CORONA DISCHARGES IN ASYMMETRIC ELECTRIC FIELDS AND ITS IMPACT
ON IONIC WIND GENERATION

A Dissertation

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The challenge of thermal management in small form-factor electronic devices drives the development of novel technologies for heat dissipation. Ionic wind devices, which operate on the principle of electrohydrodynamic interaction, are being studied as a replacement for conventional fans because of the inherent advantages of small acoustic signature, low weight, low power consumption, and the absence of moving parts. In particular, corona discharge driven ionic winds are favored for their ease of operation in direct current (DC) mode and stability at atmospheric pressures. Miniaturization of ionic wind blowers to extremely small form factors (heights < 3 mm) is accompanied by various challenges. The operating potentials too are constrained to ~2000V to minimize safety hazards. To obtain flow rates comparable to fans under such constraints necessitates development of novel configurations and new modes of operation.

This dissertation presents a multi-electrode corona discharge as a solution to the challenges arising from miniaturization of duct heights in ionic wind devices. An overview of fundamentals of corona discharges and ionic winds, and a literature survey
of various ionic wind devices and numerical modeling procedures is included. Data from preliminary experiments on sub-millimeter scale coronas is presented and compared to theory to study the limiting conditions for corona formation and sustenance.

Corona discharges are studied experimentally and numerically in configurations that induce asymmetric electric fields in the discharge space. Multiple collector configurations are a particular subset of these and are studied in more detail to characterize their fundamental behavior and to understand the differences from traditional discharges involving a single collecting electrode. The configurations are shown to present characteristics that are suitable for mitigating some of the problems encountered in device miniaturization. The three-electrode configurations are shown to reduce the onset potentials for device operation, increase the total current production, and present a favorable redistribution of current to the various collectors. Traditional corona modeling procedures are demonstrated to have significant shortcomings in asymmetric configurations and an alternative modeling procedure is developed for application in these conditions.

The multi-electrode configurations were adapted to the development of an ionic wind blower. In a laboratory setup, these configurations are shown to improve flow rates by a factor of ~3× and reduce power consumption by up to 0.5×. A prototype fabricated within the constraints imposed by handheld electronic systems on size and operating potential is described. The performance of the prototype-installed system is compared to the baseline system for flow and acoustic characteristics and is shown to be comparable in terms of the flow rates generated and significantly better in the acoustic signature levels. The technology presented in this dissertation has been patented [1].
Dedicated to my father,

Whose love for science is written in my genes,

And whose words taught me to read them.
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CHAPTER 1:
INTRODUCTION

1.1 Motivation

Over the past decade electronic devices have undergone a significant reduction in size, particularly with the introduction of handheld devices of varying sizes. Accompanying the size reduction is a growing demand for increased performance from the integrated processors and accompanying electronics. As such, the management of the generated thermal power has become an increasingly researched topic both in industry and in academia. To date, most actively cooled small form-factor electronics, like notebooks and handheld devices, use conventional fans to dissipate the thermal energy through forced air convection. However, while suitable for notebooks, conventional fans have acoustic noise signatures that are typically beyond the comfort limits for handheld devices. This has prompted research into alternative “silent” cooling technologies for small form-factor electronic devices such as synthetic jets [2], phase change materials [3], closed loop liquid cooling [4], thermoelectrics [5], and ionic winds [6].

Air movers that utilize ionic winds, which are plasma discharge driven air flows, are attractive because forced convection cooling is easy to implement, and also because ionic wind blowers can be fabricated as a direct replacement for the conventional fan. Among the various ionic wind devices, blowers operated using corona discharges are in particular attractive because they are stable in atmospheric pressure, operate in direct
current (DC) mode, have no moving parts, and consume little power. The term ionic wind blower refers to devices operated within enclosed channels. To date, corona discharge driven ionic wind blowers that have been studied by various groups are ~10 mm in duct height and operate at potentials > 5 kV. To integrate them with small form-factor electronics requires reduction in size to < 3 mm and lowering of operating potentials to ~ 2000 V to comply with safety limits. However, scaling down corona discharges to millimeter heights, particularly in enclosed ducts, is accompanied by various challenges that need to be addressed.

This chapter describes the general principle of corona wind devices and highlights the challenges of miniaturization. A preliminary introduction to the concept of multi-electrode coronas, the focus of this research, is presented in the final section. A review of the basic theory of corona discharges and a survey of literature is presented in Chapter 2 to provide the background on studies carried out on ionic wind blowers in the past and to provide perspective and justification for the current research being carried out by the author. Subsequent sections of the report detail the research that has been carried out by the author. Chapter 3 describes preliminary studies conducted on wire-plate corona discharges in gap sizes less than 1 mm with the intention of characterizing corona performance in the small length scales that are of interest in miniature ionic wind devices. Results from experiments are presented and compared to existing theoretical relationships to validate their applicability at limiting scales. Corona discharges in asymmetric and multiple-electrode configurations, the primary subject of this research, are studied in Chapter 4. Experimental investigation of multi-electrode corona discharges is conducted in ideal configurations to characterize their behavior and highlight their differences,
advantages, and limitations compared to standard two electrode coronas. Numerical modeling of coronas in asymmetric electric fields is performed, and a new modeling procedure is proposed to overcome the limitations of existing procedures used in simulating coronas on macroscopic scales. The new model accounts for ionization events on the microscopic length scales and bridges the gap between micro- and macro-scale simulations. Chapter 5 describes the application of multi-electrode coronas to the development of ionic wind blowers and characterizes the improvements in their performance. Results from electrical and flow measurements are presented and the effect of the former on the latter is discussed, particularly in context of multi-electrode configurations. Experimental setups as well as developmental prototypes are presented along with data on the performance of the prototype compared to similar sized mechanical fans.

1.2 Basic Operating Principle of an Ionic Wind Blower

Corona discharges are partially ionized gas discharges that occur between a sharp electrode (called a corona source), typically a needle or a wire, and a blunt electrode (called a collecting electrode or counter electrode) such as a plate or a cylinder. A corona discharge can be operated in direct current (DC) mode and alternating current (AC) mode or in pulsed mode. DC corona discharges can be operated in both positive and negative polarity, depending on the whether the high voltage is applied to the corona source or the collecting electrode. The present research is conducted only on positive DC corona discharges and hence the document focuses primarily on positive coronas. The other forms of coronas were considered and discounted for various reasons. Compared to positive coronas, negative coronas generate significantly higher quantities of toxic ozone,
and it is difficult to miniaturize high voltage A.C and pulsed power sources to sizes that can be installed in small form factor electronics.

A typical positive corona discharge between a needle and a plate is shown in Figure 1.1. Ionization of the interstitial gas molecules requires the magnitude of the electric field to be greater than a certain critical value ($E_c$). Unlike a glow discharge between parallel plates, where the field is uniform, in a corona discharge, the field is enhanced near the sharp corona source resulting in a high field region localized around the source. As a result, ionization of gas molecules occurs only in this region which is called an ionization zone, and the corona discharge is thus said to be a locally ionized plasma. Farther away from the corona needle, the electric field magnitude drops below the required threshold value ($E_c$) and no ionization occurs. This allows for stable operation of corona discharges in high (~atmospheric) pressures. A complete volumetric breakdown of the entire interstitial gas (like in a glow discharge) poses higher risk of sparking between the electrodes. Corona discharges are only locally ionized and hence can be operated in a range of potentials that localizes the critical field ($E_c$). Sparking occurs in a corona only when the potential is high enough for the critical field to be exceeded throughout the gap. The ions created in the ionization zone, under the influence of the electric field, drift through the region beyond this zone towards the collecting electrode and hence this space outside the region of ionization is termed as the drift zone. Negative coronas operate by a slightly different mechanism. In a negative corona, the sharp electrode is the cathode and the blunt electrode forms the anode. As such, the field enhancement and the bulk of the ionization occurs near the cathode. But the electrons also drift across the interstitial space towards the collecting electrode (anode). Thus both
electron collision and electron attachment reactions occur throughout the gap giving rise to positive and negative ions respectively. Fewer ionization events occur farther away from the needle since the decreasing electric field magnitude is not sufficient to accelerate the electrons to the energy required for ionization. Electron attachment reactions are more favorable, producing negative ions.

As the gaseous ions generated by ionization near the corona source are driven across the interstitial gas by the applied electric field, they collide with neutral molecules and transfer their momentum. Thus they set the gas molecules in motion and generate a bulk flow that is called as an ionic wind (also electric or corona wind), or more generally, an electrohydrodynamic (EHD) flow. This is illustrated schematically in Figure 1.2.

Figure 1.1 Schematic of a positive corona discharge.
1.3 Challenges in Miniaturization

An ionic wind blower is a device that operates a plasma discharge (in this case, a corona) within a duct. The motion of ions between electrodes of the discharge set up an electrohydrodynamically driven airflow through the duct. In order for them to be installed in portable (handheld) electronic systems, the ionic wind blowers need to be reduced both in size and in the range of potentials at which they operate. As a result of the reduced height of the ducts, the discharges operating within the blower, which drive the flow, are also reduced in their size. Reduction of duct heights to ~ 3 mm implies the corona discharges operate in a gap distances ~ 1 - 1.5 mm.

Corona discharges are governed by physical laws that are, in theory, favorable to scaling. As the gap distance between the electrodes is reduced, so does the potential that needs to be applied to onset a corona. However, this scaling is limited in practice by various reasons, particularly in their application to ionic wind generation. Even when the corona discharge can be operated in small gaps, it may have a detrimental effect on the ionic wind generated.
One of the main challenges arises from the necessity to minimize the operating potentials. Reduction in the applied potential leads to lower discharge currents, and lower driving force, resulting in decreased flow rates. Miniaturization also leads to a reduction in inter-electrode gaps, which results in smaller drift zones. This again has a negative impact on the flow generation since the ions undergo fewer momentum-transfer collisions with the bulk air molecules. Another important challenge to miniaturization arises from the problems of corona stabilization in small duct heights. It has been observed by the author and in other studies [7] that stabilizing a corona discharge becomes increasingly difficult as duct heights are reduced below 5 mm. In these cases, the discharge transitions quickly to spark. One possible reason put forth as an explanation for this observation is that the dielectric channel walls constrain the electric field lines to be tangential along the dielectric surfaces and hence confine the electric field lines to flow within the channel (see Figure 1.3). As the channel height is reduced, the field lines become almost parallel, and there is insufficient inhomogeneity in the electric field to generate a stable corona discharge. As such, the discharge takes on the characteristics of a uniform field glow discharge, which is typically not stable at atmospheric pressure leading to sparks. While the above explanation is speculative, the fact that a traditional corona discharge is hard to maintain in small channels motivates the exploration of novel design configurations to obtain higher flow velocities in narrow channels.
1.4 Multi-Electrode Corona Discharges: An Introduction to the Concept

In this document, the author presents a multi-electrode configuration that addresses a number of the above challenges. The concept is to use a primary collecting electrode to ignite the corona discharge and then to use one or more additional collecting electrodes downstream to enhance the drift region and increase flow. The applied potential can be different for each collecting electrode (unbalanced potential) and the distance from the source to each electrode can be varied (asymmetric geometry) to optimize the flow. Ideally, the primary collecting electrode is used to reduce the operating potential (a gate electrode) while the multiple downstream electrodes help mitigate the subsequent loss in flow by lengthening the drift region.
While corona discharges have previously been carried out in multiple electrode configurations, both with multiple sources and multiple counter electrodes, they have typically maintained all the electrodes at the same potential (balanced potential) and the multiple collecting electrode electrodes are equidistant from the corona source (symmetric geometry) [8] [9] [10] [11], i.e., the arrangement is only a multiplication of a single discharge. Very few [12] [13] have carried out any research on configurations in which the various electrodes are each maintained at their own potential. Bendaoud et al [14] used a similar concept for electrostatic precipitators. Jewell-Larsen [15] described a concept similar to the one studied in this document involving an enhancement electrode and a collecting electrode, but the microfabricated device was never functional. Recently, Colas et al [16] used the same concept of multi-electrode configurations and claim to have decoupled the ionization and acceleration processes, but in large duct heights (10 mm) and at very high potentials (20 kV).

In a traditional two-electrode discharge, the positive ions are driven by the electric field from the source towards the counter electrode. The conceptual impetus for the three-electrode arrangement is to apply an additional electric field downstream of the ion source to pull the ions away from the primary counter electrode (labeled as electrode-2) and drive them towards electrode-3. A basic schematic of a multiple-electrode positive corona discharge is shown in Figure 1.4a. In principle, the distance between the primary electrode (2) and the corona source (1) could be reduced without reducing the flow rate, allowing a reduction in both the onset and operating potential. Essentially, in this configuration electrode-2 acts as a gate electrode whereas electrode-3 acts to drive the ionic wind as illustrated in Figure 1.4b. The technology has been patented [1].
Figure 1.4 (a) Schematic of a typical multi-electrode corona discharge and (b) Schematic illustrating concept of flow generation.
CHAPTER 2:
LITERATURE REVIEW AND BACKGROUND

References to corona discharges have existed for over two thousand years, in the form of a phenomenon known amongst sailors as St. Elmo’s fire. But in more recent history, corona discharges have been a field of study since early in the 20th century as a detrimental mode of breakdown in high voltage conductors. The physical laws that govern the discharges were studied extensively by Townsend [17], Loeb [18], and Peek [19] both theoretically and empirically through experiments. Stuetzer [20], in his seminal work, theoretically studied the ion drag from coronas and developed a basic theory for the body force exerted by the ions on neutral gas and the resulting pressure drop. Since then, corona discharges and ionic winds have been studied for various applications like electrostatic precipitation [21], ion sources for mass spectrometers [22], and ozone generation [23]. In the 1990’s, advancement in electronics renewed interest in them as an alternative technology for convective heat transfer, both as a mechanism for spot cooling [24] [25] [26] and for the development of ionic wind blowers [8] [9] [10] [11]. This chapter contains a review of literature pertaining to research on corona driven ionic wind generation. The chapter is divided into three major sections. The first section reviews fundamental theory of corona discharges relevant to this research. The second section surveys literature on miniaturization of corona discharges and various ionic wind blowers developed to date. The third section presents a review of the studies on numerical
simulation of corona discharges, both macroscale simulation of ion drift and microscale
simulation of the ionization zone.

2.1 Theory of Corona Discharges and Ionic Winds

In 1914, Townsend [17] derived an approximate relationship for the voltage-
current (φ-i) characteristic of a steady state corona discharge. In a generic form, the
relationship is given by

\[ i = k \Phi(\Phi - \Phi_0), \]  

(2.1)

where \( i \) is the current, \( \Phi \) is the applied potential and \( \Phi_0 \), the onset potential, is the
minimum potential required to ignite a steady corona. The proportionality constant \( k \)
varies with configuration and is a function of the geometric parameters, like radius of the
corona source and the gap distance. \( k \) also depends on the properties of the interstitial gas
like the mobility of ions within the gas and permittivity. It should be mentioned that an
alternative form given by \( i = k(\Phi - \Phi_0)^2 \) has also been suggested in literature [27] but
the form in Equation 2.1 has much wider acceptance. An analytical derivation by the
author for wire-plate discharges, detailed in Chapter 3, also provides credibility to the
form in Equation 2.1.

