Ignition Capability of Pulsed Plasma Thruster with Green Liquid Propellant

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Abstract: Green propellant means lower toxicity and it is substitution of hydrazine, which is one of the monopropellant and has self-exothermic reaction. In this study, we suggested applying the exothermic chemical energy to a pulsed plasma thruster (PPT) in addition to the electromagnetic and electro thermal forces produced by the PPT operation. We prepared parallel plate and coaxial PPTs which had 8 J of electric discharge energy. And an electrospray system was constructed in order to inject ethanol or SHP163 which is hydroxyl ammonium nitrate based green propellant. When ethanol made a droplet at the tip of capillary tube and then high voltage was applied to the capillary, the droplet diffused to the gap of PPT electrodes, and then pulsed electric discharge of PPT was induced. We measured 46.5 μNs and 49.0 μNs of average impulse bit by a parallel plate PPT and a coaxial PPT, respectively. Moreover, we confirmed that SHP163 induced the discharge in both parallel plate and coaxial PPTs. The parallel plate PPT generated 45.9 μNs of averaged impulse bit. On the other hand, the coaxial PPT produced 103 μNs of that. We considered that the exothermic energy of SHP163 transferred efficiently in case of the coaxial PPT because it had the geometrical advantage in view of aerodynamic force.

I. Introduction

TYPICAL pulsed plasma thruster (abbreviated as PPT) utilizes solid propellant such as Polytetrafluoroethylene (PTFE). Solid propellant has advantage about simplicity of the thrust system by removing storage and feeding systems. A characteristic of solid PPT is inconsistency of period between electric discharge and propellant ablation, which makes its thrust efficiency low[1]. And regression of propellant surface by uneven ablation will vary the thrust performance. On the other hand, study of application of liquid or gaseous propellant to a PPT has been progressing in order to improve its stable performances with exceeding system complexity[2-4]. As these liquid or gaseous propellants are inert chemically as same as solid one, energy of a pulsed electric discharge transfers to electromagnetic, electro thermal, and aerodynamic forces to accelerate the exhaust plume.

In this study, we suggested applying liquid monopropellant to the PPTs, in order to increase total input energy at thruster systems. Monopropellant is usually employed at chemical rocket systems because of its self-exothermic reaction initiated by contacting a solid catalyst bed without oxidizer[5]. We strongly expect that the electric discharge of PPT will affect not only electromagnetic, electro thermal, and aerodynamic forces, but also the ignition of auto-exothermic reaction of monopropellant instead of a solid catalyst bed. The most major monopropellant is hydrazine. Although hydrazine has excellent characteristics as monopropellant that the decomposition will initiate spontaneously, immediately and repeatedly, its handling and treatment are significantly severe by high toxicity. Therefore, substitution of hydrazine, we call green propellant as much lower toxicity than hydrazine, was studied in several laboratories[6-10].

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Hydroxyl ammonium nitrite (abbreviated as HAN, whose chemical formula is $(NH_3OH)^+(NO_3)^-$) is one of the promising green propellants for space propulsion. Because HAN contains both a reducing agent and oxidizer, it is explosiveness even by itself. And water and fuel components are mixed with HAN in order to handle as an aqueous solution and control the reaction characteristics including stability, as called HAN based propellant. Consequently, we employed HAN based propellant that mix water, ammonium nitrate (AN), and methanol (MeOH) with HAN, called SHP163, as liquid propellant of PPT. The mass ratio of HAN/H_2O/AN/MeOH is 95/8/5/21, respectively[6]. The characteristics of SHP163 are summarized in Table 1, with these of hydrazine[6, 11]. SHP163 is higher energy density and higher theoretical specific impulse, and lower freezing temperature than hydrazine. And its toxicity is much lower than that of hydrazine. These characteristics are the reason that SHP163 is one of the promising green propellants. In addition, since the adiabatic flame temperature reaches about 2,300 K, we expected that its exothermic reaction would contribute to increasing thrust performance of PPTs.

Table 1. Properties of SHP163 and hydrazine[6, 11].

