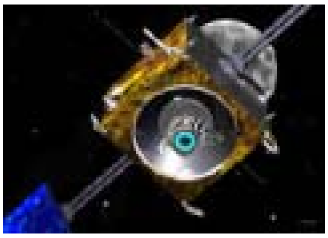
IEPC 2003



2003 International Electric Propulsion Conference

IEPC-03-087

Liquid Propellant Pulsed Plasma Thruster

Koizumi, H., Kakami, A., Furuta, Y., Komurasaki, K., and Arakawa, Y.

The University of Tokyo
Department of Aeronautics and Astronautics
7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, Japan
+81-3-5841-6586
koizumi@al.t.u-tokyo.ac.jp

28th IEPC, March 17-21, 2003
Toulouse, France

LIQUID PROPELLANT PULSED PLASMA THRUSTER *

Koizumi, H., Kakami, A., Furuta, Y., Komurasaki, K., and Arakawa, Y.
The University of Tokyo
Department of Aeronautics and Astronautics
7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, Japan
+81-3-5841-6586
koizumi@al.t.u-tokyo.ac.jp

IEPC-03-087

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 μg 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 μNs, 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 μNs 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.

* Presented as Paper IEPC-03-087 at the 28th International Electric Propulsion Conference, Toulouse, France, 17-21 March, 2003.

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.

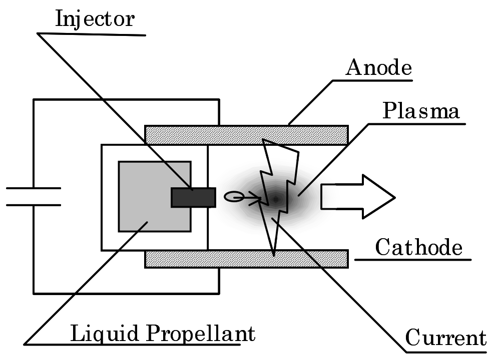


Figure 1: Concept of Liquid Propellant PPT

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 μs. 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.

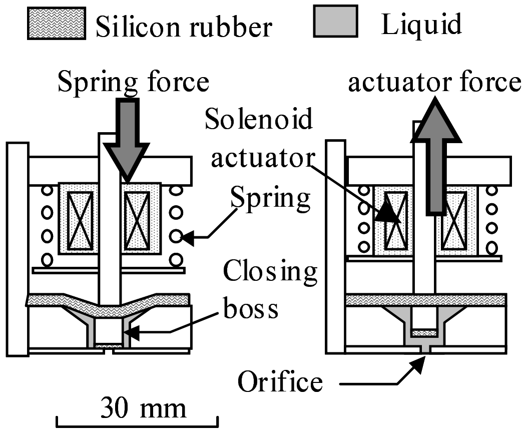


Figure 2: Cross-section view of the valve injector

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 $7 \times 7 \times 21$ 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.

This valve injector injected liquid propellant in vacuum; the minimum mass shot was 3 μg. The mass injected per one shot, namely mass shot, was calculated by comparing the injector weight after over 1000 shots to the initial weight. The mass shot was controlled by adjusting the applied voltage to the actuator and the pulse width. The liquid injection of 4 μg in the vacuum chamber was observed with a high-speed camera of 1000 frames/s. Injected liquid was thin stream and the injection was found only in a single frame. Hence, several fraction of propellant was supplied in the liquid phase and that duration was less than 1 ms.

The energy level of the thruster have to be adjusted to our mass shot levels, since the injector could supply was restricted in the range of over 3 μg. The equation of thrust efficiency is

$$E = \frac{g^2 Isp^2}{2\eta m} \tag{1}$$

where E is the capacitor storage energy, g is the gravitational constant, Isp is the specific impulse, m is the mass shot, and η is the thrust efficiency. In the present work, the tentative goals of the specific impulse and the thrust efficiency are 1000 seconds and 10 %, respectively. Then energy suitable for the mass shot of 10 μg is calculated as about 10 J. This energy was much larger than injector-consumption energy ranging from 0.1 to 0.2 J.

