A Novel Variable Mode Emitter for Electrospray Thrusters

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A novel geometry of electrospray emitter has been developed for achieving dual-mode propulsion. The hybrid emitter consists of a capillary emitter with a protruding, coaxial needle. This design takes advantage of the natural increase in specific charge of emission as current decreases to produce high specific impulse operation at low flow rate and high thrust-to-power operation at high flow rate. A needle in the center of a capillary emitter promotes stable emission at low flow rate in an externally-wetted emission mode. When flow rate is increased, the meniscus extends past the needle to emit in a capillary or cone-jet mode. The emitter has produced emission at roughly 2 nA and 360 to 430 nA for externally-wetted and capillary modes respectively. Representative images of each emission mode were obtained from video microscopy of the emitter in operation. Analyses of these visualizations and collected emission current data show that the hybrid emitter exhibits two distinct stability regions for high and low flow rates and allow for the characterization of instabilities outside these regions.

Nomenclature

d	= emitter to extractor offset
I	= current
K	= conductivity
m	= mass
$\dot{m}$	= mass flow rate
P	= power
q	= charge
Q	= volumetric flow rate
R	= emitter radius
T	= thrust
V	= voltage
γ	= surface tension
ϵ	= relative permittivity
ϵ_0	= vacuum permittivity
η	= thrust efficiency
θ_T	= Taylor cone half angle, 49.3°
ρ	= density

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I. Introduction

Electrospray emitters use a conductive liquid to produce an electrified meniscus from which charged droplets and/or ions are emitted. Electrostatic stress and capillary pressure are in equilibrium along the meniscus, naturally forming a cone-like fluid volume. At the tip of the cone, the electrostatic stress overcomes capillary pressure to form a fine, highly accelerated jet. If the electric stress is sufficiently strong, it can overcome intermolecular forces to emit ions from the free surface. Additionally, electrospray propulsion can achieve high efficiency operation due to the pre-ionized state of the ionic liquids, which are typically used as propellant. On the contrary, electrospray devices are susceptible to unstable emission modes when operated at off-nominal flow rates or extraction voltages. Whether a capillary, porous media, or externally-wetted surface is used to form an electrospray, the emitter geometry is selected to produce the desired performance. Ionic liquid electrospray thrusters are unique in that they have been developed over a wide range of specific impulse: from 200 s for the Colloid MicroNewton Thruster (CMNT)[1] to nearly 5000 s for porous emitters.[2] A single electrospray device that can operate over this large performance range however remains elusive.

The objective of this project is to develop an electrospray thruster capable of both a high specific impulse mode and a high thrust-to-power mode at separate operating conditions. To achieve this goal, we have developed a new electrospray emitter geometry capable of operating stably over a wide range of flow rates.

II. Background

Early electrospray experiments utilized capillary emitters, where small diameter tubing encloses a pressure driven flow of propellant to an emission site. This type of emitter was used on the CMNT.[1,3] The specific impulse of the CMNT is low, but its stable emission makes it suitable for high-precision thrust applications. Due to the low specific charge and pre-ionized state of ionic liquids, the thrust-to-power ratio of capillary emitters is very high.

In contrast, externally-wetted tungsten needles have a robust history of producing high specific impulse, ion-mode emission in a laboratory setting.[4,5] Propellant flows from a reservoir to the emission site due to the reduced pressure at the emission site because of electric stress. Flow is restricted by the viscosity of the fluid.[5] The development of externally-wetted electrospray thrusters[6] has been limited outside of Field Emission Electric Propulsion (FEEP) applications.

Dual-mode propulsion describes the use of a propulsion system operating on a single propellant supply to offer both high specific impulse and high thrust operating modes.[7] Dual-mode systems have been envisioned using electrospray propulsion for the high specific impulse component and cold gas thrusters[8] or monopropellant rockets[9] for the high thrust component. Having the ability to operate in both modes allows for greater flexibility in the usage of the device, allowing for increased trajectory optimization and/or drastic changes to a mission, even after launch.[10,11]

