Spatially-Resolved Mass Flux and Current Measurements of Electrospray Plumes

IEPC-2019-571

Presented at the 36th International Electric Propulsion Conference
University of Vienna, Austria
September 15-20, 2019

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In order to understand the performance and lifetime capabilities of electrospray thrusters, the evolution of their plumes downstream from the emission site must be characterized. This study investigates current density and mass flux measurements of an ionic liquid electrospray plume for implications on thruster performance and lifetime. A capillary electrospray emitter is operated using 1-ethyl-3-methylimidazolium bis(trifluoromethylsulfonyl)imide (EMI-Im) propellant to determine plume profiles at multiple emitter flow rates and emitter bias voltages. A quartz crystal microbalance (QCM) and current probe are swept across the plume to independently measure spatially-resolved mass flux and current density profiles out to high half-angles of 40°. Measured profiles show that mass flux and current density profiles deviate from each other, with the mass flux profiles exhibiting a flat-top distribution with a steeper-than-Gaussian decay. Charge-to-mass ratio distributions are estimated and show that the small half-angle regions of the plume have higher ratios of larger droplets to smaller droplets, while the large half-angle regions are primarily composed of smaller droplets.

Nomenclature

\( A \) = area
\( C_1 \) = electrospray device-specific flow rate coefficient
\( \mathcal{F} \) = Fourier transformation
\( f \) = frequency
\( I \) = current
\( m \) = mass
\( Q \) = volumetric flow rate
\( \rho \) = density
\( \mu \) = shear modulus
\( \theta \) = half-angle from emitter centerline

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I. Introduction

Electrospray thrusters electrostatically emit and accelerate ions and/or charged droplets for thrust in the I_sp range of 150 – 6000 seconds. A common choice of propellant for electric propulsion applications is the ionic liquid 1-ethyl-3-methylimidazolium bis(trifluoromethylsulfonyl)imide (EMI-Im), which exhibits the favorable properties of low vapor pressure, high conductivity, and low viscosity. Electrospray devices offer unique benefits including passive propellant flow, unpressurized propellant storage, and a wide range of thrust-to-power ratio for devices. The primary drawback of electrospray thrusters is the short lifetimes of existing devices.\(^1\) Current efforts at the University of California, Los Angeles (UCLA) Plasma and Space Propulsion Laboratory (PSPL) are focused on investigating lifetime and performance of electrospray thrusters, specifically the Colloid Microthruster Technology (CMT) for the Laser Interferometer Space Antenna (LISA) project.

As part of this effort, several mechanisms contributing to lifetime reduction of electrospray devices have been identified and are presented in.\(^1,3-6\) The primary concern for electrospray lifetime is overspray, where propellant at wide plume angles impinges on the extractor and accelerator grids/electrodes. Addressing this failure mechanism requires a rigorous understanding of the plume profiles, specifically the mass flux and current density profiles. While electrospray plume current density profiles for devices operated in droplet-mode using EMI-Im propellant have been previously measured,\(^7\) the existing data are not resolved to high half-angles that are of significance for lifetime investigation efforts. Additionally, the only measurements of mass flux of EMI-Im were conducted for an externally-wetted emitter operated in a low flow rate regime,\(^8\) and indicated negative flux beyond 20° in the high half-angle region that is of significance for lifetime investigation. Using data-fitting techniques on these measurements to extrapolate the properties at high half-angles has proved challenging as uncertainty overwhelms the data fit values beyond the range of the experimental data. Current density and mass flux measurements in the large half-angle regions (impingement regions) can greatly improve understanding of electrospray performance and lifetime. The objective of this study is to obtain and analyze charge- and mass- flux measurements of an ionic liquid electrospray plume to investigate implications on thruster performance and lifetime.

II. Experimental Approach

The Highly Optimizable Apparatus for Groundbreaking Investigations of Electrosprays (HOAGIE) facility at UCLA PSPL was developed to investigate various aspects of capillary electrospray emission. The primary objectives of the facility are to provide critical data for electrospray performance, lifetime estimation, and support computational models.\(^2\) This study utilizes HOAGIE for experimental electrospray plume characterization to measure mass flux and current density profiles resolved to high half-angles. A schematic of the HOAGIE system configuration with the diagnostics suite employed in this study is shown in fig. 1a.

