A SPECTROSCOPIC INVESTIGATION OF A SURFACE-DISCHARGE-MODE, DIELECTRIC BARRIER DISCHARGE

A dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy

By

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ABSTRACT


The use of aerodynamic actuators, such as leading edge slats, trailing edge flaps, roughing strips and ailerons interact with the air during flight, providing maneuverability for air vehicles. These mechanical devices have many inherent, detrimental attributes, such as space requirements on the wing, added wing weight, second response times, increased drag, and increased airframe vibration, resulting in the production of noise. The potential to eliminate or improve upon these detrimental attributes may be realizable by replacing the current mechanical actuators with plasma actuators. Specifically, the surface-discharge-mode, dielectric barrier discharge (SDBD), plasma actuator has a response time on the order of microseconds to milliseconds, does not increase vibration by mounting flush to the wing surface, does not increase drag, and adds negligible weight to the wing. Unfortunately, these devices are not yet powerful enough to perform many of the tasks required for aerodynamic applications; however, they have demonstrated the potential to do so, providing motivation for the current study. Currently, the approach of the research community has focused on coordinating studies designed to determine the physics of the device and parametric studies to determine optimal configurations required for immediate application.

In this work, an experimentally based study utilizing optical emission spectroscopy, current-voltage measurements, and a force balance have been successfully applied, contributing new, specific detail to the morphology and characterization of the SDBD. The results of this study were tailored to aid the development of the appropriate, essential physics required for computational modeling of the SDBD. Initially, force measurements of the induced thrust were obtained to demonstrate how week the induced thrust is, justifying the need for a fundamental study. These results are also important in understanding an apparent discrepancy in the reported dependence of the induced thrust upon applied voltage amplitude.
Electrical properties of the device such as breakdown voltage, surface charge voltage, effective capacitance with and without a discharge, electrical current, dissipated power, and the details of breakdown are measured as a function of applied voltage. The measured surface potential is of particular interest because it provides information about one of the boundary conditions needed to solve Maxwell equation’s of electromagnetics. Measurements showed that the surface charge potential along the dielectric surface is around 4000 and 4200 volts for the positive and negative voltage half-cycle, respectively, at an applied potential of 6000 volts.

Properties determined from emission, including the relative concentrations of \( \text{N}_2(C^3\Pi_u) \) and \( \text{N}_2^+(B^2\Pi_g) \), and rotational and vibrational temperatures, as a function of position, voltage amplitude and phase of the driving voltage, have been measured. The spatially resolved relative concentrations of \( \text{N}_2(C^3\Pi_u) \) and \( \text{N}_2^+(B^2\Pi_g) \) are useful in demonstrating the difference in structure between the discharge occurring during the positive voltage half-cycle versus the discharge occurring during the negative voltage half-cycle. The rotational temperature obtained from the 1\(^{st}\) negative band system of \( \text{N}_2^+ \) was shown to be significantly greater than the rotational temperature obtained from the 2\(^{nd}\) positive band system of \( \text{N}_2 \) and was shown to be a direct consequence of the local electric field. This is shown to be important when calculating the rate constants for reactions involving ions and neutrals. For example, neglecting this deviation in temperature results in an order-of-magnitude difference in rate constants. Therefore in modeling the plasma, measurements show it is important to calculate the ion temperature via the Wannier relationship and then calculate the rate constants.

The details of these experiments including set-up, results, significance and discussion, along with an exhaustive summary of the current understanding of the surface-discharge-mode, dielectric barrier discharge, constitutes the bulk of this dissertation.
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Nomenclature

\( A_{v',j'} \)  Einstein coefficient for a vibrational transition
\( A_{v'',j''}^{v',j'} \)  Einstein coefficient for a rovibrational transition
\( c \)  Speed of light
\( d \)  Diameter of fiber bundle
\( D_{\text{eff}} \)  Effective diameter of lens
\( E \)  Electric field
\( f \)  Force per unit volume
\( f_1 \)  Focal length of front lens
\( f_2 \)  Focal length of back lens
\( F \)  Force
\( F_{J'} \)  Rotational energy of the \( J' \) energy level
\( g \)  Gap distance between lens 1 and lens 2
\( g_{J'} \)  Degeneracy of the \( J' \) energy level
\( G(v') \)  Energy of the \( v' \) energy level
\( h \)  Planck’s constant
\( I_{v'',j''}^{v',j'} \)  Intensity of a rovibrational line
\( J' \)  Upper state rotational quantum number
\( J'' \)  Lower state rotational quantum number
\( J_i \)  Current density
\( k \)  Boltzmann constant
\( K_n \)  Knudsen number
\( L \)  Plasma depth
\( L_{v''}^{v'} \)  Theoretical vibrational band
\( L_{v'',j''}^{v',j'} \)  Theoretical rotational line
\( n \)  Total number of data points
\( N_{\text{Fit}} \)  Number of fit parameters
\( N_{v'} \)  Number of molecules in the \( v' \) vibrational level
\( N_{v',j'} \)  Number of molecules in the \( v' \) and \( J' \) energy level
\( P(\lambda, \lambda') \)  Instrumental line shape
\( Q_{r} \)  Rotational partition function
\( Q_{v} \)  Vibrational partition function
\( R \)  
Ideal gas constant

\( S_{jj''} \)  
Rotational line strength

\( T \)  
Temperature

\( T_{\text{rot}} \)  
Rotational temperature

\( T_{\text{vib}} \)  
Vibrational temperature

\( \bar{v} \)  
Velocity

\( V \)  
Voltage and volume

\( W_{\nu'''}(\lambda) \)  
Spectral line

\( y_i \)  
Measured data point

\( y(x_i) \)  
Fit to the measured data point

\( \chi^2 \)  
Chi squared statistical parameter

\( \chi^2_R \)  
Normalized chi squared called reduced chi squared

\( \Phi(\lambda, \lambda_{\nu''', jj''}) \)  
Line shape function

\( \lambda \)  
Wavelength

\( \lambda_D \)  
Debye length

\( \lambda_{\nu''', jj''} \)  
Wavelength of a rovibrational line

\( \mu \)  
Mobility

\( \nu' \)  
Upper state vibrational quantum number

\( \nu'' \)  
Lower state vibrational quantum number

\( \theta \)  
Collection cone angle

\( \sigma \)  
Standard deviation

\( \sigma_i^2 \)  
Standard deviation of the noise in the measurement

\( \omega_e \)  
Spectroscopic constant

\( \omega_{pe} \)  
Fundamental plasma frequency

\( \omega_e X_e \)  
Spectroscopic constant

\( \omega_e Y_e \)  
Spectroscopic constant
Firstly, I would like to thank my wife, family and friends for their patience and support. I would like to thank my academic advisor, Dr. James Menart, my mentors, Dr. Joseph Shang and Dr. Charles DeJoseph, and my committee Dr. Jerry Clark, Dr. Roger Kimmel, Dr. Bill Bailey and Dr. Dan Young. I would like to thank Karen Lee for proofing the dissertation. I would also like to thank The Dayton Area Graduate Studies (DAGSI), Air Force Research Labs with Dr. Roger Kimmel as grant monitor, and Wright State’s Ph.D. in Engineering Program Assistantship Ph.D. Program for financial support.
CHAPTER 1: Introduction

The desire and push for better performing, more efficient technological advances, stemming from every discipline defines the trend of technology in modern society. Many of these new technologies have roots leading back to fundamental research and the development of the governing physics obtained through experimental, computational, and theoretical studies. For example, in the last fifty years the development of cellular phones, computers, the Internet, nuclear power, hydrogen fuel cells, and GPS navigation all have origins within fundamental research. With this in mind, the work presented in this document is an attempt to develop a more comprehensive understanding necessary for successfully implementing potential technologies associated with dielectric barrier discharges, hereafter referenced within this document as DBD. In particular, optical emission spectroscopy, current/voltage measurements, and other experimental diagnostics are used as tools to characterize a particular type of DBD, known as a surface-discharge-mode, dielectric barrier discharge. In this document, the surface-discharge-mode, dielectric barrier discharge will be referred to as SDBD. The goals of this document are to present, in a self-contained, consistent format, the research conducted for SDBD’s by the general SDBD research community and, most importantly, to adequately present and discuss, in detail, the results obtained by the author over the past four years of research. Some of the potential benefits that could come from the contributions of this study include: improving existing DBD technologies, such as surface modification for surface coatings, sterilization of surfaces, and removal of harmful gasses along with developing new technologies, such as enhanced aerodynamic performance and increased efficiency of air vehicles. It is the latter two aerospace applications for which the work within has been specifically tailored.

The components of an air vehicle, such as airfoils, the fuselage and turbo machinery are the mechanisms which allow the vehicle to interact with the surrounding air. These interactions ultimately determine the performance of the vehicle and are responsible for maneuvering, preventing flow separation, reducing drag, and controlling lift. It is qualitatively reasonable that greater control over these interactions could lead to enhanced performance. This is the intended function of aerodynamic actuators, which can be broken into two types: mechanical and plasma actuators. Examples of mechanical actuators are trailing edge flaps, leading edge slats, vortex generators, and roughing strips. These types of actuators are
detrimentally identified with moving components, inherent complexity, increasing wing weight, taking up space when not in use, and providing sources for airframe noise and vibration\textsuperscript{1}. Plasma actuators, including SDBD actuators, involve no moving parts, take up little space, are light weight, and have a much faster response time. Unfortunately, plasma actuators currently are found only in laboratories.