2.3 Designed Thrusters

Several types of liquid propellant PPT have been designed; they are classified by its electrodes type and ignition method. Figure 3 shows 10 J designed LP-PPTs: (a) is a coaxial PPT and (b) is a parallel plate LP-PPT with an ignitor plug. The former thruster has a shorter interelectrode space to initiate discharge only by liquid injection. The latter, on the other hand, has wider interelectrode space, which provides higher value of inductance per unit length, and higher electromagnetic acceleration. Figure 4 is a photograph of the parallel plate LP-PPT. These electrodes were made of copper and bound by the side walls made of silica glass. These side walls assist the pressure rise due to the liquid vaporization between electrodes, and contribute to spontaneous discharge. Moreover they prevent irregular discharge between the electrodes and injector. These thrusters use a 3 μF capacitor bank which is capable of being charged to 3 kV, correspond to the energy of 13.5 J.

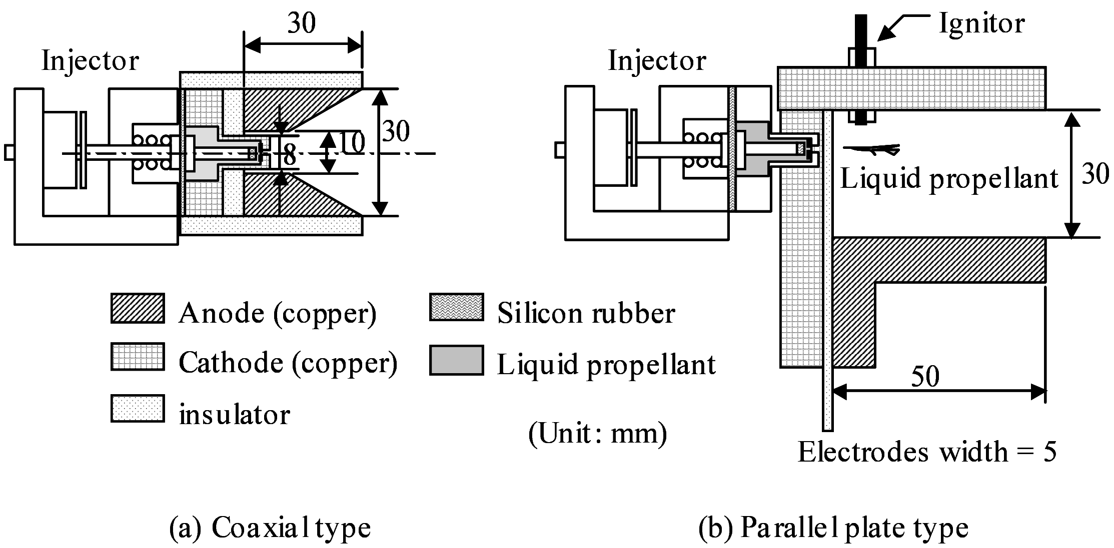


Figure 3: Schematic diagram of coaxial and paralell plate LP-PPT

Water and alcohol (methanol, ethanol, and butanol) were examined for liquid propellant. Water would be attractive propellant since it includes no carbon and no toxicity. Alcohol has more stability than water which is likely to be ice in vacuum, although alcohol includes carbon and could be the cause of electrodes contamination [7].

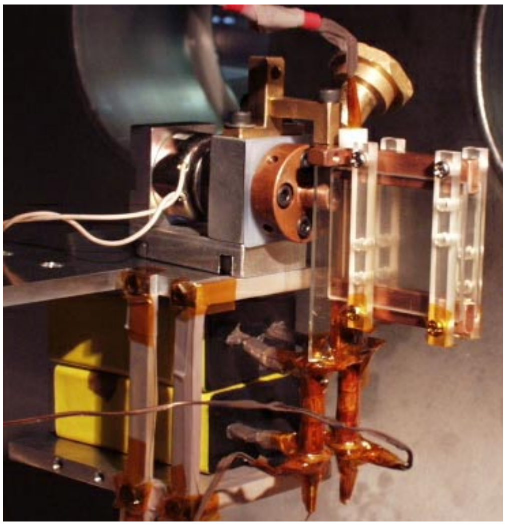


Figure 4: Picture of a parallel plate LP-PPT

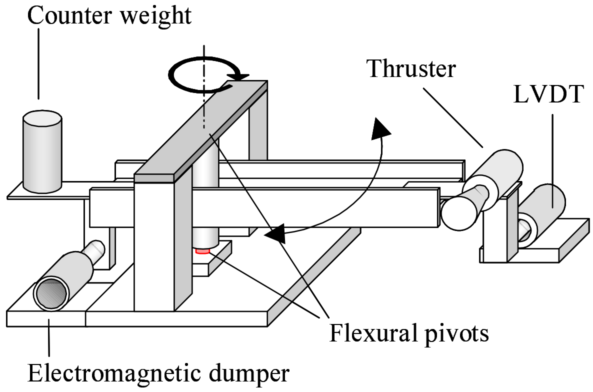


Figure 5: Schematic diagram of a thrust stand

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

$$A = \frac{I_{bit} l_I l_m}{J \omega_0} \tag{2}$$

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 ω_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 μm. 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 μNs/V, and its 95 % confidence interval was $\pm$0.4 μNs.