	SHP163	Hydrazine
Density (297 K), 10^3 kg/m^3	1.4	1.0
Freezing point, K	< 236	274.4
Specific impulse, s	276	233
Flame temperature, K	2373	873
Toxicity LD50, mg/kg	500-2000 (Oral)	60 (Oral)
	> 2000 (Skin)	91 (Skin)
Viscosity (293 K), mPa·s	11.9	0.97

We estimate standard enthalpy of reaction of SHP163. The ideal chemical reaction of SHP163 is as follows:

$$16\ (NH_3OH)^+(NO_3)^- + 7\ H_2O(liq.) + (NH_4)^+(NO_3)^- + 10.5\ CH_3OH \rightarrow 10\ CO_2 + 17\ N_2 + 61\ H_2O(gas) + \text{others} \quad (1).$$

Enthalpy of formation about component molecules of SHP163 and its reaction products are indicated in Table 2[12, 13]. Therefore, the standard enthalpy of reaction $\Delta_r H$ is obtained as follow:

$$\Delta_r H = \{10\ (-393.5) + 61\ (-201.0)\} - \{16\ (-333.5) + 7\ (-285.8) + (-365.2) + 10.5\ (-239.2)\} = -8471\ \text{kJ/mol} \quad (2).$$

Note that the negative number of enthalpy of reaction means exothermic reaction.

Table 2. Enthalpy of formation about component molecules of SHP163 and its reaction products[12, 13]

Item	$(NH_3OH)^+(NO_3)^-$	H_2O (liq.)	$(NH_4)^+(NO_3)^-$	CH_3OH(liq.)	CO_2	H_2O (gas)
$\Delta_r H$, kJ/mol	-333.5	-285.8	-365.6	-239.2	-393.5	-241.8

In this paper, as the beginning of study, we constructed an electrospray system to emit a liquid propellant to a PPT instead of electric ignitor. Ethanol was applied as a substitute propellant in order to demonstrate the injection system. And we confirmed conditions that induce a pulsed electric discharge of a PPT. When the electric discharge was occurred stably, the impulse bit was measured. Finally we applied SHP163 to the liquid PPT system in the some conditions. The inducibility of pulsed discharge operation by SHP163 and its impulse bit were evaluated.

II. Experimental Equipment

All experiments about PPT operation were carried out in a vacuum chamber. In this section, we describe the experimental equipment including the vacuum chamber, an electrospray system, and variation of PPT.

A. Vacuum chamber, propulsion system, and measurement system

The vacuum chamber, power supply, and measurement equipment are illustrated in Fig. 1. The diameter and length of camber are 600 mm and 1000 mm, respectively. And the chamber pressure reaches about 10^{-2} Pa, where specifications of vacuum pumps are described at each condition below.

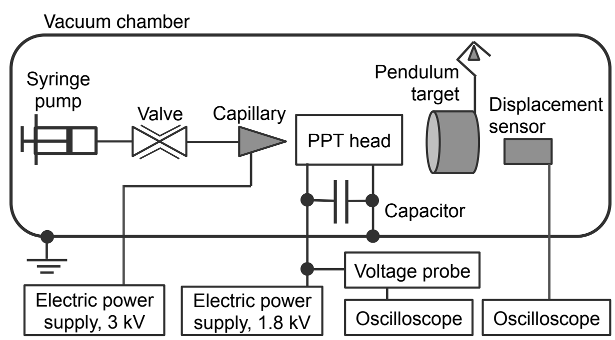


Figure 1. Experimental configuration and equipment.

As a propulsion system, a PPT thruster head, a capacitor bank, and an electro spray system are set in the chamber. A PPT thruster head connects to the capacitor bank. Electric power supplies are set in the atmosphere, which connect to the capacitor bank and a capillary tube of electro spray. The capacitor bank has 5 μF of capacitance, and we applied 1.8 kV of voltage, which is equivalent to 8 J of charge energy. And 3.0 kV was applied to the capillary to emit a liquid propellant. The electrospray system is described at the next subsection.

As measurement systems, a pendulum target and a displacement sensor are set in the chamber. The pendulum target swings by capturing plume exhausted from a PPT, and the displacement sensor measures the slight oscillation, which converts into impulse bit. Specification of the displacement sensor is described at each condition below. And high voltage probe is set in the atmosphere to measure the discharge voltage of a PPT.

B. Electrospray system

An electrospray is one of the methods to emit and atomize liquid. Figure 2 illustrates the concept of an electrospray. Liquid on the tip of very small capillary tube receives high voltage by electric field concentration. When the Coulomb force of the charged liquid exceeds surface tension, the liquid divides into tiny droplets, and diffuses toward a counter electrode.

