Testing Of A Digital Colloid Thruster For Precise Thrust Throttling

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Mark D. Paine[*]
Queen Mary, University of London, London, E1 4NS, United Kingdom

Abstract: The concept of a Nanoelectrospray colloid thruster incorporating switchable clusters of emitters is presented for the provision of precisely throttled thrust over wide ranges. An incremental prototyping program is described wherein the underlying concepts are tested. Experiments to characterize the Nanoelectrospray from single emitters are described along with results showing a 6 times increase in current . Test results for a simple 4 emitter prototype that successfully demonstrated the concept of individually switchable emitters are shown. A recently fabricated 19-emitter prototype is also presented, which incorporates clusters of emitters that can be turned on independently, providing precise increments in thrust, without pumps or pressure regulation.

Nomenclature

I = current
K = conductivity of liquid
Q = volumetric flowrate
$<q/m>$ = mean specific charge
T = thrust
ρ = density of liquid

I. Introduction

ELECTROSPRAY as a source of charged particles for spacecraft propulsion was researched by several groups in the late 1960's and early seventies[1,2,3] and attained a fair level of maturity before the low thrust density was deemed impractical. Increased understanding of the electrospray process provided scaling laws[4] for the spray current and drop sizes leading to a renewed interest in electrospray use for colloid thrusters[5]. The increasing use of microspacecraft, particularly for science missions requiring very low thrust levels, has meant that the microNewton thrusts produced by colloid thrusters have become desirable. A colloid thruster system[6] is a candidate propulsion system for the Laser Interferometer Space Antenna (LISA) mission in 2012 and is due to be tested in 2007 by the ST-7 DRS mission aboard the LISA Pathfinder spacecraft[7]. The LISA mission requires 2-30µN thrusts with a resolution < 0.1µN and ground tests of the Busek system[6] show that it meets the requirements. It is this type of requirement for precision throttling of microNewton thrusts that the work described here is attempting to meet.

A. Current approaches to thrust throttling

In traditional electrospray liquid is fed through a nozzle at a flowrate fixed by a pump or by a regulated gas pressure head. However with this implementation problems exist with supplying liquid at the low flowrates required (typically less than 1nanolitre per second), since the use of pressurised systems or liquid pumps adds complexity, cost and mass to the thruster subsystem. To vary the thrust conventional colloid thrusters either vary the flowrate or

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[*] Lecturer in Aerospace Engineering, Engineering department, m.d.paine@qmul.ac.uk

alter the acceleration voltage neither of which are free from drawbacks. Increasing flowrate away from the minimum stable flowrate increases the size dispersion of the emitted droplets and reduces their specific charge; these factors cause a reduction in efficiency and specific impulse respectively. Increasing the acceleration voltage, besides the practical upper limits of high voltage, corresponds to an increase in the electrical power used. The extraction voltage can be used to vary the thrust on these Forced Flow electrosprays[8] and in fact this phenomena is more pronounced around the minimum, which is also the optimum, flowrate. However, the range of throttling by this method may be limited by the sudden onset of multiple jets and steps in current above a certain voltage.

B. Nanoelectrospray for colloid thrusters

A thruster using Nanoelectrospray could offer alternative methods of thrust control. Nanoelectrospray is widely used as an ionization source in mass spectrometry. It is generally implemented by injecting the liquid to be sprayed into glass capillaries pulled to a 1 to 2μm exit diameter[9,10], which offers considerable ease of use and inherently low flowrates in the nanoliter per minute range. A broad definition of Nanoelectrospray includes the optional use of pressurized gas to drive the liquid. However, the narrow definition employed here and throughout is when, neither liquid pumps or backing pressures are used, but instead, only the applied voltage is used to start and control the flow. This implementation offers many advantages to a colloid thruster. Indeed several research groups have already experimented with thruster configurations which would fit into this definition of Nanoelectrospray. The first of these was a slit thruster on which electrospray cones anchored on the ends of the fingers of a rake structure[11], however the majority of the work focussed on forced flow situations. A more recent investigation was into the use of externally wetted emitters, where ionic liquids were sprayed from the sharpened tip of a tungsten wire[12].

