Characterization of a Liquid-propellant Pulsed Plasma Thruster Using Various Nozzle Configurations

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Liquid-propellant pulsed plasma thrusters (LP-PPTs) perform better than conventional solid-propellant (typically PTFE) PPTs because the use of an LP can eliminate the problems of late-time ablation and particulate emission associated with solid propellants. In the present study, the performance and characteristics of a prototype LP-PPT are investigated using a range of nozzle and electrode configurations. Two types of conical nozzles were tested: a ceramic nozzle with an annular anode placed at the nozzle tip and a monolithic-anode nozzle made of stainless steel. The area ratio ε, divergent angle θ, and cavity length L of the ceramic nozzle were varied from 10 to 30, 10° to 40°, and 5 to 20 mm, respectively. Ethanol was used as the propellant. The thrust measurements showed that the LP-PPT prototype demonstrated superior performance when it was fitted with the embedded annular anode ceramic nozzle than when it was fitted with the monolithic-anode nozzle. Among all of the tested nozzle configurations, the highest performance was observed for a ceramic nozzle with ε = 30, θ = 20°, and L = 10 mm, which yielded an impulse bit of 167 µNs, a specific impulse of 1,150 s, a thrust efficiency of 5.9%, and a thrust–power ratio of 11 µNs/J at a capacitor-stored energy of 14 J and a propellant mass shot of 14.8 µg.

Key Words: Pulsed Plasma Thruster, Liquid Propellant, Nozzle Configurations

Nomenclature

- $C_0$: electrical capacitance, F
- $E$: capacitor stored energy, J
- $g$: gravitational acceleration, m/s²
- $I_{ba}$: impulse bit, Ns
- $I_{ET}$: impulse bit by electrothermal acceleration, Ns
- $I_{EM}$: impulse bit by electromagnetic acceleration, Ns
- $I_{sp}$: specific impulse, s
- $J$: discharge current, A
- $L$: cavity length, mm
- $L_0$: electrical inductance, H
- $R_0$: electrical resistance, Ω
- $r_i$: inner radius of annular electrode, mm
- $r_c$: radius of central electrode, mm
- $t$: time, s
- $T/P$: thrust–power ratio, Ns/J
- $\alpha$: logarithmic decrement, 1/s
- $\varepsilon$: area ratio
- $\Delta m$: mass shot, kg
- $\theta$: divergent angle, deg
- $\eta_t$: thrust efficiency
- $\mu_0$: permeability constant, H/m
- $\omega$: angular frequency, rad/s

1. Introduction

A pulsed plasma thruster (PPT) is an electric propulsion device that produces an impulse thrust using both electromagnetic and electrothermal acceleration. Recently, the PPT has been attracting attention as a potential microthruster owing to key features such as 1) light weight and compactness, 2) low power consumption, 3) discrete impulse thrust, and 4) the ability to fire without warming up.1–5) Features 1) and 2) allow PPTs to be applied in small, low-power satellites such as micro- or nanosatellites. Features 3) and 4) enable PPTs to provide precise attitude control and station-keeping.1)

Owing to these advantages, some universities and companies have built prototype PPTs for microsatellites. Busek and Mars Space Ltd. prototyped the mPPT2) and Pulsed Plasma Thruster for CubeSat Propulsion (PPTCUP),3) respectively. Kyushu Institute of Technology and Nanyang Technological University developed the microsatellite ABOA-VELOX III, equipped it with PPTs and released it from ISS on January 2017.4) Osaka Institute of Technology is developing micro-PPTs for microsatellite PROITERES 2.5)

