Performance Characteristics of Electrothermal Pulsed Plasma Thrusters with Insulator-Rod-Arranged Cavities and Teflon-Alternative Propellants

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Abstract: In this study, an electrothermal pulsed plasma thruster (PPT) with an insulator rod in a cavity (discharge room) was designed and examined in order to enhance energy transfer efficiency from a capacitor block to pruduced plasma by increasing plasma resistance. High transfer efficiency achieved due to the high plasma resistance would allow PPTs arranged in a satellite flexibly, because long transmission cables could be used. Various insulator-rod lengths of 0-19 mm were examined with fixed cavity dimensions of 3 mm in diameter and 19 mm length, and a fixed insulator-rod diameter of 2.0 mm. As a result, the transfer efficiency increased from approximately 62 to 80 % with the insulator rods, though the other performances did not change intensively. It was suspected that small cross-sectional area of the cavity lead to increasing viscosity effect. However, it was also suggested by a calculation that the other performances with an insulator rod will be better than those without an insulator rod. Furthermore, Teflon® (poly-tetrafluoroethylene : PTFE), 3 kinds of low-melting glasses, Pyrex® glass, and Tefzel® (ethylene-tetrafluoroethylene : ETFE) were evaluated as a Teflon-alternative propellant with an electrothermal PPT, which has a cavity with 2.5 mm in diameter and 19 mm in length. The PPT with PTFE achieved impulse bit of 1.2 mNs at an initial stored energy of 14.6J. The PPT with ETFE achieved a specific impulse of 570 s. The PPT with Pyrex glass achieved a specific impulse of 460 s. Therefore, it was suggested that each propellant could be utilized depending on mission maneuver.

I. Introduction

Attention is currently focused on thrusters for small satellites. Pulsed plasma thrusters (PPTs) have some features which are superior to other kinds of electric propulsion.[1] The PPTs have simple structure and high reliability, which are benefits of using a solid propellant, mainly Teflon® (poly-tetrafluoroethylene : PTFE).

In the PPT system, mass of capacitor blocks has a large fraction of the system. Therefore, considering a PPT system as shown in Fig.1 as an example, a total mass of the system would be lighter if the capacitor block was shared by the all PPTs. However, longer transmission cables leads to lower transfer efficiency from the capacitor block to plasma in the PPT because of higher electric resistance of the cable. And then, all thrust performances

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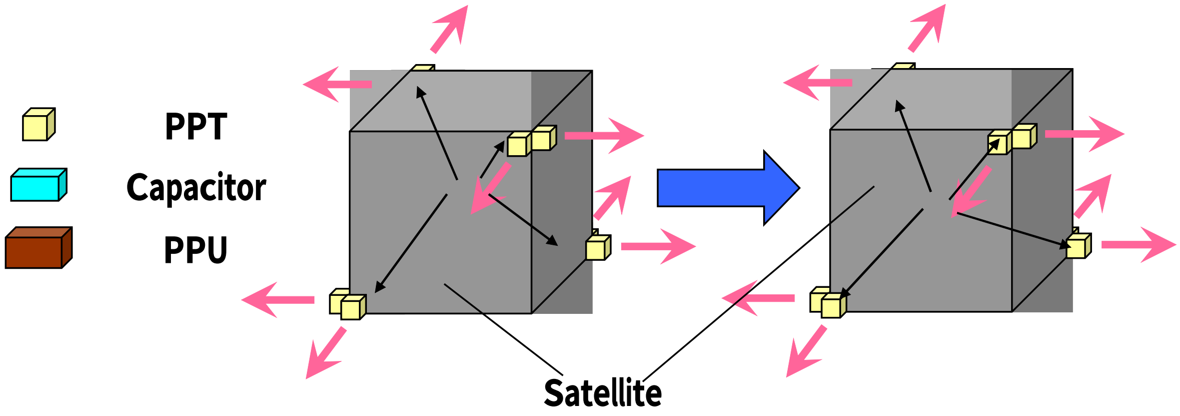
becomes lower. Accordingly, we should reveal that a light-weight PPT system needs high electric resistance of plasma.

