Double Discharge Operation for Pulsed Plasma Thrusters*†

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In order to improve the propellant vaporization issue and thruster performance of pulsed plasma thrusters, a "Double Discharge Method" was proposed and tested experimentally. In this method, it is expected that part of late-time vaporization gas in the primary discharge is accelerated by the secondary discharge. We compared the thruster performance for both cases of an ordinary and a double discharge to examine the effectiveness of our proposal. In the double discharge operation, the delay time and the capacitance ratio between the primary and the secondary discharge were changed. It was found that the double discharge operation with the delay time of approximately 5 μs and the capacitance ratio of 2/2 was the best of all done this time in impulse bit, specific impulse and thrust efficiency.

Introduction

Pulsed Plasma Thrusters (PPTs) have attracted attention again for station keeping, drag make-up and the attitude control of small satellites because of advantages such as its simplicity and robustness in recent years[1][2]. To qualify PPTs as such candidate thruster efficiency must be improved. Also it has been pointed out that the propellant continues to be consumed for a while even after an electric discharge in ablation-fed PPTs. This vaporization gas (late-time vaporization gas) is neither accelerated well nor eventually contributes for thrust[3]. The late-time vaporization is considered one of the causes to lower PPTs' performance. Only few attempts have been made on the improvement of the late-time vaporization issue.

In this paper, we propose what we call a "Double Discharge Method" in order to improve the propellant vaporization issue. In this method, the separate sets of capacitors are designed so as to make successive discharges. It is expected that part of the late-time vaporization gas in the primary discharge is accelerated by the secondary discharge. We compared the thruster performance for the both cases of an ordinary and a double discharge to exam the effectiveness of our proposal.

Experimental

Double Discharge Operation

In PPTs, the propellant continues to be consumed for a while after an electric discharge. This phenomenon called "late-time vaporization" results in a deterioration of thrust efficiency and specific impulse. Double Discharge Method is based on two successive

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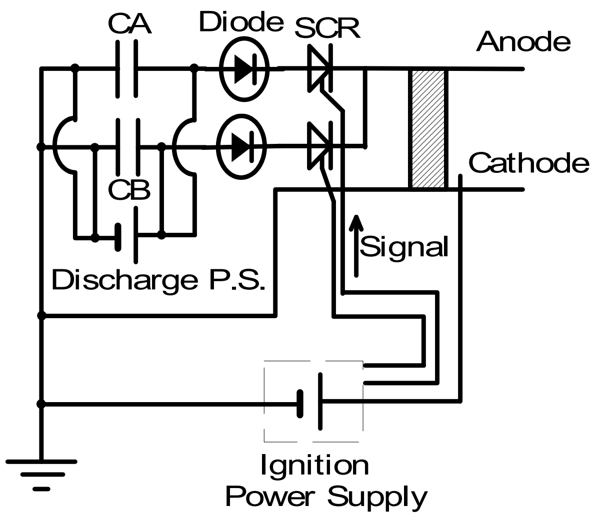

Fig. 1 Schematic of electric circuit for double discharge operation.

discharges where the late-time vaporization gas in the primary discharge is intended to be accelerated by the secondary one.

Figure 1 shows the electric circuit for the double discharge operation. Two individual sets of capacitors (*CA* and *CB*) are connected to the anode of the PPT through diodes and SCRs. The signal to turn on the SCR switch is sent from the ignition power supply simultaneously with the ignition pulse. Since the two consecutive ignition pulses can be made and the interval between them can be selected optionally in the ignition power supply, two successive (but independent each other) discharges can be produced. The delay time can be adjusted by changing the interval of the ignitor firings. The delay time between the primary and the secondary discharge (delay time, τ) is determined with reference to the time that the late-time vaporization continues (ex. 1 ms following the 20 μs arc discharge[3]) and passes between the electrodes. The diode is also placed between the capacitor and the electrode in series to the SCR. This circuitry may also improve PPT performance by preventing the inversion of discharge current[4] and it seems meaningful to investigate on this issue.

