Plume Characterization of a Porous Electrospray Thruster

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Abstract: This paper introduces the recent testing results of the University of Southampton porous electrospray thruster. The thruster was manufactured using low-cost techniques, manufactured in-house at the University of Southampton. Previous studies on this thruster suggested it can achieve a high specific impulse with relatively high thrust. In this paper, the plume properties of the thruster were further studied. The distribution of particles' retarding potentials in the plume was characterised, and the plume energy distribution was measured and analysed. Measurements of the plume angle were completed. A long-term operation test was attempted, suggesting the thruster was able to operate for 18 hours with reasonable performance variations.

Nomenclature

\( m_1 \) = mass of the charged particle before fragmentation
\( m_2 \) = mass of the charged particle after fragmentation
\( q_1 \) = electric charge of the particle
\( \tau_p \) = the proportion of the acceleration voltage before fragmentation over the overall acceleration voltage
\( U_1 \) = total acceleration voltage
\( U_{1,1} \) = the acceleration voltage before fragmentation
\( U_{1,2} \) = the acceleration voltage after fragmentation
\( U_2 \) = deceleration voltage
\( v_{1,1} \) = velocity of the charged particle at fragmentation position while within the electric acceleration field
\( v_{1,2} \) = velocity of the charged particle at the end of the electric acceleration field after fragmentation
\( \eta_{nk} \) = non-kinetic energy

I. Introduction

Electrospray thrusters are an emerging electric propulsion system which generates thrust by using electrostatic force to extract and accelerate charged particles directly from a liquid contained on and within a solid medium. The propellant is usually a conductive liquid and the emitted particles can be charged droplets or ions. A well-known example of electrospray propulsion is the Colloid Micro-Newton Thruster developed for Laser Interferometer Space Antenna Pathfinder mission to measure gravitational waves¹. As droplets generally have much smaller specific charge values compared to other electric propulsion propellants such as xenon ions, they often result in lower specific impulse approximately 100 to 200 s. In order to expand the application of electrospray thrusters for the uses in long-term station-keeping missions of small satellites, higher specific impulse is considered beneficial and needed. Through studies on ionic liquids propellants with high conductivity, electrospray thrusters can now emit more proportion of lighter ions with higher overall specific impulse²,³.

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In this paper, an electrospray thruster developed at University of Southampton is introduced. The electrospray thruster uses a porous emitter, a type of electrospray thruster particularly of interest currently. Previous work regarding the development of this thruster has strongly suggest that the emitted particles are mostly ions. Further characterization of the plume is introduced here.

II. Thruster and Experimental Apparatus

A. Electrospray Thruster Design

The Porous-emitter Electrospray Thruster, termed the PET-100-MK2 thruster, uses 1-Ethyl-3-methylimidazolium tetrafluoroborate (EMI-BF$_4$) as the propellant. As illustrated in Figure 1, The thruster consists of an emitter, an extractor, a reservoir, a set of thruster mounts, and shielding parts. The emitters were CNC machined from a substrate of porous borosilicate material, which has a void ratio approximately 0.5 and a pore size of either from 1 to 1.6 µm or from 10 to 16 µm, depending on the porous grade of the material used. A 10 × 10 array of emitter tips, with a pitch distance of 2 mm, was manufactured on a 20 × 20 mm emitter substrate. The reservoir was also a porous stainless-steel substrate which is 10 mm thick and has larger pores than the emitter material, allowing the propellant passively transported. The conductive porous substrate also acted as a distal electrode to mitigate detrimental electrochemical effects during the electrospray. The extractor was waterjet cut from a 0.25 mm thick stainless steel sheet. The apertures have a diameter of 1.5 mm. These components were held in a thruster mount made of ceramic-filled resin material using 3D printing technology. The thruster was covered by a set of shielding parts made of aluminium and stainless steel to reduce the interference of electric field pulse from thruster to other electronics placed in the surrounding environment.

![Figure 1. PET-100-MK2 thruster design and manufactured results.](image)

The manufacturing quality of the emitters was measured using a confocal optical scanning machine. The scanning data was used to rebuild 3D models of the manufactured emitters for analysis. The height of the emitter tips was approximately 1.82 mm. Depending on the porous material, the average emitter tip radius is approximately 40 µm for P5 grade porous glass material and 70 µm for P4 grade, as illustrated in Figure 2.

