Performance Modulation of Colloid thrusters by the Variation of Flow rate with Applied Voltage

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The effect of voltage on flow rate within cone jet mode electrospraying has been investigated, with particular emphasis on the effect of emitter geometry. Using a high fidelity flow meter a set of experiments investigated the effect of the emitter geometry on the flow rate relationship to voltage, in cone jet mode electrospray. It is demonstrated that there are various parameters that influence the flow rate sensitivity to voltage, including the inner and outer diameter of the emitter, and the emitter to extractor distance. By a simple derivation, the latter two parameters relationship is explained by the variation of theoretical electric pressure with voltage, as the geometry is varied. The theoretical and experimental agreement has important implications for variable throttling of thrust in colloid thrusters, and could lead to the optimization or selection of a particular thrust variation.

Nomenclature

\[ a = \text{twice the distance from plane electrode to focus of hyperboloid} \]
\[ A_f = \text{corrective factor} \]
\[ E_0 = \text{electric field at emitter tip [V/m]} \]
\[ g = \text{gravitational constant} \]
\[ I_{sp} = \text{specific impulse} \]
\[ m_{pe} = \text{change of electric pressure with voltage in cone jet mode [Pa/V]} \]
\[ m_Q = \text{change of flow rate with voltage in cone jet mode [nL/s/kV]} \]
\[ P_E = \text{electric stress (pressure) [Pa/V]} \]
\[ Q = \text{Electrospray flow rate, in cone jet mode [nL/s]} \]
\[ r_e = \text{outer radius of emitter} \]
\[ R_T = \text{hydraulic resistance} \]
\[ T = \text{thrust} \]
\[ V_{acc} = \text{acceleration voltage} \]
\[ V_{AT} = \text{total acceleration voltage} \]
\[ V_{ext} = \text{applied extraction voltage} \]
\[ z_0 = \text{distance between extractor plate and emitter} \]
\[ \varepsilon_0 = \text{permittivity of free space} \]
\[ \eta = \text{extractor potential efficiency factor} \]
\[ \eta_0 = \text{hyperboloid surface chosen to represent the emitter} \]
\[ \phi_0 = \text{potential difference between emitter and extractor electrode} \]
\[ \rho = \text{density of propellant} \]

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I. Introduction

With the need for precise attitude control of some space missions, EP techniques that can be easily miniaturized have attracted more attention. Colloid thrusters are one such propulsive device, which rely upon the formation of charged particles by means of the electrospray process.

The concept of the colloid thruster was first realized in the early 1960’s, but consisted of conventionally fabricated systems that had a low thrust to mass ratio and relatively large power requirements. Such systems in the main employed doped glycol solutions as propellants, which resulted in low specific impulses, mitigated by the use of large voltages on the acceleration grids. Recently colloid thrusters have experienced a resurgence, thanks to the advent of appropriate micro-fabrication technologies and the use of ionic liquids as a propellant. These new systems exhibit potential performance parameters that appear highly competitive for many low thrust, high I_sp missions, where power is limited.

By the process of electrospray colloid thrusters can create a cloud of fine charged particles. An extraction grid at a high voltage removes the propellant from the end of an emitter. At the tip of the emitter a Taylor cone is formed, at the apex of which solvated ions are extracted. The ions move through an aperture in the extraction electrode, and are then accelerated by a secondary voltage grid. Typically the thrust produced from a single emitter is of the order of µN, whilst the specific impulse is the order of 1000s.

Work by Smith et al. revealed that the variation of the applied voltage can have a significant effect on the flow rate in electrospray, and have suggested that this flow rate sensitivity to voltage could be used to vary the thrust from a colloid thruster in a simple fashion. Smith et al. defined the change in flow rate with voltage in cone jet mode as:

\[
m_Q = \frac{\partial Q}{\partial V_{ext}} \mid_{\text{Cone jet mode}}
\]

where \( Q \) is the flow rate in cone jet mode, and \( V_{ext} \) is the applied extraction voltage. The results identified an increase of flow rate by up to ~45%, as the voltage was increased. The effect was found to be linear, and it was suggested that it would be more effective at varying thrust than increasing the voltage on the acceleration grid. By increasing the voltage the flow rate and thrust would increase, although it is coupled with a decrease in the specific impulse. In addition, on the basis of limited data it was suggested that this linear change of flow rate with voltage, identified as \( m_Q \), was dependent upon both the inner and outer diameter of the emitter.

Following on from these results a recently published study found \( m_Q \) to be effected by the ID and OD of the emitter, due to two separate effects. The effect of inner diameter was identified to result from the variation in the hydraulic resistance (\( R_T \)), with ID. In contrast, the effect of the OD on \( m_Q \) was attributed to the variation in the electric field sensitivity to voltage, with OD. Using a simple model for the electric field-to-voltage relationship, a strong agreement between theory and experiment was demonstrated. This theory further suggests that any significant variation of the geometry will affect the value of \( m_Q \).

