Pulsed Plasma Thruster Using Powdered Propellant

IEPC-2007-116

Presented at the 30th International Electric Propulsion Conference, Florence, Italy
September 17-20, 2007

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Abstract: Pulsed Plasma Thrusters (PPTs) are now getting growing attention in practical use on microspacecraft because of their simple structure, robustness, and ability to operate in limited power. However, they have some weaknesses such as poor thrust efficiency and inadequacy in long-life-time operation. A powdered propellant PPT was suggested to overcome these weaknesses. We made an experimental PPT with which we can experiment using both solid propellant and powdered propellant. Some experimental investigation on performance of the powdered propellant PPT compared with the traditional ablative PPT were conducted First, discharge current was measured. Then use of powdered propellant proved to have an advantage over solid propellant in thrust-to-power ratio. Second, we measured pressure rise in the vacuum chamber after each discharge, investigated relationship between mass loss and pressure rise, and compared them using solid propellant and powdered propellant. As a result, little difference was found in the amount of gas evaporation when using both solid propellant and powdered propellant. But total mass loss is much larger when powdered propellant was used. It can be considered that particulate emission reduces the specific impulse when powdered propellant was used.

Nomenclature

d	=	width of the electrodes
h	=	distance between the anode and the cathode
I_b	=	impulse bit of a pulsed plasma thruster
J	=	discharge current
t_0	=	time of breakdown
t_f	=	time of the end of the discharge process
W	=	energy stored in capacitor
Δm	=	mass shot (mass loss per shot)
η_t	=	thrust efficiency
μ	=	space permeability

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I. Introduction

PULSED plasma thrusters (PPTs) have been studied for long years. There have been variable types of PPT which were developed up to the present time. Although there have been some studies about PPTs using fluid propellant such as gas propellant[1] and liquid propellant,[2] the most typical PPTs are Ablative PPTs (A-PPTs) using solid propellant such as PTFE. Because of their simple structure, A-PPT is now expected as one of the most adequate thrusters to be used on microspacecraft, which are called "microthrusters".[3, 4]

However, there are some motivations for researching on propellant type of PPTs furthermore. An A-PPT has a restriction of configuration of solid propellant. For example, an A-PPT with parallel plate electrodes requires only rectangular solid propellant. So we have to prepare long rectangular solid propellant to make a long-life-time A-PPT.

We suggest an entirely new idea of using powdered propellant instead of such rectangular solid propellant for a PPT. We name it PP-PPT (Powdered Propellant Pulsed Plasma Thruster). Powder is not a fluid, but a solid, of course. However, powder propellant has a fluidical nature, that is, it can be supplied freely. So the problem of restriction of propellant configuration can be solved.

Additionally, typical A-PPTs have a problem of nonuniform ablation. Generally, ablation of solid propellant does not occur uniformly. There are preferential ablations near electrodes.[5] Therefore, after long-life-time operation, the surface of propellant changes its shape. Then the performance of the thruster should changes gradually and it can never be controlled. Using powdered propellant, and controlling its supply, we can renew the propellant surface exposed to plasma in optional timing. So a PP-PPT could have an advantage over traditional A-PPTs in long time operation.

Furthermore, a PP-PPT has some possibility of advantage over a typical A-PPT in thrust-to-power ratio. There are two reasons. First, powdered propellant has much larger surface area per unit mass than rectangular solid propellant. Second, as there are a lot of pore spaces between particles, powdered propellant have lower heat transfer coefficient in totally than solid propellant. From these reasons, powdered propellant can absorb energy more efficiently than solid propellant. Therefore, given the same energy in one shot, a PP-PPT could generate larger impulse bit than a typical A-PPT.

II. Concept of Powdered Propellant Pulsed Plasma Thruster

Figure 1 shows conceptual diagram of the whole device of a powdered propellant pulsed plasma thruster.

High voltage is applied between the propellant container and inner surface of the insulant roller. Powder charges positively and is stably provided from the propellant container, and then electrostatically adsorbs on the surface of the rotating insulant drum because of the electric field. Then the powder is supplied to the ejection point by the rotation of the insulant roller, and there accelerated electromagnetically. In this way, the thrust is generated.

There is a magnet roller between the outlet of the propellant container and the outer surface of the insulant roller. If the powder is, at least partly, ferromagnetic, the magnet roller can assist electrostatic adsorption of the powder by magnetic force. It is not necessary that all of the powder is ferromagnetic. Non-magnetic powdered propellant can be supplied effectively by being mixed with some ferromagnetic powder as a carrier.

