Feasibility Study of a Micro-Electrospray Thruster Based on a Porous Glass Emitter Substrate

IEPC-2017-485

Presented at the 35th International Electric Propulsion Conference
Georgia Institute of Technology • Atlanta, Georgia • USA
October 8 – 12, 2017

C. Ma 1, T. Bull 2, and C. Ryan 3
University of Southampton, Southampton, Hampshire, United Kingdom

Abstract: Electrospray thrusters utilize a strong electric field to extract and accelerate charged particles contained at a needle tip in a liquid state [1]. Electrospray thrusters are one of the few types of electric propulsion systems that can offer high specific impulses (i.e. >1000 seconds) whilst still being scalable down to fit within a 1U CubeSat form structure. These small electrospray thrusters, here termed micro-electrospray thrusters, are attracting considerable interest due to this Nanosatellite system suitability [2]. The thrust though from an individual downscaled micro-electrospray emitter is relatively small, of the order of 0.1 μN [3]. Given this small value, it is necessary to ‘multiplex’ the thrust by having an array of hundreds or indeed thousands of emitters [4–7]. To create these large arrays many different manufacturing methods have been investigated, including microelectromechanical system (MEMS) methods [8, 9], electrochemical etching [10, 11], laser ablation [12–14], computer numerical control (CNC) machining [3, 15, 16] and additive manufacturing [17]. Many of these techniques result in an electrospray emitter design with an emitter tens of micrometres in height and with emitter diameters of the order of ten micrometres if not smaller. This results in a ‘postage stamp’ sized emitter array, which in itself is considerably smaller than perhaps what is required onboard a CubeSat. Alternatively somewhat larger emitters may produce greater charged particle current per emitter, and therefore greater thrust. To investigate the feasibility of a larger emitter design, this paper studies a thruster using an emitter manufactured from sintered porous glass using a CNC machining technique. The emitter manufactured is of a pyramidal shaped design, with an emitter height of 5 mm and side surface angles ranging from 10° to 30°. Five different prototype emitter shapes are manufactured, investigating the feasibility of manufacturing single emitters using the method. Initial experimental results are illustrated, demonstrating good operation particularly in a bipolar, alternating voltage, mode. Initial Time-of-flight measurements would seem to indicate that the emitter was operating in a purely ionic regime, with a thrust of the order of 9.25 μN per emitter and a specific impulse of the order of 4550 seconds at 3443 V with 60 μA emission current from the one emitter. This value of thrust is particularly high from one emitter, with one reason suspected being the occurrence of multiple emission sites at the emitter tips during the electrospray process. Prototype designs of array of emitters, and also more spike like emitters, are presented with the manufacturing demonstrating the reasonable promise of this very low cost, simple and quick to iterate manufacturing process.

Nomenclature

\[
\begin{align*}
d_{EC} & = \text{Distance between the thruster extractor and the collector} \\
e & = \text{Elementary charge, } 1.602 \times 10^{-19} \text{C} \\
E_a & = \text{Electric field strength at the emitter apex} \\
g_0 & = \text{Standard gravitational acceleration at the Earth’s surface, } 9.807 \text{ m/s}^2 \\
l(t) & = \text{Collector current over time} \\
I_p & = \text{Specific impulse} \\
L & = \text{The distance between the ToF gates and the collector}
\end{align*}
\]

1 PhD student, Astronautics Group, Faculty of Engineering and the Environment, c.ma@soton.ac.uk.
2 PhD student, Mechatronics Research Group, University of Southampton, tb10g11@soton.ac.uk
3 Lecturer, Astronautics Group, Faculty of Engineering and the Environment, c.n.ryan@soton.ac.uk.

The 35th International Electric Propulsion Conference, Georgia Institute of Technology, USA
October 8 – 12, 2017
I. Introduction

CubeSats have been in existence for almost 20 years, with the time of commercial and scientific exploitation of the form structure now here. Hand-in-hand with this greater utilization is a need for greater CubeSat capability, with one important developmental area required being a propulsion system that is reliable, small and yet offers reasonable change in velocity capability to the satellite.

