Observation of Discharge Plasma of Liquid Propellant PPT

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Abstract

On a liquid propellant PPT, the discharge processes that discharge was initiated and plasma was accelerated was observed by using a ultra high speed camera. Liquid propellant PPT is a pulsed plasma thruster using liquid as propellant. Our past study showed the successful operation of liquid propellant PPT and the thruster showed high specific impulse. However, its acceleration mechanism has not been clarified. In this study we observed the plasma acceleration processes in order to deepen our understanding of the acceleration mechanism.

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 which pushes the ablated and recessed solid 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) The causes of the low performance of APPT are considered as follows. Low speed vapor continues to be provided from the solid propellant surface after the main discharge[2], because the surface temperature remains high. Additionally the emission of large particulates was observed[3], which could not be effectively accelerated.

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[4] and it limited the life time of thrusters.

3) The nonuniformity of current density and Teflon surface temperature conducts the preferential ablation near the electrodes. 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.

Since a few years ago, we have proposed a Liquid Propellant Pulsed Plasma Thruster (LP-PPT)[5], which uses liquid as propellant in order to overcome 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.

Especially we focused on water as propellant, namely Water Propellant PPT. Water, of course, can be arbitrarily throttled for effective utilization. In addition it would reduce plume contamination on the sensitive devices of spacecraft less than Teflon, since it includes only hydrogen and oxygen. Also, it can be shared with other systems like life support system. Then water is very attractive as propellant. In electric propulsion, however, water has not been used as propellant. It is because that water leads severe oxidation on electrodes whose temperature becomes very high. In contrast, Pulsed Plasma Thruster does

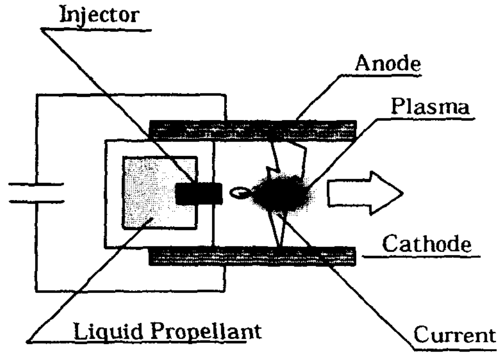

Fig. 1 Concept of Liquid Propellant PPT

not have such high temperature electrodes due to its pulsed operation, and the oxidation would not be problem.

Our past study showed that Water Propellant PPT had high specific impulse. That well agreed with the result of OHIO state University group[6], who also study Liquid Propellant PPT with using other propellant feed system. However, the acceleration process, how liquid is changed into gas and plasma and how the plasma is accelerated, has not been cleared yet.

In this study, to clear the acceleration processes of Liquid Propellant PPT, we perform the observation of the discharge plasma by using a ultra high speed camera. We took pictures with the frame rate of 5 Mpps and the exposure time of 30 ns. Then how the discharge plasma was generated and accelerated was observed.

Experimental Methods

Liquid Propellant PPT

A liquid propellant PPT addressed here consists of a parallel plate electrode with glass side walls, 3 uF capacitor, ignitor, and liquid injector. The electrode is made of SUS and has the interelectrode space: 20 mm, the length: 34 mm, and the width: 10 mm. The anode and cathode was insulated by a ceramic back wall. The ignitor was installed into the cathode. The injector fed water droplets of a few micro grams into the interelectrode.

Two types of liquid propellant PPT have been designed by the configuration of the injection; vertical injection type and horizontal injection type. The vertical type thruster injects liquid droplets through the cathode toward the anode. The direction of the liquid flow is vertical to the plasma flow. On the other hand, the horizontal type thruster injects liquid through the backwall. The direction of liquid flow is parallel to the electrodes and plasma flow.

Observation of Discharge Plasma

In order to observe the discharge plasma of a liquid propellant PPT, a ultra high speed camera: NAC Ultra 8 was used. It can take a series of 8 pictures with the maximum frame rate of 100 Mpps. Here we took pictures with the frame rate of 5 Mpps (200 ns) and the exposure time of 30 ns; we observed 1.6 μs once. Because the period of the current ringing was about 4 μs and longer than the 1.6 μs, shooting was performed several times for one series of pictures.

