Title:

Effect of Solute Mixing in the Liquid Propellant of a Pulsed Plasma Thruster

Authors:

Hiroyuki Koizumi [a*], Yoko Kawazoe [a], Kimiya Komurasaki [a], and Yoshihiro Arakawa [a]

Affiliations:

[a] Department of Aeronautics and Astronautics, University of Tokyo

7-3-1 Hongo Bunkyo-ku, Tokyo, 113-8656, Japan

*Corresponding Author:

Hiroyuki Koizumi
University of Tokyo
7-3-1 Hongo Bunkyo-ku, Tokyo, 113-8656, Japan
Tel: 03-5841-6586
Email: koizumi@al.t.u-tokyo.ac.jp

Abstract:

Sodium chloride or ammonia was dissolved in the water propellant of pulsed plasma thrusters to improve the performance. Pulsed plasma thrusters using liquid propellant utilize water as attractive alternative instead of Teflon. Water propellant enables the controlling propellant mass flow and leads high specific impulse. However, liquid propellant pulsed plasma thrusters have larger plasma resistance and lower thrust power ratio than common Teflon propellant thruster. Here, sodium chloride and ammonia solution of water was examined to decrease that plasma resistance. As a result, emission lines attributed from the solute were observed using sodium chloride aqueous solution propellant, and a 5 % reduction of the plasma resistance was shown, and the thrust to power was increased. However, ammonia aqueous solution decreased the thruster performance.

Keywords:

Electric Propulsion, Pulsed Plasma Thruster, Liquid Propellant, Solute mixing, Seeding.

1. Introduction

In recent years, Pulsed Plasma Thrusters (PPTs) have attracted a lot of attention as promising thrusters [1]. The most common PPTs are using Teflon as propellant (Teflon PPTs). The main thruster discharge initiated by an ignitor ablates surface of a Teflon block located on the breech or side of the electrodes, and the evaporated Teflon gas is supplied to the discharge plasma as propellant. Capacitor-stored energy is converted to the kinetic energy of exhaust gas by electrothermal expansion and electromagnetic acceleration. The eroded Teflon block is commonly pushed by a spring for the succeeding pulses. They have a very simple structure and high reliability. Moreover, they provide small and precise impulses at high specific impulse with arbitrarily low power, and are suitable for power and mass limited microspacecraft.

The problems associated with Teflon PPTs are their low efficiency and contamination to spacecraft. The low efficiency mainly causes low speed of the ejected vapor from Teflon surface and emission of large particulates during the main discharge. Moreover, spacecraft contamination by the exhaust gas of carbon and fluorine would become a serious problem.

As a challenge, use of a liquid propellant was proposed for pulsed plasma thruster (LP-PPT) by the authors[2,3]. The liquid propellant is supplied using an intermittent injector into an interelectrode space. Some fraction of injected liquid is vaporized into gas. Main discharge is initiated with a spontaneous discharge or with pre-discharge from an ignitor. The main discharge converts the liquid and gaseous propellant into plasma. The plasma is accelerated both electromagnetically and electrothermally, and puffed out of the thruster. However, other types of PPT using a liquid propellant were also proposed[4,5], in which liquid (water) is supplied by allowing diffuse through a porous material with constant mass flow rate.

Water was selected as promising propellant, because it would reduce spacecraft contamination on the sensitive devices of spacecraft. Also, it has an advantage capable sharing with other systems like life support system. In our previous study, it was shown that a liquid propellant PPT had higher specific impulse than Teflon PPT, because the liquid propellant PPT controlled the mass shot via a liquid injector. However, the thrust power ratio was lower than Teflon PPTs, and the thrust efficiency remained as the same level. In this study, some solutes to the liquid propellant were examined in order to decrease the plasma resistance and increase the thrust power ratio using liquid propellant for PPTs.