In addition to SDBD’s, other types of electrical discharges have been proposed for aerodynamic actuators such as DC corona discharges\textsuperscript{2-8}, radio frequency discharges (RF) \textsuperscript{9-12}, microwave discharges (MW) \textsuperscript{13-16}, DC glow discharges\textsuperscript{17-29}, and laser created plasmas\textsuperscript{29}. The selection of the discharge type is traditionally determined by the particular flight conditions. For example, typical discharges studied for high speed flows include DC glow discharges, RF, and MW discharges. Generally, DC glow discharges are used at low pressure, high altitude flight conditions, whereas RF and MW discharges can be extended to higher pressure zones. The advantage of DC glow discharges over the RF and MW discharges is lower power requirements; however, DC glow discharges are more restricted because they can only be generated on top of surfaces. SDBD’s and DC corona discharges are typically utilized for low speed flows at atmospheric pressure.
1.1 History of the Dielectric Barrier Discharge

The history of DBD’s has been eloquently documented elsewhere and will only be summarized below. The DBD was discovered in 1857, by W. Siemens. In Siemens’s studies, the DBD was similar to that shown in Figure 1.1c, consisting of two coaxial glass tubes, one within the other, separated by a small space. A discharge was established within oxygen flowing in the small gap by an oscillating electric field. Siemens noted that the discharge produced ozone (O$_3$), and his first documented report focused on the generation of this species. Three years later, in 1860, Andrews and Tait published work on the characteristics of the DBD and coined the name silent discharge, which is still in use today. In addition to the production of O$_3$, Hautefeuille and Chappuis (1881) and Warburg and Leitha¨user (1909) noticed the production of NO. After identifying NO, Warburg worked on developing an understanding of the physics associated with the DBD. During the 1920’s, the development and understanding of DBD’s, obtained over the past 60 years, finally paid off and the first industrial application was developed. This application focused on the production of ozone, which was used to purify water.

In 1932, Buss used Lichtenberg figures to take photographic traces of the electrode, and voltage-current measurements to discover that the discharge region of the DBD was composed of many microdischarges. The discovery of microdischarges caught the interest of the DBD research community and spurred an abundance of work on their nature. While a lot of attention was given towards understanding microdischarges, other work was being conducted simultaneously; and in 1941, Manley used closed voltage-charge Lissajous figures to determine the dissipated power. Manley then used the power values obtained to verify an equation derived for the power dissipated by the device. During this time period and up to the early 1990’s, DBD’s were used exclusively as a process for generating O$_3$, which, as mentioned, had an application in water treatment. During the 1970’s, more advanced diagnostics were available, capable of filling in some of the finer details associated with the electrical discharge. From this work, new applications such as ion nitriding, hard coating deposition, enhanced adhesion and wettability on polymer surfaces, sterilization, PCB hole etching, air purification, carbon material synthesis, film deposition, excimer light sources and lasers, plasma display panels, flame stabilization, and fluid dynamic actuators appeared. Today computational,
experimental, and theoretical research continues striving to explain the detailed processes associated with the DBD and to develop a more descriptive, useful model. It is reasonable to predict, from historical events, that new, undiscovered applications for this device are lingering at the edge of discovery.

The specific requirements for the numerous applications of DBD’s have led to the use of many different configurations, illustrated in Figure 1.1. The first three configurations, Figures 1.1a-1.1c, are used for flow control applications and are labeled as SDBD actuators. For the SDBD actuator, the electrode held at high voltage is referred to as the exposed electrode, and the embedded electrode held at ground is referred to as the encapsulated electrode. The SDBD in Figure 1.1a is used to induce a wall jet, in Figure 1.1b it produces force vectoring, which has not yet proved to be very successful, and in Figure 1.1c produces a vortex jet. The last three configurations, (d-f), are used for surface modification applications and are labeled as parallel electrode dielectric barrier discharges, referenced henceforth as PDBD’s. The discharge is formed by applying an oscillating electric field of sufficient strength between electrodes separated by a dielectric material. This qualitatively simple, but quantitatively complex device has led to many applications from all disciplines of science including physics, chemistry, biology, and engineering. The characteristics of the discharge are rich in terms of its spatial and temporal structure. The discharge ranges from a glow to a cluster of filamentary streamers or microdischarges depending on the driving frequency, operating pressure, and detailed chemistry associated with the surrounding gases. One could describe a “glow” discharge as a diffuse light source, with several distinct regions and, in a similar manner; a “streamer” has an appearance of a flash of light, similar to that of a small scale lightning bolt. The atmospheres in which DBD’s are utilized are diverse and include, but are not limited to, air, N₂, O₂, He, Ar, Ne, CO₂, CH₄, N₂/He, N₂/Ar, and N₂/Ne. The parameters of operation include applied voltage, driving frequency, and pressure, which varies depending on application, typically ranging from 2-20 kVolts, 2-100 kHz, and 0.01-1 atm, respectively.
Figure 1.1: Schematic of the common DBD configurations. Figures a-c represent SDBD configurations used for aerodynamic applications and d-f represent PDBD configurations used for surface modification applications.
CHAPTER 2: The Surface-Discharge-Mode, 
Dielectric Barrier Discharge

The volume of experimental, computational, and theoretical studies of SDBD actuators, developed over the past ten years, provides an excellent foundation for the initial development of the underlying physics. However, it is still insufficient for producing an effective aerodynamic actuator. For example, it has been shown that SDBD actuators are capable of controlling the properties of flow fields characterized with low Reynolds numbers. The problem is that aerodynamic applications within the range of Reynolds numbers suitable for the use of SDBD actuators are very small, and to make matters worse, more effective aerodynamic actuators exist for these applications. This does not mean that SDBD actuators have no future. Instead it means that these devices only have a future if a breakthrough occurs resulting in a significant increase in capability.

Several approaches have been applied simultaneously to try and accomplish this feat. The first involves optimizing the SDBD in terms of operating parameters. This approach has been carried out for the past ten years and has led to some improvement; however, it has reached a point of diminishing returns. The results of this approach produce an SDBD actuator with capabilities that fall below useful. The second approach involves understanding the underlying physics from first principles, and then using this information to design the device. This methodology has several advantages and disadvantages when compared to the first approach. First, this approach gives a more complete picture of the potential capabilities of the device, which can ultimately answer the question whether such a device is worth pursuing. Secondly, this methodology has the ability to determine doubt an actual optimal configuration, whereas the first methodology cannot distinguish if an optimal point is local or global. However, as is apparent from the above discussion, in this author’s opinion, the first approach has been exhausted and the second approach is required.

The first approach has been useful and has led to the development of valuable information. For example, the body force produced by the SDBD actuator was found to be directly proportional to the driving frequency of the applied voltage, and similarly, proportional to $V^{7/2}$ where $V$ is the applied voltage. Notice that the first approach gives information on how force varies, but it cannot determine the
mechanism(s) responsible for force production. In contrast, the second approach was able to determine that the induced gas flow is indirectly caused from the interaction of the electric field and the neutral species, via momentum transferring collisions between the ions and neutrals. This coupling phenomenon of the electric field with the bulk flow is known as the electrohydrodynamic effect or EHD and plays a fundamental role in the application of SDBD actuators. Its exact nature is still not completely understood. For example, the role negative ions (O\(^{−}\), O\(_2^{−}\) and O\(_3^{−}\)) play within the discharge during the various stages of the applied AC voltage is still not well known. Also, since the EHD effect relies on the generation of charged particles, it is intricately coupled with the detailed chemical processes associated with the production of these types of species. These chemical processes are still not completely understood. The difficulty of understanding these mechanisms stems from the nature of the SDBD in that it is transient, non-equilibrium, and typically operated at high pressure, resulting in adverse conditions for many of the traditional plasma diagnostic techniques.

The discussion so far has been geared towards developing a qualitative picture of the SDBD actuator and the methodological approaches used to investigate it. Moreover, an effort was made to highlight the fact that many questions associated with the fundamental operation of the device remain. This sets the stage for the current qualitative discussion to transition into a quantitative description, based upon available literature for the device. This is the focus of the rest of this chapter, which has been broken into three sections. The first, Section 2.1, is dedicated to presenting an extensive summary of experimental results. The second, Section 2.2, is a summary of computational results and the third, Section 2.3, summarizes the current state of applicability of SDBD actuators to aerodynamic applications.
2.1 Experimental Studies of Surface-Discharge Mode, Dielectric Barrier Discharges

Many different diagnostic tools and techniques have been used to study SDBD actuators including voltage probes, current probes, photomultiplier tubes, high-speed cameras, particle image velocimetry (PIV), stereoscopic PIV, Schlieren streak video, laser Doppler velocimetry (LDV), smoke wire, force balances, accelerometers, surface pressure taps and pitot probes, V-dot probe, electrostatic voltmeter probe, hot-wire and cold-wire anemometry, optical emission spectroscopy, hot film measurements, and microphone acoustic measurements. The data obtained from these diagnostics provides insight on the electrical, optical, chemical, and induced flow field properties of the SDBD. The discussion that follows has been broken into three sections: the first, Section 2.1.1, summarizes the properties of the induced flow field, the second, Section 2.1.2, presents a summary of the electrical and optical properties, and finally, Section 2.1.3, summarizes the results obtained from spectroscopic investigations of DBD’s.
2.1.1 Properties of the Induced Flow Field

As previously mentioned, the SDBD actuator induces a flow on the surrounding gas through an EHD coupling of the ion momentum with the neutrals, via momentum transfer collisions. Figures 2.1 and 2.2 show the rich structure of the induced flow field, in quiescent air, resulting from this process. The coordinate system used is the same as that given in Figure 1.1a. Both figures demonstrate that the surrounding air is drawn down towards the plasma region at around \(x = 0\), and is then redirected forming a wall jet with velocities ranging from 1 to 7 m/s for a sinusoidal voltage waveform. The wall jet, entrainment flow towards the SDBD surface, and recirculation make up the large scale flow structures of the flow field. However, as Figure 2.1b shows, there are also small perturbations. The cause of these small perturbations, which are shown to be reproducible, are not known, but could be due to flow instabilities, buoyancy from surface heating, tracking charged seeded particles, or a part of the EHD effect.

