Plasma Flow Behaviors and Their Effects on the Performance of Pulsed Plasma Thrusters

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I. Introduction

Pulsed plasma thrusters (PPTs) are space propulsion options using electromagnetic acceleration of plasma by a pulsed discharge. The most common PPTs use solid polymer as the propellant, usually polytetrafluoroethylene (PTFE). The surface of a polymer propellant is exposed in the discharge chamber and the ablated polymer is fed into the plasma as a propellant. These PPTs are called ablative pulsed plasma thrusters (APPTs). They were increasingly studied in the 1960s and 1970s for primary space propulsion systems. However, the development at that period eventually ebbed due to their lower performance than other thrusters, e.g., ion engines. In recent years they have again attracted interest as promising thrusters for microspacecraft. Low electric power requirements and the simple, compact structure of APPTs make them appropriate for miniaturization and attractive as onboard propulsion options.
for microspacecraft. APPTs designed for micropropulsion systems have the following specifications: electric power, 1 – 100 W; dimension, 1 – 10 cm; and weight, 0.1 – 1 kg. Also, various geometries have been proposed and studied; standard rectangular electrodes with breech-fed or side-fed, coaxial electrodes, Z-pinch configuration, and extremely miniaturized devices. They are expected to be used for station keeping, attitude control, drag-free operation, and constellation control of formation flight.

The plasma acceleration mechanism in APPTs, however, is still not fully understood in spite of the relatively long research history of the filed. This is largely due to the extremely short pulsed discharge (~ 10 µs), the complicated interaction of the ablation and ionization of the polymer propellant, and the complex composition of the plasma with multiple species (C, C+, F, F+, C2, CF, and CF2, etc). The complexity of the system makes it difficult to solve the tow major problems associated with APPTs: low thrust performance and spacecraft contamination by exhaust gas. Actually APPTs have a typical thrust efficiency of < 10 % and exhaust velocity of < 10 km/s, whereas other plasma propulsion systems have the performance of 50 % and 20 – 30 km/s. Several researchers have pointed out that the low performance is caused by low propellant utilization. The polymer propellant continues to be ablated even after the termination of discharge, known as late-time ablation. This gas can make almost no contribution to the electromagnetic acceleration, and thus causes the low performance. Although the importance of late-time ablation is well known to researchers, comprehensive understanding has not yet been achieved. In order to improve the performance of APPTs and make them more suitable for microspacecraft, it is necessary to understand the plasma acceleration and associated neutral particle behaviors.

Diagnostics of the plasma in APPTs has several difficulties because the phenomena are relatively short-lived and the spark plug and the pulsed discharge itself produce considerable electromagnetic noise. Nevertheless, some researchers have succeeded in measuring the plasma properties using triple or quadruple probes. These studies have produced useful information for the contamination problem. They obtained some interesting insights on the acceleration processes, such as the existence of two kinds of plasmoid with different velocities in the plume. These diagnostcs were carried out in the exhaust plume of APPTs, however, and can not clarify the acceleration mechanism inside the electrode channel: how solid propellant is ablated, ionized, and accelerated. In order to obtain such information, diagnostics of the interelectrode space is required.

Recently Choueiri and colleagues extensively investigated the plasma behavior under the electromagnetic acceleration processes using an accelerator with rectangular electrodes. They used a gas-fed PPT in order to understand the electromagnetic effect. The interelectrode space was initially filled with gas and the discharge was initiated using a spark plug. They found and analyzed several interesting phenomena, such as current sheet canting. The dimensions and power of the device were much higher than those of microthrusters, however, and the interaction of plasma and polymer ablation, which plays an important role in an APPT, was not investigated. Investigation using an ablative PPT is essential to understand the actual acceleration processes. Interferometric density measurement is an effective method to quantitatively measure the plasma in the interelectrode space of APPTs, because it is not affected by electromagnetic noise and does not disturb the plasma. Several studies have revealed the time history of the plasma density at a few spatial points in the interelectrode space, but it is difficult to measure neutral gas behavior, for which much higher sensitivity and two-color interferometry are necessary. Spanjers et al. detected the presence of high density neutral gas from the response long after the discharge, but the transient state and interaction with the plasma were not clarified. To date, there has been no study to clarify the behavior of both the neutral gas and the plasma in the acceleration processes.

