The Design and Characterization of a Porous-emitter Electrospray Thruster (PET-100) for Interplanetary CubeSats

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Using nanosatellites for interplanetary flights is an advanced mission concept in space industries, but the development of an effective on-board micro-propulsion system for such mission has been a main challenge due to the constraints in terms of size, mass and power capability of a nanosatellite. Among various micro-propulsion concepts, electrospray thrusters is a promising candidate due to the high specific impulse, which can be higher than 4000 s, and the compact system configuration. An electrospray thruster utilizes a strong electric field to extract and accelerate charged particles from the surface of a liquid propellant, which is generally an ionic liquid, held on the tip of a protruding emitter. The emitters are generally multiplexed to increase the over thrust output because the thrust of a single emission site is only at the level of 0.1 $\mu$N. This paper introduces the development of an electrospray thruster with a porous glass emitter, which has an array of 100 emitter tips, manufactured through computer-numerical-controlled machining. A porous reservoir was used to passively transport the propellant to emitter tips using capillary action, leading to a pressure-free thruster configuration. The overall size of the thruster is 4 cm $\times$ 4 cm $\times$ 3 cm. The thruster was tested in a vacuum chamber at the University of Southampton, and its propulsive performance was characterized using a time-of-flight (ToF) system, showing a specific impulse higher than 7500 s, a thrust higher than 220 $\mu$N with a total thruster power around 14 W and a power efficiency of 62%. With this specific impulse, a propellant mass of only 12.7% of total satellite mass is required for 10 km/s velocity change. Several issues regarding the electrochemical effects and the plume angle should be further studied and improved.

Key words: CubeSat, Interplanetary, Electric propulsion, Electrospray thruster, High specific impulse

Nomenclature

- $g_0$: the gravity acceleration, 9.81 m/s\textsuperscript{2}
- $I_{sp}$: specific impulse, s
- $m_i$: initial mass of the spacecraft, kg
- $m_d$: finial dry mass of the spacecraft, kg
- $v_e$: propellant exhaust velocity, m/s
- $\Delta V$: velocity change, m/s

1. Introduction

CubeSats is a low-cost nanosatellite system with a standard mass and volume. With the miniaturization of satellite components, the missions proposed to nanosatellites have moved from a purely educational tool to more advanced missions, including a growing interest in deep space mission. During the last decade, several science missions using interplanetary CubeSats have been proposed and developed. For example, the IceCube one is a 6 U CubeSat that is designed to be launched to the Moon’s orbit by Space Launch System (SLS) and investigate the evidence of ice in the soil on the surface of the Moon\textsuperscript{1,2}. Two MarCO 6 U CubeSat were launched in May 2018 to flyby Mars as a frist demonstration of using CubeSat for deep space missions\textsuperscript{3}.

Some deep space CubeSats are designed to be launched using a ‘piggyback’ method where a mother spacecraft with a main propulsion system carries the CubeSats and completes high velocity change manoeuvres\textsuperscript{4}. In comparison, there is a trend of using CubeSat’s on-board propulsion system directly transport the CubeSat from LEO or GEO to the target orbits near Lunar or in deep space. For such deep space missions that require a large change in velocity, electric propulsion (EP) systems are a more suitable choice due to their high specific impulse. For example, the Lunar IceCube was equipped with a Busek Ion Thruster 3-cm (BIT-3) with a thrust of 1.2 mN and a specific impulse of 2500 s\textsuperscript{1}. And that Hayabusa-2, which although is 600 kg and not a CubeSat, was launched to collect samples from a near-earth-asteroid; its main propulsion system consisted of 4 ion engines with a maximum thrust of 28 mN and a specific impulse of 2800 s\textsuperscript{2}.

In this paper, various electric propulsion systems were firstly compared based on the propulsive requirements of interplanetary CubeSat. Then a suitable candidate, electrospray thrusters, was introduced. Following by the description of the design, test and performance of a low-cost and high-performance electrospray thruster that was developed at the University of Southampton.