Figure 2.1: The induced flow field obtained by PIV. Taken from Kimmel et al.

![Figure 2.1: The induced flow field obtained by PIV. Taken from Kimmel et al.](image-url)
At this point it is imperative that some of the potential problems associated with the use of PIV within or near plasma discharges are discussed. The motivation for this discussion goes beyond the present results, and has more to do with the fact that PIV has become a standard diagnostic for determining the flow fields produced by SDBD actuators. The technique relies on tracking the motion of seeded particles within the flow field, and under an ideal situation, the motion of the seeded particles is determined only by momentum exchange with the surrounding fluid. However, the presence of free charges within the discharge can result in charge attachment to the seed particles, creating a situation in which the motion of the seed particles is given as the superposition of both Coulombic forces and momentum exchange with the surrounding fluid. The latter is desirable, whereas the former has to be eliminated or shown negligible for
the diagnostic to provide useful information about the flow field. Specific examples of the potential problems associated with charged seed particles, within SDBD actuators, have been investigated by Roupassov et al.\textsuperscript{116} and Boucinha et al.\textsuperscript{117} Roupassov et al.\textsuperscript{116} seeded smoke particles within the surrounding air of an SDBD actuator driven with a nanopulsed voltage waveform. This type of SDBD actuator, as will be discussed in greater detail later, does not induce a flow by EHD coupling; however, when the seed particles entered the discharge they were accelerated. The seed particles were then prevented from entering the same discharge, but were allowed to approach the edge. In this case, the velocities of the seed particles are shown to be strictly due to random thermal motion. Similarly, Boucinha et al.\textsuperscript{117} measured the velocity profile of the wall jet produced by an SDBD actuator with a Pitot tube and LDV, for three different kinds of seed particles. The diagnostic technique, LDV, relies on seed particles in an almost identical way as PIV. The measured velocities of the wall jet, along with the experimental parameters reported, are summarized in Table 2.1. Cleary from these results, the presence of seed particles has an effect on the induced flow field; however, the cause may not necessarily be charging of seed particles. Finally, Boucinha et al.\textsuperscript{117} reported that the discharge current was different when seed particles were present. How the conductive current changed was not reported, but one could speculate that the conductive current decreased. This is based on measurements presented in reference 26, which demonstrated that the presence of an electronegative gas significantly lowers the conductive current of a DBD due to the formation of negative ions.

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<th>LDV System</th>
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<td>Maximum Velocity (m/s)</td>
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\textbf{Table 2.1}: Summary of results taken from Boucinha et al.\textsuperscript{117}

As indicated, another way to measure the velocities within the flow field is by using a Pitot tube, which does not require the use of seed particles. Typical velocity profiles obtained using this technique are shown in Figure 2.3\textsuperscript{105}. In these results, the SDBD is operated on top of a flat plate in low speed flow produced by a wind tunnel. The velocity profile just upstream and just downstream of the SDBD actuator is
given in Figure 2.3a, and Figure 2.3b, respectively. These results demonstrate that the wall jet remains close to the surface; completely contained within the boundary layer. This has serious implications on application and will be discussed in Section 2.3. This result is consistent with the measured flow field presented earlier in Figures 2.1a and 2.2. The fact that the induced wall jet is completely contained within the boundary layer suggests that the height of the discharge is small. An upper bound for the plasma height of 100 micrometers has been measured by Cristofolini et al.\textsuperscript{106} using Schlieren imaging. The image produced using this technique is dependent upon the local index of refraction, which is solely determined by the local density. The discharge can change the local density by depositing energy into the air increasing the temperature. Thus, the height measured corresponds to the height of the region produced by this process, which can be larger than the discharge height due to thermal diffusion.

\textbf{Figure 2.3:} (a) Velocity profile measured just upstream of the SDBD actuator and (b) the velocity profile measured just downstream of the SDBD actuator. Taken from Baughn et al.\textsuperscript{105}

The dependence of the wall jet velocity on the operating parameters has been investigated by Forte et al.\textsuperscript{95} using LDV. The parameters included in this study, along with the range given in parenthesis, include the electrode gap (-5 to 15mm), width of the encapsulated electrode (1 to 50 mm), frequency of the sinusoidal voltage waveform (100 to 2000 Hz), voltage amplitude (8 to 30 kV), permittivity of the dielectric barrier (3 to 10), thickness of the dielectric barrier (1 to 3 mm), and the number of actuators (1 to 4). The dependence of the induced velocity upon the electrode gap, width of the encapsulated electrode,
frequency, voltage, permittivity, and thickness are shown in Figure 2.4 through 2.9, respectively. Figure 2.4 shows that the maximum velocity occurs for an electrode gap of 5 mm. Figure 2.5 shows the induced velocity asymptotically approaches a maximum value as the encapsulated electrode width increases. A similar asymptotic dependence with frequency and voltage is observed. The relationship between velocity and dielectric permittivity, shown in Figure 2.8, was obtained using glass (permittivity of 10) and PMMA (permittivity of 3). At lower voltages, the use of glass resulted in slightly higher velocities; however, for higher voltages, the use of PMMA produces greater velocities. At high voltages there is a region where velocity is constant with respect to voltage. This region occurs first for glass and is the reason why PMMA produced greater velocities at larger voltages. For dielectric thickness, Figure 2.9 shows lower voltages produced greater velocities for thinner dielectric layers; however, they cannot be operated at higher voltages. Therefore, for large voltages, higher velocities are induced using a thicker dielectric barrier.

For multiple SDBD actuators, the presence of an adjacent SDBD actuator places an encapsulated electrode on both sides of the exposed electrode, resulting in breakdown in both directions. This particular configuration is shown in Figure 2.10 and induces a flow in both directions each producing an almost equivalent momentum, resulting in a net gain of zero. This was eliminated by insulating the backside of the exposed electrode, resulting in breakdown on only one side of the exposed electrode for each actuator. The effect of two adjacent actuators on the induced velocity for when breakdown occurs in one and two directions is shown in Figure 2.10. The detrimental effect produced by breakdown in two directions is clearly evident since the induced flow produced by the first actuator is reduced to zero. The induced flow produced by four actuators properly set-up is shown in Figure 2.11. Results show that four actuators are capable of accelerating the flow to a velocity of 7 m/s.
**Figure 2.4:** Wall jet velocity as a function of electrode gap spacing. Taken from Forte et al.⁹⁵

**Figure 2.5:** Wall jet velocity as a function of encapsulated electrode width. Taken from Forte et al.⁹⁵
Figure 2.6: Wall jet velocity as a function of frequency. Taken from Forte et al.\textsuperscript{95}

Figure 2.7: Wall jet velocity as a function of voltage. Taken from Forte et al.\textsuperscript{95}
Figure 2.8: Wall jet velocity as a function of voltage for two different dielectric materials with different permittivity values. Glass has a permittivity of 10 and PMMA has a permittivity of 3. Taken from Forte et al. 

Figure 2.9: Wall jet velocity as a function of voltage for different dielectric layer thicknesses. Taken from Forte et al. 


Figure 2.10: The induced velocity produced by two SDBD actuators. The pink curve is for a single breakdown per actuator whereas the blue curve is for breakdown on both sides of the second actuator. Taken from Forte et al.\textsuperscript{95}

Figure 2.11: Wall jet velocity for four aligned SDBD actuators. Taken from Forte et al.\textsuperscript{95}
From the results discussed so far, it is clear that the SDBD actuator induces a flow in quiescent air. The fact that the mass of the air is accelerated from an initial velocity of zero to an induced velocity of several meters per second, indicates some sort of body force acting on the air molecules. If this does indeed occur from an EHD interaction, then the reactant force produced by the body force is equal in magnitude, opposite in direction, and applied to the SDBD through the electric field. This reactant force has been measured by several researchers using force balances\textsuperscript{96-101}, accelerometers\textsuperscript{101,102}, and by measuring the change in displacement with a laser and photoelectric cell.\textsuperscript{101, 102} The body force has been measured using Pitot probes coupled with the momentum equation.\textsuperscript{101,103,104} These values are time averaged, and from Hoskinson et al.\textsuperscript{118}, velocity profiles obtained using a Pitot probe required one hour for an SDBD operated in quiescent air before reaching quasi-steady state. Typical values of the time-averaged reactant forces, obtained from force balance measurements, ranged from 0.5 mN/m, at 5 kHz and 10.5 kV\textsubscript{pp}, to 5.8 mN/m, at 20 kHz and 15 kV\textsubscript{pp}. The reactant forces were shown to have linear dependence on frequency (up to around 20 kHz) and power dissipated.\textsuperscript{75} The same dependence was verified by Gregory et al.\textsuperscript{100} who extended the range and showed this relationship does not hold for larger dissipated powers. Enloe also showed the power dissipated was proportional to $V^{7/2}$, therefore the reactant force is proportional to $V^{7/2}$.\textsuperscript{75} They noted that this was irrespective of the voltage waveform; however, it should be mentioned that this statement can only be applied to the waveforms studied, which included a square, triangle, and sinusoid wave at 5000 Hz. It is possible that this is true within the range studied, and will be illustrated with an example shortly, but first there is another problem with the reported proportionality of thrust. Specifically, Abe et al.\textsuperscript{119} used the same technique to measure thrust and determined it was proportional to $V^{11/2}$ for similar conditions. At this point it is not clear which set of data is correct. However, Abe also showed that the induced body force varies significantly with pressure and was at a maximum at 0.6 atmospheres. This is important because Bernard et al.\textsuperscript{120} measured the velocities as a function of pressure using PIV and showed they were at a maximum at 0.6 atmospheres, providing some support for the results reported by Abe. The values of the reactant force, obtained using a mass balance, are in excellent agreement with the body force obtained by measuring the velocity profile with a Pitot probe at each face of a control volume and applying the momentum equation.\textsuperscript{101} The displacement of an SDBD mounted onto a pendulum, measured by the
photoelectric cell and laser, is shown in Figure 2.12. The figure shows that starting the SDBD causes ringing, requiring about one minute to damp out. Another interesting characteristic is the slow moving periodic response of the displacement, with a period on the order of 100 seconds. The reason for this slow oscillation was not determined, but could be related to the 1 hour requirement needed to reach a quasi-steady state.\textsuperscript{118}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure2.12.png}
\caption{Temporal response of the displacement of a SDBD. Taken from Porter et al.\textsuperscript{102}}
\end{figure}