Peek [19] in 1915 conducted experiments that were mainly concerned with
establishing empirical laws to determine the corona losses associated with high voltage
conductors. Using electric field distributions in simple theoretical geometries, he derived
the minimum gap distance required to initiate a steady state corona and also defined an
empirical relationship to obtain the potential required to onset the corona. These
theoretically simple configurations form the foundation for most practical configurations
used in experiments. For example, in a wire-to-plate configuration, Peek determined that
the minimum gap distance \((d)\) required to sustain a corona was \(2.925 \times r_0\), where \(r_0\) is the radius of the wire. The semi-empirical Peek’s law defines the minimum electric field on the wire necessary to initiate the discharge, which in this case is given by

\[
E_0 = E_c m_v \delta^2 \left(1 + \frac{0.0301}{\sqrt{\delta r_0}}\right). \tag{2.2}
\]

The electric field on the wire \((E_{\text{wire}})\) is given in terms of the applied potential \((\Phi)\) as

\[
E_{\text{wire}} = \frac{\Phi}{r_0 \ln \left(\frac{2d}{r_0}\right)}. \tag{2.3}
\]

Substituting Equation 2.3 into 2.2 gives the criterion for onset potential as

\[
\Phi_0 = E_c m_v \delta^2 r_0 \left(1 + \frac{0.0301}{\sqrt{\delta r_0}}\right) \ln \left(\frac{2d}{r_0}\right), \tag{2.4}
\]

where \(E_0\) is the magnitude of electric field on the wire at onset, \(E_c\) is the disruptive critical potential gradient, which is about \(3 \times 10^6\) V/m for air, and \(m_v\) is a factor that accounts for surface impurities on the wire. The parameter \(\delta\) is the gas density factor based on pressure and temperature and is given by

\[
\delta = \frac{3.92 p}{273 + T}, \tag{2.5}
\]

where \(p\) is the pressure in cm of Hg and \(T\) is the temperature in degrees Celsius. At standard temperature and pressure \(\delta\) is 1. \(m_v\) is 1 for smooth wires but practically varies from 0.85 to 0.98 based on the condition of the wire. Incidentally, despite having different ionization mechanisms, the onset potential for both positive and negative coronas is approximately the same for a given geometry.
In 1947, Kaptzov [28] proposed that post onset, the electric field at the wire’s surface ($E_{\text{wire}}$) remains at the value dictated by Peek’s onset criterion ($E_0$) irrespective of the potential applied on the wire. Kaptzov’s hypothesis is often used in macroscale simulations of corona discharge [29] [30] since it provides a methodology to avoid the reaction chemistry in the ionization zone.

One of the first studies on corona-driven ionic winds was by Stuetzer [20]. He considered the momentum transfer collisions of ions with neutral air molecules as a body force in the Navier-Stokes equations as shown in Equation 2.6.

$$\rho \left( \frac{\partial \vec{v}}{\partial t} + \vec{v} \cdot \nabla \vec{v} \right) = -\nabla p + \mu \nabla^2 \vec{v} + \left( \rho_{sc} \vec{E} \right). \quad (2.6)$$

The body force term is given by $\rho_{sc} \vec{E}$, where $\rho_{sc}$ is the space charge density and $\vec{E}$ is the electric field. In static equilibrium, i.e., no flow condition, comparison of terms in the Navier-Stokes equation dictates the pressure drop across the gap in a wire-plate configuration to given by

$$\Delta p \approx \frac{i}{b} \frac{d}{A} \ln \left( \frac{2d}{r_0} \right), \quad (2.7)$$

where $\Delta p$ is the pressure drop, $i$ is the total current, $A$ is the area of the collecting electrode, $b$ is the ion mobility in air, $d$ is the gap distance and $r_0$ is the wire radius. A simple substitution of Townsend’s relationship (Equation 2.1) into Equation 2.7 gives the pressure drop in terms of the applied potential. Power consumed in a corona discharge is given simply as

$$P = \Phi i = k \Phi^2 (\Phi - \Phi_0). \quad (2.8)$$
Various definitions of efficiency exist in literature on ionic winds. Stuetzer defines an efficiency as \( \eta = \Delta p/P \). In the case where free flow exists, the efficiency can be defined as

\[
\eta = \frac{\text{dynamic pressure power}}{\text{total power consumed}} = \frac{(dm/dt)v^3}{\Phi i} = \frac{\rho v^3 A}{k\Phi^2(\Phi - \Phi_0)} = \frac{\rho Q^3}{kA^2\Phi^2(\Phi - \Phi_0)},
\]

(2.9)

where \( \rho \) is the density of the gas, \( v \) is the velocity and \( Q \) is the volume flow rate. In Equation 2.9, \( A \) is the flow area and is defined by the configuration. In the early 1960’s, Robinson [31] studied the efficiency of corona driven ionic wind blowers and showed that corona discharges are only about 1-2% efficient in converting electrical energy into kinetic energy. Till date, the efficiency of ionic wind blowers remains in the same range, quite often < 1% [9] [32].

Another important semi-empirical theory concerning corona discharges is Warburg’s law. First proposed in 1899 [33] and later studied by other researchers in the latter half of the 20\(^{th}\) century [34] [35], Warburg’s law describes the distribution of current density on the collecting electrode in a point-to-plate system. This concept can be extended to other geometries where the collecting electrode is a plate. The law is given as

\[
j(x) = j(0)\cos^m(\theta) \quad ; \quad \theta = \tan^{-1}\left(\frac{x}{d}\right),
\]

(2.9)

where \( j(x) \) is the current density at a location on the plate \( x \) from the center, \( j(0) \) is the current density at the center, \( d \) is the gap distance between the needle and the plate. The various geometric variables are shown in Figure 2.1. The value of \( m \) is empirically determined and varies based on configuration. It is typically ~4-5.
2.2 Review of Miniature Corona Discharges and Ionic Wind Blowers

Among those studies that have explored scaling down corona discharges, a number have focused on ionic wind generation for cooling electronic devices. Hsu et al. [8] microfabricated sharp electrode tips with a radius of ~0.5 µm for use in electrode gaps from 1 mm to 6 mm. They showed that corona onset increased from 2000 V to 2500 V as the gap increased, and currents ranged from ~1.5 µA to as high as 30 µA as the tip voltage increased. Schlitz and Singhal [36] designed a miniature, corona-driven fan that utilized curved (semi-cylindrical) blunt electrodes with a wire sharp electrode, and reported operation in gaps as small as 500 µm. Go et al. [25] [26] showed that an offset configuration, where a 50 µm wire was placed not directly above a 6.35 mm wide blunt electrode but laterally shifted, produced a quadratic current (i)-potential (Φ) relationship for electrode gaps from 3.15 mm to 6.78 mm. At even smaller dimensions where the
blunt electrode was only 125 µm wide and the gap was 715 µm, the offset configuration was able to maintain steady corona and still generate an ionic wind [6].

In another possible application, Lee et al. [37] microfabricated a corona-driven micromotor that had an electrode gap of only 50 µm and sharp electrodes with tip radii from 3 µm to 5 µm. They observed corona onset at 700 V to 800 V, and sparking at voltages beyond 1100 V. They did not present current data, but they did note that the current was less than µA, which is the typical order of magnitude for a corona discharge. Chua et al. [38] conducted the first in-depth study of a miniature corona discharge device suggesting that these devices could be used as ionization gas sensors because different gas compositions will generate different current responses. In their work, they used Peek’s criterion for corona onset and Warburg’s law to optimize the electrode spacing. They then microfabricated a needle-to-grid device with a 20 µm wide needle tip and electrode gaps ranging from 1.4 to 2.2 mm. In negative corona mode, the onset voltage ranged from ~1.4 kV to 2.0 kV, and qualitatively matched with the analytical prediction. They also showed that because the corona discharge is driven by the surface electric field on the pin, the radius of the pin played little role for the gaps they tested. While the above studies show that miniature coronas are possible, not all of them translate to the development of an efficient ionic wind blower.

Within the last few years, a number of studies have been carried out on the design of ionic wind blowers. Various electrode geometries in both positive and negative polarities have been used in these designs, the most popular being pin-to-plate, wire-to-plate, wire-to-mesh, and wire-to-cylinder configurations. Researchers from the University
of Washington [9] [24] [30] and later Tessera Technologies, Inc. [39], have conducted multiple studies, both experimental and numerical, on the design of an ionic wind blower, which they term an electrostatic fluid accelerator (EFA). In their studies, the EFA utilizes a wire or a blade as the corona source with the counter electrodes being plates forming the walls of the channel or in some cases, cylinders located downstream. Tessera Technologies, Inc. [39] recently demonstrated implementing an ionic wind blower in a laptop in place of an axial fan. Researchers from McMaster University [10] [40] [41] have conducted fundamental studies on the ionic wind generated in both polarities using wire-to-plate configurations, and a group from University of Oklahoma [11] [42] has also carried out basic studies on corona-driven EHD flows. In order to increase the total mass flow rate, Rickard et al. [43] [32] studied the effect of stacking EHD gas pumps in series, where they used circular ducts with needles as corona sources and ring counter electrodes. Though there has been some progress in miniaturization [44], most blower designs are still typically 10 mm or larger in duct size and require > 5 kV. Takeuchi and Yasuoka [7] carried out ionic wind experiments in circular ducts of diameters varying from 3 mm to 20 mm. They observed that obtaining a stable corona discharge becomes increasingly difficult as the cross section of the duct is reduced and becomes nearly impossible for diameters less than 5 mm.

2.3 Review of Numerical Simulation of Corona Discharges

Studies on numerical simulation of corona discharges are typically split into two camps, those that simulate the ionization zone and those that simulate the drift region. The former consists of groups primarily interested in studying the reaction chemistry within the ionization zone with the intention of mapping the concentrations of various
species produced. The latter primarily focus on the drift of ions in the interstitial gap with the intention of studying its effects on EHD flow or interactions of the discharge with externally driven bulk flow. This section reviews some of the prominent works from both camps along with a description of the numerical methodology.

2.3.1 Simulation of the ionization zone

In the latter half of the 20th century, a few studies have modeled the reactive chemistry within the ionization zone [45] [46]. Since 2001, Chen and Davidson [47] [48] [49] have conducted a series of simulations modeling the ionization zone. The typical domain used in their studies is shown in Figure 2.2, where the shaded area indicates the region of interest. The boundary of the ionization zone is the distance at which the electric field magnitude drops below the critical value of $3 \times 10^6$ V/m.

![Figure 2.2 Typical computational domain used in simulations of the ionization zone.](image)

Their studies comprised of two procedures to model the ionization zone. Their preliminary study [47] considered the charged species as a collective, one each for electrons, positive ions and negative ions. The governing equations were then the drift
equations for the ions and the drift-diffusion equation for the electrons. Diffusion was found to be insignificant in the case of ions and neglected. The production of the species through electron-neutral collisions is included in the model as source terms in the governing equations. These equations are explained in detail in Chapter 4. Their model was one dimensional in a cylindrical geometry and hence only had radial variations.

Their later studies [48] [49] modeled the reactive chemistry within the ionization zone by following a similar procedure. A set of 10-15 species involving N\textsubscript{2} and O\textsubscript{2} were considered along with about 25 reactions involving these species for which kinetic rate coefficients have been empirically established in literature. The procedure uses the same governing equations as the above but each species is governed by its own transport equation with the kinetic rate of production/depletion now forming the source terms. Concentration of various species was also obtained as function of the radius. However, it was observed that most of the species, being reactive, exist only for a short duration and ozone is the only stable by-product that diffuses beyond the boundary of the ionization zone. Yanallah et al. [50] [51] also conducted simulations of the ionization zone with similar procedures.

2.3.2 Simulation of the drift zone

Most of the authors interested in engineering applications of corona discharges dismiss the reaction chemistry within the ionization layer and quite often dispense with the entire layer itself. This is justified since the ionization layer is small, being only on the order of the wire radius. There are numerous studies in literature that model the ion transport in the drift zone [11] [25] [29] [30] [52]. The fundamental procedure for simulation of a corona discharge on the macroscale, \textit{i.e.}, the ion drift, is similar in all of
these studies. The difference only arises in the numerical techniques used to model the equations. The methodology consists of simulating Poisson’s equation and ion transport equation in a coupled fashion. The ion transport equation is a drift-diffusion-advection equation that governs the transport of ions through the gas. In these simulations, since the ionization zone is no longer modeled and the focus is the drift region, only positive ions are considered to exist in the space. Thus, it can only be used for simulating positive DC coronas. The entire system is modeled on continuum scale. Details on the model are provided in Chapter 4 along with its differences to the reaction model.

While many studies have simulated corona discharges in various configurations, it has often only been as a supplement to experiments. But to the author’s knowledge, the procedure has only rarely been shown to match experimental current measurements [29]. Jewell-Larsen et al. [9] used simulations to choose between configurations in the design of their Electrostatic Fluid Accelerator. Go et al. [25] simulated the effects of near surface discharge on the boundary layer of an externally driven flow to study convective heat transfer enhancement. Both temperature and heat transfer coefficients match the experiments in trends but not in magnitude. These studies indicate that the procedure has been quite well established to predict trends in typical corona discharges.

Particular to the present project, very few simulations exist of discharges in multiple electrode configurations similar to the ones being studied by the author. Adamiak and Deng [13] simulated a similar tri-electrode system where the primary discharge was between a needle and a grid with a plate behind the grid forming a secondary collecting electrode. But since their numerical results were not validated with any experimental results, it is difficult to judge the validity of the procedure in these
situations. Other studies have carried out research on multi-electrode corona simulation, primarily with an interest in polymer charging [53] [54]. Again, the length scales on these studies are typically much larger than those of interest in miniature ionic wind blower, and as will be shown in Chapter 4, the modeling procedure used in the above studies is insufficient in accuracy for millimeter-scale coronas.
CHAPTER 3:
CHARACTERIZATION STUDIES ON WIRE-PLATE DISCHARGES IN SUB-MILLIMETER GAPS

This chapter describes a fundamental study conducted by the author to characterize corona discharges in sub-millimeter gap regimes. The primary purpose of this study was to push the limits of scaling theory and test the behavior of coronas in these extreme gaps and compare them against known governing equations. A wire-plate configuration was chosen for the study due to the existence of relatively well established theoretical relationships which are studied in literature [19] [34] [35] for large gap distances (> 5 mm) and wire-radii (>1 mm). Comparisons are made of the experimental data collected from the experiments to the existing relationships to ascertain their validity in sub-millimeter gaps. A theoretical relationship is derived using order of magnitude estimates to obtain the dependence of the voltage-current characteristics on the geometric parameters, viz., wire radius ($r_0$) and gap distance ($d$). The first section of the chapter describes the experimental procedure and presents a discussion of the results. The second section details the derivation of the voltage-current characteristic equation. This work was published by the author in the *Journal of Electrostatics* [55].

An essential step towards minimizing the overall operating potentials of the device is to reduce the potential at which the corona onsets. As described in Chapter 2, this onset potential is given by Peek’s law (Equation 2.2) and depends on the gap
distance between the electrodes \( (d) \) and the wire radius \( (r_0) \). Peek’s law dictates that reduction in \( d \) and in \( r \) lowers the onset potential. To test the limits of this scaling, a preliminary study was conducted to characterize the behavior of corona discharges in sub-millimeter gaps under theoretically well established conditions between a wire and a plate. Peek [19] also derives that the minimum gap distance between the wire and plate required for a stable corona is \( 2.925 \times r_0 \). Thus, establishing stable coronas in sub-millimeter gaps requires the use of corona electrodes of very small diameters.

### 3.1 Experimental Setup and Results

Tungsten wires of 50 \( \mu m \) and 25 \( \mu m \) diameters were used as the corona source and a copper plate was used as a collecting electrode. A Bertan 225 High Voltage DC power supply provided the potential to wire. The collecting electrode was grounded through a Keithley 6485 picoammeter. The protection circuit was introduced between the collector and the ammeter to prevent damage to the ammeter when the discharge sparks. The setup is shown in Figure 3.1a and the schematic of the circuit is shown in Figure 3.1b. The wire was held taut across prongs made of acrylic. This was mounted on a motorized linear stage (Newport MFA-CC) that has a positioning accuracy of 0.1 \( \mu m \). To set the electrode gap, the wire was first brought into contact with the plate and then backed away to the required distance. The potential was then incrementally increased in steps of 50 V until the discharge sparked. A delay of 10 s was provided between the voltage increment and current measurements to allow the discharge to reach steady state. This procedure was repeated for gap distances from 300 \( \mu m \) to 5 mm.
This section presents the results for both the 50 μm and the 25 μm diameter wires. Figures 3.2a and 3.2b show the \( I-\Phi \) characteristics between corona onset and spark. Prior to corona onset, the current measurements were in the nA range, indicative of noise, and the currents increased to the μA range after onset. The point of this sudden increase is noted as the experimentally determined onset potential. Generally, the results are as expected from the theory. As the gap distance decreases, the onset potential decreases and the magnitude of current increases. Peek’s limit for the minimum gap distance required for a stable corona dictates that a corona should be possible at 150 μm for the
wire of diameter 50 μm. However, it was observed that the discharge was unstable and unrepeatable with 300 μm gap, below which the discharge sparked before a stable corona could be initiated. For the 25 μm wire, it was observed that below 800 μm, the wire deformed and deflected towards the plate. This is presumed to be the result of electrostatic forces overcoming the tension in the wire. A simple comparative analysis of the tension in the wire and electrostatic forces is presented in Appendix A.