Conventional PPTs (ablative PPTs or A-PPTs) use solid polytetrafluoroethylene (PTFE) propellants and suffer from contamination due to propellant vapor. The plume from an A-PPT may cause damage to solar panels and to the optics of observation devices because PTFE contains carbon atoms that charring, and fluorine atoms that are reactive with most materials.1) Nonuniform propellant consumption by A-PPTs causes the shape of the propellant surface to change after repetitive firing. Consequently, more propellant is consumed near the center, and eventually, the propellant at the periphery remains unused at the end of operation. This requires extra propellant to be used to compensate for the propellant that remains unused. The resulting nonuniformity of the propell-
lant surface may also induce misfiring owing to a change in distance between the spark plug and the propellant surface. One study reported that a higher spark voltage was needed to ensure ignition during repetitive firings.\textsuperscript{6} A-PPTs have thrust efficiencies 5% to 15% lower than those of other electric propulsion devices at a capacitor-stored energy of approximately 10 J\textsuperscript{7} because most of the ablated propellant is unused or is not accelerated by pulse-arc discharge owing to two processes: late-time ablation and particulate emission.\textsuperscript{8,9} In late-time ablation, the solid propellant continues to sublime after the pulse-arc discharge is halted because the temperature of the arc-heated propellant surface remains above the sublimination point, and this sublimed PTFE is expelled without being accelerated effectively. In particulate emission, low-speed solid particles emitted from the heated surface are not accelerated by arc discharge and hence produce negligible thrust.

In an attempt to improve propellant utilization, other solid propellants have been tested as alternatives to PTFE. Guman conducted thrust measurements using Kynar\textsuperscript{8}, Viton\textsuperscript{8}, and other propellants.\textsuperscript{10} However, most of the propellants that have been tested yield specific impulses lower than that of PTFE, and PTFE remains the most suitable solid propellant for A-PPTs.

Several gases and liquids have also been tried as PPT propellants. Ziemer proposed a gas-fed PPT in which Ar or water vapor was injected through a high-response gas valve and accelerated by a train of pulsed-arc plasmas provided by large capacitor banks.\textsuperscript{11} The gas-fed PPT successfully produced thrust with a specific impulse of 10,000 s, but the heavy capacitor banks imposed a low payload ratio. Scharlemann used a porous material to feed small amounts of liquid propellant in gaseous form.\textsuperscript{12} In their thruster, however, the propellant flowed passively, and excess propellant was fed after the pulsed-arc discharge was completed. Szelecka et al. proposed the use of a perfluoropolyether fluid as a PPT propellant to improve thrust efficiency, but the plume from their PPT contained C and F ions in the same way as those from conventional PPTs.\textsuperscript{13} A method to overcome the problems is to inject an adequate mass of propellant into an electrical-discharge channel prior to pulsed-arc discharge. For space applications, the use of liquid propellant is advantageous because no high-pressure tanks are required, allowing the weight and size of the satellite to be reduced.

To increase the propellant utilization of PPTs and match the impulse bit and capacitor-stored energy levels of conventional PPTs, Kakami et al. proposed a liquid propellant PPT (LP-PPT).\textsuperscript{14,15} In this LP-PPT, droplets are injected into an electrical-discharge channel just before initiation of the pulsed-arc discharge and become ionized, thereby producing thrust by both electromagnetic and electrothermal acceleration. A pulsed droplet injection system that is synchronized with the pulsed-arc discharge would allow LP-PPTs to utilize most of the injected propellant and produce small discrete thrusts at arbitrary times. Non-toxic and eco-friendly liquids such as water and ethanol are good candidates as LP-PPT propellants. In thrust measurements, an LP-PPT with parallel-plate electrodes yielded a specific impulse of 4,300 s, higher than that of conventional PTFE PPTs, at a capacitor-stored energy of 20 J.\textsuperscript{16}

Although thruster configurations of LP-PPTs are surely expected to affect the performance, characterizations through systematic measurements using various nozzles have not been reported yet. In this study, we experimentally characterized the performance of an LP-PPT using various types of nozzles with coaxial electrodes and different configurations of electrode type, cavity size, area ratio, and divergent nozzle angle. Such a coaxial electrode LP-PPT potentially offers a thrust–power ratio higher than those of parallel-plate electrode LP-PPTs because of the assistance provided by electrothermal acceleration.\textsuperscript{16,17}

