

The Effects of Geometry and Material Variations on the Onset Voltage of Electrospray Emitters

A Thesis Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

Justin Michael Jones

May 2020

© by Justin Michael Jones, 2020
All Rights Reserved.

Acknowledgments

I would first like to thank my advisor Dr. Trevor Moeller for guidance not only through this work, but through my academic career. I would also like to thank the additional members of my committee, Dr. Lino Costa and Dr. Brian Canfield, for their valuable input on the project. In addition, I am grateful for the research undertaken at the Center for Laser Applications at the University of Tennessee Space Institute by Dr. Lino Costa, Dr. Brian Canfield, and Alexander Terekhov. Their work has given great insight into the practical realizations of much of the theoretical work examined here. Finally, I would like to acknowledge the community of the University of Tennessee Space Institute as a whole for supporting me through my graduate studies.

Abstract

Electric propulsion is becoming an increasingly desirable technology as space missions become more complex and more commonplace. Electrospray propulsion specifically is proving promising as a low-thrust, high specific impulse technology with the ability to execute very precise thrust maneuvers in applications such as attitude adjustments to small satellites. Electrospray devices operate by electrostatic acceleration of charged droplets and/or ions to produce thrust. The current technological trend is to drive these devices towards the micro-scale. To become a viable space propulsion technology, the manufacturability, the required footprint, and the power requirements of electrospray devices are areas which must be addressed. With regards to manufacturability, this work proposes a new electrospray device design which utilizes liquid-filled through-channels bored in a dielectric material, as opposed to the free-standing needles in a more traditional electrospray device. This is achieved through technology at the Center for Laser Applications at the University of Tennessee Space Institute utilizing picosecond laser pulses shaped into a Bessel beam. This approach has shown potential to be both easier to manufacture and more robust than creating free-standing needles. In addressing required footprint and power requirements, this work performs a comprehensive study on the effects of geometric and material variations on the onset voltage of electrospray emitters. This study provides insight towards the creation of a design configuration that can minimize onset voltage and maximize thrust density. The effects of the thickness of the dielectric material, relative permittivity of the dielectric material, extractor distance, radius of the ionic liquid channel, and emitter pitch on the onset voltage are examined. Results show that, in general, tall, small-radius channels surrounded by a material with a low relative permittivity value and with emitter pitch values resulting in a ratio of emitter pitch to emitter height of 2.5 or greater give the lowest onset voltages.

The relationships between the various parameters are complex, however. These complexities are discussed in detail within this work.

Table of Contents

1	Introduction	1
1.1	Electric Propulsion Overview	1
1.2	Electrospray Thrusters	3
1.2.1	Overview	3
1.2.2	Typical Emitter Designs	5
1.2.3	Applications in Space Propulsion	5
1.3	Previous Work in the Literature	7
1.4	Motivation	11
1.5	Organization	12
2	Background	13
2.1	Electromagnetic Governing Equations	13
2.2	Fluid Dynamics Governing Equations	16
2.3	Physics of Electrospray Devices	17
2.3.1	Electrohydrodynamic Model	17
2.3.2	Quasi-Static Evolution	20
2.3.3	Taylor Cone	23
2.4	Proposed Electrospray Device Design	25
3	Methodology	28
3.1	Computational Model	28
3.2	Obtaining Onset Voltage	29
3.3	Simulation Variations	32

4	Results and Discussion	34
4.1	Thickness of Dielectric	34
4.2	Relative Permittivity of Dielectric	43
4.3	Extractor Distance	52
4.4	Radius of Ionic Liquid Channel	55
4.5	Pitch in Emitter Arrays	58
4.6	Further Discussion	60
5	Conclusions and Future Work	62
5.1	Conclusions	62
5.2	Capabilities and Limitations	63
5.3	Suggestions for Future Work	64
	References	65
	Vita	71

List of Tables

1.1	Typical specific impulse values for various types of propulsion [29].	3
3.1	Relative permittivity values for various media (from ANSYS EDT materials library [1]).	33

List of Figures

1.1	Basic operation of an electrospray device.	4
1.2	Schematic of typical electrospray emitter designs.	6
2.1	Qualitative plot of equilibrium voltage as a function of apex radius. Note that the apex radius axis uses a log scale.	23
2.2	Plot of conic section representation of the liquid meniscus with $\beta = 49.3^\circ$ and $r = 0.5 \mu\text{m}$	25
2.3	Schematic of newly proposed electrospray device design.	26
2.4	Optical microscope image of $170 \mu\text{m}$ thick SiO_2 wafer with through-channel sub-micron capillaries formed by the CLA at UTSI using picosecond laser pulses shaped into a Bessel beam. Bottom surface on the left, and top surface on the right	27
3.1	Setup of computational model in ANSYS EDT for a single, isolated emitter.	29
3.2	Setup of computational model in ANSYS EDT for an emitter array.	30
3.3	Flow diagram of methodology used to determine the onset voltage.	31
4.1	Onset voltage as a function of dielectric thickness. Each subplot corresponds to a different capillary radius. For all cases $d = 100 \mu\text{m}$	35
4.2	Sketch of semi-inifinite model.	38
4.3	Background electric field strengths as a function of thickness of the dielectric for the semi-infinite model.	40
4.4	Plots of α as a function of h . Linear fits (solid lines) of the form $\alpha = ah + b$ have been applied to the data.	42

4.5	Plots of $\partial V_{onset}/\partial h$ as a function of h for the parameter space considered in this study.	44
4.6	Potential contours for two different emitter configurations. Top: $h = 200 \mu\text{m}$. Bottom: $h = 500 \mu\text{m}$. Right: expanded views of the liquid tip regions. . . .	45
4.7	Onset voltage as a function of relative permittivity of dielectric material. Each subplot corresponds to a different capillary radius. For all cases $d = 100 \mu\text{m}$	46
4.8	Background electric field strengths as a function of relative permittivity of the dielectric for the semi-infinite model.	48
4.9	Plots of α as a function of ϵ_r . Fits (solid lines) of the form $\alpha = 1/\left(a(\epsilon_r)^b + c\right)$ have been applied to the data.	49
4.10	Plots of $\partial V_{onset}/\partial \epsilon_r$ as a function of ϵ_r for the parameter space considered in this study.	51
4.11	Onset voltage as a function of extractor distance for $h = 100 \mu\text{m}$. Each subplot corresponds to a different capillary radius.	53
4.12	Onset voltage as a function of extractor distance for $h = 500 \mu\text{m}$. Each subplot corresponds to a different capillary radius.	54
4.13	Onset voltage as a function of capillary radius. Each subplot corresponds to a different emitter height. For all cases $d = 100 \mu\text{m}$	57
4.14	Normalized voltage as a function of the ratio of emitter pitch to emitter height in an array of emitters. For each case $r_c = 0.5 \mu\text{m}$. Top: entire parameter space. Bottom: p/h range with only moderate shielding.	59

Nomenclature

Note that boldface characters denote vectors and double overbars denote tensors.

Electromagnetics

α	Electric field amplification factor	—
ϵ	Scalar permittivity	F/m
ϵ_r	Relative permittivity	—
$\hat{E}$	Electric field strength in the absence of the emitter	V/m
$\mathbf{B}$	Magnetic induction	Wb/m^2
$\mathbf{D}$	Electric displacement	C/m^2
$\mathbf{E}$	Electric field intensity	V/m
$\mathbf{F}_{\mathbf{EM}}$	Lorentz force	N/m^3
$\mathbf{F}_{\mathbf{E}}$	Electrostatic force	N/m^3
$\mathbf{f}_s^{\mathbf{EM}}$	Interfacial electromagnetic forces	N/m^2
$\mathbf{H}$	Magnetic field intensity	A/m
$\mathbf{J}$	Electric current density	A/m^2
$\mathbf{M}$	Magnetization	A/m

$\mathbf{P}$	Polarization	C/m^2
μ	Scalar permeability	H/m
μ_r	Relative permeability	—
Φ	Electric potential	V
$\overline{\overline{\chi}}_e$	Electric susceptibility	—
$\overline{\overline{\chi}}_m$	Magnetic susceptibility	—
$\overline{\overline{\epsilon}}$	Permittivity tensor	F/m
$\overline{\overline{\mu}}$	Permeability tensor	H/m
σ	Electrical conductivity	S/m
τ_E	Characteristic time for electric phenomena	—
τ_M	Characteristic time for magnetic phenomena	—
C	Ratio of E_{apex} to $V_{applied}$	$1/m$
E_0	Equilibrium electric field	V/m
E_{apex}	Electric field strength at the apex of the liquid shape	V/m
K	Linear current density	A/m
q	Volumetric free space-charge density	C/m^3
q_s	Surface charge density	C/m^2
V_0	Equilibrium voltage	V
$V_{applied}$	Applied voltage between emitter and extractor grid	V
$V_{onset,single}$	Onset voltage of single, isolated emitter	V
V_{onset}	Onset voltage	V

Fluid Dynamics

γ	Surface tension coefficient	N/m
κ	Local radius of curvature	$1/m$
$\mathbf{F}_G$	Gravitational body force	N/m^3
$\mathbf{f}$	Body force	N/kg
$\mathbf{u}$	Velocity	m/s
ρ	Mass density	kg/m^3
τ_v	Viscous stress tensor	N/m^2
e_0	Total specific energy	J/kg
k	Heat transfer coefficient	$W/(m \cdot K)$
p	Pressure	N/m^2
R	Specific gas constant	$J/(kg \cdot K)$
T	Temperature	K

Device Geometry

d	Extractor distance	m
h	Dielectric thickness	m
p	Emitter pitch	m
r_c	Capillary radius	m

Other

β	Taylor cone semi-vertex angle	$^\circ$
δ_{ij}	Kronecker delta	—

$\mathbf{n}$	Unit normal vector	—
ϕ	Angle of revolution of conic section	rad
θ	Angle from horizontal to exterior of Taylor cone	rad
a	Fitting coefficient	
b	Fitting coefficient	
c	Fitting coefficient	
l	Characteristic length	m
r	Radius of base of conic section	m
r_a	Liquid surface apex radius	m
s	Parametric variable for conic section	—
t	Time	s
w	Sharpness parameter of conic section	—

Physical Constants

ϵ_0	Permittivity of free space	$8.854 \times 10^{-12} F/m$
μ_0	Permeability of free space	$1.257 \times 10^{-7} H/m$
g_0	Standard gravitational constant	$9.807 m/s^2$

Propulsion Performance Parameters

Δv	Velocity increment	m/s
I_{sp}	Specific impulse	s
m_0	Initial spacecraft mass	kg
m_f	Final spacecraft mass	kg

m_p	Propellant mass	kg
u_e	Exhaust velocity	m/s

Subscripts and Superscripts

n	Normal direction	—
t	Tangential direction	—
1	Medium/region 1	—
2	Medium/region 2	—

Chapter 1

Introduction

The purpose of this research is to numerically investigate the effects of geometry and material variations on the onset voltage of electrospray emitters. A variety of parameters are examined which give general guidelines for the design of electrospray devices. Before detailing the research effort, this report will cover the importance of electric propulsion, where electrospray thrusters fit in this field, and background knowledge necessary to take on this research.

1.1 Electric Propulsion Overview

One of the most important factors in the design of a space mission is mass. How much useful payload mass is allowed? Or, in other words, what mass of propellant will be necessary for a spacecraft of a certain mass to complete a maneuver (or set of maneuvers) in a mission? This problem can be summarized by the famous rocket equation [14]:

$$\Delta v = u_e \ln \frac{m_0}{m_f}, \quad (1.1)$$

where Δv is the velocity increment required for the maneuver, u_e is the propellant exhaust velocity, m_0 is the initial mass of the spacecraft (including propellant), and m_f is the mass of the spacecraft after the maneuver. Take the simple case of $m_0 = m_f + m_p$, where m_p is the mass of propellant consumed to achieve the desired Δv , and it is easy to see that if the

goal is to minimize the required propellant mass, then it is desirable to drive the mass ratio, m_0/m_f , towards unity. Rearranging Eq. (1.1) to isolate the mass ratio yields

$$\frac{m_0}{m_f} = \exp\left(\frac{\Delta v}{u_e}\right). \quad (1.2)$$

Thus, in order to drive the mass ratio towards unity, it is necessary to drive the argument of the exponential, $\Delta v/u_e$, towards zero. The value for Δv is set by the required maneuver; therefore, driving this argument towards zero must be satisfied by achieving a high exhaust velocity, u_e . It is often more common when considering thruster performance to refer to specific impulse, I_{sp} , instead of exhaust velocity. The relationship between these parameters is given by:

$$u_e = I_{sp}g_0, \quad (1.3)$$

where g_0 is standard gravity (9.81 m/s² in mks units). Thus, achieving high exhaust velocities is synonymous with achieving high values of specific impulse.

Satisfying this constraint is where electric propulsion becomes attractive. Especially as it has matured, electric propulsion has become a very efficient means of space propulsion. Jahn [14] defines electric propulsion as, “The acceleration of gases for propulsion by electrical heating and/or by electric and magnetic body forces.” Electric propulsion devices offer much higher values of specific impulse than conventional chemical rockets. Many chemical rocket upper stages have specific impulse values in the 400 s range. Electric propulsion devices can have specific impulse values ranging up to many thousands of seconds. Table 1.1 shows typical specific impulse values for a variety of propulsion technologies [29]. The high specific impulse values of electric propulsion devices come at a cost, though. These devices are low-thrust. Even the most powerful electric propulsion devices are only capable of producing minute levels of thrust, compared to a chemical rocket, only on the order of 1 N.

Taking all of this into account, electric propulsion emerges as a strong choice in two main areas. First, electric propulsion devices are strong candidates for unmanned deep space missions. These are missions requiring high Δv and where it is important to keep mass low, since more mass equates to more cost for the initial launch of the vehicle from the Earth’s surface. In these missions, efficiency (i.e., cost reduction) takes precedence over higher thrust

Table 1.1: Typical specific impulse values for various types of propulsion [29].

Type of Propulsion	I_{sp} (s)
Chemical Rocket	200–470
Nuclear Thermal	500–860
Electrothermal	280–1200
Electrostatic	1200–5000
Electromagnetic	700–2500

values. Second, electric propulsion devices are desirable for precision control applications. Since electric propulsion devices are low-thrust, they are typically capable of delivering small, precise thrust commands, making them perfect candidates for attitude control and station keeping.

1.2 Electrospray Thrusters

1.2.1 Overview

This work focuses on electrospray thrusters. As such, it is necessary to understand their place in electric propulsion and to begin to understand the principles behind their operation. These devices are typically made up of emitters, an extractor grid, a liquid propellant, a power-processing unit, and a propellant feed system. Power-processing units and propellant feed systems will not be discussed in this work, as they do not have an influence on the parameters of concern in this research. Electrospray thrusters operate through the acceleration of a liquid propellant by an electrostatic field. The physics governing this operation are discussed in more detail in Sec. 2.3; but for now examine Fig. 1.1 for a schematic representation of this operation. An electric field is created due to an applied potential difference between the emitter and extractor grid. This electric field, which is intensified by a typically sharp emitter, causes the liquid propellant to deform into what has become known as a Taylor cone [30]. The Taylor cone is a very important factor in

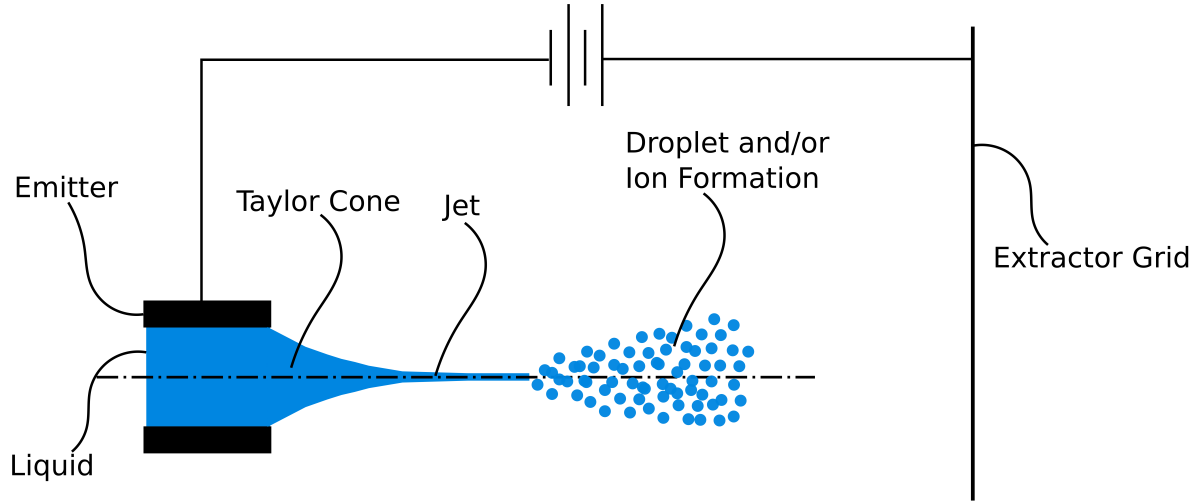


Figure 1.1: Basic operation of an electrospray device.

the operation of an electrospray thruster and will be more thoroughly discussed later. This feature is a formation that arises due to the balance of electrical stress and surface tension stress at the liquid interface. Due to the increasingly sharp apex of the liquid cone, a jet emerges that breaks up in the form of charged liquid droplets, ions, or a combination of both. The expulsion of these droplets and/or ions out of the device, through the extractor grid, is the mechanism by which thrust is produced.

Electrospray thrusters are typically small devices, with early designs utilizing emitters with diameters in the millimeter range. As technology has advanced, cutting-edge designs are now employing emitters with diameters in the micrometer range. Of course, at such small scales thrust levels for these devices are quite low. Depending on device design and the number of emitters in a thruster, electrospray devices typically produce thrust levels on the order of micro-Newtons [25]. Specific impulse values, however, can be high in thrusters operating in a purely ionic mode of emission. Droplet mode devices typically have specific impulse values in the hundreds of seconds, while thrusters operating in a purely ionic mode can reach specific impulse values of several thousand seconds [25].

1.2.2 Typical Emitter Designs

Electrospray devices are typically comprised of emitters in one of three categories: capillary emitters, externally wetted emitters, or porous emitters, as shown in Fig. 1.2. All three emitter types share a common trait; the emitter is designed in a needle-like fashion to create a sharp feature, which leads to a locally intense electric field at the tip of the emitter. In a capillary emitter, liquid is drawn up to the emitter tip through an internally fed needle-like capillary, where the liquid deforms into a Taylor cone due to the presence of the strong electric field, such as the electrospray device developed by Krpoun and Shea [19]. Externally wetted emitters are solid needle-like features which utilize the proper materials and coatings to increase surface wettability. Careful selection of emitter material and liquid propellant ensure that the liquid wets the surface of the emitter, which places liquid at the emitter tip where it deforms into a Taylor cone. The electrospray device developed by Lozano and Martínez-Sánchez [22] utilizes externally wetted emitters. Porous emitters, as are present in the electrospray device developed by Courtney and Lozano [5], work in a very similar manner; however, rather than flooding a solid emitter with liquid, pores in the emitter allow fluid to be drawn up through the emitter, which then wets the surface. The liquid present at the needle tip then deforms into a Taylor cone.

Part of this work is the proposal of a new electrospray emitter type that utilizes through-channels in a dielectric. This new design aims to eliminate some of the various manufacturing issues that arise in the micromachining of traditional emitter designs. A thorough explanation of this design is presented in Sec. 2.4.