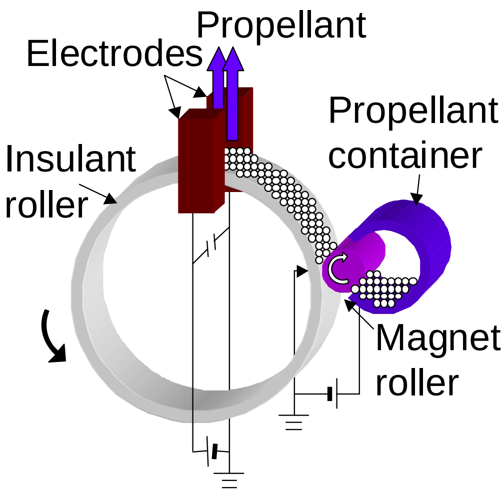


Figure 1. Conceptual diagram of the whole device of PP-PPT.

III. Experiment and Results

A. Electrostatic Adsorption of Powder

In our past research, we conducted a fundamental experiment about electrostatic adsorption of powder on the surface of solid insulant. And we proved the propellant supply method using electrostatic adsorption useful, especially useful with adsorption assist by some mixed carrier powder and magnetic roller. Please refer to Ref. 6 for further information about this experiment.

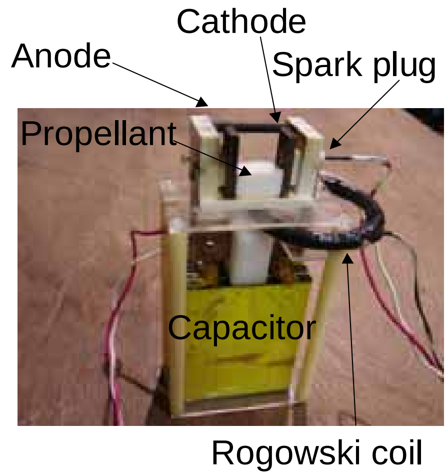
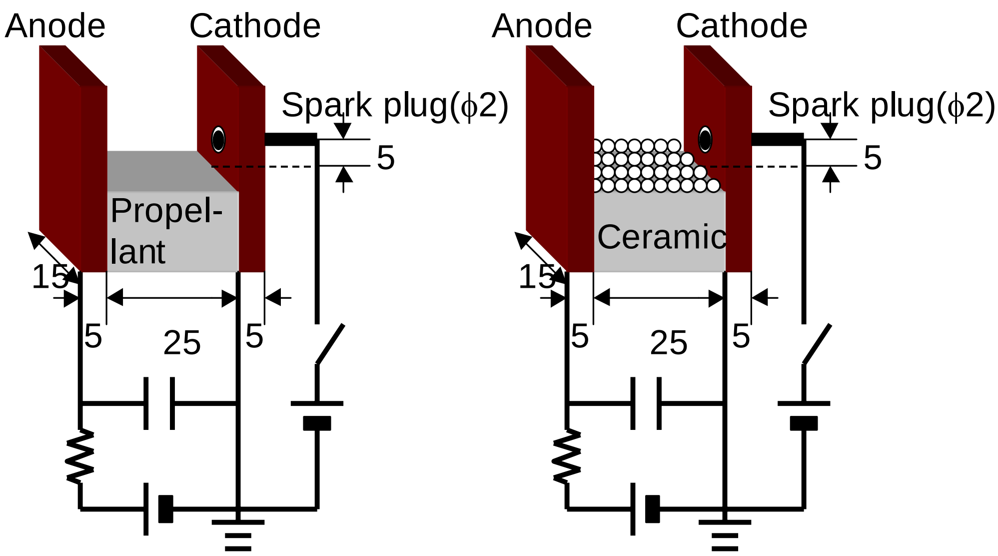


Figure 2. Test model thruster.

Figure 3. Operation of the test model thruster.
When operated as a PP-PPT.



(a) **(b)**

Figure 4. Configuration of the test model thruster.
Figure (a) shows the test model thruster used as an A-PPT with solid propellant. Figure (b) shows the thruster used as a PP-PPT.

B. Test Model Thruster

We have made a test model thruster for examining the character of PP-PPT and compare with typical A-PPT. The test model thruster is shown in Fig. 2. The capacitance of the capacitor bank is 6.0 μF. The anode and cathode are made of copper and spark plug is tungsten. Solid PTFE or powdered PTFE is used as propellant. Most of the structure of the thruster is quite similar to traditional A-PPT with parallel plate electrodes. Figure 3 is a picture of thruster operation.

The configuration of the test model thruster is shown in Fig. 4. Experimenting as A-PPT with solid propellant, we put a rectangular solid PTFE between the electrodes (Fig. 4-a). Experimenting as PP-PPT, we put a rectangular solid ceramic between the electrodes in the same configuration as the above solid PTFE, and spread PTFE powder (particle diameter is around 0.25 μm) on the ceramics with a uniform thickness of about 1 mm (Fig. 4-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.