In this study, an electrothermal PPT with an insulator rod in a cavity (discharge room) was designed and examined in order to enhance energy transfer efficiency. By arranging the insulator rod, cross-sectional area of the cavity decreases. Then, it is expected that the transfer efficiency becomes higher, because the electric resistance of plasma becomes larger and the electric resistance of cables are kept constant. Various insulator-rod lengths of 0-19 mm are examined with fixed cavity dimensions of 3 mm in diameter and 19 mm length, and a fixed insulator-rod diameter of 2.0 mm. Furthermore, numerical simulation is also carried out and compared with experimental results. The codes of the simulation were based on Refs. 2 and 3.

In previous reports, several kinds of propellants were evaluated with an electromagnetic PPT.[4] Then, Teflon which could generate the highest thrust to power ratio was the best for an electromagnetic PPT. Other propellants that had high specific impulse and low thrust to power ratio were not suitable for an electromagnetic PPT. In Osaka Institute of Technology, we achieved that a two-cavity electrothermal PPT generated a high thrust to power ratio of 75 μNs/J.[5] However, it is required to enhance specific impulse. In this study, PTFE and other propellants are examined with an electrothermal PPT in order to find Teflon-alternative propellants.



(a) (b)

Figure 1. PPT systems. (a) is PPTs thrust system of the Dawgster[1] type; (b) is the PPT system suggested in this study.

II. Energy Efficiencies

Energy conservation during a discharge is written as follows[2]:

$$\begin{aligned} E_0 &= E_{in} + E_{loss} \\ &\approx R_{p,eq}\int J^2 dt + R_1\int J^2 dt \end{aligned} \tag{1}$$

where $R_{p,eq}$ is the equivalent plasma resistance,[6] and R_1 is the direct-current resistance of the transmission lines, the electrodes and the capacitor, and E_{loss} is the energy loss in capacitors, transmission lines and electrodes. In Eq. (1), E_{in} increases if $R_{p,eq}$ increases and R_1 is kept constant. To increase the direct-current resistance of the plasma is effective when the transmission lines are long.

The transfer efficiency and the equivalent plasma resistance are written as follows:

$$\eta_{tran} = \frac{E_{in}}{E_0} = \frac{1}{1+(R_{tran}+R_c)/R_{p,eq}} \tag{2}$$

$$R_{p,eq} \equiv E_{in} / \int J^2 dt \tag{3}$$

where R is direct-current resistance, and subscripts p, tran and c represent plasma, transmission lines including electrodes, and capacitors, respectively. J is discharge current, E_0 is the energy initially stored in capacitors, and E_{in} is the energy supplied to the plasma.

III. Experimental Apparatus

A coaxial electrothermal PPT, as shown in Figs. 2 and 3, was designed for this study.[2,3] The PPT has an anode at the upstream end and a divergent nozzle as a cathode with 23 mm length and 20 degrees half-angle at the exit of the cavity. Both the anode and the cathode are made of stainless steel. The distance of 19 mm between the anode and the cathode is equal to the cavity length. The diameter of the insulator rod is 2 mm, and various rod lengths of 0, 4, 9, 14, 19 mm are examined.

Figure 4 shows a thrust stand in a vacuum chamber for precise measurement of an impulse bit. The PPT and capacitors are mounted on the pendulum, which rotates around fulcrums of two knife edges without friction. The displacement of the pendulum is detected by an eddy-current-type gap sensor (non-contacting micro-displacement meter) near the PPT.

Furthermore, another cavity diameter was used to examine influences of propellant species on thrust performance. The cavity diameter of 2.5 mm is smaller than that of conventional electrothermal PPTs,[7] because a result was obtained that an electrothermal PPT generates high performances with a small cavity diameter.[3] Solid propellants of PTFE, three kinds of low-melting glasses, Pyrex® glass, and Tefzel® (ethylene-tetrafluoroethylene : ETFE) are examined.