This has consequences for the utilization of voltage modulation of flow rate in colloid thrusters. The geometry of the thruster will strongly affect the value of \( m_Q \), and could lead to a thruster being performance-variation optimized by altering its geometry. By numerically calculating the maximum electric field variation with voltage for certain thruster geometry, the variation of specific impulse and thrust can be calculated, leading to the design of a thruster for optimum performance variation.

These results are used to evaluate suitable thruster configurations to meet spacecraft requirements wherein thrust throttling may be used for mission objectives such as formation flying.

II. Experimental Method

The experiments were using the same equipment and method as reported previously. Three sets of experiments were completed; firstly varying the ID, secondly varying the OD, and thirdly varying extractor to emitter distance.

The emitter needle was held in a 1/16 in. stainless steel bulkhead union by a vespel ferrule, with 34mm of the emitter protruding from the steel union. For the ID and OD experiments the emitter tip was optically aligned 3mm above an extractor electrode, consisting of a 20 mm diameter stainless steel disk, with a 6mm diameter aperture. A second collector electrode was positioned below the extractor electrode, and both the collector electrode and emitter union were connected to ground. A negative voltage was applied to the extractor electrode, using a FUG HCL 14-6500 supply, with the output controlled by LabView software, via an NI USB-6008 DAQ card.
For experiments varying the emitter tip to extractor electrode distance, the emitter union was attached to a translation stage, which could then be adjusted to vary the distance to the extractor electrode.

The electrospray fluid was supplied to the emitter union from a fluid reservoir. All the experiments were completed at atmospheric conditions at both the emitter tip and reservoir, with any initial (nominal) flow rate being gravity fed. In-line between the reservoir and emitter was a high fidelity flow meter, capable of measuring down to picoliters per second; this has been described in detail and used previously. The liquid used was chosen to produce a large (and consequently undemanding to measure) change in flow rate with applied voltage. As this has been found to decrease with the hydraulic resistance of the system, the low viscosity solvent propylene carbonate was chosen. This solvent was doped with sodium iodide to a conductivity of $3 \times 10^{-3}$ S/m. We note that the low conductivity and vapour pressure, makes propylene carbonate would be unsuitable for real colloid thrusters, we are merely using this fluid for characterization processes. Indeed as previously reported the flow rate sensitivity to voltage was found to be independent of the type of liquid including its conductivity, it would seem that these tests should still provide an idea of the fundamental physics, which can then be applied to appropriate fluids in flight colloid thrusters.

## III. Experimental Results

Figures 1 through 3 illustrate the effect of geometry on the value of $m_Q$; specifically they illustrate the effect of ID, OD, and emitter tip to extractor distance, respectively. The results are the averaged over at least eight experiments, with the error bars being the determined standard deviation for the experimental data sets. From this data it is clear that the geometry of the system has the ability to vary the effect of voltage on flow rate in cone jet mode by an order of magnitude.
By taking the product of $m_Q$ with the hydraulic resistance $R_T$ of the entire emitter-reservoir system, it has been previously shown that the effect of the ID is removed\(^6\):

$$m_{\text{pe}} = m_Q R_T$$  \hspace{1cm} (2)

Here $m_{\text{pe}}$ is the linear change in electric pressure with applied voltage. Consequently using this approach the effect of hydraulic resistance is removed, and this is shown in Fig. 4. It is now apparent that $m_{\text{pe}}$ does not vary significantly with ID; we believe the slight change is most probably due to inaccuracies in calculating $R_T$.

Presenting the analysis in this way reveals that the ID of the emitter affects the value of $m_Q$ purely through the hydraulic resistance. There is however a second effect which would seem to show a variation of $m_Q$ with the other emitter geometry studied here as in Figures 2 - 3. A simple theory has been put forward to attempt to account for this second effect\(^6\), described in the next section.

**IV. Theoretical comparison**

Once the Laplace equation is solved in orthogonal coordinates (assuming hyperboloid geometry) and with suitable boundary conditions, the electric field at the tip of a Taylor cone-jet can be calculated\(^8,10\);

$$E_0 = -\frac{2 \phi_0 / a}{(1 - \eta_0^2) \log \left(\frac{1 + \eta_0}{1 - \eta_0}\right)}$$  \hspace{1cm} (3)

where $\phi_0$ is the potential difference between the emitter needle and the extractor electrode (taken as the onset voltage), $\eta_0$ the hyperboloid surface chosen to represent the emitter, and $a$ twice the distance from the plane electrode to the focus of the hyperboloid\(^8,11\):

$$a = \frac{z_0}{\eta_0} \quad \eta_0 = \frac{1}{\sqrt{1 + r_e / z_0}}$$  \hspace{1cm} (4a, b)

where $z_0$ is the distance between an emitter tip and the extractor plate, and $r_e$ is the outer radius. Loeb, and separately using the method of images Jones, simplified Equation (3) using the assumption $z_0 \gg r_e$, resulting in\(^{12,13}\):

$$E_0 = -\frac{\phi_0}{A_l r_e \ln \left(\frac{4z_0}{r_e}\right)}$$  \hspace{1cm} (5)

where $A_l$ is a constant of the order unity. Different authors have derived different values for $A_l$; Loeb finds a value of 0.707, whilst Jones derives 0.5. Here we will allow $A_l$ to be adjusted to fit theoretical to experimental data, as done previously when comparing theoretical to experimental cone jet onset voltages\(^{14}\).

