COMSOL as a Laplacian Potential Simulator for an Electrospray Propulsion System Extraction Region

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Abstract: Electrostatic two-dimensional analysis of the extraction region of an electrospray electric spacecraft thruster was conducted. A comparison study was made to validate COMSOL's finite element solving applied to extraction region characterization. The Laplacian electrostatic field potential for an electrospray system was modeled, followed by the Accion Systems iEPS thruster. A Gallium emission electrospray system studied by Ward and Seliger, with an emission bead diameter of 1000Å, was recreated in COMSOL for verification; the iEPS thruster was modeled with a 150,000Å bead diameter system. The Sphere-on-Orthogonal-Cone (SOC) model of electric potential was used in MATLAB for juxtaposition. Acceptable margins of divergence were found between SOC models and COMSOL's finite element solutions. The SOC model as well as COMSOL underestimated electric potential compared to previous data, which is attributed to finer resolutions.

Keywords: Space Propulsion, Electrostatics, Electric Fields, Finite Element Methods

1. Introduction

Electrospray propulsion is a contemporary type of thruster technology that electrostatically drives particles through an extractor grid without the need of a pump. The basis of this propulsion system is the coalescence of propellant into a Taylor cone and through a charged extraction grid. Analysis of the Taylor cone to extraction grid area, known as the extraction region, aims to define the formation of the thruster plume to the end of characterizing the beam formation and divergence, as well as particle trajectory tracking. Understanding the formation of the plume and how particles propagate through space from their source will aid the prediction of plume backflow onto spacecraft surfaces [1, 2].

Research by Ward and Seliger [3] on a Ga^+ emission system was utilized as a basis for the COMSOL model, and Wiesner and Everheart's Sphere on Orthogonal Cone model was used as a comparison piece [4]. The characterization of electrospray plumes has also been explored by Lozano [5], whom alongside Gamero-Castaño [2] and Ward and Seliger [3] provided a basis for the electrodynamic modeling of the plume. These three build upon conventional particle beam models [5] such as the paraxial ray equation.

A model of backflow and ion thruster impingement was developed and validated by research done by Roy et al. [1]. The takeaway justified inevitability that can be assumed for the occurrence of backwash/backflow effects is a strong contributor to the necessity of this research. Roy's study also includes notes on the potential for electrically-reactive propellant damaging electrical components by virtue of deposited propellant forming impromptu "wire" that can bridge between electrical components and short circuit parts of the spacecraft.

Today, mercury and many metallic propellants are considered obsolete and have largely been replaced. The MIT/Accion Systems electrospray technology utilizes EMI-BF_4 [7], a molten salt explored by Lozano and Perez-Martinez as a propellant. EMI-BF_4 still has the potential to backflow due to sputtering as well as plume satellite formation, however.

Previous work [2-5] provides information on the composition and development of the electrospray plume, with findings and discussions of relationships between particles at different radii at any given distance of the plume. Gamero-Castaño [2] postulated that higher-power plumes have a wider divergence angle, with much higher mass-to-charge ratios at lower angles of divergence, showing a denser plume at higher angles. Satellite particles form at higher angles, and those particles that are not influenced by the particle beam space charge to detach from divergent spacecraft magnetic fields may backflow towards the spacecraft [1].

While Gamero-Castano's research brings empirical data and Ward's research supports experimental procedure on analyzing electrospray systems electrostatically, Lozano provides a background and specifications for the electrospray thruster technology in particular, separate from chemical substrate electrospray.

2. Governing Equations

Defining the Laplacian potential in the extraction region is a time-stationary procedure: the propagation of charge in a vacuum is dependent on the permittivity of space and the special sources across the system. The first step in characterizing the extraction region simply was simplifying the problem by removing potentially time-dependent or moving components. As such, the Taylor cone is taken to be an equipotential surface.