2. Coaxial LP-PPT Prototype

Figure 1 shows a schematic of our coaxial-electrode LP-PPT prototype. It includes a pulse injector that also serves as a cathode, as well as a nozzle with a cavity. The pulse injector consists of an electromagnetic actuator, a spring and rod, a rubber seal, and an orifice with an inner diameter of 25 µm. The rubber seal covers the orifice to prevent the liquid propellant from being expelled by the spring force of the rod. When a pulse voltage is applied to the electromagnetic actuator, liquid propellant is injected through the orifice into the cavity. The cavity has an inner diameter of 3 mm and is made of machinable ceramic to insulate the electrodes and withstand the high heat flux from the arc plasma. The droplets injected evaporate, increasing the cavity pressure and inducing a spontaneous pulsed-arc discharge, eliminating the need for an ignitor. This spontaneous ignition mechanism allows the size and weight of the LP-PPT to be reduced.

The nozzle and anode geometry must be designed to enhance both the electromagnetic and electrothermal accelerations. The impulse bit of a coaxial PPT is described by the sum of the electromagnetic and electrothermal components:

\[ I_{\text{bit}} = I_{\text{EM}} + I_{\text{ET}} \]  

(1)

Assuming that the current density profile is axisymmetric in a discharge channel, the impulse bit by electromagnetic acceleration can be written as

\[ I_{\text{EM}} = \frac{\mu_0}{2\pi} \left( \ln \frac{r_a}{r_c} + \frac{3}{4} \right) \int J^2 dt \]  

(2)

where \( \mu_0 \) is a permeability constant, \( r_c \) is the inner radius of the cavity, and \( J \) is the current density.
the annular electrode, \( r_c \) is the radius of the central electrode, and \( J \) is the arc discharge current.\(^1\) The electrothermal acceleration is a combination of joule heating and aerodynamic acceleration of the plasma in the nozzle. The electromagnetic component of the impulse bit for a coaxial LP-PPT can be enhanced by increasing the electrode–radius ratio \( r_a/r_c \). Two types of nozzles were therefore prototyped in an attempt to improve the impulse bit. Nozzle A was the ceramic nozzle with an annular stainless-steel anode shown in Fig. 2(a). Nozzle B is the monolithic stainless-steel nozzle illustrated in Fig. 2(b). Nozzle A is designed such that aerodynamic acceleration is enhanced rather than electromagnetic acceleration in order to enhance the thrust-to-power ratio. Since arc discharge current was confined in the cavity, the plasma was heated with Joule heat and become radially compressed by electromagnetic force (pumping force). Then, the plasma aerodynamically accelerated in the divergent section.

In contrast, the nozzle B design emphasizes electromagnetic acceleration to produce a higher specific impulse. The arc-discharge current is curved in the divergent section, and accordingly exerts electromagnetic force toward the nozzle exit (blowing force). This design enables the thruster to produce higher velocity plasma owing to the direct acceleration resulting from the electromagnetic force.

Both nozzles have a comparatively simple design, whereas studies on MPD tested and proposed various nozzle geometries, some of which might be effective for LP-PPTs. However, the knowledge discovered in MPD studies is not always applicable to LP-PPTs. This is because the LP-PPT yielded a concentrated mass density profile of the propellant in the electrical-discharge channel due to droplet injection, whereas MPD would present almost uniform profiles. Moreover, there are a few studies on coaxial LP-PPTs. Hence, to obtain baseline data for coaxial LP-PPTs, simple nozzles were designed.

Both nozzles were tested under condition 1 in Table 1. Area ratio \( \varepsilon \) is the area ratio of the nozzle exit to the throat. In condition 1, the aerodynamic acceleration of the two nozzles would be the same as they had the same divergent angle and area ratio. Any difference between the performances of the two nozzles could therefore be attributed to a difference between the electromagnetic acceleration and joule heating of their plasmas. For nozzle A, the area ratio \( \varepsilon \), divergent angle \( \theta \), and cavity length \( L \), which influence electrothermal acceleration, were varied from 10 to 60, 10° to 40°, and 5 to 20 mm, respectively. The area ratio is the area ratio of the nozzle outlet and throat.

