Multi-injection Type Pulsed Plasma Thruster Using Water Propellant

By Akinori HOSHI,[1)] Atsushi KURANAGA,[1)] Keita NISHII,[1)] and Akira KAKAMI[1)]

[1)] *Tokyo Metropolitan University, Hino, Japan*

In this study, we designed and tested a 25J pulsed plasma thruster (PPT) with multiple injections of water propellant to enhance the thrust-to-power ratio. PPTs generally uske solid polytetrafluoroethylene (PTFE) as a propellant. However, the use of PTFE contaminated the electrodes and the PTFE surface due to charring. Moreover, the propellant was lost without contributing thrust production through late-time ablation and particulate emission. Therefore, we focused on water owing to its storability, availability, and controllability of flow rate. However, our previous study of PPT using water propellant presented a lower thrust-to-power ratio than PTFE-propellant PPTs. This seems attributable to poor propellant utilization because of the mismatch of the spatial distributions of droplets and discharge current. Hence, we examined multiple injections of water droplets into the discharge chamber. This study evaluates the influence of multiple injection on the main discharge current and voltage.

Key Words: Space Propulsion, Pulsed Plasma Thruster, Water propellant

Nomenclature

E	:	capacitor stored energy, J
Δm	:	mass shot, μg
$J(t)$	:	discharge current, A
V_0	:	Initial voltage across the capacitor, V
J_0	:	Initial amplitude of discharge current, A
R	:	Resistance in the discharge circuit, Ω
L	:	Inductance in the discharge circuit, H
C	:	Capacitance of the capacitor, F
ω	:	Angular frequency of the underdamped RLC circuit, rad/s
T	:	Characteristic damping time constant, s
α	:	Damping coefficient, 1/s
t	:	Time after initiation of discharge, s

1. Introduction

A pulsed plasma thruster (PPT) is an electric propulsion device that generates impulsive thrust through a combination of electromagnetic and electrothermal acceleration. Today, PPTs have emerged as an attractive option for microthrusters due to their unique features, such as 1) lightweight and compactness, 2) low power consumption, 3) discrete impulse thrust, and 4) the ability to fire without warming up.[1~4)] 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)]

Due to these advantages, some universities and companies have built prototype PPTs for microsatellites. Mars Space Ltd prototyped the Pulsed Plasma Thruster for CubeSat Propulsion (PPTCUP).[2)] Kyusyu Institute of Technology and Nanyang Technological University developed the microsatellite AOBA-VELOX 3 equipped with PPTs and released it from ISS in January 2017.[3)] Osaka Institute of Technology developed micro PPTs for microsatellite PROITERES 2.[4)]

Conventional PPTs (ablative PPTs or A-PPTs) use solid polytetrafluoroethylene (PTFE) propellants but inherently face three major issues. The first issue is contamination caused by ablated propellant. The plume generated by an A-PPT may damage the solar panels and the optics of observation devices because the plume contained carbon and fluorine atoms, which induced charring and chemical damage.[1)]

The second issue is the nonuniform consumption of the propellant. Repetitive firing engraved propellant in specific regions such that a portion of the propellant was not usable. As a result, an additional propellant must be loaded to compensate for the unused portion. Change in the PTFE surface prolonged the distance to the spark plug to cause shot-to-shot variations in impulse bits and misfiring. Higher spark voltage was reportedly required to ensure ignition during repeated firings[5)] but possibly emits severe electromagnetic interference.

The third issue is propellant-loss processes such as “late-time ablation,” in which propellant continues to evaporate even after the arc discharge has ended, and “particulate emission,” in which low-speed solid particles emitted from the heated PTFE surface are not accelerated by arc discharge to produce negligible thrust.[6,7)] These processes led to a reduction in propellant utilization. As a result, 10-J class A-PPTs yielded thrust efficiencies of 5–15%, which were lower than those of the other electric propulsion systems. [8)]

In an attempt to overcome these problems, other solid propellants have been tested as alternatives to PTFE. Guman conducted thrust measurements using Kynar®, which is composed of Polyvinylidene fluoride, Viton®, which is composed of a vinylidene-fluoride copolymer, and hexafluoropropylene, and other propellants.[9)] However, most of the propellants that have been tested yield specific impulses lower than that of PTFE, and PTFE seems to be the most suitable solid propellant for A-PPTs.