![Figure 2. Scanning results of the manufactured emitters.](image)
B. Testing facilities

The PET-100-MK2 thruster was tested in the David Fearn Electric Propulsion Laboratory at the University of Southampton. The testing chamber of the vacuum system is 2 m in diameter and 4 m in length, fitted with one roughing pump, two turbo-pumps with pumping rates of 2,100 L/s each, and two cryopanels with an equivalent pumping rate of 15,000 L/s. During electrospay thruster operation, the vacuum system can maintain a background pressure from $6 \times 10^{-6}$ to $9.8 \times 10^{-7}$ mbar depending on the propellant flow rate.

![Figure 3. Integrated testing platform of the PET-100-MK2 thruster.](image)

The thruster was mounted in a rotational platform located on an integrated testing platform, which also included a full emission current collector and a retarding potential analyser, as illustrated in Figure 3. The voltage supplied to the thruster’s metal reservoir is conducted through a metallic bar placed in the rear of the thruster, which is connected to a power source outside the vacuum chamber. The power source consisted of two HCP 35-3500 high voltage power supplies and a voltage switching unit, periodically switching the polarity of the voltage output to the thruster. However,
these power supplies are not programmable. In order to output the power supply voltage in a controllable way, the rotational control knob on each power supply was connected to a stepper motor through a 3D printed connector. The motions of the stepper motors were controlled using Arduino boards, allowing well-synchronized remote control of the power supplies outputs. Two resistors were placed in the connection to the emitter and the extractor, and their voltages were monitored using a Teledyne LeCroy WaveSurfer 3034Z oscilloscope for the calculation of emitter current and extractor current.

The current of emitted charged particles in the plume was measured using a full emission current collector. The total emission area of the thruster is 2 × 2 cm. For a plume half-angle less than 45 degrees, a 15 × 15 cm collector was placed approximately 6.5 cm away from the thruster to collect all the emitted particles from the thruster. The collecting plate is a 2 mm thick aluminium. Two layers of nickel meshes were placed in front of the collecting plate with a gap distance of 5 mm each. The mesh closest to the collecting plate was applied with a negative voltage to suppress the secondary electron emission (SEE) generated from the bombardment of high-energy particles on the collecting plate surface. The other grid in the upstream is grounded, ensuring a non-acceleration region between the grid and the extractor.

As the emitted particles of an electrospray thruster are nearly solely accelerated by the electrostatic force, their energy distribution can be measured using a retarding potential analyser (RPA). The design of the RPA is introduced in section IV. The distance between the RPA collecting plate and the thruster extractor plane was approximately 35 cm. The RPA was also used to collect the particle current while rotating the direction of the thruster, for the measurement of plume current angular distribution.

III. Current - Voltage Characteristics and Secondary Electron Emission

As the objective of this paper is to characterize the plume properties of the PET-100-MK2 thruster, the current-voltage characteristics regarding the emission current were first collected supporting further characterizations.

When high-energy particles collide on a material surface, a certain amount of energy can be transferred to the electrons around the atom nucleus, resulting in the emission of energized electrons. Secondary electron emission (SEE) is usually observed in high-energy ion bombardment tests, such as plasma thruster experiments. SEEs are more likely to occur on surfaces of metal materials. The SEE effects were also observed in electrospray thruster experiments when using a metallic plate to collect emitted particles for emission-current measurement. The emitted secondary electrons tend to draw more electrons from other sources to maintain the grounded state, generating interferes to the signals with positive offsets. A method commonly used to mitigate the effects of SEE is adding a conductive grid upfront the metallic surface, and the grid is applied with a negative voltage to suppress the movement of secondary electrons.

A set of tests were completed in order to investigate the effects of SEE on the collected emission current and to determine the suppression voltages required to eliminate SEE effects. The PET-100-MK2 thruster was operated in a bipolar mode with a polarity switching frequency of 2 Hz. During the measurement, the stepper motors ramped up the voltage output from 0 to ±3500 V at a steady rate, and the data of the collected emission current versus time was recorded. The signals of stepper motor output versus time were recorded in order to synchronize the time and the voltage output. These processes were completed multiple times at different values of SEE suppression voltage. For example, with a SEE suppression voltage of -100 V, the raw data of the stepper motor signal and collected emission current versus time is shown in Figure 4. The start and end time of the stepper motor were taken as the time point of power supplies outputting 0 and ±3500 V. Therefore, the function of emission current versus applied emitter voltage can be converted. Using the method described above, Figure 5 shows the current-voltage characteristics of the thruster emission current at different SEE suppression voltage from 0 to -100 V. These collected current curves are summarized in Figure 6 for comparison.
Figure 4. Synchronized data of the collected emission current and the signals of stepper motors controlling power supplies.