2. Comparison of various EP systems

Interplanetary CubeSats often require a lager change of velocity for changing orbits and trajectories. The velocity change from LEO to higher-earth-orbits, Lunar’s orbits, near-earth-asteroids or Mars’ orbits varies 2 km/s to more than 10 km/s. The total velocity change from a thruster, $\Delta V$, can be obtained from the Tsio1kovski equation

$$\Delta V = v_e \ln \frac{m_i}{m_d}$$  \hspace{1cm} (1)

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where the $v_e$ is the propellant exhaust velocity, $m_0$ is the initial mass of the spacecraft and $m_d$ is the final dry mass of the spacecraft with all propellant depleted. As $v_e = \text{Isp} \cdot g_0$ ($g_0$ is the gravity acceleration 9.81 m/s$^2$), given different values of total velocity change, the required propellant mass proportions, which is the required propellant mass over the total initial spacecraft mass, can be obtained. These proportions at different specific impulses are shown in Figure 1. It can be found that, a high specific impulse can greatly reduce the required propellant mass.

In order to find the suitable EP candidates for interplanetary CubeSats, the typical performance values of some EP systems are shown in Figure 2, whose data was obtained from various literature 6–9.

There are many electric propulsion concepts that can provide a high specific impulse (> 1000 s), but for interplanetary CubeSats, the constraints in system mass, volume and power capability limit the suitable options. Several electric propulsion systems can be miniaturized to fit in a CubeSat, such as miniaturized Hall Effect thruster 10, miniaturized ion thruster 11, Helicon thruster 12 and vacuum arc thruster 13. But many of them have the issue of performance drop, in particular the efficiency, when the thruster power is scaled down 14,15. Whilst the Field Emission Electric Propulsion (FEEP) 16,17 and electrospray thrusters 18,19 do not have such issue. In particular, we designed and tested several types of low-cost miniaturized electrospray thrusters, which achieved high specific impulses from 4500 s to 8200 s 8,20,21. They are labelled as the PET category shown in Figure 2. This paper focuses on the high-thrust PET-10 type, whose introduction, analyses and improvements are given in the following sections.

3. Porous-emitter electrospray thruster (PET)

In an electrospray thruster an electric field is applied between the liquid propellant and a downstream extractor, as illustrated in Figure 3. The equilibrium condition between the electrostatic force and the liquid surface tension forms a conically-shaped liquid meniscus termed a Taylor cone 22. The surface electrostatic force is strong enough to extract and accelerate charged particles, producing thrust.

The liquid propellant used in this paper is a room temperature ionic liquid 1-Ethyl-3-methylimidazolium...
tetrafluoroborate (EMI-BF₄), which is held on the tip of a pyramidal-like porous emitter. EMI-BF₄ has a high surface tension and electrical conductivity, which can lead to an emission with purely ions without droplets, resulting in a high specific impulse²³. EMI-BF₄ also has a negligible vapour pressure so that it can be passively transported from the propellant reservoir to the emitter tip solely rely on capillary action²⁴, resulting in a compact and pressure-free thruster configuration. Electrospray thrusters scale well with very little loss in efficiency when the thruster is miniaturized to a low power level²⁵. Therefore, electrospray thrusters are one of the few high-performance EP systems suitable for small satellites.

**Figure 3 Illustration of multiple emission site at a porous emitter tip.**

### 4.1 Emitter manufacturing

As illustrated in Figure 3, a porous emitter has multiple emission sites at its tip, resulting in a much greater thrust than other types of emitter, such as capillary emitters and externally-fed emitters. The thrust can be further increased by multiplexing the emitter tips to an array. In our previous studies, low-cost computer numerical controlled (CNC) machining was used to produce single or an array of porous glass emitters⁸,²⁰. 25-emitter-arrays and 100-emitter-arrays were manufactured, and their geometries was checked through confocal laser scanning, showing a reasonably good quality⁸. For example, the maximum nominal pore size of the a 100-emitter-array is 10 to 16 µm. The height of each emitter tip is about 2 mm and the pitch distance between adjacent emitter tips is 2 mm. Its picture is shown in Figure 4. Borosilicate was chosen as the emitter material as it is more inert to ionic liquids, leading to a longer emitter lifetime. Our previous tests on these CNC machined single emitters or emitter arrays demonstrated a specific impulse from 4000 to 8500 s and a thrust from 2.2 to 7 µN per emitter⁸,²⁰, which is considerably higher than the typical value around 0.02 to 0.4 µN from conventional electrospay thrusters¹⁸,¹⁹.