1.2.3 Applications in Space Propulsion

As previously mentioned in Sec. 1.1, one main area of application of electric propulsion is in missions requiring low-thrust, precision-control maneuvers, such as attitude control and station keeping. This is the area for which electrospray thrusters are most well-suited. While, to date, electrospray thruster use on in-space missions has been limited, electrospray thrusters are good candidates for use on missions utilizing small spacecraft, such as CubeSats. While many different types of electric propulsion devices are capable of operating at the

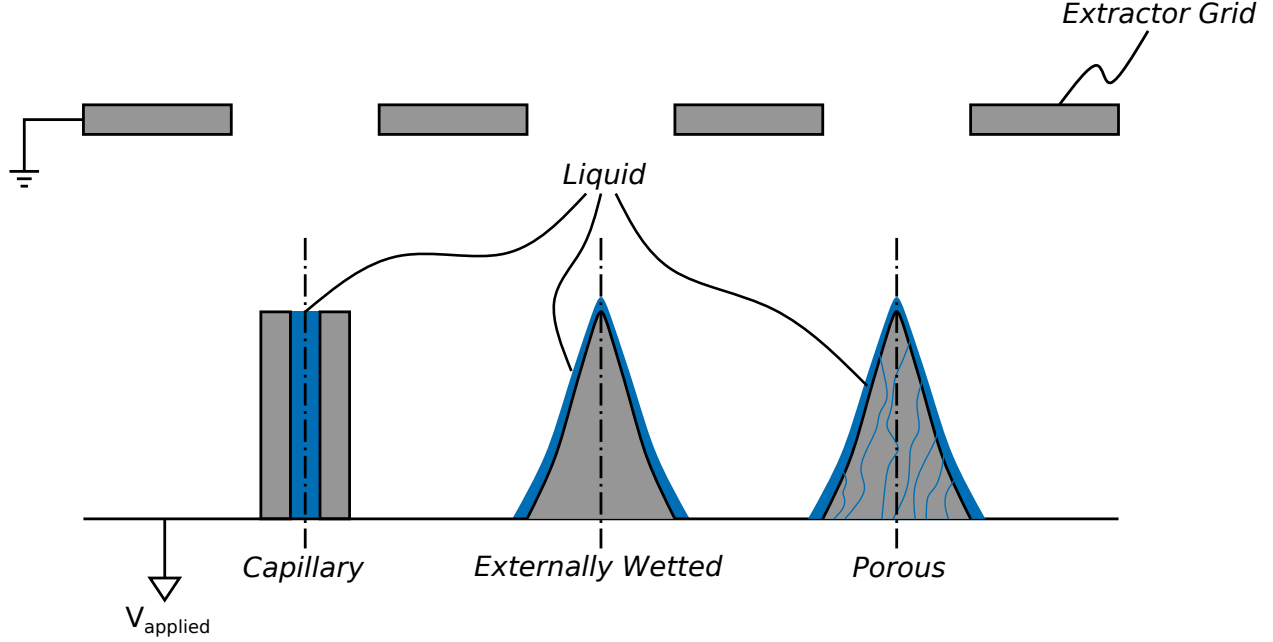


Figure 1.2: Schematic of typical electro spray emitter designs.

appropriate thrust and specific impulse levels required for small satellite missions, many of them are much too large to fit within the confines of a small satellite or leave little to no space for scientific payloads. Electro spray thrusters, however, have great potential to be miniaturized down to the scales necessary for small satellite use. Much of the current research into electro spray technology focuses on creating thrusters on micro- and nanoscales [17, 19, 6, 31].

So far, electro spray thrusters have been demonstrated in space in only one large-scale mission, the NASA Space Technology 7 (ST7) European Space Agency Laser Interferometer Space Antenna (LISA) Pathfinder mission [34]. In this mission, the Colloid Micronewton Thrusters developed by Busek Company, Inc. successfully demonstrated the ST7 performance requirements of 5–30 μN of thrust with 0.1 μN resolution and $\leq 0.1 \mu\text{N}/\text{Hz}^{1/2}$ thrust noise [34]. This mission served as a technology demonstration for ESA’s LISA program which aims to use laser interferometry to measure gravitational waves. In the full-scale LISA mission, electro spray thrusters on the spacecraft must be able to maintain positioning within about 10 nm between free-floating test masses and the spacecraft for the

mission to provide accurate gravitational wave measurements. Outside of this mission, the only other in-space demonstrations of electrospray thrusters have come from a handful of academic demonstrations on CubeSats, namely the two CubeSats launched as part of the Irvine CubeSat STEM Program, which utilized electrospray thrusters developed by Accion Systems, Inc. [12, 13].

1.3 Previous Work in the Literature

Some of the earliest work relevant to electrospraying behavior dates back to research examining the deformation of liquids in the presence of electric fields. In his 1914 work [32], while studying electrical discharges from liquids, Zeleny appears to have, somewhat accidentally, captured electrospraying phenomenon. In a follow-on work published in 1917 [33], Zeleny further examined this behavior, where he presented photographs of the spraying behavior and qualitatively described various modes of emission. His descriptions detailed the same behavior in electrospray devices that are still being studied to this day. At one point Zeleny [33] stated,

Under certain conditions of potential and hydrostatic pressure it is possible to get the alcohol drop at the end of the tube to assume the form of a cone with a fine thread of liquid coming from its apex. This condition is quite steady and is especially suited for a closer study of the liquid thread, which characterizes the state of the instability, as well as of the droplets into which the thread disintegrates. (p. 4)

Whether he knew it or not, Zeleny had just demonstrated a capillary-type electrospray emitter operating in a droplet mode. The “certain conditions of potential” that he described refer to what is now known as the onset voltage, and the “cone with a fine thread of liquid coming from its apex” is known today as Taylor cone-jet emission.

After Zeleny’s efforts, the next major works started to focus more on the structure of the cone-jet behavior. First, in 1964, Taylor [30] derived the conditions for which a conical fluid meniscus could exist in equilibrium in an electric field. His analysis showed that such

a surface could only exist for a cone with a semi-vertex angle of 49.3° . In the same work, Taylor validated this derivation experimentally by capturing several photographs of cone-jet electrospray emission. This research contribution is what ultimately led to the conic deformation of a liquid in an electric field to be called a Taylor cone.

Five years later, in 1969, Melcher and Taylor [24] presented a work focused on an in-depth mathematical description of the physics governing this type of behavior. This work brought together the field of fluid mechanics with the field of electrodynamics, and laid out the governing equations for electrohydrodynamics. Electrohydrodynamics is concerned with the class of behaviors in which the electrodynamics can be reduced to electrostatics. This reduction is possible when the dynamic currents are small enough that magnetic induction is negligible, and thus, the electric field is irrotational. After presenting the governing equations, Melcher and Taylor went on to perform a variety of experiments of special cases in order to validate the model. In the developed model, the influence of electrical stress on the fluid motion was included, but the model did not include an influence of the fluid motion on the electric field. Through the experiments, this model was shown to be valid when the electric Reynolds number, defined as the ratio of charge-relaxation time to the time for the fluid to move a characteristic length at a characteristic velocity, was much less than unity.

More recently, research has turned to focus on the development of more refined electrospray devices. Since this work focuses on numerical modeling of electrospray emitters, the remainder of this review will focus on contemporary research in this area. There are numerous works concerned with numerical modeling of the full electrohydrodynamic behavior found in electrospray devices, such as the works of Rahmanpour and Ebrahimi [27], Lastow and Balachandran [20], and López-Herrera, Popinet, and Herrada [21].

In their 2016 work, Rahmanpour and Ebrahimi [27] coupled the commercial computational fluid dynamics (CFD) software ANSYS FLUENT [1] with a custom electrostatic solver to numerically simulate cone-jet electrospray behavior. Their method coupled the electrostatics with the fluid dynamics through the addition of an electrostatic momentum source term to the fluid momentum equation. This source term was simplified to a

contribution by only the Coulombic force as

$$\mathbf{F}_E = q\mathbf{E}, \quad (1.4)$$

where q is the volumetric free charge density and $\mathbf{E}$ is the electric field, under the assumptions that the simulated liquid was incompressible, of constant electrical permittivity, and that the charge-relaxation time was small compared to the characteristic breakup time of the liquid. The last of these assumptions corresponds with the restriction on the electric Reynolds number given by Melcher and Taylor [24]. The model that they developed performed well when compared to experimental work on a similar setup performed by Hartman et al [11].

Lastow and Balachandran [20] took on a similar endeavor; however, in their numerical simulations the commercial CFD code CFX 4.4 [1] was used. Rather than using a custom electrostatic solver, Lastow and Balachandran modified the heat equation solver built into the CFD code to solve for the electrostatic potential. In this way, they created a coupled model, just as Rahmanpour and Ebrahimi, by adding the same electrostatic momentum source term to the fluid momentum equation. The results from this model were compared with experimental work by Gañán-Calvo, Dávila, and Barrero [9]. Results compared well between the simulations and experiments when comparing the range of operating voltage; however, Lastow and Balachandran stated that the jet diameter of the cone-jet in the numerical simulations was not compared to the experiments due to insufficient mesh resolution.

The work of López-Herrera et al. [21] differs from the previous two articles mentioned. This work focused on the development of a numerical scheme to deal with electrohydrodynamic problems and performance of the scheme in test cases for verification. López-Herrera et al. developed a scheme that incorporates electric forces into the Navier-Stokes equations, similar to the other works mentioned here, but went farther by also incorporating the migration of charge by both convection and conduction in the electric charge conservation equation. The scheme was implemented into the open-source solver Gerris [26] as an electrohydrodynamic extension. The main deviation between this scheme and the other works mentioned here is the inclusion of an additional governing equation to enforce the

conservation of charge:

$$\frac{\partial q}{\partial t} + \nabla \cdot \mathbf{J} = 0, \quad (1.5)$$

where q is the volumetric free charge density and $\mathbf{J}$ is the current density vector. After laying out the method of discretization and implementation of this scheme, López-Herrera et al. detailed the results of various test cases for the new scheme. The last of these test cases was the deformation of a conducting drop under the influence of an electric field. The success of the method in this test case shows great promise for the ability of this scheme to be extended to the simulation of electrospray devices. In fact, López-Herrera et al. list the modeling of electrospray devices as a possible future application of their work.

The methods of numerical analysis detailed so far have provided many informative results; however, these methods are not well-suited for determining the onset voltage of electrospray emitters. These methods require the potential difference between the extractor electrode and the emitter to be specified as a boundary condition. Therefore, one can only determine the onset voltage by a trial and error approach. This is very time-consuming, not only due to the nature of attempting different potential difference values, but due to the computationally expensive nature of the full electrohydrodynamic modeling. These methods are most useful for the transient analysis of the cone-jet development and examination of dynamic effects such as inlet flow rate and space-charge variation.

There is a different approach of numerical simulation that has been suggested by Krpoun and Shea [18] that uses a series of electrostatic simulations to determine the emitter onset voltage. This method is discussed in more detail in Sec. 3.2, but as an introduction, the basis for this method relies on the assumption of a quasi-static evolution of the Taylor cone. In this method, a series of electrostatic simulations are performed on various assumed liquid shapes that evolve towards an ideal Taylor cone. Krpoun and Shea showed that after the assumed shape reaches a certain apex radius, the applied potential that would be necessary for that liquid shape to be in equilibrium (balance of surface tension stress with electric stress) becomes constant. Results from this method agreed well with the onset voltage values for experimental devices examined by Krpoun and Shea.

This approach is very well-suited for determination of onset voltage because the simulations are not dependent on the applied potential boundary conditions, since the applied potential can be normalized by the electric field found at the tip of the assumed shape. Furthermore, these electrostatic simulations are much less computationally expensive than the full electrohydrodynamic models. Thus, this approach can be used to find the onset voltage of an emitter much quicker than the other methods discussed here. Of course, this comes at the expense of losing all of the transient data and examination of the dynamic effects that the other methods give. Since this work is focused only on the onset voltage variation in electrospray emitters, this method of simulation will be adopted. Sections 2.3 and 3.2 will provide details on the physics allowing for this approach, as well as the implementation for use in this study.

1.4 Motivation

Motivation for this research originates from the Micro Scalable Thruster for Adaptive Mission Profiles in Space (μ STAMPS) project at the University of Tennessee Space Institute. The goal of the μ STAMPS project is to develop a micro-scale electrospray thruster suitable for small satellite missions. Two main constraints are set for small satellite suitability: low onset voltage and high thrust density. Striving for low onset voltage will help keep satellite bus voltages low and put less complexity in power supply requirements. High thrust density is necessary to keep the thruster footprint as small as possible, while still meeting the thrust levels required by the mission, in order to leave ample capacity for mission-specific payloads. This research aims to move this project forward by examining the effects that geometry and material variations have on the onset voltage of electrospray emitters via numerical simulation. The results of this research will provide valuable trends and guidelines to follow in the development of an electrospray thruster design.

1.5 Organization

The remaining content in this document is structured as follows. Chapter 2 lays out the governing physics necessary to examine the behavior of electrospray devices and provides details on the new thruster design proposed in this work. Chapter 3 details the implementation of the simulation approach and explains the parameter space that will be examined. Results are discussed in Chapter 4. Finally, conclusions and suggestions for follow-up work are given in Chapter 5

Chapter 2

Background

2.1 Electromagnetic Governing Equations

At the most detailed level, the behavior of electrospray devices is governed by the full set of equations governing electromagnetics coupled with the full set of equations governing fluid dynamics. The equations governing electromagnetics are Maxwell's equations:

$$\nabla \times \mathbf{E} + \frac{\partial \mathbf{B}}{\partial t} = 0, \quad (2.1)$$

$$\nabla \times \mathbf{H} - \frac{\partial \mathbf{D}}{\partial t} = \mathbf{J}, \quad (2.2)$$

$$\nabla \cdot \mathbf{D} = q, \quad (2.3)$$

$$\nabla \cdot \mathbf{B} = 0, \quad (2.4)$$

where $\mathbf{E}$ is the electric field intensity, $\mathbf{B}$ is the magnetic induction, $\mathbf{H}$ is the magnetic field intensity, $\mathbf{D}$ is the electric displacement, $\mathbf{J}$ is the electric current density, and q is the free charge density. To make this set complete, a set of constitutive relations is also needed to relate $\mathbf{D}$ and $\mathbf{B}$ with $\mathbf{E}$ and $\mathbf{H}$:

$$\mathbf{D} = \epsilon_0 \mathbf{E} + \mathbf{P}, \quad (2.5)$$

$$\mathbf{B} = \mu_0 (\mathbf{H} + \mathbf{M}), \quad (2.6)$$

where $\mathbf{P}$ is the polarization, ϵ_0 is the permittivity of free space, $\mathbf{M}$ is the magnetization, and μ_0 is the permeability of free space.

The nature of $\mathbf{P}$ and $\mathbf{M}$ can be complicated; however, in this work a linear relationship between $\mathbf{P}$ and $\mathbf{E}$ and between $\mathbf{M}$ and $\mathbf{H}$ is assumed, yielding

$$\mathbf{P} = \epsilon_0 \bar{\bar{\chi}}_e \mathbf{E} \quad (2.7)$$

and

$$\mathbf{M} = \bar{\bar{\chi}}_m \mathbf{H}, \quad (2.8)$$

where $\bar{\bar{\chi}}_e$ and $\bar{\bar{\chi}}_m$ are the electric and magnetic susceptibility tensors, respectively. Substituting Eq. (2.7) into Eq. (2.5) and Eq. (2.8) into Eq. (2.6) gives

$$\mathbf{D} = \epsilon_0 \mathbf{E} (\delta_{ij} + \bar{\bar{\chi}}_e) \quad (2.9)$$

and

$$\mathbf{B} = \mu_0 \mathbf{H} (\delta_{ij} + \bar{\bar{\chi}}_m), \quad (2.10)$$

respectively. From here, an electrical permittivity and a magnetic permeability of a medium can be defined as

$$\bar{\bar{\epsilon}} = \epsilon_0 (\delta_{ij} + \bar{\bar{\chi}}_e) \quad (2.11)$$

and

$$\bar{\bar{\mu}} = \mu_0 (\delta_{ij} + \bar{\bar{\chi}}_m), \quad (2.12)$$

respectively. For isotropic media, these two properties are reduced to constant scalar terms denoted ϵ and μ . These quantities are often used to define a relative permittivity, ϵ_r , and a relative permeability, μ_r , where

$$\epsilon_r = \frac{\epsilon}{\epsilon_0} \quad (2.13)$$

and

$$\mu_r = \frac{\mu}{\mu_0}. \quad (2.14)$$

Now, Eq. (2.5) and Eq. (2.6) finally become

$$\mathbf{D} = \epsilon_0 \epsilon_r \mathbf{E} = \epsilon \mathbf{E} \quad (2.15)$$

and

$$\mathbf{B} = \mu_0 \mu_r \mathbf{H} = \mu \mathbf{H}. \quad (2.16)$$

Thus, the electromagnetic behavior is fully described by Maxwell's equations (Eqs. (2.1)–(2.4)) and the final form of the two constitutive relations (Eqs. (2.15) and (2.16)).

Note, the charge conservation equation can be obtained by taking the divergence of Eq. (2.2),

$$\nabla \cdot \nabla \times \mathbf{H} - \frac{\partial}{\partial t} (\nabla \cdot \mathbf{D}) = \nabla \cdot \mathbf{J}, \quad (2.17)$$

applying the vector identity $\nabla \cdot \nabla \times \mathbf{A} = 0$, where $\mathbf{A}$ is any vector, and using the relation in Eq. (2.3), yielding

$$\frac{\partial q}{\partial t} + \nabla \cdot \mathbf{J} = 0. \quad (2.18)$$

Finally, as the problem in this work involves interacting media with different electromagnetic properties, the treatment of the interfacial conditions of these properties must be examined. The interface boundary conditions are given by [16]

$$D_{n1} - D_{n2} = q_s, \quad (2.19)$$

$$E_{t1} - E_{t2} = 0, \quad (2.20)$$

$$B_{n1} - B_{n2} = 0, \quad (2.21)$$

$$H_{t1} - H_{t2} = K, \quad (2.22)$$

where the subscript n denotes the component normal to the interface, the subscript t denotes the component tangential to the interface, the subscripts 1 and 2 denote medium 1 and medium 2, respectively, q_s is the surface charge density on the boundary, and K is the linear density of current flowing in a current sheet at the interface. Simplifications that can be made to these governing equations due to the nature of the operation of electrospray devices are discussed in Sec. 2.3.

2.2 Fluid Dynamics Governing Equations

In general, fluid dynamics are governed by the principles of conservation of mass, conservation of momentum, and conservation of energy, along with an equation of state. The mass conservation equation states

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0, \quad (2.23)$$

where ρ is the mass density of the fluid and $\mathbf{u}$ is the fluid velocity vector. Conservation of momentum is written as

$$\frac{\partial (\rho \mathbf{u})}{\partial t} + \nabla \cdot (\rho \mathbf{u} \mathbf{u}) = -\nabla p + \rho \mathbf{f} + \nabla \cdot \tau_v, \quad (2.24)$$

where p is pressure, $\mathbf{f}$ represents body forces (force per unit mass), and τ_v is the viscous stress tensor. And, the energy conservation equation is

$$\frac{\partial (\rho e_0)}{\partial t} + \nabla \cdot (\rho e_0 \mathbf{u}) = -\nabla \cdot (p \mathbf{u}) + \rho \mathbf{f} \cdot \mathbf{u} + \nabla \cdot (k \nabla T) + \nabla \cdot (\tau_v \mathbf{u}), \quad (2.25)$$

where e_0 is the total specific energy, k is a heat transfer coefficient, and T is temperature. A typical equation of state is that of an ideal, calorically perfect (constant specific heat) gas:

$$p = \rho R T, \quad (2.26)$$

where R is the specific gas constant.

The problem of concern in this study also involves a fluid-fluid interface; therefore, Eqs. (2.23)–(2.26) must be solved simultaneously for each fluid. In addition, there must be some inclusion of the surface tension effects. Surface tension is an interfacial phenomenon that is only present at the fluid-fluid interface. Therefore, surface tension does not appear in the equations given above as they govern the bulk fluid flow. The surface tension is applied through the interfacial boundary condition. At a fluid-fluid interface, the surface

stress boundary condition is [2]

$$(p_1 - p_2 + \gamma\kappa) \mathbf{n} = (\tau_{v1} - \tau_{v2}) \mathbf{n} + \nabla \cdot \gamma, \quad (2.27)$$

where the subscripts 1 and 2 denote the two different fluids, $\mathbf{n}$ is the unit normal vector in the direction from fluid 1 into fluid 2, γ is the surface tension coefficient, and κ is the local radius of curvature of the interface. This results from a balance of surface stresses at the boundary. This formulation has ignored surface stresses that arise due to electromagnetic phenomenon. For the case of concern in this study an additional term should be added to Eq. (2.27) to yield

$$(p_1 - p_2 + \gamma\kappa) \mathbf{n} = (\tau_{v1} - \tau_{v2}) \mathbf{n} + \nabla \cdot \gamma + \mathbf{f}_s^{EM}, \quad (2.28)$$

where $\mathbf{f}_s^{EM}$ represents surfaces forces that arise due to electromagnetic effects.