II. Digital Nanoelectrospray thruster

A. Concept

The long-term aim of this project is to microfabricate a large number array of Nanoelectrospray nozzles. The concept uses Nanoelectrospray combined with a digital approach to thrust provision with the hope of meeting a wide range of thrust throttling requirements with decreased system complexity but increased precision. The design concept uses nozzles suitable for Nanoelectrospray which are grouped together into clusters. Each cluster of emitters should be capable of being turned on independently of the surrounding clusters and produce a fixed minimum thrust level that is the same for each cluster, T_{min}. By turning on N number of clusters a thrust of $N.T_{min}$ would be produced permitting thrust throttling from T_{min} to some maximum determined by the total number of clusters making up the thruster. To achieve this each of the clusters must have some means of creating a localized electric field. There may also be wide scope for tailoring a thruster design to a particular mission, through flexibility with regards to the number of emitters in a cluster and the possible use of sub-clusters (e.g. 4 emitters) and super-clusters (e.g. hundreds of emitters) for small and large thrust increments respectively.

This concept is based upon a previously published design[13] which was microfabricated but tested unsuccessfully. However, that work showed the viability of microfabricating extraction electrodes capable of withstanding 3kV on the surface of a silicon substrate[14], which is one way of creating a localised electrostatic field. The other way is to electrically isolate each cluster from the others, necessitating a separate fuel plenum for each, and applying a potential to the plenums of those clusters we wish to turn on. This approach has already been used in the microfabricated electrospray nozzles that are commercially available for mass spectrometry[15], a more detailed explanation is given in the description of prototype 2.

Further possibility for thrust throttling lies in the ability of a Nanoelectrospray emitter to produce a wide range of currents, flowrates and therefore thrusts, by varying the applied voltage used for extraction. If the thrust produced by one cluster can be varied over the range T_{min} to $2*T_{min}$ then the precision of the thrust throttling is limited only by the accuracy of the voltage control. Potentially then this approach offers ultra-high precision thrust throttling over extremely wide ranges.

Large numbers of emitters are needed to produce thrust levels above ~10μN so several research groups worldwide have turned to the use of microfabrication techniques to produce arrays of electrospray nozzles[16,17,13,18]. Microfabrication allows nozzles with exit diameters as small as 3μm[13], as many as 20,000 emitters on a 75mm diameter disc[16], and complex hydraulic systems for flow control[17] to be produced. However, for all the benefits, the complexity of many microfabrication sequences (often hundreds of process steps are required) makes its use a costly and high-risk endeavour. Therefore the present work is focussed on the production and testing of a range of prototypes fabricated with conventional methods. The prototypes are on a rising slope of complexity each designed to test some critical aspect of this concept and showing an increase in the emitter number and density.

The prototype testing programme follows a sensible sequence of:

- single emitter characterisation
- small number array of individually addressable emitters (Prototype 1)
- small number array of individually addressable clusters (Prototype 2)

which, while cautious in its approach allows the optimisation of emitter choice, array element pitch, cluster size etc. The entirety of the work undertaken so far has been in atmospheric pressure air for the sake of simplicity. Clearly though any thruster must be tested in vacuum and the thrust measured directly. This work will be performed once the underlying principles of this concept have been tested.

B. Prototype testing

1. Single Nanoelectrospray emitters

Experiments to study the Nanoelectrospray process using water in atmosphere have provided some insight into how it differs from, and in what regards it is similar to, traditional forced flow electrospray. No complete theory exists for describing the Nanoelectrospray process. However, it has been proposed that the emitter geometry has a significant effect and that current scales roughly with applied voltage[9]. Simple experiments using single emitters allow the spray currents and operational conditions to be determined; this can give indications of the performance expected.

Often a particular liquid will spray very well with one particular type of nozzle but not at all if certain aspects of the nozzle geometry, for instance the internal diameter, is altered. For this reason a systematic investigation into Nanoelectrospray requires the use of emitters with carefully controlled geometries. The 1 to 2μm tips often used in mass spectrometry are made by either pulling apart a thin glass fibre or breaking it between tweezers. This process results in a rough and variable surface as illustrated in the S.E.M. image of such an emitter in Fig. 1. These emitters do not provide consistent performance as the electrospray cone anchors to various places in a seemingly random fashion.