2. Resistances of Pulsed Plasma Thruster

Generally, a PPT can be assumed as an electrical circuit which has discrete elements of varying inductance, capacitance, and resistance [6]. Electromagnetic impulse that the thruster generates (the momentum given to the plasma by electromagnetic acceleration) is expressed as

$$I_{\mathrm{EM}} = \frac{1}{2} L' \int_0^{\tau} J^2 dt = \frac{1}{2} L' \frac{E}{R_{\mathrm{total}}} \tag{1}$$

where *L'* is the inductance per unit length, *J* is the current, *E* is the capacitor-stored energy, and R_{total} is the total resistance of a PPT. The total resistance consists of the resistance of the external circuit $R_{circuit}$ (capacitor, electrodes, and feed through), the resistance of the plasma R_{plasma}, and the effective resistance of electromagnetic work R_{EM}.

$$R_{\mathrm{total}} = R_{\mathrm{circuit}} + R_{\mathrm{plasma}} + R_{\mathrm{EM}} \tag{2}$$

Here we assume that the resistances R_{plasma} and R_{EM} are approximately constant, although they are actually time varying. Equation (1) means that the small total resistance gives high thrust power ratio and the impulse generated from electromagnetic accelerator is essentially no dependence on the mass.

Table 1 shows the resistances estimated from current waveforms for a liquid propellant PPT and Teflon PPT, which have the same electrodes and external circuits. The total resistances R_{total} are estimated by the curve-fit of a current waveform during the discharge into the following equation.

$$J(t) = J_0 \exp(-\mu t)\sin(\omega t), \quad \text{where} \quad \mu = R/2L \quad \text{and} \quad \omega = \sqrt{1/LC - (R/2L)^2} \tag{3}$$

The resistance of the external circuit $R_{circuit}$ was obtained from the curve-fit for a current waveform when the electrodes were shorted by a copper plate in the atmosphere. The resistance of the copper plate was less than 0.3 mΩ and negligible. The resistance of the spark generated between the electrode and copper plate was estimated by measuring voltage drop over that spark. The residual resistance $R_{plasma}+R_{EM}$ was obtained by subtracting $R_{circuit}$ from R_{total}. The effective resistance of electromagnetic work is defined by

$$R_{EM} \equiv \frac{1}{2} L' \int_0^{\tau} v J^2 dt \Big/ \int_0^{\tau} J^2 dt \cong \frac{1}{2} L' \bar{v} \tag{4}$$

where $\bar{v}$ is a squared-current-averaged plasma velocity, and the inductance depends on the configuration of the electrode. A thruster presented in the following section has an inductance per unit length of 0.71 nH/mm. In our past study, puffing velocity of the plasma was observed using a 5 Mfps high speed camera, and R_{EM} was roughly estimated as 10 mΩ for a liquid propellant PPT [7].

The liquid propellant PPT had a larger total resistance than a Teflon PPT, which was confirmed also by Scharlemann and York [4]. It means that that a liquid propellant PPT has lower thrust power ratio than the Teflon PPT, which was confirmed also from the thrust measurement[7]. The difference of the total resistance was because of the plasma resistance and effective resistance of electromagnetic work. One of the methods to reduce the plasma resistance is utilization of solute and injecting additives, which can ionize at relatively low temperatures into the plasma.

3. Experimental Set Up

3.1 Thruster and propellant

A liquid propellant PPT addressed here (schematic diagram is shown in **Fig. 1**) consists of parallel plate electrodes with glass side walls, 3 μF capacitor, ignitor, and liquid injector. The electrodes are made of SUS and the interelectrode space is 20 mm, the length: 34 mm, and the width: 10 mm. The anode is insulated from the cathode by a ceramic back wall. The injector has a 50 μm diameter orifice, which is normally closed by a spring force and opened when the actuator pull the plug. Liquid droplets of a few micro grams were fed into the interelectrode space through a hole opened on the cathode.

In this study, purified water was used as liquid propellant. Sodium (Na) and ammonia (NH_3) was selected as solute to the propellant. These materials were chosen because of their ionization potential and handling abilities. The ionization potentials of sodium and ammonia are much lower than that of water (H_2O). Sodium was mixed into water as sodium chloride aqueous solution, and ammonia as ammonia aqueous solution. **Table 2** shows the ionization potential of H_2O, Na, and NH_3 and the solution concentration to water by mole percent.

3.2 Measurement

Experiments were conducted in a 1.0-m-diam, 1.4-m-long vacuum chamber under the background pressure below 4.0×10^{-5} Torr. Current waveform during a PPT fire was measured using a Rogowski coil. Impulse bit produced by a PPT was measured by a thrust stand [8], shown in **Fig. 2**, which is a horizontally swinging torsional balance. A thruster is installed on the end of the arm, and its repulsive force is measured from the displacement of the balance. Calibration is performed by striking a force transducer attached to the thrust stand with impact pendulum. The accuracy of the thrust stand was better than 2 % within the PPT impulses of 30 to 60 μNs.

