

# LIQUID PROPELLANT PULSED PLASMA THRUSTER \*

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In this paper, we proposed a new type pulsed plasma thruster using liquid propellant, namely Liquid Propellant PPT. To date, most PPTs are ablative PPTs which use solid propellant due to its simplicity and reliability. However, their performance is generally low among electric propulsions because of the ablation propellant feed system. To improve the performance, flow rate controllable propellant like liquid is necessary. Especially we focused on water which includes no carbon and toxicity. We demonstrated the operation of a LP-PPT. Liquid injectors suitable for LP-PPT were examined and the liquid injection of the 10  $\mu\text{g}$  order was achieved. 10 J class thrusters using that injector were designed and operated. Impulse bit was measured by a thrust stand with the resolution of 1  $\mu\text{Ns}$ , and the thrust performances were evaluated. Liquid injection allowed the spontaneous discharge type thrusters. The use of an ignitor made the operation range expand. Water propellant PPT was successfully operated with high reproducibility. The impulse bits were measured in the range from 22 to 82  $\mu\text{Ns}$  in proportion to the capacitor stored energy of 3 to 13.5 J.

## 1 Introduction

In recent years, Pulsed Plasma Thrusters (PPTs) have attracted great attention as promising thrusters [1]. PPTs are pulsed electric propulsion, and can provide high specific impulse in low power levels, while most electric propulsions requires high power levels. The PPT power throttling is managed simply by adjusting the pulse repetition frequency and does not affect the performance. These characteristics are suitable for orbit raising and acquisition of the power limited microspacecraft. In addition, PPTs can generate small impulse bit, and precise arbitrary impulse as well as the power throttling. Hence PPTs are attractive for the accurate positioning, attitude control, and stationkeeping.

To date, the most common PPTs are the Ablative PPTs (APPTs) which use solid propellant. The current flows in a plasma adjacent to the surface of solid propellant. The solid surface is ablated by the current, and supplies the working gas into the plasma. The only moving part is a spring that passively feeds the propellant. Hence APPTs have a very simple structure which provides high reliability, and they are suitable for microspacecraft. However, APPTs have several problems: 1)poor performance characteristics, 2)contamination, 3)nonuniform ablation. 1) For instance, a flight-qualified APPT design had an efficiency of about 8 % [2]. Several researchers in this field have pointed out that the excessive propellant feed which does not contribute to the thrust is the cause of the low efficiency. Low speed vapor continues to be provided from the solid propellant surface after the main discharge [3][4], because the surface temperature remains higher than the boiling point of the propellant. Additionally the emission of large particulates was observed [5], which could not be effectively accelerated. In order to improve the propellant efficiency, it is necessary to supply only an minimum amount of propellant for both ionization and acceleration. 2) Contamination on the spacecraft by the exhaust gas would become a serious problem, since most APPTs use Teflon for the propellant, which includes carbon and fluorine. The carbonization was observed on the ignitor plug [6], and it limited the life time of thrusters.

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Attempts to use alternative propellant failed due to the severe carbonization [7]. Although there is a research that the contamination did not affect spacecraft [8], strong reactive elements like fluorine would be serious problems, especially for applications involving sensitive diagnostics like optics on the future spacecraft. 3) The nonuniformity of current density and Teflon surface temperature conducts the preferential ablation near the electrodes [9]. The nonuniform ablation varies the impulse bit trend in successive operation. Further it decreases the amount of usable propellant, and specific impulse in the thruster. This phenomena was remarkable for the small energy levels and small size [10][11]. Then it would be problem for Micro PPTs.

We propose a Liquid Propellant Pulsed Plasma Thruster (LP-PPT), which uses liquid as propellant in order to avoid the above mentioned problems of APPTs: excessive propellant, contamination, and nonuniform ablation. Figure 1 shows a schematic diagram of a LP-PPT. It supplies liquid propellant by an intermittent injector into an interelectrode region. 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 liquid and gaseous propellant into plasma. The plasma is accelerated both electromagnetically and electrothermally, and exhausted out of the thruster.