While the internal electrical energy of the cone is defined by a ~$1/r^2$ relationship, focusing on the force-generating electric fields first and foremost allows for the creation of a foundation for future trajectory work. The emission point for Taylor cones is at a statistically steady state during firing, and so the force components driving particle motion are sought first. Emission phenomena in electrospray are understood to the extent that they can be ignored [2-4] in this electrostatic context.

Due to the stationary qualities of the model, equations were primarily constants: boundary voltages, permittivity of free space. The electric field force propagated through free space from a given source is defined in Eq. 1 [6] as:

$$F_e = \frac{1}{4\pi\varepsilon_o} * \frac{Q}{r^2} \qquad \text{[Eq. 1]}$$

Eq. 1 and derived relationships are utilized by COMSOL's finite element analysis to determine, piecewise, the distribution of charge from the extraction grid to Taylor cone. However, there are more exact models which were utilized outside of COMSOL. The Taylor cone emission point forms as a sphere beading the tip of the cone. Fittingly, the Sphere-on-Orthogonal-Cone (SOC) model, defined in Eq. 2 [4], is classically used to define the voltage potential around the emission point in colloid electrospray systems:

$$V(r,\theta) = V_r \left(\frac{a}{R}\right)^n \left(\left(\frac{r}{a}\right)^n - \left(\frac{a}{r}\right)^{n+1}\right) \times P_n\big(cos(\theta)\big) - V_0 \qquad \text{[Eq. 2]}$$

In Eq. 2, V stands for voltage, with the *r* and *0* subscripts denoting electrode and emission point voltage. Due to discontinuities, the base voltage begins at 10% of the extraction grid voltage. a is the diameter of the emission bead, 1000Å, and n is a coefficient that has empirically been found to be equal to 0.22 with a Taylor cone of 15°, which the Ga^+ system contains. P_n is a Legendre function of the cosine of the radial coordinate θ.

This equation was used to compare with finite element solutions in both COMSOL and Herrmannsfeldt. Other notable features of the model laid in the conceptual and structural composition of the model, rather than governing equations. However, the potential is a key aspect in learning the electric field strength within the extraction region (Eq. 3), which is a driver of particle motion regardless of space charge effects.

$$E = -\nabla * V \qquad \text{[Eq. 3]}$$

3. Use of COMSOL Multiphysics

Using COMSOL Multiphysics' electrostatics AC/DC module, the extraction region's axial electrostatic field was constructed. By constructing each component, such as the Taylor cone, extraction grid, and the bead of fluid at the tip of the cone, then utilizing the subtraction function on the geometry with a large rectangle, a working region "cut out" was created, as seen in Figure 1. This region was made to be vacuum, with a relative permittivity $(\varepsilon/\varepsilon_0)$ of 1; permittivity of vacuum is $8.854 \cdot 10^{-12}\,\frac{\text{F}}{\text{m}}$ [6].

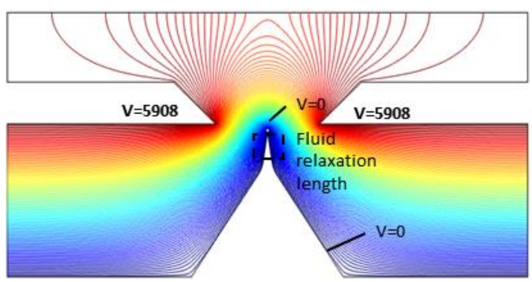

Figure 1: The electrospray extraction region as per Ward's [1] specifications.

As per standard practices [2-4], the Taylor cone and emission bead were assumed to be equipotentially 0 Volts in potential. The base of the model, beyond the Taylor cone elevation, was created as a ground. The extraction grid, placed at a zero-separation configuration, was created with a potential of 5908 V. These charges were placed on the boundaries with the working region.