The system consists of a platinum capillary emitter matching ST7-DRS dimensions and a stainless steel extractor plate, with aperture dimensions matching that of the ST7-DRS. High voltage is applied to the emitter while the extractor plate is held at ground, resulting in an electric potential differences on the order of kV that produces electrospray emission. A pressure-over-fluid (POF) feed system is used to flow degassed EMI-Im propellant to an emitter in vacuum. The POF chamber is equipped with a high-precision pressure transducer and two mass flow controllers (MFCs) connected to vacuum and nitrogen pressurization lines, respectively, that enable precision flow rate control. The hydraulic resistance of the emitter line is measured before testing, and is used along with the POF chamber pressure measured by the pressure transducer to determine the emitter flow rate in-situ. An emitter current monitor is used to for high-voltage emitter current measurements with nA-resolution at a 10 kHz sampling rate. The emitter current can be used to command the emission flow rate setpoint since they are directly related by eq. 1 for droplet mode, where \(I\) is the emitter current, \(C_1\) is the device-specific flow rate coefficient, and \(Q\) is the volumetric flow rate.\(^9\)

\[
I = C_1Q^{\frac{1}{2}} \tag{1}
\]

A spherical current probe is mounted on the diagnostics mount, as seen in fig. 1b, and is connected to a probe current monitor. The probe current monitor can measure the extractor or probe current with nA-resolution at a 10 kHz sampling rate. All current measurements presented in this paper have a record length of 1 s, with uncertainty on the measurements determined from the 10,000 datapoints collected over that record length. Longer record lengths were conducted to ensure that no larger timescale effects were
unaccounted for. A quartz crystal microbalance (QCM) with a shutter is also mounted on the diagnostics mount, as seen in fig. 1b, to measure mass flux. The frequency response of the quartz crystal is measured over a sampling period. The slope of the measured response is used with eq. 2, also known as the Sauerbrey Equation, to determine the mass flux to a resolution on the order of 1 pg cm$^{-2}$ s$^{-1}$. Here, $\frac{dm}{dt}$ is the mass flux, $\rho_q$ is the density of the quartz crystal, $\mu_q$ is the shear modulus of the quartz crystal, $f_0$ is the initial resonant frequency, and $\frac{df}{dt}$ is the rate of change of the measured frequency. Uncertainty on the mass flux measurements is determined from propagating the root mean square (rms) on the fit to the raw frequency data in determining the slope.

$$\frac{dm}{dt} = -\frac{\sqrt{\rho_q \mu_q}}{2f_0} \frac{df}{dt}$$  \hspace{1cm} (2)

The diagnostics mount is height-adjustable and actuated with two perpendicular translation stages that allow the probes to move in a user-selectable horizontal plane across the electrospray plume for current and mass flux mapping. Additionally, the diagnostics are mounted on a rotation stage for angular plume sweeps about a horizontal rotation axis aligned with the tip of the emitter.

A long-distance microscope (LDM), with stereoscopic optics enabling multiple lines of sight simultaneously, observes the electrospray emission region in-situ at 30 frames per second (fps) to ensure nominal emission conditions and to identify operating setpoints that produce off-axis emission. The LDM is additionally used in conjunction with a high-speed camera in another study to understand the implications of off-axis and unstable emission modes on lifetime.$^6$ Additional details about the HOAGIE facility, diagnostics, and complementary efforts can be found in Wirz et al.$^2$
III. Plume Measurements

In order to characterize the electrospray emission response of this system, voltage sweeps were conducted to determine the start-up voltage and operational stability range. The resulting I-V curve is shown in Fig. 2 with arrows labeled 1, 2, and 3 to indicate the chronology of the sweep. The voltage sweep was conducted at a flow rate of 480 pl s$^{-1}$. The emitter voltage was set initially to 1200 V and then ramped up in 50 V increments with a 10 s duration at each voltage setpoint. Extractor current was recorded at each setpoint. No emission was observed until 1550 V, which agrees with the estimation of start-up voltage required for emission for this geometry. As the emitter voltage is further increased incrementally up until 2000 V, the emitter current increases as expected for low flow rate electrospray systems. As the voltage is swept back down from 2000 V to 1200 V in identical increments, the emitter current decreases as expected. The hysteresis effect of emission continuing below 1550 V is due to the existence of a stable cone-jet which allows for emission to continue below the start-up voltage threshold.

