Voltage Effects on the Volumetric Flow Rate and Thrust produced in Electrospray Propulsion Systems

IEPC-2005-087

Presented at the 29th International Electric Propulsion Conference, Princeton University,
October 31 – November 4, 2005

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The effect of extractor voltage on the propellant flow rate through an ES emitter has been determined for a tri-ethylene glycol sodium iodide solution using an in-line high accuracy flow measurement system. In these experiments a nominally fixed flow rate, obtained by providing a fixed supply pressure, is observed to be influenced by the applied voltage during electrospray production. The relative sensitivity of this 'nominal' flow rate to applied voltage was found to be higher as the nominal flow rate decreased. This volumetric flow rate sensitivity holds particular significance for colloidal ES thruster systems, which operate at or near minimum flow rate conditions.

Nomenclature

I	=	electrospray current
I_{sp}	=	specific impulse
$\dot{m}$	=	mass flow rate
P	=	pressure
q/m	=	charge to mass ratio
Q	=	volumetric flow rate
T	=	thrust
V	=	thruster acceleration voltage
ε	=	relative permitivity
ε_o	=	permittivity of vacuum
γ	=	surface tension
κ	=	fluid conductivity
μ	=	fluid viscosity
ρ	=	fluid density

I. Introduction

THE development of colloid thrusters for propulsive applications can be traced to the early 1960s[1,2,3]. They offer many desirable features when compared to other forms of propulsion, including high thrust density and low power demand. Early work on the development of working colloid thrusters in the 1960's and 1970's suffered and generally failed however, principally as a result of poor technical understanding of the physical elements underlying the electrospray process, and hence control of critical parameters including the charge to mass ratio of sprayed

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droplets. Later, an improved understanding of electrospray processes followed from the work by Fenn's group at Yale[4] during the 1980's, and from Fernandez de la Mora's work[5] during the early 1990's. There is now a broad characterization of the relationship between spray current, flow rate, the applied electric field and the charge to mass ratio (q/m) of the electrosprayed charged droplets during stable cone-jet operation, although these relationships are principally derived from electrospray systems operating into a gas at atmospheric pressure.

This improved understanding has led to renewed interest in colloid ES propulsion systems, principally focused on new space mission applications that require ultrafine thrust control for attitude control, drag-free flying and formation flying of microsatellites, such as the LISA mission. The low thrust level delivered by a single electrospray emitter, typically in the order of only 0.1µN, necessitates the use of large numbers of emitters if a sufficient level of thrust is to be obtained, to make such devices applicable to space missions. Present thruster design concepts commonly involve a number of discrete emitter arrays that can be operated individually to give a scalable thrust output[6], where the total thrust available is simply a function of the number of emitters[7]. The experimental work and results described in this paper aim to characterize the dependence of volumetric flow rate through the ES system on the applied extractor voltage. The variation in flow rate is related to changes in the thrust produced from a single ES emitter. The flow rate dependence on voltage will provide additional thrust control and scalability in colloid ES thruster systems and allow a reduced number of ES emitters within each array to satisfy the same mission thrust requirements.

II. Experimental Details

A. Electrospray Testing Rig

A schematic of the electrospray test system is shown in Fig. 1. The stainless steel capillaries used for comparison with the micro-emitters had an outer diameter of 560µm, inside diameter of 305µm and were mounted in a standard SGE Ltd ferule. The required electrostatic field at the emitter to achieve a stable Taylor cone-jet structure was obtained using a stainless steel extractor electrode, which was fixed at an appropriate distance from the emitter, typically 3-4mm. The extractor electrode had a 6mm diameter centralized circular hole, which was optically aligned on the axis of the emitter. A flat plate collector was positioned a further 7cm downstream from the extractor. The emitter/grid assembly was housed in a grounded stainless steel vacuum test chamber, shown in Fig. 1: this was evacuated down to pressures below 10^{-3} mbar during testing using a turbo molecular pump backed by a rotary vane pump (RVP). The currents on the emitter and extractor electrode were measured on-line by a custom built two stage, optically isolated system, which is described in detail elsewhere[8]. This approach safely converted the signal from high voltage to a data logger at ground potential, which is then directly and safely interfaced with a PC for data collection and storage. This system was designed to measure currents up to ±2µA, with a voltage response of ~1mV/nA and a time response of 1s. The current at the flat plate or faraday cup collector was monitored using a Keithley Instruments pico-ammeter model 486, which was not interfaced to a data logging computer. A CCD camera with zoom lens was used to confirm the cone-jet mode of operation.