As a solid propellant, PTFE, three kinds of low-melting glasses (LMG1, LMG2 and LMG3), Pyrex glass, and ETFE are tested. The LMG1, LMG2 and LMG3 contain different materials and have different characteristics. Table 1 shows softening points and specific gravity of three kinds of low-melting glasses and Pyrex glass.

The low-melting glass is the generic term of glasses of which softening point is between 500-900 K. Characteristics of low-melting glass can be conditioned by compounding its materials. On the contrary, Pyrex glass has high softening point and low specific gravity.

The ETFE had been evaluated with an electromagnetic PPT in Ref. 4. Higher specific impulse and lower thrust to power ratio than PTFE were shown, and it was concluded that ETFE was not suitable for a PPT in the report. In this study, we investigate the availability of utilizing ETFE as a solid propellant with an electrothermal PPT.

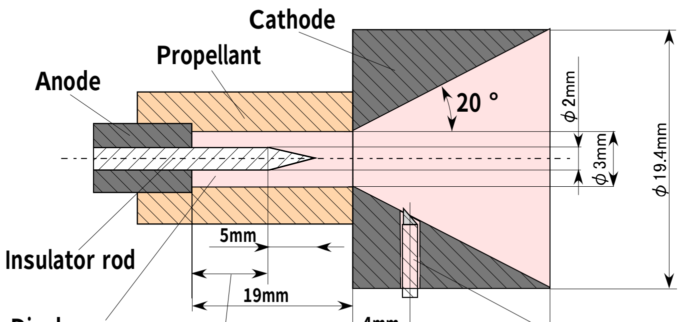


Figure 2. Cross-sectional view of PPT with insulator rod.

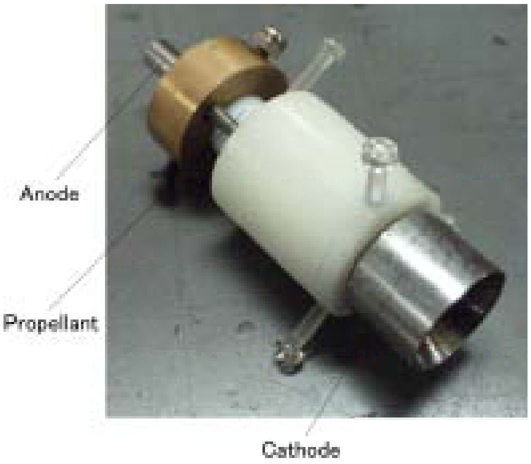


Figure 3. Photograph of PPT.

Table 1. Softening points and specific gravity of three low-melting glasses (LMG1, LMG2, LMG3) and Pyrex glass.

	LMG1, 2, 3	Pyrex
Softening point, K	670, 770, 795	1120
Specific gravity	5.2	2.2

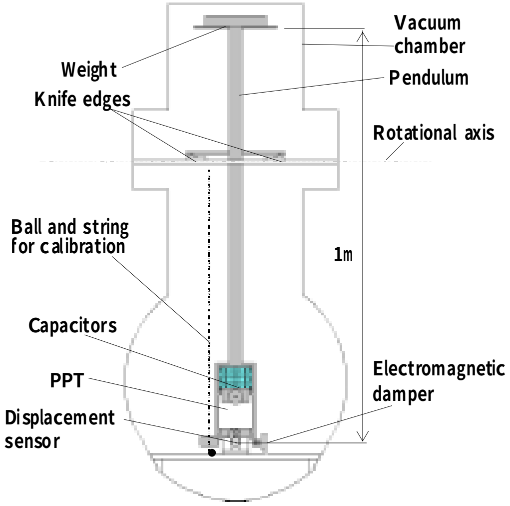


Figure 4. Schematic view of thrust stand.