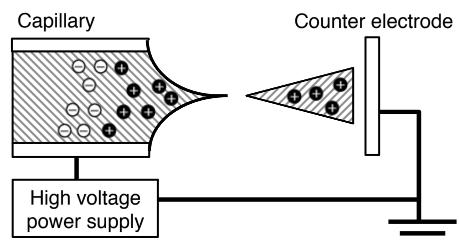


Figure 2. Overview of electrospray.

We constructed an electrospray system, as shown in Fig. 3. It has a capillary tube, a pinch valve, a syringe, and a syringe pump. Liquid propellant was injected to the syringe, before we reduced the pressure of the vacuum chamber. The pinch valve shuts a silicon tube during decompression to prevent leakage of the liquid from the syringe. When a PPT operates, the valve opens and the syringe pump pushes the syringe, by stepping motor controlled from the atmosphere, then the capillary draws liquid propellant. Finally, 3.0 kV of high voltage is applied to the tip of the capillary, and the liquid diffuses to the space between electrodes of a PPT. Detail specification about capillary tube is described at each configuration below.

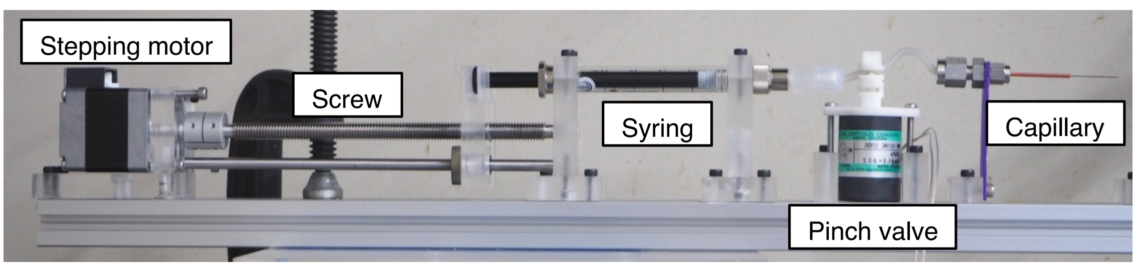


Figure 3. Photograph of electrospray system we constructed in this study.

C. Pulsed plasma thrusters

We employed ethanol and SHP163 as liquid green propellant. And some kinds of PPT heads were prepared. The following describes these combination and experimental conditions.

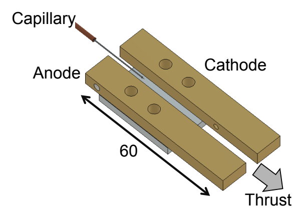
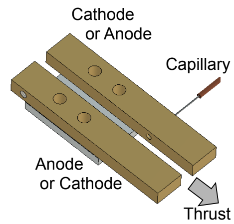
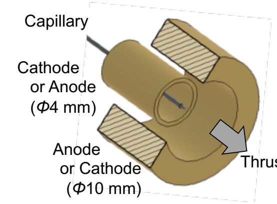
1. Ethanol as liquid propellant

The purpose of applying ethanol is to verify the operation of the electrospray system in the vacuum environment, and to attempt to operate PPTs. In cases a PPT operates stably, we measured the impulse bit. The vacuum chamber had a turbo molecular pump and a rotary pomp, as a main pump and a backing pump, respectively. And a laser displacement sensor was attached to measure the amplitude of oscillation of the pendulum target.

Table 3 shows PPTs and experimental conditions in case of ethanol application. Parallel plate PPT has a pair of rectangular parallelepiped electrodes. The length of the discharge channel is 60 mm. The gap between electrodes is 5 mm or 10 mm. Two directions of the capillary insertion were applied. One is from upstream between the electrodes, and that is parallel to the discharge channel. The length of insertion of the capillary to the channel is 10 mm. And the other is from a hole on the electrode perpendicularly to the thrust axis. The hole diameter is 2 mm and length form the edge of downstream electrode is 19 mm. And the position of the capillary tip is 2 mm from the hole exit.

Coaxial PPT has inner and outer electrodes with same center axis. The diameter of the inner electrode and outer electrode are 4 mm and 10 mm, respectively. When the inner electrode is connected to the cathode or anode, the outer electrode has the counter polarity. The distance between tips of inner electrode and outer electrode, which corresponds to the length of the electric discharge channel, is 10 mm. The gap between electrodes is filled at upstream of outer electrode by acrylic resin. The capillary is inserted from upstream of the center axis. The position of the capillary tip is 5 mm downstream from the tip of inner electrode.