In this paper, we show the results of the improvements of the 100-emitter-array, and further analyse its application on interplanetary CubeSats.

### 4.2 Thruster design

With the intention of application for interplanetary CubeSats, a porous-emitter electrospray thruster (PET) was designed, as shown in Figure 5. The PET analysed in this paper has a CNC machined 100-emitter-array, termed PET-100. The 1.5 mm apertures on the extractor sheet were cut using water-jet. The thruster body was 3D printed from high-detail resin. The whole thruster is miniaturized with low-cost.
4. Experimental setup

The PET-100 was tested in the David Fearn vacuum chamber at the University of Southampton, as shown in Figure 6. The chamber is 2 m in diameter and 4 m in length with two turbo-pumps (2100 L/s of N₂ each) and two cryopanels (15,000 L/s of Xe each), which can achieve a base pressure of 9.8 × 10⁻⁷ mbar.

The thruster was operated only in bipolar mode. The overall testing system set up and current measurement method are illustrated in Figure 7, which are similar to that were described in one of our previous papers.

The emission current, i.e. the current of the total emitted particles, was not directly collected but defined as the difference between the emitter current and the extractor current. The velocities of the emitted particles were measured by using a Time-of-Flight (ToF) system, which contains a ToF gate and a ToF collector. The ToF gate, whose aperture size is 15 mm in diameter, was placed 50 mm away from the extractor and a ToF collector plate was placed 90 cm downstream from the ToF gate. The specific charges of the emitted particles can thus be calculated based on their time of flight. Note that in these early tests, we did not use a grid applied with a negative voltage to suppress the emission of secondary electrons from the ToF collector, but this grid should be included in our future tests. The thruster was mounted on a rotational stage. Through rotating the emission angle of the thruster, the variation of current received by the ToF collector can be used to calculate the plume angle. More details about the testing system setup and specifications can be found in a previous paper.

5. I-V characteristics of PET-100

The tests of PET-100 had an alternating bipolar frequency of 1 Hz, in an attempt to mitigate the detrimental electrochemical effects. The I-V curves of its emitter current, extractor current and the emission current are shown in Figure 8 with 10% estimated error values.

In these tests, the applied voltage was gradually increased and then decreased to get the onset voltage (i.e. the voltage when the emission starts) and the offset voltage (i.e. the voltage when the emission stops). From Figure 8, PET-100 had an initial onset voltage of ±2200 V with a minimum emission current of ±2.5 µA. When the voltage being decreased, at ±1700 V the emission current turned to zero from a very small current of ±1.2 µA at ±1800 V, therefore the ±1800 V was considered as the offset voltage of thruster. The
offset voltage was lower than the onset voltage, agreeing with our previous tests\textsuperscript{20}. At a thruster voltage of +2970 V and -2890 V, the maximum emission currents of PET-100 were +3.19 mA and -4.75 mA with nearly 33% of the positive emitter current and 14% of the negative emitter current lost through the extractor.

6. Time-of-flight characterization of PET-100

The ToF traces of PET-100 were collected at both positive voltages and negative voltages from about ±2000 V to about ±3000 V, as shown in Figure 9 and Figure 10. Assuming all charged particles contain one elementary charge and translating the x-axis into the molecular mass, the corresponding molecular mass distributions of particles in the plume are also shown in the figures.

![Time-of-flight traces.](image1)

(a) Time-of-flight traces.

![Molecular mass distribution.](image2)

(b) Molecular mass distribution.

Figure 9 ToF traces and molecular mass distribution at positive voltages.