Figure 3.2 $I$-$\Phi$ characteristics for (a) 50 μm diameter wire and (b) 25 μm diameter wire
According to the Townsend’s discharge relation (Equation 2.1), $I/\Phi$ is linearly related to the applied potential $\Phi$. Figures 3.3a and 3.3b plot this relationship to test the validity of Townsend’s relationship in small gaps. As can be observed from the plots, while the relationship holds true for gaps greater than 800 μm, for smaller gaps, the curves deviate a little from the linear fits. This is a lot more prominent in the 25 μm wire, but that may be because of the wire deflections mentioned above.

Figure 3.3 $I/\Phi$ as a function of $\Phi$ for (a) 50 μm diameter wire and (b) 25 μm diameter wire with corresponding linear fits.
Onset potential ($\Phi_0$), can be determined in three ways using a combination of experiments and theory. As explained above, it can be experimentally determined by observing the potential at which currents jump from noise levels in nA to $\mu$A range. Peek’s law (Equation 2.4) provides a semi-empirical formulation for the onset potential based on geometric parameters. A third option is from Townsend’s discharge relationship (Equation 2.1) from which the onset potential ($\Phi_0$) can be obtained as the intercept of the linear fit in Figures 3.3a and 3.3b. Figures 3.4a and 3.4b show all three onset potentials plotted against the gap distances. It was observed that the three values do not match at large gaps, but seemed to have good concurrence at small gaps. This could be attributed to surface characteristics and atmospheric conditions, but could also be more significant as the numerical values in Peek’s Law are only empirical and might differ for such small electrode diameters and gaps. The lowest onset potential achieved was approximately 1800 V.
Figure 3.4 $\Phi_0$ as a function of $d$ for (a) 50 μm diameter wire (b) 25 μm diameter wire

3.2 Derivation of Voltage-Current Characteristic for Wire-Plate Corona Discharge

While Townsend’s discharge equation does provide the basic relationships between the current ($i$), applied potential ($\Phi$) and the onset potential ($\Phi_0$), it includes a proportionality constant ($k$) that should include all the geometric parameters. A scaling theory was developed to determine this constant in terms of the wire radius ($r_0$) and gap distance ($d$) and was determined to be,
\[ \frac{I}{l} \propto \frac{2\pi \varepsilon_0 \mu}{r_0 d} \ln \left( \frac{2d}{r_0} \right)^2 \Phi (\Phi - \Phi_0). \]  

where \( I/l \) is the current per unit length of wire, \( \varepsilon_0 \) is the permittivity in vacuum and \( \mu \) is the ion mobility in air. The detailed derivation is provided below.

A scaling approach is taken to derive a form of the Townsend’s relation for a wire-to-plane geometry, where the current (\( I \))-voltage (\( \Phi \)) relationship is based on the geometric parameters of the electrode configuration, viz., the wire radius (\( r_0 \)) and the gap distance (\( d \)). A positive corona discharge between a wire and a plane with a gap distance \( d \) can be equivalently modeled as a corona between two wires (wire-to-wire) of the same diameter separated by twice the distance (\( 2d \)) with the plane along the line of symmetry as shown in Figure 3.5. The wires are at opposite potentials (+\( \Phi \) and –\( \Phi \)) and so the plane is at 0 V, similar to the experiments presented here.

Figure 3.5 Schematic of a corona discharge between parallel wires

The electric field in a wire-wire geometry has been calculated by Peek [19], and at any point \( x \) along the line joining the centers of the two wires,
\[ E(x) = \frac{2\Phi \sqrt{d^2 - r_0^2}}{\left\{ (r_0 + x)(d - r_0) - \frac{x^2}{2} \right\} \ln \left( \frac{d}{r_0} + \sqrt{\left( \frac{d}{r_0} \right)^2 + 1} \right)} \] (3.2)

For \( d \gg r_0 \), Eq. (3.2) can be simplified and the electric field at the wire \((x = r_0)\) is

\[ E_{wire} = E(r_0) = \frac{\Phi}{r_0 \ln \left( \frac{2d}{r_0} \right)} \] (3.3)

The total current per unit length from the wire can be described as the rate of change

\[ \frac{I}{l} = \frac{d\lambda}{dt} = \frac{d\lambda}{dx} \frac{dx}{dt} \] (3.4)

where \( \lambda \) is the charge per unit length around the surface of the wire.

In a positive corona discharge, the ionization zone (shown in Figure 3.6) is a compact region around the anode where the air molecules are ionized.

Figure 3.6 Figure showing the ionization zone around a corona wire
If $\rho(r)$ is the space charge density in this zone, Poisson’s equation states that

$$\frac{1}{r} \frac{d}{dr} (rE) = \frac{\rho(r)}{\varepsilon_0}.$$  \hspace{1cm} (3.5)

Since the corona discharge is a steady process, an estimate of the total charge being transported across the drift region is given by the total space charge in the ionization zone. The net space charge per unit length of the wire at an applied potential of $\Phi$ can be calculated by integrating the space charge density within the ionization zone between the limits of the wire radius ($r_0$) and the location of the ionization zone boundary ($r_i$). Thus,

$$\int_{r_0}^{r_i} \rho(r)(2\pi r)dr = (2\pi\varepsilon_0) \int_{r_0}^{r_i} d(rE) = \left(2\pi\varepsilon_0 \right) \left( r_0 E_{wire} - r_i E_{c} \right),$$  \hspace{1cm} (3.6)

where $E_{wire}$ and $E_{c}$ are the electric fields at the wire surface and the zone boundary respectively. The space charge being transported across the gap at the applied potential ($\Phi$) is that which is accumulated in the zone as the potential is increased from the onset value ($\Phi_0$) to the applied potential ($\Phi$), and can be obtained as a difference of the above integral for the two states. Since the size of the ionization zone is relatively unchanged with potential i.e., $r_i \approx r_{i,\text{onset}}$ and on the same order of magnitude as the wire radius, the space charge being transported across the gap is

$$\lambda \sim \left(2\pi\varepsilon_0 \right) \left( r_0 E_{wire} - r_0 E_{wire,\text{onset}} \right).$$  \hspace{1cm} (3.7)

Using Laplacian values of electric field as an estimate, Equation 3.3 for the electric field can be applied at the corresponding wire potentials to get,
\[
\lambda \sim (2\pi\varepsilon_0) \left( \frac{\Phi}{\ln\left(\frac{2d}{r_0}\right)} - \frac{\Phi_0}{\ln\left(\frac{2d}{r_0}\right)} \right) = \frac{(2\pi\varepsilon_0)}{\ln\left(\frac{2d}{r_0}\right)} (\Phi - \Phi_0). \quad (3.8)
\]

The total quantity of ions transported across the gap can be scaled as

\[
\frac{d\lambda}{dx} \sim \frac{\lambda}{d}. \quad (3.9)
\]

The speed of the ion flow \((dx/dt)\) scales as the drift velocity, or

\[
\frac{dx}{dt} \sim \mu E_{\text{wire}} = \mu \frac{\Phi}{\ln\left(\frac{2d}{r_0}\right)}, \quad (3.10)
\]

where \(\mu \, [\text{m}^2/\text{Vs}]\) is the ion mobility in the interstitial gas.

Substituting Equations (3.8), (3.9), and (3.10) into Equation (3.4) produces the Townsend relation for a wire-to-plane configuration as

\[
\frac{I}{l} \sim \frac{2\pi\varepsilon_0\mu}{r_0d} \Phi (\Phi - \Phi_0). \quad (3.11)
\]

The validity of this relationship was tested by comparing the slopes with experimental data. According to Equation 3.11, if \((I/\Phi)r_0d \left[ \ln\left(\frac{2d}{r_0}\right) \right]^2\) is plotted as a function of \(\Phi\), the slope of the curve should be a constant regardless of the wire-to-plane geometry \(d\) and \(r\). Further, this slope should have a magnitude on the order of \(2\pi\varepsilon_0\mu l\) where \(2\pi \sim 10\), \(\varepsilon_0 \sim 10^{-12}\), and \(\mu \sim 10^{-4}\) for air (in metric units). In this experiment, \(l \sim 10^{-2}\) (about 5 cm), such that \(2\pi\varepsilon_0\mu l\) should be on the order of \(10^{17}\). The slopes calculated from the linear curve fits to the data for both the 50 \(\mu\)m and 25 \(\mu\)m wires are plotted in Figure 3.7.
Figure 3.7 Extracted slopes from the curve fits of $(l/\phi) r_0 d \left[ \ln \left( \frac{2d}{r_0} \right) \right]^2$ vs $\Phi$ plotted as a function of $d$ as well as the average slopes for both the 50 mm diameter wire and 25 mm diameter wire. Note that the anomalous values for $d = 4$ mm and 5 mm are neglected in calculating the averages.

It can be seen that the values are fairly constant as the gap distance is varied and the magnitudes are on the order of $10^{-17}$ as predicted by Equation 3.11. This adds confidence to the form of the derived relationship. However, it can be observed that the slope values for gap distances of 4 mm and 5 mm appear to be slightly lower than the rest, and this is more pronounced for the 50 µm wire. Since the discharge relationship is obtained using an argument which only takes into consideration the order of magnitudes of the various parameters involved, it is unclear whether the deviation at these large gaps is a result of the assumptions made in the analysis or if it is merely a function of experimental variability. It is likely that the scales considered in the derivation vary for sub-millimeter and millimeter gaps.
3.3 Summary

This study demonstrated that stable coronas can be achieved in sub-millimeter gap sizes down to about 400 μm. The basic governing relationships established in literature are valid qualitatively and are seen to describe the trends even in sub-millimeter regimes. However, their use is limited in quantitatively predicting the necessary variables required in practical design. The comparison of experimental data with theory suggested that the deviations are greater for wires with extremely small diameters (in this case 25 μm). This is not surprising since most of the early studies which established these theoretical and empirical relationships between parameters involved in a corona discharge have been conducted for much larger length scales, in fields like high voltage engineering of transmission lines. Even in the last few decades, the primary uses of corona discharges have been in electrostatic precipitation and in xerography for photocopier. The study indicates the necessity of further research into understanding the fundamental nature of coronas and better relationships to predict the onset potentials and ion currents.
CHAPTER 4:
FUNDAMENTAL SCALING STUDIES ON ASYMMETRIC AND MULTI-ELECTRODE CORONA DISCHARGES

This dissertation comprises of two broad concentrations, the understanding of the physics of multi-electrode corona discharges and the development of an ionic wind blower that utilizes the technology to overcome the challenges put forth in Chapter 1. The previous chapter demonstrated that corona discharges can be sustained in sub-millimeter configurations. However, the theoretical limits of the gap distance at which coronas can be sustained were not attained. Additionally, these discharges were characterized in an open configuration, as opposed to enclosed/ducted geometries where the problems of stability arise due to confinement of the electric field. To stabilize the discharge in narrow ducts, as well as to improve flow rates of ionic wind generated from the discharges, the concept of multi-electrode discharges is proposed, as described in Section 1.4.

The present chapter focuses on fundamental studies of corona discharges in asymmetric geometries and in configurations with multiple collecting electrodes. The intent of the study is to characterize the behavior of a corona in conditions similar to the one proposed as a concept in Section 1.4, but in more idealistic configurations for which both experimental data and well established theoretical relationships exist in literature. The study is conducted both via experiments and numerical modeling of the corona
discharge to obtain a better understanding of asymmetric and multi-electrode corona discharges and the differences compared to symmetric and traditional two-electrode configurations.

Figure 4.1a shows a conceptual arrangement of a multi-electrode corona discharge in a duct. The advantage of the configuration is illustrated in Figure 4.2b. In order to drive an EHD flow through the duct, a typical two-electrode discharge requires the collecting electrodes to be positioned downstream. This results in the requirement of high operating potentials to onset the corona as well as to create sufficient electrical current to drive the flow. To reduce the onset and operating potentials, a three-electrode configuration uses a gate electrode (or primary collector) to onset the corona. Due to its proximity, the primary collector dictates the corona onset. The secondary collectors positioned downstream of the duct exert a downstream electric field that drive the ions generated at the source through the duct, generating an EHD flow. As a result, the flow is generated at a lower potential, and as will be shown in this chapter, when compared to two-electrode configurations, higher flow rates are achieved for the same potential.
The chapter is divided into two broad sections. The first section presents fundamental proof-of-concept studies on multi-electrode discharges through experiments. These studies are on larger gap distances (~2-10 mm) than the targets for the ionic wind blower (~1-3 mm) but provide valuable insight into the fundamental physics and behavior of multi-electrode discharges. These studies were published by the author in the journal *IEEE Transactions on Dielectrics and Electrical Insulation* [56] and in the
conference proceedings of *Annual Meeting of the Electrostatics Society of America, 2010* [57]. The second section of the chapter focuses on the numerical modeling of asymmetric corona discharges in a wire-cylinder configuration. Along with assisting in the understanding of the physics of corona discharges in millimeter-scale asymmetric geometries, the model also exposes the shortcomings of the traditional procedure used to simulate corona discharges, and as an extension, ionic winds. Unlike the traditional numerical procedures, the new model takes into consideration the ionization within the plasma zone and highlights the necessity of its inclusion in modeling miniature corona discharge devices. The numerical study is in the process of being submitted to the *Journal of Electrostatics* and to the conference *Annual Meeting of the Electrostatics Society of America, 2013*.

4.1 Characterization Studies on Multi-Electrode Discharges

Multiple electrode configurations are asymmetric in geometry and unbalanced in potentials, thus resulting in distorted electric fields around the corona source. To be able to understand and apply this complex phenomenon, a study of the effect of non-uniform fields on the ion production and space charge distribution becomes imperative. This section details a conceptual experiment that has been conducted by the author to study the multi-electrode corona discharge. The simplicity in geometry is advantageous for analyses, assisted by the established relationships for wire-plate discharges.

4.1.1 Experimental Setup and Procedure

Figure 4.2 shows the schematic of the experimental setup used for the study. Henceforth in this report, this setup shall be termed as Test-Configuration. A positive
corona was operated between a wire (electrode c) and two collecting electrodes (electrodes 1 and 2). Tungsten wire of 50 µm diameter was used as the corona source and copper plates 25 mm × 25 mm were used as the two collecting electrodes. The distance from the wire to the primary collecting electrode was maintained constant \(d_1\) while the distance to the secondary collecting electrode \(d_2\) was varied with a linear positioner. The potential on the wire \(\Phi_c\) was slowly increased and both the collecting electrodes were grounded through two individual picoammeters \((\Phi_1 = 0 \text{ V}; \Phi_2 = 0 \text{ V})\) in order to measure the current through each of them. Two sets of experiments were conducted for two fixed values of \(d_1 = 2 \text{ mm}\) and \(d_1 = 4 \text{ mm}\). In the following section, “two-electrode configuration” refers to the case where the collecting electrode at \(d_1\) is absent and only one collecting electrode is present at a (variable) distance \(d_2\) from the wire. In the “three-electrode configuration”, all three electrodes are present. The geometry is thus asymmetric \((d_1 \neq d_2)\). The Test-Configuration is however balanced in potential since both the collecting electrodes are grounded. However, the asymmetric geometry ensures a non-uniform electric field distribution in the discharge space.

Figure 4.2 Schematic of Test-Configuration
A Bertan 225 HV power source was used to apply the potential to the corona source and two Keithley 6485 picoammeters were used for current measurement from each of the two collecting electrodes. The potential was ramped up in increments of 50 V with a pause time of 10 s between the potential increment and the current measurement.

4.1.2 Results

The concept of multi-electrode discharges was intended to introduce a “gate-electrode” and reduce the potential at which the device operates, i.e., to increase currents to a farther collector. As explained previously, one of the primary requirements would be for the so called gate-electrode or primary electrode (in this case electrode-1) to reduce the onset potential and have ion currents flowing to the secondary collector (electrode-2) at potentials where normally no current would exist. Figures 4.3a and 4.3b show the onset potential, defined as the potential when current flows to the secondary collecting electrode, as a function of its distance from the wire ($d_2$), in both two-electrode and three-electrode configurations. The two-electrode configuration consists of only one collector at a distance $d_2$, while the three-electrode configuration consists of two collectors, one each at $d_1$ and $d_2$ with Figure 4.2a corresponding to $d_1 = 4$ mm and Figure 4.2b corresponding to $d_1 = 2$ mm. As can be observed, the potential at which current flows through the secondary electrode is significantly reduced due to the presence of the primary electrode. Moreover, it was also observed that current to both electrodes commenced at the same onset potential, indicating that it was a single discharge that distributed ions to both electrodes. Interestingly, this “dual” onset potential was always at (or near) the onset potential to initiate a corona when only using a solitary collecting
electrode at $d_1$ (in the absence of the secondary electrode at $d_2$), and not a function of $d_2$. This suggests that the primary collecting electrode acts as a gate to ignite the discharge, enabling current flow to the farther secondary collecting electrode, even though electrode-2 only imposes a modest electric field at the wire’s surface. Hence this discharge is an “assisted corona discharge”.