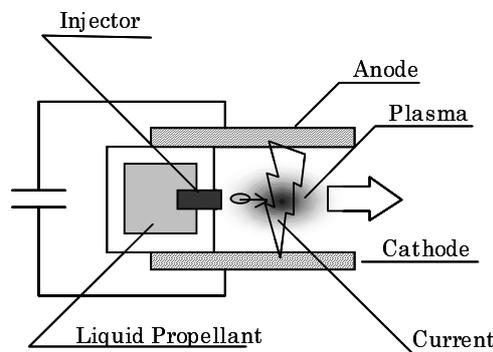


Figure 1: Concept of Liquid Propellant PPT

## 2 Liquid Propellant Pulsed Plasma Thruster

### 2.1 Liquid propellant

#### 2.1.1 Comparison to solid propellant

High simplicity and reliability of APPTs are achieved through the use of solid propellant and the discharge ablation propellant feed system . As above mentioned, however, it leads to the several problems. The use of liquid as propellant would allow the following advantages. First, mass flow rate of liquid propellant can be controlled and the late-time vaporization and large particulates problems would be avoided. Secondly, water, one of the attractive liquid propellants, includes no carbon and no reactive element like fluorine, and it is a promising liquid propellant.

#### 2.1.2 Comparison to Gaseous propellant

Gaseous propellant has the similar characteristics as liquid. The use of gaseous propellant for PPTs was examined in the initial stage of space development, early sixties. Gas injected into the discharge chamber quickly fills the interelectrode region and escapes during about  $100 \mu s$ . Fast acting valves are required to effectively use the propellant. However, it is difficult to develop such fast acting gas valves with high reliability and long life time. To solve this problem, recently, Gas fed PPT with high repetition rate discharge has been proposed [12][13], and dramatically improved its propellant utilization efficiency. Nevertheless it is not suitable for microthrusters, because one set of operation demands at least 20 pulses, and 100 J.

Liquid propellant is different from gaseous propellant with respect to the following points. First, liquid injected into the vacuum diffuses more slowly than gas, and there is no need of fast acting valve. For instance, the calculation of the vaporizing mass regarding the temperature and vapor pressure gave the result that only 20 % of water would be vaporized in 10 ms since it is injected into the vacuum. Secondly, there is no need of high pressure tank to storage liquid propellant. It would conduct to the weight and size saving.

## 2.2 Liquid Injector

Liquid Propellant PPT requires an intermediate injector to supply liquid propellant. In the present work, ink-jet printer type injector and shut off valve injector were examined. For these injectors, the following abilities are demanded, operation in vacuum, supply of a few micro grams liquid, small and light body, high reliability and long life time.

### 2.2.1 Ink-jet type injector

First of all, we attempted to apply the ink-jet technology in printers into the injector for PPT. Ink-jet printers inject liquid droplets from a small pinhole with the pressure increase by piezoelectric device. It has no shut off valve and seals liquid by the surface tension. Then it have a simple and compact structure, and supply a extremely small amount of droplets. These characters are suitable for liquid propellant PPT injector. We designed piezoelectric capillary injectors. It worked in the atmosphere. In vacuum, however, it could not work, since leaking liquid adhered around the pinhole and prevented the injection of liquid.

### 2.2.2 Valve injector

Figure 2 shows a designed valve injector, which injects liquid from an orifice by its inner pressure. In the closing state (normally state), the force of a spring presses the closing boss downward to the orifice. Sealing is enhanced by the use of flexible silicone rubber. This boss is moved upwards by the actuator force. Then the valve is opened, and liquid is ejected by the inner pressure.

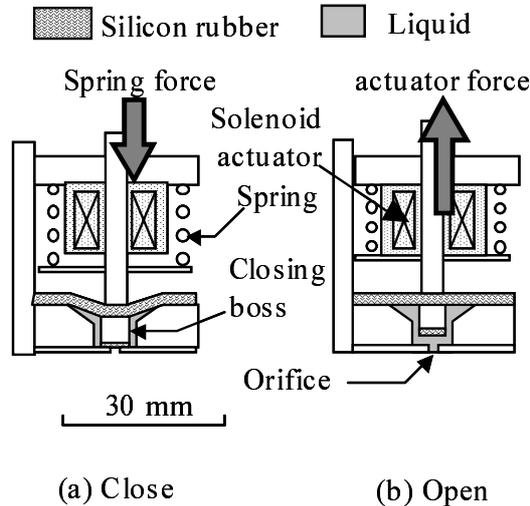


Figure 2: Cross-section view of the valve injector

The use of mechanical valve can be disadvantage in terms of the lack of the simplicity, but recent growth of MEMS technology would remove these defects. Recently, there are a number of studies of microvalves using MEMS. These researches can be applied to the liquid propellant PPT. For instance, MEMS technology allowed a more miniaturized injector whose size was  $7 \times 7 \times 21 \text{ mm}^3$  [14], with the same mechanism as Fig. 2. Furthermore, high pressure valve is not necessary for liquid propellant. It would enable saving the weight and size saving.