To this point, the body force $\rho\mathbf{f}$ has been left as a generic representation, but note that $\rho\mathbf{f}$ can include many different physical phenomena. Relevant to this study, $\rho\mathbf{f}$ can include electromagnetic forces and gravitational forces. Further discussion of this topic is included in Sec. 2.3. As stated in Sec. 2.1, simplifications that can be made to these governing equations due to the nature of the operation of electrospray devices are discussed in Sec. 2.3.

2.3 Physics of Electrospray Devices

2.3.1 Electrohydrodynamic Model

Taking the full set of governing equations as they are given in Secs. 2.1 and 2.2 is a very complex problem. Fortunately, the nature of electrospray device operation allows for some simplifications to be made to these equations.

First, consider simplifications that can be made to Maxwell's equations (Eqs. (2.1)–(2.4)). The characteristic time for electric phenomena, τ_E , is [28]

$$\tau_E \equiv \frac{\epsilon_r \epsilon_0}{\sigma}, \quad (2.29)$$

where σ is the electrical conductivity of the medium. Similarly, the characteristic time for magnetic phenomena, τ_M , is [28]

$$\tau_M \equiv \mu_r \mu_0 \sigma l^2, \quad (2.30)$$

where l is a characteristic length. As stated by Saville [28], an electrostatic approximation can be applied to the electromagnetics when $\tau_E \gg \tau_M$. Take, for example, deionized water, where $\epsilon_r \epsilon_0$ is on the order of 10^{-11} F/m, $\mu_r \mu_0$ is on the order of 10^{-6} H/m, and σ is on the order of 10^{-6} S/m [21]. On a micrometer length scale ($l = 10^{-6}$ m), τ_M/τ_E is on the order of 10^{-19} . Clearly, in this case, $\tau_E \gg \tau_M$, and an electrostatic assumption would be appropriate. However, in electrospray thrusters, ionic liquids are commonly used as propellant and have electrical conductivity values much higher than that of water. For 1-ethyl-3-methylimidazolium tetrafluoroborate (EMI-BF₄), a common electrospray thruster propellant, $\sigma = 1.4$ S/m [15]. Keeping $\epsilon_r \epsilon_0$ and $\mu_r \mu_0$ the same, since there is relatively little variation in these values, τ_M/τ_E is on the order of 10^{-7} . For the case of EMI-BF₄ τ_E is still several orders of magnitude longer than τ_M ; therefore, applying an electrostatic assumption is still valid in this scenario.

Applying an electrostatic assumption yields the following changes to the electromagnetic governing equations. In Eq. (2.1) the $\partial \mathbf{B}/\partial t$ term goes to zero and the equation becomes

$$\nabla \times \mathbf{E} = 0. \quad (2.31)$$

Therefore, the electric field is irrotational. This allows for the electric field to be written as the gradient of the scalar potential field, Φ :

$$\mathbf{E} = -\nabla \Phi. \quad (2.32)$$

Equation (2.2) becomes

$$-\frac{\partial \mathbf{D}}{\partial t} = \mathbf{J}. \quad (2.33)$$

Gauss's law for electricity, given by Eq. (2.3), and the constitutive relation, given by Eq. (2.15), remain unchanged, and Gauss's law for magnetism, given by Eq. (2.4), and the constitutive relation, given by Eq. (2.16), are no longer necessary for the model (since $\mathbf{B} =$

$\mathbf{H} = 0$). Notice that taking the divergence of Eq. (2.33) and combining with Eq. (2.3) yields the same equation for the conservation of charge (Eq. (2.18)) as before. A final simplification can be made by representing the current density vector as [21]

$$\mathbf{J} = \sigma \mathbf{E} + q\mathbf{u}, \quad (2.34)$$

where the first term on the right side of the equation represents current from conduction and the second term represents current from convection.

Now, consider simplifications to the equations governing the fluid dynamics. Assuming the fluids in an electrospray devices to be incompressible is a major simplification that can be made in this area. This is a valid assumption, since the propellant in the device is a liquid, and the velocity of the fluid surrounding the device, air for example, is very low. Under the assumption of an incompressible fluid, the density is a constant. Thus, the mass conservation equation (Eq. (2.23)) can be reduced to

$$\nabla \cdot \mathbf{u} = 0. \quad (2.35)$$

The momentum conservation equation given by Eq. (2.24) can be written as

$$\rho \frac{\partial \mathbf{u}}{\partial t} + \rho \nabla \cdot (\mathbf{u}\mathbf{u}) = -\nabla p + \rho \mathbf{f} + \nabla \cdot \boldsymbol{\tau}_v. \quad (2.36)$$

Further, the energy conservation equation (Eq. (2.25)) is no longer necessary as the incompressibility assumption has decoupled the thermodynamics and kinematics of the flow. The equation of state given by Eq. (2.26) remains unchanged, but is only necessary as an algebraic expression to find the temperature based on the density and pressure.

Next, it is necessary to characterize the body forces, $\rho \mathbf{f}$, in Eq. (2.36). Note that all of the body forces will have units of force per unit volume. The simplest inclusion is the gravitational force:

$$\mathbf{F}_G = \rho \mathbf{g}, \quad (2.37)$$

where $\mathbf{g}$ is the gravitational acceleration. It is also necessary to include body forces due to electromagnetic effects. Electromagnetic body forces are given by the Lorentz force:

$$\mathbf{F}_{\text{EM}} = q(\mathbf{E} + \mathbf{u} \times \mathbf{B}). \quad (2.38)$$

However, under the electrostatic assumption, magnetic effects are negligible; therefore, the electromagnetic body forces in Eq. (2.38) reduce to

$$\mathbf{F}_{\text{EM}} = q\mathbf{E}. \quad (2.39)$$

At this point, the full set of governing equations has been reduced to an electrohydrodynamic model. To summarize, this model is described by the following set of governing equations:

$$\nabla \cdot (\epsilon \nabla \Phi) = -q, \quad (2.40)$$

$$\frac{\partial q}{\partial t} + \nabla \cdot (-\sigma \nabla \Phi + q\mathbf{u}) = 0, \quad (2.41)$$

$$\nabla \cdot \mathbf{u} = 0, \quad (2.42)$$

$$\rho \frac{\partial \mathbf{u}}{\partial t} + \rho \nabla \cdot (\mathbf{u}\mathbf{u}) = -\nabla p + \rho \mathbf{g} - q \nabla \Phi + \nabla \cdot \boldsymbol{\tau}_v. \quad (2.43)$$

This set of equations was formed by using Eq. (2.32) to eliminate $\mathbf{E}$, combining Eqs. (2.18) and (2.34), and replacing $\rho \mathbf{f}$ in Eq. (2.36) with the relations developed in Eqs. (2.37) and (2.39). The interface conditions given by Eqs. (2.19), (2.20), and (2.28) must also be imposed.

2.3.2 Quasi-Static Evolution

Since the study presented here is focused only on the onset voltage of electrospray devices, there is a further simplification that can be made. The onset voltage is the applied potential between the extractor grid and the emitter necessary to start emission. This study is not concerned with behavior after the start of emission. Therefore, in this work, the behavior up to the point immediately before emission begins is of concern. Before emission begins, there is no free space-charge present in either fluid (propellant or surroundings) as there

have been no ions or charged droplets emitted from the propellant into the surroundings. Thus, q in the equations describing the electrohydrodynamic model (Eqs. (2.40)–(2.43)) becomes zero. This essentially decouples the electrostatics from the fluid mechanics in the bulk of the fluids. However, stresses at the interface are still of importance. In this state of simplification, dynamic modeling would still be necessary to determine how the liquid propellant deforms due to stresses at the interface and approaches the onset of emission. Krpoun and Shea [18] have shown that if the shape of the liquid propellant as it deforms is known, a series of static models can be combined to determine the onset voltage of the device instead of using dynamic models. This essentially reduces the governing equations to only Eq. (2.40). Setting q equal to zero and taking the permittivity to be constant, this reduces to

$$\nabla^2\Phi = 0. \quad (2.44)$$

For now, assume the shape the liquid follows as it deforms is known. It will be shown in Sec. 2.3.3 that the shape is known from the early work by Taylor [30].

Knowing the shape that the liquid follows removes the need for a dynamic model in determining the onset voltage. After making the assumption that q is zero in the bulk preceding the onset of emission, the only need for a dynamic model is to understand how the interfacial stresses deform the liquid meniscus. Now, using an assumed liquid shape, the method proposed by Krpoun and Shea [18] can be used to determine the onset voltage. In this method, which Krpoun and Shea have also validated experimentally, a quasi-static evolution of the liquid meniscus is assumed. A series of electrostatic simulations are performed on different liquid shapes corresponding to the shapes through which the liquid progresses as it deforms, leading up to the onset of emission. For each shape, the interfacial surface tension stresses and the interfacial electrical stresses are assumed to be in equilibrium. This condition is satisfied mathematically by [18]

$$\frac{2\gamma}{r_a} = \frac{1}{2}\epsilon_0 E_0^2, \quad (2.45)$$

where r_a is the apex radius of the assumed liquid shape and E_0 is an equilibrium electric field strength. This is the electric field strength that would be necessary to satisfy the assumed equilibrium condition. The linear nature of Eq. (2.44) stipulates that for each assumed

shape, a constant ratio can be found between the voltage applied across the boundaries and the electric field strength at some point in the domain. It is convenient in this study to pick the apex of the liquid as the point of interest for the electric field strength, which gives

$$C = \frac{E_{apex}}{V_{applied}}. \quad (2.46)$$

This relationship also allows for the development of an equilibrium voltage, V_0 , corresponding to the equilibrium electric field in Eq. (2.45):

$$V_0 = \frac{1}{C} E_0. \quad (2.47)$$

Combining Eqs. (2.45) and (2.47) the equilibrium voltage can be written as

$$V_0 = \frac{1}{C} \sqrt{\frac{4\gamma}{\epsilon_0 r_a}}. \quad (2.48)$$

It is important to note that C and r_a are different for each assumed shape, and, therefore, V_0 varies with the assumed liquid shape. Physically, V_0 is the applied voltage between the extractor and emitter necessary to hold the assumed shape in equilibrium.

When the liquid is assumed to follow the shape of a Taylor cone (further discussion in Sec. 2.3.3), an interesting phenomenon is observed when the equilibrium voltage is plotted as a function of the apex radius. As the apex radius becomes small (i.e., the liquid apex becomes sharper) the equilibrium voltage becomes constant with respect to the apex radius, as shown qualitatively in Fig. 2.1. Krpoun and Shea [18] have shown that the constant value of the equilibrium voltage that is reached coincides with the onset voltage of the electrospray emitter. Thus, following the method described by Krpoun and Shea, the onset voltage of an electrospray emitter can be found by carrying out a series of electrostatic simulations for a liquid meniscus deforming as a Taylor cone, removing the need for computationally expensive dynamic simulations. Chapter 3 includes discussion on how this method is implemented with regards to this work.

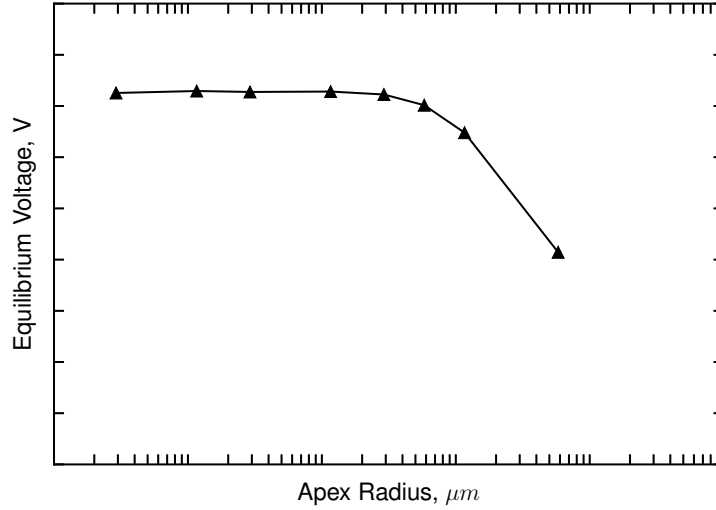


Figure 2.1: Qualitative plot of equilibrium voltage as a function of apex radius. Note that the apex radius axis uses a log scale.

2.3.3 Taylor Cone

In Sec. 2.3.2 it was assumed that the liquid in the electrospray emitter will follow the shape of a Taylor cone. Here, the phenomenon of the Taylor cone will be discussed, showing the validity of this assumption. The Taylor cone derives its name from the early work of Taylor [30] studying the behavior of liquid deformation in the presence of electric fields. Taylor found that previous analyses failed to give useful models for the observed behavior. Following from visual analysis, Taylor decided to approach the problem from the point of view of determining under what conditions that a liquid with a conical point could exist in equilibrium in an electric field. Taylor assumed the liquid to be a perfect conductor, which imposes that the surface of the cone must be an equipotential surface. He then examined the conditions under which electric stress would balance surface tension stress at the conical surface. Taylor found the solution to the problem reduced to finding the solution to

$$P_{\frac{1}{2}}(\cos \theta) = 0, \quad (2.49)$$

where θ is the angle between the horizontal and the exterior of the cone and $P_{\frac{1}{2}}(\cos \theta)$ is the Legendre function of order 1/2. Equation (2.49) has only one solution for $0 < \theta < 180^\circ$, $\theta = 130.7^\circ$. Thus, Taylor showed that the only conical surface which can exist in equilibrium with an external electric field is one with a semi-vertex angle of $180^\circ - 130.7^\circ = 49.3^\circ$.

This result has proven to be a good approximation of an ideal case; however, more recent research has shown the cone angle can deviate from this ideal case based on liquid properties, flow rate conditions, and space-charge effects [8]. In this work, a conical deformation with semi-vertex angle of 49.3° will be assumed. As suggested by Krpoun and Shea [18], the liquid meniscus will be modeled as a conic section expressed by a Bernstein-Bézier curve [7] as it progresses through its deformation towards the onset of emission. This shape follows from visual observations of experimental setups, as well as coinciding well with the shape suggested by Taylor. With the conic section revolved around the z -axis, it can be represented parametrically in Cartesian coordinates as

$$x(s, w, \phi) = \frac{(1 - 2s)r}{1 - 2s(1 - s)(1 - w)} \cos \phi, \quad (2.50a)$$

$$y(s, w, \phi) = \frac{(1 - 2s)r}{1 - 2s(1 - s)(1 - w)} \sin \phi, \quad (2.50b)$$

$$z(s, w) = \frac{2(1 - s)twr \cot \beta}{1 - 2s(1 - s)(1 - w)}, \quad (2.50c)$$

where $s \in [0, 0.5]$ is the parametric variable, r is the radius of the base of the conic section, $w \in [0, \infty)$ relates to the sharpness of the conic shape, $\phi \in [0, 2\pi)$ defines the revolution, and β is the cone semi-vertex angle. A plot of this shape is shown in Fig. 2.2 for various values of w . As w increases, the surface evolves from an ellipsoid to a paraboloid to a hyperboloid. As w approaches infinity, the shape approaches a perfect cone. Finally, note that the apex radius, or radius of curvature at the tip of the conic shape, is given by [18]

$$r_a = \frac{r}{w} \tan \beta. \quad (2.51)$$

This is the model that will be adopted in this work. Chapter 3 discusses how this model is used along with the method proposed by Krpoun and Shea [18] to perform a study on the effects of geometric and material variations on the onset voltage of electrospray emitters.

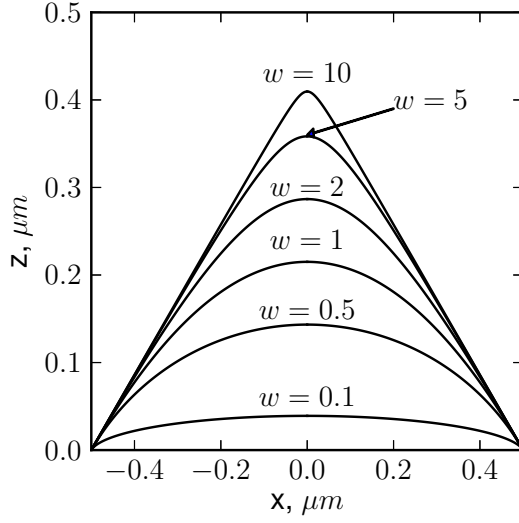


Figure 2.2: Plot of conic section representation of the liquid meniscus with $\beta = 49.3^\circ$ and $r = 0.5 \mu\text{m}$.

In particular, this method will be used to analyze the newly proposed electrospray emitter design detailed in Sec. 2.4.

2.4 Proposed Electrospray Device Design

This work will focus on the analysis of a newly proposed electrospray device design that utilizes through-channel capillaries in a dielectric as emitters rather than conventional needle-type emitters shown in Fig. 1.2. A schematic of this new design is shown in Fig. 2.3. This device uses through-channels of radius r_c in a dielectric material with relative permittivity ϵ_r to mimic the needles in traditional electrospray devices. The narrow liquid column formed by the channel is similar to a needle in vacuum, but some weakening of the electric field is expected, since the column is embedded in a dielectric material. The geometric parameters labeled in Fig. 2.3 are defined as follows. The capillary radius, r_c , is the radius of the through-channel capillary. The dielectric thickness, h , is the distance from the base of the dielectric to the top of the dielectric. This is the height of the liquid column, and is analogous to the height of a traditional electrospray emitter. The extractor distance, d , is the distance from

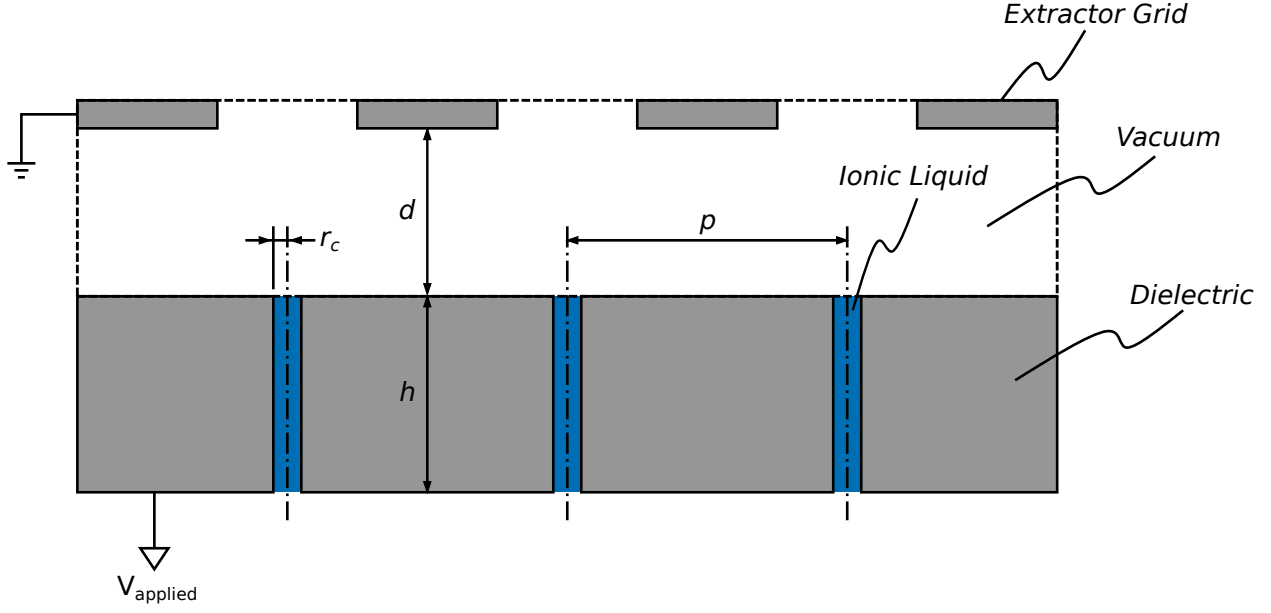


Figure 2.3: Schematic of newly proposed electrospray device design.

the top of the dielectric to the extractor grid. Finally, the emitter pitch, p , is the distance between emitters in an emitter array.