![Voltage Sweep Graph](attachment:Voltage_Sweep.png)

Figure 2: Emitter current versus emitter bias shown along with impinging extractor current for each voltage setpoint. Arrows labeled 1, 2, and 3 indicate the order at which the emitter voltage was swept to highlight the hysteresis.

![EMISSION IMAGES](attachment:EMISSION_IMAGES.png)

Figure 3: Sequence of images of emission shows the shape of the meniscus during nominal emission and the off-axis emission at elevated emitter bias of 2 kV.

Extractor current measurements show that the extractor current increases with increasing emitter voltage as expected since the emitted current is increasing. The elevated extractor current at the high and low voltage region is likely due to the onset of off-axis and/or unstable emission events. Visual evidence of off-axis emission that occurred at higher emitter voltages is shown in fig. 3. An 8° tilt in the direction of emission is evident in comparing fig. 3b and 3c, which can be extremely detrimental for device performance and lifetime.4,6
In addition to voltage sweeps, flow rate sweeps were performed to characterize the system and determine the device-specific flow rate coefficient. The sweep was conducted at a fixed emitter bias of 1.6 kV. The flow rate was initially set to 400 \( pl s^{-1} \) and increased in 50 \( pl s^{-1} \) increments. The I-Q sweep results are shown in fig. 4 with abscissa expressed as the square root of the flow rate to allow for a linear fit determining the flow rate coefficient. The linear fit to the data indicates that the system exhibits the expected emitter current response shown in eq. 1. The slope of the fit represents the device-specific flow rate coefficient, determined here to be \( 517 \ nA \ n l^{-1/2} \ s^{-1/2} \) for this system, which allows for conversion between emitter current and flow rate for analysis and modeling efforts.

\[
E_{\text{current}} = C_1 Q^{1/2}, \ n l^{1/2} \ s^{-1/2}
\]

Figure 4: Emitter current flow rate relationship exhibits expected behavior for capillary emission.

A 2D map of the plume current was measured by conducting a planar sweep of the diagnostics probe across the electrospray plume. The diagnostics arm was positioned 5.125” above the emitter tip for the sweep where emitter current and probe current measurements were obtained. A contour map of the resulting plume profile is shown in fig. 5. Uncertainty on the measurements were less than 1% and is not shown in the figure. The contour indicates that the plume is axisymmetric and provides the location of the centerline along which angular sweeps were conducted.

Angular sweeps of the diagnostics mount were conducted at the centerline determined from the 2D plume contour to measure the plume current density and mass flux profiles. The angular sweeps were conducted for varying emitter voltages and flow rates with the QCM and current probe sweeping through the center of the plume, and were repeated to ensure measurement precision. The current profiles are shown in fig. 6a and 6b for varying flow rates and emitter voltages respectively. All current density profiles appear almost Gaussian but are not truly Gaussian. As the flow rate was increased, the peak magnitude of the current density profiles decreased but the width of the profiles increased, growing from 20° to 33°. The plume profiles deviate further from a Gaussian shape with increased flow rate. As the emitter bias voltage was increased, the peak magnitude of the current profiles increased slightly and the plume profiles became slightly more narrow. A sharp change in the profile width occurred at 1.8 kV due to off-axis emission as mentioned previously and further demonstrated with the mass profiles. In general, the measurements reported in this study show good agreement with other published measurements of current density profiles of ionic liquid electrospray devices.\(^{11}\)

The mass flux profiles are shown in fig. 7a & 7b for varying flow rates and emitter voltages respectively. It is evident from the measurements that the mass flux profiles are not Gaussian. Instead, the profiles are flat top distributions with sharper-than-Gaussian decay. The shape of the mass flux profiles differs notably from that of the current density profiles, highlighting the significance of these measurements for thruster performance and lifetime efforts. As the flow rate was increased, the peak magnitude of the mass flux profiles increased and the profiles grew wider. The broadening of the profiles decreased with increased flow rate.
Figure 5: 2D profile of current 5.125” downstream from emitter.

Figure 6: Current density as a function of half angle for varying a) emitter flow rate and b) emitter bias voltage.