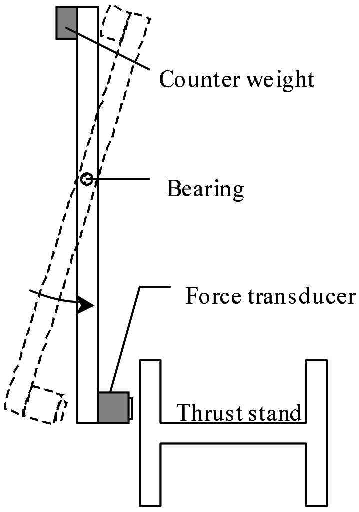


Figure 6: Impact hammer

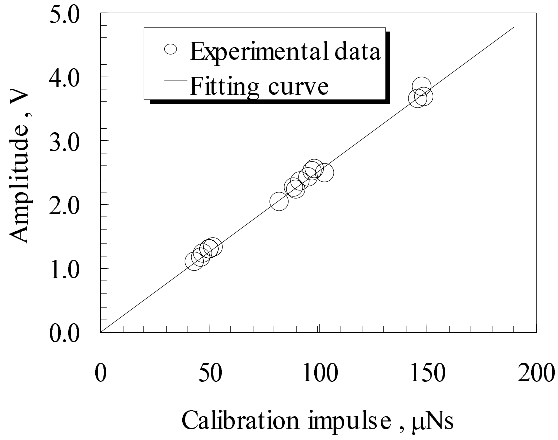


Figure 7: Typical result of calibration

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 μm, corresponding to 1 μNs, by electromagnetic dumper and counterweights. Hence the resolution of the thrust stand was $\pm$1 μNs.

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 μg. 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.