De la Mora showed that the emission current of an electrospray is proportional to the square root of flow rate for an electrospray. An important result of this relation is that the average specific charge of emitted species, q/m, increases as the mass flow rate, $\dot{m}$, decreases, as follows:[12]

$$\frac{q}{m} = F(\epsilon)\left(\frac{\gamma K}{\rho \dot{m}}\right)^{1/2} \tag{1}$$

where $F(\epsilon)$ is a function of the propellant permittivity, γ is the propellant surface tension, K is the propellant conductivity, and ρ is the propellant density. Thus, in order to reach high specific impulse operation without changing propellant properties, the flow rate must be decreased to achieve high specific charge emission. In contrast, the thrust-to-power ratio, T/P, has the opposite trend when varying specific charge:

$$\frac{T}{P} = \eta\sqrt{\frac{2}{V}\frac{m}{q}} \tag{2}$$

where η is the thruster efficiency, V is the emitter voltage. As a result, an electrospray emitter capable of operating in a high thrust-to-power mode and a high specific impulse mode simply requires operation at high and low flow rates respectively. The main challenge, however, is maintaining stable operation over drastic changes in flow rate. When operating at off-nominal flow rates and voltages, capillary emitters will exhibit pulsating and/or off-axis emission.[13] To address these challenges, the stable operating region may be modified by altering propellant properties.[14,15] Additionally, more complicated emitter geometries have been used to produce electrospray devices with expanded stable emission regions.[16] The flow rate to externally-wetted emitters is often controlled by varying the propellant viscosity by heating, and as such have a narrow range in operational flow rate without multiplexing emission sites.

The startup voltage for an electrospray device, V_{start}, was approximated by solving for the electric field produced on the surface of a charged, semi-infinite cylinder near an infinite plane. The startup condition is reached when the electric pressure on the tip of the cylinder balances with capillary pressure, as follows:[17,18]

$$V_{start} = \sqrt{\frac{\gamma R \cos\theta_T}{2\epsilon_0}} \ln\left(\frac{4d}{R}\right) \tag{3}$$

where R is the emitter radius, θ_T is the Taylor cone angle, ϵ_0 is the vacuum permittivity, and d is the emitter-extractor offset. When applying an extraction voltage below this threshold, propellant supplied to the emission surface will accumulate, drip, or spray in a pulsating mode from the emitter.[17] Unstable operating modes such as these may degrade thruster performance and lifetime.[19]

III. Hybrid Emitter Design

In the Plasma & Space Propulsion Laboratory at UCLA,[20] a hybrid emitter design has been developed to incorporate emitter geometries that enable both high thrust-to-power and high specific impulse operation separately. The addition of a needle to a capillary emitter assembly allows for the hybrid emitter to operate in both an externally-wetted operating mode and a capillary emission mode. When operated at low flow rate, the needle provides an electric field concentration point. Electric stress pulls propellant from the capillary in the same way that propellant is pulled from a reservoir for a traditional externally-wetted emitter. While operating at high flow rate, the meniscus of the cone extends past the needle, suppressing its effect on emission. The meniscus can form a stable cone-like shape associated with emission due to pressurized flow from a capillary. Representative diagrams of the hybrid emitter in these operating modes can be seen in Fig. 1. These two modes will be referred to as externally-wetted and capillary emission modes in the following sections.

IV. Experimental Setup

The hybrid electrospray emitter was tested in vacuum in the UCLA Highly Optimizable Apparatus for Groundbreaking Investigation of Electrosprays (HOAGIE) test facility, which includes a pressurized feed system for precision flow rate control, integrated propellant degassing, and an advanced diagnostics

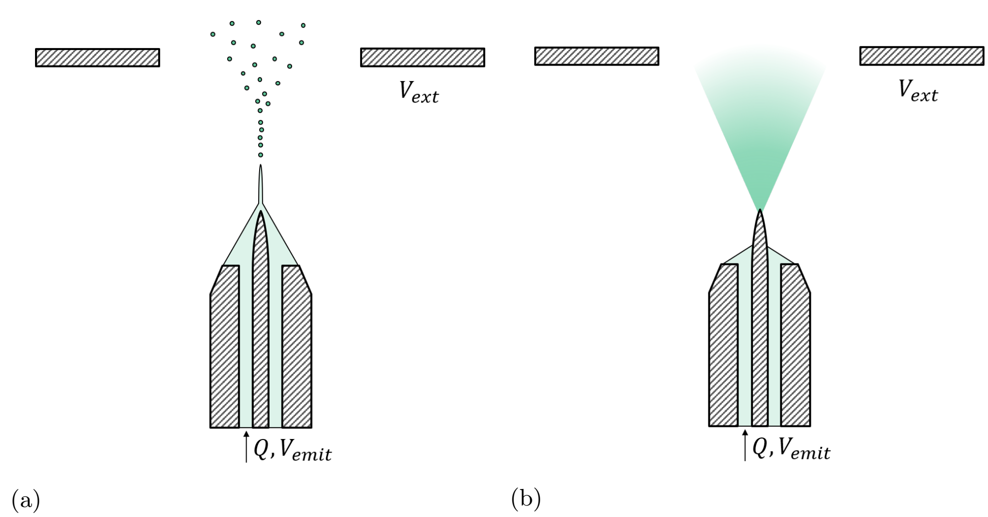
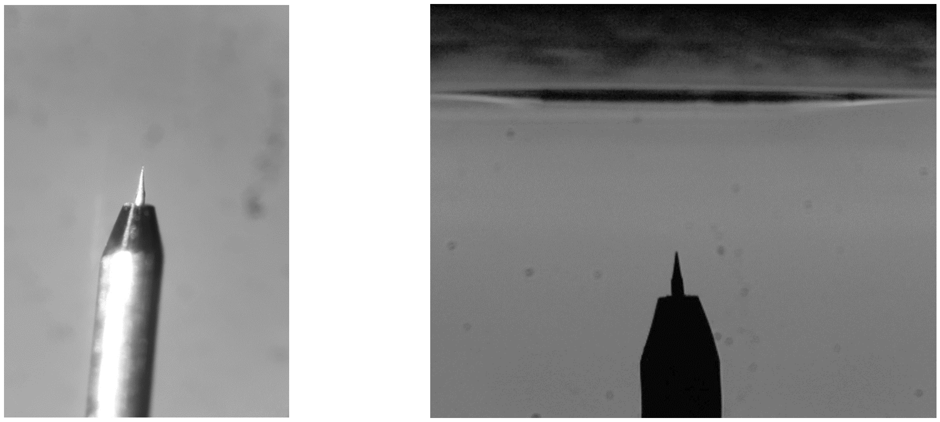