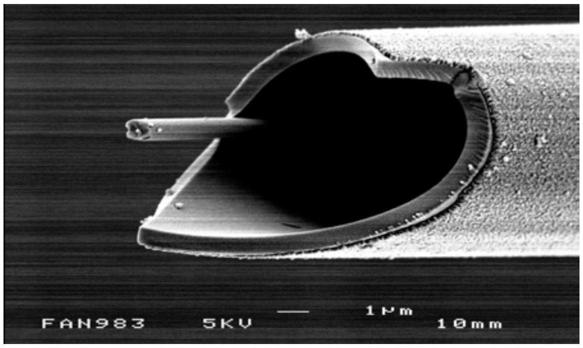


Figure 1. Scanning electron microscope image of a typical mass spectrometry emitter.

The results below were obtained using commercially available borosilicate glass electrospray tips chemically etched to a 4μm tip diameter and with an external metal coating [Offline Glasstips, New objective, MA], these have a well defined tip geometry. The liquid used was previously deionised water doped with NaI to different conductivities measured in-house using a novel triangular waveform method[19]. The emitter was held at ground potential 3mm away from an extracting planar electrode held at the applied voltage, V. Spray current was measured via a DMM across a 100kΩ resistor in series with the emitter. The effect of conductivity is shown in Fig. 2 where for higher conductivities the I vs. V slope increases. This is contrary to the prediction[9] of the spray current's independence from liquid conductivity. In Fig. 3 high resolution images of the electrospray cone jet show how the diameter of the jet increases as the applied voltage and hence the spray current increases. If Nanoelectrospray follows similar scaling laws[4] to forced flow electrospray, and it is difficult to see how it could differ so greatly, then an increase in jet diameter corresponds to an increase in flowrate. These images were taken using a 10x long working distance microscope lens and a 6.5x variable zoom on a CCD camera. All work in this programme uses high resolution video microscopy to monitor the tips as the spray regime cannot readily be determined by spray current alone.