In the present study, we have investigated plasma acceleration processes in the electrode channel using a 10 J class APPT with a rectangular geometry. High speed photography of the interelectrode space and current profile measurement using a magnetic probe were conducted. The species emitted from the discharge plasma were identified by emission spectroscopy, and two wavelengths for high speed photography were selected. Successive images taken by an ultra high-speed camera gave us the overall aspect of the acceleration processes of both the neutral gas and plasma. Measurement of the magnetic field profile showed the current pass, and the location where electromagnetic acceleration took effect.

Additionally, we have applied these diagnostic techniques to a liquid propellant pulsed plasma thruster (LP-PPT), which was proposed by the authors and have been investigated since 2000. LP-PPTs use liquid as the propellant (e.g. water) to control the mass shot and improve the performance. In the past study, it has been verified that LP-PPTs have higher specific impulse than APPTs. In actual, high speed photography of a LP-PPT showed faster exhaust of the plasma than that of APPTs. Here higher resolution photography has been performed by using a more sophisticated optical system and magnetic field profile has been measured to obtain quantified information of the acceleration processes.

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II. Experimental Facilities and Methods

A. Thrusters, vacuum chamber, and thrust stand

A pulsed plasma thruster used here consists of rectangular electrodes, 3.0 μF capacitor, spark plug, and PTFE propellant. In the case of LP-PPT, a thruster has a liquid propellant injector instead of PTFE propellant. The mass shot can be adjusted by controlling the liquid injector. The thruster geometry and configurations are shown in Fig. 1. The electrodes are made of two parallel plates of stainless steel with an interelectrode space of 20 mm and width of 10 mm. The length was 25 mm in the APPT and 35 mm in the LP-PPT. Voltage applied to the capacitor was changed from 1.5 to 3.0 kV. In the high speed photography, thrusters were operated with the applied voltage of 2.2 kV (stored energy in the capacitor was 7.4 J). Glass sidewalls were installed on both sides of the electrodes in order to perform magnetic probe measurements. Experiments were carried out in a 1.0-m-diam, 1.2-m-long space chamber. The base pressures were less than $5 \times 10^{-5}$ Torr.

Impulse bit produced by a PPT was measured by a micro-Newton thrust stand, 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 30–60 mNs. Figures 2 and 3 show the energy dependence of impulse bit and specific impulse of the APPT and LP-PPT. In the operation of the APPT, applied voltage higher than 2.5 kV occasionally lead to breakdown between the electrodes along the PTFE surface. Hence the data over that voltage was not obtained. The APPT showed higher impulse bit than the LP-PPT, but the specific impulse was low around 700 s. The LP-PPT showed much higher specific impulse up to 2000 s.

B. High speed photography

Plasmas were observed during the discharge using an ultra high-speed camera (DRS Technologies, Inc., Ultra 8). This is a high speed framing camera using an ICCD and can take a series of eight images at a maximum frame rate of 100 Mfps. Here images were taken at a frame rate of 5 Mfps and with an exposure time of 100 ns. Photographs were taken in two or three successive firings, changing the delay time to first exposure and connecting the photos as successive images of one sequence. The photography was carried out during the first and second half cycle of the current ringing, because most of the energy (85%) was consumed in those stages.

In the experiment of the APPT, two wavelengths were selected for the photography, based on the results of the emission spectroscopy: 514.5 nm emission from neutral particle and 426.8 nm from ions using band pass filters. Emission spectroscopy showed the strong spectrum band around 514 nm of C2 molecules (neutral particle) and strong...
peak at 426.8 nm of C\(^+\) ions. The bandpass filters used here have a FWHM of 10 nm. The 514.5 nm filter covers almost all of the band spectra of C\(_2\) around 514 nm and no other lines and the 426.8 nm filter includes the strong 426.82 nm line and a few weak lines of C\(^+\). Therefore it can be assumed that the emissions of 514.5 and 426.8 nm respectively represent the motion of neutrals and ions in APPTs.