Figure 1: The hybrid emitter with an externally-wetted needle located coaxially in a capillary emitter. The emitter is operated at (a) high flow rate to form a cone-jet emission site staked to the capillary and (b) low flow rate to stake the meniscus to the needle for high specific charge emission.



(a) (b)

Figure 2: Hybrid emitter, (a) shown with 320 µm outer diameter stainless steel capillary and 61 µm diameter needle, and (b) in situ with an extractor electrode.

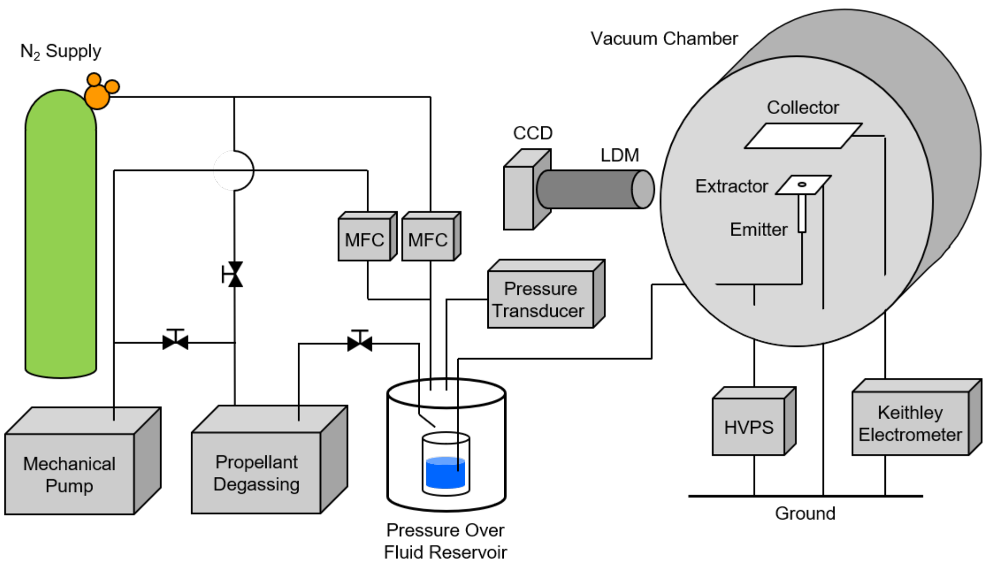
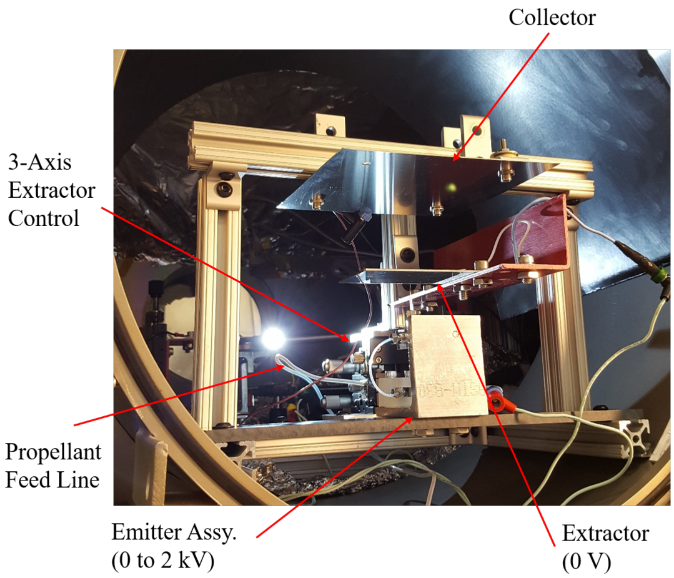


Figure 3: Electrospray experimental apparatus.

