Optical measurements of ablation process of double-cylindrical pulsed plasma thruster

IEPC-2019-860

Presented at the 36th International Electric Propulsion Conference
University of Vienna • Vienna, Austria
September 15-20, 2019

Tomoya Inaba [1], Yoshimasa Matsui[2], Koji Nishigaki [3], Shoki Kumagai[4],
Riku Ono[5], Takeshi Miyasaka[6] and Makoto Asahara[7]
Gifu University, Gifu, 501-1132, Japan

Abstract: Previous studies showed that the thruster performance of coaxial pulsed plasma thrusters (PPTs) were influenced by cavity geometries. As a surface area per volume ratio of the hollow propellant increases, the impulse bit and the efficiency were improved. In this study, to obtain the ratio larger than a limit value of the hollow propellant, a double-cylindrical propellant was introduced. As a result, the double-cylindrical propellant increased the thruster performance. In addition, a more appropriate ratio that effected on the performance including the double-cylindrical propellant was obtained.

I.Introduction

A coaxial pulsed plasma thruster (PPT) is a promising space propulsion system because of its easily controllable properties. PPTs have been studied experimentally and numerically[1-15]. At Gifu University, investigations of the coaxial PPTs have been carried out[9-15]. Thruster performance of the PPT including the impulse bit is strongly influenced by the ablation and the exhaust process in the cavity. At Gifu University, direct observations of the ablation process in the cavity have been performed by high-speed photography[10-13]. By the direct observations, late-time phenomena have been investigated.

In the coaxial PPT operations, geometric parameters strongly affect the thruster performance. Especially, “inner surface area of a hollow propellant / cavity volume” is a significant ratio that effects on the thruster performance. As the cavity diameter decreases, the ratio becomes larger. For a large ratio, the mass shot and the plume velocity become higher. At the large ratio, an energy is supplied to the surface efficiently. Results of previous measurement reveal such dependence on the area / volume ratio.

However, there is a limit of the cavity diameter for stable operations. In the experiment at Gifu University, the limit is around 2 mm. This indicates that the impulse bit has the highest value for the diameter of 2 mm. To achieve the surface area per cavity volume ratio higher than that for the diameter of 2 mm, a double-cylindrical propellant was introduced. The double-cylindrical propellant is obtained by inserting a cylindrical PTFE (cylindrical part) to an ordinary coaxial propellant (hollow part). Schematics of the ordinary propellant (hollow propellant) and the double-cylindrical propellant are shown in Fig.1. Because of the cylindrical part, the surface area per cavity volume ratio of the double-cylindrical propellant increases compared with that of the hollow propellant with the same hollow diameter. Thus, as shown in Fig. 2, the double-cylindrical propellant has the area per volume ratio which exceeds the limit of the hollow propellant.

In this study, to confirm advantages of the double-cylindrical propellant, the mass shot, the plume velocity of the first peak, and impulse bit were measured for various combinations of the hollow and the cylindrical diameters ϕ_h and

---

[1] Grand Student, Department of Intelligence Science and Technology, y4525009@edu.gifu-u.ac.jp
[5] Grand Student, Department of Intelligence Science and Technology, y4525019@edu.gifu-u.ac.jp
[6] Professor, Department of Mechanical Engineering, miyasaka@gifu-u.ac.jp
[7] Assistant professor, Department of Mechanical Engineering, asahara@gifu-u.ac.jp

ϕ_c of the double-cylindrical propellants and compared with those for various hollow diameters ϕ_h of the hollow propellants. Dependencies of the values on the area per volume ratio were examined.