Figure 2 shows the arrangement of a thruster, high speed camera, photo detector, Rogowski coil, and control system. The liquid injection and ignition were controlled by a control computer. The photo detector detected the light emission from the discharge plasma. The output signal from photo detector was transformed into TTL and delivered to the Ultra 8 as a trigger signal. The motivation for using a photo detector was a large noise by the operating ignitor. The ignition generated several large and random noises before the main discharge. They effected any electrical signal from a thruster (like current or voltage). Therefore we needed a trigger completely isolated from the ignitor. The electrical system of the photo detector and Ultra 8 was isolated from one of the thruster. However, that trigger system had the delay time of about 0.5 – 1.0 μs. Then the rising of the main discharge could not taken by that photo detector trigger. Then random noises were used as trigger for taking pictures of those. The trigger time was quite random but several times operation provide pictures of discharge rising.

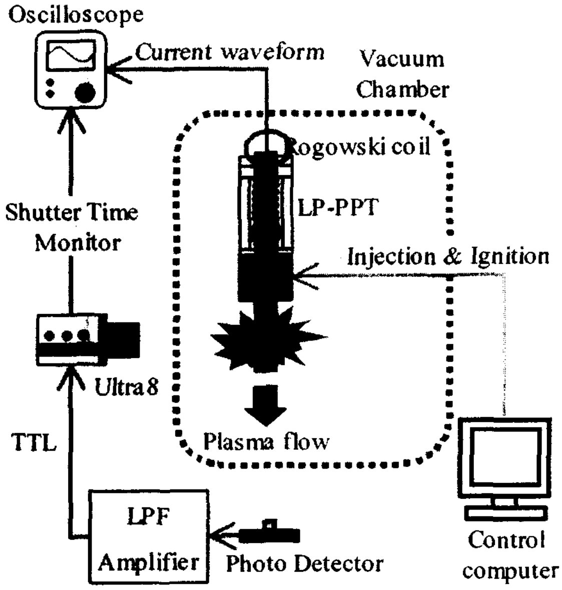

Fig.2 Schematic diagram of observation system.

A signal of shutter time from the high speed camera and current waveform was recorded by a digital oscilloscope.

Result and Discussion

Discharge processes of LP-PPT

Figure 3 shows pictures of discharge for several successive time of horizontal injection type thruster. Above those pictures, corresponding current waveforms and the monitor signals from a high speed camera are shown. Those pictures were taken by three times of operation in the same conditions. Although pictures were taken every 200 ns, only the pictures spaced 400 ns apart are shown.

