Influence of Electrode Configuration of a Liquid Propellant PPT on its Performance

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Abstract: A liquid propellant pulsed plasma thruster (LP-PPT) has high performance in comparison with a conventional Teflon PPT because it can avoid phenomena that deteriorate performance, such as particulate emission and late-time ablation. Whereas a LP-PPT with coaxial electrodes provides higher thrust to power ratio than that with parallel plate ones due to electrothermal acceleration, there are few studies on the coaxial LP-PPT. The present study deals with the influence of electrode configuration on the performance. The divergent angle θ and area ratio ε of the anode nozzle were varied from 10° to 30°, and from 30 to 90, respectively. Ethanol was used as a propellant. Thrust measurements, conducted at a capacitor-stored energy E = 15 J and a mass shot Δm = 14.8 μg, showed that the prototype with $\theta = 30°$ and $\varepsilon = 30$ yielded the highest impulse bit of 130 μNs and corresponding specific impulse of 890 s. On the other hand, the prototype with $\varepsilon = 60$ presented the lowest thrust when θ was set both at 20° and 30°.

Nomenclature

E	=	capacitor-stored energy
I_{bit}	=	impulse bit
I_{sp}	=	specific impulse
T/E	=	thrust to power ratio
Δm	=	mass shot
ε	=	area ratio

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η_t = thrust efficiency
θ = divergent angle

I. Introduction

A pulsed plasma thruster (PPT) is a kind of electric thrusters that utilizes electromagnetic and electrothermal accelerations to produce thrust. Since the PPT provides an impulsive thrust (impulse bit, I_{bit}), thrust level is readily varied by adjusting the repetition frequency. The advantage allows the PPT to provide precise attitude control and station keeping for space-craft without any complex throttling devices.

On the other hand, conventional PPTs using solid Teflon propellant show relatively low thrust efficiency ranging from 5 to 15 % among electric propulsion devices, because most of supplied propellant are not accelerated with pulse-arc discharge before being expelled from the thruster. This is caused by two processes. One is late-time ablation; solid propellant continues to evaporate even after pulse-arc discharge finished because the temperature of arc-heated Teflon surface remains higher than the sublimation point. The other is particulate emission; low-speed solid particles are emitted from the heated surface without producing thrust[1, 2].

To avoid the processes, a PPT using liquid propellant (LP-PPT) has been proposed[3-7]. LP-PPTs have a pulse injector for injecting adequate mass of liquid propellant in order to improve the propellant utilization. Hence, LP-PPTs can avoid the processes that deteriorate the performance for the conventional PPTs. Thrust measurements have showed that a LP-PPT with parallel plate electrodes yielded a higher specific impulse of 4300 s than conventional PPTs, at a capacitor-stored energy of 20 J[8].

Whereas a LP-PPT with coaxial electrodes provides higher thrust to power ratio than that with parallel plate ones due to electrothermal acceleration, there are few studies on the coaxial LP-PPT[3-7]. The present study deals with the influence of electrode configuration of the coaxial LP-PPT on its performance.

II. Prototyped LP-PPT

Figure 1 shows a schematic of a prototyped coaxial LP-PPT. An anode nozzle, a cavity, and a pulse injector, which works also as a cathode are coaxially arranged. The anode nozzle, made of stainless steel, is used as both anode and diverging nozzle to accelerate a plasma electromagnetically and electrothermally. The cavity of 3 mm in diameter and 10 mm in length is made of machinable ceramics to insulate electrodes and endure high heat flux by arc plasma. The pulse injector consists of an electromagnetic actuator, a rod, a spring, a sealing rubber and an orifice. The sealing rubber touched the orifice to prevent liquid propellant from expelling. By applying voltage to the electromagnetic actuator, liquid propellant is injected through the orifice into the cavity. Vaporization of injected droplets increases a pressure between anode and cathode, and induces a spontaneous pulse-arc discharge without ignitor. This spontaneous ignition of arc discharge allows the LP-PPT to reduce its size and weight, because it requires no spark plug.