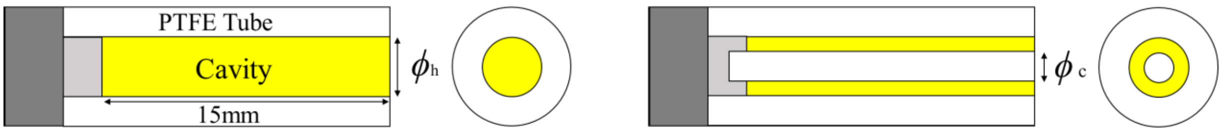

Figure 1. Schematics of two types of propellant, hollow propellant and double-cylindrical propellant consisting of hollow and cylindrical parts

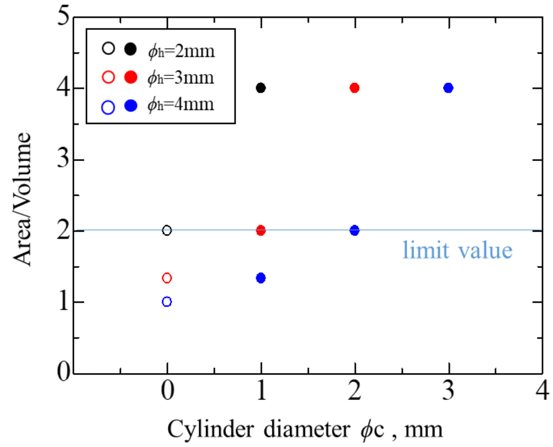

Figure 2. Surface area per volume ratio for hollow and double-cylindrical propellants

II.Experimental Procedure

A. PPT experiment system and experimental conditions

A schematic of PPT experiment system at Gifu University is shown in Figure 3. The coaxial PPT consists of a PTFE propellant and a nozzle. The PPT set in a glass-vacuum chamber. The inner diameter and length of the chamber are 230 mm and 400 mm, respectively. The vacuum system consists of a rotary pump and a diffusion pump. The experimental conditions of this study are shown in Table 1.

B. Measurement setup

The plume velocity was measured by TOF (time of flight) method. The velocity measurement system consists of optical fibers and avalanche photodiodes (APD). A schematic of the system is shown in Fig. 3. To reduce strong electromagnetic noises caused by the main discharge, the emission from the plume was captured by the optical fibers. The light is converged to a voltage by the APD installed away from the PPT. Figure.4 shows a graph of the light emissions converted into voltage signals by avalanche photodiodes. The plume velocity can be measured from the time difference between the first peaks of the emissions. The optical fibers are installed at positions 10 mm and 30 mm downstream of the nozzle. The characteristics of the avalanche photodiode for this study are shown in Table 2.

A pendulum thrust stand was used for direct measurement of impulse bits. A schematic of the thrust stand is shown in Fig. 5.

Table 1. Experimental conditions

Charging voltage, E_0	2 kV
Capacitance, C	4 μF
Ignition voltage, V_i	10 kV
Base pressure, P	8.7×10^{-3} Pa

Table 2. Characteristics of avalanche photodiode

Output impedance	50 Ω
Active area	3 mm
Frequency bandwidth	4 k to 80 M Hz
Spectral response range	400 to 1000 nm