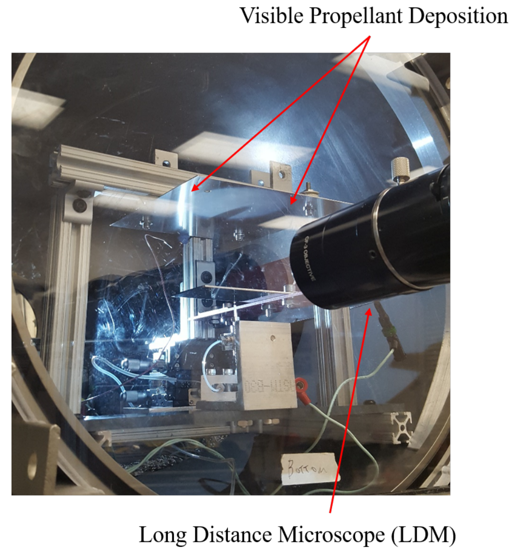
suite. The pressurized feed system is controlled by two mass flow controllers (MFC). The HOAGIE system and capabilities are described in detail by Wirz *et al.*,[21] whereas the specific configuration used for the presented experimental effort is shown in Fig. 3. EMI-Im was used as a propellant throughout the presented experimental effort.

The emitter consists of a chamfered stainless steel capillary (SIS Metal TaperTip electrospray emitter) and 61 µm diameter tungsten wire. The tungsten wire was electrochemically-etched to a sharp tip, as described by Brady.[22] The etching procedure was modified by using a short immersion depth to create a short needle taper length. Concentricity of the needle in the capillary is crucial for successful operation and is achieved by hand. Prior to experimentation, the hydraulic resistance of the emitter was measured using a mass flow controller; the hydraulic resistance was used for calibrating the pressurized feed system to estimate the flow rate to the emitter. The emitter geometry used in this experiment is shown in Fig. 2b. Equation 3 predicts startup voltages of 1300 V for emission from the capillary and approximately 300 V for externally-wetted emission from the needle. The decreased startup voltage for emission from the needle is due to the decreased offset to the extractor and increased sharpness compared to the capillary.

The experimental setup used in vacuum is shown in Fig. 4. A stainless steel extractor was made with



(a)



(b)

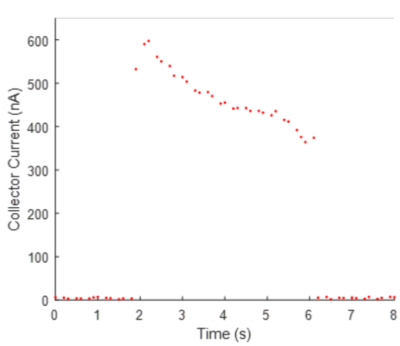
Figure 4: Experimental setup: (a) before testing and (b) after testing in vacuum.

a 1.3 mm aperture and a 300 µm thickness for this experiment. A 15 by 15 cm plate of stainless steel was used as the collector plate, placed at 6.4 cm above the extractor. The collector was held at ground potential while measuring the current using an electrometer. Results for collector current have their polarity reversed such that positive collector current indicates positive emission from the emitter intercepting the collector. All data were recorded at 10 Hz. Videography of the emission process was obtained using a long working distance microscope and a digital camera.

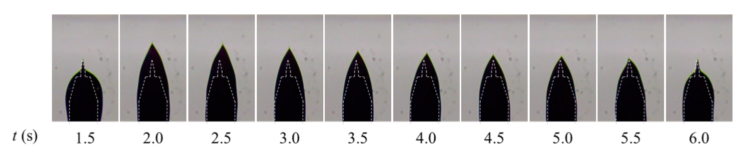
V. Results

Experimental results from the testing of a prototype hybrid emitter are presented. Results for both stable and unstable emission are separated into their relevance to capillary or externally-wetted emission modes.