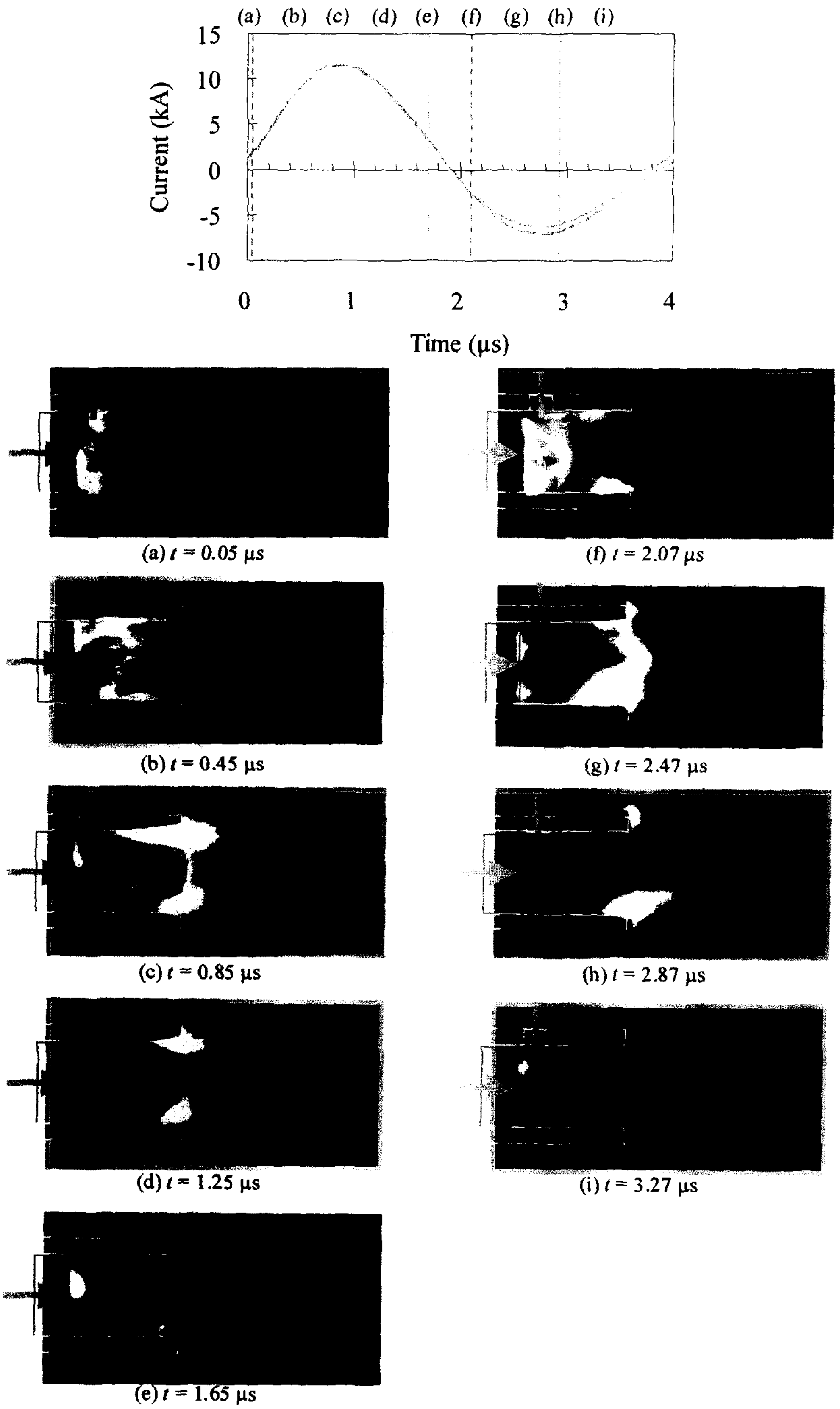

Fig. 3 Successive pictures of discharge plasma for horizontal type thruster and the current waveform.