In the last five to ten years various CubeSat propulsion systems have become available. This includes cold gas thrusters [18,19] and chemical monopropellant systems [20,21], which offer relatively small change in velocities within the small CubeSat propellant tank constraints. Recently various electric propulsion systems have become available, including pulsed plasma thrusters [22,23], vacuum arc thrusters [24], gridded ion thrusters [25], and Hall Effect thrusters [26]. The latter two are of particular interest as they offer the higher specific impulse and therefore higher change in velocity abilities, but they do seem to be somewhat larger and need more power than what is possible in a small CubeSat structure (for example the BIT-3 gridded ion thruster developed for SLS CubeSat missions would seem to fit to a 2U structure with a power requirement of 55 – 75 W [25]). Field Emission Electric Propulsion (FEEP) [27] and micro-electrospray thrusters [14,28] have also recently been developed to flight or close to flight ready status. Both these systems offer high specific impulse, but within a small enough form structure and power requirement to fit within a 1 U CubeSat structure. It would seem that this may be the space that micro-electrospray thrusters offer; relatively high performance within the constraints of a 1U form structure, but at the penalty of a reduced thrust. For example the micro-electrospray thruster developed at MIT offers 11 – 12.5 μN in thrust, with a specific impulse at 760 seconds [14]. The emitters are manufactured by laser ablation of porous glass resulting in 480 emitters each 170 μm in height with the apex radii of approximately 15 μm. This results in a thrust per emitter of ~ 26 nN. This thrust per emitter can be compared to other larger emitter designs. For example the thrust per emitter from the Lisa Pathfinder micro-electrospray thruster can around 0.56 μN to 3.33 μN per emitter[29] from an emitter which is 10 μm in inner diameter. In this paper we investigate the use of larger emitters than the typical 10 μm diameter emitters utilized, under the hypothesis that a larger emitter will offer a greater thrust per emitter.

Another interesting and active area of research in micro-electrospray thrusters is the method of manufacturing the emitters. Many different techniques are currently being investigated, including microelectromechanical system (MEMS) methods [8], electrochemical etching [10], laser ablation [30], computer numerical control (CNC) machining [31] and additive manufacturing [17]. Unsurprisingly given the requirement to produce arrays of very small (10’s of μm) emitters, many of these manufacturing techniques are costly and expensive. Here though, given that the emitters being considered are somewhat larger, we have opted for CNC machining. This would seem to offer the ability to machine suitable emitters with enough precision to at least have a workable device [3], and is also relatively inexpensive.

This article is arranged in the following sections. Firstly, the emitters designed are presented, and the prototype thruster design described. Secondly, simulations of the emitter are presented. Based on their geometric settings, simulations of the onset voltage are presented. The onset voltage calculation is of particular importance as given the larger emitters (larger emitter diameters, larger emitter to extractor distances) considered here the applied voltage required for charged particle emission is likely significantly higher. Then the preliminary experimental results including time-of-flight are discussed.
II. Porous micro-electrospray thruster Design and manufacturing

A. Emitter Design

The emitter is made of porous glass of P4 grade with the nominal maximum pore size of 10-16 μm, while the reservoir is also a porous glass substrate at P0 to P3 grades with the nominal maximum pore size of 160-250 μm, 100-160 μm, 40-100 μm and 16-40 μm, respectively. The pore sizes of the porous glass material used as the reservoir are larger than that of the emitter, which can help to generate a Laplace pressure difference to transport liquid [15].

The whole emitter is a substrate with a needle, with the ‘walls’ on edges designed to control the distance between the emitter and the extractor during assembly. Five emitter substrates are designed with different geometries, including three pyramid-like emitters, and two spike-like emitters, as shown in Figure 1 (b). Each emitter has the same height of 5 mm but different side surface angle. This emitter size is considerably larger than typical micro-electrospray thruster emitters, but it is hypothesized that it may result in a greater thrust. Pyramid emitters have side angles of 10°, 20° and 30° and the spike-like emitters have approximate side angles of 10° and 20°.

There are multiple fabrication methods for electrospray thruster emitters. Recently Courtney et al. [3] have machined emitters with parallel prisms shapes using CNC machining, and in this paper we utilize the same technique for emitter fabrication. To achieve the pyramid shaped emitter, the milling cutter swept around the porous glass substrate in 50 μm vertical layers. The CNC milling cutter has a 3 mm diameter. It linearly moves at 2 perpendicularly directions on a plane. By carefully design the path, a pyramid shape can be formed. By using a milling cutter of 20˚ tapered angle, a pyramid shape emitter with 20˚ side wall angle is manufactured as shown in Figure 1 (c).