To confirm the presence of solutes in the plasma, emission spectroscopy was conducted. The spectrometer (Hamamatsu; model C5094) has the focal length of 250 mm and 1200 gr/mm grating yielding the reciprocal linear dispersion of 2.5 nm/mm. The dispersed light is detected by a 1024 ch ICCD array. Emission from the discharge was collected into an optical fiber (not focused), and exposure time was set as much longer (2 s) than the PPT discharge. The typical slit width was 100 μm. The spectrogram was scanned at 30 nm increment steps from 320 to 780 nm. The spectral wavelength, and radiance was calibrated using an argon discharge tube and a standard source.

4. Results and Discussion

4.1 Spectroscopy

Figure 3 shows spectrum lines from PPT discharges for sodium chloride solution and ammonia aqueous solution propellant, where thrusters were operated with capacitor-stored energy of 11.5 J. Sodium (Na I) and ionized chlorine (Cl II) were identified in the plasma of 1.9 % NaCl aqueous propellant by comparing acquired emission lines with a standard reference. Additionally, emission lines from neutral and singly ionized oxygen were identified. They were more intensified than using purified water. On the other hand, in the case of 5.5 % NH_3 aqueous propellant, spectrum line attributed from ammonia was not identified, and the overall emission lines became weaker than purified water.

4.2 Thrust and resistance

Table 3 shows the dependence of measured thrust power ratio on the capacitor-stored energy for three types of liquid propellants: purified water, sodium chloride aqueous solution, and ammonia aqueous solution. Capacitor-stored energy was varied from 2.9 to 11.5 J. The measured impulse was divided by the energy and averaged over 20 or 12 shots. The associated errors mean the 90 % confidence intervals.

Sodium chloride aqueous solution propellant showed higher thrust power ratio than purified water. At the energy of 11.5 J, it increases 9.5 % from 5.2 to 5.7 μNs/J. This increasing tendency become strong as the energy increases. The average increments of impulse was 5.5 %. On the other hand, ammonia aqueous propellant showed lower performance. This result seems to agree with the result of strong emission lines from NaCl and weak lines for NH_3.

Table 4 shows the dependence of total resistance of a liquid propellant PPT on the energy, which is obtained from the curve-fit of the current waveform. Sample of the current waveform and the fitting curve is shown in **Fig.4**. The resistance in Table 4 shows the average over 20 or 12 shots. Sodium chloride aqueous propellant showed smaller resistance than purified water, whose average decrement was 5.7 %. Ammonia aqueous solution had larger resistance than purified water had.

4.3 Discussions

For the plasma from sodium chloride aqueous solution, emissions from neutral sodium and singly ionized chlorine were observed. Ionized sodium and neutral chlorine were not be observed because they have strong emission lines out of the range of spectrometer, less than 320 nm and higher than 800 nm respectively. Presence of those lines means that some fraction of sodium and chlorine dissolved in water appeared in the plasma.

The results of the impulse and total resistance measurements are consistent with Eq. (1): small total resistance means high thrust to power ratio. Considering the result of emission spectroscopy, mixing of sodium would increase the plasma density of liquid propellant PPT. Then the total resistance was decreased. However, when ammonia mixing in water, the thrust power ratio was decreased against our expectation. It seems that the plasma density became lower. Some energy might be excessively consumed for dissociation of the ammonia molecule.

Whereas solute mixing succeeded to decrease the total resistance, it is still 20 % larger than a Teflon PPT. Two reasons are considered. Firstly, solutes had only slight effect on the increment of plasma density, secondly, plasma density was already high but the low electron temperature caused the high resistance (electrical conductivity in fully ionized plasma is proportional to $(kT_e)^{3/2}$ and does not depend on the plasma density). Quantitative measurements for plasma density and temperature are required to clarify those processes.

5. Conclusion

Effect of solute mixing in water propellant was investigated to reduce the total resistance of a liquid propellant pulsed plasma thruster, and the following results were obtained. Sodium chloride aqueous solution showed lower total resistance and higher thrust to power ratio than purified water. In consistent to the result, emission lines from sodium and chlorine and intensified other emission lines were observed.. On the other hand, ammonia aqueous solution increased the resistance, decreased the thrust, and weakened emission intensity of the plasmas.

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Figure Captions:

Fig. 1 Schematic diagram of the liquid propellant PPT.

