almost the same as case A (solid propellant). We made a hypothesis that, in case C, the propellant surface subjected to plasma was similar to that of case A.

6. Observation of the Porous Ceramics

In order to validate above hypothesis, we observed the surface of the porous ceramics into which we rubbed powder. We used a 280-power digital microscope. We compared following surfaces.

A) The surface into which we did not rub powder.
B) The surface into which we rubbed powder as uniformly as possible.
C) The surface into which we rubbed powder, after the experiment (After discharges stopped).

We show the 3D views of above three cases in fig. 11 to 13. Full range of x axis is 1230μm and y axis is 922.5μm.

In brown (dark) region we can see porous ceramics (Alumina) and in white (light) region we can see powdered PTFE. Although the surface of porous ceramics was rough before rubbing powder, the surface became very smooth after rubbing powder. We think that the whole material (porous material with rubbed powder) behaves as if it were a solid PTFE propellant. That may be the reason why the performances of case A and case C in chapter 5 was almost the same.

In addition, we can see that some powder remains at the bottom of pores after discharges stopped. But we can also see the porous ceramics at the relatively higher positions. We think that the area of the latter region increased enough to block the current passes of the creeping discharges, and prevented the initiation of the main discharge.

7. Summary

We summarize the measurement of impulse bit and mass shot of solid propellant PPT and powdered propellant PPT using the thrust mass stand as follows.

- We measured impulse bit and mass shot of PPT at once in vacuum using thrust mass stand.

- Focusing on impulse bit, there was not so much difference between a solid propellant PPT and a powdered propellant PPT. However, using powdered propellant, propellant loss without vaporization decrease specific impulse significantly.
- Significantly non-uniform powder feed makes initial thrust poor.
- By rubbing powdered propellant into the surface of porous ceramics, specific impulse becomes as high as solid propellant PPT.
- Sufficiently smooth surface of powder-rubbed porous ceramics behaves as a solid PTFE.

Acknowledgments

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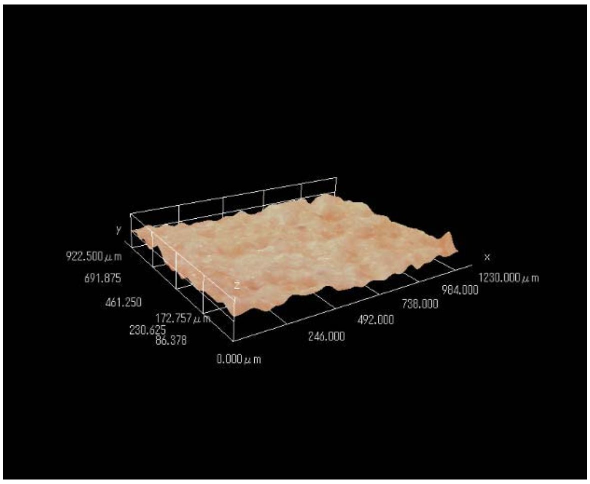

Fig.11 The surface into which we did not rub powder.

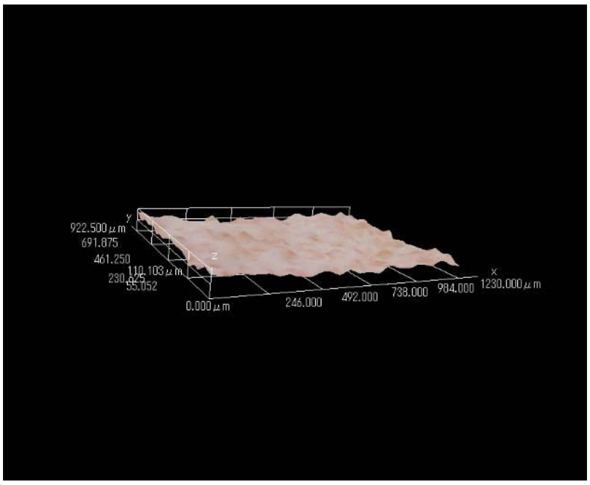

Fig.12 The surface into which we rubbed powder (Before the experiment).

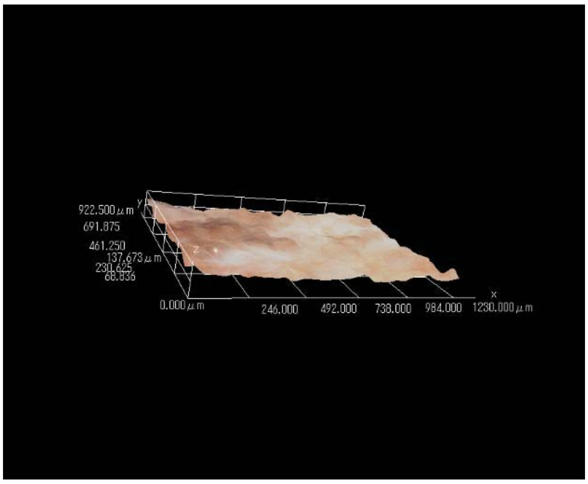

Fig.13 The surface into which we rubbed powder (After the experiment).