Divergent angle θ and area ratio ε of the anode nozzle were varied from 10° to 30°, and from 30 to 90, respectively, to optimize the performance for the coaxial LP-PPT.

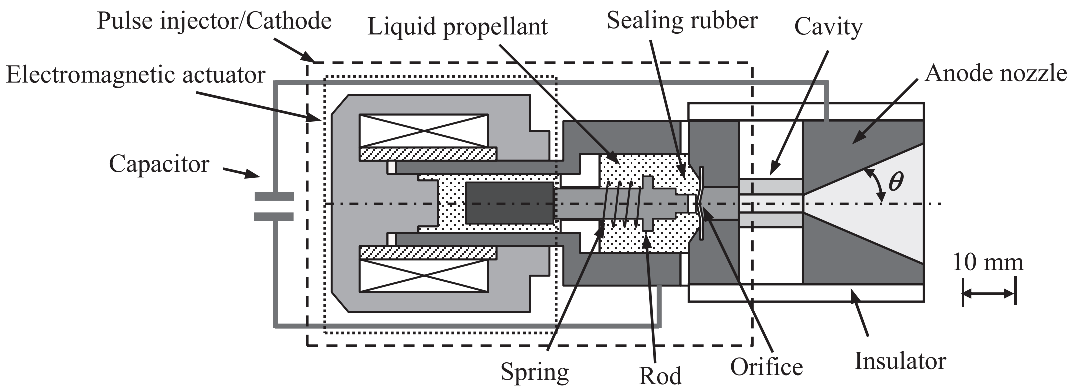

Figure 1. Schematic of a coaxial LP-PPT prototype.

III. Experimental

Figure 2 and Table 1 show an experimental setup and conditions, respectively. The LP-PPT prototype and a thrust target for measuring impulse bit are placed in a vacuum chamber. Back pressure in the vacuum chamber is kept below 0.03 Pa with a rotary pump and a turbo molecular pump. Three 1.5 μF mica paper capacitors are connected in parallel to raise a capacitor-stored energy. Capacitor-stored energy is varied up to 15 J by adjusting charging voltage. Pulse-arc discharge current is measured using a Rogowski coil with a resistance-capacitance integrator circuit, and recorded with an oscilloscope.

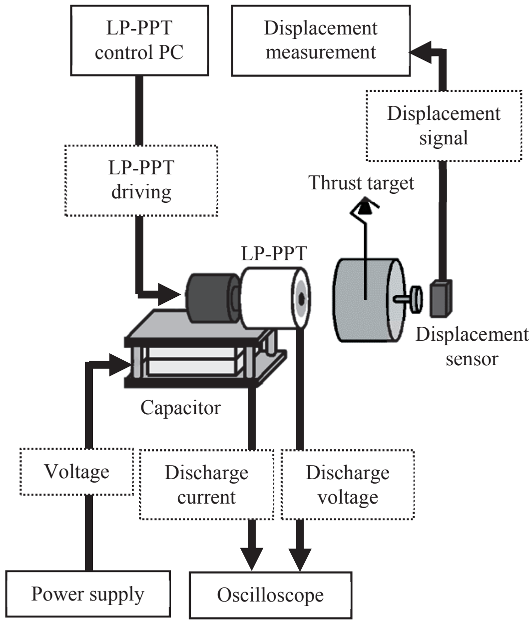

Figure 2. Experimental setup.

A. Mass Shot

Ethanol is used as a propellant. Injected ethanol mass is regulated by the pulse width and driving voltage for the pulse injector. An average mass shot is calculated by dividing difference in the injector weight before and after repetitive injection by the number of injections. Mass shot Δm is kept at 15 ± 1.5 μg in all tests.