IV. Experimental Results and Discussion

A. Insulator-Rod-Arranged Cavities

Table 2 shows experimental conditions for the present study. Figure 5 shows the measured and calculated impulse bit versus insulator-rod length. The measured impulse bits roughly agree with the calculated results when the insulator-rod length is less than 9 mm. With longer insulator rods, the calculated impulse bits are higher than the experimental results.

Figure 6 shows the measured and calculated mass shot versus insulator-rod length. The mass shot means mass loss of propellant per shot. In experimental results, the mass shot suddenly increases with an insulator-rod length. In all insulator rod lengths, the measured mass shots are larger than that with no insulator rod. This reason can be explained as follows. Generally, the plasma column of arc discharge is constricted by the pinch effect. However the insulator rod prevents the effect because it is arranged at the center of the cavity. Therefore, the plasma generates near the propellant surface. As a result, the propellant obtains more energy, and the mass shot increases. But because the simulation code is one-dimensional calculation, the pinch effect is not considered. Therefore, the calculated mass shots are much lower than the measured ones. Some improvements in the calculation model are needed in future work.

Table 2. Experimental conditions.

Capacitance, μF		9
Charging voltage, V		1800
Stored energy, J		14.6
Discharge room	Length, mm	19
	Diameter, mm	3
Nozzle	Length, mm	23
	Half angle, degree	20
Insulator-rod length, mm		No insulator rod, 0, 9, 14, 19, 24

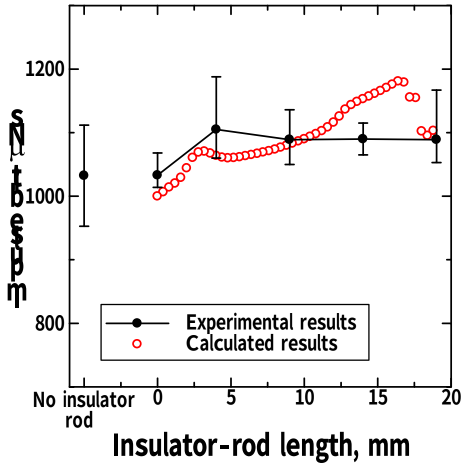


Figure 5. Impulse bit versus insulator-rod length.

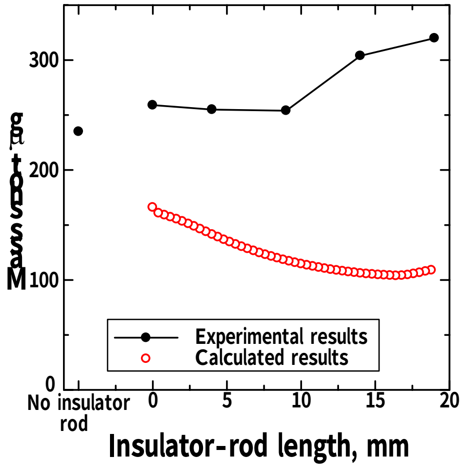


Figure 6. Mass shot versus insulator-rod length.

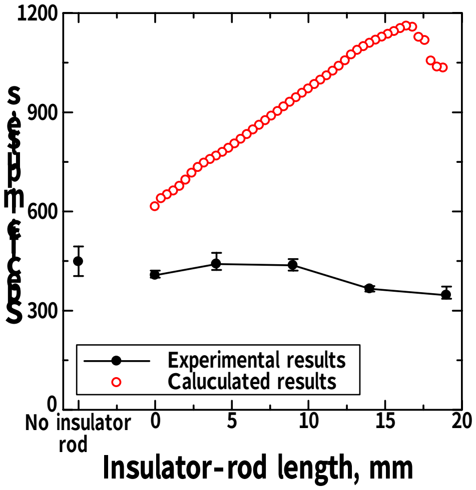


Figure 7. Specific impulse versus insulator-rod length.