Figure 4.3 Onset potential to electrode-2 ($\Phi_0$) against the distance $d_2$, for (a) $d_1 = 4$ mm and (b) $d_1 = 2$ mm.
For an assisted discharge to be more effective than its two-electrode counterpart, the current that flows into the secondary collector at $d_2$ should be higher than the usual current that would have flown through it had it been the only collector at a distance $d$ from the wire such that $d = d_2$. This is observed to be true as can be seen in Figures 4.4a and 4.4b which plot the current ($I_2$) through the secondary collector at $d_2$ and compares it against the current through it in a two-electrode configuration with $d = d_2$. As is clearly observed, at any given potential, the current $I_2$ in an assisted discharge is significantly higher than the current in a two-electrode configuration. Plotting the current through the corona source, $I_c$, (Figures 4.5a and 4.5b) shows an increase in the total current generation in the case of an assisted discharge. This indicates that the increased current to the secondary electrode is not a redistribution of ions between the two electrodes but is an enhancement in the rate of ionization around the wire that results from the modest increase in electric field provided by the presence of the far away secondary collector.
Figure 4.4 Current to electrode-2 ($I_2$) against the applied potential ($\Phi_c$), for (a) $d_1 = 4$ mm and (b) $d_1 = 2$ mm.
Figure 4.5 Total current from the source ($I_c$) against the applied potential ($\Phi_c$), for (a) $d_1 = 4$ mm and (b) $d_1 = 2$ mm.

Once the ions are created and are in the drift zone, the transport of the ions should be dictated by the field lines. The excess current ($\Delta I_c$) can be defined as the increase in the total current from a two-electrode to a three-electrode configuration, i.e., $\Delta I_c = I_{c,3\text{-elec}} - I_{c,2\text{-elec}}$. However, the excess current does not all drift to the secondary collecting electrode. Table 4.1 outlines the changes in current generation and the fraction that is transported to the secondary collector. For the sake of brevity, only data for $d_1 = 2$ mm has been included. As can be observed from the table, the presence of a distant secondary collector at $d_2 = 3 \times d_1$, increases currents by factors of 1.5x – 1.8x. But only about 30%
of this total increase is transported to the secondary collector and the rest towards the primary collector.

**TABLE 4.1**

**THE CURRENT DISTRIBUTION IN THE TEST-CONFIGURATION FOR** $d_1 = 2 \text{ mm}$

AND $d_2 = 6 \text{ mm}$

<table>
<thead>
<tr>
<th>$\Phi_c$ (V)</th>
<th>$I_{c,2}\text{-elec}$ (µA)</th>
<th>$I_{c,3}\text{-elec}$ (µA)</th>
<th>$\Delta I_c$ (µA)</th>
<th>$\Delta I_c / I_{c,2}\text{-elec}$ (%)</th>
<th>$I_{2,3}\text{-elec}$ (µA)</th>
<th>$I_{2,3}\text{-elec} / \Delta I_c$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3200</td>
<td>24.60</td>
<td>44.80</td>
<td>20.20</td>
<td>82.1</td>
<td>5.57</td>
<td>27.6</td>
</tr>
<tr>
<td>3400</td>
<td>42.40</td>
<td>69.96</td>
<td>27.56</td>
<td>65.0</td>
<td>8.13</td>
<td>29.5</td>
</tr>
<tr>
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<td>62.50</td>
<td>98.98</td>
<td>36.48</td>
<td>58.4</td>
<td>11.00</td>
<td>30.2</td>
</tr>
<tr>
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<td>84.00</td>
<td>131.80</td>
<td>47.80</td>
<td>56.9</td>
<td>14.18</td>
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</tr>
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<td>109.00</td>
<td>164.58</td>
<td>58.58</td>
<td>53.7</td>
<td>17.67</td>
<td>30.2</td>
</tr>
</tbody>
</table>

4.1.3 Discussion

Despite areas that require further study and improvements, the results from the above proof-of-concept experiments indicate that electrical characteristics of multi-electrode corona discharges demonstrate fairly good potential to overcome the challenges of miniaturization, particularly in lowering operating potentials and in stabilizing coronas in narrow channels. Numerical simulation of the Test-Configuration was attempted with the procedure that is commonly used in modeling coronas. The simulations were conducted in the commercial Finite Element Solver, COMSOL. While the results from corona simulations have rarely been shown to match the experimental results, the trends predicted by the numerical model, primarily the ratio of currents $I_1/I_2$ was significantly
different from the experimental results. This necessitated more in-depth modeling that takes into account the asymmetry in electric field distribution not only in charge transport but also charge production. This is detailed in the next section.

4.2 Numerical Modeling of Corona Discharges in Asymmetric Electric Fields

In order to develop a design methodology for development of ionic wind blowers, it is necessary to obtain a complete understanding of the discharge physics. This consists of three main areas of study – modeling the ionization near the source, analyzing the drift of ions in the interstitial gap or drift zone, and establishing a bridge between the two zones. Various studies exist in the literature on the former two areas but there is little research that allows for complete modeling of the discharge in non-uniform fields and geometries. While there have been numerical studies accounting for the reaction chemistry within the ionization zone [48] [51], it has only been with assumptions of symmetric coverage of the zone around a wire and in a one-dimensional electric field. Barring some rules like Kaptzov’s assumption [28] and Warburg’s law [33] discussed in Chapter 2, there is little or no research that bridges the gap between detailed simulation of the ionization-zone and large scale modeling that is required for device design. The present work by the author extends the procedure of Chen and Davidson [47] to two dimensions and asymmetric fields.

4.2.1 Description of the two models

Fluid models of a corona discharge typically consist of solving the Poisson’s equation for the electric field and a set of scalar drift-diffusion equations for the ion
transport in the interstitial space. A different transport equation, shown in Equation 4.2, is solved for each species, viz., electrons \((e)\), positive \((p)\) and negative ions \((n)\).

\[
\nabla^2 \Phi = - \nabla \cdot \vec{E} = - \frac{\rho}{\varepsilon_0}. \quad (4.1)
\]

\[
\nabla \cdot \left( \rho_i \mu_i \vec{E} - D_i \nabla \rho_i \right) = S_i. \quad (4.2)
\]

Here, \(\Phi\) is the potential, \(\rho\) is the net space charge density, \(\varepsilon_0\) is the permittivity in free space, \(\rho_i\) is the charge density of species \(i\), \(\mu_i\) is the species mobility in air, \(\vec{E}\) is the electric field, \(D_i\) is the diffusivity of species \(i\) in air. \(S_i\) accounts for the production or depletion of the charge species \(i\) and is typically dependent on the charge density of the other species involved in the discharge. Hence, this is the term that couples the reaction chemistry of the various charge species. The product of mobility and electric field \((\mu_i \vec{E})\) gives the drift velocity of the charge species in the presence of an electric field. The diffusion is often neglected because its flux is a few orders of magnitude lower than the electric field driven drift flux. This can be qualitatively shown by comparing the magnitudes of the drift velocity and diffusivity scaled with the radius of the ionization zone, which is typically \(\sim 4 \times\) the wire radius. For positive ions, mobility \(\mu = 2 \times 10^{-4}\) m\(^2\)/Vs and diffusivity \(D = 10^{-5}\) m\(^2\)/s. Using a typical electric field of \(10^6\) V/m and \(l \sim 10^{-4}\) m gives the drift velocity as \(\mu_i \vec{E} \sim 10^2\) m/s and \(D/l \sim 10^{-1}\) m/s. Two models will be compared in this section, both of which use the same basic equations described above. The first model that is widely used to model positive corona discharges in macroscopic geometries will henceforth be called the Transport Model. The new model that is studied by the author will be called the Plasma Model because it accounts for the ion production within the ionization zone. Both the models solve the Poisson’s equation to obtain the
electric field. The difference in the two models is in the implementation and solution of charge transport equations. The main intent of the new model is to obtain more accurate estimates of the current ratios to the various collecting electrodes in multi-electrode configurations. As will be shown in this section, the existing model that is widely used is limited to large $R/r_0$ ratios. As the value of $R/r_0$ decreases, the ionization zone becomes a significant fraction of the gap distance, and thus it becomes necessary to consider its effects on the overall charge distribution.

The Transport Model makes the basic assumption that the size of the ionization zone is negligible when compared to the gap distance between the electrodes and hence can be neglected. Only positive ions are considered in the entire model, since the density of electrons and negative ions is negligible outside the ionization zone. Also, since the model dispenses with the ionization zone where all the reactions mainly occur, it does not include any production terms in the ion transport equation. As an extension of the assumption of negligible size, the ionization zone is assumed to be uniformly distributed around the corona source. Thus, neglecting diffusion, the Transport Model reduces Equation 4.2 to

$$\nabla \cdot \left( \rho_p \mu_p \vec{E} \right) = 0,$$

(4.3)

where $\rho_p$ is the positive ion charge density and $\mu_p$ is the ion mobility. Equation 4.3 is solved in conjunction with Equation 4.1 to simulate the discharge. The boundary conditions of Equation 4.1 are relatively simple and are given by fixed potentials on the electrodes and zero Neumann fluxes on any dielectric boundaries. Equation 4.3 requires one boundary for the space charge density $\rho_p$. This is applied as an injection boundary condition on the surface of the emitting electrode, specified as $\rho_{p0}$. 
The Plasma Model includes the presence of both electrons and positive ions and also includes the production terms for both these species. Negative ions were also included by the author in a trial run but the rate of production of negative ions is 2 orders of magnitude lower than that of positive ions and hence their contribution to the current was negligible. Hence the model henceforth neglects negative ions and only considers electrons and positive ions. Including production of electrons and positive ions, Equation 4.2 reduces to

\[
\nabla \cdot \left( \rho_e \mu_e \bar{E} \right) = -(\alpha - \beta) (\rho_e \mu_e |\bar{E}|) \tag{4.4a}
\]

\[
\nabla \cdot \left( \rho_p \mu_p \bar{E} \right) = + (\alpha \rho_e \mu_e |\bar{E}|) \tag{4.4b}
\]

Here, the subscript \( e \) refers to electrons and \( p \) to positive ions. \( \alpha \) is Townsend’s first ionization coefficient which quantifies the number of ionizing collisions between electrons and molecules per unit path length. \( \beta \) is the similar coefficient for electron attachment (resulting in negative ion formation). Since an electron impact with a neutral molecule results in the production of a positive ion and an additional electron, the rate of production of both ions and electrons is coupled by the local charge concentration of electrons. Near the wire surface, \( \alpha \) is two orders of magnitude higher than \( \beta \), but due to a more rapid decrease of \( \alpha \) with reducing electric field, \( \alpha \) and \( \beta \) become equal at a certain distance away from the wire surface [47] [58]. This location, where the electron production by ionization is balanced by its depletion through attachment marks the boundary of the ionization zone. At atmospheric pressures, this equality occurs when the electric field strength is about \( 3 \times 10^6 \) V/m, a value widely used to define the boundary of the ionization zone [19] [47] [58].
Two boundary conditions are needed for Equation 4.4, one each for positive ions and electrons. In a positive corona discharge, the focus of this research, the emitter is the anode and hence all positive ions move away from it. Hence a value of \( \rho_p = 0 \) is set on the emitter. The electron charge density \( \rho_e \) then decides the total current generated by the discharge. Since the electron production is relatively small outside the ionization zone, a value of \( \rho_e = \rho_{e0} \) is set for the entire gap beyond this boundary, where \( |E| = 3 \times 10^6 \) V/m.

There are two ways of deciding the value for \( \rho_{p0} \) for the Transport Model and \( \rho_{e0} \) for the Plasma-Model – a semi-empirical approach where the value is iterated until the calculated total current matches experimental data, or a theoretical approach using Kaptzov’s hypothesis, which states that irrespective of the applied potential, the electric field on the wire’s surface remains at the value it attains at the time of onset (Chapter 2). In the latter approach, the value of \( \rho_{p0} \) is iterated until the electric field on the surface of the wire attenuated by space charge matches that at the onset condition. While the second approach is often used and matches trends, the simulated results rarely match up with experimental data. Additionally, due to lack of literature, the basis of the hypothesis and conditions of its validity are unclear. Hence the semi-empirical method is used in this work to compare the two models.

4.2.2 Configuration and Numerical Procedure

A wire-in-cylinder configuration was chosen because of its relative simplicity, both for grid generation as well as for specifying the boundary conditions. A schematic of the configuration chosen is shown in Figure 4.6 along with the experimental setup. The cylinder is 3 mm in radius. Wires of three radii (25µm, 50 µm and 100 µm) were chosen. A positive potential is applied to the wire and the cylinder is grounded. Asymmetry in
electric field distribution is obtained by moving the wire off-center by a distance $\delta = 1$ mm. Experiments were conducted to obtain the voltage-current characteristics to compare with the models. In the experiments, the cylinder was split in half and separated by thin dielectric spacers so that currents could be measured individually on the two halves ($I_1$ and $I_2$). In the case where the wire is located off-center (henceforth called the eccentric-configuration), it is closer to the bottom half as shown in Figure 4.5b. This makes the configuration similar to that of multi-electrode. Similar configurations have been used by other researches [52] [59] to study heat transfer augmentation in circular tubes using the Transport Model.

![Diagram of a wire in a cylinder with concentric and eccentric configurations](image)

**Figure 4.6** Wire in cylinder with (a) the wire concentric and (b) the wire eccentric by a distance $\delta$. Dielectric spacers are used to separate the halves of the cylinder. $I_1$ and $I_2$ are the currents measured on each of the halves. (c) shows a picture of the experimental setup.

Since Equation 4.2 is a first order hyperbolic equation, method of characteristics was used to solve the charge transport equations. In this case, as well as in the case of the
related Equations 4.3 and 4.4, the characteristics are simply the electric field lines.

Taking advantage of the closed geometry, an elliptic grid was used to discretize the domain and the discretized Cartesian \((x,y)\) points in the physical domain were mapped onto an orthogonal curvilinear coordinates \((\xi,\eta)\) in the computational domain. The basic premise of generating the curvilinear discretization is to solve two Poisson’s equations (Equation 4.5) and generate a one-to-one mapping between \((x,y)\) and \((\xi,\eta)\). The equations for \(\xi\) and \(\eta\) are

\[
\begin{align*}
\xi_{xx} + \xi_{yy} &= P(x,y) \\
\eta_{xx} + \eta_{yy} &= Q(x,y),
\end{align*}
\]  

(4.5)

where \(P\) and \(Q\) are functions that are used to control the local grid density. In the present problem, \(P\) and \(Q\) are used to input the space charge density into the grid generation procedure to obtain a grid that corresponds to the constant potential lines and electric field lines in the interstitial gap. By interchanging the dependent and independent variables in Equation 4.5, the transformed system in the computational domain is obtained as

\[
\begin{align*}
a x_{\xi\xi} - 2b x_{\xi\eta} + c x_{\eta\eta} + J^2 (P x_{\xi\xi} + Q x_{\xi\eta}) &= 0 \\
a y_{\xi\xi} - 2b y_{\xi\eta} + c y_{\eta\eta} + J^2 (P y_{\xi\xi} + Q y_{\xi\eta}) &= 0,
\end{align*}
\]  

(4.6)

where \(a, b, c\) are functions of the first derivatives of \(x\) and \(y\) with respect to \(\xi\) and \(\eta\). \(J\) is the metric tensor of the transformation.

Figure 4.7a shows a typical domain with the boundary conditions used to solve Equation 4.6. The entire physical domain of Figure 4.3 is split along the line of symmetry. Figure 4.7b shows the discretized domain. Orthogonality at the wire and cylinder boundaries (Figure 4.7b inset) was implemented by the procedure in Thomson
[60]. If the limits of $\xi$ are set as the potential on the wire and cylinder, the space charge density can be input as the function $P(\xi, \eta)$ such that constant $\xi$ lines corresponding to the constant potential lines. $Q(\xi, \eta)$ was set to zero. Constant $\eta$ lines correspond to the electric field lines. A relaxation technique was used to solve Equations 4.6 with an absolute convergence criterion of $10^{-10}$ m. Details of the procedure are included in Appendix B.