A. Capillary Emission Mode

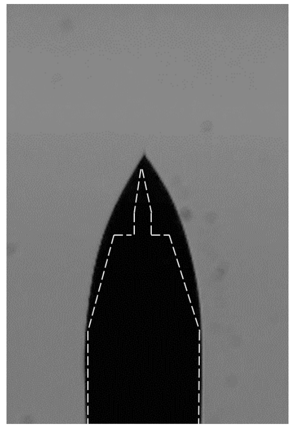


(a)

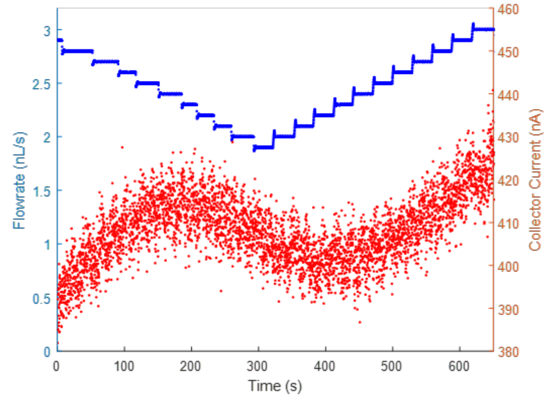


(b)

Figure 5: Intermittent emission at 1550 V emitter voltage, 3.0 nL/s flow rate. In (a) collected current is shown as a function of time and in (b) images of electrospray emission are shown for corresponding times, with the emitter shown as a dashed line.

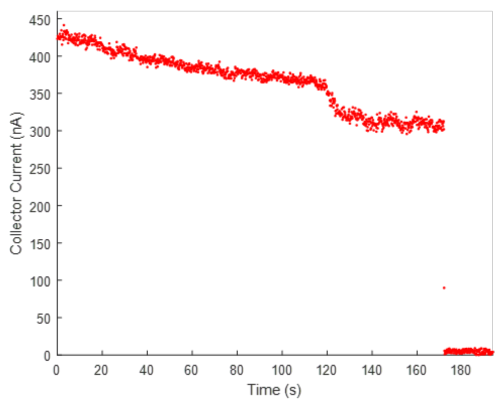


(a)

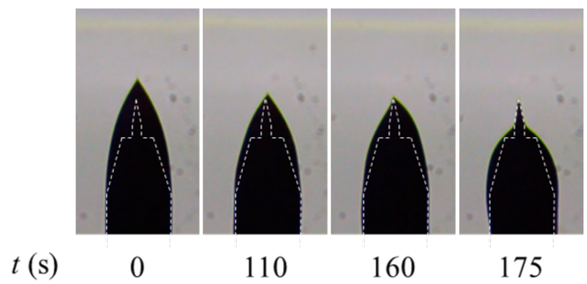


(b)

Figure 6: Emission from a meniscus staked to the capillary, at 1500 V emitter voltage; (a) image of the cone-jet emission with the emitter shown as a dashed line and (b) flow rate and collected current over time.



(a)



(b)

Figure 7: Flowrate shutdown test at 1500 V emitter voltage where driving pressure was removed at the start of the test, represented as (a) collected current over time and (b) images with the emitter as a dashed line.

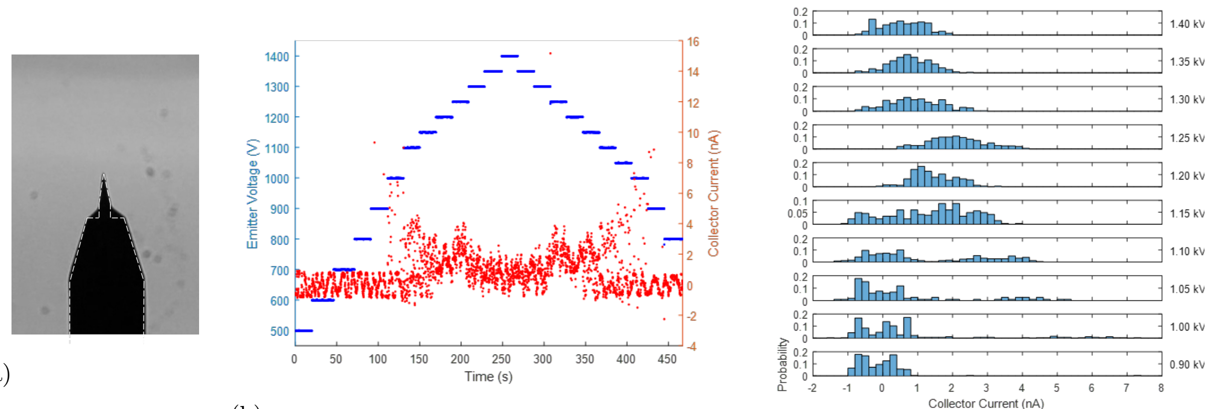
Stable and unstable emission from the capillary were achieved in order to investigate optimal operating conditions for the hybrid emitter in the capillary emission mode. When operating at 1550 V and 3.0 nL/s, intermittent emission of roughly 500 nA for several seconds was observed. The period for this event was over 10 s. Collected current and corresponding images of emission are shown for one event in Fig. 5. Immediately following this event, the emitter voltage was reduced by 50 V to produce steady emission.