A very fine mesh was utilized to characterize the Ga^+ extraction region, shown in Figure 2:

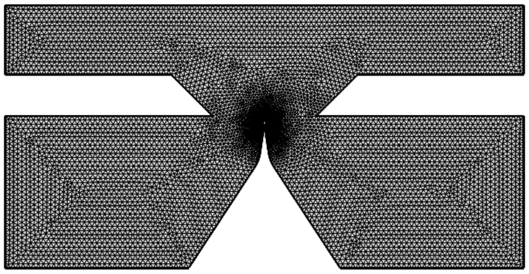

Figure 2: The Ga^+ extraction region meshed. Note fineness near emission point.

Resolution studies noted that roughness correlated with overestimation of voltage in the near-emission region. As such, high accuracy was sought to observe how much these inaccuracies could be removed. The COMSOL model's fineness was designed to improve upon results acquired by Ward [3] through the Herrmannsfeldt finite element modeling program.

4. iEPS Characterization

The iEPS system geometry was created to conduct preliminary analysis on particle trajectories in the electrospray thruster. Due to the value of understanding the electrostatic fields in an extraction region, the first step towards characterizing plume formation and particle trajectories was determined to be developing an electric potential model.

A very fine model with key aspects noted in Table 1 in the Appendix was developed, and is shown in Figure 3. Of note is the large emission bead; the ionic liquid propellant and lower electric field strengths seen in the iEPS system induce a larger residence time in the fluid, which creates a larger bubble.

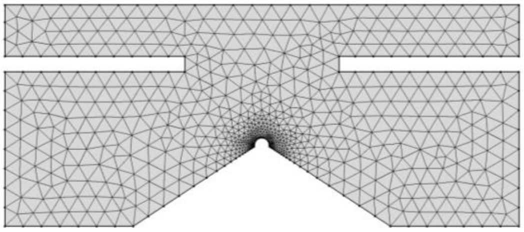

Figure 3: Meshing of iEPS geometry used in analysis.

By charging the surfaces of the extraction grid to 1200V at a 45μm separation from the Taylor cone [8] and running a stationary study akin to what was done with the Ga^+ source, the stationary electrostatic potential and field strengths were solved for (Figures 4, 5):

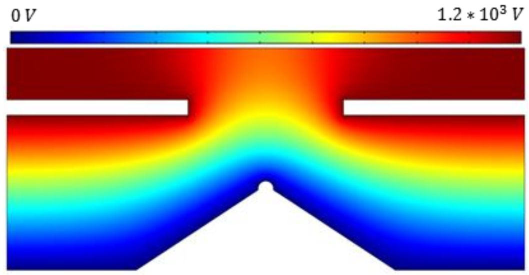

Figure 4: Laplacian potential distribution across iEPS extraction region.

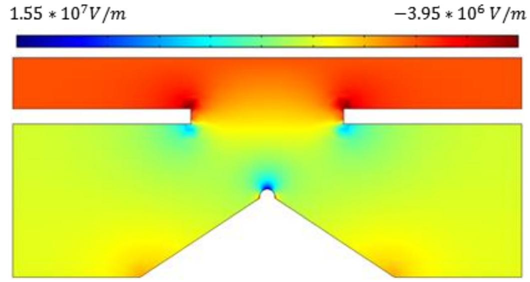

Figure 5: Y-axis axial electric field distribution.

A high-fidelity electrostatic model of the iEPS system in a validated solving environment is expected to be key to future analysis, and was the main driver for this research.

5. Results

COMSOL notably underestimated voltage potential compared to the original findings by Herrmannsfeldt's finite element solutions. The SOC model input into MATLAB found almost exact matching with Ward's SOC model data. The SOC model and COMSOL findings agreed in some respects: exact matches of potential at a mid-range axial distance are found, but notable divergence near the extraction grid exit. These findings are summarized in Figure 5. A resolution study found that lower resolutions corresponded with higher voltage potentials; a 2000-node analysis along a θ of 0 from the emission point was deemed to be sufficient resolution for COMSOL, and it is suspected that previous work simply did not utilize high enough resolution, and thus overstated potential.