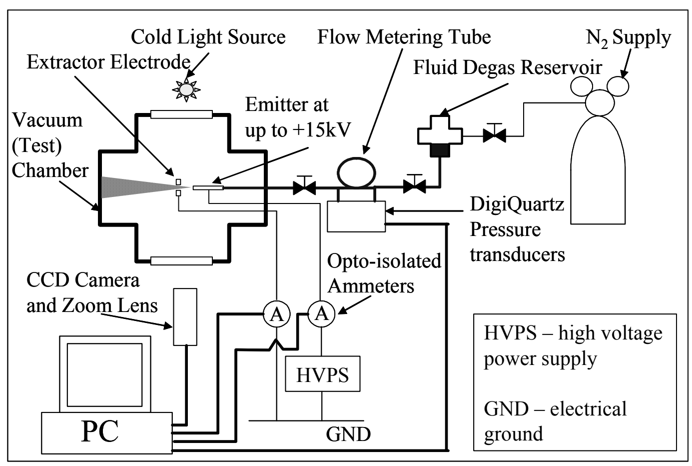

Figure 1. Electrospray experimental arrangement.

B. Fluid Reservoir and Feed System

A DN40 four-way cross from Caburn MDC was used as the fluid reservoir. An RVP connected to one arm of the cross enabled evacuation of the reservoir to allow propellant fluids to be degassed. An inlet on the opposing arm allowed the reservoir to be pressurized to an atmosphere with dry N_2. The pressure in the reservoir was monitored using a Bourdon gauge attached via a T-piece to the same arm as the RVP. An outlet valve on the base of the reservoir was attached to a capillary feed system, which allowed introduction of the fluid to the flow measurement system and into the spray chamber.

C. In-Line Flow Rate Measurement

The in-line flow rate measurement was achieved by measuring the pressure drop, within a limited section of the fluid feed pipe-work, using a pair of Paroscientific Digiquartz 740-23A quartz crystal pressure transducers. This pressure drop, ΔP, is directly proportional to the volumetric flow rate Q as described by the Poiseuille equation

$$Q = \frac{\Delta P \pi R^4}{8 \mu L} = \frac{\dot{m}}{\rho} \tag{1}$$

Where $\dot{m}$ is the mass flow rate, ρ is the fluid density, μ is the fluid viscosity, R is the internal radius of the pipe section and ΔP is the pressure change along length L of the pipe. A detailed description of the instrument is provided in Smith[9]. The dimensions of the measurement section of the pipe-work could be tailored to give the desired sensitivity and the setup used in the present work was designed to give a flow rate resolution of 0.001nL/s.

D. High Voltage Power Supply

The high voltage power supply (HVPS) used was a HCL 14-20000 from F.u.G. Electronik. For electrospray testing the power supply negative terminal was connected to the extractor grid to give extractor voltages up to 15kV.

E. Electrospray Solutions

The triethylene glycol (TEG) and sodium iodide (NaI) used in the present work were supplied by Sigma-Aldrich and were purchased as Analar grade reagents. A TEG solution containing 12.5g/L NaI was prepared under a dry nitrogen atmosphere within a dry box to prevent absorption of water. The TEG solution had a conductivity of 0.01S/m.