The tips of the emitters were characterised using a XYris 4000 CLx laser scanner with a scanning resolution of 2 μm developed by TaiCaan Technologies, as shown in Figure 2. The 50 μm high steps caused by CNC process can be clearly seen. The emitter tip curvature was calculated from this images and were found to range from 58 μm to 100 μm. From Figure 2 it is apparent that the emitter tips were far from perfect, but these geometries were good enough for initial testing. It should be noted that although the emitter was made of P4 grade porous glass with the nominal maximum pore size of 10-16 μm, the scanning results showed that the actual characteristic sizes of the surface microstructures were only several micrometers, which can be considered as the minimum Taylor cone base diameter at the emitter apex.

![Figure 1](image-url)

**Figure 1.** (a-b) CAD models of the manufactured pyramidal porous emitters with different tip shapes and surfaces side angles. (c) Example of manufactured emitter, manufactured from P4 sintered glass. For reference the edge length of these emitters is 30 mm.
B. Thruster design

The thruster design utilized is shown in Figure 3. The front-mount and back-mount were 3D-printed using FormLabs resin 3D printer. The extractor was made of a 0.25 mm thick stainless steel sheet by waterjet cutting, aligned to the emitter using an indentation in the 3D printed mount. The extractor has hundred apertures (to allow for array testing in the future) with the aperture diameter set to 1.5 mm. The extractor was situated 1.2 mm above the emitter tip.

A porous reservoir with larger pore sizes than the porous emitter is designed to combine with the porous emitter, and use the Laplace pressure difference these two substrates to transport propellant to the emitter [15,16]. A larger area ‘distal’ electrode was situated to the rear of the reservoir.

III. Simulations of the onset Voltage

The onset voltage is determined by multiple simulations. The electrospray process involves the particles emission from a Taylor cone [32] in a liquid state when applying a voltage between the conductive liquid surface and an external extractor. The surface of Taylor cone liquid experiences an equilibrium condition between the surface tension and the surface electrical stress as
where $\gamma$ is the liquid surface tension, $\beta$ is the Taylor cone half angle, $r_a$ is the Taylor cone apex radius, $\varepsilon_0$ is the permittivity of free space and $E_a$ is the electric field strength at Taylor cone apex. Therefore, stronger electric fields result in smaller liquid surface curvatures.

The onset voltage can be approximately theoretically calculated. But for a more accurate result Krpoun et al. [33], calculated the onset voltage by applying a set of sequentially smaller apex radii to by varying a Bernstein-Bézier curve which act to approximate the Taylor cone liquid meniscus [34]. When the apex curvature radius is reduced, the equilibrium voltage would firstly grow to generate the equilibrium electric field strength, meanwhile the sharp tip electric field enhancement effect also gets stronger. Therefore, the equilibrium voltage curve finally gets convergent to a value and stops growing with smaller apex curvature radius. This value is considered as the onset voltage. This calculated onset voltage value is dependent on many factors, such as the geometry of the emitter and extractor, including the distance between emitter and extractor and aperture size, and also the Taylor cone size which is related to the flowrate and emitter tip size.

The thruster studied in this simulation has a constant overall geometry using a cone-shaped emitter with a 5 mm height and 20˚ side surface angle, however, the size of Taylor cone at the emitter tip is not clear as the flowrate is passively controlled by the Laplace pressure difference between the porous reservoir and the porous emitter. Hence, the onset voltages of a set of different Taylor cone sizes of 20 μm, 10 μm, 5 μm, 2.5 μm and 1 μm are simulated and compared to the experimental onset voltage value, which can be used to determine the actual Taylor cone size range. It should be noted though that, for a porous emitter, when the applied voltage is increase above the onset voltage, multiple Taylor cones can be formed from both one emission point and also from multiple emission points.

The overall electric potential distribution near the emitter region with varying applied voltage is shown in Figure 4 (a), where Taylor cones with different sizes are placed on the apex of emitter. Figure 4 (b) illustrates the electric field at the tip with Taylor cone with a cone base radius of 10 μm present. Please note that the distance between the emitter apex and the extractor plane is 400 μm, which is shorter than that of 1.2±0.2 mm in the manufactured thruster.