Decreasing the emitter voltage to 1500 V allowed for stable capillary emission and high flow rates of 2.4 to 2.8 nL/s were commanded to the emitter. High flow rates were required to extend the meniscus past the needle such that the two did not intersect. Collector current and flow rate as a function of time are shown in Fig. 6b as well as a representative image of emission in this mode. These data show that the collected current lags the pressure control; this is thought to be largely due to a convoluted flow path and bubbles in the feed line to the emitter.

To determine the stable operating range for emission from the capillary at 1500 V potential, the pressurized flow to the emitter was halted and the volume of propellant at the emission site was allowed to emit in a shutdown condition. Collected current over time is shown in Fig. 7. The hydraulic resistance and bubbles in the flow line may have caused the current response to be slowed. This operating condition highlighted some of the transition conditions for the emitter at this potential. During this event, the meniscus receded as the volume of propellant at the emission site reduced. At approximately 120 s the meniscus intersected with the needle, causing the tip of the cone to cant off at a small angle. This causes a distinct drop in collector current, however it is not known whether this is due to decreased emitter current or increased extractor interception.

Additionally, the hybrid emitter was briefly operated at 1700 V and above. Both continuous and intermittent off-axis emission were observed. These operating modes resulted in rapid propellant deposition on the extractor electrode and were not investigated further for this effort.

B. Externally-Wetted Emission Mode



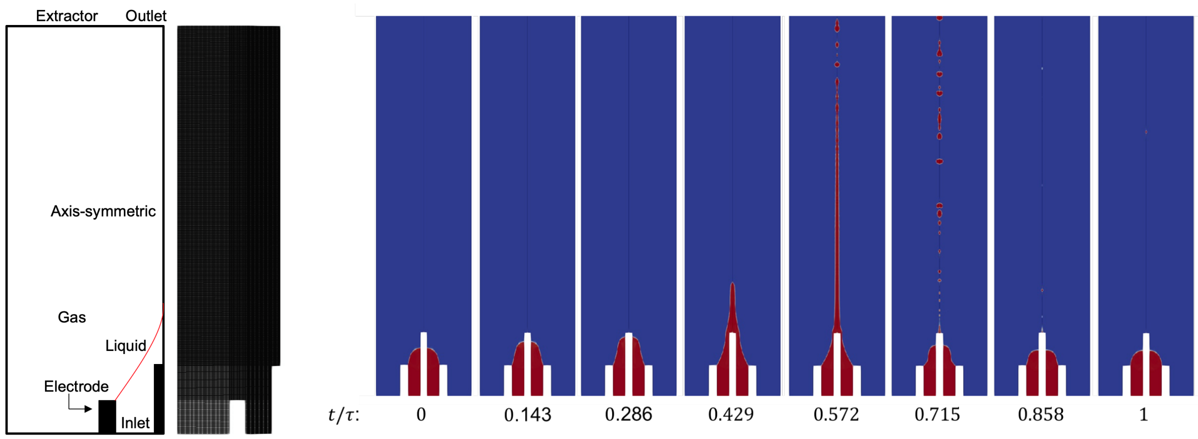
(a) (b) (c)

Figure 8: Emission from a meniscus staked to the needle: (a) shown visually with the emitter represented as a dashed line, (b) emitter voltage and collected current with time, and c) histograms of collected current at each emitter voltage setpoint.

For externally-wetted emission mode, the driving pressure to the emitter was reduced to the emitter gravity head, dropping the driving flow rate to a negligible level. When operated in an externally-wetted emission mode, propellant is driven to the tip of the needle due to a combination of surface wettability, capillary forces and Maxwell pressure effects. Emitter voltage was raised from 500 V to determine stable emission conditions, as shown in Fig. 8b. To illuminate the emission characteristics at each operating voltage, collected current data are presented as histograms. In Fig. 8c, the histograms describe the normalized frequency of recording each range of collector current at each emitter voltage setpoint. Below 1000 V emitter potential, the collected current was negligible; the distribution of collected current is due to electrometer noise. Between 1000 and 1200 V, the emission was characterized by intermittent bursts of positive current. At 1000 V emitter potential, the collected current was nominally negligible, with intermittent emission recorded up to 8 nA. Increasing potential to 1150 V increased the duty cycle of emission pulsations while decreasing the intermittent maximum current; distributions transition from skewed right at 1000 V to bimodal at 1100 V and vaguely multimodal at 1150 V. Then, at 1200 V pulsations subsided and the nominal collected current increased to 2 nA. Increasing the emitter potential past 1250 V yielded a decrease in the collected current. At 1350 V and 1400 V, the distribution of collected current was wider than the noise signal with a positive offset, indicating that roughly 1 nA of emission was collected by the collector. After ramping emitter voltage from 500 to 1400 V, the voltage was ramped down until emission stopped, with no noticeable hysteresis in current response. Noise from the amplifier is seen as a distribution with a roughly 2 nA width in all histograms.