Set-up and Procedure

Figure 2 shows the experimental set-up. Waveforms of the discharge current were measured by the current monitor installed in cathode-to-ground line. Approximately 18.5 μF of capacitance was charged as

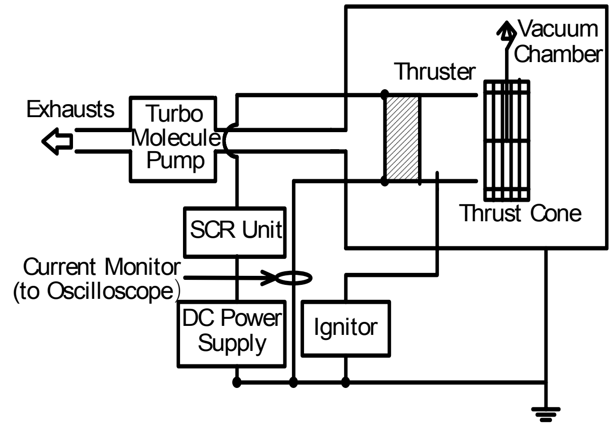

Fig.2 Experimental set-up.

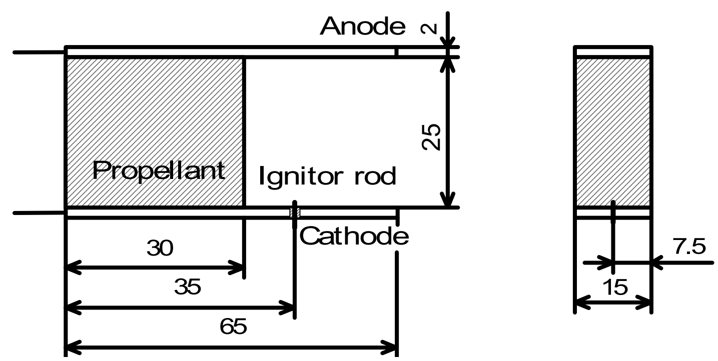

Fig.3 Thruster head used in this study.

high as 1.0-2.2 kV, so the stored energy in the capacitor was 10-45 J. The voltage of the ignitor was fixed at 2 kV. (Power consumption of the ignitor is 0.2 J.) A propellant is placed in the light shaded portion in the figure.

The thruster used in this study has parallel plate electrode arrangement as shown in Fig. 3. Polytetrafluoroethylene (PTFE) was used as propellant throughout the experiments. Experiments were conducted with 25 mm electrode gap and an ignitor–propellant distance of 5 mm.

The experimental conditions are shown in Table 1. The delay time τ for the double discharge were approximately 5, 100 and 1000 μs. (Although we had intended to set the shortest delay time in 10 μs, the obtained value was lower than 5 μs. This discrepancy was attributable to a time lag between the signal for

SCRs and the ignition firing.) The effects of the ratio of the primary discharge energy to secondary one on thruster performance were also examined. (In the experiment, the capacitance ratio (CA/CB) was varied.) Propellant mass consumption per shot (mass shot, Δm) was obtained as the average value of 500 firings of the thruster. Impulse bits of the thruster were measured by a target method.

Table 1 Experimental conditions

Propellant		PTFE
Ignition discharge voltage	(kV)	2.0
Main discharge voltage	(kV)	1.0-2.2
Delay time τ	(μs)	5, 100, 1000
Capacitance ratio *CA*/*CB*		4/0, 3/1, 2/2, 1/3

Results and Discussion

Figure 4 shows the discharge current for various discharge conditions. Figure 4-(a) is one for the case what we call "Ordinary discharge" that a conventional PPT circuit was used. Figure 4-(b) is for "Single discharge" using the electric circuit for the double discharge operation shown in Fig. 1. In this case, all stored energy was used at one time in the primary discharge. Figures 4-(c), (d), and (e) are the ones for "Double discharge" with the delay time τ of 5, 100 and 1000 μs respectively. All current waveforms were obtained under the same capacitor energy E of approximately 23 J. From Fig. 4 it can be confirmed that the electric circuit shown in Fig. 1 successfully operates, that is, Figs. 4-(d) and (e) show the existence of two individual pulses. The reason for disappearance of double pulse in Fig. 4-(c) is the mergence of the primary and secondary discharge because the delay time is shorter than the discharge duration. Figures 4-(b) to (e) also show that the negative part of the discharge current was eliminated by the effects of the SCR and diode. That is, the electric circuit we use for the double discharge operation generate such a different discharge pattern. It has been also reported that reduction of the amplitude of voltage-reversal on the capacitor improves reliability at high energy density[4], so the difference of the waveform should be discussed in near future. It can be said from Figs. 4-(b) and (c) that the current peak of (c) is larger than that of (b) under the same capacitor energy condition. This is probably because the secondary discharge began before the primary one had not ended yet and therefore two discharges merged.