B. Impulse Bit

Impulse bit is measured with a cylindrical thrust target. A plume of the LP-PPT impinges the thrust target and then, alters its direction in perpendicular to the thruster machine axis by a train of annular target plates and a subsequent conical target. Since an amplitude of the pendulum oscillation induced by an impulsive force is proportional to the magnitude of impulse, impulse bit is determined from the pendulum displacement, which is measured with a LED-type displacement-sensor.

Table 1. Experimental conditions.

Back pressure, Pa	$< 3 \times 10^{-2}$
Capacitance, μF	4.5
Capacitor-stored energy, J	0 ~ 15
Charging voltage, kV	0~ 2.58
Mass shot Δm, μg	15 ± 1.5
Propellant	Ethanol

IV. Results and Discussion

A. Influence of expansion angle

Figure 3 illustrates the time history of pulse-arc discharge current for the LP-PPT prototype with divergent angles θ of 10, 20, and 30°, at an area ratio ε of 30 and a capacitor-stored energy E of 11 J, where the time origin is a moment when the arc discharge was initiated. The discharge current exhibits a first peak of 11 kA at t = 0.8 μs, and a second peak of -2.5 kA at t = 2.8 μs. The discharge current was independent of divergent angle.

Figure 4 shows the influence of divergent angle on impulse bit. Impulse bit increases with enlarging divergent angle θ and capacitor-stored energy E, and has a maximum value of 130 μNs with θ = 30° at E = 15 J. Impulse bit seems to be proportional to the square of E, and from the result, thrust to power ratio is also rose with E as shown in Fig. 5. Thrust to power ratio was monotonically increased with θ at E =11 and 15 J, and achieves a maximum value of 8.1 μNs/J with θ = 30° at E = 15J.

Figure 6 shows the relation between thrust efficiency η_t and specific impulse I_{sp} for different divergent angle θ. Thrust efficiency increased with I_{sp} as quadratic or cubic curve.

B. Influence of area ratio

Area ratio affected the performance of the prototyped LP-PPT. The dependence of performance on area ratio is also influenced by divergent angle θ.

Figure 7 illustrates the time history of pulse-arc discharge current for the LP-PPT prototype with area ratios ε of 30, 60, and 90, at a divergent angle θ of 20° and a capacitor-stored energy E of 11 J. While the prototype with ε = 60

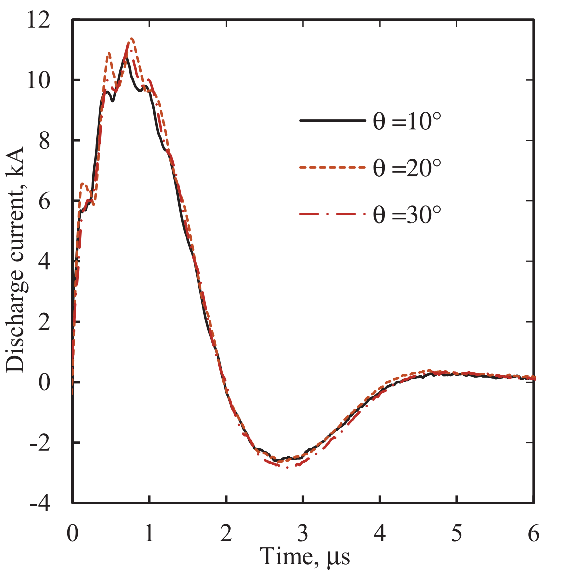

Figure 3. Time history of discharge current for different divergent angle.