Several gases and liquids have also been tried as PPT propellants. Ziemer proposed gas-fed PPTs (GFPPTs) in which Argon or water vapor were injected through high-response gas valves and accelerated by a train of pulsed-arc discharge provided by large capacitor banks.[10] GFPPTs successfully achieved 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.[11] In the thrusters, however, adjusting the flow rate and timing was not flexible enough that propellant was fed excessively or kept injected even after the completion of the pulse-arc discharge. Szelecka et al. proposed the use of a perfluoropolyether (PEFE) fluid as a PPT propellant to improve thrust efficiency, but the plume from their PPT contained Carbon and Fluorine ions in the same way as those from conventional PPTs.[12]

Therefore, Kakami et al. proposed a liquid-propellant PPT (LP-PPT).[13,14] The droplets are injected into a discharge channel just before initiation of pulsed-arc discharge and then ionized through the arc discharge to produce a thrust through both electromagnetic and electrothermal acceleration. The LP-PPT had a pulsed droplet injector, and ignition timing was adjusted using a spark plug. Hence, appropriate timings of the injector and spark plug could allow efficient propellant utilization. Water and ethanol are non-toxic and eco-friendly to be potential liquid propellants for LP-PPTs. A coaxial type LP-PPT yielded a specific impulse of 1150 s, thrust efficiency of 5.9 %, and thrust power ratio of 11 μNs/J using ethanol propellant.[15] The water propellant could yield comparative performance because the LP-PPT presented negligible dependence in performance on the propellant. In addition to its advantages in storability and availability, we focused on water as propellant. However, the thrust power ratio is low compared to the A-PPTs for a given capacitor-stored energies.

Magnetoplasma dynamic (MPD) thrusters, which have structures and acceleration processes that are similar to those of PPTs, were examined using water-direct injection. The thrust-to-power ratio was enhanced by injecting droplets through multiple injectors.[16] Hence, the appropriate spatial distribution of water droplets would improve the performance.

Therefore, we propose a multiple injection type PPT that allows the adjustment of the propellant spatial distribution in the discharge chamber. In this study, we examined multi-injection type PPT both under single-injection operation and multi-injection operation to evaluate the discharge characteristics.

2. Experimental

2.1. Multi-injection Type Pulsed Plasma Thruster

Figures 1 and 2 show schematics of a multi-injection type pulsed plasma thruster with dimensions; Fig. 3 presents a picture. The thruster was composed of coaxial electrodes made of stainless steel. The anode and cathode had diameters of 8.2 and 1.5 mm, respectively. A ceramic cavity and nozzle were placed between the anode and cathode. To prevent abnormal discharges, ceramic insulators were also installed on the end surface of the anode. The nozzle had a divergent angle of 20° to accelerate plasma both electromagnetically and electrothermally. The ceramic cavity had a cylindrical shape of 10 mm in length and 3 mm in inner diameter. The nozzle and cavity dimensions were designed with reference to a prototype that demonstrated the best performance among the liquid-propellant pulsed plasma thrusters developed in our laboratory.[15]

An igniter, which has a 1-mm-diam. cylindrical rod made of lanthanotid tungsten (La-W), is placed 5 mm from the cathode. This thruster has a central injector (Lee Corp., INKA2438010H) and two outer injectors. The injectors were connected to a water storage tank, as shown in Fig. 4. The injectors, which were the solenoid valves, injected the droplets through a 0.076-mm diameter orifice when driving voltage is applied to the solenoid. In single-injection operation, only the center injector was driven. For the evaluation of the injected mass per shot (mass shot) by the injectors, the injector repetitively fed water droplets 2,000 times for driving voltage pulse widths, and the weight of the tank and the injector was measured to determine the total injected mass. Figures 5 and 6 show the ambient-pressure history in the vacuum chamber for repetitive injection of water droplets into the vacuum chamber and a zoomed-up history for 300-400 s. The increments in the ambient pressure were induced by the repetitive feeding of droplets and would reflect the mass shot. The ambient pressure increment was almost the same; the reproducibility of the mass shot was negligible.