VI. Computational Modeling

Computational modeling of propellant extraction from a simplified hybrid emitter geometry was performed in OpenFOAM. This model has been described in greater detail by Huh and Wirz[23] and by Wirz *et al.*[21] The code requires no simplification of the charge conservation laws, such that the full charge conservation equation is applied in order to consider both leaky dielectrics and perfect conductors in this model.



(a) (b)

Figure 9: Computational modeling: (a) Computational domain for the hybrid emitter. The capillary outer diameter is 180 µm and the needle outer diameter is 30 µm. The capillary-extractor distance is 1.32 mm. For this geometry, a mesh was created with 61,850 cells. (b) Computational results for intermittent emission with the hybrid emitter using heptane ($\epsilon = 1.76 \times 10^{-11}$ F/m, $\rho = 684\,\mathrm{kg/m^3}$, $\gamma = 21\,\mathrm{mN/m}$). One period of emission is represented in 8 characteristic frames. Red regions indicate heptane and blue represents vacuum.

While the objective of the electrospray computational model is to investigate the cone-jet emission mode, its scope has been extended to investigate operating modes of the hybrid emitter. In order to capture electrospray physics with reasonable run times and domain resolutions, heptane was used as the propellant instead of EMI-Im. The lower conductivity increases the jet diameter, making spray features more apparent. A blunt capillary and blunt needle were used for the emitter geometry in the simulation, which is shown in Fig. 9a. Equation 3 predicts a startup voltage of 1100 V for emission from the capillary. Emission was simulated for an extraction voltage of 8 kV and a flow rate of 565 nL/s. Results for this applied flow rate and voltage are shown in Fig. 9b. Time for this simulation was normalized by the emission period, $\tau = 140\,\mu\mathrm{s}$. Future computational modeling efforts will help guide future hybrid emitter design efforts for higher conductivity propellants.

VII. Analysis and Discussion

Based on the operating conditions leading to capillary emission and externally-wetted emission modes, we propose a stability plot as shown in Fig. 10. The externally-wetted and capillary emission modes are distinct and separated by unstable operating modes. Externally-wetted emission mode occurs at low emitter voltages and becomes unstable at higher voltages. Low flow rate is necessary for externally-wetted emission: flow rate in excess of that which can be pulled to the emission site by electric stress leads to intermittent emission as shown in Fig. 5. Capillary emission mode occurs for higher voltages as predicted by Eq. 3 and is stable for voltages and flow rates that cause a meniscus which does not intersect with the needle. For this prototype of the hybrid emitter, capillary emission operated in a narrow voltage range. Increasing voltage led to intermittent emission due to meniscus-needle intersection. Reducing the needle protrusion may increase the operating range of the capillary emission mode of this emitter such that stable operating regimes of a hybrid emitter and a traditional capillary emitter are indistinguishable, apart from the addition of the externally-wetted operating mode.

These experiments show that for both capillary and externally-wetted emission modes, the hybrid emitter did not achieve stable emission until higher voltages than predicted by Eq. 3. The surface of the tungsten needle has not been roughened, so it will exhibit reduced wettability. The needle will not operate stably until the electric field can support fluid motion to the tip of the needle. For emission from the capillary, the fluid meniscus intersecting with the needle causes an intermittent emission mode that deviates from the behavior of a traditional capillary emitter. Additionally, Eq. 3 was derived assuming a Taylor cone on the surface of the emitter; the meniscus for capillary emission deviates significantly from the 49.3° predicted by