Fig. 2 Thrust stand to measure the impulse bit.

Fig. 3 Emission spectrum from 320 to 780 nm during the PPT discharge using solved liquid propellant: a) sodium chloride aqueous solution and b) ammonia aqueous solution.

Fig. 4 Sample of the discharge current waveform and the fitting curve using purified water propellant at the capacitor-stored energy of 11.5 J.

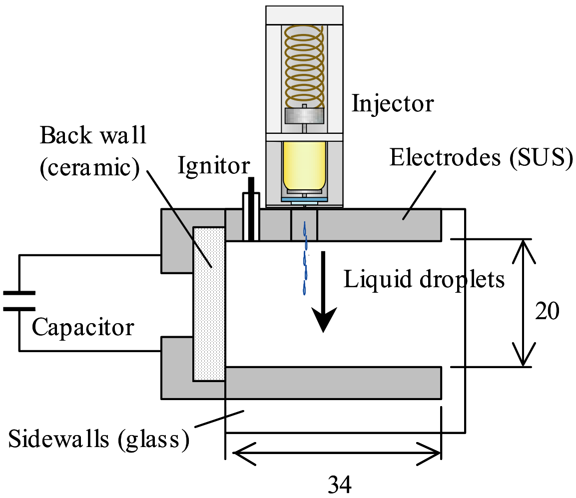


Fig. 1 (reduction rate: 1) Hiroyuki Koizumi

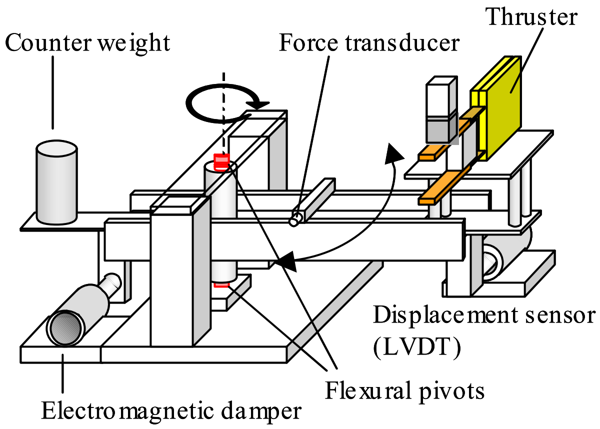
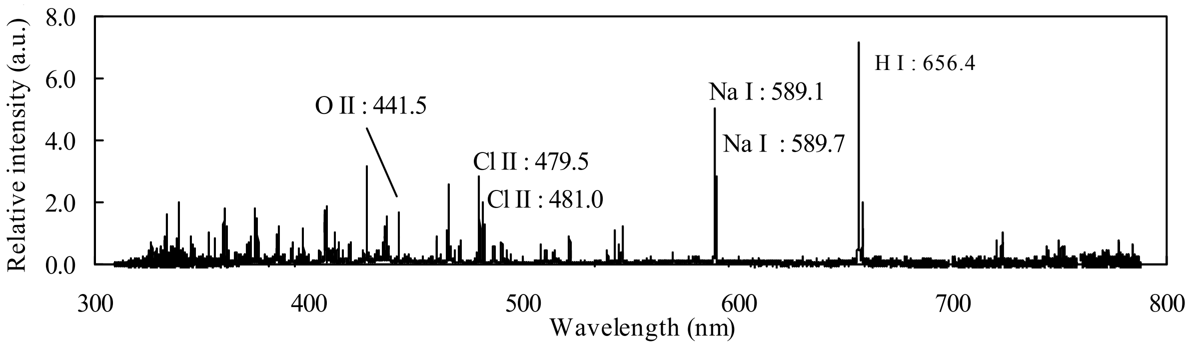
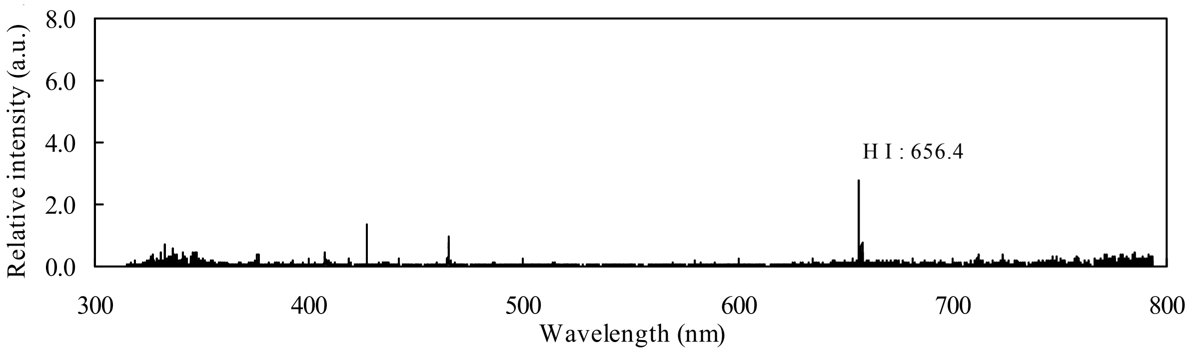