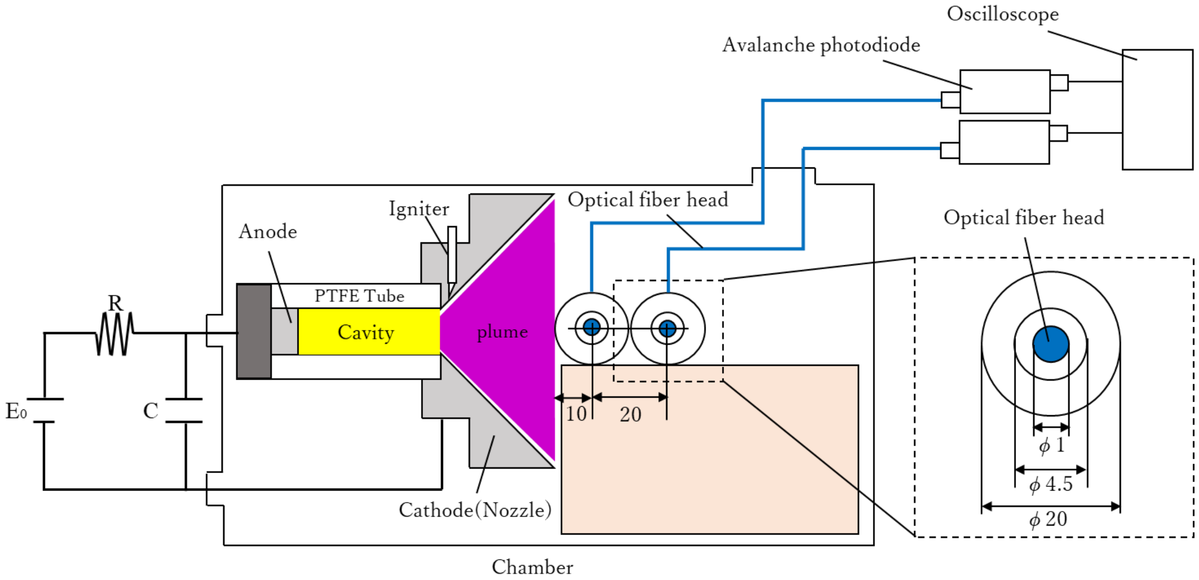

Figure 3. A schematic of PPT experiment system at Gifu University

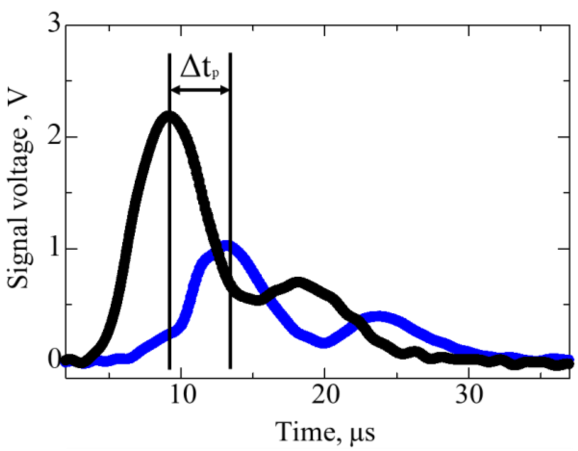

Figure. 4 Wave forms of plume emissions

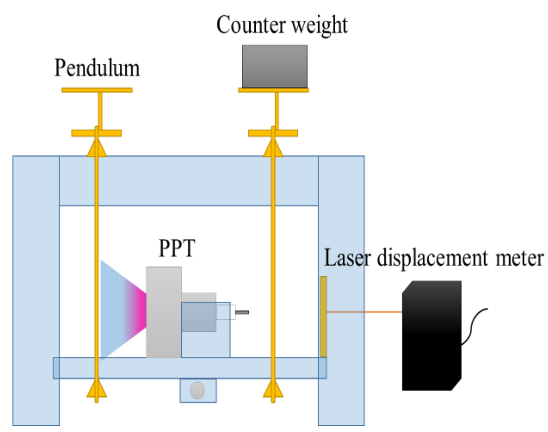

Figure 5. A schematic of thrust stand

III. Results and Discussion

A. Dependencies of estimated performances on surface area per cavity volume ratio

Figures 6 and 7 show the mass shots and the plume velocity of the first peak of the plume for various combinations of diameters of the propellant. The closed circles and the open circles represent the results of the double-cylindrical and the hollow propellants, respectively. The black, the red, and the blue circles represent the results of the hollow diameter ϕ_h of 2 mm, 3mm, and 4 mm, respectively. Both the mass shot and the plume velocity for the double-cylindrical propellant increase with the surface area per cavity volume ratio. The trends are similar to those for the hollow propellants. These results indicate that the energy is supplied to the surfaces efficiently for a high area per volume ratio also in the case of the double-cylindrical propellant. Dependencies of the impulse bit and the thruster efficiency on the area per volume ratio were estimated from the mass shot and the plume velocity. Figure 8 shows the product of the mass shot and the plume velocity. The thruster efficiency was calculated using the product and the mass shot in Fig. 8. Figure 9 shows the thruster efficiency. The product and the thruster efficiency were normalized by the values for the hollow diameter of 4 mm of the hollow propellant. Since both the mass shot and the plume velocity in Figs. 6 and 7 increase with the area per volume ratio, the results in Figs. 8 and 9 show similar tendencies.