Table 3. Electrode arrangement of PPT and capillary in case of ethanol application.

Electrodes arrangement of PPT	Parallel		Coaxial
Capillary insertion to thrust axis	Parallel	Perpendicular	Parallel
Configuration image			
	Electrode gap: 5 mm@ ϕ 10 μm, 10 mm@ ϕ 30 μm, and ϕ 100 μm		Channel length: 10 mm
Diameter of capillary	ϕ 10 μm, ϕ 30 μm, and ϕ 100 μm		

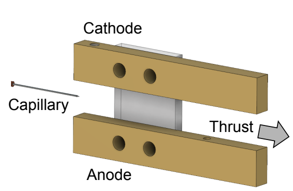
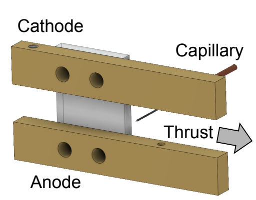
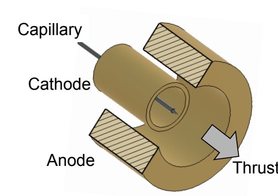
On all experimental configurations shown in Table 3, we attempted 10 μm, 30 μm, and 100 μm of capillary diameter, in order to adjust the mass of propellant emission. The capillary tube of 10 μm and 30 μm is made of metal-coated silicon. And the capillary of 100 μm is made of SUS304.

2. SHP163 as liquid propellant

The purpose of applying SHP163 is to evaluate availability of liquid monopropellant to PPTs. And the impulse bit was measured when the PPT operates successfully. The vacuum chamber had an oil diffusion pump and a rotary pomp, as a main pump and a backing pump, respectively. And a linear variable differential transformer was attached to measure the amplitude of oscillation of the pendulum target.

Table 4 shows PPTs and experimental conditions in case of SHP163 employment. As same as in case of ethanol application, parallel plate and coaxial electrodes were prepared. In the case that parallel plate electrodes are applied and the capillary tube is inserted from downstream parallel to the discharge channel, the position of the capillary tip is same as the edge of upstream electrode. The diameter of the capillary is 30 μm. And we also adopted a situation of a perpendicular insertion of the capillary, whose diameter is 100 μm, to the channel form the gap of the electrodes. The position of the capillary tip is 25 mm upstream from the edge of downstream electrode. Moreover, in case of the coaxial PPT, the inner electrode is cathode. The diameter of the capillary is 100 μm, and its tip is same as the edge of downstream inner electrode.

Table 4. Electrode arrangement of PPT and capillary in case of SHP163 application.

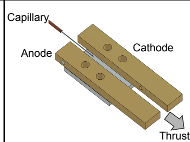
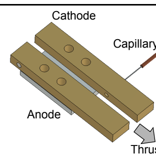
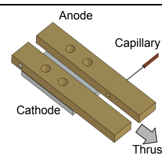
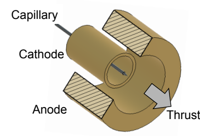
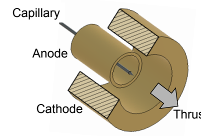
Electrodes arrangement of PPT	Parallel		Coaxial
Capillary insertion to thrust axis	Parallel	Perpendicular	Parallel
Configuration image			
	Electrode gap: 10 mm		Channel length: 10 mm
Diameter of capillary	ϕ 30 μm	ϕ 100 μm	

III. Results and Discussions

A. Verification of electrospray and PPT operation in case of ethanol application

The operational capability of the PPTs, which is whether electric discharge was occurred between electrodes, in case of ethanol application is summarized in Table 5. When the diameter was 10 μm, irregular discharge was observed when the capillary was inserted from cathode hole, which corresponds to #2 in Table 5. And the other cases did not induce electric discharge. We consider that one of the reasons of the irregular discharge is liquid propellant collection near the cathode hole, and vaporization of the remaining ethanol induced unexpected electric discharge. Moreover, in the other situation, it may be too little quantity to induce the discharge, although ethanol is injected to the gap. In contrast with 10 μm of capillary diameter, uncontrollable and undesirable electro discharge was observed when 100 μm of that was attached even when no voltage was applied to the capillary. It is considered that excessive injection and vaporization of ethanol proceeded to the gap, as shown in Fig. 4.

Table 5. Operational capability of PPTs with ethanol injection.