Based on the onset voltage determination method by Krpoun et al. [33], the equilibrium voltage curves with Taylor cone apex radii are shown in Figure 5. For example, of the Taylor cone with the cone base radius of 10 μm, when the Taylor cone apex radius is smaller than ~1 μm the equilibrium voltage asymptotes to a constant value. Thus, this equilibrium voltage of 1760 V is considered as the onset voltage for this particular Taylor cone size. Based on the same method, the onset voltage of the Taylor cones with the base radii of 20 μm, 5 μm, 2.5 μm and 1 μm are 1550 V, 1950 V, 2500 V and 3800 V, respectively. For this emitter model, a larger Taylor cone would require less onset voltage. However, the electric field of a smaller Taylor cone is severely influenced by the nearby emitter geometry, leading to a higher onset voltage. These simulation results can be compared to the experimental result to give an idea of what the real Taylor cone’s size scale. However, it should be noted that these simulation results only gives a guidance on determining the emission Taylor cone size, but their values might vary from the actual onset voltage, mainly because the surface of the actual emitter has intricate microstructures that can work as electric field concentrators, and these
microstructures. In addition, the distance between the emitter and the extractor is 400 μm in these simulations while it is 1200±200 μm in the actual thruster, therefore the actual onset voltages would be higher than those in these curves.

![Graph](image-url)

**Figure 5.** Variation of equilibrium voltage with Taylor cone apex curvature radius, for different Taylor cone base radii of 20 μm, 10 μm, 5 μm, 2.5 μm and 1 μm, respectively.

### IV. Thruster Testing

#### A. Test environment and equipment

To remove dirt from the manufacturing process the emitters were soaked in deionized water and cleaned using an ultrasonic cleaner. Then, the porous substrates were put into a vacuum chamber where the pressure was decreased to 10\(^{-3}\) mbar, allowing the water left inside the porous substrates to vaporize. After the chamber was re-pressurized to atmospheric pressure, the porous substrates were soaked into a pre-degassed (i.e. water removed by putting ionic liquid in a vacuum chamber) ionic liquid bath, and then inserted in the same low pressure chamber again, allowing the ionic liquid to sufficiently fill into the porous material but without the absorbance of moisture. After re-pressurizing the chamber, these porous substrates were taken out from the bath. Any overflowing ionic liquid on the surface was wicked away using clean paper. These porous substrates were stored in sealed containers to avoid water vapour in the air being absorbing.

An illustration of the overall test facility is shown in Figure 6. The experiments were completed in a ~ 0.5 m diameter, 0.5 m long vacuum chamber within the Astronautics Group at the University of Southampton. The chamber is equipped with a turbo-pump allowing pressures of 10\(^{-7}\) mbar to be reached, although during thruster operation the chamber pressure increased to 10\(^{-6}\) – 10\(^{-5}\) mbar.
The thruster was first operated in the unipolar mode and then the bipolar mode, with in bipolar mode the applied voltage polarity periodically switched using a function generator and a house manufactured voltage switching unit. The current versus voltage (I-V) curves of the thruster were recorded using a downstream 10 cm × 10 cm planar collector connected to the monitor through a Femto DHPCA-100 current amplifier and a Pico-scope oscilloscope. It should be noted that this collector did not have a grid to suppress secondary electron emission. The voltage was applied to the emitter by DC power supplies including a HCP 350-12500 and two HCP 35-3500 from FuG Elektronik GmbH. The current was measured on the emitter and extractor by measuring the voltage drop across a 100kOhm resistor.

Following initial collection of I-V curves, the Time-of-flight (ToF) spectrometry system was set-up in the system to characterize the plume composition. The time-of-flight system consists of three 10 mm × 10 mm plates, with all plates having an aperture diameter of 25 mm. Gauze with 90% transparency was used to cover these apertures. The front and the back plates were kept grounded, while the middle plate can be applied with same potential of the emitter. A signal generator and a PVX-4140 pulse generator from Directed Energy Inc. was used to rapidly switch on the potential of the middle ToF gate within tens of nanoseconds. Those charged particles which already passed through the gate would continue to fly towards to the collector. The downstream collector in the ToF system was a stainless steel plate with the diameter of 27 mm and its front-side was covered by a second electron emission suppression grid. Thus the time when the current decreases on the collector indicates the flight time of different species. Based on the energy conservation, and assuming that the full voltage applied to the emitter accelerates the charged particles, the specific charges of those species can be calculated as

\[ \frac{q}{m} = \frac{1}{2} \frac{L^2}{V t^2}, \]  