In this high speed photography, thrusters were operated with the applied voltage of 2.2 kV. The APPT used here generated an impulse of 55.0 µNs by a single shot at the energy. The propellant consumed per firing was 7.1 µg, which was measured from the weight difference before and after the experiment. The specific impulse was 790 s calculated from the impulse and mass shot. In the case of the LP-PPT, the thruster has the specific impulse of over 1700 s and impulse bit of 37 µNs at the minimum mass shot of 3.0 µg and capacitor stored energy of 7.4 J.

C. Magnetic probe

Two magnetic probes were fabricated, and used simultaneously to efficiently measure the magnetic field profile. Both the probes were made by winding a 0.12-mm-diam copper wire on a 2.0-mm-diam polymer rod. The wire was wrapped in 120 turns in six layers. The ends of the probe were connected to an RC integration circuit and the integrated output was recorded. The probes were calibrated by comparison with a standard probe, which was precisely fabricated with 20 turns and a single layer and its sensitivity can be accurately calculated. The probes and the standard were compared by inserting them successively into a pulsed magnetic field with the same frequency as the APPT. The detailed theory of magnetic probes can be found in the elsewhere.31

It was difficult to make a probe much smaller than the interelectrode space of the APPT designed for microspacecraft, which have dimensions of several centimeters. To prevent the magnetic probe from disturbing the plasma, glass sidewalls were installed on both sides of the electrodes and the probes were placed just outside that wall. The walls also help to reduce the electromagnetic noise on the probe and keep the plasma behavior two-dimensional. Of course the walls might disturb the plasma. In order to check the difference, high speed photography was performed for both configurations, and it was confirmed that there was no essential difference between them.

The position of the probe was remotely manipulated using a two-axis linear stage. Measurements were performed at 108 positions in the interelectrode space to obtain a magnetic profile. Configurations of the probes are shown in Fig. 1. At every spatial location, the probe data was obtained by averaging signals from six firings.
III. Experimental result

A. Discharge current and Magnetic field: APPT

Figure 4 shows the discharge current measured by the Rogowski coil and the shutter timings of the ultra high speed camera. The current waveform had good reproducibility and the curve in Fig. 3 is the averaged waveform from all the measurements. The current has an oscillatory waveform that is generally observed in PPT discharge. Particularly low power PPTs are likely to have this kind of ringing waveform because of the small capacitance. The LP-PPT showed higher current peak than the APPT, but its dumping coefficient was higher. Therefore, in the second cycle, the LP-PPT showed lower current peak. Generally a PPT can be assumed to be an RLC circuit with discrete, constant elements. In past studies using the same thruster, the resistance was measured as 48±1 mΩ and 64±2 mΩ for the APPT and LPPT respectively. The external outside circuit (electrode, feed through, and capacitor) was found to have a resistance of 31±4 mΩ and 47±5 mΩ for the APPT and LP-PPT.29,35 The latter consists of the resistance of the plasma and equivalent resistance of electromagnetic acceleration.1

Figure 5 and 6 show the output signals of the magnetic probes, which are located 8 mm away from the anode (line of $y=0$ in FIG. 1). A spatial profile of the magnetic field in the interelectrode space is drawn in the succeeding section using the 108 position signals.

In the case of APPT, the furthest upstream probe (located inside the PTFE block) showed almost the same waveform as the discharge current, because the current always flowed further downstream than that probe and the strength of the magnetic field was simply proportional to the current. The output signals of the downstream probes

![Figure 4. Discharge current of the APPT and shutter timing of the high speed photography.](image)

![Figure 5. Output of the magnetic probes 8 mm away from the anode.](image)

![Figure 6. Output of the magnetic probes 8 mm away from the anode.](image)
showed rapid increases at the times when the field (current) reaches to the probe position. Obviously, the farther the probe is downstream, the later it respond. In the case of the LP-PPT, the qualitative behavior of the probe is similar to the APPT, but the rising time is much higher. This means that current passes the probe at much earlier time than the APPT.