Situation		#1	#2	#3	#4	#5
Configuration						
Diameter of capillary	10 μm	No discharge	Irregular	No discharge	No electrospray	No discharge
	30 μm	No discharge				
	30 μm (from droplet)	Controllable		No discharge	Controllable	No discharge
	100 μm	Uncontrollable			N.A.	Uncontrollable

As same as the case of 10 μm, the capillary of 30 μm of diameter did not induce the electric discharge by continuous emission of ethanol in any configuration. Therefore, we tried to apply voltage to the capillary in pulses after a droplet of ethanol was made at the tip of capillary, as shown in Fig. 5, in order to increase ethanol emission to the gap. Table 5 also indicates the inducibility of discharge. When the capillary was near the anode, which corresponds to #3 and #5 in Table 5, the discharge of PPT was not observed. In the other cases, however, the pulsed electric discharge occurred normally. Figure 6 indicates these impulse bit. In case of parallel plate electrodes and that the capillary insertion was upstream parallel to the discharge channel, average impulse bit was 22.7 μNs.

And when the capillary was inserted from the hole of cathode, such as #2 in Table 5, we obtained 46.5 μNs of average impulse bit. In this condition, we also measured the impulse bit by only the pulse injection of the electrospray, and the average was 21.0 μNs. This confirmed that the PPT accelerated and exhausted ethanol. And we assumed that the higher impulse bit was obtained when the capillary was nearer the pendulum target, because the vapor expanded from the tip of capillary.

Moreover, the coaxial PPT with inner cathode generated 49.0 μNs of average impulse bit by ethanol injection. And the average by only electrospray injection was

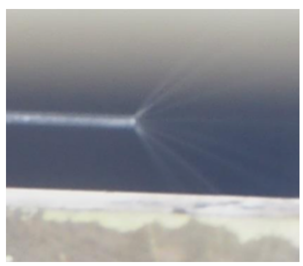


Figure 4. Irregular injection of ethanol from a capillary whose diameter is 100 μm.

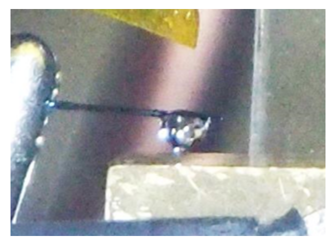


Figure 5. Droplet of ethanol at the tip of capillary.

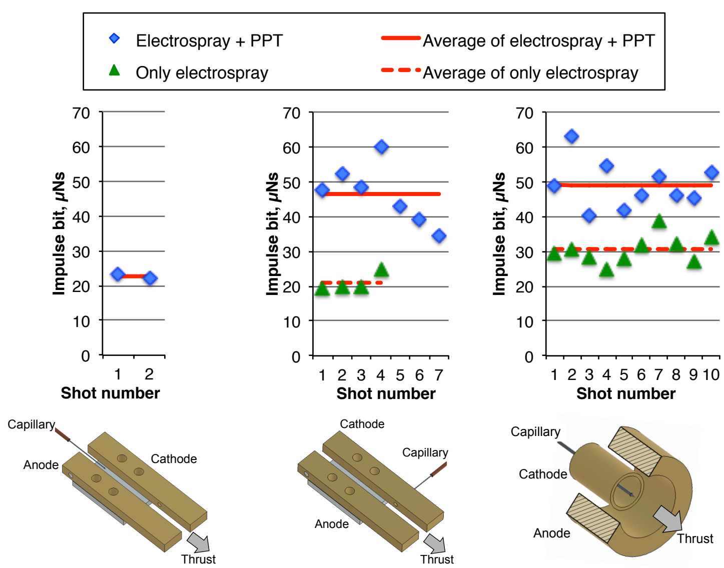


Figure 6. Impulse bit of PPT operation by ethanol injection.

30.5 μNs. These values are similar to the parallel plate with perpendicular insertion of capillary from cathode hole.

Waveforms of the electric discharge voltage are compared in Fig. 7, which also indicates a waveform of a parallel plate PPT by typical solid PTFE as reference. We considered that the electric discharge with ethanol resembled the one with solid propellant.