Figure 5 shows the comparison of impulse bit (I_{bit}) by discharge conditions. The effect of delay time on the thruster performance is focused on here. The impulse bits increase nearly in proportion to the capacitor energy for all discharge conditions and the impulse bits of Single discharge are smaller than those of Ordinary discharge. Impulse bits become larger by setting the delay time shorter, largest at 5 μs among all. These tendencies agree with the trend of the current peak difference shown in Fig. 4. In other words, the impulse bit could be improved by increasing the current peak of the discharge which may be supported by the simplified expression of the impulse bit; [5]

$$I_{bit} \propto \int I^2 dt .$$

In Fig. 5, it can be said that Double discharge operation at τ = 5 μs was most effective for the improvement of impulse bit. As a next step, the experiment to investigate the influence of the capacitance ratio of the primary to secondary discharge (*CA*/*CB*) was carried out.

Figure 6 shows the comparison of impulse bit under different *CA*/*CB* ratio of 4/0, 3/1, 2/2, 1/3 at τ = 5 μs and Ordinary discharge condition. The operation with *CA*/*CB* = 4/0 corresponds to Single discharge operation. Figure 7 shows the discharge current for the each *CA*/*CB* condition under capacitor energy of approximately 40 J. Figure 7-(a) is for Ordinary operation and Figs. 7-(b) to (e) correspond to the case with the *CA*/*CB* = 4/0, 3/1, 2/2 and 1/3 respectively. Figure 6 shows that the influence of the *CA*/*CB* ratio on impulse bit is more clearly distinguished in larger capacitor energy region and the impulse bits have following order; I_{bit} (2/2) > I_{bit} (3/1) > I_{bit} (1/3) > I_{bit} (Ordinary) > I_{bit} (4/0 (Single)). This order agree with that of the magnitude of the current peak shown in Fig. 7 as was the same in the relationship between Fig. 4 and Fig. 5. This is probably because impulse bit is proportional to the square of discharge current as mentioned above. So far, we can summarize that Double discharge operation with the delay time of 5 μs and capacitance ratio of 2/2 is the best of all done in impulse bit.