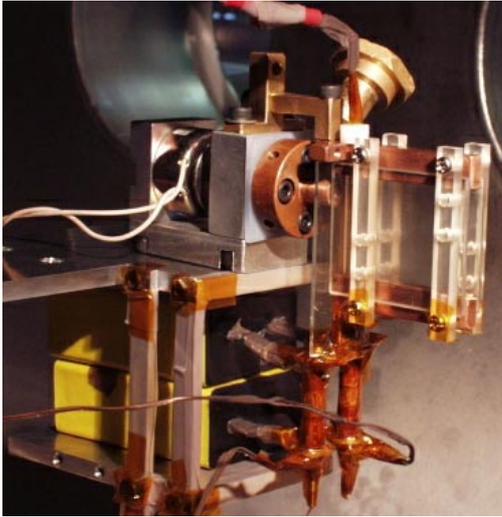


Figure 4: Picture of a parallel plate LP-PPT

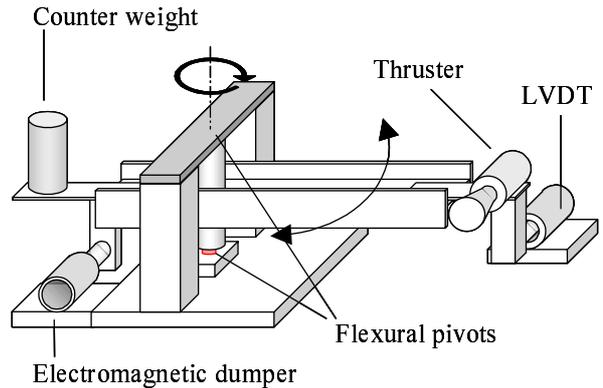


Figure 5: Schematic diagram of a thrust stand

### 3 Thrust Stand

Measurement of impulse bits was performed with a torsional thrust stand, whose schematic diagram is shown in Fig. 5. The thrust stand is based on a torsion balance. A thruster is installed on the arm of the thrust stand, and impulse bit is calculated from the response by the reaction force. The relation of the delivered impulse:  $I_{bit}$  and the amplitude of the thrust stand oscillation:  $A$  is

$$A = \frac{I_{bit} l_I l_m}{J \omega_0} \quad (2)$$

where  $l_I$  and  $l_m$  is the distance away from the rotational axis to the thruster and the measurement point,  $J$  is the moment of inertia, and  $\omega_0$  is the natural angular frequency.

#### 3.1 Structure of the thrust stand

Our thrust stand consists of four components:

- (a) torsional balance
- (b) displacement sensor
- (c) electromagnetic dumper
- (d) counterweights.

- (a) The torsional balance consists of a vertical rotational tube and a horizontal H-section beam. The rotational tube is connected to the stationary frame through two commercial available flexural pivots, whose spring rate is 0.19 Nm/rad. A thruster is installed on the end of the horizontal beam (30-40 cm from the rotational center). On the other end of the beam, electromagnetic dumper and counterweights are installed. Natural period of the balance was about 4 seconds in the state that the thruster and counterweights were installed.
- (b) Deflections of the balance were detected by a LVDT (linear variable differential transducer); the resolution is about 0.1  $\mu\text{m}$ . The transformer coils were attached to the stationary structure and the iron core was attached to the torsional balance.
- (c) An electromagnetic dumper was installed to dissipate undesirable vibrations induced by background vibrations. Signal of a LVDT is fed back to the electromagnetic dumper and it generates the force proportional to the derivative of the displacement. Strength of the dumping can be controlled from outside of the vacuum chamber. All measurement were performed under no dumping by turning off the dumper just before the PPT fire.

- (d) Counterweights enable the rotating structure to be statically balanced, and reduce the influence of the background vibrational noise.

### 3.2 Calibration

Calibration was carried out by striking the thrust stand with an impact hammer, on which a force transducer (PCB 209C01) is attached (see Fig 6). The hammer is remotely manipulated by the DC motor stopper. Output signal of the force transducer was recorded during an impact, and impulse delivered to the thrust stand was obtained by integrating the output signal. Figure 7 shows a typical result of calibration. This is a plot of the delivered impulse by the impact hammer and the amplitude of the thrust stand oscillation (LVDT output). The mean ratio of the delivered impulse to the amplitude was  $39.5 \mu\text{Ns}/\text{V}$ , and its 95 % confidence interval was  $\pm 0.4 \mu\text{Ns}$ .