Figure 4.7 The domain of simulation with (a) schematic showing the boundary conditions for elliptic grid generation and (b) the generated grid of 30×30 points. Inset shows the orthogonality at the surface of the wire.

The advantage of the elliptic grid is that it reduces the Poisson’s equation as well as the charge transport equation to one dimensional equations along constant $\eta$, i.e., along the field lines which can then easily be solved either analytically or numerically. Poisson’s equation in this computational domain is given by,
\[
\frac{1}{h_{\xi} h_{\eta}} \left[ \frac{d}{d\xi} \left( h_{\eta} \frac{d\Phi}{d\xi} \right) \right] = \frac{\rho}{\varepsilon_0},
\]

(4.7)

where \( h_{\xi} \) and \( h_{\eta} \) are the transformation coefficients. Equation 4.7 can be integrated numerically using the trapezoidal rule between the limits of \( \xi \) to get the potential field. Electric field \( \bar{E} \) is then determined as the derivative of \( \Phi \). It should be noted that because the constant \( \xi \)-lines are equipotential curves, \( \bar{E}(\xi, \eta) = E(\xi) \hat{\xi} \). The detailed algebra is included in Appendix B.

Along the field lines, charge transport of species \( i \) (Equation 4.2) then reduces to

\[
\frac{1}{h_{\xi} h_{\eta}} \left[ \frac{d}{d\xi} \left( h_{\eta} \rho_i \mu_i E \right) \right] = S_i(\xi, \eta),
\]

(4.8)

which is solved for the charge density \( \rho_i \) using a second order upwind scheme.

Current density is given by \( J = \rho \mu E \) and the total current from the discharge is obtained by integrating the current density as \( I = \int (\rho \mu E r L) d\theta \), where \( r = r_0 \) on the wire surface and \( r = R \) on the cylinder. Grid independence tests for Equations 4.7 and 4.8 are included in Appendix B. A minimum 400 points were used in the \( \xi \)-direction to obtain satisfactory resolution at the wire surface (~1 \( \mu \)m) and 100 points were used in the \( \eta \)-direction to ensure reasonable continuity when integrating to obtain currents. Empirical relationships for the coefficients (\( \alpha \) and \( \beta \)) and for mobilities (\( \mu_e \) and \( \mu_p \)) are obtained from [47] and presented in Appendix B.

The general procedure is outlined below. The procedure is identical in most steps for both the Transport Model and the Plasma Model.

i) The following parameters are specified.

- Geometric: wire radius (\( r_0 \)), cylinder radius (\( R \)), offset distance (\( \delta \)).
− Electrostatic: wire potential \( (\Phi_{\text{wire}} = \Phi_0) \), cylinder potential \( (\Phi_{\text{cyl}} = 0) \).

− Charge transport: \( \rho_{p0} \) (for Transport Model), \( \rho_{e0} \) (for Plasma Model).

ii) The domain is discretized with an elliptic grid assuming zero space charge density.

iii) The potential \( (\Phi) \) is calculated at each point of the computational domain using Equation 4.7 and the electric field magnitude is obtained as its \( \zeta \)-derivative.

iv) The calculated electric field is used to solve Equation 4.8 for the charge densities as follows:

− In the case of the Transport Model the equation used corresponds to Equation 4.3. \( \rho_{p0} \) is specified uniformly on the wire’s surface and a second order backward difference scheme is used to calculate the positive ion charge density \( (\rho_p) \) throughout the domain.

− In the case of the Plasma Model, \( \rho_{e0} \) is specified as a constant for the region of the domain where \( |E| > 3 \times 10^6 \) V/m and electron charge density \( (\rho_e) \) is solved for within the ionization zone using a second order forward difference scheme using the equation corresponding to Equation 4.4a. Substituting the calculated \( \rho_e \) into Equation 4.4b, and with \( \rho_{p,\text{wire}} = 0 \), the positive ion charge density \( (\rho_p) \) is obtained in the entire domain.

v) The net space charge density is calculated as \( \rho = \rho_p - \rho_e \). The new value of \( \rho \) is input into the grid generation and steps (iii) and (iv) repeated. The presence of the space charge density attenuates the electric field which in turn alters the charge production and transport.
vi) The problem is assumed to be converged when the difference in electric field values between two successive iterations is less than 1%.

vii) The final values of $\rho_p$, $\rho_e$ and $E$ are obtained and the currents ($I$'s) and current densities ($J$'s) calculated on both the wire and cylinder.

Integrating the current densities, the simulated currents on the bottom half ($I_1$) and the top half ($I_2$) of the cylinder can be obtained.

The Plasma Model encounters a very steep gradient in both positive ion density and electron density near the wire surface and as a result it requires a much higher resolution than the Transport Model. Also, to obtain a converged $E$-$\rho$ combination, the number of iterations needed increases as the total current increases. While some acceleration procedures were attempted, like the use of multi-grid methods and under-relaxing the electric field between successive iterations, they did not greatly improve the convergence rate without significantly altering the final converged solution. Since the primary purpose of the Plasma Model is to show the necessity of including ionization and not to reproduce experimental results, the value of $\rho_{e0}$ in the Plasma Model was maintained at a reasonable value $\sim 10^{-10}$ C/m$^3$ for all applied potentials. The resulting positive ion density was on the order of $10^{-4}$ C/m$^3$ which is typical of atmospheric pressure plasmas. While, with this choice, the simulated currents were only about 1/5$^{th}$ the experimental values, $I_{ratio}$ matched the experimental values much better than the Transport Model. A test of $I_{ratio}$ vs $\rho_{e0}$ showed a slight increase in the ratio with increasing $\rho_{e0}$, but it was still reasonably close to the experimental values and much more accurate than the Transport Model. The value of $\rho_{p0}$ for the Transport Model was chosen such that the simulated currents matched those of the ones obtained from the Plasma Model for the
corresponding wire potential. Details on the choice of $\rho_{e0}$ and of its impact on the solution are included in Appendix B.

4.2.3 Results

To compare the two models and to check their validity, the parameter $I_{ratio} = I_1/I_2$ is evaluated and compared with the experimental data for the eccentric configuration case with ($\delta = 1 \text{ mm}$). This parameter was chosen since it is the quantity of primary interest in multi-electrode corona discharges, and when applied to blower geometries, will dictate the improvements in flow generation, as will be seen in Chapter 5. The variation of $I_{ratio}$ with the applied potential $\Phi$ are presented for two wire radii – 50 µm and 100 µm with the cylinder radius being a constant at 3 mm and the results from the two models are compared to experiments. To explain the behavior and any discrepancies with experiments, the variations in fundamental properties (like ionization coefficients) are also analyzed. Possible reasons are presented to account for the limitations of the model as well as observed differences with the experiments.

Figure 4.8 plots the variation of $I_{ratio}$ with the applied potential ($\Phi_0$) for the two chosen wires of radii 50 µm and 100 µm. Data obtained from the two numerical models are presented along with experimental results. As can be seen from the figures, the values predicted by the Plasma Model are a significantly better match to the experimental data.
Figure 4.8 Plots showing the variation of $I_{ratio}$ with the applied voltage ($\Phi_0$) for (a) wire with $r_0 = 100 \, \mu m$ and (b) wire with $r_0 = 50 \, \mu m$.

From Table 4.2, it can be observed that the $I_{ratio}$ prediction for $r_0 = 100 \, \mu m$ (average = 0.16) matches well with the experimental value (average = 0.12). For $r_0 = 50 \, \mu m$ however, the predicted value (average = 0.26) is relatively higher than the experimental value (average = 0.16). The prediction by the Transport Model (average ~ 0.4) is much higher for both the wire radii.

The primary reason for the better fit from the Plasma Model is the inclusion of ionization. In the Transport Model, the distribution of space charge in the discharge gap and, as a consequence, the variation of current density around the cylinder is dictated only by the asymmetry in electric field. The uniform ion density distribution around the wire is only redistributed in the gap. This is insufficient to correctly model the discharge as is shown above. Along with accounting for asymmetric redistribution, the Plasma Model also considers asymmetric production of ions. The combination of the two leads to a much higher distribution ratio, with a larger fraction of the current going to the closer collecting electrode. Figure 4.9 plots the space charge density distribution from the two
models for the same total current. As can be seen, there is a much higher angular distribution from the Plasma Model than in the Transport Model.

**TABLE 4.2**

EXPERIMENTAL AND NUMERICAL VALUES OF $I_{ratio}$ VS APPLIED VOLTAGE ($\Phi_0$) FOR THE WIRES WITH (a) RADIUS 100 $\mu$m AND (b) RADIUS 50 $\mu$m.

<table>
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<tr>
<th>Voltage (V)</th>
<th>Expt</th>
<th>Plasma Model</th>
<th>Transport Model</th>
</tr>
</thead>
<tbody>
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<td>0.10</td>
<td>0.18</td>
<td>0.42</td>
</tr>
<tr>
<td>4000</td>
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<td>0.42</td>
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<td>0.42</td>
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<td>0.42</td>
</tr>
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<tr>
<td><strong>Average</strong></td>
<td>0.12</td>
<td>0.16</td>
<td>0.42</td>
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<table>
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<tr>
<th>Voltage (V)</th>
<th>Expt</th>
<th>Plasma Model</th>
<th>Transport Model</th>
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<tbody>
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</tr>
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<td>0.27</td>
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<tr>
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<td>0.16</td>
<td>0.26</td>
<td>0.40</td>
</tr>
<tr>
<td>3800</td>
<td>0.16</td>
<td>0.25</td>
<td>0.41</td>
</tr>
<tr>
<td>3900</td>
<td>0.16</td>
<td>0.25</td>
<td>0.41</td>
</tr>
<tr>
<td>4000</td>
<td>0.16</td>
<td>0.25</td>
<td>0.41</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td>0.16</td>
<td>0.26</td>
<td>0.40</td>
</tr>
</tbody>
</table>
Figure 4.9 Distribution of the positive ion density in (a) the Plasma Model and (b) the Transport Model. Note that the range of charge density values for the two plots are different.

Figure 4.10 plots the variation of non-dimensionalized current density around the wire, $J_{wire}$, for both the Plasma Model and the Transport Model for three wire radii – 25 μm, 50 μm and 100 μm. It can be observed that the variation is much higher for the Plasma Model (solid lines) than for the Transport Model (dashed lines). Also, the relative variation among the Plasma Model data reduces as the wire radius decreases, slowly approaching the values of the Transport Model, which are almost uniform around the wire surface.
Figure 4.10 Plot showing the variation of the non-dimensionalized current density around the wire surface for the plasma model (solid lines) and the transport model (dashed lines). Angle on the wire surface ($\theta$) is defined as shown on the left.

Figure 4.11a plots the variation of $\rho_p$ around the wire for the three wire radii for data from the Plasma Model. Figure 4.11b plots the variation of $\alpha$ for the same. As can be seen from Figure 4.11a, the positive ion density is not uniform around the wire surface as presumed by the Transport Model. These figures, in which the variations tend to even out for smaller wire radii, also demonstrate the decreasing effectiveness of the Plasma Model for wires with extremely small radii, where the values predicted by the two numerical models are similar and differ from the experiments significantly. Data on ionization and attachment coefficients, as well as on electron mobilities are sparse for electric fields $> 2\times10^7$ V/m, a range which is achieved by the wires of radii 25 $\mu$m and 50 $\mu$m and the formulations used in this study may not be accurate. This could potentially be one reason to explain the discrepancies between the Plasma Model and the experimental data.
As the wire radius decreases, the electric field at the surface of the wire increases and the radius of the ionization zone decreases. Since the Plasma Model relies on the combined effects of asymmetry in electric field and in ionization, its predictions differ from the Transport Model only as long as the ionization zone is non-negligible. Since the size of ionization zone is related to the wire radius, the parameter \(d/r_0\), where \(d\) is the shortest gap distance, represents the fraction of the interstitial space occupied by the ion-zone and can be employed to understand the behavior. To check this relation, the Plasma Model and Transport Model were repeated in two other conditions with cylinder radii \(R\) of 1.5 mm and 2 mm, and offset distances \(\delta\) of 0.5 mm and 1 mm, such that the gap distances, \(d\), was 1 mm in both cases. Table 4.3 shows the predicted ratios for the two models. For the same wire radius of \(r_0 = 25 \, \mu\text{m}\), the difference between the Plasma Model and the Transport Model is more noticeable when \(d/r_0\) is 40, rather than 80 as in the previous case. Eccentricity can be parameterized by the ratio \(R/\delta\), and it can be observed from Table 4.3 that the ratio of currents predicted by the Transport Model is
dependent on this value. Experiments weren’t conducted for the second and third set of geometric parameters \((R = 1.5 \text{ mm and } 2 \text{ mm})\), the intention only being to highlight the difference between the two models.

**TABLE 4.3**

**VARIATION OF THE CURRENT RATIO \(I_{\text{ratio}}\) WITH THE ION-ZONE FRACTION PARAMETER \((d/r_0)\) AND THE ECCENTRICITY PARAMETER \((R/\delta)\) FOR THE TWO NUMERICAL MODELS.**

<table>
<thead>
<tr>
<th></th>
<th>(r_0) [µm]</th>
<th>(R) [mm]</th>
<th>(\delta) [mm]</th>
<th>(d) [mm]</th>
<th>(d/r_0)</th>
<th>(R/\delta)</th>
<th>(I_{\text{ratio}}) Plasma Model</th>
<th>(I_{\text{ratio}}) Transport Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Set-1</td>
<td>25</td>
<td>3.0</td>
<td>1.0</td>
<td>2.0</td>
<td>80</td>
<td>3</td>
<td>0.40</td>
<td>0.41</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>3.0</td>
<td>1.0</td>
<td>2.0</td>
<td>40</td>
<td>3</td>
<td>0.27</td>
<td>0.41</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>3.0</td>
<td>1.0</td>
<td>2.0</td>
<td>20</td>
<td>3</td>
<td>0.15</td>
<td>0.42</td>
</tr>
<tr>
<td>Set-2</td>
<td>25</td>
<td>1.5</td>
<td>0.5</td>
<td>1.0</td>
<td>40</td>
<td>3</td>
<td>0.27</td>
<td>0.42</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>1.5</td>
<td>0.5</td>
<td>1.0</td>
<td>20</td>
<td>3</td>
<td>0.14</td>
<td>0.42</td>
</tr>
<tr>
<td>Set-3</td>
<td>25</td>
<td>2.0</td>
<td>1.0</td>
<td>1.0</td>
<td>40</td>
<td>2</td>
<td>0.16</td>
<td>0.24</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>2.0</td>
<td>1.0</td>
<td>1.0</td>
<td>20</td>
<td>2</td>
<td>0.07</td>
<td>0.24</td>
</tr>
</tbody>
</table>

As the cylinder radius \((R)\) increases, for a constant gap distance \((d)\), the geometry tends to that of a wire-plate configuration. The current density distribution on the plate is given by Warburg’s law (Equation 2.9) as described in Chapter 2. The Plasma Model was tested for \(R = 10 \text{ mm and } \delta = 8 \text{ mm, i.e., gap distance } d = 2 \text{ mm.}\) From Figure 4.12, which plots the current density distribution around the cylinder and also the theoretical trend, it can be observed that the Plasma Model closely predicts Warburg’s law as well.
Figure 4.12 Comparison of the Plasma Model to Warburg's Law \( (J_B = J_A \cos^m(\theta_{cyl})) \). The value of \( m \) is empirical and is typically ~ 4-5. Here, for suitable comparison, \( \cos(\theta_{cyl}) \) was approximated as \( \frac{OA}{OB} \).

4.2.4 Discussion

As demonstrated in this section, the Plasma Model works reliably on both the small scales, predicting the events within the ionization zone, as well as on the macroscopic scales of predicting trends in current distributions. While the Transport Model is sufficient when the gap distances are far larger than the size of the ionization zone, the Plasma Model needs to be used when the zone is no longer negligible. The procedure can be extended to ionic wind generation by coupling the space charge density with Navier-Stokes equations as discussed in Chapter 2. The summarized procedure is given below.

i) Solve the electric field for the chosen blower configuration

ii) Locate the boundary of the ionization zone (\( |E| = 3 \times 10^6 \) V/m) and assume a value of \( \rho_{e0} \) at the boundary surface. Solve for the space charge density.
iii) Iterate Poisson’s equation and charge transport equation till a converged $E-\rho$ combination is obtained.

iv) Solve the Navier-Stokes equation with the coulombic force ($\rho E$) replacing the body force to obtain the flow field.