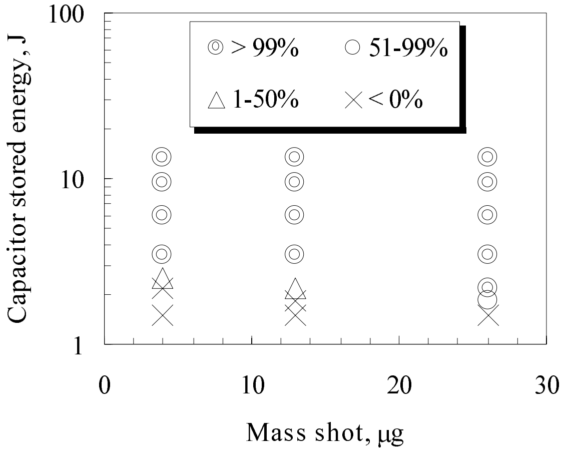


Figure 8: Discharge initiation probability

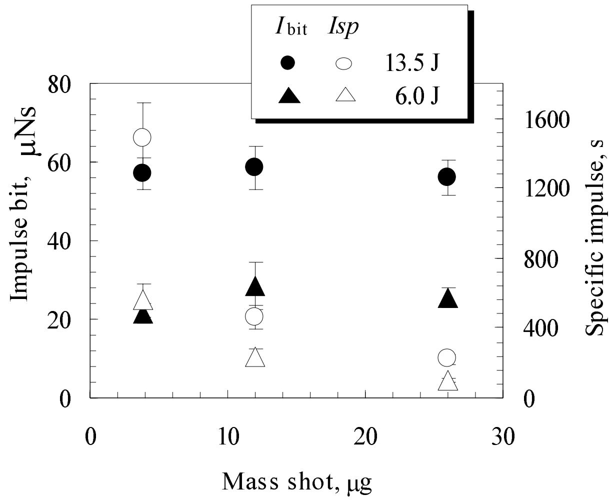


Figure 9: Measured thrust performance

4.2 Ignitor type

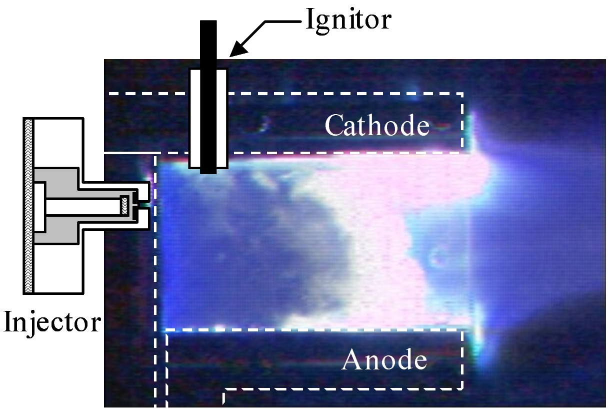
A parallel plate LP-PPT was successfully operated by using water as liquid propellant, namely water propellant LP-PPT. Figure 10 is a streak photograph of the firing. The impulse bit, specific impulse, and thrust efficiency were 89 μNs, 3400 s, and 11 % respectively at the mass shot of 2.7 μg and the energy of 13.5 J. Figure 11 shows the shot to shot variation of water propellant PPT over 20 shots. The average impulse bit was 86.6 μNs and the standard deviation of the shot to shot variation was 4.5 μNs. 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 μg. 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]:

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

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.



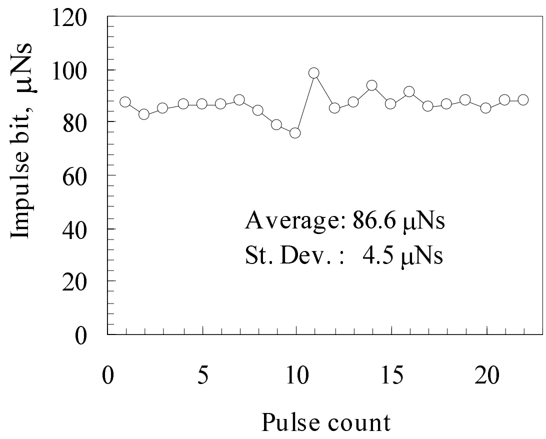
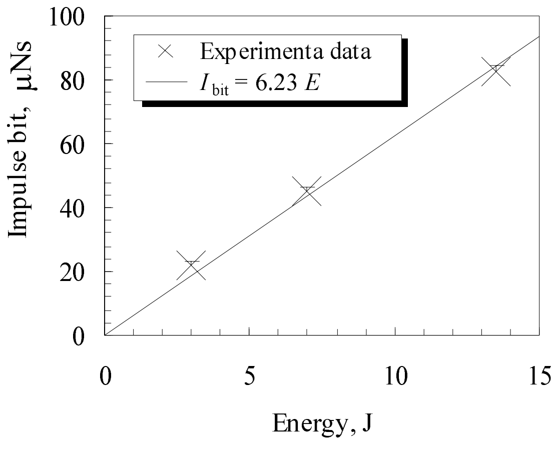


Figure 10: Streak potograph of parallel plate LP-PPT firing

Figure 11: Shot to shot varition 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 μg, 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.



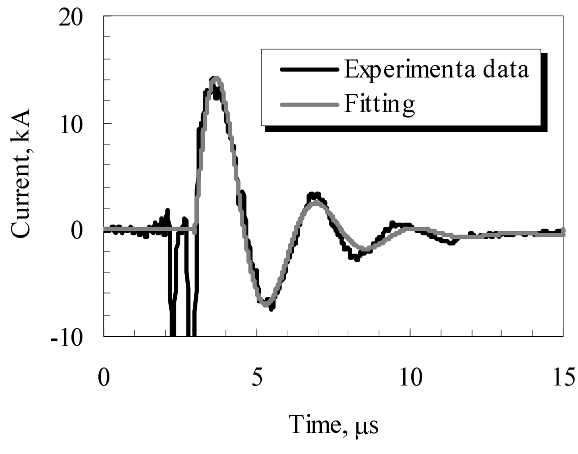


Figure 12: Impulse bit as a function of the capacitor stored energy

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]. Dumped 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 mΩ respectively. On the other hand, analytic formula for the inductance of a closed circuit of rectangular conductors gives $L = 15.6$ nH, $L' = 0.88$ nH/mm, and $\Delta L (\equiv L' \times l) = 25.6$ 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 electrodes 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 μg 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 μNs, 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 μNs in proportion to the capacitor stored energy of 3 to 13.5 J.