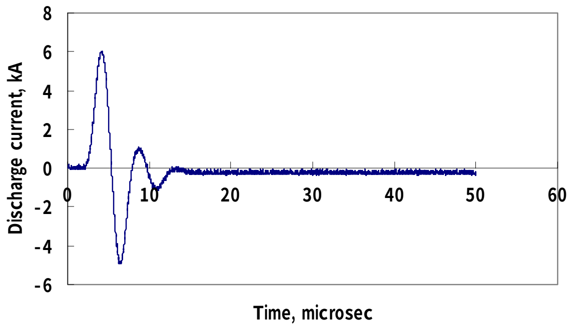


Figure 5. Typical discharge current waveform.

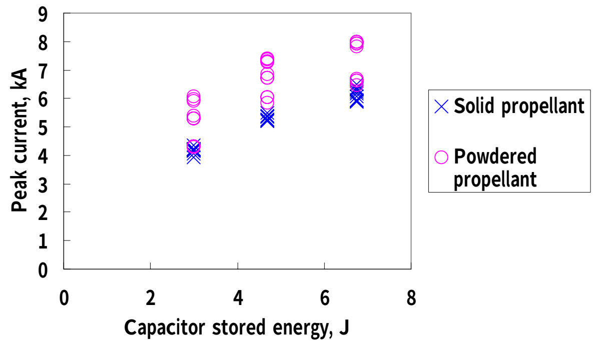


Figure 6. Comparison of peak discharge current.

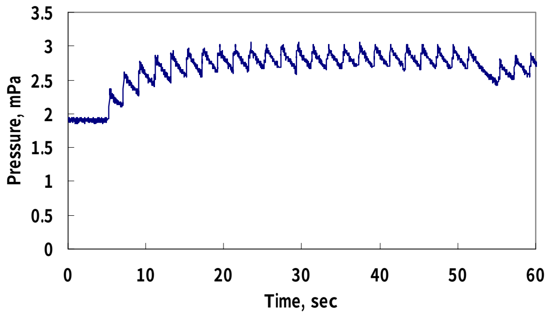


Figure 7. Pressure history in the vacuum chamber.

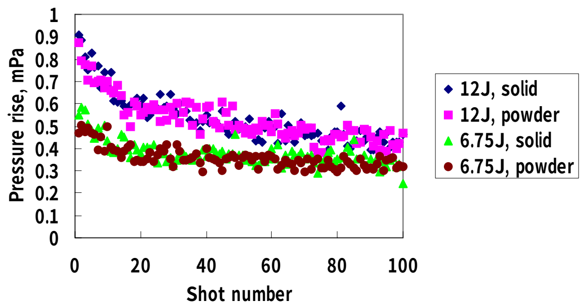


Figure 8. History of pressure rise.

C. Comparing the Peak Current

In a PPT, impulse bit is expressed in following equation.

$$I_b = \frac{\mu h}{2d} \int_{t_0}^{t_f} J^2 dt \tag{1}$$

According to Eq. 1, impulse bit is proportional to the time integration of squared discharge current. Therefore, the history of the discharge current is an important parameter to estimate the performance of the thruster. In order to examine the difference of discharge process between A-PPT and PP-PPT, we measured the discharge current using a Rogowski coil and RC integration circuit. A typical discharge current waveform of this thruster is shown in Fig. 5.

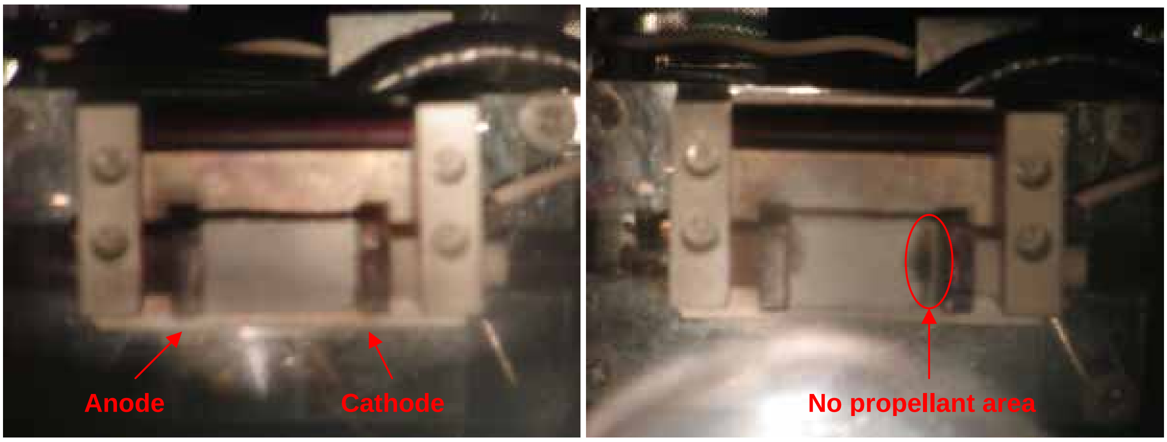
Figure 6 shows the peak current of A-PPT and PP-PPT. PP-PPT has higher peak current than A-PPT when the same energy is stored in the capacitor bank. This may expresses that the thrust power ratio of PP-PPT is higher than that of A-PPT.