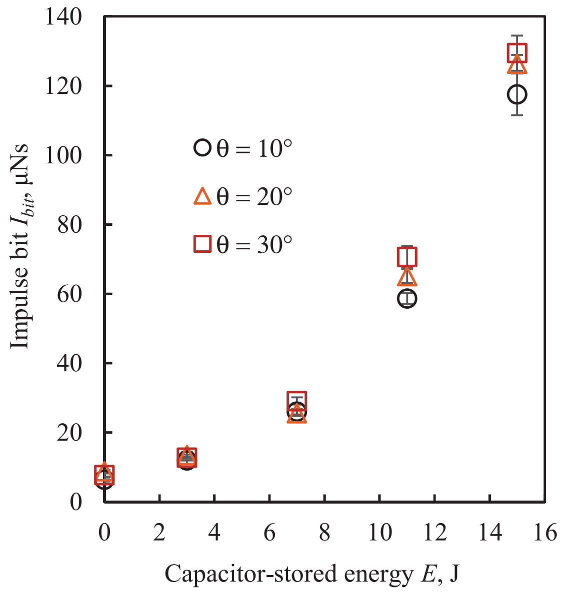

Figure 4. Influence of divergent angle on impulse bit.

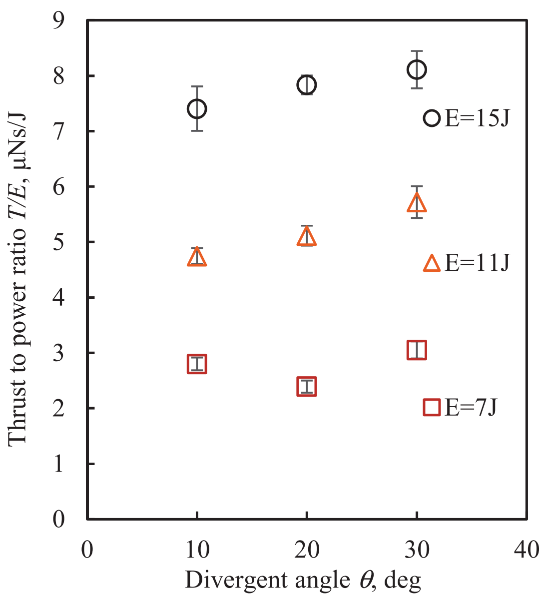

Figure 5. Relation between thrust to power ratio and divergent angle for different capacitor-stored energy.

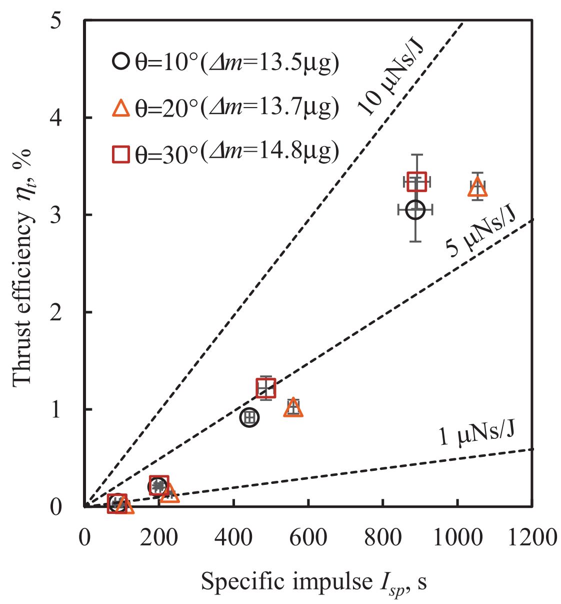

Figure 6. Relation between thrust efficiency and specific impulse for different divergent angle.

yields larger second peak current of -3.2 kA at t = 2.7 μs than that with other ε, first peak of discharge current was not influenced by area ratio ε.

In contrast, area ratio affected impulse bit. Figure 8 shows the influence of area ratio ε on impulse bit, at a divergent angle θ of 20°. The prototype with ε = 30 presents the highest impulse bit among area ratios tested. In all area ratios tested, increasing capacitor-stored energy monotonically augments impulse bit.

Figure 9 shows the relation between thrust to power ratio T/E and area ratio ε, at a divergent angle θ of 20°. The prototype with ε = 30 yielded a T/E of 5.1 μNs/J at E = 11 J, which was 23 % greater than that with ε = 60.