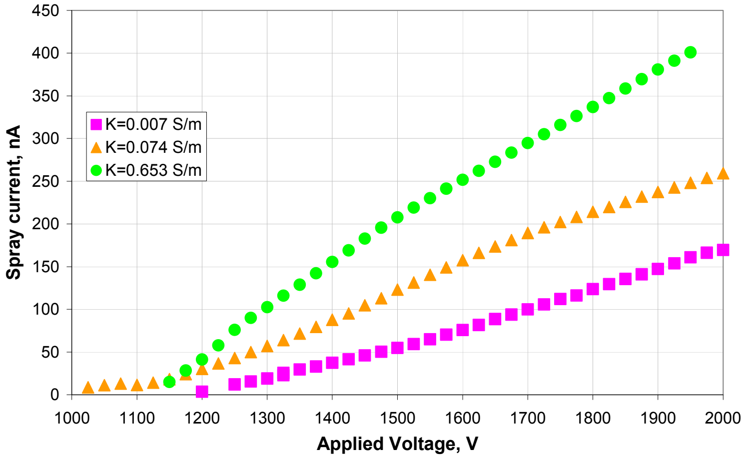


Figure 2. The effect of liquid conductivity on the I V slope in Nanoelectrospray

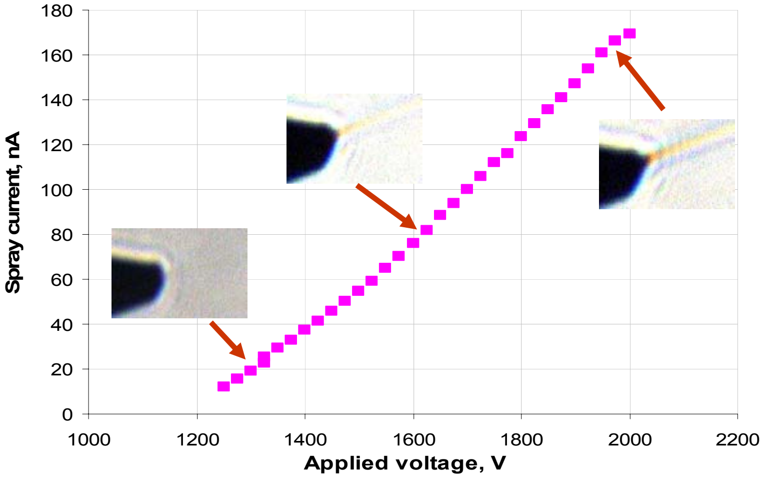


Figure 3: Increasing jet diameter associated with increasing current for water with K=0.007 S/m

So long as the spray stays in a stable spray mode the standard scaling laws of electrospray theory should apply; i.e. $I\ \alpha\ Q^{1/2}$ and $\langle q/m \rangle = I\ /\ \rho.Q$ for the droplets. Then, starting from the electrostatic thrust equation, substituting Q with I^2 and assuming that the spray current varies linearly with applied voltage, it can be shown that $T\ \alpha\ V^2$. For the data in Fig. 3 this suggests an increase in thrust of greater than 200% over the stable voltage range. Clearly, water solutions are unsuitable for space applications. Experiments using Triethylene glycol doped with NaI to 0.02S/m sprayed from a 4μm emitter produced more pronounced results. Figure 4 shows the linear effect of voltage on the spray current to hold over a 200% increase in voltage, if these assumptions do hold this would mean a 400% thrust

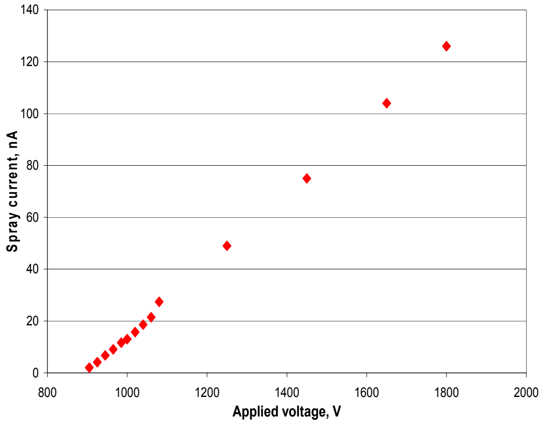


Figure 4. I vs. V for Triethylene Glycol doped to 0.02 S/m

increase. Additionally, the specific impulse will remain constant over the thrust range as the decrease in specific charge associated with increasing flowrate is offset by the increase in voltage.

2. *Individually addressable emitters*

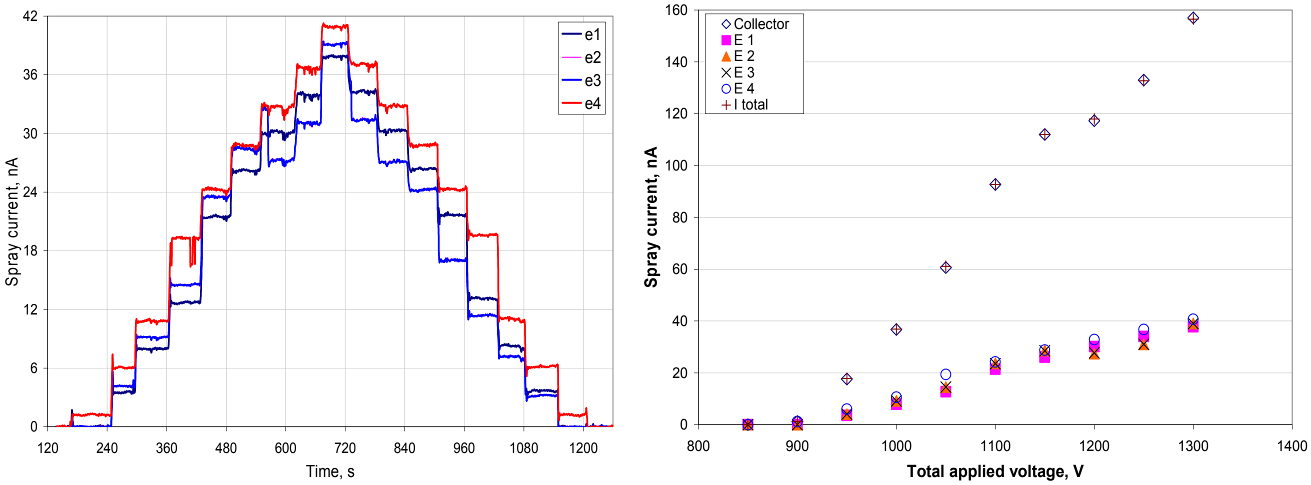
The next set of tests used a simple arrangement of four of the 4μm emitters, each of which is housed in a modified fluidic union. The union makes electrical contact with the emitter coating via a conducting ferrule and a 2mm screw contacts the rear of the union.