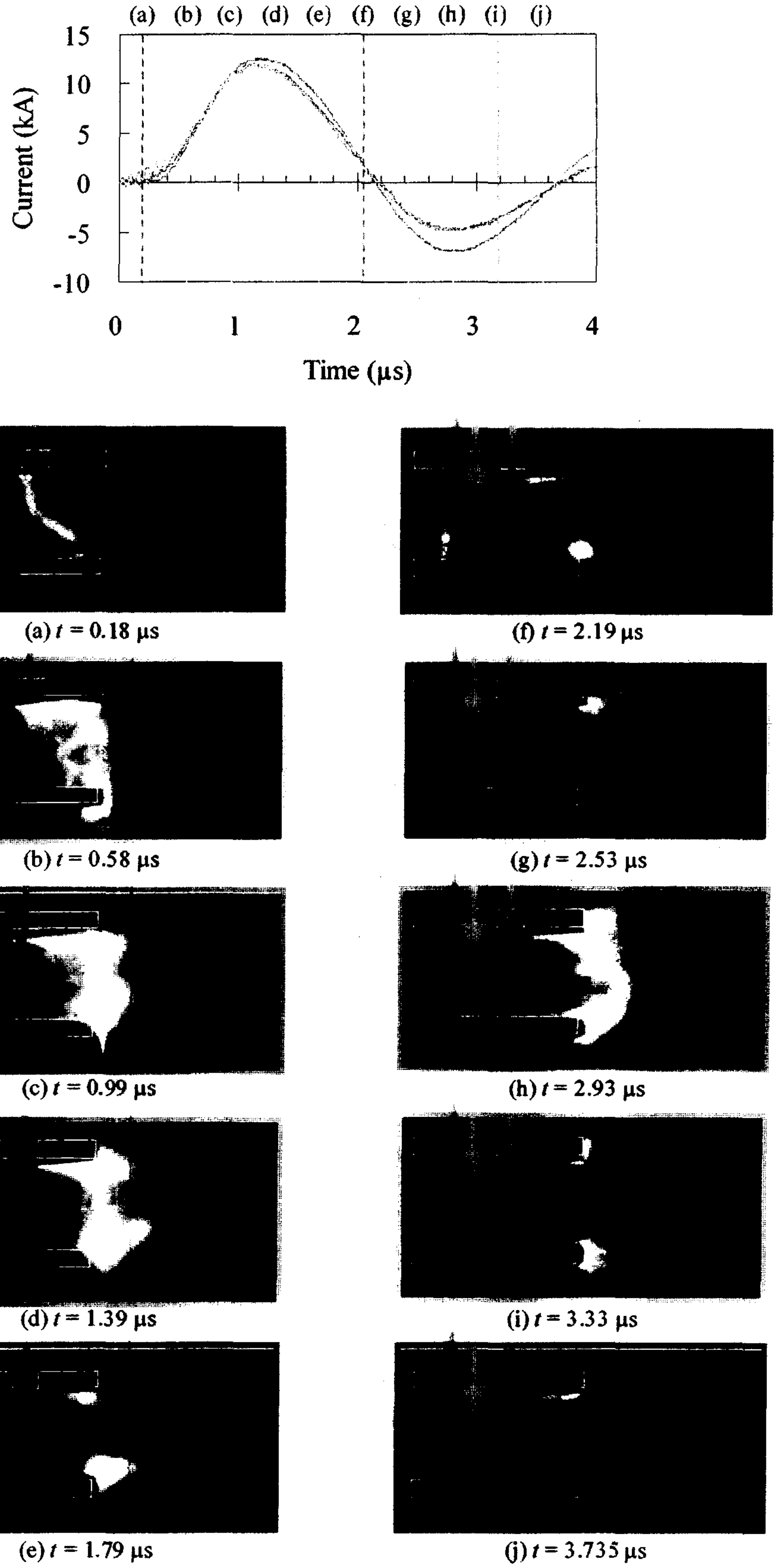

Fig. 4 Successive pictures of discharge plasma for vertical type thruster and the current waveform.

First, discharge was initiated and initial plasma was generated between the ignitor and electrode just under the ignitor, and the plasma was accelerated to the downstream. The plasma expanded into the entire interelectrode and flew downstream. It did not form a clear current sheet. At the time that first half cycle of current was finished, most of the plasma ejected from the electrodes. Once the second half cycle started, breakdown occurred near back wall again and new plasma was generated there. The plasma was ejected from the electrode in the almost same fashion as the firs half cycle. Here we can see clearer current sheet than first half cycle, which expanded outside the electrodes forming an arc current pass.

In this study, we observed canting of current sheet. Markusic et al. observed current sheet canting on gas fed PPT[7,8]. There the current was over dumped, not to reverse the current. The current sheet always canted such that the anode arc attachment point leads the cathode attachment point, with no relation to capacitor bank voltage, gas pressure, and gas species. The cause of that difference from our study would be the difference of energy and electrode scaling. Their electrode had the length of 600 mm and the width of 150 mm and their energy was 2 kJ.

Through both the first and second half cycle, strong light emission was observed around the water injection orifice. It would because there was rich vaporized water near the injection orifice.

In addition, during first half cycle top electrode (cathode) showed stronger emission than the bottom. On the other hand, during second half cycle, the bottom electrode, which became cathode because of current reverse, was bright. It means that the electrode surface which emitted electrons are always more bright than the other. This tendency was confirmed for the next vertical type thruster also.