At higher thruster operation voltages, the emitted particles contain higher energy. As a result, the secondary electrons are likely to obtain higher energy, requiring higher SEE suppression voltage. At lower SEE suppression voltage from 0 to -20 V, the positive current collected were much higher than the negative current, suggesting potent SEE occurring. As a result of more effective SEE suppression by increasing the voltage from -40 to -80 V, the values of the positive currents collected approach to the negative currents collected. There were a few positive current spikes occurring at -100 SEE suppression voltage, but they were considered outlier data and they do not affect the overall current variation trends. The collected current curves of -80 V and -100 V are nearly overlapping, suggesting that -80 V suppression voltage was high enough to eliminate all the SEE effects within the ±3500 V thruster operation voltage.
Figure 5. The thruster emission current-voltage characteristics at different SEE suppression voltages.

Figure 6. Current-voltage characteristics comparison at different SEE suppression voltages.
The volt-ampere curve with -80 V and -100 V SEE suppression voltage represent the actual thruster emission current. The onset voltage of the thruster was approximately ±1900 V. The collected emission current ramped up with the applied emitter voltage with a maximum value of +0.9 and -1.2 mA at ±3500 V. Compared to many other electrospray thrusters\textsuperscript{2,3}, the maximum emission current was relatively large, which was possibly a result of the relatively large emitter tip size as well as the highly excessive applied voltages\textsuperscript{4}. The negative emission current was higher in value than the positive at the same voltage, which agrees with previous testing results on previous versions of the PET thruster series\textsuperscript{4}. As previous studies suggested that the emitted particles were mainly monomer and dimer of ions, a possible explanation is that the negative ions, such as BF\textsubscript{4}\textsuperscript{-} and (EMI-BF\textsubscript{4})BF\textsubscript{2}-, are lighter than positive ions, such as EMI\textsuperscript{+} and (EMI-BF\textsubscript{4})EMI\textsuperscript{+}, and their higher specific charges result in less extraction energy cost. Therefore, more negative ions than the positive can be extracted by the same level of electrical stress.

IV. Retarding Potential Analysis

The energy of the emitted particles cannot be directly calculated from the applied voltage due to non-kinetic energy losses. The electricity passes through the stainless-steel propellant reservoir experiencing little electric impedance; however, the ionic liquid propellant acts as the only conductive medium when the electricity conducting through the porous emitter. Although the EMI-BF\textsubscript{4} propellant has a relatively low electric impedance, it generates a drop of voltage along with the electricity conducting path. As a result, the voltage between the upfront boundary of the emission tips and the extractor is usually smaller than the voltage applied from the power supply. Also, the extraction process of charged particles from the liquid on emitter tips consumes power, resulting in a further drop of particle acceleration voltage and power efficiency. In order to calculate these non-kinetic voltage losses, a retarding potential analysing system was designed to measure the actual energy of the plume particles.

A. Retarding Potential Analyser Design

A retarding potential analyser (RPA) consists of a collecting plate, a metal shielding and multiple, typically four, layers of conductive grids with different voltages. In a four-grids RPA design, energised flying particles enter the device through its front aperture; eventually, they arrive on the collecting plate located behind the fourth grid. The third grid is connected to a controllable voltage source, which can apply a low-to-high sweeping voltage. As the energised particles are accelerated by electrostatic force, each particle will be stopped and repelled as the voltage of the third grid reaching a threshold value. Therefore, as the voltage of the third grid increases, the current received on the collector is gradually reduced, based on which the energy distribution of the measured region of the plume can thus be calculated. The first grid is typically grounded as well as the metal shield, preventing any voltage change inside the RPA from interfering outside electric field. The second and the fourth grids are applied with negative voltages to suppress the SEE on the metal grid and the collector surface.

The voltage of the third RPA grid was controlled using a programmed stepper motor, in a similar way of the emitter voltage control method in volt-ampere characteristics tests. However, the stepper motor was mounted on a third power supply outputting the sweeping voltage while the two power supplies generating emitter voltages were kept constant output. The rising time of the RPA sweeping voltage was limited by the rotational speed and accuracy of the stepper motor. In order to maintain a high signal fidelity with reasonable synchronization accuracy, the emitter electrical polarity was switched every 30 s, allowing a full round of RPA voltage sweep, from 0 to negative or positive 3500 V, to be completed within one emission polarity. The RPA characterizations were completed in negative and positive voltages separately.