Fig. 2 (reduction rate: 1)   Hiroyuki Koizumi



a)



b)

Fig. 3 (reduction rate: 1) Hiroyuki Koizumi

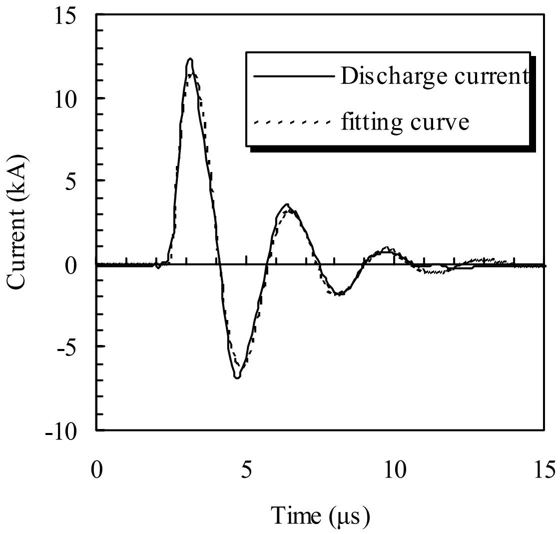


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Fig. 4 (reduction rate: 1)　　Hiroyuki Koizumi

Table Captions:

Table 1 Typical resistances of a LP-PPT and Teflon PPT at the energy of 10 J

Table 2 Properties of H_2O, Na, and NH_3.

Table 3 Dependence of thrust power ratio on capacitor-stored energy.

Table 4 Dependence of total resistance on capacitor-stored energy.

	LP-PPT	Teflon PPT
R_{total}	64±2 mΩ	48±1 mΩ
$R_{circuit}$	17±3 mΩ	17±3 mΩ
$R_{plasma} + R_{EM}$	47±5 mΩ	31±4 mΩ

Table 1 Hiroyuki Koizumi

	Ionization potential	Solution concentration
H_2O	12.7 eV ($\rightarrow H_2O^+$)	-
Na	5.1 eV ($\rightarrow Na^+$)	1.9 %
NH_3	5.9 eV ($\rightarrow NH_3^+$)	5.5 %

Table 2 Hiroyuki Koizumi

Capacitor stored energy (J)	Thrust power ratio (μNs/J)		
	Pure water	Sodium chloride aqueous solution	Ammonia aqueous solution
2.9	4.49 ±0.27	4.52 ±0.17	4.79 ±0.16
4.1	4.72 ±0.17	4.81 ±0.11	–
5.1	4.90 ±0.13	5.00 ±0.10	–
6.8	4.85 ±0.10	5.20 ±0.10	–
8.0	4.97 ±0.10	5.31 ±0.11	4.81 ±0.18
10.0	5.11 ±0.07	5.51 ±0.10	–
11.5	5.23 ±0.08	5.72 ±0.08	4.98 ±0.13

Table 3 Hiroyuki Koizumi

Capacitor stored energy (J)	Total resistance (mΩ)		
	Pure water	Sodium chloride aqueous solution	Ammonia aqueous solution
2.9	70.3 ±1.9	64.1 ±1.3	70.8 ±2.5
4.1	67.9 ±1.2	61.6 ±0.8	–
5.1	65.5 ±1.4	61.5 ±0.8	–
6.8	64.5 ±1.3	61.5 ±1.3	–
8.0	63.6 ±1.0	62.3 ±1.4	65.9 ±1.8
10.0	64.0 ±1.4	61.6 ±1.0	–
11.5	62.2 ±1.5	58.8 ±1.2	61.4 ±1.6

Table 4 Hiroyuki Koizumi