Figure 4 shows the discharge pictures of vertical injection type thruster. It is remarkable that the discharge was initiated between the ignitor plug and the dead end of the anode. It would be because the ignitor plug was installed more downstream than horizontal type thruster. Due to this initiation, the plasma expanded only the more downstream than the first discharge pass. Notwithstanding, at the beginning of the second half cycle, discharge was initiated near the back plate and the plasma was accelerated as well as the horizontal type thruster.

Also, there is strong light emission around the propellant. On the bottom electrode surface, located just under the water injection orifice, there is light emission. It would be due to droplets attaching on the bottom electrode surface. However, that emission was observed only during the second half cycle, because the initial plasma of first half cycle was generated more downstream than injection orifice.

Exhaust velocity of plasma

In order to quantitatively estimate the motion of plasma, intensity profile of the light emission along the flow direction was calculated. All pictures were converted into numerical data of the light intensity. Those were integrated in a longitudinal direction (vertical to the electrode), and intensity profile of the lateral direction (parallel to the electrod) were obtained. Figure 5 shows the example of the lateral direction intensity profile and its original image (horizontal type thruster; $t = 0.65\mu s$).

Here we regarded the average position of the plasma as the gravity center of the intensity profile. It becomes equal to the mass average position, if the light emission from plasma is proportional to the plasma density. Figure 6 shows the time history of the average position of the light emission for horizontal type thruster. In those figures, the corresponding squared current waveforms are also drawn. First the average position moves toward the downstream, but it backs toward upstream and again moves downstream. This movement can be explained by the restriking. Before the first peak of current, plasma is increasingly accelerated. After that peak, the acceleration force becomes low (but the plasma keeps to be accelerated)

Fig. 5 Emission intensity profile along the flow direction and its original image

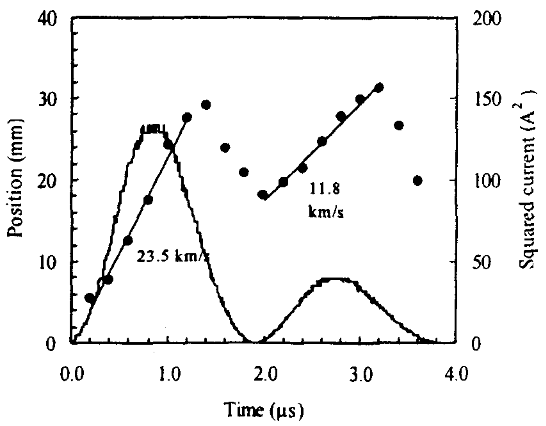

Fig. 6 Time history of the gravity center of the emission intensity and squared current.

and the light emission also becomes dark. When current is reversed, new plasma is generated at z = 0 while the first expelled plasma has not emitted yet. Because we defined the average position of plasma as the gravity center of the emission intensity, it shifted backward. Thereafter the new plasma is accelerated in the same way.

We can estimate an exhaust velocity of the plasma from a slope of that curve. Those velocities were 23.5 and 11.8 km/s for the first and second half cycle respectively. Those values almost agreed with the values obtained from the thrust measurement. Liquid propellant PPT addressed here showed the impulse of 69 μNs and the exhaust velocity of 11.2 km/s

Conclusion

We observed the plasma formation and acceleration on a liquid propellant PPT by using a ultra high speed camera. From the observation, the following conclusions are obtained

New plasma was generated every current reversing. At the time first half cycle ended, first accelerated plasma was exhausted outward the electrode and second breakdown occurred near the beginning of the electrode.

Clear current sheet was not observed. Only during the second half cycle of current, vague current sheet was observed. It showed no clear canting and expanded outward the electrodes with forming arc; the current pass was extended up to about twice of the electrode length.

Around the water injection orifice and the place on which droplets would attached, there are strong light emission. Also, cathode surface showed stronger light emission than anode even after the current reverse. In short, the electrode which emitted electrons were always bright.

The exhaust velocity estimated from the emission intensity of plasma almost agreed with the value obtained from thrust measurement.

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