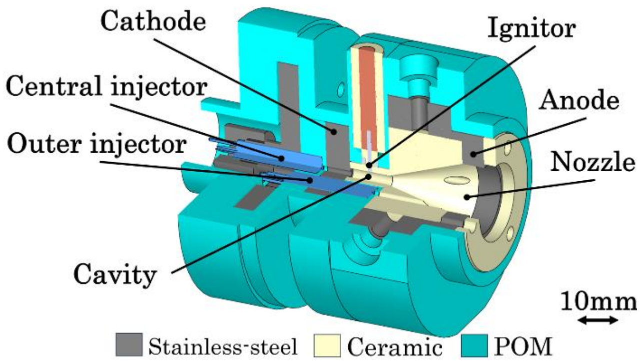

Figure 1. Schematic of the Multi-injection Type PPT

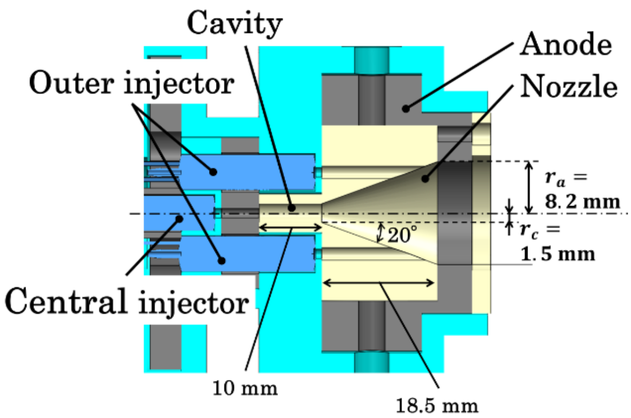

Figure 2. Dimensions of the Multi-injection Type PPT

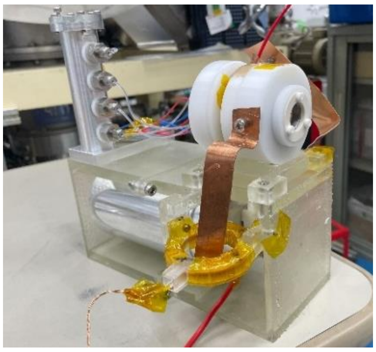

Figure 3. Multi-injection type PPT

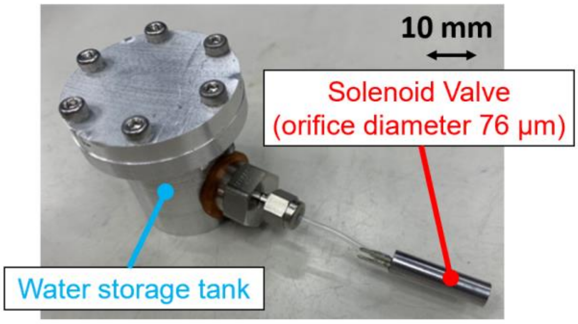

Figure 4. Injector and water storage tank

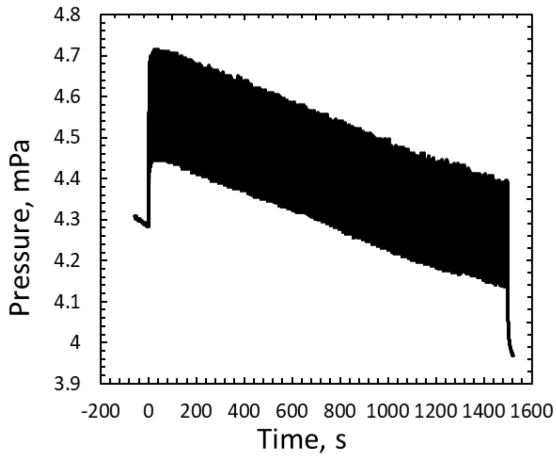

Figure 5. The pressure history in the vacuum chamber during repetitive injection.