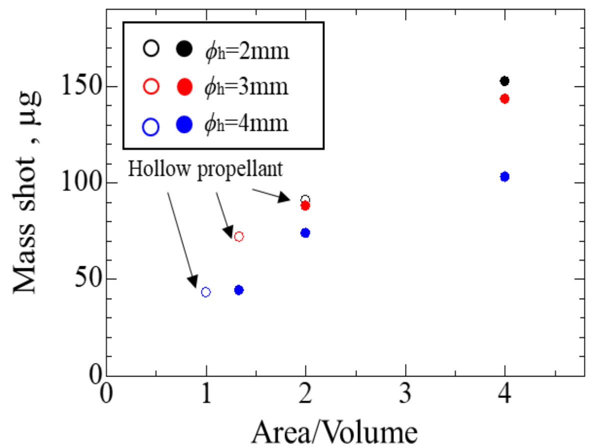

Fig. 6 Mass shot versus surface area per cavity volume ratio.

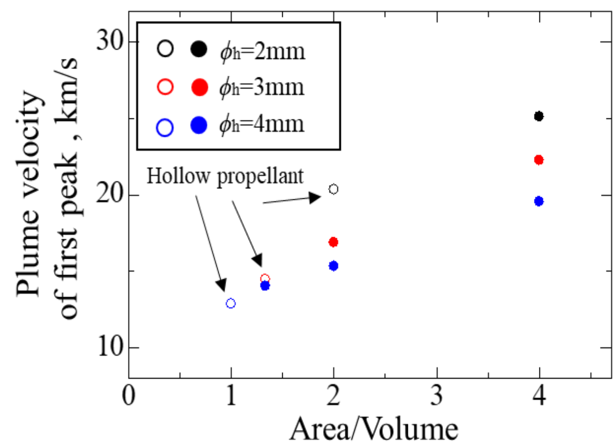

Fig. 7 Plume velocity of first peak versus surface area per cavity volume ratio.

B. Dependencies of estimated performances on surface area per cavity volume per hollow diameter ratio

The impulse bit and the thruster efficiency in Figs. 8 and 9 also depend on the hollow diameter. In Fig. 8, at a fixed area per volume ratio, the impulse bit decreases with the hollow diameter. In Fig. 9, the dependence on the hollow diameter becomes stronger. At the surface per volume ratio of 4, the impulse bit and the thruster efficiency for the hollow diameter ϕ_h of 4 mm decrease by 47 % and 59 % compared with 2 mm, respectively. In Figs 6 and 7, both the mass shot and the plume velocity also depend on the hollow diameter. The increase in the inner surface area of the hollow part decreases the energy supplied to the surface per area and causes the decrease in the performance. Thus, a new ratio by dividing the area per volume ratio by the hollow diameter was introduced. Figures 10 and 11 show the impulse bit and the thruster efficiency by taking the new ratio in the horizontal axis instead of the area per volume ratio. Both the impulse bit and the thruster efficiency show a strong dependency on the new ratio. In addition, at a fixed ratio, no significant difference among the values for various hollow diameters is observed. These results suggest that the new ratio is an important geometric parameter for evaluating the performance.

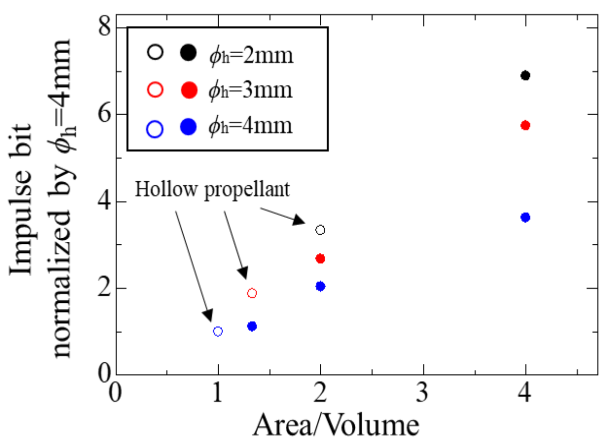

Fig. 8 Normalized impulse bit estimated from product of mass shot and plume velocity versus surface area per cavity volume ratio.