3. Experiment

3.1. Apparatus

Figure 3 shows a schematic of the experimental apparatus. The LP-PPT prototype and a cylindrical thrust target used to measure the impulse bit were placed in a vacuum chamber with an inner diameter of 260 mm and a length of 600 mm. The pressure in the vacuum chamber was kept below \( 3 \times 10^{-2} \) Pa using a rotary pump and a turbo molecular pump. Three 1.5 \( \mu \)F mica paper capacitors (SOSHIN, CMP92B202155K-02) were connected in parallel, and the capacitor-stored energy was varied from 8 to 14 J by adjusting the charging voltage. The propellant injection was controlled by a computer placed outside of the vacuum chamber.

3.2. Pulsed-arc discharge measurement

The pulsed-arc discharge current was measured using a Rogowski coil with a resistance-capacitance integrator circuit at a time constant of 0.27 ms, and recorded by an oscilloscope (Tektronix, TDS3000). The Rogowski coil was calibrated beforehand using a current monitor (Pearson, 5046).

The electric inductance and electric resistance were determined using the temporal variation of the pulsed-arc discharge current. Since the circuit for the capacitors and PPTs were assumed to be an inductance–capacitance–resistance circuit, the time variation in the discharge current is written as

\[
J = J_0 \exp(-\alpha t) \sin \omega t
\]

\[
\alpha = \frac{R_0}{2L_0}
\]
and ethanol have the same dependence of performance, \(^{15}\) suitable for the actual PPT use. Nevertheless, since water possesses the possibility of inducing charring, and therefore may not be used as alternative propellant for water to clarify the performance of a co-axial electrode LP-PPT.

3.3. Propellant
Ethanol was used as the propellant even though there is a possibility of inducing charring, and therefore may not be suitable for the actual PPT use. Nevertheless, since water and ethanol have the same dependence of performance, \(^{15}\) ethanol can be used as alternative propellant for water to clarify the performance of a co-axial electrode LP-PPT.

The mass shot \(\Delta m\), which is the mass of the propellant injected in each shot, was adjusted using the actuator-driving voltage and its pulse width. The average \(\Delta m\) was calculated by dividing the difference between the injector masses before and after injection by the number of injection. The average \(\Delta m\) was set and maintained at 15 ± 1.5 \(\mu g\) in all of the tests.

3.4. Impulse bit measurement
The impulse bit of the LP-PPT prototype was measured using a cylindrical thrust target whose front plate had an inner diameter of 65 mm. When the plume from the LP-PPT impinged upon the thrust target, its axial momentum was transferred to the thrust target. Because the amplitude of the pendulum oscillation induced by an impulsive thrust jet is proportional to the magnitude of the impulse momentum, the impulse bit was determined from the pendulum displacement, measured by a displacement sensor (OMRON, ZAD-D01). In each experiment, the impulse bit was measured five times, and the standard deviations were calculated and shown with error bars. To calculate the specific impulse \(I_{sp}\), thrust efficiency \(\eta_t\), and thrust–power ratio \(T/P\), the following equations were used:

\[
I_{sp} = \frac{I_{bit}}{\Delta m g} \quad (6)
\]

\[
\eta_t = \frac{P_{bit}}{\Delta m g} \quad (7)
\]

\[
T/P = \frac{I_{bit}}{E} \quad (8)
\]

The accuracy of the thrust measurement is influenced by the distance between the target and the thruster. Yanagi and Kimura studied this measurement error using a cylindrical thrust target and several types of PPT, and concluded that the experimental error was less than 3% when the distance was less than 40 mm. \(^{18}\) Hence, all of the tests in this study were conducted at a distance of 20 mm.