Ignoring tangential terms, the electric stress can be given by;

$$P_e = \frac{1}{2} \epsilon_0 E_0^2$$

$$= \frac{1}{2} \epsilon_0 \left(\frac{\phi_0}{A_l r_e \ln \left(\frac{4z_0}{r_e}\right)}\right)^2$$  \hspace{1cm} (6a, b)

where $\epsilon_0$ the permittivity of a vacuum. Differentiating with respect to $\phi_0$ gives;
The thrust $T$ and specific impulse $I_{sp}$ for a colloid thruster can be given by:

$$T = \sqrt{2 \rho Q V_{AT}} \quad I_{sp} = T/Q \rho g$$  \hfill (8, 9)

where $\rho$ is the density of the ionic liquid, $I$ is the spray current, $V_{AT}$ is the total acceleration voltage and $g$ is the gravitational constant. The total acceleration potential is the sum of the extraction potential, $V_{ext}$ and the acceleration potential $V_{acc}$.

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stage potential $V_{acc}$. There is though a loss in potential due to the cone formation process, with the assumed total acceleration potential for this case is given by:

$$V_{AT} = \eta V_{ext} + V_{acc}$$  \hspace{1cm} (10)

with the efficiency factor $\eta$ taken to be 0.9$^{16}$. The current can be estimated from the experimental EMIBF$_4$ current-flow rate relationship found previously $^4$, $I$ (nA) = 1290$Q^{0.42}$. The onset cone jet flow rate is taken to be the theoretical minimum flow rate$^{17}$ for EMIBF$_4$, calculated to be 0.01 nL/s. The acceleration voltage used is 7500V, whilst the onset voltage is taken from R. Krpoun et al$^{18}$.

The preceding calculations result in an estimate of the thrust and specific impulse for this colloid thruster emitter geometry over an extraction voltage range, as shown in Fig. 7. The large theoretical value of $m_Q$ is used, which results in the thrust increasing by nearly two orders of magnitude. This though has the considerable negative effect of the specific impulse decreasing to what are probably unusable values. The theory outlined above though allows for the variation of $m_Q$ at the design stage. For example by increasing the resistance, possibly by inserting 5 micrometer beads into the emitter$^{19}$, the value of $m_Q$ can be decreased. Increasing the hydraulic resistance to $5 \times 10^{16}$ Ns$^{-5}$, comparable to an emitter ID of 8 micrometer, the $m_Q$ value would be adjusted to 0.42 nLs$^{-1}$kV$^{-1}$. This would lead to the variation of thrust and specific impulse as shown in Fig. 8. Here the variation is still considerable, but the change in specific impulse is perhaps acceptable.

We note that these thrust calculations have considerable uncertainty as a result of the current at the minimum flow rate and the potential for the system to operate in an ion mode rather than as here assumed a droplet mode. The theoretical evaluation does seem though to allow for the selection of $m_Q$ for a particular thruster. If the theoretical value is found to be too high, the thruster geometry can be varied at the design stage to reduce the value of $m_Q$. This can either be done by varying the OD or emitter to extractor distance, or if this is not possible due to manufacturing constraints, then the hydraulic resistance can be increased by varying the ID, or by inserting microbeads.

Finally, it can be expected that $m_Q$ will be varied by other geometry parameters not included in Eq. 7. The onset voltage is found to be effected by other parameters$^{18}$, for example the emitter length. As the theoretical analysis effectively uses the same electric field to voltage relationship as Eq. 7., it is reasonable to assume that the change of flowrate with voltage will vary with any significant geometry parameter.
V. Conclusions

It has been shown that the emitter and extractor geometry can significantly affect the change of flow rate with voltage in cone jet mode. The effect of inner diameter on $m_Q$ is shown to be a result of the hydraulic resistance, whilst the effect of the OD and emitter to extractor distance on $m_Q$ are due to changes in electric pressure with voltage. A theory is used to demonstrate this, with good agreement between theoretical and experimental results.

The change of flow rate with voltage for a typical colloid thruster emitter geometry is estimated using the theoretical method. The resulting value of $m_Q$ is large, suggesting that the change of flow rate with voltage is very significant. This though is an estimate, with further work needed to corroborate the result. It would though result in significant changes in thrust with extraction voltage, and if the simulation is proved correct it could be possible to choose a certain change in thrust in voltage at the colloid thruster design stage.

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References