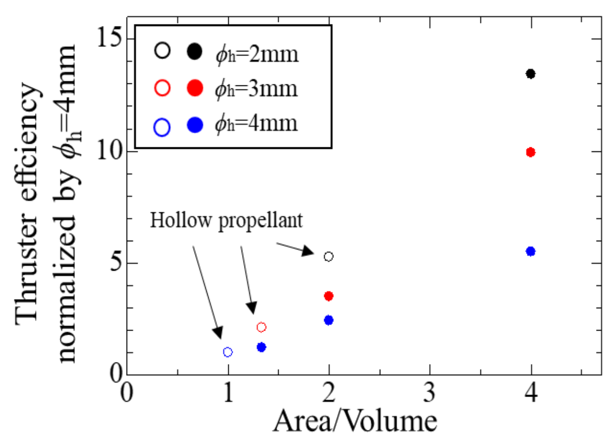

Fig. 9 Normalized thruster efficiency estimated from mass shot and plume velocity versus surface area per cavity volume ratio.

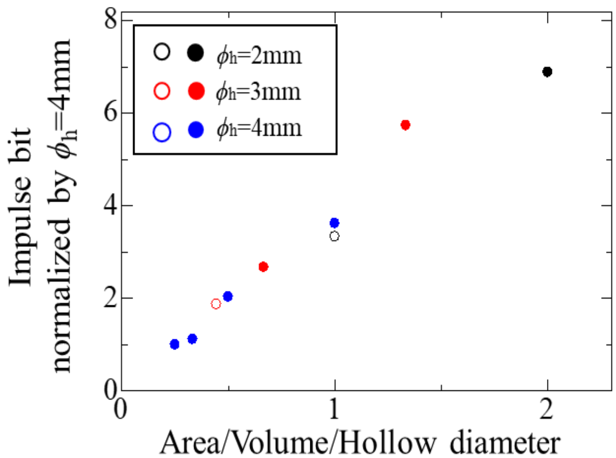

Fig. 10 Normalized impulse bit estimated from product of mass shot and plume velocity versus surface area per cavity volume per hollow diameter ratio.

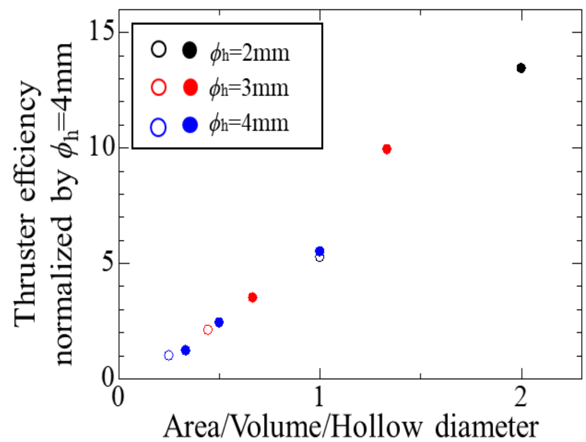

Fig. 11 Normalized thruster efficiency estimated from mass shot and plume velocity versus surface area per cavity volume per hollow diameter ratio.

C. Measured impulse bit and thruster efficiency

The impulse bit and the thruster efficiency in Figs. 10 and 11 were estimated indirectly from the mass shot and the plume velocity. In addition, because the plume velocity was the first peak value, the impulse bit and the thruster efficiency were overestimated. Therefore, to confirm the dependency of the performance on the new ratio, the impulse bit was measured using the thrust stand shown in Fig. 5. Figure 12 shows the measured impulse bit. The impulse shows the same tendency as the estimated impulse bit in Fig. 10 and strongly depends on the new ratio. These results indicate that the new ratio controls the thruster performance. The impulse bit at the ratio of 2 of the double-cylindrical propellant with the hollow diameter ϕ_h of 2 mm is lower than that at the ratio of 4/3 while the estimated impulse bit in Fig. 9 is higher. The hollow and cylindrical diameters ϕ_h and ϕ_c of the propellant are 2 mm and 1mm, respectively. The small cavity is insufficient to supply energy to the plasma efficiently. The small cavity causes the decrease in the impulse bit. These results reveal that the cavity of the double-cylindrical propellant also has a limit. Thus, in the present study, the impulse bit becomes a maximum at the ratio of 4/3. The hollow and cylindrical diameters at the ratio of 4/3 are 3 mm and 2 mm, respectively.