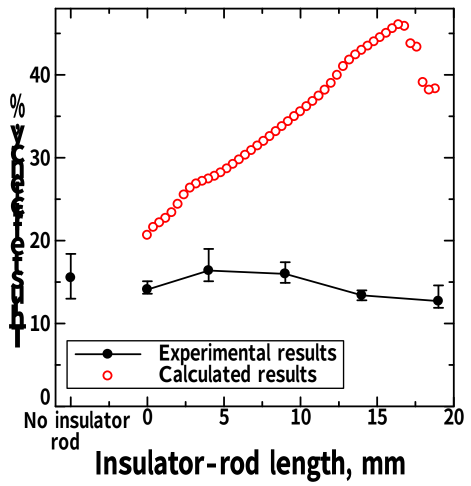


Figure 8. Thrust efficiency versus insulator-rod length.

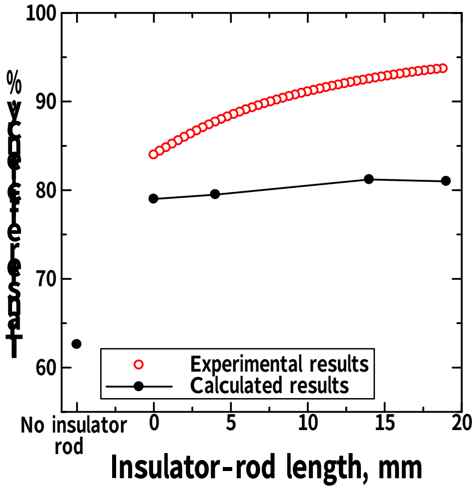


Figure 9. Transfer efficiency versus insulator-rod length.

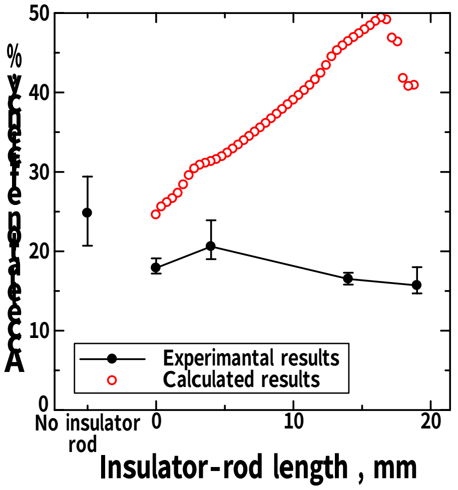


Figure 10. Acceleration efficiency versus insulator-rod length.

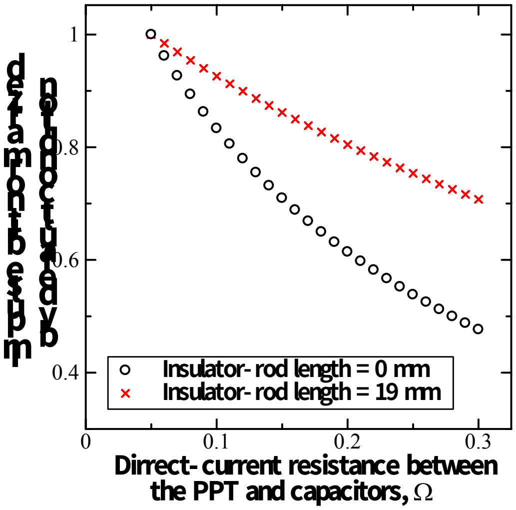


Figure 11. Impulse bit normalized by default condition versus direct-current resistance between the PPT and capacitors.

Figures 7 and 8 show the specific impulse and the thrust efficiency versus insulator-rod length, respectively. Both calculated specific impulse and calculated thrust efficiency are higher than the experimental results because lower mass shots are calculated than experimental results.

Figure 9 shows the measured and calculated transfer efficiency versus insulator-rod length. The transfer efficiencies with insulator rods are higher than that without an insulator rod due to the effect of the insulator rod, though the calculated transfer efficiency is a little higher than the measured one.