This prototype allows easy interchange of the emitters so that different liquids can be tested. The protrusion of each emitter can be easily modified under a video microscope to the same length. The emitters are 7mm apart in a square pattern and are insulated from each other by the polymer holder up to at least 300V. An applied potential difference of roughly 1kV is required to start the spray emission, the majority of which is provided by an extracting electrode held at -900V and placed 3mm away from the tips. Applying +100V to any emitter starts spray emission and 200V remains for voltage-controlled spray throttling. Restricting $V_{throttle}$ to < 300V allows the use of non-specialist electronics and prevents discharges.

Figure 5. The addressable emitter prototype.

An Agilent 34970A multiplexing and switching unit uses relays to switch the emitters between ground and $V_{throttle}$. The spray current for each emitter is then measured as the scanning multiplexer connects a DMM to measure the potential drop across a 100kΩ resistor wired in series with that emitter; this is done twice a second. The results of an experiment where all four emitters were filled with the 0.02 S/m TEG and connected to the same voltage is shown in Fig. 6. The voltage was stepped up or down by 50V on 60s intervals and each of the emitters shows a similar response both in time and magnitude of the spray currents.

Each of the emitters can be switched on or off at will using the switching relays and when this was performed the individual currents of each emitter added to the total current which matched that measured at the collector. An



(a) (b)

Figure 6. Current response of 4 emitters to 50V modifications of voltage, (a) as acquired, (b) current vs. voltage

earlier test of this prototype with a different set of nozzles revealed one emitter to be spraying intermittently and at much lower currents. This demonstrates the usefulness of monitoring individual emitter currents since it allowed the poor response of one of the emitters to be identified. Clearly it would not be possible to monitor the currents of each emitter on large number arrays, but it may be possible to monitor each of the clusters in later designs.

It is perhaps not surprising that the operation of one emitter had no effect on its neighbour as the pitch is so large and the space charge from these low currents is quite small, even in air. This situation may alter when the emitter spacing is reduced for later prototypes. Even so, the testing of this prototype usefully demonstrates the concept of turning on more emitters to obtain larger spray currents.

Further tests will be carried out to prove the wide-range, precise thrust throttling capability. This test will turn on one emitter and ramp from I_{min} (i.e. 20nA in Fig 6b) to $2*I_{min}$ using voltage, then turn switch both emitter 1 and 2 to I_{min} and ramp the second emitter up to twice I_{min}. Clearly then each with emitter turned on and ramped to $2*I_{min}$, this prototype would demonstrate a total range of I_{min} to $8*I_{min}$. With the use of higher voltage switching electronics the range could be extended and using the data of Fig. 4 the range for 4 emitters ramped from V=1050 to V=1800 would give a range of up to $24*I_{min}$. This test requires that a different $V_{throttle}$ is applied to each emitter.

3. Addressable cluster prototype

The next prototype increases the complexity further to test the concept of using clusters of emitters. The benefits of using clusters rather than a multitude of individually addressable single emitters are twofold. Firstly, grouping emitters together reduces the number of switches and current monitoring lines required. Secondly, since each addressable emitter or cluster requires its own insulated fuel plenum the packing density increases if emitters are clustered as much as possible. This is limited by the step size allowed in the thrusts and also because the failure of one emitter is more likely in a bigger number cluster and is less likely to be noticed.