At this point I would like to go back and illustrate a counter argument, using an example, to the claim that the proportionality of thrust is independent of the voltage waveform. Other voltage waveforms, such as nanosecond pulsed, have been used to drive SDBD actuators. These types of SDBD actuators have been well documented by Roupassov et al.\textsuperscript{116} As previously mentioned, the nanosecond pulsed SDBD does not induce a velocity via EHD coupling\textsuperscript{116}, as all observed flow field changes are due to thermal deposition. The mechanism responsible for an almost zero net momentum exchange according to Roupassov et al.\textsuperscript{116}, by an EHD interaction to the neutral air molecules, falls out of the dynamics associated with the streamers produced by this type of discharge. Namely, an initial streamer sweeps across the encapsulated electrode imparting momentum to the neutrals and charging the surface. The amount of surface charge is sufficient in reversing the direction of the electric field, resulting in the development of a secondary streamer in the opposite direction of the initial streamer. The secondary streamer imparts essentially the same amount of momentum because the characteristic time for both streamers is on the order of 10 nanoseconds; not long enough for charge leakage or recombination. The net reactant force, acting on a nanosecond pulsed SDBD actuator, has been measured using a mass balance by Opaits et al.\textsuperscript{109} and was found to be proportional to $V^{3/2}$;
significantly different than $V^{7/2}$ or $V^{11/2}$, illustrating the point. The fact that a reactant force is measured was attributed to the development of a shock wave from the large thermal deposit produced within the volume the streamer passed through. The shock wave propagates outward and reflects from the SDBD, thereby imparting a time varying momentum. The thermalization was found to occur very rapidly, on the order of nanoseconds, indicating the released energy is most probably from a rapidly occurring mechanism such as dissociation and ionization of molecules from direct electron impact.

The results presented so far are averaged in time, providing useful insight about some of the properties of the flow fields produced by SDBD actuators; however, this information is insufficient for determining a vital piece of information, when momentum transfer occurs. Many attempts, using a range of diagnostics, have been employed for this purpose, the results of which are now presented. Enloe et al.\textsuperscript{121} achieved temporal resolution of the reactant force acting on the SDBD actuator by mounting it onto a pendulum and measuring the deflection as a function of time using a Michaelson laser interferometer. Results showed that 97\% of the induced momentum occurs during the negative voltage half-cycle (exposed electrode is at a negative polarity). This result was further verified using an SDBD mounted onto a torsional pendulum\textsuperscript{122} and measuring the angular displacement as a function of time with a laser interferometer. The angular velocity, shown in Figure 2.13, is obtained by taking the time derivative.

Results show that the SDBD accelerates and decelerates twice each cycle, resulting in a larger net change in angular velocity during the negative voltage half-cycle, designated as $\Delta \omega_f$, than during the positive voltage cycle, designated as $\Delta \omega_b$. The ratio of $\Delta \omega_f/\Delta \omega_b$ is around 94\%, verifying the previous results. Interestingly enough, both voltage half-cycles seem equally capable of accelerating the SDBD; however, most of the generated momentum, during each half-cycle, is loss. The mechanism behind this lost has yet to be identified.
Figure 2.13: Phase correlated voltage with angular velocity of the SDBD actuator. Taken from Enloe et al.\textsuperscript{122}

The above results indicate in a convincing manner the importance of the negative voltage half-cycle; however, they are not the only results to do so. Another example comes from the work of Abe et al.\textsuperscript{115} who attempted to correlate measured acoustic noise emitted from an SDBD actuator with the applied voltage. As Figure 2.14a shows, triggering the discharge and microphone simultaneously results in a delay of the measured acoustic signal. This delay could be caused by many factors such as the finite speed of the signal (travels at the local speed of sound), and the delay in momentum transfer taking place between the discharge and surrounding gas. In this work, Abe assumed that the delay was produced entirely from the finite speed of the signal, which is approximately 343 m/s for the present thermodynamic state. The measured delay was then subtracted from the measured acoustic signal, achieving phase correlation with the driving voltage, as shown in Figure 2.14b. One way to check the validity of these results is to compute the speed of the signal from the measured time delay, and the distance between the signal source and microphone. These quantities were reported as $2083.3 \times 10^{-6}$ seconds and 0.3 meters, respectively, resulting in a velocity of 144 m/s. This
simple calculation does not bode well for the reported values, which attempted to indicate the production of momentum occurred during the negative voltage half-cycle.

Figure 2.14: (a) Plot that shows the delay between the applied voltage and measured acoustic wave. (b) Phase correlated voltage and acoustic wave obtained by shifting the wave forms. Taken from Abe et al.\textsuperscript{115}

Other time resolved results have been obtained utilizing LDV, which has a bandwidth of around 10,000 Hz. These results are now presented, and as mentioned previously, must be interpreted with caution due to the use of seeded particles. Forte et al.\textsuperscript{93,94} determined that the induced flow field pulsed in phase with the applied voltage. These results are shown in Figure 2.15 for a driving frequency of 700 Hz. It is interesting to note that the period of the voltage waveform is 1.5 ms, which is around ten times smaller than
the 10 to 20 millisecond response time they reported. Also, the signal of the flow, with the voltage waveform, is characterized by a clean signal and does not show any sign of the inertial damping effects one might expect the neutrals to experience during the momentum transfer process. This, along with the potentially detrimental effect of charged seeded particles, sheds doubt on the results. However, these results have been shown to be reproducible by Boucinha et al.\textsuperscript{117}, using the same diagnostic. In addition to the previous results, Boucinha et al.\textsuperscript{117} showed that the induced flow only followed the frequency of the voltage waveform for the region right above the discharge. As the induced flow propagated downstream, the frequency bandwidth of the fluctuating velocities was reduced and centered on lower frequencies. The magnitude of the velocity with respect to phase of the driving sinusoidal voltage is shown in Figure 2.16a. The corresponding direction of the velocity is given in Figure 2.16b. Note that the results are reported in polar coordinates where the angle is measured from the dielectric surface. The results show that the induced flow is obtained from a small push during the positive voltage half-cycle, followed with a large push during the negative voltage half-cycle. The magnitude within the inner-electrode gap is around 1 m/s during the positive voltage half-cycle, increasing to almost 2 m/s during the negative voltage half-cycle. Even though the positive voltage half-cycle does not alter the magnitude of the velocity, it is shown to change the direction from 60 degrees to -5 degrees; contributing a tangential component to the total acceleration. During the negative voltage half-cycle, the direction of the velocity is changed gradually from -5 degrees to 3 degrees. In this case the total acceleration is almost entirely translational. As you go downstream from the inner-electrode gap, the change in direction is complete and the velocity is pointed entirely downstream. This corresponds to the formation of a wall jet along with an increase in magnitude from 2 to 2.6 m/s, consistent with the structure of the flow field discussed earlier.
Figure 2.15: Response of the induced flow to the voltage waveform. Taken from Forte et al.93

Figure 2.16: (a) Shows the velocity magnitude at various locations downstream from the SDBD in polar coordinates and (b) the corresponding direction of the velocity. Taken from Boucinha et al.117

Other attempts at determining information associated with momentum transfer within the SDBD actuator have been made by using phase locked PIV.83,123,124 Results presented by Kim et al.123 are for an SDBD actuator mounted onto a sphere placed within a low speed wind tunnel, as shown in Figure 2.17. The corresponding voltage and current profiles are given in Figure 2.18. Different regions, labeled as (a), (b), and (c), are indicated in the figure. The corresponding flow fields for these regions are given in Figure 2.17a, 2.17b and Figure 2.17c, respectively. Results show that when the exposed electrode is negatively
biased, there is a significant suction flow into the encapsulated electrode. According to Kim et al., this provides compelling evidence that negatively charged ions are created during this phase of the discharge, moving towards the dielectric surface, producing the observed flow. It should be pointed out that they claim the detrimental effect, produced by charged seed particles, is negligible by comparing the density distribution of the seed particles with and without the presence of the discharge.
Figure 2.17: PIV measured flow fields for an SDBD actuator operating on a sphere in a low speed wind tunnel for (a) the negative voltage half-cycle, (b) the positive voltage half-cycle and (c) the negative voltage half-cycle at lower applied voltage. Taken from Kim et al.\textsuperscript{123}
In a similar study, designed to build from the previous results, two SDBD actuators are applied to the same configuration as shown in Figure 2.19. The flow fields are again obtained using phase locked PIV. The corresponding voltage and current profiles are shown in Figure 2.20. Results show that during the negative voltage half-cycle, the flow field lines originating from the first actuator bend around the second actuator; however, during the positive voltage half-cycle, the flow field lines originating from the first actuator are observed to go into the exposed electrode of the second actuator. Based on this, a similar claim is made; namely, the observed flow field is produced by the drift of negative ions. It is further claimed that this can be seen by comparing the difference between the current-voltage profiles in Figure 2.18 with those given in Figure 2.19.
Figure 2.19: PIV measured flow fields for (a) no discharge, (b) phase locked with the discharge for 50-170 microseconds and (c) phase locked with the discharge for 450-570 microseconds. Taken from Do et al.\textsuperscript{124}
Figure 2.20: Voltage and current profiles for the SDBD actuator. Taken from Do et al.¹²⁴
2.1.2 Electrical and Optical Properties