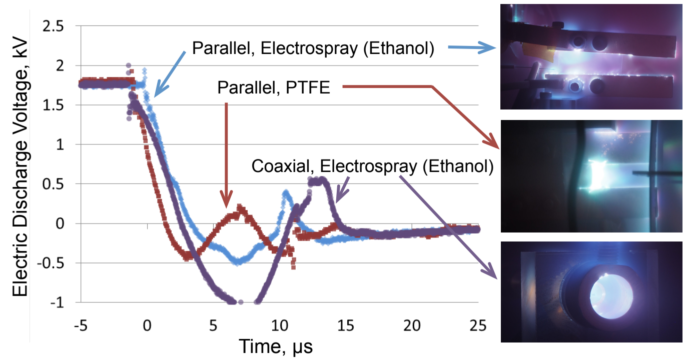


Figure 7. Waveforms of electric discharge voltage and photos.

B. Verification of PPT operation in case of SHP163 as green liquid propellant

In all conditions, the PPT produced successful electric discharge by injecting a drop of SHP163 in pulses. A different result than ethanol injection was that the impulse bit was not observed by only SHP163 injection when the voltage was not applied to a PPT. The individual impulse bit that was generated by the PPTs operation with SHP163 is summarized in Fig. 8. When the capillary was inserted from upstream parallel to the discharge channel, 11.4 μNs of average impulse bit was obtained. This count is about one-fourth the value of that by ethanol. And a voltage waveform of this situation is shown in Fig. 9. It is considered that the voltage waveform had no damping oscillation compared to a case of solid PTFE. From these results, we considered that injection quantity of SHP163 from the capillary, that had 30 μm of diameter, was less than that of ethanol because of higher viscosity of SHP163. The viscosity of ethanol and SHP163 is 1.07 mPa･s at 298 K and11.9 mPa･s at 293 K, respectively[6, 13].

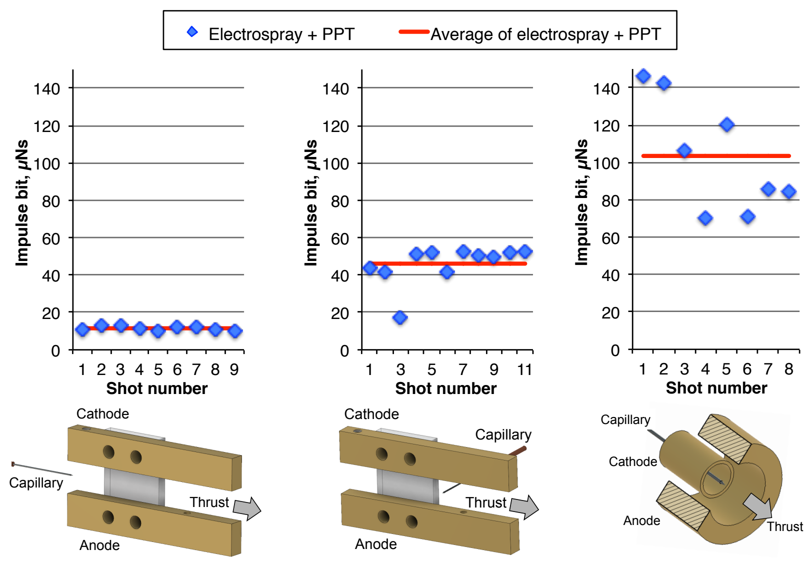


Figure 8. Impulse bit of PPT operation by SHP163 injection.

Therefore, we replaced 30 μm of capillary diameter with 100 μm at the other configurations. As a result, in case of the perpendicular insertion of capillary to the channel, 45.9 μNs of impulse bit was observed as average. This value is similar to the ethanol application with that the capillary was inserted from the cathode hole.

The coaxial PPT with inner cathode generated 103 μNs of average impulse bit by SHP163. This value is more than double the impulse bit of that by ethanol. We considered two reasons about this improvement. One is the increase of mass of SHP163 injection by expanding the diameter of capillary. However, this assumption is contradictory to the results of parallel plate PPTs. And the other is that the chemical reaction of SHP163 was induced by the electric discharge, and aerodynamic expansion influenced effectively by the coaxial configuration.

We will estimate the exothermic chemical energy of SHP163 in the PPTs. We assume that a sphere of SHP163 that simulates a droplet at the tip of the capillary, such as Fig. 5, will inject to a PPT in one pulse operation. If the diameter of the sphere is 0.5 mm, which is the equivalent to 0.0654 mm^3 of volume, the mass of the sphere is 91.6 μg, as reference to Table 1. Therefore, we estimate the ideal exothermic chemical energy of the sphere is 9.7 J, because of 80.12 g/mol of averaged molecular weight and -8471 kJ/mol of enthalpy of reaction. This estimated chemical energy is similar to electric discharge energy in this experiment that was 8 J.