Figure 7. A rotational thruster mounting platform.
B. Retarding Potential Measurement Results

The collected RPA current data was amplified using a FEMTO DHPCA-100 current amplifier with a 1 MHz bandwidth limit. However, the signals contained intense high-frequency noises, which were therefore filtered using low-pass Butterworth filters. As a typical example, a filtered current data curve collected at +2500 V emitter voltage is shown in Figure 8 (a).

![RPA at +2500 V](image)

(a) Current data of RPA at +2500 V.

As the RPA sweeping voltage increases, the variation of the collected current can be divided into five parts, corresponding to different physical effects occurring. Initially, the collected current keeps around a similar value until it enters the second stage at approximately 800 V, where the current drastically decreases over a minor voltage increase. Then the collected current gradually decreases at a moderate rate. Afterwards, the current enters another drastically decreasing stage before it finally reaches a stable near-zero value. The two stages with a sizeable current decrease of collected current indicate the energy and intensity of most particles in the plume. The stage with a moderate current decreasing rate suggests a small fraction of the charged particles have a relatively wide energy distribution. The overall current data curves share similar trends with some other RPA studies of electrospray thrusters\(^5,6\).

The slope data of the collected current curves are used to indicate the signal intensity of particles with different energies. However, the current data has high-frequency noises, which creates misleading slope values if the calculations are based on any adjacent two points. Instead, the slope values were calculated based on data points with interval steps. A short interval does not generate an analysable data, such as the example shown in Figure 8 (b), while an overly large interval reduces the fidelity of the slope data, such as the example shown in Figure 8 (d). Only intervals within a moderate range would result in reasonable smoothness while keeping a high data fidelity, with an example shown in Figure 8 (c).

![RPA at +2500 V](image)

(b) 10 steps interval.

![RPA at +2500 V](image)

(c) 200 steps interval.

![RPA at +2500 V](image)

(d) 400 steps interval.

Figure 8. RPA of the plume at +2500 V with different calculation interval lengths.

These data process methods were also performed on other RPA measurement data at different voltages, as shown in Figure 9 and Figure 22 in appendix. Although the voltage with highest signal intensity increases with the emitter voltage, all the RPA current data curves share similar trends.
Figure 9. RPA of the thruster at ±2400 V and ±2200 V.
C. Voltage Losses

The voltages of current intensity peaks in stage 4 are slightly smaller than the applied emitter voltage, and they represent the energy of the charged particles without fragmentation. These charged particles were considered fully energized by the electric acceleration field; therefore, their energy can be used to calculate the value of acceleration voltages as well as the overall voltage losses, which are the difference between the acceleration voltage and the applied emitter voltage. The loss of voltage possibly resulted from the conducting voltage loss and the extraction voltage loss, from which the non-kinetic energy efficiency can be calculated, as shown in Table 1 and Figure 10.

<table>
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<tr>
<th>Applied voltage (V)</th>
<th>-2100</th>
<th>-2200</th>
<th>-2400</th>
<th>2100</th>
<th>2200</th>
<th>2300</th>
<th>2400</th>
<th>2500</th>
<th>2600</th>
</tr>
</thead>
<tbody>
<tr>
<td>η_{nk} (%)</td>
<td>92</td>
<td>90.18</td>
<td>88.46</td>
<td>91.24</td>
<td>87.91</td>
<td>89.65</td>
<td>86.5</td>
<td>85.52</td>
<td>86.69</td>
</tr>
<tr>
<td>Voltage loss (V)</td>
<td>168</td>
<td>216</td>
<td>277</td>
<td>184</td>
<td>266</td>
<td>238</td>
<td>324</td>
<td>362</td>
<td>346</td>
</tr>
</tbody>
</table>

Table 1. Voltage loss and non-kinetic energy efficiency at different voltages.