(2)

where \(V\) is the applied voltage, \(t\) is the particle flight time and \(L\) is the distance between the ToF gates and the collector. This can then be utilized to find an approximation of the thrust and specific impulse, as long as the plume current is known. Note that the above equation is only correct when there is only one species in the plume. If there is more than one species then the specific impulse can be obtained by

\[ I_{sp} = \frac{L}{2g_0} \int_0^\infty \frac{I(t)}{t} dt, \]  

(3)

where \(g_0\) is standard gravitational acceleration at the Earth's surface and \(I(t)\) is the collector current over time. The thrust can also be calculated from the ToF trace.

\[ \text{Figure 6. Schematic of time-of-flight setup utilized.} \]
$T = \frac{2V}{L} \int_{0}^{\infty} I(t) \, dt.$ \hfill (4)

### B. Single emitter performance at the unipolar mode

For the first reference test, a spike-like P4 emitter with 10° side angle was tested without any reservoir at its back. The distance between the emitter and the extractor is about 1.2 mm, which was measured using an optical microscope. Voltages over 5000 V were applied between the emitter and the extractor, however, there was no obvious current readings from the collector.

The reason for this lack of spray was possibly due to there was no Laplace pressure difference to transport the propellant to emitter tip, which has been considered as a crucial influence factor for the performance of micro-electrospray thrusters using porous glass emitters [15,16]. Hence a P1 reservoir was added at emitter’s back. The voltage was still applied again in unipolar mode with the emitter being positive and the extractor being ground. This time, starting from +4200 V, the collector had continuous current readings, indicating the thruster was continuously emitting charged particles. However, the current value is not stable. Figure 7 (a) shows the emitter current change over time at 4200 V, starting from 100 s. From near 200 s to 400 s where an emitter current jump from 5 μA to nearly 50 μA can be seen, with the corresponding collector current also jumped from near 3 μA to 30-40 μA. After that the emitter current dropped down to about 10 μA, while the collector current is about 7 μA, accounting for 60% to 80% of the emitter current. The extractor current was around 0.01 μA throughout. Figure 7 (b) shows the emitter current changing over time with 4300 V applied, illustrating a large current increase and then a severe decay over time. After continuously operating at 4300 V for about 1000 s, the emitter and collector currents were almost zero. Afterwards, the electrical polarity was switched, the thruster did not work continuously and only random pulse emissions were detected. This indicated that the thruster stopped running and the emitter is potentially damaged during the continuous operation at positive polarity.

![Figure 7. Emitter current change over time at the applied voltage of (a) +4200 V and (b) +4300 V.](image)

Then, the other 10° side angle emitter is tested in a continuous operation while the voltage is changed over a short amount of time. Curves of emitter voltage over time, emitter current over time, and collector current over time is recorded in Figure 8. It can be found that the onset voltage is near 4300 V, which is similar to the previous emitter. Meanwhile, its offset voltage was about 1600 V which was much lower than the onset voltage. Collector data from 165 s to 200 s is lost as the readings were out of measurement range. There are 4 characteristic regions in this curve. From 200 s to 280 s, when the voltage was between 5000 V to 4000 V, it can be found that the emitter and collector currents were both extremely unstable. After that to 360 s, when the voltage was dropping from 4000 V to 3000 V, the emitter and collector current gradually dropped linearly. From 360 s to 455 s, when the voltage is between 3000 V to 2100 V, there was a stable region where the current barely varied with voltage and time. Afterwards, currents linearly dropped with the voltage until offset. It can be concluded that thruster operation at lower voltage is more stable than that at higher voltage.
After the both tests using the 10° side angle emitters, the emitters were visually examined. Dark brown and black colour occurred on the emitter tip and some regions near the tip, as shown in Figure 9 (a). These coloured matter can be cleaned and peeled-off in a deionized water bath using ultrasonic cleaning machine at 30°C for 2 hours, leaving a much less coloured tip. However, the geometry of the cleaned tip had noticeably changed, the tip was blunter and the emitter height was shorter (not shown). Thus, it can be inferred that the coloured matter might be the accumulation result of continuous electrochemical reaction products, and also that they mainly deposit

![Figure 8](image1.png)

Figure 8. Curves of emitter potential, emitter current and collector current changing over time, with varying emitter voltage. Note that between 165 s and 200 s, no collector current was collected.