As explained above, the exact choice of $\rho e_0$ requires the total current from experiments. But the relatively small variation in the dependence of ion transport to the various electrodes on $\rho e_0$ implies that a reasonable choice should provide the qualitative flow pattern. A more thorough study on the selection of boundary conditions is required to obtain a model that can provide a quantitative flow field. The Plasma Model requires solving two transport equations instead of one, but the similarity in the equations implies that it requires no extra effort procedurally. However, the Plasma Model requires significantly higher resolution at the wire surface which is computationally more expensive. In addition, the Plasma Model allows for the inclusion of reaction chemistry in the design process, with an individual transport equation for each species, which can be used to predict ozone generation from ionic wind blowers.

Chen and Davidson [47] also consider the diffusion of electrons and show that it alters the solution very close to the wire’s surface, at a distance of $\sim 1 \mu \text{m}$). The electron charge density ($\rho_e$) at the surface of the wire was shown to be increased by an order of magnitude. This would increase the total current in the discharge and could potentially explain the lower currents simulated in our model. Note however, that the inclusion of diffusion would result in a 2$^{\text{nd}}$ order PDE for electron transport requiring two boundary conditions. This can be obtained as a Neumann condition at the boundary of the ionization zone by considering photoionization. Very few studies exist on details of the
processes whereby photons ionize molecules and a lot more research, both experimental and numerical, is necessary before the process can be tuned to a design methodology, especially in asymmetric electric fields.

4.3 Summary

This chapter focused on understanding the fundamental behavior of corona discharges in asymmetric electric fields, of which multi-electrode configurations are a particular subset. The experimental results from the Test-Configuration which uses two collecting electrodes shows promise in addressing the challenges posed in miniaturizing ionic wind blowers. As described in Chapter 1, miniaturization leads to reduction in total current and drift lengths, adversely affecting the flow rate. As seen from the results of the Test-Configuration, the use of multiple collecting electrodes increases the electric field stress on the corona source, thus improving ionization and generating higher currents. And the increased distance to the farther collecting electrode implies that the drift length of the ions is increased. The operating potentials are also reduced significantly since the onset potential is dictated by the primary (gate) electrode. The proximity of the primary electrode to the corona source also mitigates the chances of sparking, a concern described in Chapter 1. As such, the multi-electrode concept of the Test-Configuration shows promise in its implementation for an ionic wind blower.

The understanding of multi-electrode corona discharges in particular and coronas in asymmetric electric fields in general required a more detailed study into the ionization mechanisms around the corona source. The procedure that is typically used by researchers in modeling the ion distribution was shown to be inadequate for asymmetric configurations, particularly in regimes involving small gap sizes. An alternative modeling
procedure (Plasma Model) was proposed that incorporated both the ionization and transport of ions that predicted results significantly closer to experimental data. Limitations and drawbacks of the new model were also analyzed along with potential areas of improvement. A roadmap for the implementation of the Plasma Model in the simulation of ionic wind blowers was also presented.
CHAPTER 5:
APPLICATION OF MULTI-ELECTRODE CORONA DISCHARGES FOR
ELECTROHYDRODYNAMIC FLOW GENERATION

The electrical characteristics obtained in multi-electrode corona discharges shows appreciable potential to improve ionic wind generation in narrow channels. Based on the electrical characteristics of assisted discharges, evaluating the impact multi-electrode configurations have on ionic wind generation is not straightforward. While simple relation between the flow velocity and current \( u \propto \sqrt{i} \) can be obtained from the Navier-Stokes equations for EHD flow (Equation 2.6), the real effects, both local and global, in an overall discharge is harder to comprehend, especially in more complicated situations like multi-electrode coronas. The impetus for flow generation is a body force exerted by the drift of ions under the influence of electrostatic forces. Thus the flow rate depends both on the space charge density and the electrostatic forces in play. Because these two quantities vary through the entire region, the above relationship, while true locally, cannot be extrapolated to the overall flow field. In particular, neither the space charge distribution nor the magnitude and direction of the local electric field can be specified in a multi-electrode discharge without further simulations and modeling for each particular configuration. Thus the effect of the assisted discharge on ionic wind generation is bound to be specific for each configuration. The first section of this chapter, published in IEEE Transactions on Dielectrics and Electrical Insulation [56], presents a preliminary attempt
at evaluating this effect and obtaining some insight for further product development through optimization. Later sections present the details of a prototype development that incorporates the multi-electrode concept and characterizes its performance when integrated in a portable electronic system. A patent has been filed on the conceptual electrode configuration [1] and with additional patents pending. Additionally, the details on the prototype design is proprietary and flow-acoustic measurements on the device and its integration into the handheld system were conducted at Intel Corp., by the author. As such, only qualitative comparisons are presented in Section 5.2.

Various possible configurations exist for ionic wind blowers. A few common configurations found in the literature are illustrated schematically in Figure 5.1. Intuitively, configurations with a downstream cylinder or grid as a collecting electrode are expected to be ideal for ionic wind generation since all the ions generated are forced to drift downstream along the centerline of the duct and away from the walls where shear forces are dominant. This would lead to higher flow rates for similar currents. However, since narrow channels (height < 5 mm) have limited cross sectional area, cylinders and grids within the duct volume reduces the open area ratio significantly leading to lower flow rates.
5.1 Effect of Assisted Discharges on EHD Flow in Narrow Channels

Due to the nature of electrohydrodynamic flow generation, it is imperative that all collecting electrodes be placed downstream of the corona source. Any discharge directed upstream would hinder the flow, making it impossible to apply the previously studied multi-electrode discharge of Section 4.1 (Test-Configuration) as-is into a flow device. Figure 5.2 shows a schematic of the configuration chosen for flow measurements where an array of needles was used as the corona source and copper plates flush with the wall surface were used as the collecting electrodes. This configuration will henceforth be termed as the Flow-Configuration for the remainder of the thesis. Unlike the Test-Configuration where the two collectors on either side figuratively distributed the interstitial space, in the Flow-Configuration, both the collecting electrodes are on the same side (downstream) of the corona source and hence share the interstitial space. This implies that the two collecting electrodes should have a combined influence on the
corona source to increase ionization but compete in the drift zone on the transport of ions. A cumulative electric field set up in the region will decide the allocation of current to the two collectors.

Another difference between the Test-Configuration and the Flow-Configuration is the application of a negative potential on the secondary collector in the Flow-Configuration. This is necessary because as mentioned above, the two electrodes share the same interstitial space for influence and the relative proximity of the primary collector results in the field being dominated by it. A negative potential on the secondary collector allows for stronger electrostatic forces that can better compete with the primary collector in driving ions towards the secondary collector, thus increasing ion current downstream and in turn the flow rates.

![Figure 5.2 Schematic of Flow Configuration (not to scale).](image)

5.1.1 Experimental Setup and Procedure

The duct was made of insulating acrylic with dimensions 4 mm × 25 mm × 100 mm. Three parallel needles with tip diameters of approximately 100 µm were used as the corona electrodes (electrode-c). Strips of copper 1.6 mm in width were used for the collecting electrodes. Both the primary (electrode-1) and secondary (electrode-2)
collecting electrodes are pairs, one each on the top and bottom of the duct, thus maintaining centerline symmetry. The spacing between the primary and secondary electrodes was 3 mm and the primary collecting electrode was positioned ~20 mm from the inlet of the duct. The exit flow velocity was measured at the end of the duct using a hot-wire anemometer.

A corona was operated in positive polarity by applying a positive potential ($\Phi_c$) to the needles while grounding the primary collecting electrode through a picoammeter ($\Phi_1 = 0$ V). The setup was operated in a two-electrode configuration by floating the secondary collecting electrode. Preliminary experiments confirmed that this was equivalent to the secondary electrode being absent and did not show any appreciable difference in onset potential, current measurements, or flow rates. For operation in a three-electrode configuration, the secondary electrode was either grounded through a second picoammeter ($\Phi_2 = 0$ V) or a negative potential was applied to it ($\Phi_2 = -500$ V). Limitations on the picoammeter did not allow for the measurement of current on the secondary electrode when a negative potential was applied to it. So for that case, the secondary current ($I_2$) was evaluated by subtracting the primary current ($I_1$) from the corona current measured through the power supply ($I_c$), i.e., $I_2 = I_c - I_1$. However, due to the power supply’s low resolution in current measurement, it is accurate only for values larger than ~ 2 µA and the accuracy increases at higher potentials as the magnitude of current increases.
5.1.2 Results

Since the arrangement of the electrodes is not exactly the same as in the Test-Configuration, the electrical characteristics of the assisted discharge are presented again in this section. However, since they followed similar trends as in the Test-Configuration, they are presented comparatively in brief. Figure 5.3 plots the current to electrode 2 ($I_2$), or the “assisted current”, as a function of the potential applied on the needle. As is expected, the assisted current is significantly increased with the application of a negative potential on the secondary collecting electrode. While the current to the primary collecting electrode ($I_1$) increased compared to the two-electrode configuration, the differences were small compared to the magnitude of $I_1$ (< 5% when $\Phi_2 = 0$ V and < 15% when $\Phi_2 = -500$ V) and are not significant enough to be noticeable on a plot. It is clear that the fundamental electrical behavior of the assisted corona discharge in the Flow-Configuration is similar to that in the Test-Configuration. However, while in the Test-Configuration only ~30% of the excess current production was transported to the secondary collecting electrode (Table 4.1), in the Flow-Configuration this figure was closer 50-70% (Table 5.1). It should be noted however that the geometries are not exactly comparable and the corona electrodes are different. Also, as in the Test-Configuration, ion transport to both the electrodes in the Flow-Configuration commenced at the same applied potential. Thus the primary electrode acts as the described “gate electrode” from the concept in Section 1.4. But the magnitude of excess current produced, and as a result the magnitude of $I_2$, was much smaller for the Flow-Configuration. The ratio of $I_2 / I_1$ was only 3-5% when the secondary collecting electrode was grounded and ~6-9% when $\Phi_2 = -500$ V.
Figure 5.3 Current to the secondary collecting electrode ($I_2$) against the applied potential ($\Phi_c$).
TABLE 5.1
THE CURRENT DISTRIBUTION IN THE FLOW-CONFIGURATION FOR (a) $\Phi_2 = 0\text{V}$ AND (b) $\Phi_2 = -500\text{V}$

(a) $\Phi_1 = 0\text{ V}$ and $\Phi_2 = 0\text{ V}$

<table>
<thead>
<tr>
<th>$\Phi_c$ (V)</th>
<th>$I_{c,2\text{-elec}}$ (µA)</th>
<th>$I_{c,3\text{-elec}}$ (µA)</th>
<th>$\Delta I_c$ (µA)</th>
<th>$\Delta I_c / I_{c,2\text{-elec}}$ (%)</th>
<th>$I_{2,3\text{-elec}}$ (µA)</th>
<th>$I_{2,3\text{-elec}} / \Delta I_c$ (%)</th>
</tr>
</thead>
<tbody>
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<td>3200</td>
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<td>1.41</td>
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<td>1.93</td>
<td>6.8</td>
<td>1.13</td>
<td>58.3</td>
</tr>
<tr>
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<td>1.92</td>
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<td>64.9</td>
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<tr>
<td>4000</td>
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<td>45.40</td>
<td>1.93</td>
<td>4.4</td>
<td>1.35</td>
<td>70.3</td>
</tr>
</tbody>
</table>

(b) $\Phi_1 = 0\text{ V}$ and $\Phi_2 = -500\text{ V}$

<table>
<thead>
<tr>
<th>$\Phi_c$ (V)</th>
<th>$I_{c,2\text{-elec}}$ (µA)</th>
<th>$I_{c,3\text{-elec}}$ (µA)</th>
<th>$\Delta I_c$ (µA)</th>
<th>$\Delta I_c / I_{c,2\text{-elec}}$ (%)</th>
<th>$I_{2,3\text{-elec}}$ (µA)</th>
<th>$I_{2,3\text{-elec}} / \Delta I_c$ (%)</th>
</tr>
</thead>
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<td>3.83</td>
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<td>69.6</td>
</tr>
</tbody>
</table>

Figure 5.4a shows the exit flow velocity against the potential applied on the needles ($\Phi_c$) for the three different cases. It can be observed that both three-electrode configurations clearly improve the flow rate in comparison with the two-electrode configuration. The mere act of grounding the secondary electrode causes the air flow to start at a much lower potential and the application of a negative potential on the secondary electrode increases the electric field in the flow direction and further improves the flow rate. Similarly, Figure 5.4b shows the flow velocity against the total potential.
(Φₜ) utilized in operating the ionic wind blower. In the two-electrode configuration and the three-electrode configuration with a grounded secondary collecting electrode, this total potential (Φₜ) is the same as the potential applied on the needle (Φₑ), but in the case where a negative potential is applied on the secondary collecting electrode, Φₜ = Φₑ + |Φₑ|. As is observed, the three-electrode configuration also improves the flow rate at lower total operating potentials. However, the difference in performance is small for the two different cases of the three-electrode configuration. At higher potentials, the velocity curve flattens out and remains a constant for a range of applied potentials, a phenomenon that has been observed by other groups [40]. In fact, multiple experiments over the course of this study indicated the velocity reaches a plateau and then reduces again at high potentials. The reason for this is unknown and needs further study, but it should be mentioned that it could also be partly a result of the velocimeter’s poor resolution of 0.1 m/s.
Figure 5.4 Plot of the exit flow velocity against (a) the applied potential ($\Phi_c$) and (b) the total potential ($\Phi_T$).

Figure 5.5a shows the power consumed by the device in generating the air flow for the various configurations. The power was calculated by using Kirchoff’s conservation law for current, with current to the primary and secondary electrodes being treated as two legs of a parallel circuit. An equivalent circuit is shown in Figure 5.5b. For a two-electrode configuration, the power consumed is $P_{\text{2-elec}} = \Phi_c I_1$ and for a three-
electrode configuration is \( P_{3\text{-elec}} = \Phi_e I_1 + (\Phi_e + |\Phi_2|)I_2 \). In Figure 5.5a, the three-electrode configurations are much more efficient in generating a particular flow velocity. For instance, to generate a very modest 0.6 m/s flow, the three-electrode configurations require only \( \sim 1/2 \) (\( \Phi_2 = 0 \) V) and \( \sim 1/5 \) (\( \Phi_2 = -500 \) V) of the two-electrode power, respectively, and the efficiency increased as a greater negative potential was applied on the secondary collecting electrode. This was because of more effective utilization of the ions as they are being driven downstream in the three-electrode configuration.

Figure 5.5 (a) Exit flow velocity vs power consumed and (b) the equivalent circuit for calculating the power consumption
5.1.3 Discussion

Overall, the assisted discharge produced increased flow rates compared to the two-electrode corona discharge. The presence of both collecting electrodes in conjunction ensures both onset at a low potential and an electric field that acts in the direction of the flow elongating the ion drift region. To confirm this, a two dimensional (2D) simulation of the Flow-Configuration was conducted using COMSOL Multiphysics to obtain the Laplacian electric field. Figure 5.6 is a logarithmic plot of the magnitude of electric field along the centerline for the three different cases. Grounding the secondary electrode increases the electric field in the region downstream of the primary collecting electrode by multiple orders of magnitude. While there is a slight increase in the region very near the primary collecting electrode, it is not very significant in comparison. Most of the increased flow generated by an assisted corona discharge is a result of this increased electric field in what amounts to a longer drift region. It should be noted that the Laplacian field is not accurate in the drift region where positive space charge accumulates and the solution to Poisson’s equation is valid. However, the effect of space charge would only have a moderate effect on the Laplacian field, such that the trends shown in Figure 5.6 are still accurate. To accurately model the space charge field, the space charge distribution at the corona source and in the drift region is required for which the procedure is outlined in Chapter 4, but has not been undertaken in this study.
As evident from the preliminary experiments, the assisted discharge presents the possibility of addressing most of the challenges that arise on the road to miniaturization of corona driven ionic wind blowers. The Test-Configuration proved the concept of having a gate electrode to ignite the corona at lower potentials and drive ions towards a farther secondary collector. The Flow-Configuration demonstrated the advantage of using assisted discharges. Besides the improvement in flow rates, while not indicative in the data presented, the author also observed that assisted discharges were also found to improve the ease of operation and stabilization of the corona. While the application of the multi-collector configuration in a blower seems to limit the potential benefits seen in the Test-Configuration, the author is confident that alternative designs and optimal positioning of the electrodes will allow for more effective utilization of the assisted discharge’s apparent capabilities.
5.2 Development of a working prototype

The primary real world application being targeted in the overall project is the development of an ionic wind blower that generates the required flow rates in small form factors. Towards this end, targets and constraints were laid out to effectively implement the proposed blower into small form factor electronics. Based on discussions with industry, a volume flow rate of 0.5 cfm was set as the target flow rate and the blower was constrained to operate at potentials < 2 kV and 100 mW. The overall device size was constrained to 50×50×5 mm. This limited the duct height to be 3 mm to account for wall thickness.