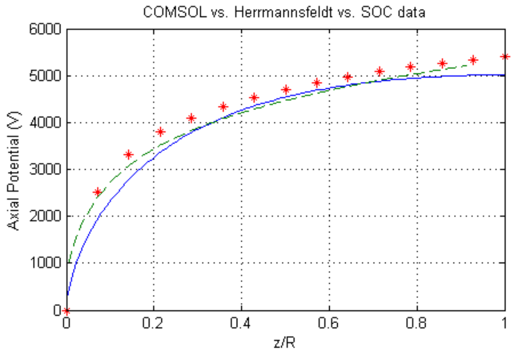

Figure 6: COMSOL (blue), Herrmannsfeldt (red), and SOC (green) data juxtaposed. z/R denotes a normalized scale from emission to extraction grid.

When comparing the normalized potential of the iEPS extraction region with the Ga^+ system (Figure 7), a more notable distinction can be made in the data. This was determined to be primarily due to scale and power differences: Table 1 in the Appendix notes some key differences between the iEPS and Ga^+ systems analyzed. The comparison between original and new Ga^+ extraction region characterization supports the iEPS data.

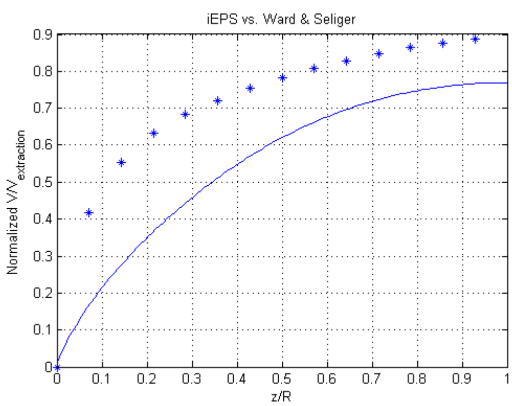

Figure 7: Comparison of iEPS (line) and Ga^+ extraction region (asterisk) normalized potential w.r.t. extraction grid voltage.

The understanding of the voltage potential across the extraction region in the iEPS system, as per the comparative analysis run between the COMSOL, Herrmannsfeldt, and SOC data, was deemed to be acceptable for the next step of this research: defining particle motion as a function of the electric fields, and modeling space charge accumulation according to that motion.

6. Future Work

Plume structure and composition is traditionally considered to a strong function of the space charge at the emission site [2, 8] more than of the extractor grid's electric field [2]. The electric field, however, is dominant in satellite and plume trajectories immediately beyond the extraction grid [1, 2, 3, 5], which influences the dominant space charge further downstream. The emitter energy (~1 V/Å in the iEPS system, 0.5V/Å in the Ga^+ system) is considered an integral contributor to far-field solid plume divergence angle. The solid plume angle is where the electrospray beam begins to break down and more "satellite" particles begin to be seen [2]. This particle type is less charged and less massive. Analyzing it is outside of the scope of this research, but $\sim 10^3$ J/m^3 energy densities were observed at the iEPS tip, much lower than the $\sim 10^7$ densities observed in the Ga^+ system; it is assumed that the discrepancy in scale has far-reaching effects in comparisons.

The case study of the Ga+ electrospray system will be utilized in the future to compare to iEPS; Ward's work's synergy with what findings are sought from this research support that procedure. Supporting experimental work utilizing the iEPS system in combination with various spacecraft polymers aims to indirectly support divergence studies by analyzing propellant deposition patterns and rates downstream of the thruster.

7. References

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9. Appendix

Table 1: Difference between the Ga^+ and iEPS system

Variable	iEPS	Ga^+
Emission bead diameter (Å)	150,000	1,000
Extraction grid potential (V)	1,200	6,000
Taylor cone half-angle (degrees)	49.7	15
Taylor cone separation (µm)	45	0.86