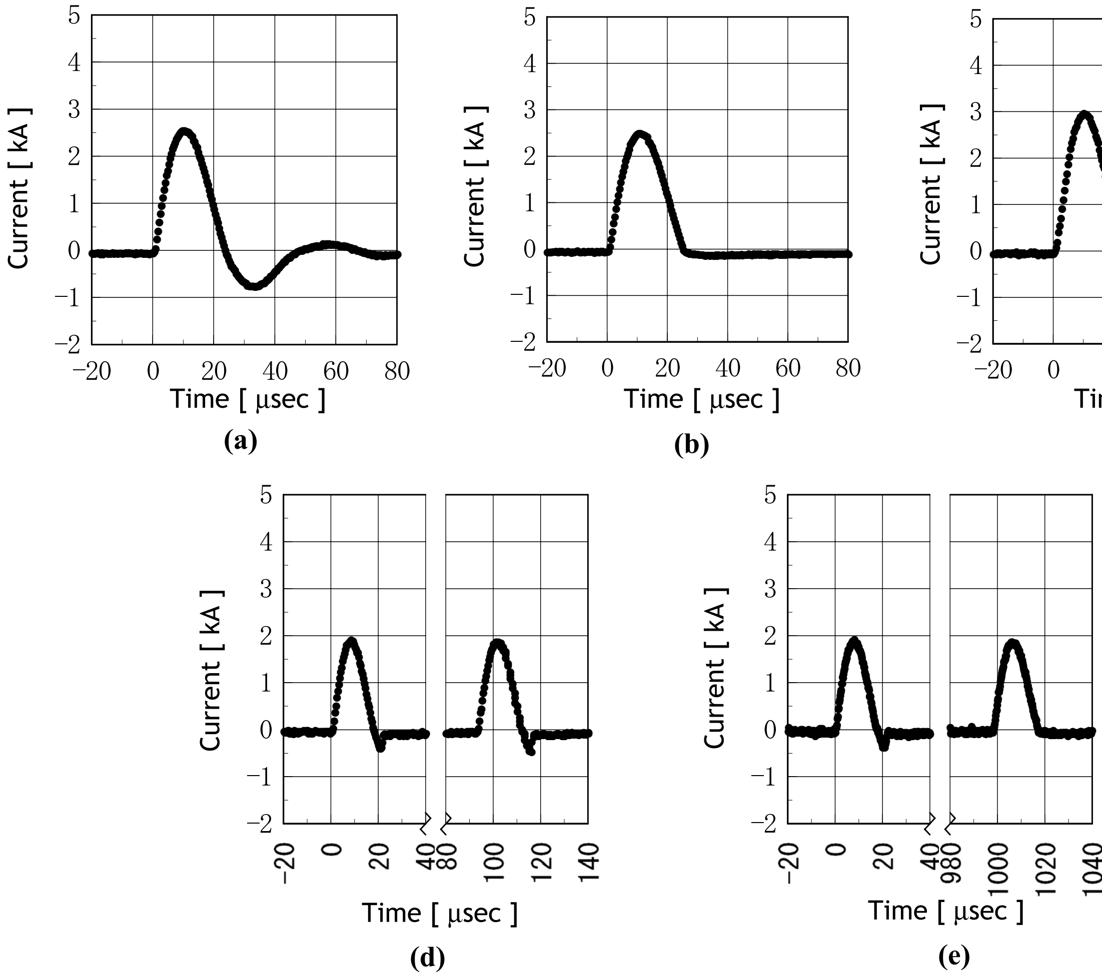

Fig. 4 Comparison of discharge current by discharge condition. (a) Ordinary, (b) Single, (c) Double (τ= 5 µs), (d) Double (τ= 100 µs), (e) Double (τ= 1000 µs). (Capacitor energy ≅ 23J)

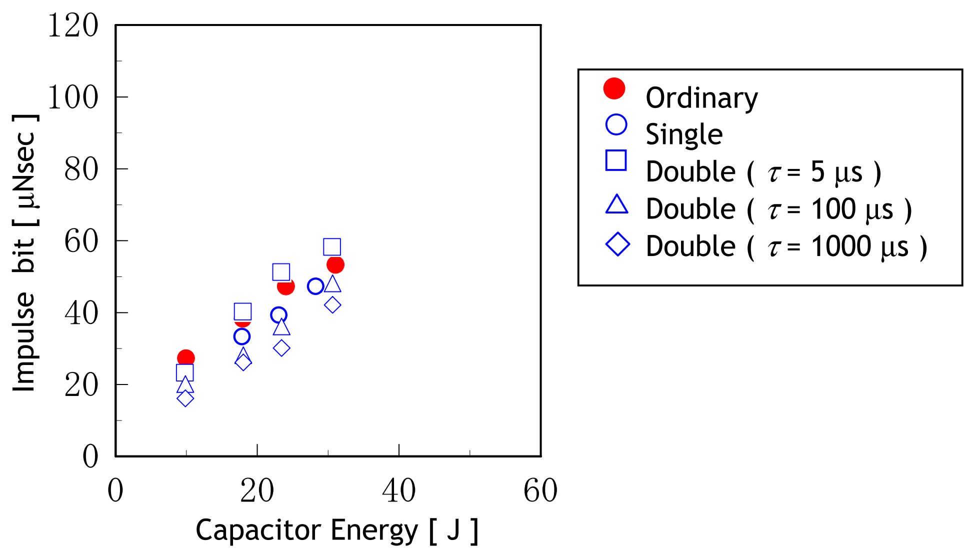

Fig. 5 Comparison of impulse bit by discharge condition.