A description of the detailed structure of an SDBD actuator can be partially obtained from current, voltage, photomultiplier tube, and high-speed camera measurements. Typical measurements of the discharge current and voltage are shown in Figure 2.21, and are observed to contain a high-degree of temporal structure. The asymmetric arrangement of the electrodes, shown in Figure 1.1 a-c, has an apparent affect on the structure of the current profile. Namely, when the polarity of the driving voltage is negative (negative voltage half-cycle), many small amplitude current spikes, at a high repetitive frequency, are observed, whereas when the polarity of the driving voltage is positive (positive voltage half-cycle), a slower repetition frequency of larger magnitude current spikes, occurs. These current spikes, which are superimposed on top of the displacement current (given as the smooth sinusoid portion of the profile), are clearly on the nanosecond time scale and give some indication to the type of breakdown occurring; namely electron avalanches. The name microdischarge has been given to these current avalanches and, as will be shown, they have a particular spatial structure dependent on the voltage half-cycle.
Figure 2.21: Current and voltage traces for a SDBD.

Figure 2.22 shows photomultiplier tube measurements of the emitted radiation with the corresponding voltage waveform obtained by Enloe et al.\textsuperscript{74}. As is shown, during the negative voltage half-cycle, the emitted radiation is less intense and more frequent than during the positive voltage half-cycle, which is identical to the pattern displayed by the measured current. A comparison done by Enloe et al.\textsuperscript{75}, between the photomultiplier tube measurements and discharge current, showed that radiation is emitted only during the microdischarge, giving some indication of the time scale associated with quenching of the discharge. This characteristic time is very fast, on the order of $10^{-8}$ seconds. Also, since the intensity of the light emissions follows the current, it is a direct indication of the plasma density. From the asymmetric currents and emission, it is evident that the discharge might be classified in two different regimes depending on the voltage half-cycle. This is further confirmed from Figure 2.23, which shows high-speed camera images of both voltage half-cycles taken by Enloe et al.\textsuperscript{77} These results have been shown to be reproducible by Bityurin\textsuperscript{92}. The images show that the spatial structures associated with the negative voltage half-cycle are diffuse, whereas the positive voltage half-cycle appears to be more of a streamer. These diffuse structures, along with small currents, indicate that the discharge during the negative voltage half-
cycle might best be approximated as operating in the glow regime; and in a similar manner, the appearance of streamers, along with larger currents, indicate that the discharge during the positive voltage half-cycle might best be approximated as cathode-directed streamers. Photomultiplier tube measurements have also shown that discharge ignition starts within the gap of the electrodes, at $y = 0$ in Figure 1.1a, and propagates across the dielectric surface.\textsuperscript{74,76} The plasma sweep velocity, which corresponds to the speed the plasma expands across the dielectric surface, was determined, for constant frequency, to be linearly proportional to the voltage amplitude, ranging from 50 to 100 m/s for 5,000 to 9,000 volts, respectively.\textsuperscript{74,76} At a constant voltage, it was found to be linearly proportional to frequency and ranged from 60 to 180 m/s for 5 to 11 kHz.\textsuperscript{74,76} Results showed that this quantity was nearly independent of voltage half-cycle, which is interesting since the propagating velocity of a streamer is characterized as being significantly faster than other types of plasma discharges. For example, Roupassov et al.\textsuperscript{116} measured the velocity of a cathode-directed streamer, produced by a nanosecond pulsed SDBD actuator, to be around $10^6$ m/s.

![Figure 2.22: Photomultiplier tube measurements along with the voltage waveform. Taken from the results of Enloe et al.\textsuperscript{74}](image-url)
In order to understand what this truly means in terms of the two different discharges (sinusoidally driven versus nanosecond pulsed), the discussion will now shift to the mechanisms governing the propagation of a streamer. The discussion that follows, along with more detail, can be found in the work by Pancheshni et al.\textsuperscript{262-267} The breakdown and propagation of an electrical discharge can typically be described using the Townsend theory; however, it was observed that for large $dV/dt$ the propagation of the discharge was much faster than Townsend’s theory predicts. The ensuing theory proposed photoionization as a possible mechanism for propagation, and the discharge regime was named streamer discharge. In the particular case presented, the type of streamer is called a cathode-directed streamer, which means that it propagates from the anode towards the cathode, as opposed to an anode-directed streamer which propagates from the cathode to the anode. The propagation of the discharge under photoionization occurs in the form of an ionization wave, whereas drift is the main mechanism in a Townsend discharge. In the latter theory, the particle has to physically move, thereby producing a slower propagating discharge. The specific details associated with propagation by photoionization in air, are as follows. The initial breakdown process starts in the form of an electron avalanche, and if the number of electrons within the avalanche is greater than some critical value, the breakdown process develops into a streamer. In the case of a cathode-directed streamer, the front of the streamer is called the streamer head and is characterized as having a large net positive charge. This large positive space charge results in the formation of a strong electric field, capable of accelerating electrons to energies sufficient for the production of $N_2(b^1\Pi_u, b^3\Sigma^+_u, c^1\Sigma^+_u)$ states. The energy associated with spontaneous radiation from these states to the ground state is sufficient to ionize
oxygen, resulting in the production of electrons immediately in front of the streamer head. These electrons are then accelerated towards the streamer head, restarting the process. Notice that the positive ions within the streamer head need not physically move since they are produced in front of the streamer head, and since the propagating velocity produced by photoionization is much faster than by drift, the streamer head propagates as a wave. Also, it follows that the propagating velocity is only dependent on the number of seed electrons in front of the head. Therefore, a meaningful lower bound can be established by considering streamer propagation across an air gap. The propagating velocity for this case should be lower than along the surface of a SDBD because the SDBD has an extra source of seed electrons stored on the dielectric surface. The propagating velocity, for this case, has a typical reported value of $10^5$ m/s, which is significantly greater than the measured propagating velocities of the negative side of a sinusoidally driven SDBD. Based on this information, either the measured propagating velocities of 60 to 180 m/s are incorrect, or the microdischarges during the positive voltage half-cycle are not cathode-directed streamers. It is felt that the microdischarges during the positive voltage half-cycle do not necessarily have to be cathode-directed streamers but that the measured propagating velocities are incorrect.

Propagation of the discharge, during the negative voltage half-cycle, starts with breakdown occurring in the gap between the electrodes where the electric field is greatest. When charge is deposited onto the dielectric surface, the electric field is locally weakened and the plasma moves to a location where the local electric field is stronger, or if the electric field strength is insufficient elsewhere, the discharge quenches. The plasma extent, defined as the distance the plasma travels across the dielectric surface, was reported to be the same for both half cycles; independent of frequency and linearly dependent on voltage, ranging from 4 to 9 mm for 5,000 to 9,000 volts, respectively. From these results it is clear that the accumulated surface charge is important to the functionality of the SDBD and that charge deposited onto the dielectric surface does not significantly move around on the surface. These important contributions to the operation of the SDBD have led to the quantification of the spatial charge distribution using an electrostatic voltmeter probe, and the spatial, temporal charge distribution using a V-dot probe. Figure 2.24, taken from reference 108, shows the surface potential distribution over the dielectric barrier obtained after running the SDBD for 15 minutes. Results show that a positive voltage is obtained on the dielectric surface, even beyond the encapsulated electrode, for both positive and negative voltage half-
cycles. Similar results, shown in Figure 2.25, were obtained by Enloe et al.\textsuperscript{77,125} using V-dot probes. It was observed that the charge distribution reached an equilibrium state after only a couple AC cycles and, as mentioned, was positively charged for both half-cycles. The charge distribution was also found to be independent of the surface properties for both half-cycles. This goes against intuition since during the positive voltage half-cycle, the discharge appears to be composed of cathode-directed streamers, which have properties that are dependent on secondary electron emission from the surface. It was also found that lowering the dielectric constant increases the plasma extent. This is to be expected since lowering the dielectric constant lowers the specific capacitance of the actuator, which has the effect of lowering the amount of charge required to raise the potential in order to locally weaken the electric field. This causes the energy per distance required for the plasma to expand across the dielectric surface to decrease.

![Figure 2.24: Surface potential distribution for a 10 kV\textsubscript{pp}, 3 kHz sinusoid. Taken from Opaits et al.\textsuperscript{108}](image-url)
Several researchers have tried to describe the SDBD actuator using circuit elements. The particular circuit representation given depends on if the grounded electrode is completely encapsulated within a dielectric material or air. The reason being, breakdown occurs on both sides of the SDBD actuator when the grounded electrode is not encapsulated within a dielectric. Compelling evidence for this phenomenon can be found from velocity profiles measured with a Pitot tube, shown in Figure 2.26\textsuperscript{126}. The figure shows induced velocities generated by the exposed and encapsulated electrode of the SDBD actuator.