$R_{p,eq}$ with an insulator-rod length of 19 mm is estimated from a discharge current waveform and circuit parameters to be about 0.18 Ω, although $R_{p,eq}$ with no insulator rod is about 0.12 Ω.[2] On the other hand, direct-current resistance of the plasma is roughly written as follows, assuming constant plasma resistivity in the cavity:

$$R_{p,eq} = \eta d / A \tag{4}$$

where d is length of the current pathway and A area of the current pathway. Direct-current resistance of plasma with an insulator rod increased because of a decrease in cross-sectional area of the current pathway.

Figure 10 shows the measured and calculated acceleration efficiency versus insulator-rod length. The acceleration efficiency is defined as:

$$\eta_{acc} = E_t / E_{in} \tag{5}$$

In the experimental results, the efficiencies with insulator rods are lower than that with no insulator rod. It suggests that a decrease in cross-sectional area of the cavity leads to an increase in viscosity loss. The calculated acceleration efficiencies are higher than the experimental results because of the underestimation of mass shot in calculations.

Figure 11 shows the calculated results of impulse bit normalized by that of default condition versus direct-current resistance between the PPT and capacitors. It is predicted that the impulse bit decreases with increasing direct-current resistance. However, the decreasing rate with an insulator rod is small than that without the rod.

B. Teflon-Alternative Propellants

The thruster operations are carried out with a charging voltage of 1800 V and a stored energy of 14.6 J. As solid propellants, PTFE, three kinds of low-melting glasses, Pyrex glass, and ETFE are evaluated.

Using PTFE or Pyrex glass, the thruster operated without miss shot. However, using low-melting glass, a miss shot was observed per approximately a hundred shot. It is suggested that the metal constituent of low-melting glass depositing on the cavity surface causes the miss shots. Conditioning the material composition of low-melting glass, the thruster with low-melting glass might operate more stably. Using ETFE, the thruster did not fire after a few hundred shots, because of charring on the igniter. In utilizing the ETFE as a propellant it is necessary to find a better position of the igniter or to use an igniter which can operate more stably.

Table 3 shows initial thrust performances of PTFE, three kinds of low-melting glasses, Pyrex glass, and ETFE. Impulse bit (thrust to power ratio) is the largest when the PTFE is used. Both specific impulse and thrust efficiency are the highest when ETFE is used, because mass shot is the lowest. As a result, ETFE is suitable for a mission which requires high specific impulse.

Table 3. Initial thrust performances of PTFE, 3 low-melting glasses, Pyrex glass, and ETFE.

	Impulse bit [μNs]	Mass shot [μg]	Specific impulse [s]	Thrust efficiency [%]
PTFE	1190	380	320	12.6
LMG1	780	240	360	8.8
2	710	250	300	7.1
3	680	250	280	6.4
Pyrex	430	100	460	6.7
ETFE	900	160	570	17.2

V. Conclusions

In this study, the following results are obtained:

An electrothermal PPT with an insulator rod in a cavity was investigated in order to enhance energy transfer efficiency.

1) The transfer efficiency increased from approximately 62 to 80 % due to the insulator rods, though the other performances did not change drastically.

2) It is predicted that the impulse bit decreases with increasing direct-current resistance, but the decreasing rate with an insulator rod is small than that without the rod.

PTFE, three kinds of low-melting glasses, Pyrex glass, and ETFE were tested as propellants with an electrothermal PPT.

1) Using PTFE or Pyrex glass, the thruster operated without miss shot. Using low-melting glass, a miss shot was observed per approximately a hundred shot. Using ETFE, the thruster did not fire after a few hundred shots.

2) ETFE is suitable for a mission which requires high specific impulse if the igniter is improved.

3) The low-melting grass has a possibility to be developed as a propellant because its characteristics can be conditioned flexibly.

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