References

[1] Burton, R. L. and Turchi, P. J., "Pulsed Plasma Thruster," *J. Propulsion Power*, Vol. 14, No. 5, pp. 716-735, 1998.

[2] Vondra, R. J., "The MIT Lincoln laboratory PPT," AIAA76-998

[3] Spanjers, G. G., McFall, K. A., Gulczinski III, F. S., and Spores, R. A. "Investigation of Propellant Inefficiencies in a Pulsed Plasma Thruster," *32nd AIAA/ASME/SAE/ASEE Joint Propulsion Conference*, July 1-3, Lake Buena Vista, 1996.

[4] Mikellides, P. G. and Turchi, P. J., "Modeling of Late-time Ablation in Teflon Pulsed Plasma Thrusters," *32nd AIAA/ASME/SAE/ASEE Joint Propulsion Conference*, July 1-3, Lake Buena Vista, 1996.

[5] Spanjers, G. G., Lotspeich, J. S., McFall, K. A., and Spores, A., "Propellant Losses Because of Particulate Emission in a Pulsed Plasma Thruster," *J. Propulsion Power*, Vol. 14, No. 4, pp. 554-559, 1998.

[6] Aston, G and Pless, C., "Ignitor Plug Operation in a Pulsed Plasma Thruster," *J. Spacecraft*, Vol. 19, No.3, pp. 250-256, 1982.

[7] Palumbo, D. J. and Guman, W. J., "Effects of Propellant and Electrode Geometry on Pulsed Ablative Plasma Thruster Performance," *J. Spacecraft*, Vol. 13, No. 3, pp. 163-167, 1976.

[8] Myers, R. M. and Arrington, A., "Pulsed Plasma Thruster Contamination," *32nd AIAA/ASME/SAE/ASEE Joint Propulsion Conference*, July 1-3, Lake Buena Vista, 1996. AIAA 96-2729.

[9] Gluczinski, F., Dulligan, M., Lake, J., and Spangers, G. G., "Micropropulsion Research at AFRL," *36th AIAA/ASME/SAE/ASEE Joint Propulsion Conference*, 16-19 July, Huntsville, Alabama, 2000.

[10] Keidar, M. and Boyd, D. I., "Analysis of Teflon Surface Charring and near field plume of a Micro-Pulsed Plasma Thruster," *27th International Electric Propulsion Conference*, October 15-19, Pasadena, California, 2001.

[11] Takegahara, H., Igarashi, M., Kumagai, N., Sato, K., and Tamura, K., "Evaluation of Pulsed Plasma Thruster System for μ-Lab Sat II," *27th International Electric Propulsion Conference*, October 15-19, Pasadena, California, 2001.

[12] Ziemer, J. K., Cubbin, E. A., and Choueiri, E. Y., "Performance Characterization of a High Efficiency Gas-Fed Pulsed Plasma Thruster," *33rd AIAA/ASME/SAE/ASEE Joint Propulsion Conference*, July 6-9, Seattle, WA, 1997.

[13] Ziemer, J. K. and Choueiri, E. Y., "Scaling Lows for Electromagnetic Pulsed Plasma Thrusters," *Plasma Sources Sci. Technol.*, 10, pp. 395-405, 2001.

[14] Bohm, S., Burger, G. J., Korthors, M. T., and Roseboom, F., "A micromachined silicon valve driven by a miniature bi-stable electro-magnetic actuator," *Sensors and Actuators*, 80, pp. 77-83, 2000.

[15] Guman, W. J., "Solid Propellant Pulsed Plasma Propulsion System Design," *J. Spacecraft*, Vol. 13, No. 1, pp. 96-100, 1976.

[16] Vondra, R. J., and Thomassen, K. I., "Performance Improvements in Solid Fuel Microthrusters," *J. Spacecraft*, Vol. 9, No. 10, pp. 738-742, 1972.

[17] Solbes, A. and Vondra, R. J., "Performance Study of a Solid Fuel-Pulsed Electric Microthruster," *J. Spacecraft*, Vol. 10, No. 6, pp. 406-410, 1973

[18] Guman, W. J., "Pulsed Plasma Technology in Microthrusters," Fairchild Hiller Corp., Farmingdale, NY, AFAPL-TR-68-132, Nov. 1968.

[19] Jahn, R. G., *Physics of Electric Propulsion*, McGraw-Hill, New York, 1968.