This prototype marks an improvement in materials used as the thruster body is made of PEEK which can withstand high voltages and can be precision machined. The emitters used in the prototype are 360µm OD fused silica capillaries with a multi layer metal coating and protected by an external polymer [Online PicoTips, New Objective, MA]. These have a wide range of available tip diameters, from 5 to 30µm, allowing a thorough optimisation to be carried out. The prototype is shown in Fig. 7.

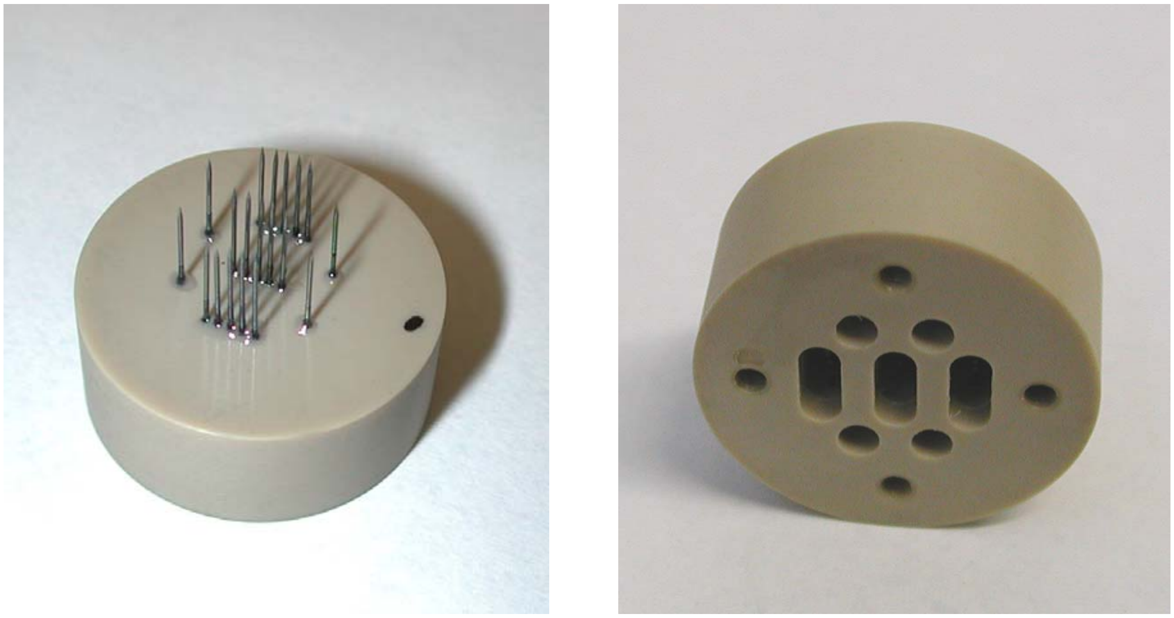
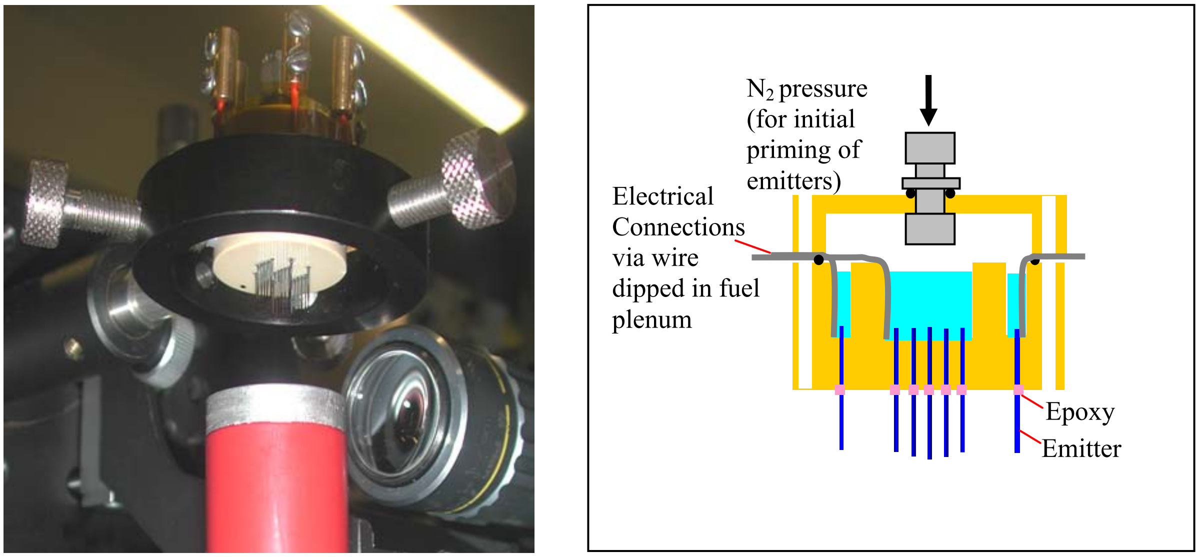