The main advantage to this design is ease of manufacturing. Especially as devices progress towards the micro-scale, manufacture of consistent and robust, free-standing needle features is a difficult task. However, the Center for Laser Applications (CLA) at the University of Tennessee Space Institute (UTSI) has proven the capability [3, 4] to manufacture through-channels in certain materials, such as fused silica (SiO_2), utilizing picosecond laser pulses shaped into a Bessel beam, as shown in Fig. 2.4. The goal of this study is to gain a better understanding of the effects of varying the geometric parameters of the capillary radius (r_c), the dielectric thickness (h), the extractor distance (d), and the emitter pitch (p), along with the relative permittivity of the dielectric material (ϵ_r). This knowledge will aid in designing an electrospray thruster of this type that minimizes onset voltage and maximizes thrust density.

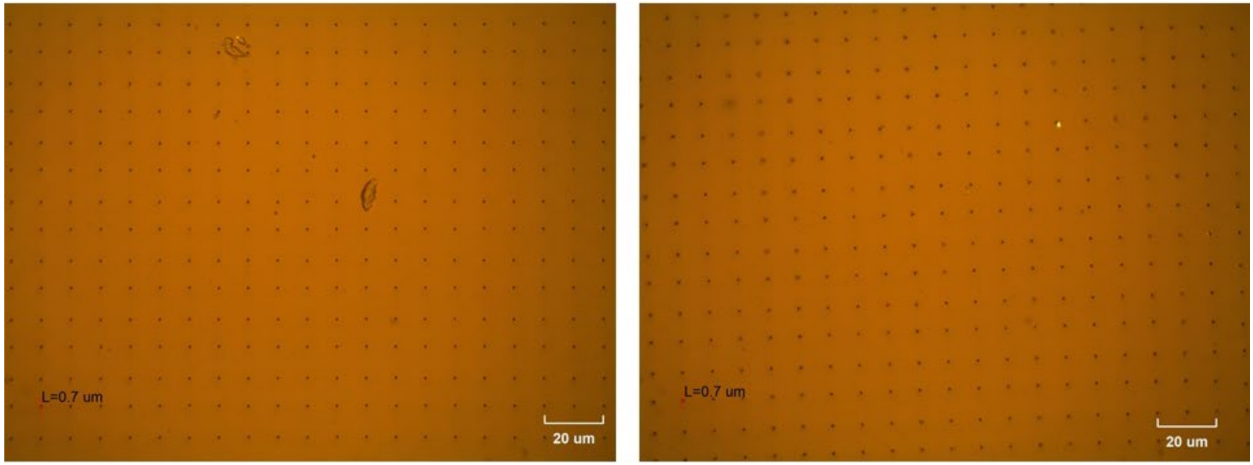


Figure 2.4: Optical microscope image of 170 μm thick SiO_2 wafer with through-channel sub-micron capillaries formed by the CLA at UTSI using picosecond laser pulses shaped into a Bessel beam. Bottom surface on the left, and top surface on the right

Chapter 3

Methodology

3.1 Computational Model

The computational models in this work are designed to correspond with the proposed electrospray device design detailed in Sec. 2.4, as shown in Fig. 3.1. Note, the corresponding dimensional parameters shown in Fig. 2.3 have been overlayed onto the computational model setup. Simulations mainly focus on a single emitter in isolation to reduce computational expense, as well as to isolate the effects of emitter pitch. Simulations are performed on a quarter-symmetry slice of the domain in order to lower the necessary computational expense. The model consists of the dielectric material (green), the geometry representing the ionic liquid (blue), and the extractor electrode (grey). The only property of the liquid propellant that is needed for this work is the surface tension coefficient, which has been chosen as $\gamma = 0.0452$ N/m to correspond with a commonly used ionic liquid, EMI-BF₄ [15]. The computational model has been designed such that the geometric parameters of concern (h , r_c , d , and p), as well as the relative permittivity of the dielectric material (ϵ_r) may be varied via user-defined design variables. With regards to boundary conditions, a symmetry condition is imposed on the two symmetry planes, a constant applied potential is imposed on the emitter and the base from which it protrudes, the extractor electrode is set to a potential of 0 V, and the far-field boundaries are set to be a sufficient distance from the emitters so as not to affect the solutions.

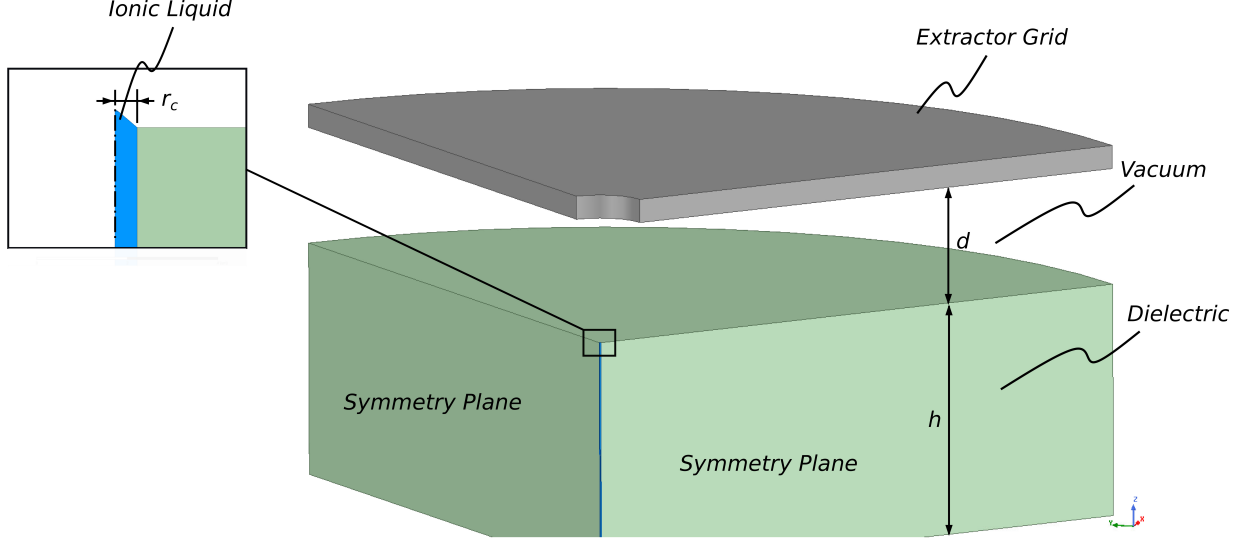


Figure 3.1: Setup of computational model in ANSYS EDT for a single, isolated emitter.

Emitter arrays are also examined in this study to understand the effects of emitter pitch on the onset voltage. For these cases, a quarter-symmetry domain is utilized again, representing a 5x5 array of emitters, as shown in Fig. 3.2. This array size has been selected based on work in the literature, which has shown that only the nearest two emitters in any direction have significant impacts on the central emitter [10]; this has also been verified through simulations performed for this study. Boundary conditions for the arrays of emitters follow those for the single-emitter cases, with the constant applied potential now imposed on each emitter and the base from which they protrude.

3.2 Obtaining Onset Voltage

Sections 2.3.2 and 2.3.3 detail the physics behind the modeling scheme that is used in this work. Here, the practical application of this framework is discussed. Once the model of the electrospray device is created (Sec. 3.1), an assumed liquid shape is placed in the emitter. This starting shape uses a large apex radius, corresponding to something similar

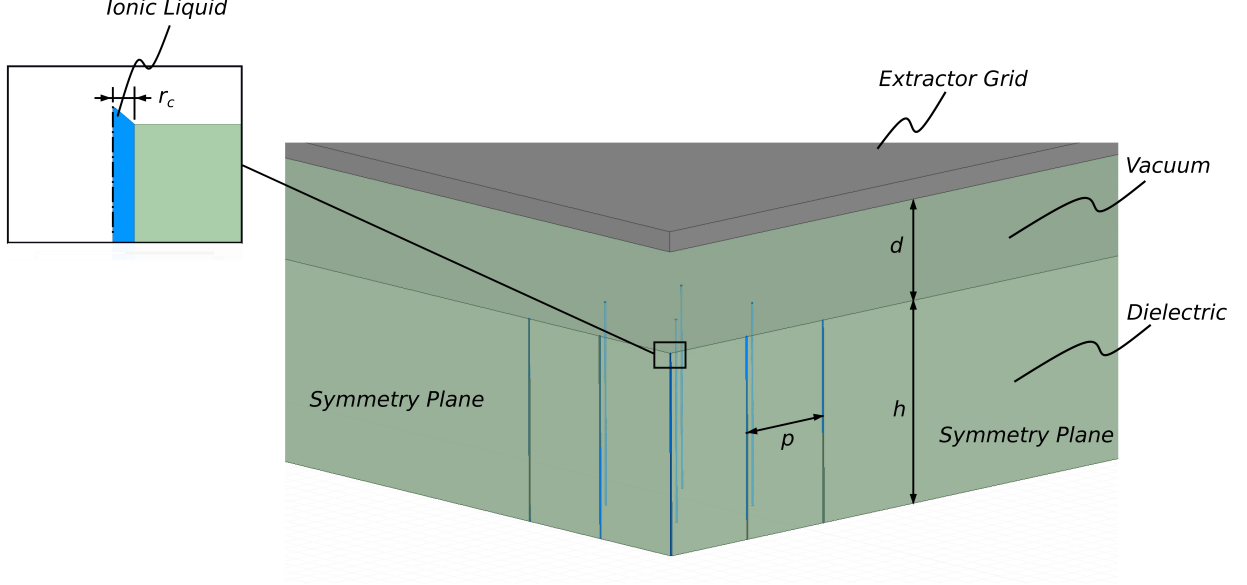


Figure 3.2: Setup of computational model in ANSYS EDT for an emitter array.

to $w = 0.1$ in Fig. 2.2. Then, an electrostatic simulation is performed on the setup with a certain potential, $V_{applied}$, between the emitter and extractor, resulting in a certain electric field strength at the liquid apex, E_{apex} . The value for C can be calculated according to Eq. (2.46), and then, the equilibrium voltage, V_0 , is calculated from Eq. (2.48). The process is then repeated for a smaller apex radius, by increasing the value of w , and the values of equilibrium voltage compared for each case. If the equilibrium voltage has become nearly constant ($\lesssim 1\%$ change), the onset voltage has been found. If the equilibrium voltage is still changing with increases in w , the process continues to repeat until the equilibrium voltage becomes nearly constant. This process is summarized in the flow diagram in Fig. 3.3.

Critical to this process is sufficient mesh resolution in the area near the liquid tip. Since the radius of curvature of this area drives the process, it is critical to accurately represent this feature in the computational domain. The software used for this work is ANSYS Electronics Desktop (EDT) (v. 19.2) [1], which contains an adaptive mesh refinement feature. To utilize this feature, an initial mesh resolution is specified, which can be customized to better resolve selected geometry for the initial iteration. Then, the problem is solved on the computational domain by the ANSYS EDT electrostatic solver. The software then increases the mesh

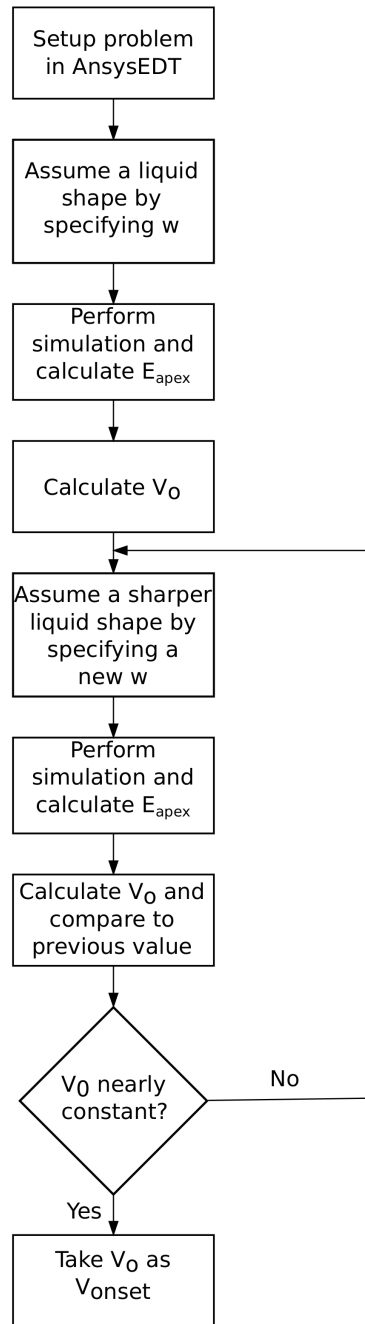


Figure 3.3: Flow diagram of methodology used to determine the onset voltage.

resolution and solves the same problem again on the finer mesh. This process is repeated until the solution no longer depends on the mesh resolution. Through this process, mesh independence of the solution can be achieved.

3.3 Simulation Variations

The goal of this work is to examine the effects of various geometric parameters (h , r_c , d , and p) and the relative permittivity of the dielectric material (ϵ_r). Thus, a wide range of discrete variations of these parameters is examined, corresponding to values that are manufacturable by the CLA at UTSI and that are representative of the desired scale for the device. The effects of h , r_c , d , and ϵ_r are examined first for a single emitter. In these cases, the dielectric thickness is chosen to vary from $h = 100 \mu\text{m}$ to $h = 500 \mu\text{m}$ (increment of $100 \mu\text{m}$), with capillary radius values ranging from $r_c = 0.5 \mu\text{m}$ to $r_c = 10.0 \mu\text{m}$ (increment of $1.0 \mu\text{m}$ between $r_c = 1.0 \mu\text{m}$ and $r_c = 10.0 \mu\text{m}$), and relative permittivity values of $\epsilon_r = 1.0$, 2.1 , 4.0 , 6.0 , 8.0 , and 10.0 . The extractor distance is held constant at $d = 100 \mu\text{m}$ for the examination of the effects of h , r_c , and ϵ_r . Then, to examine the effect that varying extractor distance has on the onset voltage, values of d are chosen to vary between $50 \mu\text{m}$ and $200 \mu\text{m}$ (increment of $50 \mu\text{m}$), with the same capillary radius and relative permittivity values, for two dielectric thickness values: $h = 100 \mu\text{m}$ and $h = 500 \mu\text{m}$. Finally, several cases corresponding to selected design candidates from the single-emitter cases are chosen to examine the effects of the emitter pitch in an array of emitters, where the ratio p/h is examined up to a value of 2.5 .

The $\epsilon_r = 1.0$ case is chosen to be similar to the case of an emitter in vacuum, while the remainder of the ϵ_r values have been chosen to fill in the range of potential material candidates for the design. Table 3.1 shows the relative permittivity values of several candidate materials as given by the materials library in ANSYS EDT (v19.2). Finally, the emitter pitch values are chosen to correspond to potential favorable designs and to highlight the data range where this parameter dominates.

Table 3.1: Relative permittivity values for various media (from ANSYS EDT materials library [1]).

Medium	Relative Permittivity
Vacuum	1.0
Teflon	2.1
Silicon Dioxide	4.0
Sapphire	10.0

Chapter 4

Results and Discussion

The results of this work are presented in sections according to the parameter space formed by the variations examined. Results for each parameter except the emitter pitch are presented for the case of a single, isolated emitter. Following the single-emitter cases is a section devoted to the examination of the effect of emitter pitch in two-dimensional arrays of electrospray emitters for several variations chosen based on results from the single-emitter cases.

4.1 Thickness of Dielectric

The first parameter examined is the thickness of the dielectric material, which corresponds to the height of the liquid column, labeled h in Fig. 2.3. In this way, the thickness of the dielectric material is very similar to the height of an electrospray emitter in a more traditional device. The results for the dependence of the onset voltage on the thickness of the dielectric material for the parameter space considered in this study are shown in Fig. 4.1. Note that the extractor distance is held constant at $d = 100 \mu\text{m}$ for each case presented in this section. The results in Sec. 4.3 will show that the onset voltage is directly proportional to d ; thus, the value of $d = 100 \mu\text{m}$ has been chosen as a representative value for the study presented in this section. Physically, this imposes the condition that as h is varied, the distance from the tip of the emitter to the extractor grid remains constant. Examining the behavior of the onset voltage, it can be seen that in each case as the dielectric thickness increases, the

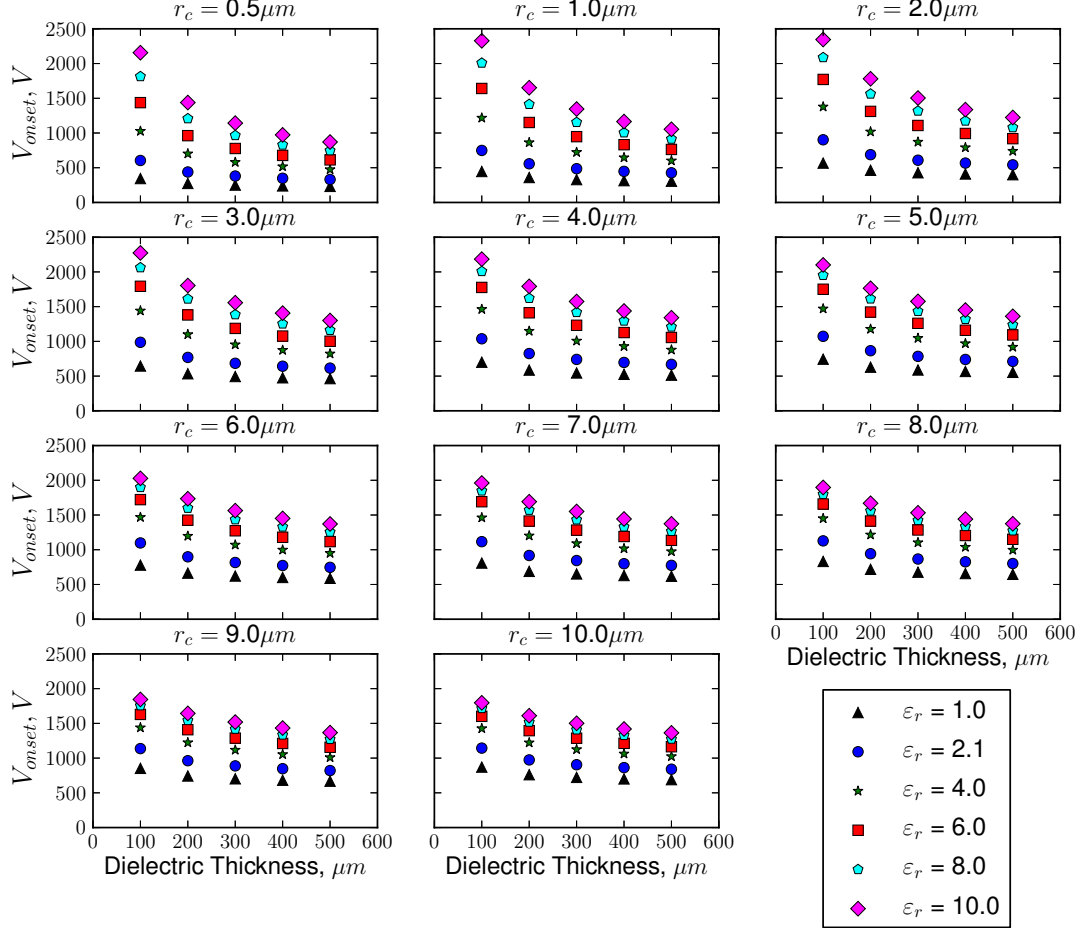


Figure 4.1: Onset voltage as a function of dielectric thickness. Each subplot corresponds to a different capillary radius. For all cases $d = 100 \mu m$.

required onset voltage decays asymptotically towards a limit. This limit is dependent on both the size of the capillary radius and the relative permittivity of the dielectric material. For low relative permittivity values and small capillary radii, a lower onset voltage is seen. Further discussion of the influence of these two parameters is contained in Secs. 4.2 and 4.4, respectively.

The dependence of the onset voltage on emitter height is a phenomenon with very little documentation. Analytical models have been derived on the assumption of long, slender emitters and have no inclusion of the influence of emitter height variations, such as the work in Ref. [23]. The definition of long and slender is not entirely known, since there has not been much work detailing the influence of emitter height. The data in Fig. 4.1 do support this assumption; once the thickness of the dielectric material reaches a certain point, the dependence of the onset voltage on emitter height diminishes (note that for the new design considered in this work, emitter height and thickness of the dielectric are synonymous). However, it appears that most of the parameter space considered in this work does not fall into the area where the assumption of a long, slender emitter is valid, as there is a strong dependence of the onset voltage on the emitter height in much of the range under consideration. Therefore, further examination is needed to begin to understand the role of the emitter height.