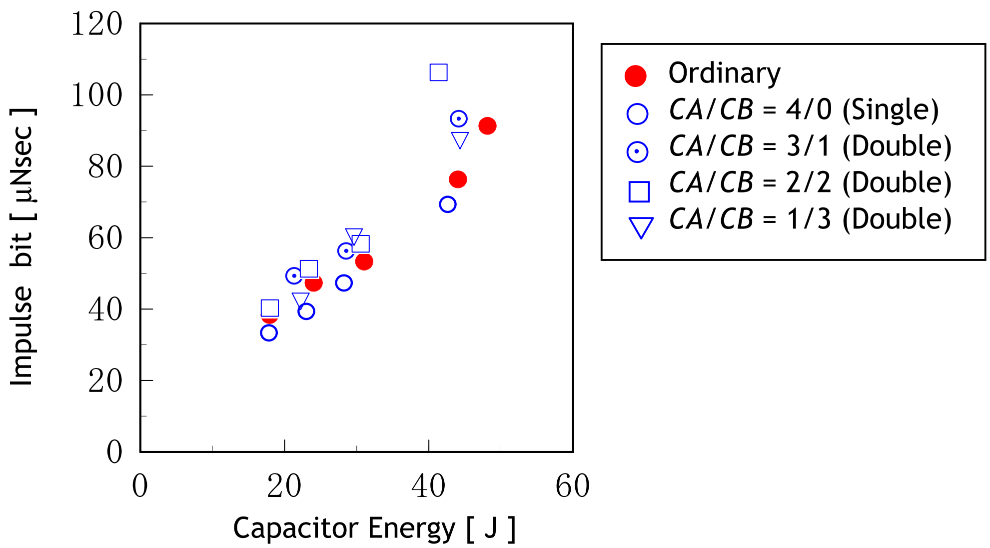

Fig. 6 Comparison of impulse bit by capacitance ratio *CA*/*CB*. (Delay time τ = 5 μs in Double discharge operation.)