B. Plasma acceleration processes; APPT

Successive images of the discharge taken using the high speed photography are shown in Figs. 7 to 9. Figure 7 is the broadband emission (without filter), Fig. 8 is the 514.5 nm emission from the neutral particles C₂, and Fig. 9 is the 426.8 nm emission from the ions C⁺. The time shown in every image is the center of the exposure time, corresponding to the shutter timing in Fig. 4. Locations and geometries of the cathode, anode, and PTFE propellant are shown in these images by dotted lines. In the broadband emission images, two emission regions are recognized. One is the strong emission near the PTFE propellant surface, which slowly moves downstream. The other region is a vague and diffuse emission which is quickly accelerated downstream. Similar images were presented in an experimental paper by Vondra and Thomassen. They observed a standing arc near the PTFE surface and accelerated plasma, but the low graphic resolution of their photographs did not permit identification of detailed structure.

Photography using bandpass filters revealed the originals of the two emissions. The former resulted from the motion of the neutral particles (514.5 nm emission) and the latter from the ions (426.8 nm emission). The broadband emissions seem to be similar to the superimposed images of the 514.5 and 426.8 nm emission images. This means that the observation of those two lines was sufficient to comprehend the plasma behavior (there was no other characteristic emission which was not reported here).

At the initiation of the discharge, a strong emission was observed near to the PTFE propellant surface. This emission was found in both the neutral particles and the ions. The detailed shape of the initial plasma did not have good reproducibility, and slight different shapes were observed every time. After the initial strong spark, neutral emission formed a thin layer perpendicular to the electrode. That thin but intense layer slowly moved downstream with no relation to the current ringing. Its flow velocity and brightness were almost constant during the discharge. The velocity was calculated as 1.8 km/s from the shifts of peak emission positions (it should be noted that the emission velocity is not flow velocity). The ions showed completely different behavior from the neutral particles. The emission from the ions had more spread and it was ejected more quickly than neutral particles. It reached the end of the electrode within the half cycle of the current (~ 1.6 µs). The ion exhaust velocity was calculated as 10-20 km/s from the images. That ion velocity agrees with a number of other studies that measured ion velocities. Vondra and Thomassen and Markusic and Spores estimated the C⁺ velocity by a Doppler shift and time-of-flight techniques: 5 – 15 km/s (Vondra and Thomassen) and 8 – 15 km/s (Markusic and Spores).
Figure 8. Successive images of the APPT firing (514.5 nm from C₂, 5 Mfps).

Figure 9. Successive images of the APPT firing (426.8 nm from C⁺, 5 Mfps).
Just before the current reversal, a secondary breakdown occurred at the upstream point and new plasma was generated. This secondary discharge has been observed in many pulsed acceleration devices and is referred to as a “restrike” or crowbar discharge. In the photographs at 1.60 and 3.18 µs, we can see newly generated and almost ejected plasmoids. The new plasmoid was ejected in the succeeding cycle in the same way as the first half cycle. The ejection of plasmoid in the second half cycle had much better reproducibility than in the first half cycle.

Figure 10 shows the evolution of the magnetic field profile calculated from the data from the magnetic probes at 108 positions. The contours show the strength of the magnetic field (absolute value) perpendicular to the paper (y direction in Fig. 1). The direction of the field was reversed as synchronized with the current reversal (1.57 and 3.13 µs). In an ideal two-dimensional geometry, contour lines of $B_z$ are consistent with the streamlines of the current flow field. Although a quantitative profile of the current density cannot be obtained here because the probes were placed outside the sidewalls, the contour lines permit qualitative conclusions. At first the current flowed through the upstream end of the channel, and it shifted toward the downstream end as time passed. At the time 1.20µs, the current pass reaches almost to the end of the electrodes, and it ceases at the time of reversal (it is interesting that neutral particles and ions continue to emit light even with no current). In the next moment the current started to flow again near the surface, when the current flowed in the opposite direction. Throughout the discharge the location of the current path was corresponding to that of the ions. In other words, the current flowed at the most downstream position in the emissive region of the ions. It should be remarked that the current did not flow near the PTFE propellant (neutral emission region).
Figure 11. Successive images of the LP-PPT firing (broadband emission, 5 Mfps).