Consider a way to break this down into a model that is easier to analyze. At its core, a traditional electrospray device consists of two plates separated by a certain distance, with an applied potential between the two plates, and a needle (emitter) protruding from the bottom plate. The new design proposed in this work is very similar, except now, the “needle” is a liquid channel surrounded by a dielectric material. In an electrospray device the emitter is typically a sharp feature with the purpose of locally intensifying the background electric field surrounding it. Essentially, the electric field strength at the apex of the emitter is the electric field strength in the absence of the emitter amplified by some factor:

$$E_{apex} = \alpha \hat{E}, \quad (4.1)$$

where E_{apex} refers, in the case of this study, to the apex of the assumed liquid shape, α is some amplification factor that is dependent on the parameters of the emitter, and $\hat{E}$ represents the electric field strength in the absence of the emitter, call this the background electric field. Further, recall Eqs. (2.46) and (2.48), which may be combined to give

$$V_0 = \frac{V_{applied}}{E_{apex}} \sqrt{\frac{4\gamma}{\epsilon_0 r_a}}. \quad (4.2)$$

Following the behavior discussed in Sec. 2.3.2, V_0 can be replaced with V_{onset} provided that the assumed liquid shape has a sufficiently sharp apex radius, r_a . Therefore, using the relationship in Eq. 4.1, the onset voltage can be written as

$$V_{onset} = \frac{V_{applied}}{\alpha \hat{E}} \sqrt{\frac{4\gamma}{\epsilon_0 r_a}}. \quad (4.3)$$

Thus, if an understanding of the background electric field behavior can be obtained, an understanding of the behavior of the onset voltage follows.

Therefore, the question arises: what does the background electric field look like for the new device design proposed in this work? Recall that the model setup is that of a single, isolated emitter surrounded by a dielectric with boundaries at a distance such that they do not affect the solution. There is also no presence of space charge. The background electric field as defined here is the electric field that would occur in the absence of the emitter. Thus, for an analytical model for the background electric field, consider a domain consisting of two distinct dielectric materials of infinite horizontal extent, one with thickness d and the other with thickness h , as shown in Fig. 4.2. The labels d and h have been chosen to correspond with d and h in the electrospray device. Let the top material have a relative permittivity of ϵ_{r1} with an electric field in that region of $\hat{E}_1$. Similarly, let the bottom material have a relative permittivity of ϵ_{r2} with an electric field in that region of $\hat{E}_2$. Let there be applied potentials at the bottom and top of the domain of V_0 and V_1 , respectively. In this model, the electric field acts only in the vertical direction, which is normal to the interface between the two materials. The electric field in each region can be found by solving the one-dimensional

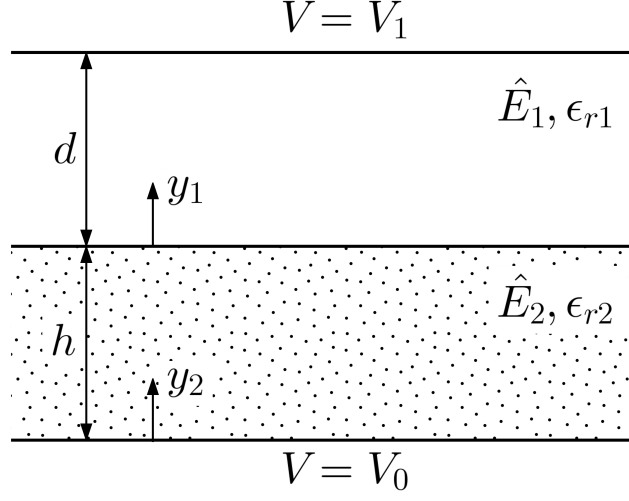


Figure 4.2: Sketch of semi-inifinite model.

Laplace equation in each region:

$$\frac{d^2\Phi_1}{dy_1^2} = 0, \quad (4.4a)$$

$$\frac{d^2\Phi_2}{dy_2^2} = 0, \quad (4.4b)$$

and noting that

$$\frac{d\Phi_1}{dy_1} = -\hat{E}_1, \quad (4.5a)$$

$$\frac{d\Phi_2}{dy_2} = -\hat{E}_2. \quad (4.5b)$$

Integrating yields

$$\Phi_1(y_1) = -\hat{E}_1 y_1 + C_1, \quad (4.6a)$$

$$\Phi_2(y_2) = -\hat{E}_2 y_2 + C_2, \quad (4.6b)$$

where C_1 and C_2 are integration constants. To solve the system of equations, the boundary conditions:

$$\Phi_1(y_1 = d) = -\hat{E}_1 d + C_1 = V_1, \quad (4.7a)$$

$$\Phi_2(y_2 = 0) = C_2 = V_0, \quad (4.7b)$$

and the interface conditions:

$$\Phi_1(y_1 = 0) = \Phi_2(y_2 = h), \quad (4.8a)$$

$$\epsilon_{r1} \hat{E}_1 = \epsilon_{r2} \hat{E}_2, \quad (4.8b)$$

must be applied. Solving the system for the electric fields yields

$$\hat{E}_1 = \frac{V_0 - V_1}{\frac{\epsilon_{r1}}{\epsilon_{r2}} h + d}, \quad (4.9a)$$

$$\hat{E}_2 = \frac{V_0 - V_1}{h + \frac{\epsilon_{r2}}{\epsilon_{r1}} d}. \quad (4.9b)$$

Finally, defining $\Delta V = V_0 - V_1$, letting $\epsilon_{r1} = 1$, and letting $\epsilon_{r2} = \epsilon_r$ gives

$$\hat{E}_1 = \frac{\Delta V}{\frac{1}{\epsilon_r} h + d}, \quad (4.10a)$$

$$\hat{E}_2 = \frac{\Delta V}{h + \epsilon_r d}. \quad (4.10b)$$

The behavior of these fields with changes in the thickness of the dielectric are shown in Fig. 4.3.

Now that a representation of the background electric field has been determined, consider again Eq (4.3). A representation of the onset voltage in terms of the background electric field can be found if α is known. To find α , rearrange Eq. (4.1) yielding

$$\alpha = \frac{E_{apex}}{\hat{E}_1}, \quad (4.11)$$

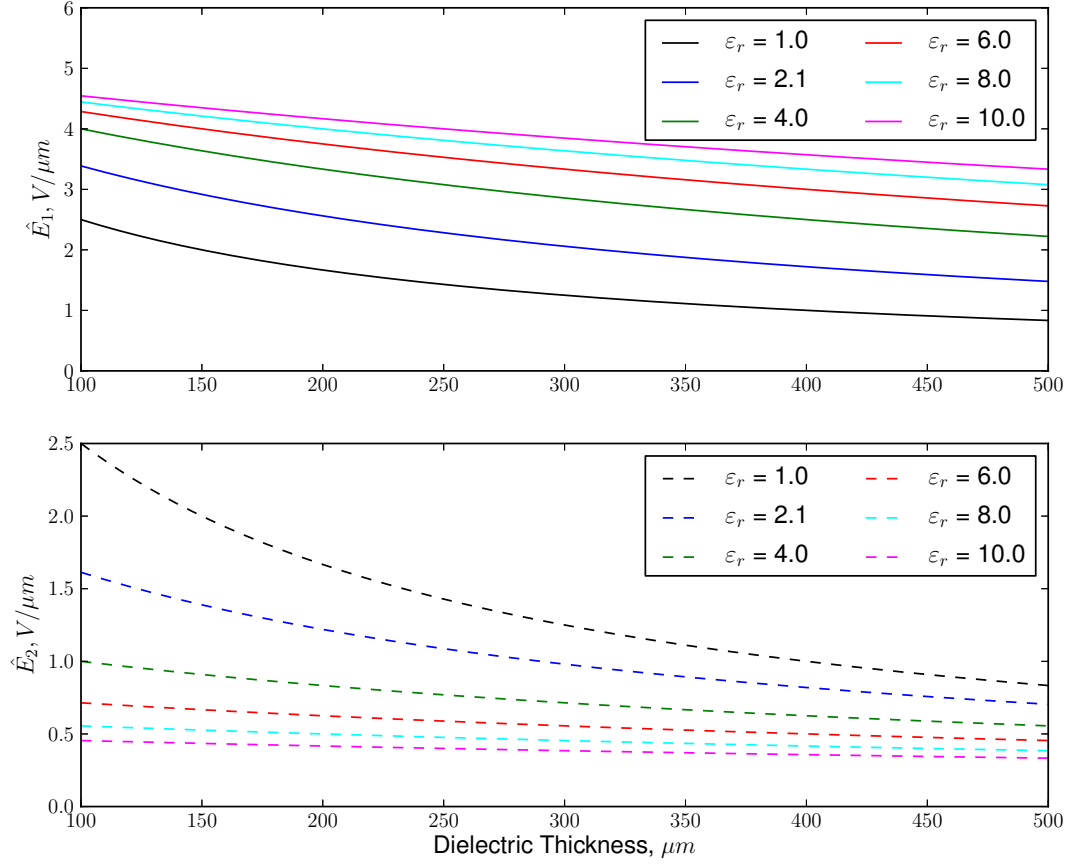


Figure 4.3: Background electric field strengths as a function of thickness of the dielectric for the semi-infinite model.

where $\hat{E}_1$ has been chosen to replace $\hat{E}$, since the liquid apex protrudes into the area represented by region 1 in the semi-infinite model. Recall that α is dependent on the parameters of the emitter. For the analysis in this section, the behavior of α with respect to the thickness of the dielectric is considered. Figure 4.4 shows plots of $\alpha = E_{apex}/\hat{E}_1$ as a function of the thickness of the dielectric. The values of ΔV , h , and d for the determination of $\hat{E}_1$ have been chosen to correspond to the computational models which provided the E_{apex} values. Linear fits of the form $\alpha = ah + b$ have been applied to the data, giving r-squared values of 0.999 or better for every case.

Using this result an equation for the onset voltage can be formed by combining Eq. (4.10a) with Eq. (4.3):

$$V_{onset} = \frac{\frac{h}{\epsilon_r} + d}{ah + b} \sqrt{\frac{4\gamma}{\epsilon_0 r_a}}. \quad (4.12)$$

Or, equivalently,

$$V_{onset} = \frac{\frac{h}{\epsilon_r} + d}{ah + b} \sqrt{\frac{4\gamma w}{\epsilon_0 r_c \tan \beta}}, \quad (4.13)$$

by using the relationship given by Eq. (2.51) and taking the radius of the base of the conic section to be that of the liquid channel ($r = r_c$). This provides a clearer understanding of the behavior of the onset voltage. The asymptotic behavior seen in Fig. 4.1 can be understood by taking the limit of Eq. (4.13) as h grows towards infinity, yielding

$$\lim_{h \rightarrow \infty} V_{onset} = \frac{1}{a\epsilon_r} \sqrt{\frac{4\gamma w}{\epsilon_0 r_c \tan \beta}}. \quad (4.14)$$

This limit results in a constant value for each data series plotted in Fig. 4.1. The rate at which the onset voltage approaches the asymptotic value, and the point at which the changes in the onset voltage become small can be found by taking the derivative of Eq. (4.13) with respect to h :

$$\frac{\partial}{\partial h} [V_{onset}] = \frac{\frac{b}{\epsilon_r} - da}{(ah + b)^2} \sqrt{\frac{4\gamma w}{\epsilon_0 r_c \tan \beta}}. \quad (4.15)$$

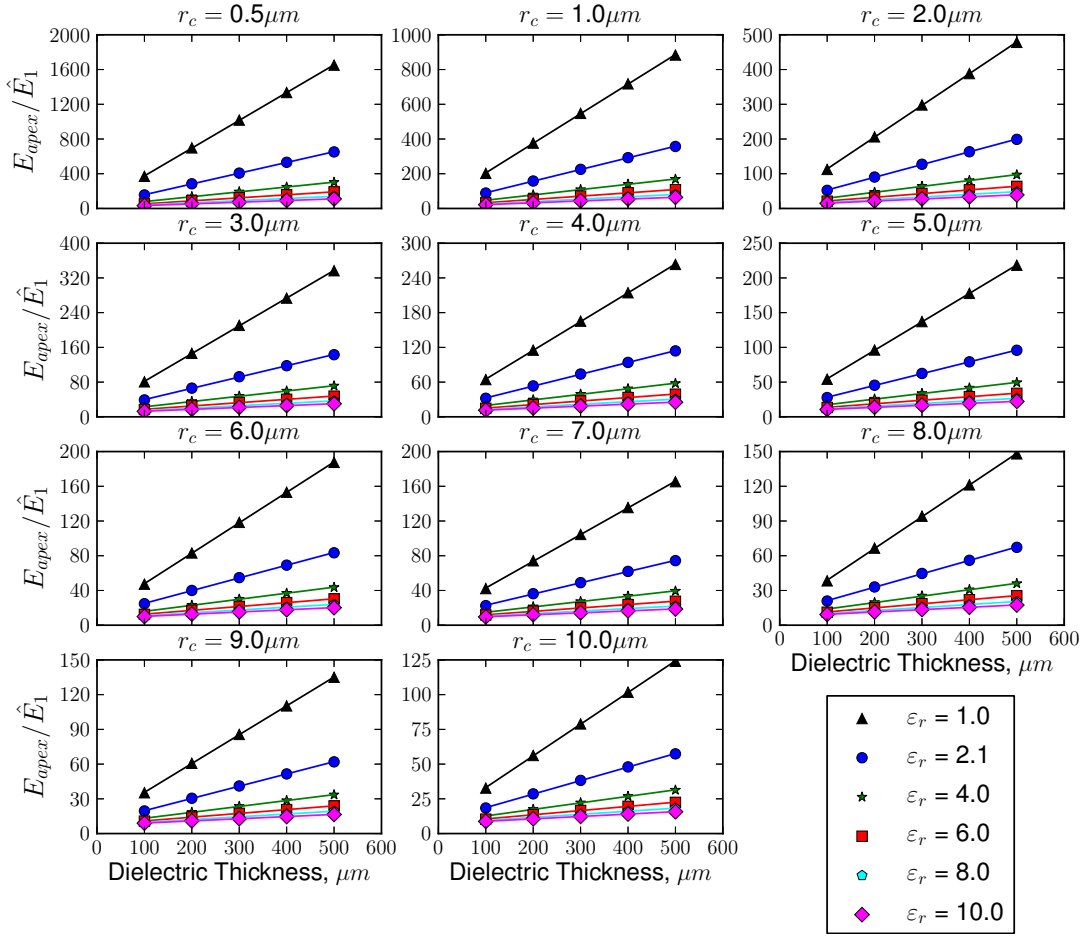


Figure 4.4: Plots of α as a function of h . Linear fits (solid lines) of the form $\alpha = ah + b$ have been applied to the data.

Plots of $\partial V_{onset}/\partial h$ as a function of h are given in Fig. 4.5, where it can be seen that in all cases the decrease in onset voltage becomes less than approximately 2 V/ μm after reaching a value of h of approximately 300 μm .

To understand physically what is occurring here, consider the potential contour plots shown in Fig. 4.6. Notice that the gradient of the potential is much stronger for the taller, $h = 500\mu\text{m}$ emitter (bottom), than for the shorter, $h = 200\mu\text{m}$ emitter (top). This difference is due to the proximity of the liquid tip to the base from which the emitters protrude, which is at the same applied potential as the emitter itself. Essentially, the proximity of the liquid apex to this feature is causing a shielding effect which is very prominent in short emitters, hence the increased required onset voltage for small values of h , and diminishes as the tip of the emitter moves away from the base (as h grows). That explains why after a certain value of h is reached, the change in onset voltage is small; after this point, the emitter tip has escaped the shielding effect of the surrounding features of the device. Therefore, when considering the thickness of the dielectric in the design of an electrospray emitter using the setup described in Sec. 2.4, one should strive to use an emitter height sufficient to escape shielding effects, but maintaining a design that is still within the realm of what is manufacturable. For the parameter space studied here, this value is approximately $h = 300\mu\text{m}$.

4.2 Relative Permittivity of Dielectric

Next, consider the effects that the relative permittivity of the dielectric material has on the onset voltage of the device. Plots of the onset voltage as a function of the relative permittivity for the variations considered in this study are shown in Fig. 4.7. In general, as the relative permittivity increases, the required onset voltage also increases; however, the behavior is complex, strongly depending on both the capillary radius and the thickness of the dielectric material. Drawing on the results of Sec. 4.1, the response from changes in the emitter height come as no surprise; as h increases, decreases in the required onset voltage are seen, with the amount of change becoming small after approximately $h = 300\mu\text{m}$. There is still a complicated behavior with respect to changes in the capillary radius. This behavior is

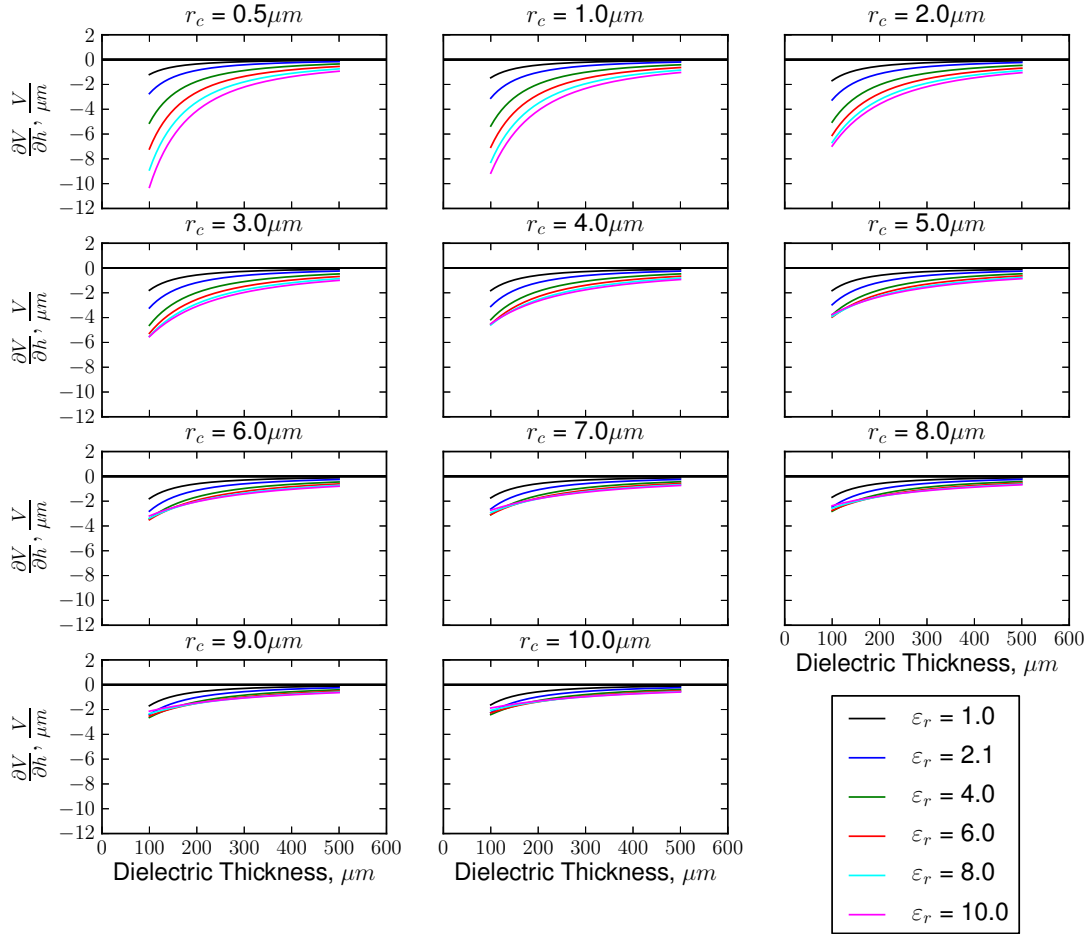


Figure 4.5: Plots of $\partial V_{onset}/\partial h$ as a function of h for the parameter space considered in this study.