**Figure 2.25**: Surface potential versus streamwise distance and time. Taken from Enloe et al.\textsuperscript{77,125}
Figure 2.26: Velocity profiles measured on the high voltage electrode and grounded electrode sides of an SDBD actuator. Taken from Dong et al.\textsuperscript{126}

The circuit model for breakdown, for just the exposed electrode side, has been given by Enloe et al.\textsuperscript{97} and is shown below in Figure 2.27. The model was developed by first recognizing that the surface charge acts as a virtual electrode, resulting in three different capacitances between each electrode. The capacitor $C_1$ is included to account for the fact that some of the field lines connect the two physical electrodes directly. The capacitor $C_2$ represents the capacitance between the virtual electrode of the charged surface and the encapsulated electrode. The capacitor $C_3$ represents the capacitance between the exposed electrode and the virtual electrode. Energy dissipation in the plasma is represented by the resistor $R$. The capacitance $C_2$ and $C_3$, along with the resistance $R$, vary in time because the plasma sweeps over the dielectric surface, changing the geometry of the virtual electrode. The electric circuit given for breakdown on both sides of an SDBD actuator was given by Pons et al.\textsuperscript{127} and is very similar to the circuit given in Figure 2.27. The only differences are the inclusion of a second set of $R$-$C$ elements, identical to the first for breakdown and in parallel, along with the single capacitor attached to the high voltage side, and the resistor-capacitor element attached to ground. Pons
also uses Lissajous charts to measure the dissipated power and to show that the voltage drop across the discharge is constant. Results show that power is directly proportional with frequency indicating that the energy per cycle is constant. The use of Lissajous charts will come up again later in Chapter 4, which is dedicated to presenting and discussing results obtained by the author; justifying the need to develop the theory behind Lissajous charts, given in detail in Appendix B.

Figure 2.27: Circuit model of an SDBD actuator with breakdown on only the exposed electrode side.
2.1.3 Spectroscopic Investigations

The chemically active environment produced by DBD’s, operating in oxygen and nitrogen at a pressure of 1 atm, is composed of many different species such as e, N, N₂, N₃, N₄, O, O₂, O₃, N⁺, N₂⁺, N₃⁺, N₄⁺, O⁺, O₂⁺, O₃⁺, O₄⁺, O₅⁺, O₆⁺, O₇⁺, O₈⁺, N₂O, N₂O⁺, N₂O₂, N₂O₃, NO, NO⁺, NO₂, NO₂⁺, NO₃, NO₄, NO₅, and NO₆.¹²⁸ The production and quenching of these species, if water vapor is considered, is described with over 500 chemical rate equations.¹²⁸ Many of these species can be eliminated, but the list of necessary species is still large. Information on the spatial and temporal concentration distribution within the discharge, population distribution of excited states, production and quenching kinetics, and lifetimes can be obtained for some of these species using spectroscopic techniques. There are numerous types of spectroscopic techniques; however, they are all similar in the sense that each one produces spectra by dispersing electromagnetic radiation in terms of energy. At the present time, not many spectroscopic investigations have been applied to SDBD actuators; however, a large amount of spectroscopic studies have been conducted for PDBD’s. The only spectroscopic technique employed for SDBD actuators is optical emission spectroscopy,¹⁰⁵,¹⁰⁶,¹¹⁰,¹¹¹ whereas for PDBD’s optical emission spectroscopy (OES),¹²⁹-¹⁴⁷ absorption spectroscopy,¹⁴⁴-¹⁴⁸ cross-correlation spectroscopy (CCS),¹⁴⁹-¹⁵¹ two-photon absorption laser-induced fluorescence (TALIF),¹⁵²,¹⁵³ laser-induced fluorescence (LIF),¹⁵⁴ laser absorption,¹⁵⁵ Fourier transform infrared spectroscopy (FTIR)¹⁵⁵-¹⁶¹, and molecular beam mass spectroscopy (MBMS)¹⁶²,¹⁶³ have been used. In this section, the results from the various spectroscopic methods are reviewed.

Rotational and vibrational temperatures have been obtained by applying either the Boltzmann plot method¹³⁵,¹⁴¹-¹⁴³ or numerically fitting the measured spectra with a calculated one.¹³³,¹³⁴,¹³⁶-¹⁴⁰,¹⁴⁵,¹⁴⁷ The details of these two methods are used in the results of this work, presented in Chapter 4, and are included within Appendix C and D. The rotational and vibrational temperatures provide a wealth of information about the spatial and temporal characteristics of the discharge. For example, details about energy transfer from chemical reactions, location of excitation, type(s) of discharge regime(s), temporal development of the discharge, and influence of metastables can be obtained. Particular cases, which give examples of how this kind of information can be obtained, are reviewed.
Luque et al.\textsuperscript{141} investigated PDBD’s operated in CH\textsubscript{4} and CH\textsubscript{4}/CO\textsubscript{2} gas mixtures using OES and determined the rotational temperature at a single location within the discharge. The rotational temperature was determined from a Boltzmann plot of the $A^2\Delta \rightarrow X^2\Pi$ electronic band system of CH. It was found that a bimodal rotational population distribution, shown in Figure 2.28, best represented the rotational distribution. Results show that the lower rotational levels give the gas temperature, which ranged from 300 to 600 K, whereas the upper rotational levels for CH\textsubscript{4} and CH\textsubscript{4}/CO\textsubscript{2} were best approximated with rotational temperatures 3450 and 4050, respectively. It was concluded that the upper rotational levels reflect the excess energy during the formation process of CH\textsubscript{2}; that is the rotational levels most affected from the vibrational energy associated with bonding.

Figure 2.28: Rotational energy distribution of CH\textsubscript{4}/CO\textsubscript{2} and CH\textsubscript{4} along with a best-fit biexponential function. Taken from Luque et al.\textsuperscript{141}
Motret et al.\textsuperscript{140} used OES to determine the rotational temperature within a PDBD operating in an environment composed of argon and water vapor. The rotational temperature was obtained from the $OH(A^2Σ^+ \rightarrow X^2Π)$ transition by using the Boltzmann plot method and was found to be 450 ± 10 K. The rotational temperature was shown to increase rapidly as the water vapor concentration increased and corresponded with a decreasing emission intensity of OH. This was attributed to an increase in the collisional relaxation compared to the radiative lifetime, and led to an increase in global heating of the heavy species within the hot filaments via low-energy collision transfer. This collisional interaction increased the energy of the OH molecules, resulting in a larger temperature, which was more representative of the temperature within the streamer than the overall gas temperature. They concluded that the gas temperature can be inferred from the rotational temperature of $OH(A^2Σ^+)$ so long as the mixture is mainly composed of atomic species.

Pellerin et al.\textsuperscript{139} used OES to determined the rotational temperature in a DBD operating in an environment composed of argon and 50% CF$_4$ and 50% Ar. They determined a rotational temperature of 2970 K from the $A^3Π_g \rightarrow X^3Π_u$ electronic band system of C$_2$ by first obtaining the rotational temperature with a Boltzmann plot and then using this value as an initial guess for a numerical fit of the spectra. This value is much larger than 400 K, which was found using traces of $OH(A^2Σ^+, ν′ = 0 → X^2Π, ν'' = 0)$. They explain the discrepancy in temperature in terms of an ‘excitation’ effect. The emission of C$_2$ and OH occurs within different spatial zones of the plasma. The OH emission bands are excited with a much lower temperature than those of C$_2$ resulting in emission from these two species occurring from different regions of the discharge. It is concluded that the rotational temperature obtained from OH best represents the wall temperature, and the rotational temperature obtained from C$_2$ gives the temperature of the gas streamer.

Tomai et al.\textsuperscript{138} used the same electronic band system as Pellerin et al.\textsuperscript{139} for a PDBD operating in an environment of CO$_2$ and obtained a rotational temperature of 2500 K using the Boltzmann plot method.

Nersisyan and Graham\textsuperscript{137} measured the rotational and vibrational temperature from the $B^2Σ_u^+ \rightarrow X^2Σ^+_g^+$ and $C^3Π_u \rightarrow B^3Π_g$ electronic band systems of N$_2^+$ and N$_2$, respectively, within a PDBD operating in air with helium flowing through the inner-electrode gap. The rotational and vibrational temperatures were found to be 360 ± 20 K and 2700 ± 900 K, respectively, by comparing the measured spectra with a numerically calculated one.
Zhang et al.\textsuperscript{135} used OES to determine the gas temperature of a PDBD operating in an argon atmosphere by applying Fermi-Dirac statistics to Ar(ii). They show that when using inert gases such as argon and helium, Fermi-Dirac statistics have to be applied.

Nozaki et al.\textsuperscript{136} measured the rotational temperature from $CH(A^2 \Delta, v' = 0 \rightarrow X^2 \Pi, v'' = 0)$ for a PDBD and compared it with the gas temperature obtained via an energy balance of the discharge. This was done for three different discharges: pure methane, 50% methane and 50% helium, and 2% methane in helium. The pure methane case corresponded to a discharge regime characterized with filamentary microdischarges, whereas the 2% methane in helium case corresponded to a glow discharge. For the filamentary discharge, the energy balance showed that 60\% of the dissipated energy was transferred to the dielectric surface above the encapsulated electrode and 20\% went into the exposed electrode. Consequently the feed gas temperature increased by 20-40 K; however, the corresponding rotational temperature exceeded the average gas temperature by 100 K. In the case of the glow discharge, the feed gas temperature increased by 20-40 K and agreed with the rotational temperature. The difference was attributed to the discharge regime, namely, the dissipated energy was concentrated within the narrow filamentary region for the filamentary discharge, whereas the glow discharge was dispersed over a larger volume.