![Figure 9](image2.png)

Figure 9. (a) The emitter after the 10 mins unipolar testing. Note blackened tip, and branch like structure at the tip. (b) The emitter after the 5 hours bipolar testing, with less blackened tip and no branching structure at the tip.
on the outside layer of the porous emitter. They were apparently detrimental for thruster operation as it can clog the flow path and lead to thruster failure. It should also be noted that newly formed radial branching structures were found at the emitter tip as a part of the black depositions, as shown Figure 9 (a). These branch like deposits have also been observed by Terhune et al. [35] and Lenguito et al. [36] on externally-wetted emitter and capillary emitter, respectively. They also probably help to explain the reason why spraying continued at lower emitter voltages, i.e. the offset voltage is smaller than the onset voltage, because the branching decreased the emitter to extractor distance and this resulted in a lower voltage needed for spray to occur.

C. Single emitter performance at the bipolar mode

Based on electrical double layer theory from Lozano et al. [37], periodically switching its electrical polarity at a reasonable frequency can help suppress the building-up of electrical double layer across the liquid-electrode interface. Therefore, in the next test the thruster was operated at a bipolar mode. The polarity switching frequency is an important factor in bipolar mode operation, apparently low frequency would lead to higher possibility of electrochemical reaction, while too high frequencies are not necessary and require more advanced switching equipment. Lozano et al. worked out that a bipolar frequency of 1 Hz is enough for a relatively small interface of a conductive tungsten emitter [37] and Krejci et al. [14] used 30 s as the switching period on a conductive porous reservoir which would have a relative large distal electrode surface area. In our initial bipolar trial tests using a nonconductive emitter material and a medium size planar distal electrode, the polarity switching frequency was selected to be 0.1 – 0.5 Hz. Using a P0 reservoir and the unused pyramid-shape emitter with 20° side surface angle and the tip curvature radius of 58 μm, the onset voltage was found to be 3200 V.

A typical bipolar waveform is shown as Figure 10 (a), its waveform does not look stable mainly because the collector data noise interfered the current data. At the bipolar mode of +3031 V and -3176 V with the polarity switching frequency of 0.1 Hz, the collector current was around ±10 μA while the emitter current was ±4 μA. Figure 10 (b) shows the stable collector current in 3.4 hours continuous operation of the overall 5 hours testing time, and no current decay was found in this duration. The emitter was visually checked after this 5 hours operation, the blackened black deposition was found to be much less than that after the unipolar operation (see Figure 9 (b)), and no branching microstructures were found at the emitter tip, indicating the electrochemical effects were significantly suppressed using bipolar mode.

Figure 10. (a) A typical collector current waveform at the bipolar mode of +3031 V and -3176 V. The polarity switching frequency was 0.1 Hz. (b) Collector current of the thruster operating for 3.4 hours with the overall testing time of 5 hours, and no current decay was found in this duration.

The current versus voltage curves of this thruster using a P4 porous glass emitter with a P0 porous glass reservoir behind operating in bipolar mode at the 0.5 Hz are shown in Figure 11. In general the onset voltage was found to be 3200 V. This onset voltage can be compared to the simulation results, suggesting that the Taylor cone is of the order of several micrometres in size. Given the same voltages at both polarities, it was found that the negative emission current was smaller than the positive emission current in all of our tests. This is probably because the required extraction energy for emitting negative species, e.g. BF₄⁻, was higher than that for positive species, e.g. EMI⁺. Thus, in order to keep the overall charge neutral at bipolar mode, the positive voltage was modulated with a higher negative
voltage by 50 $V$ to 150 $V$. However, unlike that in unipolar mode where the collector current accounts for 60% to 80% of emitter current, the collector current was found larger than the value of emitter current minus extractor current at every bipolar mode operations of this thruster, regardless of its applied voltage and polarity frequency (0.1 - 0.5 Hz), as shown in Figure 11. For example, at the applied voltage of 3300 $V$, the emitter current was 32.5 $\mu A$ and the extractor intercepted current was 11.7 $\mu A$, but the collector collected current was 45 $\mu A$. This may be due to secondary electron emission from the emitted particles colliding on the collector, however this was not found at unipolar mode. Another hypothesis of this effect is that the electrical polarity was switched before all the counter-ions reaching the distal electrode due to the high fluidic impedance of this thruster. This discrepancy will be further investigated in the next experiments.

Figure 11. I-V curves of the thruster using a P4 porous glass emitter and a P0 porous glass reservoir operating at the bipolar mode with a switching frequency of 0.5 Hz. Error bars are taken as 5% of the plotted values due to the current noises during the electrospray operation. (a) I-V curves of the emitter current and the extractor intercepted current. (b) I-V curves of the collector collected current.