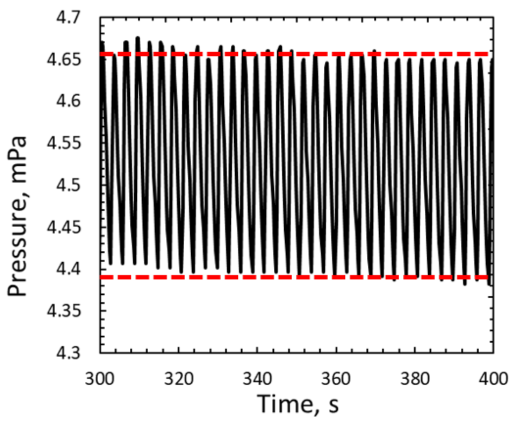

Figure 6. the pressure history between 300 and 400 seconds

2.2. Experimental setup

Figure 7 and Table 1 show a schematic of the experimental apparatus and conditions, respectively. The multi-injection type PPT and a thrust stand are placed in a vacuum chamber of 1.0 m in diameter and 1.8 m in length. Back pressures in the vacuum chamber were kept below 5.0×10^{-3} Pa using a rotary pump, a mechanical booster pump, and two turbomolecular pumps.

A 3000-V rated power supply charged a 15-μF polypropylene metalized film capacitor at 1800 V, so that capacitor-stored energy was 25 J. The electrical discharge path connecting the capacitor to the electrodes was constructed using copper. The discharge current and voltage were measured using a calibrated Rogowski coil and a 15 kV-rated high-voltage probe (HVP-15HF, PINTEK), respectively. These signals were recorded with a digital oscilloscope (MSO1074Z, RIGOL).

Thrust was measured using a torsional-type thrust stand, and the displacement was measured with a laser displacement sensor (Panasonic, HL-G103-S-J). Figures 8 and 9 show a schematic of the thrust stand and a schematic of a calibration device. The thrust stand was calibrated using a solenoid actuator and a piezoelectric load cell (PCB PIZEOTORNICS, 208C01), which was fixed on the thrust stand arm.

The Analog Discovery 2 (Digilent Inc.) was used to measure the pendulum displacement of the thrust stand and emit LV-TTL signals to the capacitor discharge ignition (CDI) circuit for the spark plug and injector drivers (Lee Corp, IECX0501350A). This is a multi-functional USB oscilloscope and signal generator. The injector driver initially provided a 24-V voltage spike for 0.35 ms and subsequently a 7.5-V voltage pulse to the injector until the input TTL signal became low. The spike voltage allowed the quick response of injection such that the response frequency reached 1000 Hz.

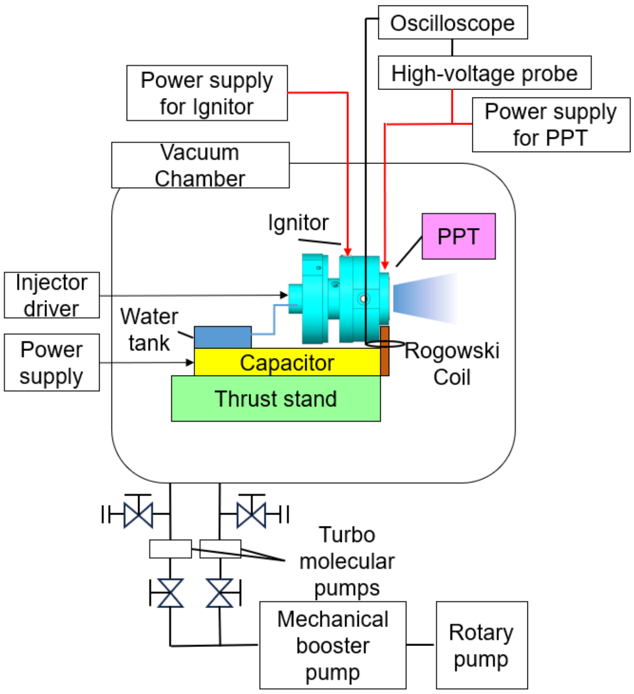

Figure 7. Schematic of experimental setup

Table 1. Experimental conditions

Back pressure, Pa	$< 5.0 \times 10^{-3}$
Capacitance, μF	15
Capacitor-stored energy *E*, J	25
Charged voltage, kV	1.8
Ignitor energy, J	90