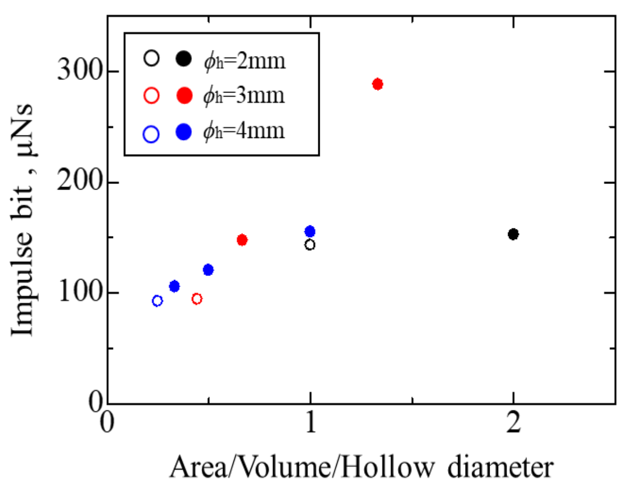

Fig. 12 Impulse bit measured using thrust stand versus surface area per cavity volume per hollow diameter ratio.

D. Total impulse

While the results of the thruster performance in Figs. 9-12 show the advantage of the double-cylindrical propellant, only the double-cylindrical propellant with the hollow and the cylindrical diameters of 3 mm and 2 mm exceeds the hollow propellant with the diameter of 2 mm due to the existence of the low limit of the cavity volume in actual operations. These results were obtained only for initial propellants. In actual operations, the total impulse is important. Thus, to investigate dependencies of the impulse bits on the total mass shot for the double-cylindrical and the hollow propellants, rates of the area per volume per hollow diameter ratio variation to the total mass shot variation were evaluated. Figure 13 shows that rates for the double-cylindrical propellant with the hollow diameter of 4 mm and the cylindrical diameter of 3 mm and the hollow propellant with the hollow diameter of 2mm. The evaluations were carried out on the assumption that the rates of ablations from the inner surface of the hollow part and the outer surface of the cylindrical part were uniform. Both initial area per volume per hollow diameter ratios are 1.0. In Fig. 13, the rate of the ratio variation to the mass shot for the double-cylindrical propellant is lower than that for the hollo propellant. This result suggests that the double-cylindrical propellant increases the total impulse in comparison with the hollow propellant.

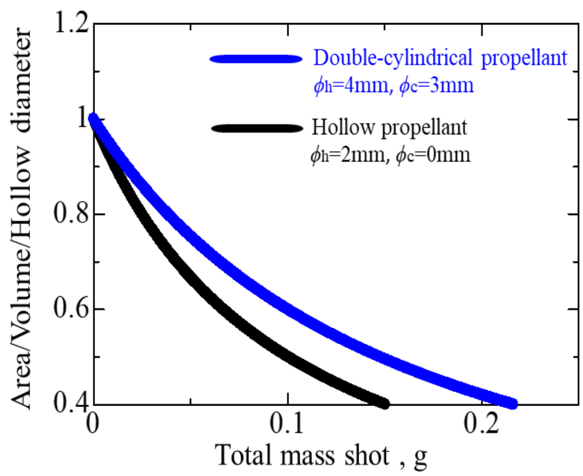

Fig. 13 Surface area per cavity volume per hollow diameter ratio versus total mass shot for hollow and double-cylindrical propellants.

IV.Conclusion

In this study, investigations of the double-cylindrical propellant were carried out. The impulse bit and the efficiency of the double-cylindrical propellant was higher than that of the hollow propellant with the same surface area per volume ratio. The results showed that the initial thruster performance of the double-cylindrical and the hollow propellants strongly depended on the surface area per volume per hollow diameter ratio. The direct measurement of the impulse bit indicated that there was an upper limit of the ratio also for the double-cylindrical propellant. However, the evaluations of the rate of the ratio variation to the total mass shot variation suggested the advantage of the double-cylindrical propellant relating to the total impulse.