Using the general ToF calculation formulas as described in one of our previous papers\textsuperscript{8}, the specific impulse and thrust of the thruster can be obtained. From the ToF traces of PET-100 at +2970 V thruster voltage, the thruster specific impulse was calculated as 7527 s, and the overall thrust is calculated to be 223 µN. From Figure 9, the majority of their plume is monomer ions without any other obvious species at positive voltages. However, as the voltage increases to +2970 V, a noticeable negative current occurred in the ToF traces, which is suspected to be a result of the secondary electron emission (SEE). SEE can be severer at high voltages as the ToF collector would experience stronger collision from the ions.

On the other hand, Figure 10 shows the negative ToF traces, which illustrated different characteristics. The ToF trace amplitude at -1997 V is relatively small, but it showed a similar trace as that of the positive ToF trace at +1997 V. However, as the negative voltage increases, it was found that the ToF collector current did not go back to zero within the collecting time of 40 µs. Taking the -2686 V trace as an example, several clear current steps can be found, indicating BF\textsubscript{4} -, (EMI-BF\textsubscript{4})\textsubscript{2}BF\textsubscript{4} - and (EMI-BF\textsubscript{4})\textsubscript{3}BF\textsubscript{4} - , respectively. But these current steps were not clear in the -3500 V, at which the ToF collector current dropped near-linearly. At least three reasons were suspected. There might be charged droplets in the negative voltage emission. It is also possible to be a result of fragmentation, which could cause distributed energies and velocities of the charged particles arriving the ToF collector, resulting in the slopes of these ToF traces. There may also be a significant contribution from SEE, whose effects can be much severer with negative charged particles’ collision. In our future tests, such SEE will be suppressed by placing a negatively charged grid screen in front of the ToF collector.

7. Initial estimation of performance range

Assuming pure monomer emission and pure dimer emission, the estimated thrust and specific impulse of the PET-100 are shown in Figure 11. It shows that the thrust can vary from 5 µN to 223 µN; and the specific impulse can vary from 6000 s to 8500 s.
However, if the negative ToF traces indicated droplets in the emission, the corresponding thrust would be much higher than the positive mode and the specific impulse would be much lower. As these negative voltage ToF traces were not completed, i.e. the ToF collector currents did not return to zero, the exact thrust and specific impulse cannot be computed.

8. Electrochemical effects

Electrochemical effects have been suspected to be a main reason limiting the lifetime of an electrospray emitter. Based on the electrical double layer theory, operating the electrospray source in bipolar mode with a fast-enough alternating frequency and placing an upstream distal electrode with a high-surface-area will mitigate such detrimental effects. The PET-100 houses a porous nickel distal electrode, and it was operated in a bipolar mode with a frequency of 1 Hz for 30 minutes. The 100-emitter-array was visually checked post-test, as shown in Figure 12. PET-100 still experienced a certain level electrochemical effects but it was less severe compared to the 25-emitter-array at 0.1 Hz without a porous nickel sheet. There are several emitter tips that are darker than the others, which was suspected to be a result of different emission current among each tip. The current variation might be resulted from the geometric difference among each tip.

9. Plume angle measurement

The extractor was checked after each test, where a noticeable amount of dark liquid was found on the surface facing the emitter, as shown in Figure 13. The curve of emission current over the emitter current versus voltage is shown in Figure 14. It can be found an increasing percentage of current was leaked through extractor with high voltages. This was suspected to be a result of the increasing plume angle at higher voltages, which led to the collision and accumulation of propellant on the extractor and ended the test. The plume angle of an electrospray thruster contributes to the overall operational lifetime, which was also found in some other studies.

In this paper, the plume angle of PET-100 was initially characterized, although with the ToF gate still in place. At ±2000 V, the thruster mounting stage was rotated. The plume current collected by the ToF collector is shown in Figure 15(a), and the filtered and smoothed positive current is shown in Figure 15(b). The plume half angle, taken as 95% of the overall current, was found to be 17 degrees.
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(a) Collected raw data of plume current.  
(b) Filtered positive plume current.  
Figure 15 Plume angle measurement.