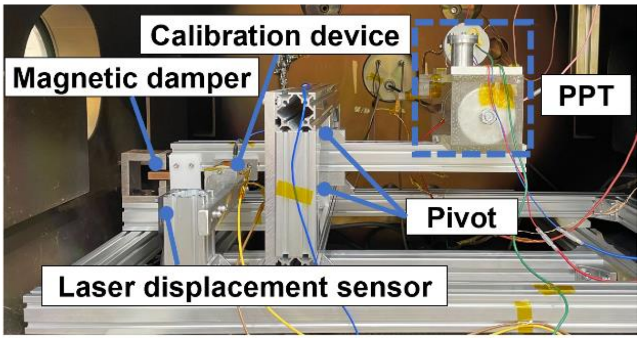

Figure 8. Schematic of Thrust stand

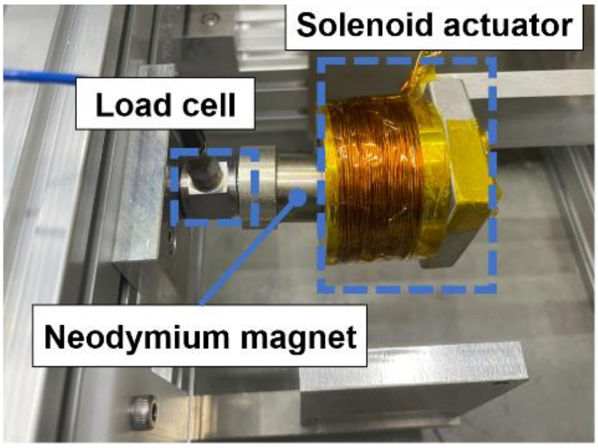

Figure 9. Schematic of Calibration device

3. Experimental Conditions and Procedures

Figure 10 shows the operation sequence for the single injection. The capacitor was first charged up using the power supply. The center injector was applied with a driving voltage pulse to supply propellant to the discharge channel, and then the ignitor was triggered to yield the main discharge. The voltage pulse width for the injector was determined such that the injected propellant mass was 54 μg. This procedure was conducted five times for a certain experimental condition to evaluate errors.

Figure 11 shows the operation sequence for multi-injection. The procedure was almost the same as that in the single injection except for the injection. The center and outer injectors were spontaneously excited with driving voltage pulses. The driving voltage for the injector was reduced to suppress the mass shot per injector to feed 27-μg water droplets, thereby archiving the 81-μg total mass shot. This procedure was also conducted five times for an experimental condition to evaluate errors.

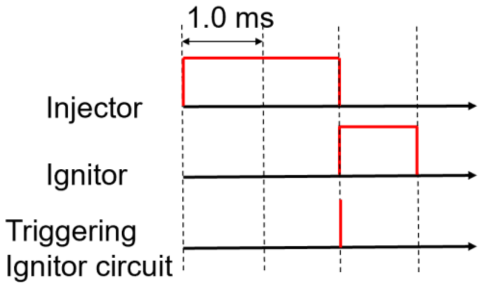

Figure 10. Typical thruster operation sequence in single-injection

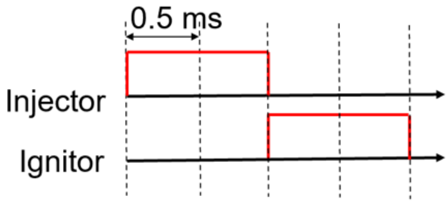

Figure 11. Typical thruster operation sequence in multi-injection

4. Results and Discussion

Figure 12 illustrates a typical time history of discharge and current time history in single injection. The main discharge was initiated 2 μs after the ignitor was triggered, and discharge current presented a peak of approximately 8 kA. The discharge current varied in the manner of the damped oscillation of 16.9 μs in period.

Figure 13 illustrates a typical time history of discharge and current time history in multi-injection. Discharge current presented a peak of approximately 7 kA. The discharge current decayed significantly within one period of the damped oscillation.

Inductance and resistance were determined using the linear circuit history. Assuming the circuit between the capacitor and the thruster head were equivalent to an inductance-capacitance-resistance circuit, the time variation in the discharge current is written as (1) ~ (3).[17]

$$J(t) = J_0 \exp(-\alpha t) \sin \omega t \tag{1}$$

$$\alpha = \frac{R_0}{2L_0} \tag{2}$$

$$\omega = \sqrt{\frac{1}{L_0 C_0} - \left(\frac{R_0}{2L_0}\right)^2} \tag{3}$$

Fitting the measured time histories using the least squares method determined α and ω, and then L and R were evaluated using Equations (4) and (5).

$$L = \frac{1}{C(\omega^2 + \alpha^2)} \tag{4}$$

$$R = \frac{2\alpha}{C(\omega^2 + \alpha^2)} \tag{5}$$

Then, the inductance and resistance were determined as listed in Table 2. While the inductance was almost the same, the multi-injection exhibited a higher resistance by approximately 76%.