But it is also obvious that the shot-to-shot variation is larger when using powdered propellant than solid propellant.

D. Pressure Rise of Vacuum Chamber

We measured pressure rise after main discharge of PPT by an ionization gauge. The sampling rate of the ionization gauge is 10 Sample/s. This time the thruster was operated with the frequency of 0.5 Hz. Then the pressure history of vacuum chamber was measured. One example of pressure history is shown in Fig. 7. Although an ionization gauge has a relative sensitivity depending on the kind of the gas which fills the vacuum chamber and the value displayed is not real value,[7] the relative sensitivity is almost constant after first five discharges from Fig. 7. Therefore, the value displayed can be indicator of pressure in the vacuum chamber.

Then the pressure rise is measured after each discharge. Figure 8 shows the history of pressure rise with shot number of 1-100. From Fig. 8, we can see that both histories of pressure rise using solid propellant and powdered



(a) **(b)**

Figure 9. Surface of propellant.
When powdered propellant was used. (a) is before the experiment and (b) is after 123 discharges. With the condition of (b), no discharge occurred.

propellant is almost the same when the same discharge energy is released per shot. So we can say the amount of propellant evaporation when using solid propellant and powdered propellant is almost the same.

In this experiment with powdered propellant, thruster operation was continued until discharge stopped. After 123 shot, no discharge occurred. Figure 9(a) is the picture of propellant surface before the experiment and 9(b) is after the experiment. We can see that powdered propellant reduces more near the electrodes, especially near the cathodes (near the igniter) and that discharge no longer occurs after a certain gap is generated between propellant and the electrode.

E. Relationship between Mass Loss and Pressure Rise

Table 1 shows the comparison between solid propellant and powdered propellant about pressure rise and mass loss. The experiment was conducted under the following condition; discharge energy is 6.75 J per shot and discharge frequency is 0.5 Hz. Mass loss was measured with an electric balance at the atmospheric pressure before and after experiment.

Table 1. Comparison between solid propellant and powdered propellant.

	Solid propellant	Powdered propellant
Number of shot	560	123
Sum of pressure rise, mPa	158	43
Average pressure rise, mPa/shot	0.28	0.35
Mass loss, mg	4.4	83.7
Mass shot, μg/shot	7.8	680.3

Although values of the average pressure rise are almost the same, values of mass shot are quite different. From this result, to use powdered propellant seems to reduce the specific impulse of the PPT. This time, powdered propellant was simply spread with the height of about 1 mm on rectangular solid ceramics, not electrostatically adsorbed. Electrostatic adsorption could have some potential to prevent the reduction of specific impulse.

IV. Conclusion

In this study, we made some comparison on thruster performance of A-PPT and PP-PPT.

By measuring discharge current, it is proved that we can earn higher discharge current with powdered propellant than with solid propellant. This expresses that PP-PPT has an advantage over traditional A-PPT in thrust-to-power ratio. However, shot-to-shot variation of discharge current is quite larger when using powdered propellant than solid propellant.

By measuring pressure rise in the vacuum chamber, it is proved that the amount of gas evaporation is almost the same regardless of whether solid propellant or powdered propellant with a given discharge energy. Now thrust efficiency is expressed as follows;

$$\eta_t = \frac{{I_b}^2}{2\Delta m W} \tag{2}$$

If the mass of gas evaporation is equal to mass shot, Δm of A-PPT and PP-PPT is the same. Therefore, from Fig. 6 and Eq. 1, the thrust efficiency of PP-PPT can be higher than that of A-PPT. The reason of this seems to be lower plasma resistance and higher ionization rate with powdered propellant having larger surface area.

However, this assumption is not true because gas evaporation is not equal to mass shot, especially with powdered propellant, from table 1. The reason of this seems that the rate of particulate emission[8] is very high with powdered propellant. So far, the thrust efficiency of PP-PPT must be lower than that of A-PPT. In this study, powdered propellant was put on the ceramics in much larger quantity than the minimum amount discharge occurs. With sufficiently small quantity of powdered propellant and successive propellant supply after each discharge, thrust performance might be optimized.

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