(a) (b)

Figure 7. Addressable cluster prototype. (a) Emitter arrangement, (b) Fuel plenum arrangement

The 19 emitters are arranged into 3 clusters of 5 emitters each, and 4 solo emitters as visible in Fig. 7a; each cluster and solo emitter has its own fuel plenum. The fuel plenums are 2mm wide and hold ~ 20 µL of liquid, they are visible in Fig. 7b. This arrangement demonstrates the idea of having sub clusters for small increments (in this case one emitter only) as well as larger clusters to reduce the number of switchable lines. The thrust can be incremented by the solo emitters from 1 to 4 units of thrust, then one of the 5 emitter cluster can be turned on and so on up to 19 units of thrust.

The fully assembled thruster is shown in testing in Fig. 8a. The schematic in Fig. 8b shows how the prototype functions, thin metallic wires are dipped into the conductive liquid stored in the fuel plenums, allowing electrical contact to each cluster/ solo emitter. This type of emitter can have a high hydraulic resistance and lack the ability of the offline emitters, used earlier, to wick liquid to the tip. Therefore before their first use gas pressure must be used to force the liquid to the emitter tip, after this the pressure is removed and true Nanoelectrospray can be performed. The emitters are positioned under a microscope to ensure consistent heights and then sealed into the 0.4mm hole entering the fuel plenum using epoxy resin on the front surface. The epoxy can be removed using solvents, allowing emitters to be replaced if blocked or broken, or if new geometries need to be tested.



(a) (b)

Figure 8. Prototype detail. (a) testing arrangement, (b) Schematic of prototype

The 5 emitters in Fig8b are shown arranged in a convex pattern, with the centre emitters protruding further than those to the sides. This is to allow investigations into the effect of emitter height, which can be varied, on the performance of the elements of a linear array. Work by other researchers[19,20,21] has shown that arrays often suffer from field shielding effects leading to those emitters in the centre having a lower field strength. By altering the proximity to the extractor this effect may be offset.

III. Conclusion

This work advocates a step by step approach towards an ambitious design goal. A digital Nanoelectrospray thruster offers the possibility of precise thrust control over wide ranges but requires several new approaches to be tested and the emitter/ fuel combinations to be carefully optimized. After this the fused silica emitters will be replaced by stainless steel emitters that have 50µm tips and 360µm OD, which are more robust. Once the concepts of thrust throttling, both by voltage and cluster switching, is proven, a more advanced prototype (though still conventionally manufactured) can be designed for proper performance testing. This testing will take place under vacuum conditions and with one of the high conductivity colloid propellants such as formamide or ionic liquids. Assumptions have been made in this work as to the likely thrust predicted on the basis of spray current. Until the thrust is measured in vacuum conditions these predictions should be treated with care. A paper detailing the flowrate measured in Nanoelectrospray emitters is in preparation, which will allow a more careful prediction of the thrust to be made. Work is being performed by colleagues in this department to carry out time of flight analysis on Nanoelectrospray emissions. It should be further noted that the concept need not be limited to a needle approach, the recent work[22] into spraying from holes in flat dielectric surfaces could also utilize this approach.

Acknowledgments

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