III. Results and Discussion

The advantage of an in-line flow rate measurement system is that the absolute flow rate through the ES system can be monitored during stable cone-jet operation. This allowed changes in the flow rate due to variation of applied extraction voltage to be accurately measured and characterized. An example of the effect of voltage on the flow rate for the TEG solution is illustrated in Fig. 2. As the extractor voltage was increased, the onset of stable cone-jet mode electrospray was observed at 2.8kV. As the voltage was increased beyond onset the flow rate was found to increase in a linear manner, as indicated by the linear regression line included in Fig. 2. Further increases in voltage beyond 4.2kV resulted in transition to a multi-jet mode. From the graph in Fig 2, the slope d{Q}/d{kV} at the nominal flow rate, Q_{nom}, of 22.9nL/s is 0.46, which is comparable to previous reported data from our own group[10] where d{Q}/d{kV} values of between 0.28 and 0.82 nL/s per kV were found for TEG solutions with conductivity ranging from 0.0025 to 0.016S/m. Similar trends of increasing flow rate with voltage were observed at each nominal flow rate

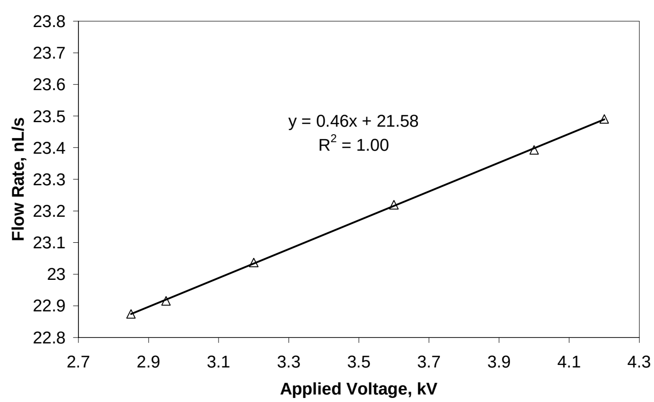

Figure 2. Effect of Voltage on Flow Rate for TEG Solutions (κ=0.01S/m)

tested and the sensitivity of flow rate to voltage, d{Q}/d{kV} remained largely independent of Q_{nom} at a value of ~ 0.45. To quantify the influence of Q_{nom}, the slopes d{Q}/d{kV} are plotted in Fig. 3 as the percentage of the Q_{nom} at which each data set were taken. From the plot, the %slope d{Q}/d{kV} follows a power law dependence on Q_{nom} with an exponent value of -0.993. Also shown in the figure is the steep increase in relative flow rate sensitivity as the value of Q_{nom} decreases. Clearly, with a constant d{Q}/d{kV} the increase in the flow rate relative to Q_{nom} is most significant at the minimum flow rate possible for stable cone-jet operation, Q_{min}. Using the expression derived by Fernandez de la Mora[5] for the minimum flow rate

$$Q_{\min} = \frac{\gamma \varepsilon \varepsilon_o}{\rho \kappa} \tag{2}$$

where γ is the surface tension, ε is the relative permittivity of the propellant, ε_o is the permittivity of a vacuum and κ is the propellant conductivity. For the TEG solution used in the present work the value of Q_{min} is predicted to be 0.74nL/s. For this value of flow rate, if we interpolate using the power law relationship from Fig. 3, the percentage increase in Q relative to Q_{nom} would be ~59% for each kV increase in extractor voltage. Indicating that for the present system, in the absence of a dedicated flow pumping device, the flow rate may be increased by almost 60% due solely to changes in the applied extractor voltage.

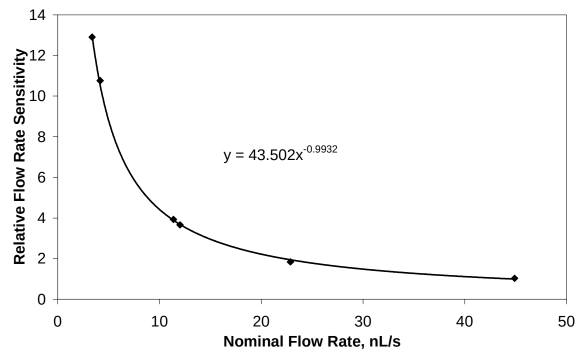

Figure 3. Variation of Relative Flow Rate Sensitivity with Nominal Flow Rate Q_{nom} for TEG Solution