The cylindrical thrust target was calibrated using reference impulses provided by a moving steel ball with a mass of 0.58 g. The velocities of the ball before and after impact were measured from high-speed video recordings. The reference impulse given to the thrust target was determined by calculating the product of the velocity and mass of the steel ball. Calibrations showed that the pendulum displacement was proportional to the reference impulse.

\[
\omega = \sqrt{\frac{1}{L_0 C_0} - \left(\frac{R_0}{2L_0}\right)^2} \quad (5)
\]

where \(C_0, L_0, R_0, \alpha, \) and \(\omega\) are the capacitance, electrical inductance, resistance, logarithmic decrement, and angular frequency, respectively. \(L_0\) and \(R_0\) were determined from \(\alpha\) and \(\omega\) using the temporal history of the discharge current.

Since it is impossible to perfectly confirm accuracy and reliability, the authors believe that the target method is just a tentative method for preliminary study or studies on propulsion devices that require large and heavy plasma sources and accelerators. Hence, the target method was used to clarify the dependence of performance on nozzle configuration using the authors’ small vacuum chamber.

4. Results and Discussion

4.1. Electrical-discharge current and resistance
With all of the nozzle configurations tested, the LP-PPT prototype successfully produced pulsed-arc plasmas and induced spontaneous arc discharge without misfiring.

We analyzed, in detail, the case where the capacitor-stored energy was 14 J. Figure 4 shows the discharge current history of the prototype with nozzles A and B, where the time origin is the moment at which the arc discharge was initiated. Nozzle B exhibits first and second peak currents higher than those of nozzle A, and a third peak current at \(t = 5 \mu s\). These differences suggest that the electrical resistance of the LP-PPT with nozzle A was higher than that of nozzle B. The calculation using Eq. (3) yielded electrical resistances of \(R_0 = 131 \text{ m}\Omega\) for nozzle A and 98 m\(\Omega\) for nozzle B. Figures 5–7 show the time histories of the pulsed-arc discharge current at different values of \(\varepsilon, \theta, \) and \(L\). The first and second peaks of the arc-discharge current attenuate as \(\varepsilon\) and \(L\) increase and \(\theta\) decreases. The attenuations of the discharge current may have resulted from elongation of the arc-discharge current path and a resulting increase in the electrical resistance of the plasma. The electrical resistances \(R_0\) in Fig. 5 were calculated to be, for instance, 118, 131, and 136 m\(\Omega\) for \(\varepsilon = 10, 30, \) and 60, respectively.

The dependence of \(R_0\) on nozzle geometry would be accountable using divergent-section length, which affects the length of the arc discharge current path. At a certain \(\varepsilon\) with
the fixed exit diameter, divergent-section length is decreased as $\theta$ increases, and accordingly, $R_0$ is reduced. On the other hand, at a certain $\theta$, increasing $\varepsilon$ increases the divergent-section length, which increases $R_0$.

4.2. Performance characteristics

4.2.1. Nozzle geometry

Thrust measurements conducted under condition 1 showed that nozzle A performed better than nozzle B. Figure 8 shows the impulse bits for nozzles A and B at $E = 8$–14 J. At $E = 14$ J, the LP-PPT prototype with nozzle A exhibits the highest impulse bit of $I_{\text{bit}} = 167\mu$Ns, which is 40% larger than that of nozzle B. Figure 9 shows the relationship between $I_{\text{sp}}$ and $\eta_1$ for nozzles A and B, with the four dotted lines depicting the cases with $T/P$ of 1, 5, 10, and 15 $\mu$Ns/J. The prototype with nozzle A shows the highest performance, with $I_{\text{sp}} = 1,150\mu$Ns, $\eta_1 = 5.9\%$, and $T/P = 11.2\mu$Ns/J at $E = 14$ J and $\Delta m = 14.8\mu$g.