The results show that the loss of voltage increases with the voltage applied to the emitter. Through comparing the voltage loss data with volt-ampere curves collected with a SEE suppression voltage of -100 V, it can be found that the trends of these two data are generally consistent. Theoretically, the extraction voltage costs of monomers and dimers are results of electrical stress exceeds ionic bonds, they should be constant values at different voltages. The total extraction energy cost increases with voltage and current. In comparison, assuming the EMI-BF4 liquid conductivity does not vary during the electrospray process at different voltages, the voltage loss caused by the propellant resistance would increase with the emitter current, which agrees with the measurement results. Therefore, it can be concluded that the resistance of propellant liquid is the main cause of voltage losses at higher emitter voltages. These results suggest that the effects of propellant liquid resistance on voltage loss are not negligible, providing feedback to the design of the thruster on the emitter material selection. However, this study only provides information regarding the overall voltage loss at different voltages, and it cannot identify the proportion of voltage loss from different sources, which will require further work.

Figure 10. Comparison of voltage losses and a volt-ampere curve.

D. Fragmentation Effects

Ideally, the emitted particles of an electrospray thruster are mono-energetic with a value close to the applied voltage, similar to the stage 4 in Figure 8 (a). The five-stages energy distribution can be results of several possible reasons. One possibility is that the emitted particles contain different species including ions and droplets, and that some species have much higher extraction voltage costs than the others, resulting in the two stages of the drastically current decrease with RPA voltages much lower than the emitter voltage. However, this is unlikely to be true as these two stages have rather concentrated energy distribution, while the masses of electrospray droplets normally follow a wider distribution pattern. In addition, previous time-of-flight characterizations regarding PET-100 thruster series suggested that their plume contained mainly monomer and dimer ions, with little if any evidence of charged droplets. Another possible reason of the five-stage energy distribution is the fragmentation effects occurring during the emission of charged particles. The fragmentations can be divided into two groups depending on whether they occur in an electric field: before and after leaving the extractor plane.

The second stage is likely a result of fragmentation occurring after leaving the intensive electric field region between emitter and extractor, as illustrated in Figure 11.
In an electrostatic acceleration system, a charged particle’s kinetic energy variation equals to the change of electrical potential energy

\[
\frac{1}{2}m_1v_1^2 = q_1U_1,
\]
\[
\frac{1}{2}m_2v_2^2 = q_2U_2,
\]

where \(m_1, v_1, q_1\) are the mass, velocity and charge before the fragmentation, respectively; \(U_1\) is the acceleration voltage; \(m_2, v_2, q_2\) are the mass, velocity and charge after the fragmentation, respectively; \(U_2\) is the RPA voltage stopping the charged particle. The electrical charge of the particle does not vary through the fragmentation, \(q_1 = q_2\). Assuming the fragmentation occurs radially and does not change the axial velocity of the particle velocity does not change during the fragmentation, \(v_1 = v_2\), the equation set (1) can thus be derived into

\[
\frac{U_1}{U_2} = \frac{m_1}{m_2}.
\]

Equation (2) suggests that ratio of the initial acceleration voltage over the RPA stopping voltage equals to ratio of the charged particle mass before and after the fragmentation. For the fragmentation of a dimer ion using EMI-BF4 propellant, \(m_1/m_2\) is approximately 2.78 for a positive ion, and approximately 3.28 for a negative dimer ion. The fragmentation processes of EMI-BF4 dimers are illustrated in Figure 12.

![Fragmentation processes of EMI-BF4 dimers](image)

(a) Fragmentation of a positive dimer ion.  
(b) Fragmentation of a negative dimer ion.

**Figure 12. Fragmentation of dimer ions into neutral molecular and monomer ions when using EMI-BF4 propellant.**

In order to verify whether the stage 2 represents dimers fragmentated after the extractor, the voltage data of the current intensity peak in stage 2 is taken as \(U_2\) and the applied emitter voltage is taken as \(U_1\). Based on data from the RPA measurement data shown in Figure 8, Figure 9 and Figure 22 in appendix, the values of \(U_1/U_2\) at different voltages are summarized in Figure 13. Although the calculated \(U_1/U_2\) values from tested data are smaller than the theoretical values, they are relatively close and steady at different voltages. Considering measurement errors, the
results strongly suggest that the stage 2 of the decreasing current can be a result of a fragmentation of dimer ions occurring after leaving the extractor.

Figure 13. Ratios of the applied emitter voltage over the voltage with the highest current intensity in stage 2.

If a proportion of dimers fragments before leaving the extractor, their energy would be between the stage 2 and stage 4. Current decreasing stage 3 is likely a result of fragmentation occurring before leaving the electric acceleration field, as illustrated in Figure 14.