For colloid ES thruster applications, operation near Q_{min} is desirable as the specific impulse of the thruster will be highest at Q_{min}. With the flow rate sensitivity to voltage also highest at Q_{min}, these findings are of particular importance to colloid ES thruster development. To investigate the influence of the flow rate voltage sensitivity on the thrust produced from an ES emitter, it was first necessary to determine the spray current, I, flow rate scaling behavior. For the TEG fluid used in the present work, the spray current flow rate scaling was found to follow a power law relationship where I (nA) = $70.04Q^{0.427}$, when Q is in nL/s. From this spray current data the average charge to mass ratio (q/m) can be calculated from

$$\frac{q}{\dot{m}} = \frac{I}{Q\rho} \tag{3}$$

where $\dot{m}$ is the mass flow rate of propellant. The expected thrust *T* produced from electrosprayed droplets is also dependent on the net acceleration voltage *V*, and can be calculated from

$$T = \rho Q \left(2V.\frac{q}{m}\right)^{0.5} \tag{4}$$

To evaluate the variation in thrust from a colloidal ES thruster device incorporating voltage control of the flow rate, it is assumed that the potential between the emitter and the extractor voltage is varied from 2 to 3kV while the accelerator electrode is held at a constant 7.5 kV relative to the extractor potential, this provides an overall acceleration voltage of around 10kV. The variation of thrust, *T*, produced from this device with changes in extractor voltage is shown in Fig. 4. From the plot, the flow rate increases by around 59% as a result of the 1kV rise in extractor voltage while the thrust produced increases by ~46% from 1.01 to 1.48μN. To achieve the same level of thrust increase in the absence of voltage control of the flow rate, with a fixed extractor voltage of 2kV and a propellant feed system actively controlled to provide a flow rate of Q_{min}, the acceleration voltage would need to be increased from 10kV to 21.2kV. The kinetic power of the variable flow rate system at maximum thrust is 0.75mW per emitter. The alternative constant control of flow rate approach results in a 74% increase in power required to produce the equivalent level of thrust. However, the thrust improvement in the flow rate modulated system is accompanied by a 12% fall in specific impulse, I_{sp}, whereas an increase in I_{sp} of 46% is produced due to increasing accelerator voltage in the system without flow rate control.

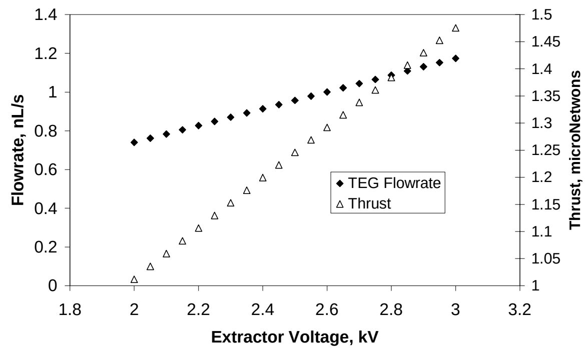

Figure 4. Effect of Extractor Voltage on Flow Rate and Thrust for TEG solution

IV. Conclusion

The variation in extractor voltage has been shown to afford considerable control over flow rate through the ES emitter. In turn, this variable flow rate allows precision control over the thrust produced from a colloid ES thruster with low power demand and without the need for a dedicated pumping device. This form of control provides a simpler approach to the modulation of thrust from a colloid ES propulsion system, rather than direct control of the flow rate. This study of flow rate sensitivity to voltage needs further expansion. In particular the fluid we have adopted here is not well suited to a realistic colloid electrospray thruster due to the inherent low charge to mass ratio for solutions of this low conductivity. It would be appropriate therefore to include in a future study, a broader range of propellant systems and nozzle dimensions to fully understand the influence of electric stress on fluid flow through a cone-jet system. Our current programme includes such a study, particularly evaluating the response of ionic liquid propellants.

Acknowledgments

The authors with to acknowledge the support of EPSRC grants GR/R21936 and GR/R21943 and also the support from the Research Councils UK under the Basic Technology Research Programme

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