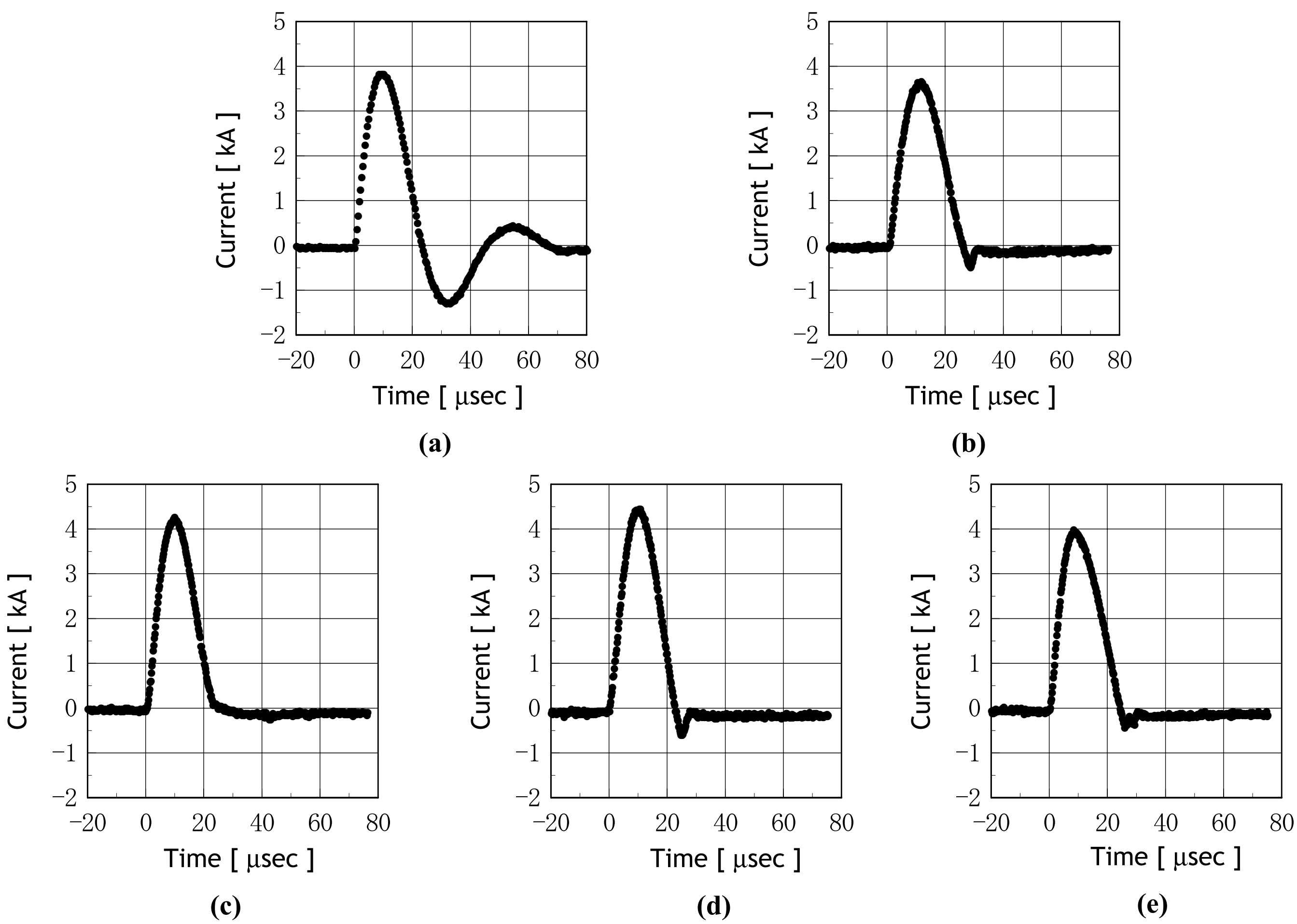

Fig. 7 Comparison of discharge current by capacitance ratio. (a) Ordinary, (b) 4/0 (Single), (c) 3/1, (d) 2/2, (e) 1/3. (Capacitor energy ≅ 40J. Delay time τ = 5 μs in Double discharge operation.)

Table 2 Thruster performance for each discharge condition

	CA/CB	τ, µs	E, J	Δm, μg	I_{bit}, μNs	I_{sp}, s	η, %
Ordinary	-	-	40	5.9	74	1300	1.1
Double Discharge	4/0	5	40	4.4	69	1600	1.3
	3/1	5	40	6.0	93	1600	1.6
	2/2	5	40	6.2	109	1800	2.2
	1/3	5	40	4.7	85	1800	1.8

Because the results described above were insufficient to discuss whether part of late-time vaporization gas was effectively used for thrust in the double discharge operation, we measured propellant mass consumption Δm (μg/shot) for the capacitor energy of approximately 40 J and calculated the thruster performance; specific impulse I_{sp} and thrust efficiency η. Table 2 shows the thruster performance for each discharge condition. This table shows that the specific impulse and the thrust efficiency for Double discharge operation with the delay time $\tau = 5$ µs and capacitance ratio CA/CB = 2/2 are higher than those of other conditions. From this result, we can say that the average exhaust velocity in Double discharge operation is higher than that in Ordinary discharge operation because exhaust velocity is proportional to specific impulse. The more detailed experimental and theoretical discussion on the utilization of the late-time vaporization must be performed in near future.

Conclusions

In order to improve the propellant vaporization issue (late-time vaporization) on Pulsed Plasma Thrusters, Double Discharge Method was suggested and the preliminary experiments were conducted to investigate the effectiveness of this method. Tests under different delay time and capacitance ratio between the primary and the secondary discharge were conducted and the following conclusions were derived. The double discharge operation with the delay time of 5 µs and the capacitance ratio of 2/2 was the best of all done this time in impulse bit, specific impulse and thruster efficiency. It was one of reasons above that the current peak of the double discharge operation of delay time of 5 µs was larger than that of the ordinary discharge operations at the same capacitor energy. In addition, it was also confirmed that the average exhaust velocity in the double discharge operation was higher than that in the ordinary discharge operation. However, the obtained results are not sufficient to discuss that these improvements are brought by the utilization of the late-time vaporization gas. Further experimental and theoretical investigations are necessary to clarify the mechanism of late-time vaporization.

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