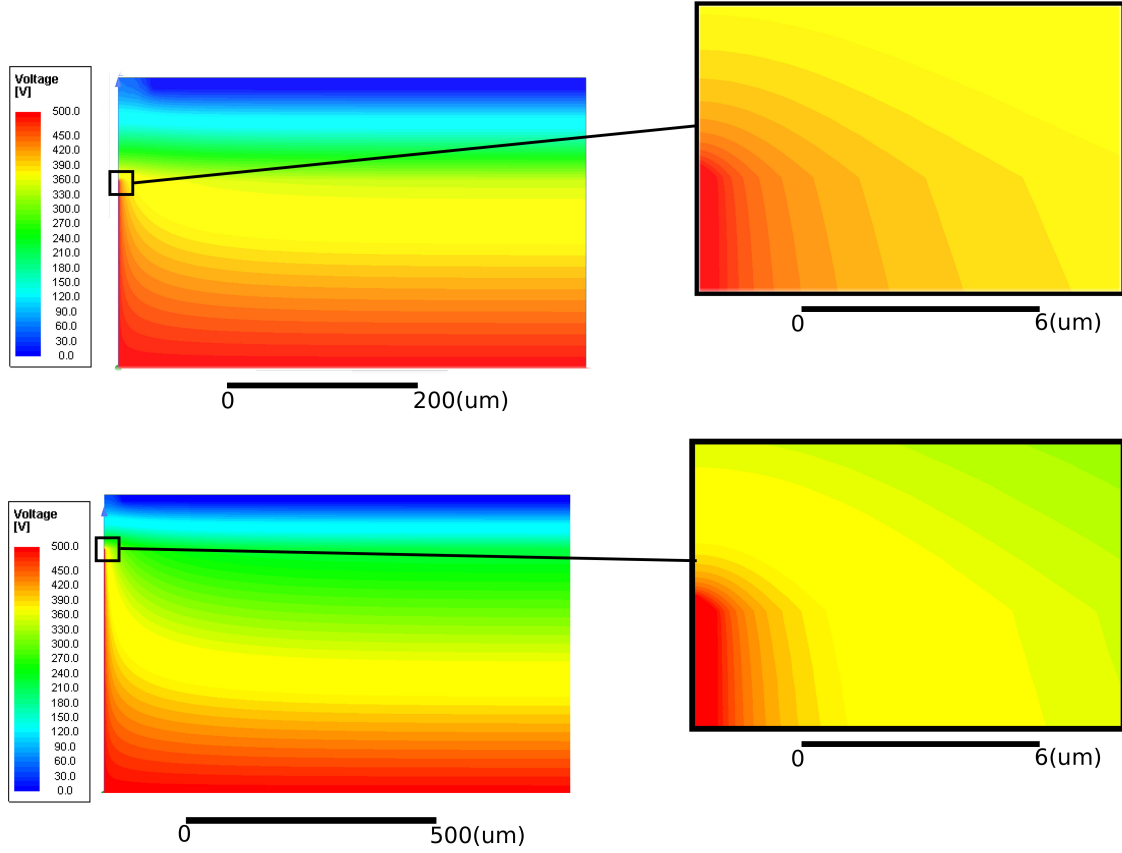


Figure 4.6: Potential contours for two different emitter configurations. Top: $h = 200 \mu\text{m}$. Bottom: $h = 500 \mu\text{m}$. Right: expanded views of the liquid tip regions.

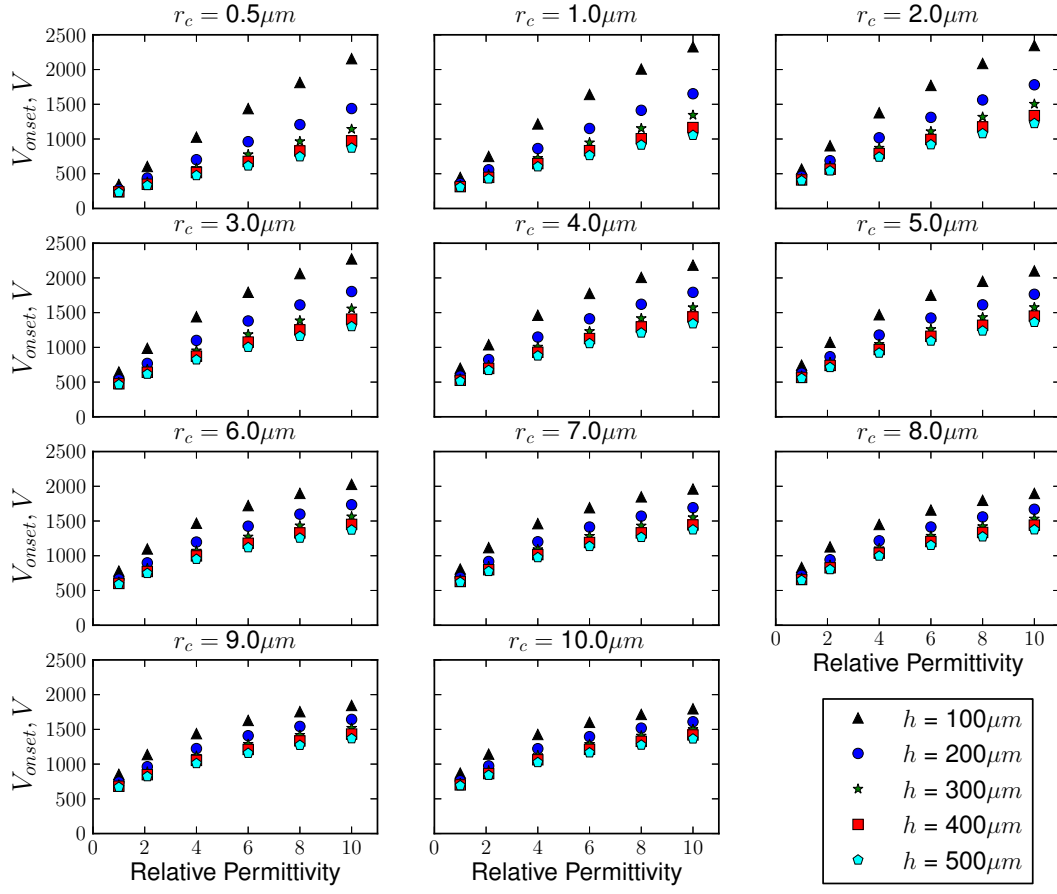


Figure 4.7: Onset voltage as a function of relative permittivity of dielectric material. Each subplot corresponds to a different capillary radius. For all cases $d = 100 \mu m$.

discussed in more detail in Sec. 4.4. In this section, the behavior in the onset voltage with respect to the relative permittivity of the dielectric material is presented.

To better understand the behavior, consider again the semi-infinite model discussed in Sec. 4.1 and represented by Eqs. (4.10a) and (4.10b). Plots of the background electric field strengths are shown in Fig. 4.8 as a function of the relative permittivity of the dielectric material. Here, the strength of the electric field in the vacuum region ($\hat{E}_1$) increases with the relative permittivity, while the strength of the electric field in the region occupied by the dielectric ($\hat{E}_2$) decreases with the relative permittivity. In both cases, the amount of change in the field strength with changes in relative permittivity becomes smaller as the relative permittivity grows. As in Sec. 4.1, take $\alpha = E_{apex}/\hat{E}_1$, where now α varies with the value of the relative permittivity. As shown in Fig. 4.9, the behavior of α with respect to the relative permittivity is nonlinear; however, fits of the form $\alpha = 1/(a(\epsilon_r)^b + c)$ provide r-squared values of 0.999 or better for each case.

Following the same procedure as in Sec. 4.1 gives

$$V_{onset} = \left(\frac{h}{\epsilon_r} + d \right) \left(a(\epsilon_r)^b + c \right) \sqrt{\frac{4\gamma w}{\epsilon_0 r_c \tan \beta}}. \quad (4.16)$$

Notice that the value of the relative permittivity contributes to the onset voltage in two ways: in the background electric field (first term in parentheses in Eq. (4.16)) and in the amplification factor of the emitter (second term in parentheses in Eq. (4.16)). Taking the limit of Eq. (4.16) as ϵ_r approaches infinity gives insight into the behavior of the onset voltage as the relative permittivity grows. The resulting limit is

$$\lim_{\epsilon_r \rightarrow \infty} V_{onset} = \sqrt{\frac{4\gamma w}{\epsilon_0 r_c \tan \beta}} \left[\lim_{\epsilon_r \rightarrow \infty} \left(\frac{h}{\epsilon_r} + d \right) \left(a(\epsilon_r)^b + c \right) \right]. \quad (4.17)$$

The value of this limit is dependent on the parameter b , which varies for each emitter height and capillary radius combination; however, for every case, $b > 0$. Thus, the limit of the onset voltage is infinite:

$$\lim_{\epsilon_r \rightarrow \infty} V_{onset} = \infty. \quad (4.18)$$

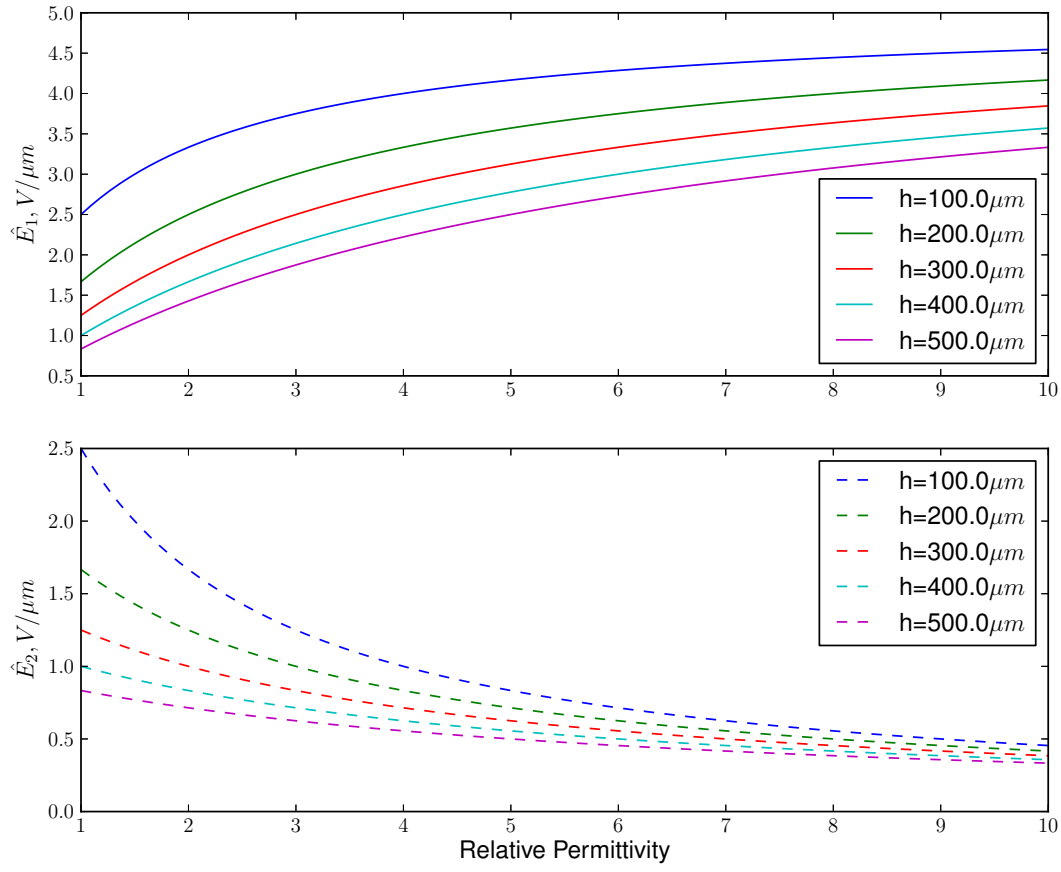


Figure 4.8: Background electric field strengths as a function of relative permittivity of the dielectric for the semi-infinite model.

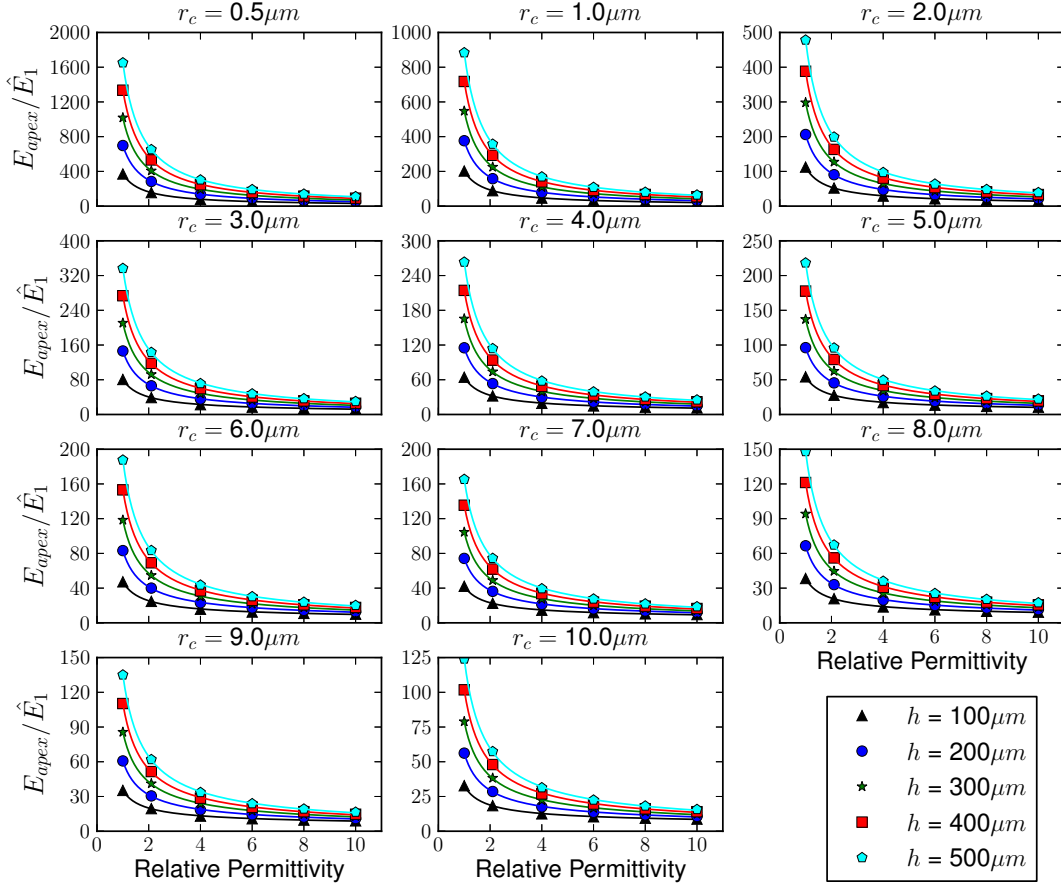


Figure 4.9: Plots of α as a function of ϵ_r . Fits (solid lines) of the form $\alpha = 1 / \left(a (\epsilon_r)^b + c \right)$ have been applied to the data.

While the limit is always infinite, the rate at which the onset voltage grows is highly influenced by the value of b , and thus, by the emitter height and capillary radius. Consider the derivative of Eq. (4.16) with respect to the relative permittivity:

$$\frac{\partial}{\partial \epsilon_r} [V_{onset}] = \left(a(b-1)h(\epsilon_r)^{b-2} + abd(\epsilon_r)^{b-1} - ch(\epsilon_r)^{-2} \right) \sqrt{\frac{4\gamma w}{\epsilon_0 r_c \tan \beta}}. \quad (4.19)$$

Plots of Eq. (4.19) are shown in Fig. 4.10. Note that the vertical axis is given in change in onset voltage, in volts, per change in the value of relative permittivity, which is unitless. Examining Fig. 4.10 provides a large amount of insight into the behavior of the onset voltage. Here, the response is much different depending on the size of the capillary radius. In contrast, in Fig. 4.5, while the quantitative responses were different for different capillary radii, the overall behavior was the same. For the smallest values of capillary radii, $\partial V/\partial \epsilon_r$ is nearly constant, indicating that the onset voltage increases without bound in a nearly linear fashion, with the slope of this line dependent of the value of h , as the relative permittivity of the dielectric material increases. This is consistent with what is seen in the first few subplots of Fig 4.7. As the capillary radius increases, there is an increase in the variation of $\partial V/\partial \epsilon_r$ with the relative permittivity. In these cases, for relative permittivity values near unity, $\partial V/\partial \epsilon_r$ is relatively large, and then decays towards a near-constant value as the relative permittivity increases. This indicates that after a certain value of ϵ_r is reached, the onset voltage goes on to increase in a nearly linear fashion as the relative permittivity increases. Furthermore, for these cases the slope of the linear behavior appears to be nearly independent of emitter height; however, emitter height does appear to determine how quickly $\partial V/\partial \epsilon_r$ reaches the constant value for a given value of r_c . Notice there is some cross-over in the $\partial V/\partial \epsilon_r$ values corresponding to individual emitter heights in certain large radius, high relative permittivity cases; however, even in those cases, the value of $\partial V/\partial \epsilon_r$ that is reached as relative permittivity increases is nearly the same across the range of emitter heights. There is strong interdependence with the size of the capillary radius, which highly influences the behavior here in some cases. This behavior is discussed in more detail in Sec. 4.4.

Despite the complicated behavior in the onset voltage with changes in relative permittivity, the general guideline for keeping the required onset voltage low is the same for all

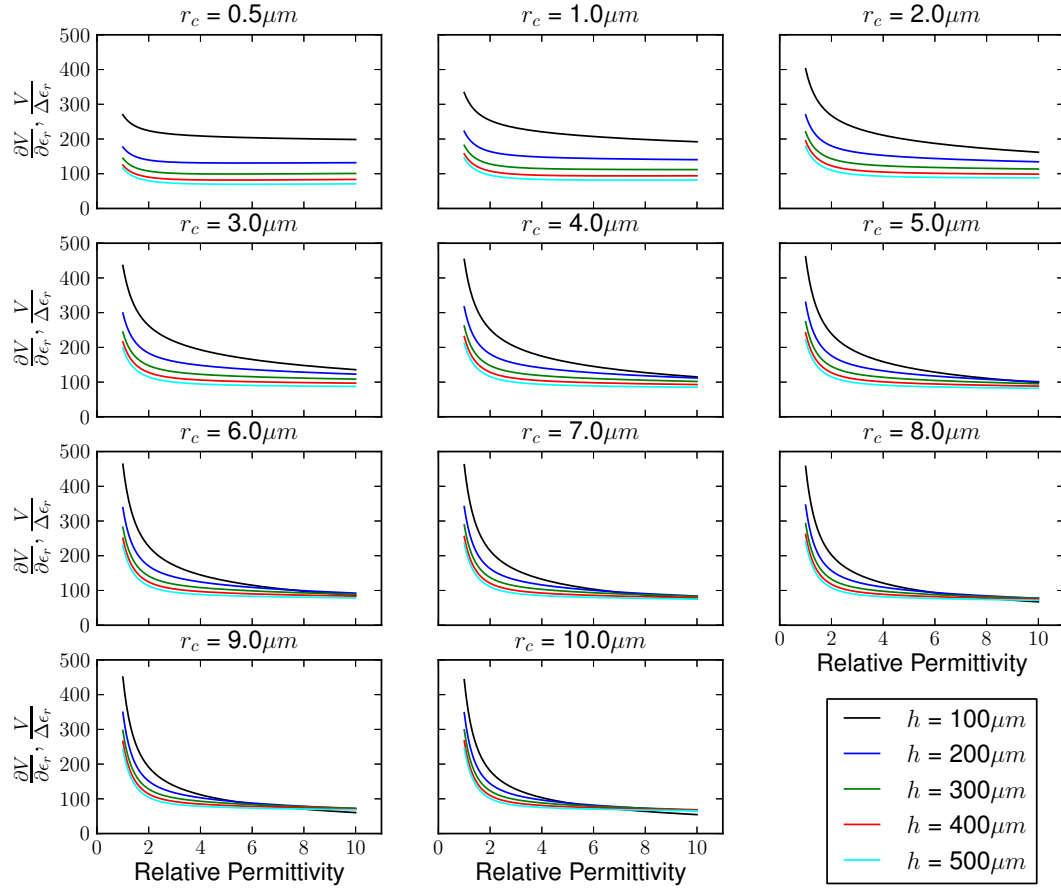


Figure 4.10: Plots of $\partial V_{onset}/\partial \epsilon_r$ as a function of ϵ_r for the parameter space considered in this study.

cases. To minimize onset voltage, the relative permittivity of the dielectric material should be as close to unity as possible. The negative impact that using a material with a higher relative permittivity has, however, is dependent both on the size of the capillary radius and the thickness of the dielectric material (emitter height). For small capillary radii, and especially combined with small emitter heights, the onset voltage grows rapidly as the relative permittivity increases. Conversely, for large capillary radii the amount of increase in the onset voltage as the relative permittivity increases is less severe.