Waveforms of the voltage when 100 μm of capillary attached are indicated in Fig. 10. Compared to a case of solid PTFE, the number of damping was little larger in case of SHP163 application. And its discharge duration was little longer than solid PTFE. And we considered that the coaxial PPT was similar to the parallel plate one in view of electric discharge circuit, because of the similarity of voltage waveforms.

To summarize, the exothermic chemical reaction was induced successfully by the electric discharge of PPTs. And the energy was utilized to the impulse bit effectively only in case of coaxial PPT because of its geometric properties in view of aerodynamic force. In order to improve impulse bit by coaxial PPT, longer channel length may be favorable, and then the effect of electro thermal and aerodynamic will increase.

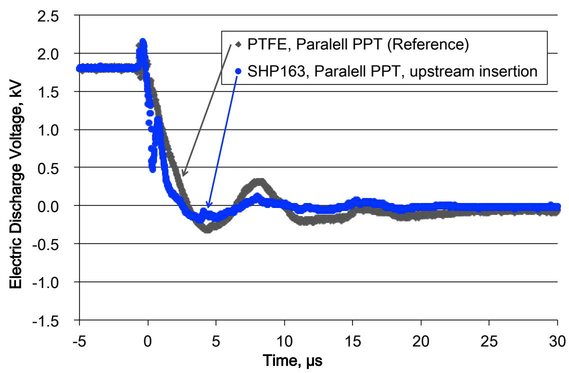


Figure 9. Electric discharge voltage of parallel plate PPT with SHP163 when 30 μm of capillary was inserted from the upstream.

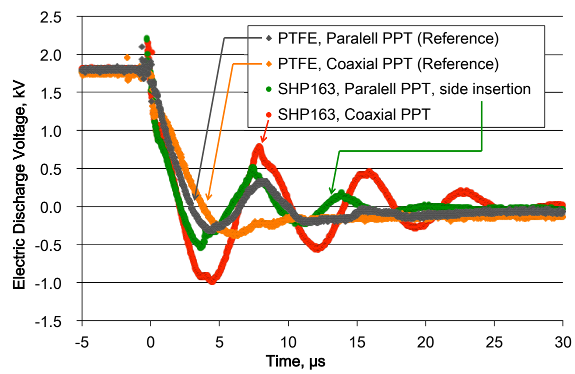


Figure 10. Electric discharge voltage of parallel plate and coaxial PPT with SHP163 when 100 μm of capillary was inserted.

IV. Conclusion

In order to apply chemical monopropellant especially green liquid propellant to PPTs, electrospray system was constructed. As liquid propellant, we employed ethanol, and SHP163 which is Hydroxyl ammonium nitrate based green propellant. And we prepared parallel plate PPTs and Coaxial PPTs which had 8 J of electric discharge energy.

Although the electrospray injected ethanol in vacuum environment, PPTs did not induce its steady electric discharge. Hence, we tried to increase emission quantity by collecting ethanol at the tip of capillary like a droplet, and then applying high voltage to inject the droplet of ethanol. As the result, when we utilized 30 mm of capillary diameter, some PPTs induced pulsed electric discharge successfully. The parallel plate PPTs generated 22.7 μNs and 46.5 μNs of averaged impulse bit when the capillary was at near 50 mm and 20 mm upstream of discharge channel from the downstream edge of electrodes, respectively. We considered that the nearer position the capillary was to the pendulum target, the higher impulse we obtained. And the coaxial PPT with inner cathode generated 49.0 μNs of averaged impulse bit.

Moreover, it is remarkable that we confirmed inducing the electric discharge of a PPT by injecting SHP163. The parallel plate PPT which the capillary was near the edge of upstream generated 11.4 μNs of averaged impulse bit. Then, we expanded the capillary diameter from 30 μm to 100 μm in order to increase injection quantity. And we also moved position of the capillary to 25 mm upstream of discharge channel form the downstream edge of electrode. As the result, 45.9 μNs of averaged impulse bit was obtained. And the coaxial PPT with inner cathode generated 103 μNs of averaged impulse bit. We estimated that the injected SHP163 had 9.7 J of ideal exothermic chemical energy, which was similar to 8 J of the electric discharge energy. In addition to the comparison with waveforms, we considered that the exothermic reaction occurred in any cases. And the energy transferred to the plume effectively in case of the coaxial PPT because of its geometric properties.

Acknowledgments

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