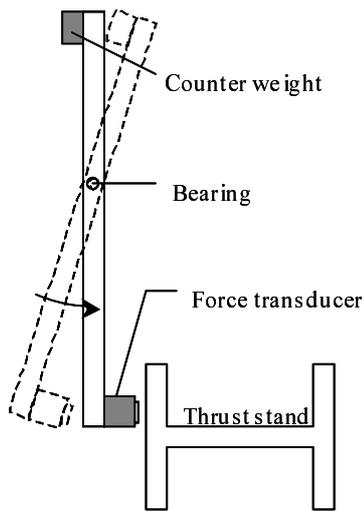


Figure 6: Impact hammer

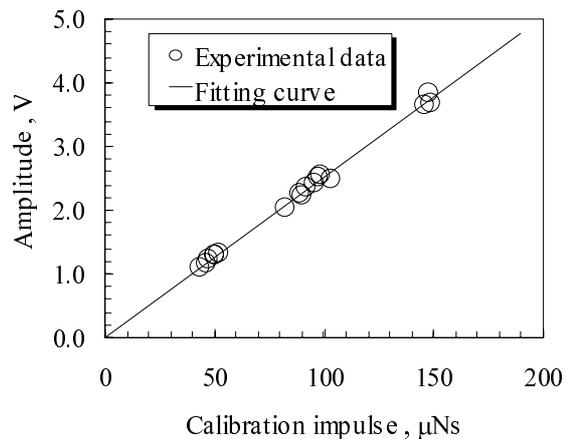


Figure 7: Typical result of calibration

### 3.3 Accuracy

Liquid injector of LP-PPT includes moving parts: core of the actuator. However, the motion of the actuator was too small to affect the impulse bit measurement. The primary cause of reducing the measurement accuracy was the noise induced by background vibrations. In the present work, this noise were suppressed down to  $0.4 \mu\text{m}$ , corresponding to  $1 \mu\text{Ns}$ , by electromagnetic dumper and counterweights. Hence the resolution of the thrust stand was  $\pm 1 \mu\text{Ns}$ .

## 4 Results and Discussion

### 4.1 Spontaneous discharge type

Arc discharge was initiated without ignitors after feeding liquid propellant in the coaxial LP-PPT shown in Fig. 3(a). No discharge was initiated unless liquid propellant was provided. Alcohol propellant was suitable for the spontaneous discharge type. Figure 8 shows discharge probability of the coaxial LP-PPT(methanol propellant under several conditions of the capacitor stored energy and the mass shot. LP-PPT operated at high probability in the range that mass shot is over  $3 \mu\text{g}$ . Figure 9 shows the dependence of the impulse bit and specific impulse on the mass shot at the capacitor stored energy ranging from 3.4 to 13.5 J. The slight inclination of impulse bit to the mass shot is due to the cold flow by liquid injection and the gas vaporized from it. From the curve of specific impulse, it is shown that specific impulse increases with decrease of the mass shot and increase of the energy.