4.2.2. Area ratio

Figures 10 and 11 show the performance characteristics of the LP-PPT prototype with different area ratios $\varepsilon$. The electrode–radius ratio $r_a/r_c$ of nozzle A was determined to be 5.5, and the theoretical electromagnetic impulse bit at $E = 14$ J was calculated to be 58 $\mu$Ns using Eq. (2). If $r_a/r_c$ is assumed to be unity for nozzle B, so that the anode spots stay near the nozzle inlet, the theoretical electromagnetic impulse bit would be 28 $\mu$Ns. This theoretical difference in impulse bits is lower than the experimentally measured one. It is hence inferred that nozzle A could offer higher additional electrothermal acceleration than nozzle B, probably because nozzle A, which showed higher electrical resistance than nozzle B, produced higher joule heating.

The impulse bits for nozzles A and B at different capacitor-stored energies.

The electrode–radius ratio $r_a/r_c$ of nozzle A was determined to be 5.5, and the theoretical electromagnetic impulse bit at $E = 14$ J was calculated to be 58 $\mu$Ns using Eq. (2). If $r_a/r_c$ is assumed to be unity for nozzle B, so that the anode spots stay near the nozzle inlet, the theoretical electromagnetic impulse bit would be 28 $\mu$Ns. This theoretical difference in impulse bits is lower than the experimentally measured one. It is hence inferred that nozzle A could offer higher additional electrothermal acceleration than nozzle B, probably because nozzle A, which showed higher electrical resistance than nozzle B, produced higher joule heating.

4.2.2. Area ratio

Figures 10 and 11 show the performance characteristics of the LP-PPT prototype with different area ratios $\varepsilon$. The ratio $\varepsilon = 30$ exhibits the highest impulse bit among all of the $\varepsilon$ values tested for any $E$, as shown in Fig. 10. Impulse bit yielded a peak at $\varepsilon = 30$, whereas increasing $\varepsilon$...
Theoretically enhances both aerodynamic and electromagnetic thrusts. Hence, there would be factors that reduce the impulse bit in a higher $\varepsilon$ region, and one of the factors might be a heat loss increase. As shown in 4.1, a rise in $\varepsilon$ enlarged $R_0$, and this is attributable to extending the arc-discharge current path in the divergent section. Hence, Joule heat production in the divergent section was increased to increase heat loss in the nozzle wall would be raised. Hence, the dependences of heat loss and $T_{\text{EM}}$ on $\varepsilon$ induce a local maximum for the impulse bit.

### 4.2.3. Divergent angle and cavity length

The effect of the LP-PPT divergent angle $\theta$ is shown in Figs. 12 and 13. The highest performance among all of the $\theta$ values tested occurs at $\theta = 20^\circ$. As $\theta$ increases, the impulse bit increases up to $\theta = 20^\circ$ and then decreases.

A drop in impulse bit for $\theta > 20^\circ$ is accountable using a correction factor. Increasing $\theta$ raises the divergent angle of the plasma jet near the nozzle wall, and reduces thrust. In
contrast, larger $\theta$ lowered $R_p$, and suppressed heat loss to nozzle wall. Hence, the dependences of correction factor and heat loss on $\theta$ yielded a peak of impulse bit.

Figures 14 and 15 show the performance of the LP-PPT with different cavity lengths $L$. The highest performance is evident at $L = 10$ mm. The performance of this LP-PPT shows no monotonic changes with increases in $\theta$ or $L$. The trends are similar to those discussed for $\varepsilon$ and may have the same cause.

5. Conclusions

The performance of a prototype LP-PPT with various nozzle configurations was characterized experimentally. An LP-PPT using a ceramic nozzle with an embedded annular anode demonstrated performance superior to that of one using a monolithic-anode nozzle. This may reflect increases in both electromagnetic and electrothermal accelerations. Among the nozzle configurations tested, the model with an area ratio of 30, a divergent angle of 20°, and a cavity length of 10 mm showed the highest performance, yielding an impulse bit of 167 $\mu$Ns, a specific impulse of 1,150 s, a thrust efficiency of 5.9%, and a thrust-power ratio of 11 $\mu$Ns/J at a capacitor energy of 14 J and a mass shot of 14.8 $\mu$g. Other nozzle configurations showed significantly worse performance.

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