The uncertainty in the position of QCM represented in fig. 7 is a result of the sensor size having a cross-section of 4°. The decay in the mass flux profile is larger than 4°, indicating that this decay is adequately resolved by the QCM. Figure 7b shows that varying the emitter bias voltage from 1.5 to 1.7 kV has no significant impact on the profiles. At 1.8 kV, the emission begins to move off-axis, as shown previously in the voltage sweep and current density profiles. The off-axis emission becomes more apparent at 1.9 kV where the plume shifted by ∼8°. A previous study examined the mass flux profiles of an externally-wetted electrospray emitter, operating in a different emission regime, and presented mass flux profiles resolved only in the small half-angle region with negative flux in the edges of this region. In contrast, the presented study provides unique mass flux measurements resolved out to higher half-angles that have been carefully conducted to correct for negative flux measurements.

The current density and mass flux profiles are represented in polar plots in fig. 8 for additional clarity. The width of the plume profiles is apparent, along with the effect of increased plume width with increased flow rate.
Figure 7: Mass flux as a function of half angle for varying a) emitter flow rate and b) emitter bias voltage.

IV. Discussion

The total volume flux captured by the measurements were calculated by performing surface integrations of the measured profiles in spherical coordinates. The integrated volume flux is shown in fig. 9 as a function of the emitter flow rate. A linear fit applied to the calculated values shows that there is a 93% agreement between the emitter flow rate, with a fixed offset in flow rate of 180 pl s\(^{-1}\) that agrees with the calculated pressure head due to gravity in the feed system. The 7% offset is well within the uncertainty in the value of propellant density used in calculating the volume flux, the emitter flow rate measurement, and propellant that is sprayed at higher half angles that are not measured. These calculations indicate the QCM measurements are capturing and resolving the majority of mass flux in the electrospray plume.

A convolution analysis was performed to ensure that the flat top plume shape was not an artifact of the finite-sized QCM sensor response. The measured plume profile, \(\Gamma(\theta)\), is a convolution of the “true”, unperturbed plume profile, \(g(\theta)\), the QCM sensor response, \(f(\theta)\), and an experimental windowing function \(W(\theta)\). The “true” plume profile can in principle be determined via a Fourier transform and the convolution theorem as shown in eq. 3.

\[
g(\theta) = \mathcal{F}^{-1} \left( \frac{\mathcal{F}(\Gamma(\theta))}{\mathcal{F}(W(\theta))} \right)
\]  

(3)

Using the measured mass flux profile, a rectangular windowing function, and assuming the QCM sensor response to be an elliptic function, the “true” plume profile cannot be a Gaussian plume. The unperturbed plume profile must be some type of distribution with a flat top, indicating that the measured profile shape is not due to sensor response and does in fact represent the shape of the mass flux profile.

These measurements are significant as they clearly demonstrate that the current density profiles and mass flux profiles are different. Although they exhibit similar general broadening to increasing flow rate, the magnitude of each profile’s response is different. As a result, the mass flux profile shifts from being narrower than the current density profile at lower flow rates to being wider at higher flow rates. These plume profiles provide valuable insight on plume structure through investigation of the average charge-mass ratio profiles, which were calculated from the current density and mass flux profiles. The charge-mass ratio profiles are shown in fig. 10a and 10b for varying flow rates and emitter voltages, respectively. The charge-mass ratio is small and nearly constant in the small half-angle region near the centerline, indicating that this portion of the plume has a relatively isotropic population of heavy droplets. The charge-mass ratio beyond the central region increases rapidly with half-angle, reaching values on the order of the charge-mass ratio of EMI-Im monomers \(([C_2F_6NO_4S_2]^- \text{ is } 344 \text{ C g}^{-1} \text{ and } [C_6H_11N_2]^+ \text{ is } 870 \text{ C g}^{-1})\), which indicates that this region of the plume is dominated by lighter droplets. As the emitter flow rate is increased, the charge-mass ratio decreases. This is a result of increased mass flow resulting in slightly heavier droplets on average and the broadening of the plume profile as observed in the mass flux and current density measurements. This trend decreases with increasing flow rate due to the limit on the size of stable droplets that can be emitted.
Figure 8: Polar plots of flux per steradian for (a and b) current density and (c and d) mass flux for varying currents and flow rates, respectively.