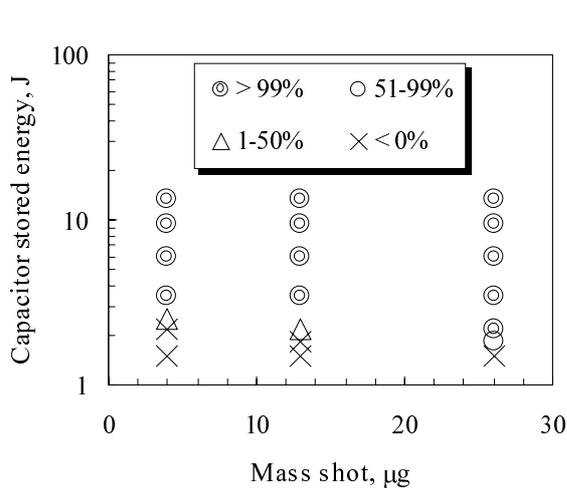


Figure 8: Discharge initiation probability

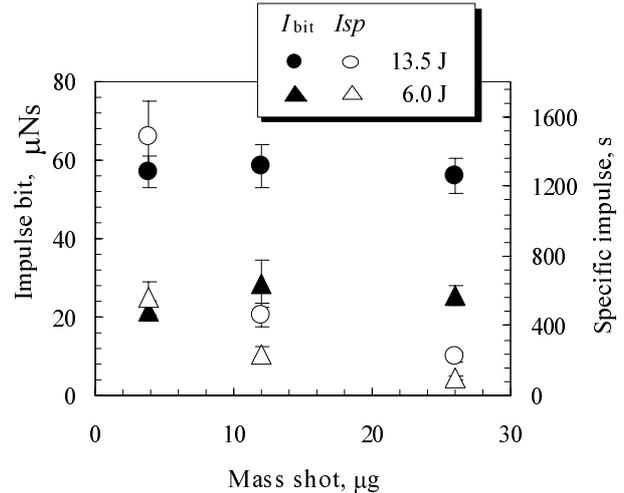


Figure 9: Measured thrust performance

## 4.2 Ignitor type

A parallel plate LP-PPT was successfully operated by using water as liquid propellant, namely water propellant LP-PPT. Figure 10 is a streak photograph of the firing. The impulse bit, specific impulse, and thrust efficiency were  $89 \mu\text{Ns}$ ,  $3400 \text{ s}$ , and  $11 \%$  respectively at the mass shot of  $2.7 \mu\text{g}$  and the energy of  $13.5 \text{ J}$ . Figure 11 shows the shot to shot variation of water propellant PPT over 20 shots. The average impulse bit was  $86.6 \mu\text{Ns}$  and the standard deviation of the shot to shot variation was  $4.5 \mu\text{Ns}$ . Thus water propellant PPT showed good reproducibility not so affected by liquid injection condition.

Water includes no carbon differently from alcohol propellant, which includes a great deal of carbon. The carbon was identified as a major life limiting component of the thruster and the ignitor [6][7]. In alcoholic propellant PPT, some degree of carbonization on the electrodes and the side walls was observed, that is, the surface was blackened after a few hundreds of shots. On the other hand, there was almost no carbonization in water propellant PPT.

Figure 12 shows the energy dependence of the impulse bit in water propellant PPT at the mass shot of  $2.8 \mu\text{g}$ . The impulse bit is proportional to the energy. The proportionality of impulse bit and energy is verified in a great deal of PPT researches [15][16][17]. The following analytic formulation for the impulse bit was proposed [7][18]:

$$I_{bit} = \frac{1}{2}L' \int j^2 dt + f\sqrt{mE} \quad (3)$$

where  $L'$  is the inductance per unit length,  $j$  is the total current,  $f$  is the proportionality constant,  $m$  is the mass shot, and  $E$  is the capacitor stored energy. The first and second terms of r.h.s. of Eq. (3) represent the electromagnetic and electrothermal acceleration respectively. In addition, the linear relation between the integration of the total current and the energy is also confirmed. For Ablative PPTs, there is agreement on a rough proportionality between  $m$  and  $E$  [17]. Then many APPTs represent the impulse bit linear dependency on the capacitor stored energy. However, this  $m$  dependency would be different for LP-PPT, in which the amount propellant is not affected by the energy. The impulse bit would represent the proportionality to the energy unless electrothermal acceleration is dominant. Therefore, from the results of Fig. 12, electromagnetic acceleration would be dominant in the LP-PPT dealt here.