D. Plume composition
In order to characterize the plume composition and calculate the thruster performance, a time-of-flight (ToF) spectrometry system was set up in the system. The distance between the ToF gates and the collector was 55 cm. A typical ToF trace while the thruster was operating at 3443 $V$ is shown in Figure 12 (a). The emitter used was pyramid-shaped with a 20˚ tapering angle, and was manufactured from P4 porous glass. A reservoir was used, made from a P3 substrate 3 mm thick. The ToF trace was collected with a positive voltage applied to the emitter, although the thruster was being sprayed in bipolar mode at the time, with the bipolar positive voltage at 3545 $V$.

The ToF trace experienced a large noise when the ToF voltage was switched on, covering the data from 0 to 7 $\mu s$. But the ToF trace with a time division of 40 $\mu s$ in Figure 12 (a) showed that a significant collector current drop occurred near 12 $\mu s$, and the ToF trace with a time division of 800 $\mu s$ in Figure 12 (b) suggested that no further collector current drop was found within 800 $\mu s$ after 12 $\mu s$, suggesting that all particles had reached the collector by 12 $\mu s$. The theoretical time-of-flight of the dimer (EMI-BF$_4$)EMI$^+$ can be calculated by

$$t = \sqrt{\frac{L^2 m}{2V q}},$$

where the mass of (EMI-BF$_4$)EMI$^+$ is 309 Da ($m = 5.13 \times 10^{-25} kg$), the electrical charge $q = 1.6 \times 10^{-19} C$, $L = 0.55 \ m$, $V = 3545 V$, thus its time-of-flight $t = 11.69 \mu s$, which agrees with the ToF trace decreased time around 12 $\mu s$ as shown in Figure 12 (a), indicating that the thruster was operated in PIR.
Figure 12. Typical ToF traces of the thruster operating at 3443 V using a P3 reservoir and the P4 emitter with a pyramid-shape and 20° side surface angle. The potential of the middle ToF gate was 3443 V. (a) A ToF trace a 40 μs time division showing a collector current drop near 12 μs. (b) A ToF trace a 800 μs time division showing no further change of collector current occurred within 800 μs.

It should be noted that the current value in ToF traces were smaller than the emission current as some of which were intercepted by the metal grids of ToF gates. Another test using a 10 cm × 10 cm square downstream collector which was 35 mm away from the thruster extractor showed that the emitter current was 38 μA, the extractor intercepted current was 12.7 μA and the collected emission current was 60 μA. Assuming all the emitted particles were the dimers of ions and the angular efficiency was 100%, the calculated thrust of this thruster at 3443 V was 8.91 μN, and the specific impulse was 4.722 s. At the lower collected current regime of 10 μA for 5 hours continuous operation at 3031 V, the thrust was calculated as 1.39 μN and the specific impulse was 4.431 s. This thrust per emitter from 1.39 μN to 8.91 μN is relatively large compared to other micro-electrospray thrusters, which generally have 0.03 μN [14] to 5.56 μN per emitter [3].

E. Plume angle

After continuously operating the thruster, a yellow imprint was noticeable on the. For the tests of these IV curves, the collector was placed 35 mm away from the thruster, thus by measuring the size of the particles collision prints, the plume half angle can be worked out from

$$\theta = \tan^{-1}\left(\frac{r_p}{d_{EC}}\right)$$

where $r_p$ is the radius of the collision print on the collector and $d_{EC}$ is the distance between the thruster extractor and the collector.
Two imprint examples are shown in Figure 13. Both thruster operations used a P0 reservoir. The left print was from the thruster using a pyramid-shape emitter with 10° side surface angle operating in unipolar mode with the voltage of 5000 V for 10 mins until the current decayed. The calculated plume full angle was 65.48°. The right image shows the imprint of the thruster operating in bipolar mode with +3031 V and -3176 V (i.e. approximately 2000 V below the previous example) applied for 5 hours, without obvious current decaying, and its plume full angle was 21.04°. Note that there is another larger bright (but not yellow) circle on the collector in this second image, it possibly indicates the plume angle of 60° when high voltages were applied at the beginning of this test. Although these two spray prints were obtained while the thruster operating at different modes, it gave a clear demonstration that the plume angle of micro-electrospray thrusters using porous emitters was strongly influenced by the applied voltage. Thus, theoretically, the minimum plume angle can be obtained while the thruster operating near onset and offset voltages, however, according to the I-V curves, the corresponding emitted currents were much lower than that at higher voltages, resulting in a lower thrust and specific impulse. In order to minimize plume angle as well as increase thrust, raising the onset voltage is a possible approach, which can be achieved by increasing the distance between the emitter and the extractor. This will be further investigated in the future work. However, it should be noted that the applied voltage should fit with the power system requirements of a CubeSat.