Figure 12. Time history of the magnetic field profile of the LP-PPT, where absolute value of the field is indicated.
C. Plasma acceleration processes; LP-PPT

Figure 11 shows the successive images of the LP-PPT, taken by the high speed photography, and Fig. 12 shows the corresponding magnetic field profile, measured by the magnetic probes. It should be cared that the LP-PPT had a little longer electrode than the APPT by 10 mm. The current patterns found from the magnetic field profile is consistent with the images of the photograph. The plasma is generated at the upstream and flowed toward the downstream synchronizing with the current reversal. At the every current reversal, restrike was observed as well as the APPT. The overall plasma behavior is similar with the APPT, but there are several differences. First, the plasma was exhausted with much higher speed than the APPT. Secondly, there was no slowly-moving plasma observed in the discharge of the APPT. Hence the acceleration of the plasma is much simpler than the APPTs. Thirdly, The restrike plasma was always generated at the farthest upstream (on the back plate).

In the Fig. 11, it is shown that the plasma is almost ejected from the interelectrode at \( t = 0.8 \mu s \), and no plasma is found at the current reversal \( (t = 1.6 \mu s) \). This is also confirmed from the current pattern of the Fig. 12. In contrast, the plasma (ion) of the APPT remains in the interelectrode even at the current reversal (see Fig. 9). This means that the LP-PPT accelerated the plasma much faster than the APPT, and it is consistent with the high specific impulse of LP-PPTs. On the other hand, the ejection of plasma from the electrode indicates the increase of the plasma resistance. This is also confirmed from the result of resistance measurement, and would be the main cause of lower thrust to power ratio of LP-PPTs.

IV. Discussion

A. Acceleration processes of the APPT

Here the acceleration processes of ions and neutrals in the APPT are analyzed in detail from successive high speed photography images. First the position of the restrike suggests several important conclusions. The restrikes did not occur on the PTFE surface, but rather there was a small gap between the surface and the restrike discharge. Also, the breakdown positions were shifted downstream at the second restrike \((3.18 \mu s)\) as compared to the first one \((1.60 \mu s)\). In most PPTs, breakdown is necessarily initiated at the farthest upstream position in the channel by transient field effects. Actually, the restrikes of the LP-PPT always occurred at the most upstream position as shown in Fig. 9. Nevertheless, the restrike in the APPTs always occurred just in front of the neutral emission layer.

This can be explained by the presence of very dense neutral gas behind the emission layer. Neutral gas will exist not only on the thin emission layer, but between the emission and the PTFE surface (only the most downstream part attaching to the plasma would emit at 514 nm). The density will be the highest adjacent to the surface, because the PTFE surface continues to be ablated during the discharge and even after it. Nevertheless, new discharge was always initiated a little downstream of the neutral emission layer, where the gas density would be much lower than the propellant surface. This means that the area between the emissive layer and the propellant surface was filled with such high density gas that breakdown was prevented. Otherwise a breakdown would be initiated further upstream by the transient field effect. The threshold of the inside gas density can be roughly estimated by assuming Paschen’s Law. Many gases have the minimum breakdown voltage when the product of the gas pressure and gap distance is around 10 Torr·mm. In the present work, with a gap distance of 20 mm, the gas pressure that satisfies the above condition is 0.5 Torr. In short, the neutral gas between the neutral emission layer and the PTFE surface was roughly estimated as at least > 0.5 Torr.

In Fig. 9, it is shown that the plasma created by the breakdown and initial discharge stays near the propellant surface in the early stage of the acceleration. It leaves the propellant surface at about 0.8 \( \mu s \) and is accelerated to over 10 km/s. Some fraction of the mass ablated before that time can be included and ionized in the plasma. The subsequently ablated mass cannot, however, catch up to the forward plasma escaping with high velocity. This means that only a fraction of the mass ablated in the first half cycle had a chance to be ionized and accelerated. In the second half current cycle, a fraction of the remaining gas was ionized by the restrike and accelerated. The quantity would be very small, however, because the restrike occurred downstream, where the density would be lower than near the propellant surface. Moreover, the energy consumed in the second half cycle was only 24 % of the energy initially stored in the capacitor, so that the second half cycle makes a relatively small contribution to thrust so much. In addition, gas newly ablated in the second half cycle is not accelerated until beginning of the third half cycle, which was further low energetic. Even mass ablated during a discharge, therefore, can contribute only a little to the electromagnetic acceleration, and most of it causes propellant loss. Additionally, it was found in several studies that the ablation continued after the end of the pulse (late-time ablation). These ablation processes lead to the low propellant utilization efficiency on APPTs.
B. Exhaust velocity