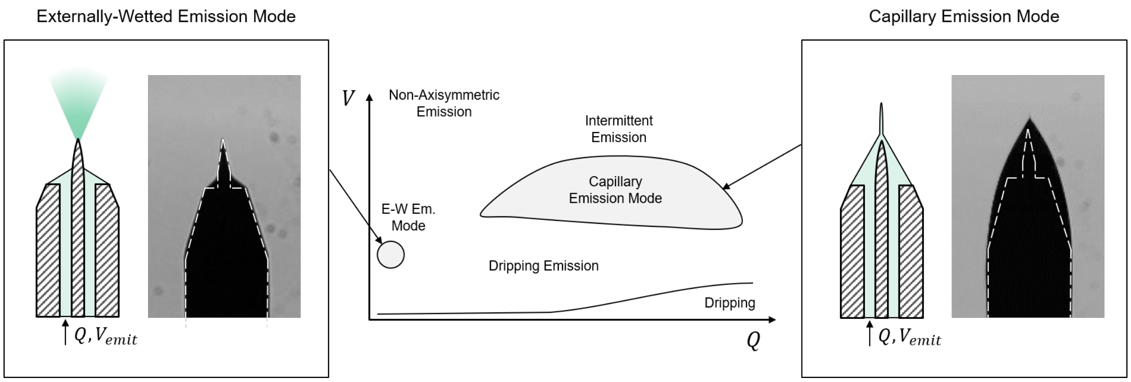


Figure 10: The operating regimes for the hybrid emitter. Adapted from Chen.[17]

Taylor.[24]

As in Figs. 5 and 7, emission tilts off-axis after the meniscus intersects with the needle. This may be due to poor needle wettability as well as needle and extractor misalignments. These effects cause meniscus-needle intersection to be a stability threshold for capillary emission. The effect on the electrospray plume is not yet confirmed, but off-axis emission has negative effects on both lifetime and performance. Because the meniscus-needle intersection leads to off-axis emission and intermittent emission, the needle geometry has a significant effect on non-ideal operation of the hybrid emitter. Furthermore, the capillary-needle distance is an important parameter for determining the low flow rate bound for the capillary emission region of this electrospray emitter.

When emitting from the needle, the collected current was observed to decrease as emitter potential increases above its stable setpoint, at 1250 V. It is unclear if this is due to increased flux to the extractor electrode as the extractor current was not measured. Both the decrease in current above 1250 V and the pulsating emission below 1200 V are not understood and warrant additional investigation.

Based on the flow rate and current in the capillary emission mode, the average specific charge is estimated to be 100 C/kg. Due to the oversprayed propellant accumulation on the extractor, some current from the emitter may not have reached the collector, leading to an underestimate of the specific charge of emission. The majority of propellant deposition on the collector was due to operation in capillary emission mode. Based on the propellant deposition diameter of 9.5 cm from Fig. 4, the angle of this plume was 37°. Assuming the plume divergence as the primary efficiency-loss (80%), we expect this mode to operate with a specific impulse of approximately 50 s, although additional experimentation is required to verify this value. While this specific impulse is low, other electrospray thrusters have used a floating emitter potential to raise or lower the specific impulse and thrust-to-power.[3,25]

The computational modeling results exhibit qualitative agreement with experimental results for intermittent emission. In both the experiments and computational modeling, intermittent emission occurred when setting the emitter voltage significantly above the predicted startup voltage. Experimentally, increasing the emitter voltage above 1700 V led to intermittent and steady off-axis emission. Computationally however, the axisymmetric domain suppresses non-axisymmetric phenomena such as off-axis emission.

VIII. Conclusion

The concept of a variable emission mode electrospray device has been validated experimentally. Variable mode emission has been achieved through controlling the meniscus shape to wet the needle or the capillary. High throughput from the emitter observed visually and through current detection is reminiscent of similar high thrust-to-power capillary emitters. A 200× decrease in current when in needle emission mode suggests much higher specific charge of emitted species. Computational modeling has yielded qualitative agreement with experimental results for pulsating emission and remains a useful tool for future design investigation. This design has strong potential for further development as the emitter approach for dual-mode electrospray thrusters.

There is significant future work necessary to understand the effects of design parameters on the performance and stable operating conditions for this emitter. Needle protrusion affects the transition from capillary emission to intermittent emission. Additionally, the meniscus from the capillary during externally-wetted emission mode suggests that the needle may be overly protruded. Further investigation into the emitter geometry may yield an expanded stability region while maintaining the ability for multiple emission modes. Needle roughening has been shown to promote favorable flow rate and electric field at the emission point for externally-wetted emitters,[5] and is expected to have a similar effect on the externally-wetted emission mode for the hybrid emitter. Insertion of multiple needles to the emission site will be investigated to scale the thrust and current while operating in an externally-wetted emission mode. Additional emission sites will decrease the power disparity between operating in capillary and externally-wetted emission modes in the current prototype device. Future work will use the various plume diagnostics in the UCLA HOAGIE facility to determine the specific charge of emitted species.[26] These species data will be used to estimate the performance of the device when operating in the capillary and needle emission modes.

Acknowledgments

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