The charge-mass ratio profiles, in conjunction with the mass flux and current density profiles, provide valuable insight on the structure of polydisperse electrospray plumes. As shown in current and past efforts, distributions in the charge and mass of particles emitted from the jet, coupled with negative velocity gradients, cause Coulombic interactions between particles and perturbations in their motions near jet break-up region (also described as the interaction region).\textsuperscript{12–14} The applied electric field amplifies the radial motion caused by the perturbations. Smaller droplets, which have less mass and therefore higher mobility, gain larger radial velocities on average. This mass dependent migration creates a filtering effect that generally results in decreasing density of lighter droplets near the centerline. As a result, the droplets generally segregate radially based on their charge-mass ratio, leading to an increased mean droplet diameter in the small half-angle region. This radial segregation agrees with the observed behavior in the charge-mass ratio profiles in fig. 10. These profiles indicate larger droplets on average are primarily located in small half-angle regions, while the high half-angle regions are dominated by larger ratios of small droplets to larger droplets. The mean axial velocity decreases with half-angle, which leads to different profiles for mass flux and current density, as observed in fig. 6 and fig. 7. The measurements reported in this study, and the plume structure discussion above, are generally consistent with reported theory and principles of electrospray plume structure and evolution.\textsuperscript{13–15}

The results of this study also have implications on performance and lifetime of electrospray thrusters. The thrust profile of an electrospray device is dependent on the charge-mass ratio profile and mass flux profile. The measurements in this study indicate flat top charge-mass ratio profiles and mass flux profiles, which result in more uniform thrust profiles for electrospray thrusters than previously anticipated. The differences between the current density and mass flux profiles, especially in response to vary flow rate, further signify the importance of mass flux measurements for accurate lifetime estimation of electrospray thrusters.\textsuperscript{1} The measurements in this study show low steady-state mass flux in the high half-angle regions at nominal thruster operating setpoints. Lifetime modeling efforts based on these measurements indicate that oversprayed mass flux at these operating conditions does not pose significant challenges to the lifetime of electrospray thrusters.\textsuperscript{5} This suggests that transient events and off-nominal operating conditions are likely the lead contributors to lifetime reduction.\textsuperscript{4–6}
Figure 9: Volume flux determined from mass flux profiles vs emitter flow rate shows 93% agreement, indicating measurements capture majority of emitted propellant.

Figure 10: Charge-mass ratio as a function of half angle for varying a) emitter flow rate and b) emitter bias voltage.

V. Conclusion

Mass flux and current density profiles of an ionic liquid electrospray plume were measured out to high half-angles of 40° to support investigations of thruster lifetime and performance. The measurements were conducted on a capillary electrospray emitter that was operated using EMI-Im propellant. A quartz crystal microbalance (QCM) and current probe were swept across the plume to independently measure the spatially-resolved mass flux and current density profiles at multiple emitter flow rates and emitter bias voltages. The measurements show that the current density profiles and mass flux profiles are different in shape and width, indicating that the current profiles cannot alone be used for accurate lifetime and performance calculations. The current density profiles are nearly Gaussian at low flow rates but deviate away from that shape with increasing flow rate. The mass flux profiles are a flat top distribution with a steeper-than-Gaussian decay. Increasing flow rate causes both current density and mass flux profiles to increase in width while increasing the emitter voltage results in off-axis emission. Average charge-mass ratio profiles provide valuable insight on electrospray plume structure, and show that heavier droplets are located in the smaller half-angle region of the plume while the smaller droplets dominate the higher half-angle regions. The mass flux profile measurements in this study provide valuable data that are used in lifetime modeling efforts to accurately
estimate thruster lifetime and performance.  

Upcoming research will focus on obtaining mass flux measurements in higher half-angle regions using a thermoelectric QCM (TQCM) for improved resolution. Masks and grids implemented on the current probe and TQCM will enable a reduced sensor cross-section for improved spatial resolution while simultaneously screening secondary electrons and species based on energy. Additionally, an accelerator grid will be introduced into the system to better replicate the geometry of thruster units. Furthermore, mass flux and current density will be measured for transient emission events to quantify their impact on thruster lifetime. These experimental efforts, in conjunction with computational modeling efforts, will support the identification and mitigation of lifetime-limiting mechanisms in electrospray thrusters.

Acknowledgments

The authors thank John Ziemer, Colleen Marrese-Reading, David Conroy, and Stephanie Leifer from NASA JPL, and Nathaniel Demmons and Daniel Courtney of Busek, Inc. for their insightful discussions. The authors also thank Oliver Fildes, Tim Simka, and Josue Castillo from UCLA for their contributions to this effort. This work was funded by grants from NASA/JPL award no. 1580267:3 and Air Force Research Laboratory award no. 16-EPA-RQ-09.

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