F. Manufacture of arrays
Following on from the relatively successful operation of a single emitter, small arrays have begun to be manufactured. The first of these to be finished is illustrated in Figure 14. In this case the array is 5×5, although 10×10 arrays are also being manufactured. The distance between these P5 emitters is 4 mm, and the emitter tapering angle is 10 degrees, whilst the emitters are 5 mm tall. Due to the proximity of the emitters the 2 mm diameter tool bit used for the single emitters could not be utilized, instead a highly tapering tool bit was used. The initial manufacturing of this array looks promising, and tests of it are planned in the near future.

V. Discussion
The time-of-flight test results showed that the plume composition likely consisted of solely ions with no droplets present. The reason for the lack of droplets may be due to a large hydraulic impedance of the emitter and reservoir. The thickness of the emitter substrate is 8 mm and the thickness of the porous reservoir is 3 mm, therefore their fluidic impedances were higher than those porous glass emitters previously made by Courtney et al. [15] and Krejci et al. [14], leading to a lower passive propellant flow rate that allows purely ionic emission.

The emission current of this single porous emitter reached from several μA to tens of μA or even hundreds of μA as the voltage was increased. Such current was particularly high compared to that from one emitter in other micro-electrospray thrusters, which is generally from 0.1 μA to 1 μA. This is suspected to result from the occurrence of multiple emission sites at the emitter apex. The lower flow rates resulted from the higher impedances allow the Taylor cones forming at a smaller scale. For example, from each pore on the emitter apex surface. With stronger electric field, more Taylor cones and emission sites were expected to occur from the microstructures on the emitter apex surface. Although the emitter was made of P4 grade porous glass with the nominal maximum pore size of 10-16 μm, the scanning results showed that the actual characteristic sizes of the surface microstructures were only several micrometers. For example, assuming the size of each emission site was 5 μm, their pitch distance was 20 μm, and there were 100 emission sites at the emitter apex with the current of each of 0.6 μA that contributed to an overall

Figure 14. 5×5 emitter array manufactured by CNC machining of porous glass.
emission current of 60 μA, the overall emission area would be 200 μm × 200 μm, which could occur on the emitter apex surface at 3443 V.

It should be noted that the emitter apex microstructure scanning results suggested that there were multiple 50 μm high round ‘steps’ resulted from the CNC machining processes. The edges of these steps were relatively sharp that could work as electric field concentrators with emission more likely to occur from these points.

Further evidence of multiple emission sites is the increase of plume angle with applied voltage. Because the trajectory direction of the charged particles were strongly influenced by the electric field gradient, which has a lateral component if the particles were released from side surfaces other than the emitter apex. As the voltage was increased, the increased plume angle suggests that some of the ions were released from sites on the emitter apex side surfaces, where the electric fields became strong enough for emission. Although it should be noted that the plume angle may also be influenced by the density of the emitted particles and space charge effect.

VI. Conclusions

A thruster using CNC machined porous emitters with single tip was then designed and tested. The CNC machining was low-cost and showed adequate manufacturing results. With the help of using time-of-flight spectrometry, the test results using these emitters showed that the thruster likely operated in a purely ionic regime, with the reason suspected to be that the fluidic impedance of this system was relatively high to effectively suppress the flow rates that were generated by Laplace pressure difference. The emission currents reached tens of μA, the calculated thrust reached several μN and the specific impulse exceeded 4000 s. Those relatively high emission currents were suspected resulted from multiple emission sites at the porous emitter tips. These test results also proved that the plume angle can be reduced by operating the thruster at lower voltages. In order to improve its thrust, three more emitters with multiplexed tips have been designed and are now being manufactured, with testing to be completed in the next few months.

References

38Rosell-Llompart, J. and De La Mora, J.F., “Generation of monodisperse droplets 0.3 to 4 μm in diameter from electriﬁed cone-jets of highly conducting and viscous liquids”, Journal of Aerosol Science, Vol. 25, No. 6, 1 Sep 1994, pp.1093-1119