Flow behaviors of the both thrusters were quantitatively analyzed by calculating the averaged position of the plasma. All images were converted into numerical data of the light intensity. The data were integrated in a longitudinal direction (vertical to the electrode), and intensity profiles of the lateral direction (parallel to the electrode) were obtained. Figure 13 shows the time history of an averaged position of the light emission of the LP-PPT. In the figure, the corresponding squared current waveform is also shown. Here the averaged position of plasma was defined as the gravity center of the intensity profile, expressed by

\[
 z_{GC}(t) = \frac{\int_z \int_t I(z,t) \, dz \, dt}{\int_z \int_t I(z,t) \, dz}
\]  

(1)

where \( I(z,t) \) is the intensity profile along the electrode. First, the average position goes downstream with the averaged velocity of 33 km/s. After that, the position remained around 35 mm, whereas the actual plasma is ejected from the electrode. It is because the most of plasma flew outside the observed area and strong emission around the edge of the electrodes. In the second half cycle, a new plasma is generated on the back wall and it proceeds downstream with the averaged velocity of 43 km/s. That exhaust velocity is much higher than one estimated from the thrust and mass shot. It means the actually accelerated plasma is much less than the mass shot. In other words, only a fraction of the injected liquid was electromagnetically accelerated as plasma.

In the case of the APP which had the two emission region, the image analysis was performed for the both 426 and 514 nm wavelengths. Figure 14 shows the time history of the emissive region of 426 and 514 nm with the same scale with Fig.13. It was clearly shown that ions go downstream as well as the LP-PPT, but the neutrals move with very slow speed and with no relation to the current ringing, as shown in the high speed photography. The ion exhaust velocity was estimated as about 16 km/s was higher than one estimated from the specific impulse. This would be clearly because of the slow neutrals. The emissive position of the neutrals moves with about 1.8 km/s. Here it should be cared that this velocity would not equal to the average velocity of the bulk neutrals. The emission of the neutrals (C\(_2\)) is caused by the electron impact which exists near them. Otherwise cold neutral gases can not emit by themselves. Hence the neutral emission region would be the furthest downstream point of the diffused neutral gas, and its movement does not equal to the whole neutral gases.

V. Conclusion

In the present work, we have investigated the plasma acceleration processes of 10 J class PPTs with rectangular electrodes. The successive photographs of 5 Mfps during the discharge clarified the flow behaviors during the
acceleration in the electrodes. In the discharge of the APPT, two wavelengths, 514.5 nm emission from neutral particles and 426.8 nm from ions, showed completely different aspect. At the initiation of the discharge, ions and neutrals were generated near the solid PTFE surface. The ions were accelerated and ejected from the channel of a velocity of 10 – 20 km/s, synchronized with the current ringing. On the other hand, the neutral particles remained near the propellant surface. The neutral motion was very slow (~ 1.8 km/s) and was not related to the current ringing. Measurement of the magnetic field profile revealed that the current always flowed not in the neutral gas but at the furthest downstream position of the ions. This means that the emissive neutral particles near the surface made no contribution to the electromagnetic acceleration. In the case of the LP-PPT, the flow behavior is simpler than the APPT. The single plasmoid is accelerated by electromagnetic acceleration, but the speed was much higher than the APPT. As a result of the image analysis, it was over 30 km/s and consistent with the measured high specific impulse.

In the discussion, the high speed images of the APPT were analyzed in detail. The location of the restrike indicates that even mass ablated in a discharge pulse can contribute to the electromagnetic acceleration only a little, and most causes propellant loss.

VI. References


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