4.3 Extractor Distance

Now consider the effect of the extractor distance on the onset voltage of the device, labeled d in Fig. 2.3. Plots of the onset voltage as a function of the extractor distance are shown in Fig. 4.11 ($h = 100 \text{ } \mu\text{m}$) and Fig. 4.12 ($h = 500 \text{ } \mu\text{m}$). The literature assessing the parameters examined in Secs. 4.1 and 4.2 is very limited; however, there is an analytical model for the onset voltage with respect to the extractor distance and the capillary radius given by Martínez-Sánchez and Lozano [23]:

$$V_{onset} = \sqrt{\frac{\gamma r_a}{\epsilon_0}} \ln \left(\frac{4d}{r_a} \right). \quad (4.20)$$

This model is derived by assuming the liquid surface and capillary to be given by a hyperboloid in a prolate spheroidal coordinate system. This model is best-suited for long, slender emitters, and does not include any analysis for an emitter surrounded by a dielectric material. Notice in Eq. (4.20), the apex radius (r_a) is used, since the radius of curvature of the liquid tip is given by $1/r_a$. To fit better with the parameters used in this work, recall the relationship given by Eq. (2.51), and take r to be equal to r_c . To correspond with the onset voltage, the value of w in Eq. (2.51) must be chosen as the value where the equilibrium voltage becomes constant for each simulation. In all of the cases modeled in this study, this occurs for a value of w of approximately 3.5. Substituting Eq. (2.51) into Eq. (4.20) with

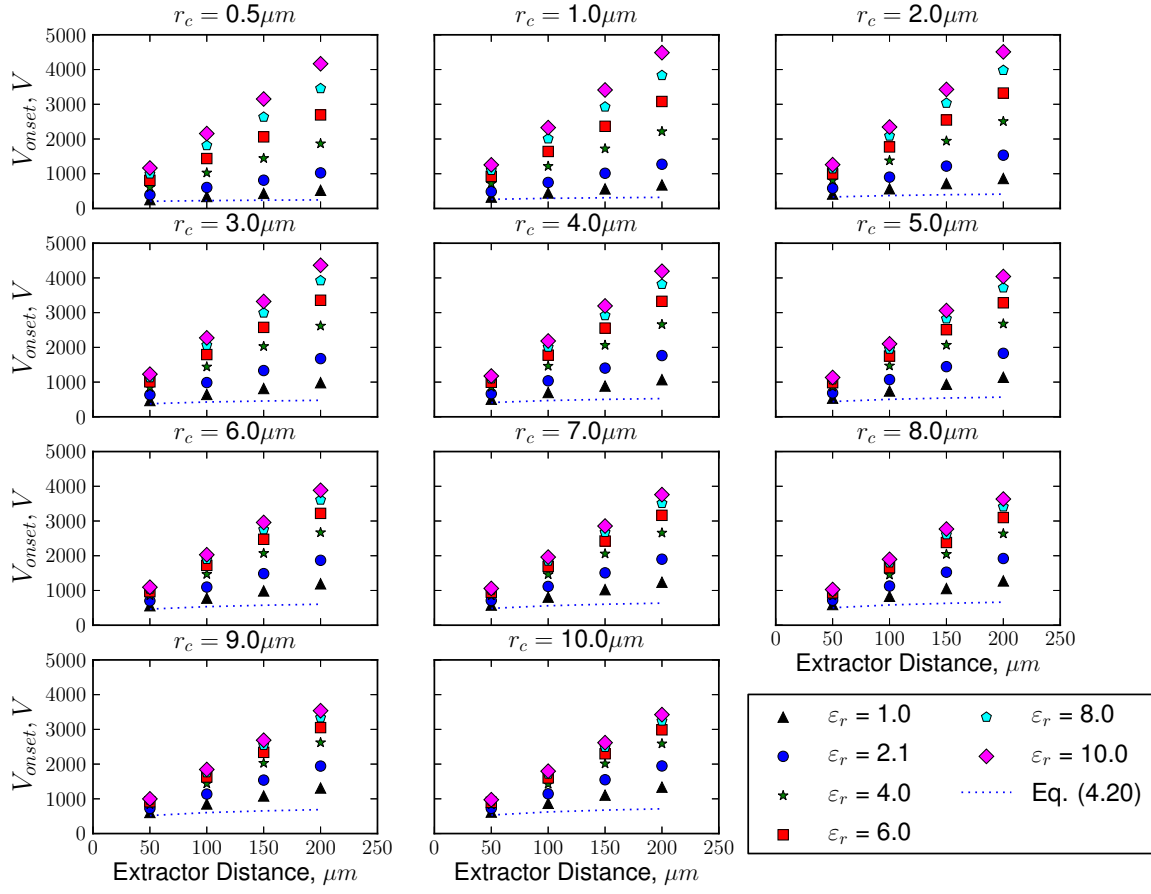


Figure 4.11: Onset voltage as a function of extractor distance for $h = 100 \mu m$. Each subplot corresponds to a different capillary radius.

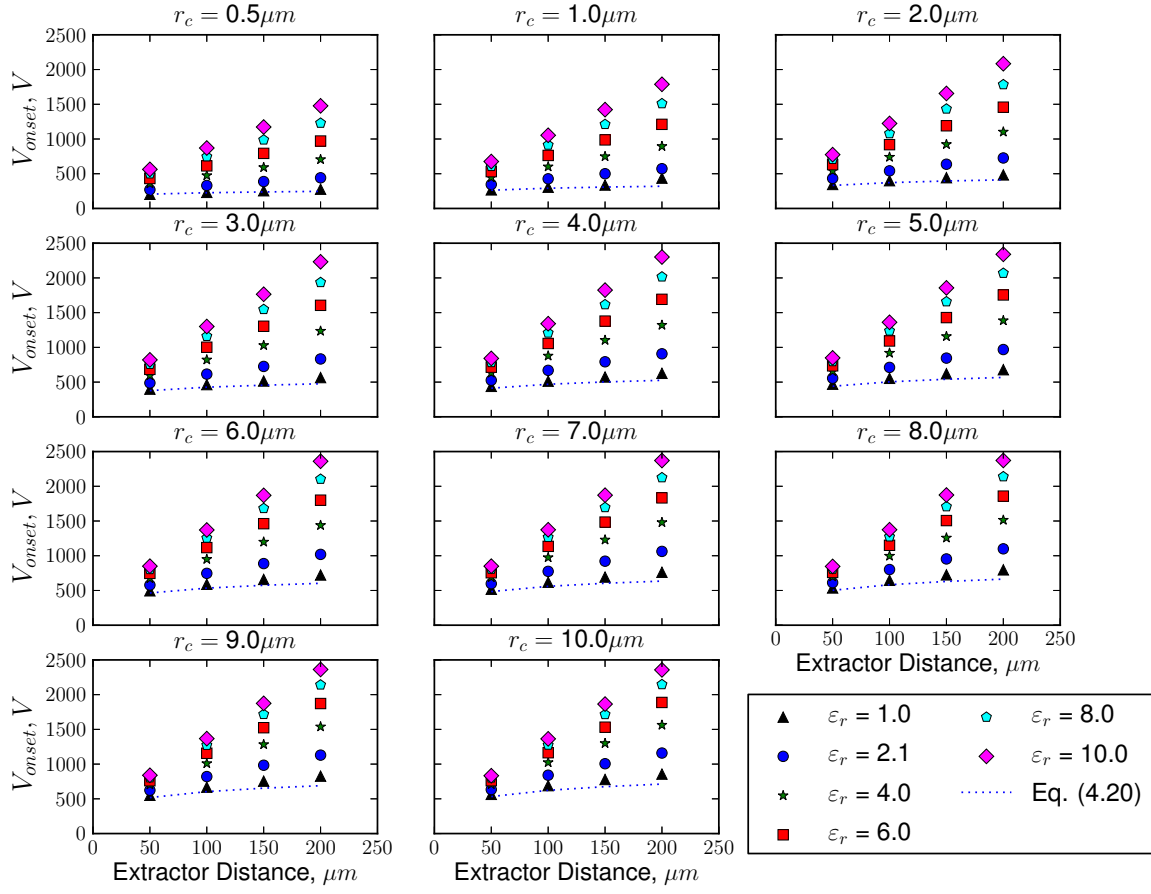


Figure 4.12: Onset voltage as a function of extractor distance for $h = 500 \mu m$. Each subplot corresponds to a different capillary radius.

the appropriate value of w gives

$$V_{onset} = \sqrt{\frac{\gamma r_c \left(\frac{\tan \beta}{w} \right)}{\epsilon_0}} \ln \left(\frac{4d}{r_c \left(\frac{\tan \beta}{w} \right)} \right). \quad (4.21)$$

Examining the data in Figs. 4.11 and 4.12 reveals a near-linear relationship between the onset voltage and the extractor distance. While the model given by Eq. (4.20) is nonlinear with d , it is near-linear for the limited parameter space considered in this study. This can be seen in the dashed lines in Figs. 4.11 and 4.12. Notice that the model given by Eq. (4.20) and the data for the emitter surrounded by a medium with a relative permittivity of unity (vacuum) have good agreement. This is especially true for the data where $h = 500 \mu\text{m}$ (Fig. 4.12), reinforcing that the model given by Eq. (4.20) works best for long, slender emitters.

Considering the cases where the relative permittivity is greater than unity, the behavior of the onset voltage is similar. A near-linear trend is seen in each case, where the slope depends on the relative permittivity. As the relative permittivity of the dielectric material increases, the rate at which the onset voltage increases with the extractor distance is increased. It is also apparent that the onset voltage requirement is higher for the $h = 100 \mu\text{m}$ cases, following the results given in Sec. 4.1.

The general guideline for the extractor distance with regard to minimizing the onset voltage is simple: use as small an extractor distance as feasible. Physically, the limit of this value has to take into account phenomena such as degradation of the extractor grid from electrical arcing and impingement of ions and/or droplets. It is also a manufacturing hurdle to produce a device with very small extractor distances due to the alignment precision required.

4.4 Radius of Ionic Liquid Channel

The final parameter considered in this study for a single, isolated emitter is the radius of the ionic liquid channel, or capillary radius. Similar to the discussion in Sec. 4.3, the effect

that this parameter has on the onset voltage can be represented by Eq. (4.20). Again, this model does not include any effects of the dielectric material in the design presented here, and it does not cover emitters which do not fall in the long, slender category. In addition, the semi-infinite model examined for understanding the effects of emitter height and relative permittivity of the dielectric material cannot be used here, as there is no parameter in that model analogous to the capillary radius. Plots of the onset voltage as a function of the capillary radius are shown in Fig. 4.13.

As in Sec. 4.3, the data for the case where the relative permittivity of the surrounding medium is unity is in good agreement with the model described by Eq. (4.20), especially for larger values of emitter height. The cases with larger emitter heights are more closely in line with the long, slender emitter assumption. Furthermore, in the cases for where the emitter height is small, an increase in the onset voltage is seen following the results given in Sec. 4.1. As the emitter height grows, the simulation results fall more closely in line with the values predicted by Eq. (4.20). It is to be expected that the data where the relative permittivity is different from unity deviates, since that model does not account for a device that contains emitters surrounded by a dielectric.

When the relative permittivity is different from unity, the behavior is more complicated; however, much of what has been detailed up to this point in this study can help make sense of the behavior. As the relative permittivity is increased, the required onset voltage values are shifted upward; this is consistent with the behavior detailed in Sec. 4.2. However, for small capillary radii and small emitter heights, the behavior is much different than a simple upward shift. Moreover, the amount of distortion from the qualitative behavior of the case where the relative permittivity value is unity is increased as the relative permittivity value increases. This can be seen clearly for the case where $\epsilon_r = 10.0$ and $h = 100 \mu\text{m}$; the behavior of this data series deviates the most from the case of an emitter surrounded by vacuum.

Looking further at the subplots for different values of h , the conclusion can be drawn that the value of the relative permittivity has more influence on the behavior of the onset voltage with changes in capillary radii, most significantly for small capillary radii, as the emitter height decreases. Further examination of Fig. 4.10 reinforces this behavior. Notice that for the subplots corresponding to small capillary radii, the response of $\partial V / \partial \epsilon_r$ is dependent

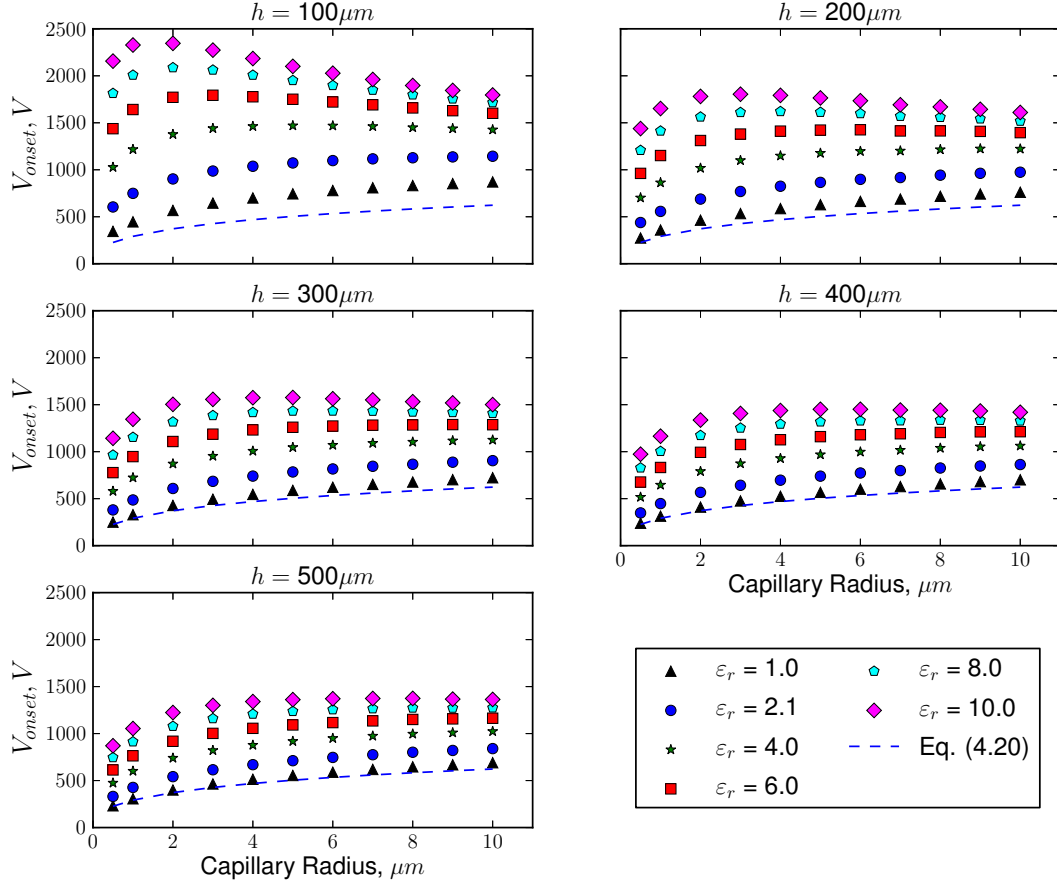


Figure 4.13: Onset voltage as a function of capillary radius. Each subplot corresponds to a different emitter height. For all cases $d = 100 \mu m$.

on the emitter height, with the value of $\partial V/\partial \epsilon_r$ being larger for smaller emitter heights. This leads to an interesting result. In these cases, the required onset voltage increases, then decreases, and then reaches a near-constant value. Conversely, in the cases that follow the behavior of Eq. (4.20), the onset voltage increases monotonically. The increase is rapid with small values of capillary radii and transitions to a continuing slight increase for large values of capillary radii.

The general guideline for achieving minimal onset voltage with respect to the size of the capillary radius is less straightforward than for the other parameters discussed in this work. For low values of relative permittivity, smaller capillary radii lead to lower required onset voltages. For larger relative permittivity values, unless a capillary radius size on the extreme small end of the values is used, it may prove to be more beneficial to use a larger capillary radius size. The case where $\epsilon_r = 10.0$ and $h = 100 \mu\text{m}$ demonstrates this most clearly.

4.5 Pitch in Emitter Arrays

The final parameter discussed in this work is the pitch in arrays of emitters. The pitch is the center-to-center spacing between emitters. This is a very important parameter in the design of electrospray devices for use in space propulsion. An electrospray thruster would not be composed of a single, isolated emitter, but rather an array of many emitters. In the microscale applications that this study focuses on, such an array may contain hundreds of thousands emitters. Harris et al. [10] have shown that shielding effects become present in arrays of emitters where the pitch is insufficient. That is, the local electric field strength at the emitter tip is decreased, leading to an increase in required onset voltage, if emitters are placed too close together. Their work showed that at an emitter pitch to emitter height ratio (p/h) of approximately 2.5, the shielding effects become negligible. This is a major challenge in the design of electrospray thrusters, as this puts the goals of minimal onset voltage and maximal thruster density in direct opposition to each other. This section examines the effect of emitter pitch on a select set of configurations chosen based on the results of the single-emitter analysis. These results are shown in Fig. 4.14.

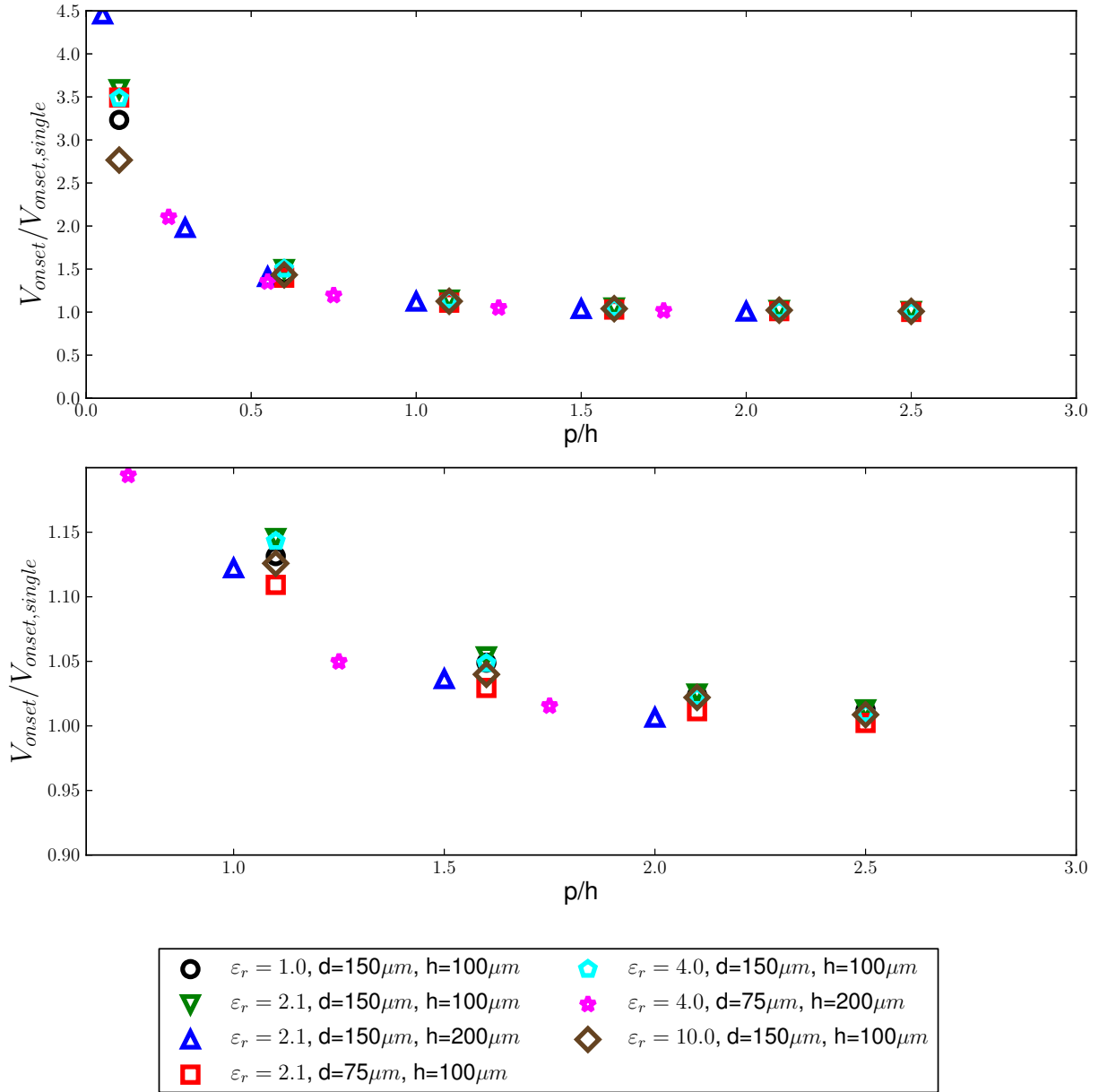


Figure 4.14: Normalized voltage as a function of the ratio of emitter pitch to emitter height in an array of emitters. For each case $r_c = 0.5 \mu m$. Top: entire parameter space. Bottom: p/h range with only moderate shielding.