Figure 14. Fragmentation occurring before leaving acceleration electric field.

In this fragmentation case, the state of a particle can be divided into 4 stages: before fragmentation and in the acceleration field, after fragmentation while still in the electric field, cruising after leaving the electric field, deceleration stage after entering RPA electric deceleration field. The energy and velocity equations during these stages are

\[ \frac{1}{2} m_1 v_{1,1}^2 = q_1 U_{1,1}, \]
\[ \frac{1}{2} m_2 (v_{1,2}^2 - v_{1,1}^2) = q_1 U_{1,2}, \]
\[ \frac{1}{2} m_2 v_{2}^2 = q_1 U_{2}, \]
\[ U_1 = U_{1,1} + U_{1,2}, \]

where \( v_2 = v_{1,2} \), the subscription 1, 1, 1, 2 and 2 represent the particle in the region of before fragmentation, after fragmentation yet before leaving electric field, and in deceleration, respectively. Solving the equation for the deceleration voltage,

\[ U_2 = U_{1,2} + U_{1,1} \frac{m_2}{m_1} \]
Define the proportion of the acceleration voltage of the particle before fragmentation over the overall acceleration voltage, \( r_p = \frac{U_{1,1}}{U_1} \), the

\[
\frac{U_1}{U_2} = \frac{1}{1 + r_p \left( \frac{m_2}{m_1} - 1 \right)}
\]  

(5)

The relationship between \( r_p \) and the ratio of full acceleration voltage versus the stopping voltage of the particle, \( \frac{U_1}{U_2} \), is shown in Figure 15. When \( r_p \) is near zero, meaning that dimer ions would fragment immediately after they have been extracted before gaining any acceleration; therefore, the fragmented monomer ions are accelerated and stopped by the full acceleration voltage, approaching stage 4 in RPA current curves. As \( r_p \) increases, the dimer ions would gain more energy before fragmentation, and after fragmentation would split its energy into two parts: a monomer ion and a neutral molecular, therefore the energy of the charged particle is reduced, resulting in less RPA stopping voltage. When \( r_p \) is near 1, the dimer ions tend to fragment at the end of the electric acceleration field, meaning that the fragmentation splits more energy from the charged particle into a neutral particle. Therefore, its RPA stopping voltage would be smaller until it approaches the values in current decreasing stage 2, where the fragmentation occurs after leaving the extractor.

![Figure 15. Effects of the voltage where particle fragmentation occurs on the stopping voltage applied on RPA.](image)

The 3rd stages in RPA current curves are gradually decreasing over the RPA sweeping voltage from the end of stage 2 until reaching the start of stage 4. Based on these analyses, stage 3 current curves suggesting that \( r_p \) could range from 0 to 1 for different particles in the plume: the fragmentation occurs throughout the electric acceleration field. The RPA current curves demonstrate a continuous energy loss trend as a result that the fragmentation of dimer ions occurring before and after leaving extractor plane. It is noticeable that if fragmentation occurs within the electric acceleration field, it will cause energy loss as the neutral molecular will not be fully accelerated. However, if the fragmentation occurs after leaving the extractor, it brings little effects on the thruster performance.

V. Plume Energy Angular Distribution Measurement

The plume distribution of an electrospray thruster is an important as it does not only directly affect the angular efficiency of the thruster, but also has significant influences on the lifetime of the thruster.

A. Rotational Thruster Mounting Platform

In order to measure the angular distribution of the plume energy density, the PET-100-MK2 thruster was mounted on a specially designed rotational platform, as shown in Figure 16. A stepper motor powered the rotation of mount through a set of gears, and the motor was controlled remotely from outside the vacuum chamber using an Arduino board. In order to avoid the high tension generated by the high-voltage cables when twisted, the cables connected to the thruster and the power feedthroughs were separated, and they were electrically connected using specifically designed slip rings with high-voltage insulation.
Figure 16. Designs of rotational thruster mounting platforms.

Figure 17. Raw data of plume angular distribution measurement.

B. Plume Energy Angular Distribution Measurement Results

The stepper motor rotational angle was synchronized over time with the collected emission current, and the current data points after each emitter polarity switching were selected to generate a plume current distribution curve, as shown in Figure 17. As the emission current collector was not applied with a SEE suppression voltage in these plume angle measurements, the collected current was unified to represent the intensity of current at different angles.