However, if the plume angle is too large, the plume could miss the ToF collector due to the blockage of the ToF gate, as illustrated in Figure 16(b). The limiting angle of such scenario is about 20 degrees. Therefore, this initial measurement setup could only measure plume half angle less than 20 degrees. In our future tests, Faraday cup should be used to collect the full plume current.

(a) Illustration of plume profiles.  
(b) Reducing the emitter-extractor distance to reduce the plume hitting the extractor.

Reduce plume hitting extractor  
Our previous studies showed that the plume angle can increase dramatically with the applied voltage. One approach to reduce the plume angle is to keep the operation voltage low but beyond the onset voltage, although this would compromise the thruster’s performance.

Another method to reduce the plume hitting extractor is to reduce the distance between the emitter and extractor, as illustrated in Figure 17.

A comparison test was performed to demonstrate this. Through changing the 3D printed thruster casing, the distance between the emitter and the extractor was reduced from 0.5 mm to 0 mm. The emitter and extractor currents are shown in Figure 18(a), and the emission current is shown in Figure 18(b). Figure 18(c) shows the emission current over the emitter current versus voltage. It can be found that the extractor current was decreased from 10-34% to less than 5% at high voltages, and it does not increase with voltage. This demonstrated that reducing the emitter-extractor distance is an effective method to reduce plume hitting the extractor and therefore to increase the thruster lifetime.

(a) Emitter current and extractor current versus thruster voltage.  
(b) Emission current versus thruster voltage.
Other approaches of controlling the plume angle and its collision with the extractor should be studied in the future. Studies on capillary emitters demonstrated that the divergence of plume can be reduced by using a downstream accelerator\(^1\), whose effects on the CNC machined porous emitters will be further investigated.

10. Discussion on performance

The experimental results demonstrated that the electrospray thrusters using porous emitter arrays manufactured through CNC machining can achieve purely ionic emission at positive voltages. But the emission at negative voltages needs to be further characterized.

At a thruster power of 14 W with a thruster voltage of +2970 V, the PET-100 can achieve a specific impulse around 7500 s and a maximum thrust of 223 µN. Such specific impulse is relatively high when compared to most other electric propulsion systems. Its thrust over power (T/P) ratio is comparable to some Field Emission Electric Propulsion (FEEP) systems, which also have high specific impulses. For example, the IFM Nano thruster developed by Enpulsion company has a nominal thrust of 350 µN and a specific impulse variable from 2000 s to 6000 s at the system power of 40 W\(^2\). Some FEEP systems’ thrust over power (T/P) ratios can reach 16.5 µN/W\(^4\), while the T/P ratio of the PET-100 was calculated as 19.1µN/W. In terms of efficiency, FEEP thrusters can lose a considerable amount of propellant through emission of large neutral droplets, whilst our tests showed that the positive emission can emit nearly pure ions which also led to an efficiency of 62%. It should be noted that the negative polarity may emit droplets which if correct would reduce efficiency. These variations should be further studied. The propulsive performance of PET-100 suggests that it is potentially suitable for interplanetary nanosatellite missions as well as long-term or precise station keeping missions of small satellites.

11. Conclusions

This study demonstrated that a low-cost micro-electrospray thruster using CNC machined emitter arrays can achieve a thrust of 223 µN and a specific impulse higher than 7000 s with a power less than 14 W, which are promising for nanosatellite manoeuvre missions requiring high velocity changes, such as interplanetary CubeSats. However, as it is in an early developing stage, several problems were identified and should be further studied. The thruster’s lifetime is currently limited by the electrochemical effects on the emitter and the liquid accumulation on the extractor, which need to be improved in the future.

The geometric uniformity of the CNC machined emitter tips was adequate for the test, but it should be further improved to reduce the performance deviation among each emitter tips. Regarding the future test set up, a secondary electron suppression grid will be placed in front of the collector, which should improve the ToF traces especially at negative voltages. A separate Faraday cup will be used to accurately measure the divergence of plume. In addition, a retarding potential analyser will be utilized to measure the energy distribution of the plume. This can enable the calculations of thruster efficiency and the ionization cost, which is the loss of electrostatic energy to extract charged particles from the liquid surface.

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