The inductance in PPTs generally originates from the inductance between the capacitor and thruster head and the equivalent series inductance of the capacitor. Hence, the evaluated inductance is the same. In contrast, the resistance originates from the collisions in the plasma and time-derivative of the inductance caused by the plasma propagation. Hence, larger resistance indicates augmented electrothermal and electromagnetic accelerations. Accordingly, the multi-injection is expected to be yield higher performance because the firing test showed that the multi-injection yielded larger electric resistance. In order to advance the performance evaluation, it is essential to conduct thrust measurements in the future.

Table 2. Inductance and Resistance of Each Mode

Injection mode	Inductance, nH	Resistance, Ω
Single	308	0.112
Multi	291	0.197

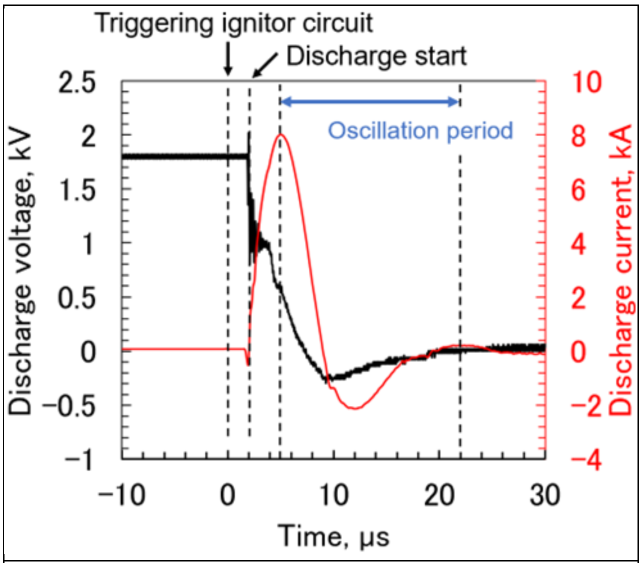

Figure 12. Typical discharge time history of single-injection operation

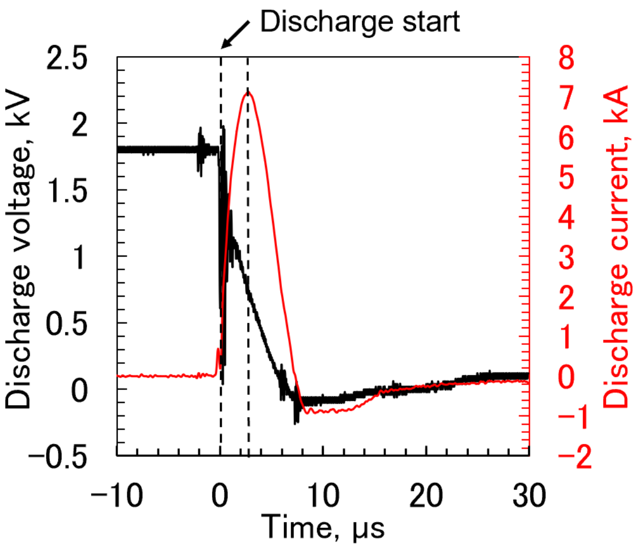

Figure 13. Typical discharge time history of multi-injection operation

5. Conclusion

This paper deals with test of the multi-injection type pulsed plasma thruster using water propellant to elucidate the effect of multi-injection. The thruster yielded a peak current of 8 kA and an ignition delay of 2 μs in the single injection, while presenting 7 kA in the multi-injection. The inductance and resistance of each injection mode were evaluated, revealing that while the inductance remained nearly constant, the multi-injection mode exhibited approximately 76% higher resistance. This suggests enhanced electrothermal and electromagnetic acceleration effects, as resistance in PPTs is influenced by plasma behavior. Given these findings, multi-injection is expected to offer superior performance.