5.2.1 Description of the Design

Various two-electrode configurations were studied to obtain the one with the lowest onset potential. Some of these configurations included wire-to-plate, wire-to-cylinder, needle-to-plate, blade-to-cylinder and needle-inside-ring. Of these configurations, a needle electrode along the axis of a circular ring delivered the lowest onset potential. The result can be explained approximately in terms of the electric field stress at the surface of the corona source. In a 2-dimensional situation like at the surface of the wire, the field varies as $1/r$, whereas the tip of a needle is a 3-dimensional case and follows a spherical variation of $1/r^2$. This increases the electric field enhancement at the tip leading to lower onset potentials. Encasing the needle in a cylinder or a ring maximizes the electrical field stress at the tip.

Figure 5.7 shows the schematic of both the entire device and an individual channel. The design comprises of 13 channels of 3 mm diameter each. Tungsten microelectrodes of ~3 μm tip diameters were used as corona sources. Copper rings of 1
mm width formed the collecting electrodes and were spaced 1 mm apart. Two guide posts, each 3 mm in diameter, hold the assembly together. Choice of individual circular ducts also had the advantage of isolating the tips of the corona sources from each other. This avoids reduction in the field enhancement at their tips due to the presence of neighboring needles at the same high potential by localizing the entire field within an individual channel. The advantage has also been noted by other researchers [36].

5.2.2 Performance Characterization

Flow performance was characterized using an airflow measurement chamber. The schematic of an air flow chamber is shown in Figure 5.8. It consists of a plenum chamber, a flow rate measurement device and a vacuum suction. The ionic wind blower is attached on the outside such that it pumps air into the plenum chamber. The suction

![Figure 5.7 Schematics of the blower and an individual channel](image)
evacuates air from the plenum and by controlling the valve operation, the pressure inside the plenum chamber can be adjusted to vary the back pressure experienced by the ionic wind blower. The laminar flow element reads out the volume flow rate.

![Figure 5.8 Schematic of an Air Flow Measurement Chamber](image)

The total operating potential of the device is a major constraint. Figure 5.9a plots the flow rate against the total potential used, similar to Figure 5.4b. Because the data is proprietary, the exact data is not shown in the plots. It was observed that the application of a negative potential on the secondary collecting electrode did not benefit the flow rate. But grounding both the collectors resulted in significant improvements to flow rate compared to a two-electrode configuration. About half the targeted flow rate value was achieved while slightly exceeding the constraint on operating potential. Figure 5.9b shows the pressure performance of the ionic wind blower. The plot is similar to a fan curve, flow rate plotted against the pressure drop across the device. Data from a similar sized mechanical fan is also included in the plot. The study is essential because of the increase in pressure drop encountered when the blower is installed in the electronic device. The maximum pressure drop that was sustained by the blower pales in
comparison to the stock fans that are used as can be seen from the plot. However, the flow rates are of similar values. Further study needs to be conducted on improving the pressure performance of the blower. To improve pressure performance, the slope of the curve needs to be steepened in order to generate high flow rates despite experiencing a back pressure.

Figure 5.9 (a) Flow rate vs the total operating potential and (b) Pressure-flow rate (P-Q) curves
The ionic wind blower was also integrated into a portable electronic system where it replaced the existing fan. Flow rate and acoustic measurements were conducted on this modified system and compared to the original baseline system. Since the choice of the system was made based on size considerations, the flow rate generated by the existing fan was significantly higher than the capabilities of the ionic wind blower. Therefore, comparisons are also made to an alternate system for which the flow rates generated by the fan were on the order of those generated by the ionic wind device.

Figure 5.10 shows the flow-acoustics and the power consumption data for the device when integrated into the system. For proprietary reasons, data is not included and only non-dimensionalized values are used. The acoustic signature from the ionic wind blower was considerably lower than that of the systems with a traditional fan. In fact, the acoustic levels of the ionic wind device were almost on the order of room noise levels. Power consumption levels were also lower for the ionic wind device to generate any specific flow.
5.3 Summary

This chapter applied the previously studied concept of multi-electrode corona discharges in the generation of electrohydrodynamic flow and the development of an ionic wind blower. From the results of the Flow-Configuration, three-electrode configurations were seen to improve the flow rates over the traditional two-electrode
configurations. The presence of the gate electrode was also observed to stabilize the corona discharge in the narrow duct heights under study and significantly reduced the occurrence of sparks. The secondary electrode’s presence improved the flow rate by a factor of $2\times - 3\times$ and also lowered the power consumption.

The concept showed promise and was implemented in a prototype with the dimensions to fit into a small form-factor electronic system. The device showed similar improvements over two-electrode configurations. Integration of the device and subsequent characterization of the system performance was also conducted. It was observed that the ionic wind device had a negligible acoustic signature compared to the system that had a fan installed. For similar flow rates, the power consumed by the ionic wind device was also lower than, or at least comparable to, that of the fan.
6.1 Assisted Discharge: A Qualitative Understanding

Drawing inferences from the experimental data and numerical simulations, it is possible to obtain a qualitative understanding of the behavior of a corona discharge under the influence of a non-uniformly distributed electric field. An assisted corona discharge is a standard corona discharge that in this dissertation uses two collecting electrodes, though it could be extended to three or more collecting electrodes. The primary collecting electrode is closer to the corona source \((d_1)\) and has some applied potential to it \((\Phi_1)\), while the secondary electrode is further from the corona source \((d_2)\) and has some potential applied to it \((\Phi_2)\). An assisted corona discharge is generated when there is an asymmetric geometry \((d_1 \neq d_2)\) and electrostatic imbalance \((\Phi_1 \neq \Phi_2)\), though this second condition is not a requirement. If no secondary collecting electrodes are used, then a standard two-electrode corona discharge is formed between the corona source and primary collecting electrode. In an assisted corona discharge, the electric field imposed by the multiple collecting electrodes is inherently asymmetric, but the electric field imposed by the secondary collecting electrode at the corona source is relatively weak – that is, the potential difference \(|\Phi_1 - \Phi_2|\) is insufficient to generate a standard two-electrode corona discharge at the distance \(d_2\). The primary collecting electrode assists the onset of the corona while the secondary collecting electrode imposes an electric field to
draw ions towards itself, such that there is ion current to both the primary and secondary collecting electrode.

A comparison of the standard numerical model (Transport Model) with the new model proposed by the author (Plasma Model) demonstrates the difference between two- and three-electrode corona discharges. As can be observed from the numerical simulations in asymmetric electric fields, the arrangement of the collecting electrodes dictates both the distribution of ionization around the corona source and also the transport of the ions to the various collectors. Multi-electrode configurations are only a subset of configurations which impose an asymmetric electric field. In the latter, as in the numerical simulation, the collecting electrodes can be a single connected electrode (cylinder). In the former, the collecting electrode is disconnected and split into multiple pieces (like in the Test- and Flow-Configurations). Application of different potentials on the various electrodes also results in an electrostatically similar problem.

Two experimental arrangements, i.e., the Test- and Flow-Configurations, have been studied to understand the changes to the electrical characteristics and its impact on the generated electrohydrodynamic flow. These two configurations are at the same time similar and dissimilar in their treatment of an assisted discharge. The basic underlying principle is the same in both cases and both configurations demonstrated similar effects and trends. The primary collecting electrode acted as the gate to ignite the discharge and the secondary collector altered the electric field distribution so as to draw ions towards it. The presence of the secondary collector was also shown to increase ionization in both configurations. However, the magnitudes of the currents and their transport ratios to the
two collectors were different in the two configurations suggesting that the geometry plays a crucial role in determining these properties.

One speculative reason that can be put forth is that the “angle of view” that the two collectors have of the corona source determines the influence that it has on both the increase in ionization and current distribution. However, it should be mentioned that the “angle of view” in this case is not a physical line of sight based quantity but a more theoretically abstract explanation on the influence an electrode plays on the corona source. It is more reasonable to study the concept in terms of electrostatic field lines, but the “angle of view” argument is easier to qualitatively imagine. Conceptually, it is similar to the eccentricity parameter \(R/\delta\) used to conduct studies in the numerical simulations.

In the Test-Configuration and in the configuration chosen for the numerical simulation, the two collecting electrodes were on opposite sides of the corona source (wire), this being exposed to equal areas of the wire’s surface. Because both the electrodes electric fields comparable in magnitude, the secondary electrode in this case, increases ionization at the wire’s surface and also transports a significant fraction of the ions towards itself. In the Flow-Configuration however, since both collectors are on the same side (downstream), the secondary electrode’s exposure to the source (needles) is limited by the primary electrode. Thus to influence the ionization and drag ions towards itself, it needs to penetrate and overcome the field imposed by the primary collector. This results in a lesser fraction of ions being transported to it than in the Test-Configuration. A better understanding of the differences between the Test- and Flow-Configurations can be obtained by using the Plasma Model to numerically simulate the two configurations.
6.2 Conclusions

This dissertation investigates the concept of multi-electrode corona discharges and their application for ionic wind generation in narrow duct heights. The goal of the research was to develop a conceptual arrangement that would mitigate the various challenges encountered in miniaturizing ionic wind devices to duct heights \( \sim 3 \) mm. A novel electrode configuration that utilized multiple collecting electrodes was proposed and the concept was studied in various configurations to understand its behavior on both large scales in ideal configurations as well as in small scales in configurations that would be implemented in ionic wind blowers.

Due to a lack of concrete data in literature on small-scale coronas, preliminary studies on characterizing corona discharges in millimeter scales were conducted. The results of these studies were compared to the existing theoretical formulations for wire-plate coronas. It was shown that the relationships were valid qualitatively, but for small diameter corona sources, the quantitative values predicted from the theory deviated from the experimental data. A semi-analytical relationship was derived for the voltage-current characteristic in wire-plate electrodes that was shown to agree well with the data extracted from experiments.

The operation of corona discharges in multi-electrode configurations was studied in simplistic geometries and was shown to display anomalous behavior in comparison to a standard two-electrode discharge. Three fundamental observations were made from the experiments on the Test-Configuration.

a) The onset of current to the farther secondary collector is dictated by the nearer, primary collector.
b) At any given potential, the current flowing to the secondary collector is higher when it is part of a three-electrode configuration.

c) Multi-electrode configurations increase the total current at the corona source. This is due to the increased electric field stress near the emitter surface which results in higher ionization.

As the traditional numerical modeling procedure (Transport Model) did not predict the redistributions accurately, a new model (Plasma Model) was proposed that incorporated ion production at the corona source. This model was studied in a closed configuration of wire-in-cylinder which induced an asymmetric electric field. The primary quantity of interest, the ratio of currents distributed to the various collectors, was used to quantify the difference in the two models and compare them to experiments. The Plasma Model was shown to be more accurate in predicting the ion production and transport. Microscale effects of ionization near the wire surface and macroscale parameters of interest, like current distributions, were shown to be well predicted by the new model bridging the gap between the two. Basic results from the simulations are summarized below.

a) The ratio of currents, $I_{\text{ratio}}$, is predicted better by the Plasma Model.

b) The reason for the increased accuracy was demonstrated to be a combined accounting by the Plasma Model of asymmetric ion production and asymmetric transport, while the Transport Model only accounts for the latter.

c) As the radius of the wire decreased, the accuracy of predictions from the Plasma Model reduced, tending to the predictions from the Transport Model.
d) For the Plasma Model, variation around the wire is more pronounced for the larger diameter wires and evens out as the wire diameter reduces.

e) The effectiveness of the Plasma Model was shown to be greater when the ionization zone is significant in size when compared to the volume of interstitial space.

Shortcomings of the Plasma Model and avenues of improvements were also studied. A procedural roadmap for the implementation of the Plasma Model as a design tool in the development of ionic wind blowers was also presented.

The three-electrode configuration was also implemented in a ducted blower configuration. It was observed that this configuration significantly improved the stability of the discharge. Multi-electrode configurations have been shown to generate excess currents by factors of 1.5×, improve flow rates by factors of 2-3× and lower power consumption. A prototype was fabricated and installed into a handheld electronic device. The integrated system demonstrated the feasibility of ionic wind blowers as a silent cooling technology and a replacement for the fan in the future.

6.3 Improvements

A lot more study on the design of the ionic wind blower is needed before achieving the targets dictated by the requirements of the electronics industry. The flow rate generated by the prototype needs significant improvement. As mentioned in the text, the efficiency of corona operated devices is significantly low (~1 %) and has remained relatively unchanged through all the research of the past decades. This implies that to improve flow rates from the ionic wind blower, the total power consumption has to
increase. This can be achieved through two possible methods – either the increasing the number of discharge channels or using a multi-stage configuration, as studied by Rickard et al. [43]. The former increases the geometric footprint of the device while the latter does not. The latter method does however include a much more complicated electrode arrangement. Alternative arrangements which use the multi-electrode concept can be designed which are much more malleable to the number of discharge channels that can be incorporated. Microfabrication techniques also offer potential avenues of improvement to the electrode configuration.

The development of the device for commercial purposes requires a numerical tool to optimize the design configuration. The numerical scheme presented in Chapter 4 needs to be further expanded to include the flow calculations by coupling the electrical characteristics (space charge density and electric field) with the Navier Stokes equations. Various improvements to the Plasma Model have been mentioned in Chapter 4. These need to be studied in detail before its implementation as a design tool. One primary area that needs to be looked into is matching the simulated currents with the experimental values. Also, since the semi-empirical approach requires experimental data on each new configuration, an alternative procedure for determining the total current needs to be established, analogous to Kaptzov’s hypothesis that has been traditionally used but found to be ineffective in this case. Photoionization is another area that needs to be explored, particularly with regards to its potential for providing the final condition needed to determine the currents \(a\ priori\).
6.4 Future Work

Ionic winds in general have a significant potential for heat transfer enhancement. As silent cooling technologies, their feasibility in portable electronics has been demonstrated. However, limited as they are due to size and constraints on operating parameters, there are many other areas where they are applicable but no so limited. The small size of the electrodes and relative ease of arrangement makes them ideal in local heat transfer enhancement in data centers, between server racks where fans cannot be installed due to lack of space. Another potential application is in heat transfer augmentation in heat exchangers, where the hot air can be locally circulated to the walls of the heat pipes.

Aside from heat transfer enhancements, ionic winds have various other applications in flow control, electrostatic precipitation and polymer charging. Removal of toxic emissions from exhaust pipes in automobiles and from chimneys can be achieved through electrostatic precipitation. Polymer charging has for a long time used corona discharges and its arrangement results in a three-electrode discharge where the polymer forms the secondary collector. Plasma-actuated flow control mechanisms have been studied for the last two decades using both corona discharges and dielectric barrier discharges and is of particular interest to the author as an area of research.
APPENDIX A:
ELASTIC BEAM THEORY ANALYSIS FOR ELECTRODE SNAPDOWN

A simple elastic beam theory analysis is presented below which models the wire as a cylindrical simply supported beam. The electrostatic force is applied as a uniform load on the beam. Figure A.3 shows a basic simply supported beam and defines the variables used in the following analysis.