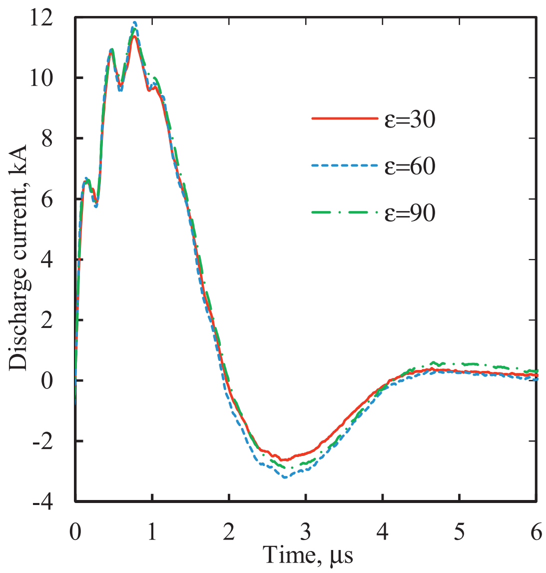

Figure 7. Time histories of discharge current for different area ratio, at a divergent angle of 20°.

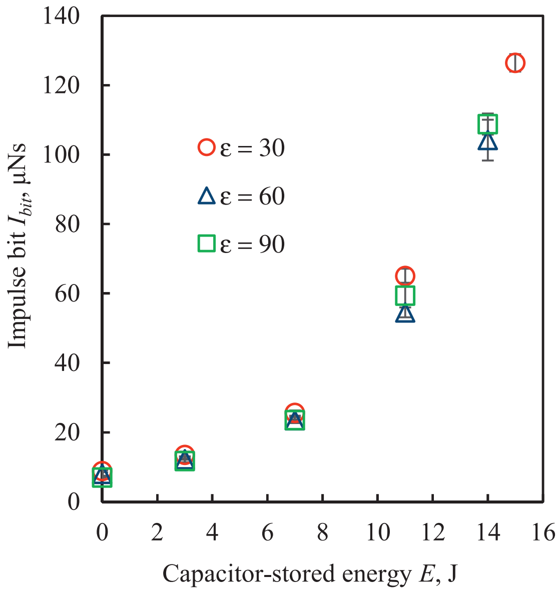

Figure 8. Influence of area ratio on impulse bit, at a divergent angle of 20°.

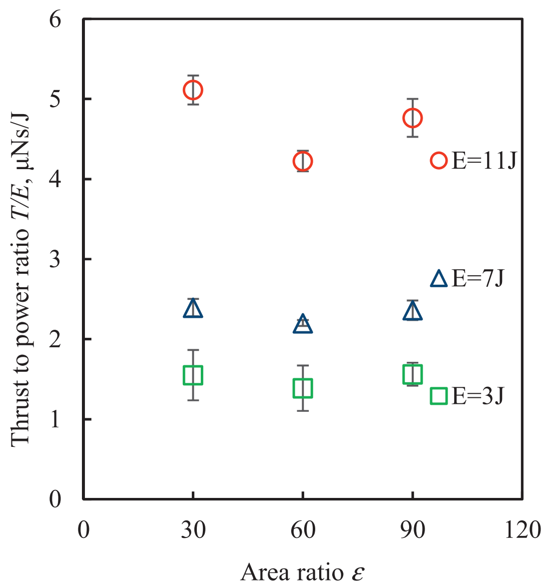

Figure 9. Relation between thrust to power ratio and divergent angle for different capacitor-stored energy, at a divergent angle of 20°.

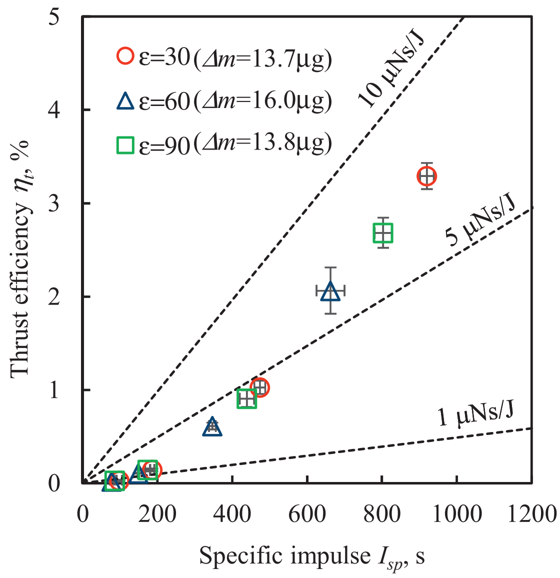

Figure 10. Relation between thrust efficiency and specific impulse for different area ratio, at a divergent angle of 20°.