The vertical axis in Fig. 4.14 is normalized by dividing the onset voltage of the emitter in an array by the onset voltage of a single emitter in isolation of the same configuration. Three different sets of values of emitter pitch are used, corresponding to $h = 100 \mu\text{m}$ and $h = 200 \mu\text{m}$ with $d = 75 \mu\text{m}$, and $h = 200 \mu\text{m}$ with $d = 150 \mu\text{m}$ cases. Previous research highlights the value of p/h at which shielding effects become negligible, but do not investigate ranges where shielding may be present in tolerable amounts. It may be desirable to design an electrospray thruster with an emitter pitch resulting in a value of p/h less than 2.5 in order to increase the thrust density of the device, while only marginally increasing the required onset voltage. For example, a thruster could be designed with a p/h value of 1.5, resulting in an onset voltage that is only around 1.05 times higher than the onset voltage of the same emitter configuration in isolation. In the design of an electrospray thruster, optimizing the balance between thrust density and required onset voltage will be very important, and requirements will come out of mission-specific constraints.

Another conclusion can be drawn out of the data in Fig. 4.14. While there is dispersion in the $V_{onset}/V_{onset,single}$ values at very low p/h values, once intermediate values of p/h are reached, the onset voltage changes are nearly the same for all configurations. This is a great benefit in the modeling of electrospray devices. It allows for modeling to be performed on a single, isolated emitter, which is much less computationally expensive, with the knowledge that once that emitter is placed in array the onset voltage will be changed by a certain percentage based on the data in Fig. 4.14, regardless of the configuration of the emitter.

4.6 Further Discussion

So far, a wide range of effects of design parameters on the onset voltage of electrospray devices have been examined. It is important to bring these results together to understand the practical limitations they impose on the design of an electrospray thruster. In Sec. 4.1, results show that larger values of the thickness of the dielectric (taller emitter heights) lead to lower onset voltages, with the amount of onset voltage reduction diminishing around $h = 300 \mu\text{m}$. Further, the results from Sec. 4.2 show that using dielectric materials with low values of relative permittivity will result in lower onset voltages, and that the negative

impact of using materials with higher relative permittivity values is the most prominent in cases with a small capillary radius and small emitter height. From Sec. 4.3, the results show that smaller extractor grid distances lead to reduced onset voltage values, with the onset voltage nearly linearly proportional to the extractor distance, and with the slope dependent on the relative permittivity of the dielectric and the capillary radius. Finally, the results in Sec. 4.4 show that, for all but the small emitter height cases, onset voltage increases with increase in capillary radius. The increase becomes very slight as the capillary radius grows, and for devices using materials with a large relative permittivity, the onset voltage becomes nearly constant for large capillary radii. In the small emitter height cases, the onset voltage follows a similar trend for low relative permittivity values, but at large values of relative permittivity, the onset voltage first increases quickly with capillary radius, then begins a gradual decrease.

There are clearly interdependences between the different parameters presented here. One main finding that comes from examining the entirety of the data, however, is that taller emitter heights prove beneficial in all of the cases. The taller emitter heights lead to lower onset voltages and also seem to diminish some of the negative impacts from other parameters. While mission-specific requirements may drive the selection of many design parameters, one rule should be followed in every case: avoid emitter heights at the low end of the range ($h < 200\mu\text{m}$). This constraint does impose limitations on thrust density, however, due to the importance of the value of p/h in arrays of emitters. Taller emitters will require a larger pitch, which leads to decreased thrust density. This impact can be minimized by choosing an emitter pitch such that p/h is around 1.5, leading to an increase in the onset voltage by a factor of only about 1.05 times the single emitter case. Clearly, in the full design of an electrospray thruster much study should focus on the optimization of parameters in order to meet mission requirements, since in full-scale mission applications goals may be much more complicated than simply minimizing onset voltage or maximizing thrust density.

Chapter 5

Conclusions and Future Work

5.1 Conclusions

The results of this work have focused on the effects that key design parameters of electrospray devices have on the emitter onset voltage. Specifically, a newly proposed design utilizing internally-fed capillary channels bored in a dielectric has been studied. The effects of variations in the thickness of the dielectric material, the relative permittivity of the dielectric material, the extractor distance, the capillary radius, and the emitter pitch have all been studied. Studies were performed using an electrostatic analysis based on the method presented by Krpoun and Shea [18], allowing for rapid simulation of a large variety of design configurations. In space propulsion applications, a desirable trait is minimal onset voltage in order to keep power requirements and satellite bus voltages low. The results presented in this work show that the following guidelines should be followed to obtain minimal onset voltage:

- A dielectric thickness (emitter height) should be chosen that is tall enough to escape shielding effects ($h > 300 \mu\text{m}$ for the parameter space in this study).
- A dielectric material with a relative permittivity as close to unity as possible should be used.
- As small of an extractor distance as feasible should be used (manufacturing capabilities and possible grid degradation must be taken into account in a practical case).

- A capillary radius as small as feasible should be used unless using materials with a large relative permittivity.
- An emitter pitch should be chosen to render shielding effects negligible ($p/h \geq 2.5$).

Keep in mind these are general guidelines. As has been discussed in this work, many of these parameters compete against each other in lowering the onset voltage. Furthermore, the relative importance of onset voltage and thrust density requirements must be considered, as these parameters directly oppose each other in the p/h requirement. That is, increasing h will generally reduce the onset voltage, but will increase the required value of p to maintain a favorable p/h ratio. This, in turn, will reduce the thrust density. In the design of mission-ready thrusters, emphasis will have to be placed on constraints imposed by mission-specific requirements to achieve an optimal design.

5.2 Capabilities and Limitations

In any study it is important to highlight the capabilities and limitations of the methods used. The simulation method used here is an electrostatic analysis based on the work presented by Krpoun and Shea [18]. This method comes out of much of the theoretical details in Ch. 2, specifically taking advantage of an assumed quasi-static evolution combined with knowledge of Taylor cone formation. This approach has the main advantage of greatly reduced computational expense compared to an electrohydrodynamic simulation. Relevant to the type of work presented here, this allows for very rapid examination of a large number of different design variations. Such an endeavor would be highly restricted using electrohydrodynamic simulation methods. This method proves to be very well-suited for quickly examining trends that arise with design parameter changes, and is capable of providing onset voltage analysis for these different configurations.

This method is not without limitations, however. Most clearly, this method does not allow for any kind of dynamic analysis. This means that useful information about Taylor cone formation, flow rate through the emitter, ion beam current, and other dynamic properties cannot be determined with this method. Further, this method focuses on the voltage

required to start electrospray emission; it does not provide any guarantee that emission can be maintained at that voltage. Since this method neglects space-charge effects, which will be present in some capacity once emission has started, any behavior in an electrospray device after the start of emission is unknown. Despite these limitations, this method provides a very good approach to quickly determine a basic starting point in understanding the onset voltage of an electrospray emitter. One could use this method to determine an optimal device design, and then, if desired, move to an electrohydrodynamic type simulation method to determine dynamic behavior of the chosen device design.

5.3 Suggestions for Future Work

A final inclusion in this work is suggestions to further build upon the foundation presented here. Considering the effects of space-charge is the next logical step in this analysis. These effects could likely be found by including some region of a certain level of space-charge in the area between the emitter and extractor grid. To do this, one would need to first determine the typical shape of the area containing free space-charge and the amount and distribution of the free space-charge within that area. This is likely to depend on emitter configurations, and, thus, will likely require some sort of iterative process. Another area of important future research should focus on an optimization study. Given some requirements on onset voltage and thrust density, as well as limits to the geometric and material constraints, there is enough data present here that could be analyzed to provide a few optimal design candidates for the buildup of a thruster. This leads to the final suggestion for future work. Ultimately, work should move towards the buildup of an electrospray thruster following the results presented here and results that may come from the other suggested future work. This would allow for examination of effects that simply cannot be found through modeling and simulation, which can in turn move this project closer to a flight-ready-type device.

References

- [1] ANSYS, Inc (n.d.). <https://www.ansys.com/>. Canonsburg, PA. viii, 8, 9, 30, 33
- [2] Brackbill, J. U., Kothe, D. B., and Zemach, C. (1992). A continuum method for modeling surface tension. *Journal of Computational Physics*, 100(2):335–354. doi: [10.1016/0021-9991\(92\)90240-Y](https://doi.org/10.1016/0021-9991(92)90240-Y). 17
- [3] Canfield, B. K., Terekhov, A., Costa, L., and Davis, L. M. (2019a). High-aspect ratio damage and modification in transparent materials by tailored focusing of femtosecond lasers. In Carr, C. W., Gruzdev, V. E., Ristau, D., and Menoni, C. S., editors, *Laser-induced Damage in Optical Materials 2019*, volume 11173, pages 7 – 18. International Society for Optics and Photonics, SPIE. doi: [10.1117/12.2536450](https://doi.org/10.1117/12.2536450). 26
- [4] Canfield, B. K., Terekhov, A., Costa, L., and Davis, L. M. (2019b). Implementation of a turret-mounted optical assembly for femtosecond laser Bessel-beam shaping for machining applications. In Dudley, A. and Laskin, A. V., editors, *Laser Beam Shaping XIX*, volume 11107, pages 53–63. International Society for Optics and Photonics, SPIE. doi: [10.1117/12.2529420](https://doi.org/10.1117/12.2529420). 26
- [5] Courtney, D. G. and Lozano, P. C. (2009). Porous ionic liquid ion source fabrication refinements and variable beam energy experiments. In *Proceedings of the 45th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit*. American Institute of Aeronautics and Astronautics. doi: [10.2514/6.2009-5087](https://doi.org/10.2514/6.2009-5087). 5
- [6] Dandavino, S., Ataman, C., Ryan, C. N., Chakraborty, S., Courtney, D., Stark, J. P. W., and Shea, H. (2014). Microfabricated electrospray emitter arrays with integrated extractor and accelerator electrodes for the propulsion of small spacecraft. *Journal of Micromechanics and Microengineering*, 24(075011):1–13. doi: [10.1088/0960-1317/24/7/075011](https://doi.org/10.1088/0960-1317/24/7/075011). 6
- [7] Faux, I. D. and Pratt, M. J. (1979). *Computational Geometry and Design for Manufacture*, chapter 5, page 132. Halsted Press, Wiley, New York. 24
- [8] Gamero-Castaño, M., Aguirre-de-Carcer, I., de Juan, L., and de la Mora, J. F. (1998). On the current emitted by Taylor cone-jets of electrolytes in vacuo: implications for liquid

- metal ion sources. *Journal of Applied Physics*, 83(5):2428–2434. doi: [10.1063/1.367002](https://doi.org/10.1063/1.367002).
24
- [9] Gañán-Calvo, A. M., Dávila, J., and Barrero, A. (1997). Current and droplet size in the electrospraying of liquids. Scaling laws. *Journal of Aerosol Science*, 28(2):249–275. doi: [10.1016/S0021-8502\(96\)00433-8](https://doi.org/10.1016/S0021-8502(96)00433-8). 9
- [10] Harris, J. R., Jensen, K. L., Shiffler, D. A., and Petillo, J. J. (2015). Shielding in ungated field emitter arrays. *Applied Physics Letters*, 106(201603):1–4. doi: [10.1063/1.4921709](https://doi.org/10.1063/1.4921709).
29, 58
- [11] Hartman, R. P. A., Brunner, D. J., Camelot, D. M. A., Marijnissen, J. C. M., and Scarlett, B. (2000). Jet break-up in electrohydrodynamic atomization in the cone-jet mode. *Journal of Aerosol Science*, 31(1):65–95. doi: [10.1016/S0021-8502\(99\)00034-8](https://doi.org/10.1016/S0021-8502(99)00034-8). 9
- [12] Irvine CubeSat STEM Program (n.d.). Team propulsion. Retrieved from: <https://www.irvinecubesat.org/propulsion>. 7
- [13] Jackson, S. (2017). NASA announces eighth class of candidates for launch of CubeSat space missions. Retrieved from: <https://www.nasa.gov/feature/nasa-announces-eighth-class-of-candidates-for-launch-of-cubesat-space-missions>. 7
- [14] Jahn, R. G. (2006). *Physics of Electric Propulsion*. Dover Publications, Inc., Mineola, New York. Original work published 1968. 1, 2
- [15] Kimber, A. M., Jorns, B. A., and Sodano, H. (2018). Dielectric materials with deposited electrode layers for electrospray arrays. In *Proceedings of the 2018 Joint Propulsion Conference*. American Institute of Aeronautics and Astronautics. doi: [10.2514/6.2018-4653](https://doi.org/10.2514/6.2018-4653). 18, 28
- [16] Kraus, J. D. (1953). *Electromagnetics*. McGraw-Hill Book Company, New York. 15
- [17] Krpoun, R., Räber, M., Shea, H. R., Smith, K. L., and Stark, J. P. W. (2007). Design and fabrication of an integrated MEMS-based colloid micropropulsion system.

In *Proceedings of the 30th International Electric Propulsion Conference*. Electric Rocket Propulsion Society. 6

- [18] Krpoun, R. and Shea, H. R. (2008). A method to determine the onset voltage of single and arrays of electrospray emitters. *Journal of Applied Physics*, 104(064511). doi: [10.1063/1.2981077](https://doi.org/10.1063/1.2981077). 10, 21, 22, 24, 62, 63
- [19] Krpoun, R. and Shea, H. R. (2009). Integrated out-of-plane nanoelectrospray thruster arrays for spacecraft propulsion. *Journal of Micromechanics and Microengineering*, 19(045019):1–10. doi: [10.1088/0960-1317/19/4/045019](https://doi.org/10.1088/0960-1317/19/4/045019). 5, 6
- [20] Lastow, O. and Balachandran, W. (2006). Numerical simulation of electrohydrodynamic (EHD) atomization. *Journal of Electrostatics*, 64(12):850–859. doi: [10.1016/j.elstat.2006.02.006](https://doi.org/10.1016/j.elstat.2006.02.006). 8, 9
- [21] López-Herrera, J. M., Popinet, S., and Herrada, M. A. (2011). A charge-conservative approach for simulating electrohydrodynamic two-phase flows using volume-of-fluid. *Journal of Computational Physics*, 230(5):1939–1955. doi: [10.1016/j.jcp.2010.11.042](https://doi.org/10.1016/j.jcp.2010.11.042). 8, 9, 18, 19
- [22] Lozano, P. and Martínez-Sánchez, M. (2005). Ionic liquid ion sources: characterization of externally wetted emitters. *Journal of Colloid and Interface Science*, 282(2):415–421. doi: [10.1016/j.jcis.2004.08.132](https://doi.org/10.1016/j.jcis.2004.08.132). 5
- [23] Martínez-Sánchez, M. and Lozano, P. (2015). Session 20: Electrospray propulsion. In *16.522 Space Propulsion*. Massachusetts Institute of Technology: MIT OpenCourseWare, https://ocw.mit.edu/courses/aeronautics-and-astronautics/16-522-space-propulsion-spring-2015/lecture-notes/MIT16_522S15_Lecture20.pdf. 36, 52
- [24] Melcher, J. R. and Taylor, G. I. (1969). Electrohydrodynamics: a review of the role of interfacial shear stresses. *Annual Review of Fluid Mechanics*, 1(1):111–146. doi: [10.1146/annurev.fl.01.010169.000551](https://doi.org/10.1146/annurev.fl.01.010169.000551). 8, 9

- [25] Nabity, J. A. and Daily, J. W. (2018). Effect of ionic liquid composition on colloid thruster emission and thrust performance. *Journal of Propulsion and Power*, 34(1):260–266. doi: [10.2514/1.B36376](https://doi.org/10.2514/1.B36376). 4
- [26] Popinet, S. (2003). Gerris: a tree-based adaptive solver for the incompressible Euler equations in complex geometries. *Journal of Computational Physics*, 190(2):572–600. doi: [10.1016/S0021-9991\(03\)00298-5](https://doi.org/10.1016/S0021-9991(03)00298-5). 9
- [27] Rahmanpour, M. and Ebrahimi, R. (2016). Numerical simulation of electrohydrodynamic spray with stable Taylor cone-jet. *Heat and Mass Transfer*, 52(8):1595–1603. doi: [10.1007/s00231-015-1680-6](https://doi.org/10.1007/s00231-015-1680-6). 8
- [28] Saville, D. A. (1997). Electrohydrodynamics: The Taylor-Melcher leaky dielectric model. *Annual Review of Fluid Mechanics*, 29(1):27–64. doi: [10.1146/annurev.fluid.29.1.27](https://doi.org/10.1146/annurev.fluid.29.1.27). 17, 18
- [29] Sutton, G. P. and Biblarz, O. (2010). *Rocket Propulsion Elements*. John Wiley & Sons, Inc., Hoboken, New Jersey, 8th edition. viii, 2, 3
- [30] Taylor, G. (1964). Disintegration of water drops in an electric field. *Proceedings of the Royal Society of London. Series A, Mathematical and Physical Sciences*, 280(1382):383–397. doi: [10.1098/rspa.1964.0151](https://doi.org/10.1098/rspa.1964.0151). 3, 7, 21, 23
- [31] Valásquez-García, L. F., Akinwande, A. I., and Martínez-Sánchez (2006). A planar array of micro-fabricated electrospray emitters for thruster applications. *Journal of Microelectromechanical Systems*, 15(5):1272–1280. doi: [10.1109/JMEMS.2006.879710](https://doi.org/10.1109/JMEMS.2006.879710). 6
- [32] Zeleny, J. (1914). The electrical discharge from liquid points, and a hydrostatic method of measuring the electric intensity at their surfaces. *Physical Review*, 3(2):69–91. doi: [10.1103/PhysRev.3.69](https://doi.org/10.1103/PhysRev.3.69). 7
- [33] Zeleny, J. (1917). Instability of electrified liquid surfaces. *Physical Review*, 10(1):1–6. doi: [10.1103/PhysRev.10.1](https://doi.org/10.1103/PhysRev.10.1). 7

- [34] Ziemer, J., Marrese-Reading, C., Cutler, C., Dunn, C., Romero-Wolf, A., Javidnia, S., Le, T., Li, I., Barela, P., Demmons, N., Hruby, V., Slutsky, J., Thorpe, J. I., Maghami, P., Hsu, O., and O'Donnell, J. (2018). In-flight verification and validation of colloid microthruster performance. In *Proceedings of the 2018 Joint Propulsion Conference*. American Institute of Aeronautics and Astronautics. doi: [10.2514/6.2018-4643](https://doi.org/10.2514/6.2018-4643). 6

Vita

Justin M. Jones first found his passion for engineering through his high school's tremendous STEM programs. He went on to study mechanical engineering at Tennessee Technological University in Cookeville, TN. As a part of that study, Justin took part in a one-year cooperative program working in the quality department for an automotive supply manufacturer. He learned a lot about engineering in that time, and through that experience made his decision to pursue graduate studies in engineering. Justin graduated from Tennessee Tech in 2018, and then enrolled in the graduate program in mechanical engineering at the University of Tennessee Space Institute (UTSI). While at UTSI, Justin has worked as a graduate research assistant under Dr. Trevor Moeller, focusing on electric propulsion technology. Justin graduated with a Master of Science degree in mechanical engineering in May 2020.