References

[1]Mukai, M., .Kamishima, Y., Sasaki, T., Shintani, K., Aoyagi, J., and Takegahara, H., "Reserch and Development on Coaxial Pulsed Plasma Thruster for Small Satellites," *Proceedings of the 30th International Electric Propulsion Conference*, IEPC-2007-243, 2007.

[2]Saito, T., Koizumi, H., and Kuninaka, H., "Pulsed Plasma Thruster Using Powdered Propellant," *Proceedings of the 30th International Electric Propulsion Conference*, IEPC-2007-116, 2007.

[3]Hallock, A.K., Choueiri, E., and Polzon, K.A.,"Current Sheet Formation in a Conical Theta Pinch Faraday Accelerator with Radio-frequency Assisted Discharge," *Proceedings of the 30th International Electric Propulsion Conference*, IEPC-2007-165, 2007.

[4]Kakami, A., Koizumi, K., Komurasaki, K., and Arakawa, Y., "Design and Performance of a Pulsed Plasma Thruster with Liquid Propellants," *Advances in Applied Plasma Science*, 4. pp.127-132, 2003.

[5]Edamitsu, T., Tahara, H., and Yoshikawa, T., "Performance Measurement and Flowfield Calculation of a Pulsed Plasma

Thruster with a Teflon Cavity," *Proceedings of Asian Joint Conference on Propulsion and Power 2005*, AJCPP2005-22083, 2005.
[6]Koizumi, H., Noji, R., Komurasaki, K., and Arakawa, Y., "Plasma Flow Behaviors and Their Effects on the Performance of Pulsed Plasma Thrusters," *Proceedings of the 30th International Electric Propulsion Conference*, IEPC-2007-189, 2007.
[7]Beiting, E.J., Qian, J., Russell, R.W., Pollard, J.E., Caven, W., and Corey, R., "Absolute Emission from a Pulsed Plasma Thruster (PPT) ," *Proceedings of the 30th International Electric Propulsion Conference*, IEPC-2007-268, 2007.
[8]Skalden, J., Llic, D., Herdrich, G., and Schönherr, T., "Characterization and Optimization of Liquid-Ablative and Air-Breathing PPT, Part I: Thrust and Discharge Performance," *Proceedings of the 35th International Electric Propulsion Conference*, IEPC-2017-174, 2017.
[9]Okabe, H., Miyasaka, T., Asato, K., and Sato, S., "Plasma Diagnostic Measurement of Pulsed Plasma Thruster ," *Frontier of Applied Plasma Technology*, 1. pp.33-36, 2008,
[10]Miyasaka, T., Sato, S., and Asato, K., "Characterization of Coaxial Pulsed Plasma Thruster by High-speed Photography," *Transactions of the Japan Society for Aeronautical and Space Sciences,* Aerospace Technology Japan, **8** Pb_103-Pb_108, 2010.
[11]Miyasaka, T., Sato, S., and Asato, K., "Luminescence Measurement of Unsteady Plasma Behavior on Coaxial Pulsed Plasma Thruster," *Frontier of Applied Plasma Technology*, 3. pp.79-84, 2010.
[12]Miyasaka, T., Asato, K., Sakaguchi, N., and Ito, K., "Otical Measurements of Unsteady Phenomena on Coaxial Pulsed Plasma Thrusters," *Vacuum*, 88. pp.52-57, 2013.
[13] Miyasaka, T., Asato, K., Ito, K., Shimizu, K., and Kobayashi, A., "Measurements of Ablation Phenomena on Coaxial Pulsed Plasma Thruster with Separated Propellant", *Frontier of Applied Plasma Technology*, Vol. 6, pp.51-56, 2013.
[14] Shimizu, K., Miyasaka, T., Asato, K., Kiriyama, T., Ito, K., "Diagnostics and Control of Late-Time-Ablation in Separated Pulsed Plasma Thruster Operations," APISAT 2013,05-05-2, 2013.
[15] Goto T., Miyasaka, T., Kajiwara, T., Goto, Y., Nishigaki, K., Matsui, Y., Asahara, M., "Evaluations of Unsteady Ablation and Exhaust Phenomena on Coaxial Pulsed Plasma Thrusters," ISTS-2017-b-79p, 2017.