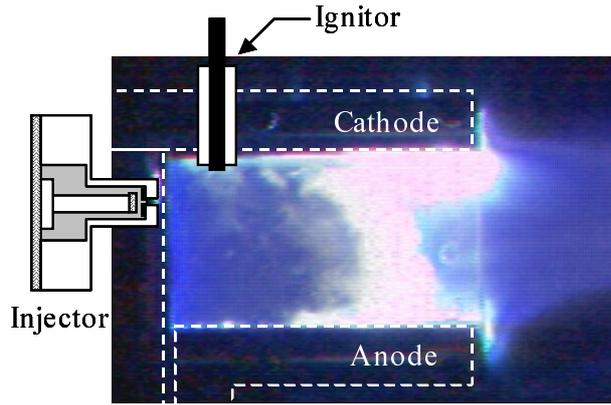


Figure 10: Streak photograph of parallel plate LP-PPT firing

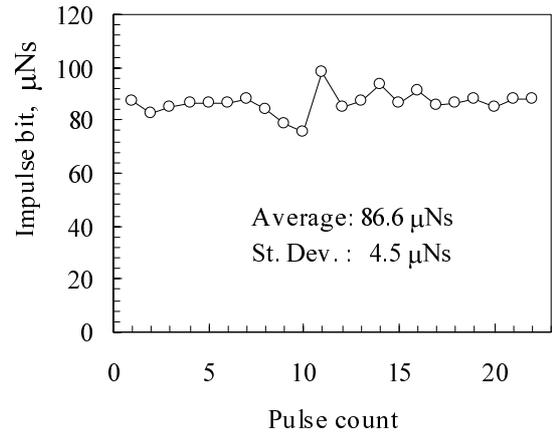


Figure 11: Shot to shot variation of LP-PPT

### 4.3 Current history

Discharge current histories were measured with a Rogowski coil. Figure 13 shows the result at water propellant, parallel plate type, the mass shot of  $2.8 \mu\text{g}$ , and the energy of 13.5 J. In all ignited condition, the current was an underdamping oscillation as shown Fig. 13. Shot to shot reproducibility of the discharge current history was very excellent.

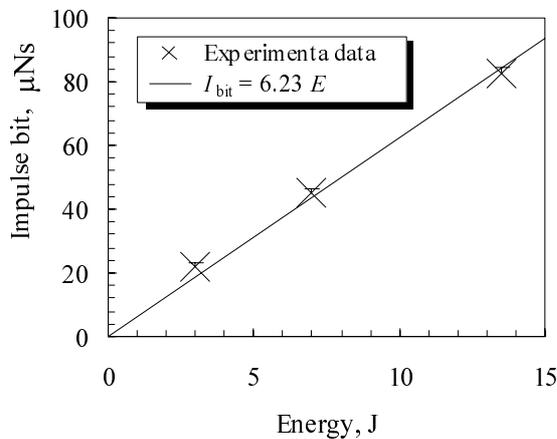


Figure 12: Impulse bit as a function of the capacitor stored energy

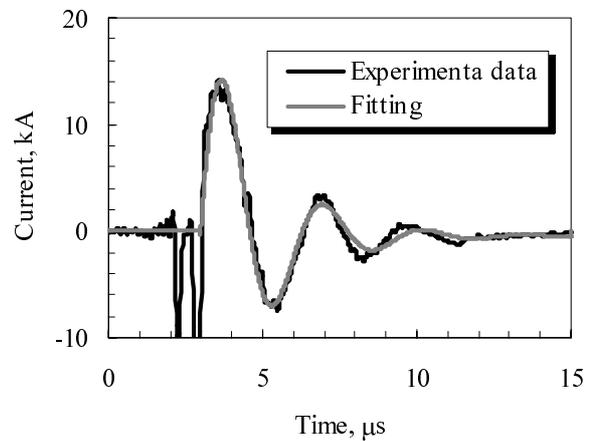


Figure 13: Time history of current

Total inductance:  $L_t$  and resistance:  $R_t$  of PPT can be calculated from the current waveform, assuming that a PPT is a LCR circuit [19]. Damped sinusoid curve fit with least-square method was performed on Fig. 13. As a result, the total inductance and resistance were 84 nH and 82 m $\Omega$  respectively. On the other hand, analytic formula for the inductance of a closed circuit of rectangular conductors gives  $L = 15.6 \text{ nH}$ ,  $L' = 0.88 \text{ nH/mm}$ , and  $\Delta L (\equiv L' \times l) = 25.6 \text{ nH}$  [1], for the parallel plate LP-PPT dealt here. The calculated electrode inductance:  $L$  was lower than the measured total inductance:  $L_t$ . This difference would be due to the capacitor and the feed-through between the elec-

trodes and capacitor. The former is about 20 nH from the data sheet and the latter is estimated as a few tens of nano henries. Therefore these inductance value would be valid.  $\Delta L/L_t$  gave the upper limit efficiency of electromagnetic acceleration of 31 %.

## 5 Summary

In this paper, we demonstrated the operation of liquid propellant PPTs, especially water propellant PPT. Liquid injectors suitable for LP-PPT were examined and the liquid injection of the 10  $\mu\text{g}$  order was achieved. 10 J class LP-PPTs were designed and operated. Impulse bit was measured by a thrust stand with the resolution of 1  $\mu\text{Ns}$ , and thruster performances were evaluated. Liquid injection allowed the spontaneous discharge type thrusters for alcohol propellant with high discharge probability. The use of an ignitor made the operation range expand. Water propellant PPT could be successfully operated with the shot to shot variation of 5 %. The impulse bits were varied in the range from 22 to 82  $\mu\text{Ns}$  in proportion to the capacitor stored energy of 3 to 13.5 J.

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