![Figure A.1 Schematic for the load analysis on the corona electrode](image)

The uniform load per unit length, \( q(x) \), is considered by assuming the action of the electric field on the wire, which is modeled as a line charge. The electric field at the wire surface, for the present purposes is conservatively assumed to be given by \( E = V/d \), where \( V \) is the applied potential and \( d \) is the gap distance. For a cylindrical conductor of radius \( r_0 \), the surface charge per unit length (\( \lambda \)) is given using Gauss law as,

\[
\lambda = 2\pi\varepsilon_0 r_0 E ,
\]

(A.10)
where $\varepsilon_0$ is the permittivity of free space. Thus the total electrostatic force per unit length, $q$, on the beam (wire) is given by

$$q = \lambda E = 2\pi\varepsilon_0 r E^2 = \frac{2\pi\varepsilon_0 r_0 V^2}{d^2}.$$  \hspace{1cm} (A.11)

For a simply supported beam under a uniform load, the maximum stress is given by

$$\sigma_{\text{max}} = \frac{qrl^2}{8I} = \frac{\pi\varepsilon_0 r_0^2 l^2 V^2}{4Id^2},$$  \hspace{1cm} (A.12)

where $I$ is the moment of inertia, which for a cylindrical cross section is given by

$$I = \frac{\pi r_0^4}{4}. \hspace{1cm} (A.13)$$

Using values of $r_0 = 25$ μm, $l = 5$ cm, $V = 2000$ V and $d = 500$ μm, the maximum stress is calculated to be 560 MPa. The yield stress for stainless steel wire is 515 MPa.
APPENDIX B:
DETAILS ON NUMERICAL PROCEDURE

B.1 Grid Generation

The basic premise of generating the curvilinear discretization is to solve two Poisson’s equations (Equation 4.5) and generate a one-to-one mapping between the physical domain \((x,y)\) and the computational domain \((\xi,\eta)\). The equations for \(\xi\) and \(\eta\) are

\[
\begin{align*}
\xi_{xx} + \xi_{yy} &= P(x,y) \\
\eta_{xx} + \eta_{yy} &= Q(x,y)
\end{align*}
\]

where \(P\) and \(Q\) are functions that are used to control the local grid density. By imposing suitable boundary conditions on \(\xi\) and \(\eta\), an orthogonal coordinate system can be generated. Using an analogous thermal problem, for a generic physical domain (shown in Figure B.1), these boundary conditions are imposed in two adjoint problems by alternating the “isothermal” and “adiabatic” conditions. Each of the two temperature fields, \(\xi\) and \(\eta\) independently satisfies the Laplace equation. The iso-contours of the two temperature fields are then orthogonal to each other. Due to the nature of the equations used to generate them, elliptic grids tend to concentrate more around convex surfaces. \(P\) and \(Q\) are functions that can be used to control the grid concentration. These functions are essentially source functions in Poisson’s equation.
Boundary conditions for the analogous heat transfer problem where $\zeta$ and $\eta$ are the two temperature fields.

By interchanging the dependent and independent variables in Equation B.1, the transformed system in the computational domain is obtained as

\[
\begin{align*}
ax_{\zeta\zeta} - 2bx_{\zeta\eta} + cx_{\eta\eta} + J^2 (Px_{\zeta} + Qx_{\eta}) &= 0 \\
ay_{\zeta\zeta} - 2by_{\zeta\eta} + cy_{\eta\eta} + J^2 (Py_{\zeta} + Qy_{\eta}) &= 0
\end{align*}
\]  \hspace{1cm} (B.2)

where $J$ is the metric tensor of the transformation, given by

\[
J = x_{\zeta}y_{\eta} - x_{\eta}y_{\zeta}.
\]  \hspace{1cm} (B.3)

The coefficients $a$, $b$ and $c$ are given by

\[
\begin{align*}
a &= x_{\eta}^2 + y_{\eta}^2 \\
b &= x_{\zeta}x_{\eta} + y_{\zeta}y_{\eta} \\
c &= x_{\zeta}^2 + y_{\zeta}^2
\end{align*}
\]  \hspace{1cm} (B.4)

The derivatives are approximated using second order central difference schemes.

In this problem, the domain and boundary conditions are shown in Figure B.2.
To maintain the iso-lines corresponding to constant $\zeta$ and $\eta$ as the constant potential lines and the electric field lines respectively, the space charge density distribution has to be introduced into the grid generation. To simplify the grid generation process, the boundary condition for $\zeta$ is specified to be the same as that of the potential problem, i.e., the value on the wire being the applied potential $\Phi_0$ and the value on the cylinder as zero. This facilitates the introduction of the space charge density as the control function $P$ in the $\zeta$-equation of B.1, i.e.,

$$P(x, y) = -\frac{\rho(x, y)}{\varepsilon_0}$$

(B.5)

where $\rho$ is the space charge density and $\varepsilon_0$ is the permittivity of free space. $Q(x, y) = 0$ for the problem.
The set of equations B.2 is then solved using iterative relaxation schemes to solve for the physical domain space \((x,y)\) in terms of the computational domain space \((\xi,\eta)\) and obtain a corresponding map between the two. An absolute convergence criterion, 
\[|x^{n+1} - x^n| = 10^{-10}\] m was used, \(n\) being the iteration count, to ensure that the error in location of the points in the physical domain was orders of magnitude less than the smallest resolution.

Orthogonality of the grid at the wire and cylinder boundaries were implemented by the procedure outlined in Thomson [60]. The points on the boundary were parameterized by \(\theta\), which were evenly distributed for the initial condition. For the wire and cylinder, the corresponding parameters, \(\theta\), were the angles subtended at their respective centers. The parameteric \(\theta\) value at each point where the \(\eta\)-line intersects the boundary is updated at each iteration to ensure orthogonality. At the boundaries, orthogonality condition is specified by

\[
\bar{x}_\xi \cdot \bar{x}_\eta = 0 \tag{B.6}
\]

where \(\bar{x} = (x,y)\). For example, along \(\xi = 0\) (or \(i = 1\)), the equation becomes,

\[
\left(\bar{x}_{2,j} - \bar{x}_{1,j}\right) \cdot \left(\bar{x}_\eta\right)_{i,j} = 0. \tag{B.7}
\]

In the following discussion, \(\theta\) is the value of the parameter at a point \((x,y)_{i,j}\) and \(\theta_0\) is the value at the same point from the previous iteration. To solve for \((x,y)_{i,j}\), the parameter value from the previous iteration, \(\theta_0_{i,j}\) is used to solve for the new value \(\theta_{i,j}\) to evaluate the new \((x,y)_{i,j}\). Taylor series is used to expand \(\bar{x}\) about \(\theta_0\) to give

\[
\bar{x}_{1,j} = \bar{x}(\theta) \approx \bar{x}(\theta_0) + \bar{x}_\theta(\theta - \theta_0) \tag{B.8}
\]

which on substituting into Equation B.7 and rearranging gives,
\[ \theta = \theta_0 + \frac{\left( x_{\eta, i,j} \cdot (x_{2,j} - x_{1,j}(\theta_0)) \right)}{\left( x_{\eta, i,j} \cdot (x_{\eta})_0 \right)}. \] (B.9)

The new value of \( \theta \) is then used to evaluate \((x,y)_{i,j}\). Similar is the procedure on the other boundary. Figure B.3 shows a discretized grid with the inset showing orthogonality imposed on the wire surface.

![Discretized domain with inset showing the orthogonality at the wire surface](image)

Figure B.4 Discretized domain with inset showing the orthogonality at the wire surface

B.2 Poisson’s and Transport Equations

An advantage of the elliptic grid is that it reduces the Poisson’s to a one dimensional equations along constant \( \eta \), *i.e.*, along the field lines which can then easily be solved either analytically or numerically. It should be noted that the computational expense of solving the Poisson’s equation is not skipped in the procedure. The expense is
transferred to generating the elliptic grid. Poisson’s equation in the computational domain is given by,

\[
\frac{1}{h_\xi h_\eta} \left[ \frac{\partial}{\partial \xi} \left( h_\eta \frac{\partial \Phi}{\partial \xi} \right) + \frac{\partial}{\partial \eta} \left( h_\xi \frac{\partial \Phi}{\partial \eta} \right) \right] = -\frac{\rho}{\varepsilon_0} \tag{B.10}
\]

where \( h_\xi \) and \( h_\eta \) are the transformation coefficients given by

\[
h_\xi = \sqrt{x_\xi^2 + y_\xi^2} \\
h_\eta = \sqrt{x_\eta^2 + y_\eta^2} \tag{B.11}
\]

Since the \( \eta \) component of electric field is zero (constant \( \eta \)-lines being field lines), Equation B.10 reduces to the ordinary differential equation

\[
\frac{1}{h_\xi h_\eta} \left[ \frac{d}{d\xi} \left( h_\eta \frac{d\Phi}{d\xi} \right) \right] = -\frac{\rho}{\varepsilon_0} \tag{B.12}
\]

which can be integrated numerically using the trapezoidal rule between the limits of \( \zeta \) to get the potential field \( \Phi(\zeta) \). Electric field \( \vec{E} \) is then determined as the gradient of \( \Phi \). It should be noted that \( \vec{E}(\xi, \eta) = E(\xi)\vec{\xi} \). When the wire is concentric with the cylinder, a theoretical solution can be obtained for the case where the space charge density is a constant value. In cylindrical coordinates, Poisson’s equation for constant space charge density \( (\rho/\varepsilon_0 = K) \) is

\[
\frac{1}{r} \left[ \frac{d}{dr} \left( r \frac{d\Phi}{dr} \right) \right] = -K \tag{B.13}
\]

for which the theoretical solution, after applying the boundary conditions \( \Phi(r_0) = \Phi_0 \) and \( \Phi(R) = 0 \), is
\[ \phi(r) = \phi_0 \frac{\log(R/r)}{\log(R/r_0)} + \frac{K}{4} \left( (R^2 - r^2) - \left( R^2 - r_0^2 \right) \frac{\log(R/r)}{\log(R/r_0)} \right) \]  \hspace{1cm} (B.14)

Figure B.4 plots the theoretical solution with the solution calculated from Equation B.12 on the generated grid. As can be seen the numerical solution matches well with the theoretical solution. The figure also plots the solution in the absence of space charge to demonstrate the effect positive space charge has on the electrostatic field.

Figure B.5 Plot of the potential along the radial direction with and without space charge.

Along the field lines, charge transport of species \( i \) (Equation 4.2) reduces to

\[ \frac{1}{h_i h_\eta} \left[ \frac{d}{d\xi} \left( h_i \rho, \mu_i E \right) \right] = S_i(\xi, \eta), \]  \hspace{1cm} (B.15)

which is solved for the charge density \( \rho_i \) using a second order upwind scheme.
B.3 Grid Independence Tests

Figure B.5 shows the grid resolution studies on the final solution of both Poisson’s equation as well as total current from the discharge. Trapezoidal rule, which is used to integrate Equation B.12, is 2\textsuperscript{nd} order accurate and this is shown from the slope of the linear fit in Figure B.5a. A constant space charge density of 10\(^{-2}\) C/m\(^3\) was used and the theoretical solution of B.14 was used to calculate the error. The choice of the space charge density was higher than any that are encountered in the simulation studies, but was chosen to highlight the effect space charge has on the electrostatic solution. The error is calculated as

\[
\text{error} = \max \left( \frac{\phi - \phi_{th}}{\phi_{th}} \times 100 \right) \quad \text{(B.16)}
\]

As can be seen, the error (plotted as a % difference) is almost negligible even for large grid sizes. The ratio of electric field components, \(E_\eta / E_\xi\), was < 10\(^{-3}\) which ensures that the constant \(\eta\)-lines are indeed the electric field lines.

Figure B.5b plots the grid resolution study for ion transport equation. Total current, the parameter of interest, is used for this study. Alternatively, either \(\rho_e\) or \(\rho_p\) can be used and the results were found to be similar. The error is calculated based on a fine grid which utilized 800 points in the \(\xi\)-direction. The difference in solution between coarser grids and this fine grid was used as an error measurement to check for convergence of the solution. The error is given by

\[
\text{error} = \left| \frac{I_{N_\xi} - I_{800}}{I_{800}} \right| \times 100 \quad \text{(B.17)}
\]
where $I_{N\xi}$ is the current solution obtained from a grid with $N\xi$ points in the $\xi$-direction and $I_{800}$ is the solution obtained for the fine grid with 800 points. As can be seen, the solution differs by less than 1% for a grid of 400 points and thus a minimum of 400 was used as the value of $N\xi$. 100 points were observed to give sufficient discretization in the $\eta$-direction and the solution did not change much with variation of $N\eta$, primarily because the equations are all solved along the field lines. The slope of the linear fit is again ~2 corresponding to the 2\textsuperscript{nd} order discretization scheme used to calculate the derivatives. Note that for the grid independence tests, the iteration to obtain a converged $\rho$-$E$ combination wasn’t performed and the Laplacian field was used to calculate the currents. This is acceptable as the test is only a check for the accuracy of the scheme in solving the charge transport equation.

Figure B.6 Plots showing the change in error with grid resolution for (a) potential from Poisson's equation and (b) total current from transport equation. The value in parantheses is the number of grid locations in the $\xi$-direction ($N\xi$).
B.4 Choice of $\rho_{e0}$

As described in Chapter 4, in the Plasma Model, the solution of the charge transport equations requires the choice of the electron charge density ($\rho_{e0}$) outside the ionization zone. This value decides the total current produced in the discharge. A semi-empirical approach is used where the total current measured from experiments is used to make the choice of $\rho_{e0}$. However, the currents measured from the experiments resulted in the requirement of $\rho_{e0}$, and a resultant positive ion density ($\rho_p$), far greater than values typical of a corona discharge simulation. While the resulting high space charge was not an issue in the Transport Model, the Plasma Model needs extremely fine grid resolutions ($< 10^{-7}$ m) to cope with the steep gradients in the $\rho_e$ and $\rho_p$ distributions near the wire surface. As explained in Chapter 4, a moderate value of $\rho_{e0}$ was used to perform the simulations of the Plasma Model to keep the computational time reasonable. However, it was observed that the choice of the $\rho_{e0}$ does not significantly affect the final solution and the distribution of current to the two halves of the cylinder. Figure B.6 shows a plot of the total current ($I$) as a function of $\rho_{e0}$ for the eccentric case with the parameters $r_0 = 100$ $\mu$m, $R = 3$ mm, and $\delta = 1$mm. As can be observed, there is a linear relationship between the two which stems from the solution to electron current conservation ($\nabla \cdot J_e = \alpha J_e$ where $J_e = \rho_e \mu_e E$) in cylindrical coordinates. The figure also plots the variation of $I_{ratio}$, the distribution of current between the two halves. It can be seen that the value does increase slightly with increase in $\rho_{e0}$ but the increase is small and the values are still close to the experimental values shown in Chapter 4.
B.5 Empirical Formulation for Various Coefficients

Data for the ionization and attachment coefficients as well as mobilities are presented below. The formulations are obtained as curve fits to experimental data. Typical data in literature is obtained at low pressures (<100 torr) where the variation of coefficients is measured with respect to $E/p$ where $E$ is the electric field and $p$ is the pressure. The data for atmospheric pressures is obtained by setting $p = 760$ torr. The data used in this research was obtained from [47].

Townsend’s first ionization coefficient ($\alpha$) is a measure of the number of electron-impact ionization events per unit length, resulting in a positive ion. As such, it is a function of the electric field strength, which is a measure of the energy possessed by the impacting electron.
\( \alpha = 3.63 \times 10^5 \exp\left(-1.68 \times 10^7 / E\right) \text{ 1/m} \quad \text{if} \quad 1.9 \times 10^5 < E < 4.56 \times 10^6 \text{ V/m} \\
\alpha = 7.36 \times 10^5 \exp\left(-2.01 \times 10^7 / E\right) \text{ 1/m} \quad \text{if} \quad 4.56 \times 10^6 < E < 2 \times 10^7 \text{ V/m} \\
(B.18)

The attachment coefficient (\( \beta \)) is a measure of the number of electron-attachment events per unit length. The attachment of an electron leads to the formation of a negative ion.

\[ \beta = 1.482 \times 10^3 \exp\left(-3.465 \times 10^6 / E\right) \text{ 1/m} \quad (B.19) \]

The electron mobility (\( \mu_e \)) is given by

\[ \mu_e = 1.2365 E^{-0.2165} \text{ m}^2 / \text{Vs} \quad (B.20) \]

Positive ion mobility in air (\( \mu_p \)) is a constant at \( 2 \times 10^{-4} \text{ m}^2 / \text{Vs} \) and negative ion mobility (\( \mu_n \)) is \( 2.7 \times 10^{-4} \text{ m}^2 / \text{Vs} \).
BIBLIOGRAPHY


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