Bibinov et al.\textsuperscript{134}, determined the rotational temperature for a PDBD operating in a He/N\textsubscript{2} environment using OES by numerically comparing the measured spectra with a calculated one. They found a rotational temperature for $N_2(C^3 \Pi_u \rightarrow B^3 \Pi_g)$, $NO(A^2 \Sigma^+ \rightarrow X^2 \Pi)$, $OH(A^2 \Sigma^+ \rightarrow X^2 \Pi)$ and $N_2^+(B^2 \Sigma_u^+ \rightarrow X^2 \Pi)$ to be 310 K, 310 K, 310 K and 600 K respectively. The discrepancy between the rotational temperature of the neutral species and $N_2^+$ was attributed to the long lived metastable species $N_2(A^3 \Sigma_u^+)$, which in a mixture of N\textsubscript{2}/He is not easily quenched. Essentially the production mechanisms of the excited neutrals are dominated by $N_2(A^3 \Sigma_u^+)$ and can be excited outside of the active time of the microdischarge, whereas $N_2^+$ is produced within the active time of the microdischarge. The Navier-Stokes equations were solved to see how the temperature changed during and after the active time of the microdischarge. Results from the Navier-Stokes equations, shown in Figure 2.29, show the active time of a microdischarge and the spatial dependence of temperature correspond well with the measured temperatures.
They conclude that $N_2^+$ emission occurs during the active time of the microdischarge when the temperature is high, whereas the neutrals emit after the microdischarge, when the temperature is lower.

Stefanovic et al.\textsuperscript{147} found the same deviation in rotational temperature between $N_2(C^3\Pi_u \rightarrow B^3\Pi_g)$ and $N_2^+(B^2\Sigma_u^+ \rightarrow X^2\Sigma_g^+)$ for a PDBD operating in dry air. The explanation given is very similar to that of Bibinov et al.\textsuperscript{134} and only differs by the reactions associated with the production of the excited states. According to Stefanovic et al., since the lifetime of $N_2^+(B^2\Sigma_u^+)$ is around 0.1 ns and since the main production mechanism is

$$N_2(X^1\Sigma_g^+) + e \rightarrow N_2^+(B^2\Sigma_u^+) + 2e,$$  \hspace{1cm} (2.1.3.1)

the spontaneous emission of $N_2^+(B^2\Sigma_u^+ \rightarrow X^2\Sigma_g^+)$ occurs on a similar time scale as the lifetime, therefore only occurring during the active time of the microdischarge. The main production mechanism of $N_2(C^3\Pi_u)$, indicated by Stefanovic, occurs from

$$N_2(A^3\Sigma_u^+) + N_2(A^3\Sigma_u^+) \rightarrow N_2(C^3\Pi_u) + N_2(X^1\Sigma_g^+),$$  \hspace{1cm} (2.1.3.2)

as well as within the microdischarge. The production of the metastable species $N_2(A^3\Sigma_u^+)$ is predominantly produced by recombination reactions effectively delaying the emission of the $C^3\Pi_u \rightarrow B^3\Pi_g$ transition of $N_2$. This means that the emissions of these two band systems occur at different times within the discharge.

They performed a computational study to see if the gas temperature could change during this time and

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure29.png}
\caption{Temperature versus time within a microdischarge and b) temperature versus radial coordinate of a microdischarge at a time of 400 ns. Taken from Bibinov et al.\textsuperscript{134}}
\end{figure}
found that, after the current pulse, a rapid jump in temperature and pressure occurred. They show that the temperature change causes the gas to expand radially outward from the microdischarge on a time scale of 0.1-1 μs. This expansion process causes the gas temperature to drop. Spontaneous emission from the $N_2^+(B^2Σ_u^+ → X^2Σ_g^+)$ band system occurs predominantly before this expansion process when the gas temperature is hot; whereas, the $N_2^+(C^3Π_u → B^3Π_g)$ band system lags behind and emits after the expansion when the gas temperature is cooler. One problem with this explanation comes from Kozlov et al.\textsuperscript{149} who shows that the spontaneous emission from $N_2^+(B^2Σ_u^+ → X^2Σ_g^+)$ only lags the emission from $N_2^+(C^3Π_u → B^3Π_g)$ by several nanoseconds. An identical result was reported by Shcherbakov and Sigmond.\textsuperscript{270} This does not appear to be enough time for the microdischarge region to cool noticeably. Also the emission of both transitions occurs at the same time current is flowing through the microdischarge. This would indicate that the microdischarge region is still heating when emission from $N_2^+(C^3Π_u → B^3Π_g)$ is occurring.

An interesting observation concerning Kozlov’s results, shown in Figure 2.30, is that the radiative process stops before the current does which is peculiar since the production of the upper states for these emission bands is dominated by electron collisions. This could indicate several things including incorrect results, but most likely, it corresponds to measuring only a portion of the emission process from the microdischarge as it moves past the measurement area.

In determining concentrations of species, OES typically cannot be used unless the excited states are exclusively excited by electrons and quenching is not important or its rate is known.\textsuperscript{146} Typically this type of quantitative information is obtained using LIF, TALIF, laser absorption and absorption spectroscopy. The results from these types of studies are now presented.
Lukas et al.\textsuperscript{152} performed TALIF measurements to determine the spatio-temporal distribution of atomic nitrogen within a single microdischarge. The PDBD was operated in pure N\textsubscript{2} and 90\% N\textsubscript{2} - 10\% O\textsubscript{2} environments and was constructed with small pins so that the microdischarge would occur at known locations. In the pure nitrogen case, atomic nitrogen was contained within a channel between the electrodes with a diameter of 200 micrometers. A steep increase in concentration was observed close to the dielectric surface. Temporal measurements show that the rate of decay of atomic nitrogen is dependent on location within the microdischarge and is smallest at the dielectric surface, increasing as the distance from the dielectric surface increases. This indicates that the dielectric surface acts as a storage bin of atomic nitrogen. Measurements show that it took milliseconds to quench atomic nitrogen and, during this time, the species did not diffuse outward. Drastic changes of these results are obtained by adding just 5\% oxygen
which effectively decreases the lifetime of atomic nitrogen by one order of magnitude to ~ 20 microseconds. Increasing the oxygen concentration further did not have a significant effect on the lifetime.

Ono et al.\textsuperscript{153} applied TALIF to a PDBD with a similar configuration as Lukas et al.\textsuperscript{152} in order to track atomic oxygen. Results show that the concentration of oxygen just after the discharge is turned off is proportional to the discharge energy per pulse and remains constant for about 10 microseconds. The decay rate increases with increasing oxygen concentration and is shown to be dominated by the three-body reaction

\[ O + O_2 + M \rightarrow O_3 + M. \] (2.1.3.3)

Results show that the atomic oxygen density, just after the discharge, is almost independent of humidity; however, the decay rate is significantly higher, indicating H\textsubscript{2}O is an effective quencher of atomic oxygen. Interaction of H\textsubscript{2}O in the discharge results in a decrease in production of O\textsubscript{3}. Similar measurements were also conducted by Dilecce et al.\textsuperscript{154} to measure the concentration of N\textsubscript{2}(A\textsuperscript{3}Σ\textsuperscript{+}) within a PDBD operating in N\textsubscript{2}, with small admixtures of O\textsubscript{2}. Measurements show an average number density over the whole gap on the order of 10\textsuperscript{13} cm\textsuperscript{-3}. This value was shown to remain constant with the addition of O\textsubscript{2}, even though the quenching rate for the metastable species increased. It was believed that the production of the metastable N\textsubscript{2}(A\textsuperscript{3}Σ\textsuperscript{+}) increased with the addition of O\textsubscript{2} because the discharge regime changed from a glow to filaments.

Bletzinger et al.\textsuperscript{145} used absorption spectroscopy to measure concentrations of O and O\textsubscript{3} within a PDBD operating in O\textsubscript{2}/Ar. Similar measurements were made to determine concentrations of NO, NO\textsubscript{2}, NO\textsubscript{3}, N\textsubscript{2}O\textsubscript{3} and O\textsubscript{3} by Vinogradov et al.\textsuperscript{146} for a PDBD operating in dry air. They show that the presence of O\textsubscript{3} oxidized NO preferentially to the highest oxidation level of N\textsubscript{2}O\textsubscript{5} and that when O\textsubscript{3} was not present N\textsubscript{2}O\textsubscript{5} was not formed. This is a direct indication of the formation process of N\textsubscript{2}O\textsubscript{5}. Vinogradov et al.\textsuperscript{146} also show that the population of O\textsubscript{3} decreases with increasing gas temperature and that a steady state concentration is reached after about 20 minutes of operation.

Studies of a single microdischarge have been done using CCS by Kozlov et al.\textsuperscript{149} with a modified PDBD, shown in Figure 2.31, capable of producing a single microdischarge. They present results of the spatio-temporal emission distribution of the 0-0 and 3-3 bands of N\textsubscript{2}(C\textsuperscript{2}Π\textsubscript{u} \rightarrow B\textsuperscript{3}Π\textsubscript{g}) and the 0-0 band of N\textsubscript{2}(B\textsuperscript{2}Σ\textsubscript{u}\textsuperscript{+} \rightarrow X\textsuperscript{2}Σ\textsubscript{g}\textsuperscript{+}) within a single microdischarge. Results show that the development of the
microdischarge has three distinct phases: pre-breakdown, breakdown and decay. The pre-breakdown phase lasts for more than 500 nanoseconds and is characterized by a continuous glow on the dielectric surfaces of both electrodes. The maximum light intensity is observed during the last 100 nanoseconds of this phase and decreases with the onset of breakdown. During breakdown, the streamer starts from the anode and propagates across the gap to the cathode with an increasing velocity and maximum magnitude of $10^6$ m/s. When the streamer propagates (breakdown phase) the electric field strength grows from 120 Td (1 Td = $10^{-17}$ Vcm$^2$) at the anode to 240 Td at the cathode. During the decay phase of the microdischarge, both the emitted light and current pulses diminish.