The angular distribution of plume current intensity at different voltages are shown in Figure 18. In general, the plume half-angle increases with the applied emitter voltage, from 12.4 degrees near the onset voltage ±1800 V to 60.8 degrees at ±3500 V. The main reason contributing to the increase of plume is likely the expanding area of emission sites on the emitter tips. As voltage increases, the electric stresses on wider emitter surface regions become strong enough to pull ions from the liquid propellant. The electric field near the lateral surface accelerates charged particles with a wider angle.
Figure 18. Plume energy angular distribution at different emitter voltages.

A wider plume angle causes more angular loss in thrust, resulting in lower efficiency. For an electrospray thruster, a smaller plume angle comes with a lower operating voltage and thus a lower thrust and specific impulse. This can be somewhat balanced by changing the design of an electrospray thruster. A blunt emitter tip would increase the onset voltage, but it can also increase the thrust and specific impulse per particle while near the onset voltage while keeping a moderate plume angle. Another suggestion is to increase the number of emitter tips and operate the thruster at a reduced voltage. This would keep a small plume angle while generating a higher level of current for the compensation of thrust.

VI. Initial Investigation of Thruster Lifetime

In order to investigate the long-term operation performance stability of the PET-100-MK2 thruster, the thruster was set to operate in a relatively moderate current mode with an applied emitter voltage of 3000 V. The polarity switching frequency was set to 2 Hz. The thruster faced to the full plume current collector whose SEE suppression grid was constantly applied to a -150 V potential. The emission current was recorded for performance monitoring.
However, this thruster was continuously tested for approximately 18 hours, then the polarity-switching unit broke down after continuously performing approximately 130,000 times of polarity switching. The collected full emission current data is shown in Figure 19. The propellant in the thruster was not refilled during the testing time.

![Graph showing emission current data during 18 hours thruster testing.]

**Figure 19. Collected emission current data during an 18 hours thruster testing.**

The emission current was not constant throughout the thruster testing period, instead the current was slowly reducing over time for approximately 10 hours. Then the current was relatively stable for 4 hours until the negative current became higher.

After the lifetime test, the emitter appears to be black as a result of accumulated electrochemical reaction effects, as shown in Figure 20. One side of the thruster casing was burned, possibly by electrical charges from minor propellant leakages. The extractor appeared to be in good condition with no obvious liquid accumulation, suggesting the plume angle was well controlled in this operation voltage. Outside surface of the extractor turned blue, possible a result of back sputtered high-energy ions.

![Images showing emitter and extractor before and after testing.]

**Figure 20. Emitter and extractor before and after an 18 hours thruster testing.**
Noticeably, there were orange coloured fragments species collected on the full emission current collector, as shown in Figure 21. These fragments are mostly needle-shaped with a length typically shorter than 0.5 mm. The residues existed mainly on the first ground grid and less on the plume current collecting plate. This phenomenon was not observed in previous experiments conducted on the PET-100-MK2 thruster series. Normally, only the collector plate had obvious yellow coloured marks suggesting particles’ collision site. A possible explanation is that the orange coloured residues are the accumulation of emitted particles intercepted by the ground grid over the 18 hours testing period. It could also be the reaction products between the metal material and the emitted high-energy particles. The exact reason remains unclear until the orange coloured being tested and identified in the future.

Figure 21. Residues on the emission current collecting plate after an 18 hours thruster testing.

VII. Conclusion

This paper focuses on the plume characterization of the PET-100-MK2 thruster. The voltage for suppressing secondary electron emission was identified, -80 V was proven effective for the thruster operation range of ±3500 V operation. The voltage losses of the emitted particles were mainly resulted from the resistance of propellant liquid, counting for 8-14% of the applied emitter voltage. The retarding potential analysis results strongly suggest fragmentation effects of dimer ions into monomers of ions occurring before and after leaving the acceleration electric field. The plume half-angle of the thruster ranges from 12.4 to 60.8 degrees depending on the applied emitter voltage, a lower operation voltage can effectively reduce the plume half-angle, although at the expense of lower thrust and specific impulse. The performance of the thruster was reasonably stable during an 18 hours long lifetime test, after which the test ended with the broke down of the polarity switching unit. The current was varying during the test but within a reasonable range. However, accumulated electrochemical effects are still the main problems limiting the lifetime of the PET-100-Mk2 thruster.

Appendix

Retarding potential analysis results of the thruster at other voltages are shown in Figure 22.
Figure 22. RPA data of thruster operating at different emitter voltages.
References