Thrust efficiency η_t increases with increasing specific impulse I_{sp}, and reaches up to 3.2 % with $\varepsilon = 20$ and $\theta = 20°$, at $E = 15$J, as shown in Fig.10.

The prototype with $\theta = 30°$ exhibited different tendencies on performance from those with $\theta = 20°$. Figure 11 illustrates the time history of pulse-arc discharge current for the LP-PPT prototype with area ratios ε of 30, 60, and 90, at a divergent angle θ of 30° and a capacitor-stored energy E of 11 J. Discharge current was not influenced by area ratio as with $\theta = 20°$.

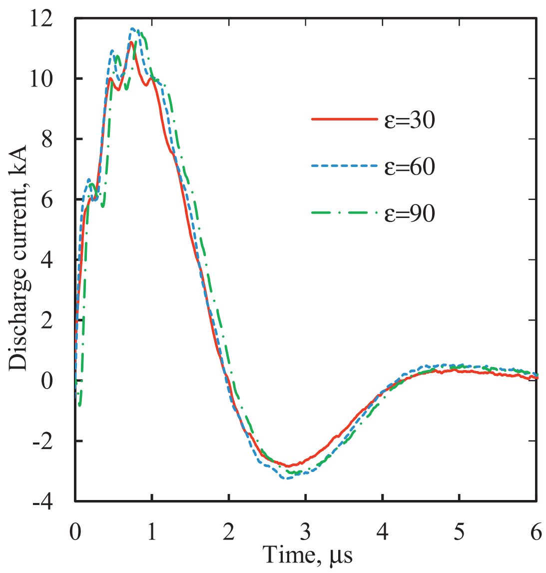

Figure 11 Time histories of discharge current for different area ratio, at a divergent angle of 30°.

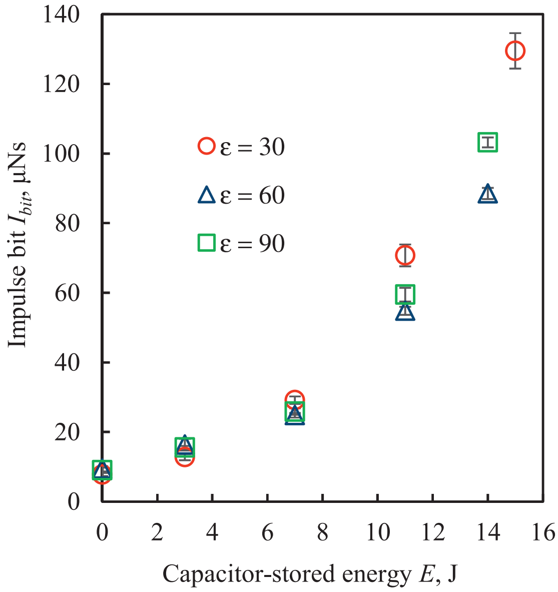

Figure 12. Influence of area ratio on impulse bit, at a divergent angle of 30°.