In future studies, experimental conditions will be optimized, and both single- and multi-injection modes will be investigated through detailed measurements of discharge characteristics and thrust. These efforts aim to elucidate the relationship between the spatial distribution of liquid droplets and the resulting discharge distribution.

References

1) Burton, R. L. and Turchi, P. J.: Pulsed Plasma Thruster, J. Propul. Power, 14, **5** (1998), pp. 716–735.
2) Ciaralli, S., Coletti, M., and Gabriel, S. B.: Qualification of a Pulsed Plasma Thruster for CubeSat Propulsion (PPTCUP), 34th International Electric Propulsion Conference, IEPC-2015-208, 2015.
3) Tran, Q. V., Lim W. S., and Bui, T. D. V.: Development of a Dual-axis Pulsed Plasma Thruster for Nanosatellite Applications, *JoSS*, 8, **2** (2019), pp. 837–847
4) Ono, K., Morikawa, N., Ryuho, K., Kanaoka, K., Fujita, R., Tahara, H., and Takada, K.: Development of Commercially-Available Electrothermal Pulsed Plasma Thruster Systems for Micro/Nano-Satellites at Osaka Institute of Technology, 35th International Electric Propulsion Conference, IEPC-2017-92, 2017.
5) Gluczinski, F. S., III, Dulligan, M. J., Lake, J. P., and Spanjers, G. G.: Micropropulsion Research at AFRL, 36th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, AIAA Paper 2000-3255, July 2000.
6) Spanjers, G. G., Lotspeich, J. S., McFall, K. A., and Spores, R. A.: Pro pellant Losses Because of Particulate Emission in a Pulsed Plasma Thruster, J. Propul. Power, 14, 4 (1998), pp. 554–559.
7) Spanjer, G. G., McFall, K. A., and Gulczinski, F. S., III and Spores, R. A.: Investigation of Propellant Inefficiency in a Pulsed Plasma Thruster, 32nd AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, AIAA Paper 1996-2723, July 1996.
8) Rezaeiha, A. and Schönherr, T.: Review of Worldwide Activities in Liquid-fed Pulsed Plasma Thruster, J. Propul. Power, 30, 2 (2014), pp. 253–264.
9) Guman,W.J.:Pulsed Plasma Technology in Microthrusters, Air Force Aero Propulsion Laboratory Technical Report, AFAPL-TR-68-132, Fairchild Hiller Corporation, Farmingdale, NY, April 1968.
10) Ziemer, J. K.: Performance Scaling of Gas-Fed Pulsed Plasma Thrusters, Ph.D. Dissertation, Princeton University, Princeton, NJ, June 2001.
11) Scharlemann, C. A.: Investigation of Thrust Mechanisms in a Water Fed Pulsed PlasmaThruster, Ph.D. Dissertation, Ohio State University, Columbus, OH, June 2003.
12) Szelecka, A., Kurzyna, J., Daniłko, D., and Barral, S.: Liquid Micro Pulsed Plasma Thruster, Nukleonika, 60, 2 (2015), pp. 257–261.
13) Kakami, A., Koizumi, H., Komurasaki, K., and Arakawa, Y.: Design and Experiments of a Pulsed Plasma Thruster (PPT) Using Liquid Propellants, J. Jpn. Soc. Aeronaut. Space Sci., 51 (2003), pp. 85–88 (in Japanese).
14) Kakami, A., Koizumi, H., Komurasaki, K., and Arakawa, Y.: Design and Performance of Liquid Propellant Pulsed Plasma Thruster,

Vacuum, 73, 3-4 (2004), pp. 419–425.
15) Miyagi, K., Kakami, A., Tachibana, T.: Characterization of a Liquid-propellant Pulsed Plasma Thruster Using Various Nozzle Configurations, Trans. Japan Soc. Aero. Space Sci., **62** (2019), No.4, pp.184-191.
16) Komatsu, D., Nishii, K., Kakami, A.: Performance of Water Direct Injection Type MPD Thruster, The 38th International Electric Propulsion Conference, IEPC-2024-454, 2024.
17) Akira, K.: Study on Pulsed Plasma Thruster Using Liquid Propellant, Ph.D. Thesis, The University of Tokyo