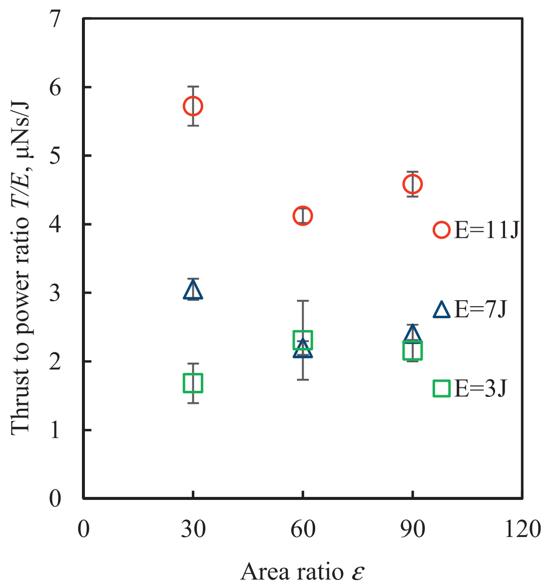

Figure 13. Relation between thrust to power ratio and divergent angle for different capacitor-stored energy, at a divergent angle of 30°.

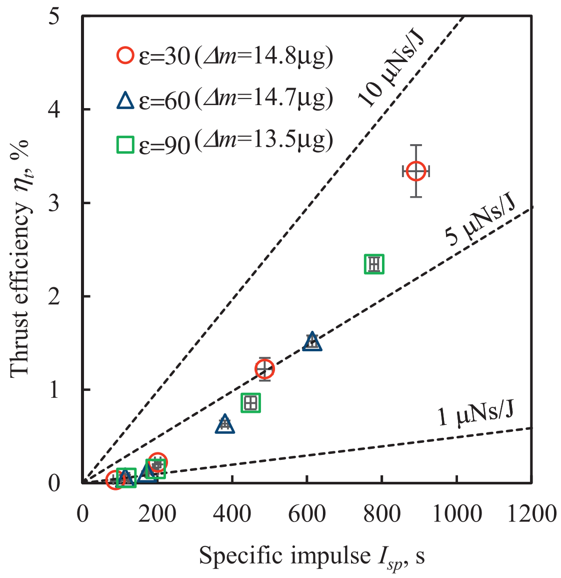

Figure 14. Relation between thrust efficiency and specific impulse for different area ratio, at a divergent angle of 30°.

Dependence of impulse bit on capacitor-stored energy is similar that for $\theta = 20°$. Figure 12 shows the influence of area ratio ε on impulse bit, at a divergent angle θ of 30°. The prototype with $\varepsilon = 30$ yielded the highest impulse bit among area ratios tested. The influence of area ratio was the same as that for $\theta = 20°$.

In contrast, the influence of area ratio ε on thrust to power ratio T/E was more significant at $\theta = 30°$ than that at $\theta = 20°$, as shown in Fig.13. Whereas the prototype with $\varepsilon = 60$ exhibits the lowest thrust to power ratio at E = 7 and 11 J, the prototype with $\varepsilon = 60$ presents the highest value at E = 3 J.

The relation between thrust efficiency η_t and specific impulse I_{sp} for different area ratio ε at a divergent angle θ of 30° is similar that at θ = 20° as shown in Fig. 14. The prototype with ε = 30 produces the highest thrust efficiency of 3.3 %, at θ = 30° and E = 15 J.

V. Summary

In this study, with different divergent angle and area ratio of an anode nozzle varied from 10° to 30°, and 30 to 90, respectively, the influence of electrode configuration on the performance of the LP-PPT was examined. The following is the summary of this paper.

1) The LP-PPT prototype with a divergent angle θ of 30° and an area ratio ε of 30 yielded the highest impulse bit of 130 μNs, thrust efficiency of 3.3 %, and thrust to power ratio of 8.1 μNs/J, at a capacitor-stored energy E of 15 J and a mass shot Δm of 14.8 μg.
2) The prototype with θ = 20° and ε = 30 provided the highest specific impulse of 920 s due to its small mass shot Δm = 13.7 μg, at E = 15 J.
3) With ε = 30, thrust to power ratio monotonically increased with divergent angle, at E = 11 and 15 J.
4) The prototype with ε = 60 presented the lowest thrust when divergent angle was set both at 20° and 30°.

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