![Figure 2.31: Modified PDBD used by Kozlov to study a single microdischarge.](image)

Kozlov et al.\textsuperscript{149} also determined the relative strength of the electric field and the relative electron number density from the emission traces. These were obtained from the kinetics based on the following argument. In air, at atmospheric pressure, a stepwise excitation of molecular and ionized nitrogen is hardly
possible because of the very effective collisional quenching of excited states by molecular oxygen. Therefore, from this approximation, the set of excitation and spontaneous emission reactions for the three transitions monitored by Kozlov are

\[
e + N_2(X^1\Sigma_g^+)_{\nu' = 0} \rightarrow N_2(C^3\Pi_g)_{\nu' = 0} \quad \Delta E = 11.0 \text{ eV} \quad (2.1.3.4)
\]

\[
N_2(C^3\Pi_u)_{\nu' = 0} + M \rightarrow N_2(B^3\Pi_g)_{\nu' = 0} + M + h\nu \quad \lambda = 337.1 \text{ nm} \quad \tau_5^0 = 40 \text{ ns} \quad (2.1.3.5)
\]

\[
e + N_2(X^1\Sigma_g^+)_{\nu' = 0} \rightarrow N_2(C^3\Pi_g)_{\nu' = 3} \quad \Delta E = 11.8 \text{ eV} \quad (2.1.3.6)
\]

\[
N_2(C^3\Pi_u)_{\nu' = 3} + M \rightarrow N_2(B^3\Pi_g)_{\nu' = 3} + M + h\nu \quad \lambda = 328.5 \text{ nm} \quad (2.1.3.7)
\]

\[
e + N_2(X^1\Sigma_g^+)_{\nu' = 0} \rightarrow N_2^4(B^2\Sigma_u^+)_{\nu' = 0} + 2e \quad \Delta E = 18.7 \text{ eV} \quad (2.1.3.8)
\]

\[
N_2^4(B^2\Sigma_u^+)_{\nu' = 0} + M \rightarrow N_2^2(X^2\Sigma_u^+)_{\nu' = 0} + M + h\nu \quad \lambda = 391.5 \text{ nm} \quad \tau_5^0 = 60 \text{ ns} \quad (2.1.3.9)
\]

The radiative lifetimes of Equations (2.1.3.5) and (2.1.3.9) are 40 and 60 nanoseconds, respectively, whereas the excited state lifetime in air for these species is around 1 nanosecond. Therefore light emission will occur for only 1 nanosecond longer than the populating kinetics. From the above kinetics, the reaction rates are seen to be directly proportional to the electron number density and the rate constants are strongly dependent on the electric field. From this it was shown for a single microdischarge that the electric field was stronger at the cathode than at the anode, whereas the electron number density was larger at the anode than the cathode. A direct attempt to measure the electric field in a PDBD, operating in pure hydrogen at 2-4 kPa, by OES was done by Wujec et al.\textsuperscript{129} from Stark splitting of the \textit{H}_\alpha Balmer line. Unfortunately the results obtained in this work cannot be compared with those from Kozlov because the discharge is operated in two completely different environments.

As shown above, plenty of work on PDBD’s has been done. The following is a quick review of the spectroscopic studies performed on SDBD actuators. Cristofolini et al.\textsuperscript{106} used OES to determine the rotational and vibrational temperature for an SDBD, operating in an air wind tunnel, at a single location within the discharge. They used an empirically obtained, approximate method to evaluate the rotational temperature and used the Boltzmann plot method to determine the vibrational temperature. Their results show that the rotational temperature increased with increasing frequency and flow speed, ranging from 290-440 K. The vibrational temperature ranged from 2700-3800 K and decreased with increasing frequency remaining constant with flow speed. Similar results were obtained by Borghi et al.\textsuperscript{107}. The rotational temperature of an SDBD actuator, operating in quiescent air, was also obtained by Wu et al.\textsuperscript{111} by
matching the experimentally measured spectra with a calculated one. They show the rotational temperature increased from 500 to 900 K as the distance between electrodes was increased. In their work, it was mentioned that emission from an SDBD actuator operating in air is dominated by from $N_2(C^3\Pi_u \to B^3\Pi_g)$ and $N_2^+(B^2\Sigma_u^+ \to X^2\Sigma_g^+)$. Other band systems of N$_2$, O$_2$, O$_2^+$ and NO contribute weak emissions. Finally, Dong et al.\textsuperscript{126} determined the rotational and vibrational temperature by visually comparing measured and calculated $N_2(C^3\Pi_u \to B^3\Pi_g)$ spectra.
2.2 Computational Modeling of Surface-Discharge-Mode, Dielectric Barrier Discharge

In this section, the various models that have been applied to surface-discharge-mode, dielectric barrier discharges is reviewed. Presently, the lack of a self-consistent, physics-based, theoretical model, capable of adequately predicting the heat and momentum source terms, has held back the development of plasma flow control technology. It should be mentioned that substantial progress has been made in the last few years, which if the rate of productivity remains constant, should give way to a useful model.

Section 2.2 is broken into three subsections with each subsection dedicated to a different type of computational model of the SDBD. In Section 2.2.1, the lumped element circuit model is presented. This includes a general description followed by the predicted results along with a comparison with experimental results. In Section 2.2.2, the particle-in-cell direct simulation Monte Carlo (PIC-DSMC) model is presented. Again this includes a general description of the model followed by a discussion of the predicted results. The final section, Section 2.2.3, is dedicated to the drift-diffusion model and follows the same format as Sections 2.2.1 and 2.2.2.
2.2.1 The Lumped Element Circuit Model

The SDBD is fundamentally an electrical phenomenon, which can be modeled using an equivalent circuit made up with appropriate electrical circuit components. This is the idea behind the lumped element circuit model, developed by Orlov\textsuperscript{164-166}. The equivalent electrical circuit used to model the SDBD is shown in Figure 2.32. As shown in the figure, the computational domain is broken up into $n$ partitions where each partition has its own equivalent circuit. Each equivalent circuit has components representing the air, the dielectric, and the plasma when it is on and off. Zener diodes are used to set a threshold voltage required for breakdown. These elements are designated as $D$ in Figure 2.32, and only allow current to flow in one direction. Breakdown occurs for both positive and negative voltage which means each circuit element requires two zener diodes in parallel, one to describe the breakdown occurring during the negative voltage half-cycle, and the other for the positive voltage half-cycle. Resistors, designated as $R$, represent the resistance of the plasma. There is a different resistor in series with each zener diode. The parallel network formed by the two zener diodes and resistors is in parallel with the capacitor $C_{1a}$, which represents the capacitance of air. Both the diode-resistor circuit representing breakdown, and the air capacitor, representing no breakdown are in series with the capacitance of the dielectric barrier, designated as $C_{1d}$.

The first subscript, on each of the circuit elements defined above, represent the partition number. The second subscript, $f$, $b$, $a$, and $d$, represents the negative voltage half-cycle, positive voltage half-cycle, air, and dielectric, respectively.

![Figure 2.32](image)

\textbf{Figure 2.32}: Electric circuit model of a surface-discharge-mode, dielectric barrier discharge. This figure was taken from the work by Orlov\textsuperscript{164}.
Each of the circuit elements identified above, are now defined in terms of the quantities associated with the DBD. The value of the air capacitor of the \( n^{th} \) element is given as

\[
C_{na} = \frac{\varepsilon_0 \varepsilon_a A_n}{l_n}
\]  

(2.2.1.1)

where \( \varepsilon_a \) is the dielectric constant of air, \( l_n \) is the length measured from the edge of the exposed electrode to the \( n^{th} \) element, and \( A_n \) is the cross sectional area of the \( n^{th} \) air capacitor. The cross sectional area, \( A_n \), is given as the product of the depth of the dielectric (\( z \)-dimension in Figure 2.32), and the height of the capacitive element (\( y \)-dimension in Figure 2.32). The value of the dielectric capacitor of the \( n^{th} \) element is given as

\[
C_{nd} = \frac{\varepsilon_0 \varepsilon_d A_d}{l_d}
\]  

(2.2.1.2)

where \( \varepsilon_d \) is the dielectric coefficient, \( A_d \) is the cross sectional area of the dielectric, and \( l_d \) is the thickness of the dielectric (\( y \)-dimension in Figure 2.32). The cross sectional area is given as the product of the depth of the dielectric (\( z \)-dimension in Figure 2.32) and the width of the partition (\( x \)-dimension in Figure 2.32). The resistance of the \( n^{th} \) element is given as

\[
R_n = \frac{\rho_a l_n}{A_n}
\]  

(2.2.1.3)

where \( \rho_a \) is the effective resistance of the air. It should be noted that each of the above circuit elements is a function of the distance from the exposed electrode edge. The time-varying voltage of the dielectric surface of the \( n^{th} \) element is given in terms of the applied voltage (\( V_{app} \)) in the \( n^{th} \) element as

\[
\frac{dV_n(t)}{dt} = \frac{dV_{app}(t)}{dt} \left( \frac{C_n}{C_n + C_{nd}} \right) + k_n \frac{l_{np}(t)}{C_n} \left( \frac{1}{C_n + C_{nd}} \right)
\]  

(2.2.1.4)

where \( I_{np}(t) \) is the time varying current and is given as

\[
I_{pn}(t) = \frac{1}{R_n} \left[ V_{app}(t) - V_n(t) \right].
\]  

(2.2.1.5)

In Equation (2.2.1.4), \( k_n \) is the Dirac delta function, which has the value of either 0 or 1, and represents when current is not flowing and flowing through the zener diode. The ratio of the resistor elements, of the negative voltage half-cycle and positive voltage half-cycle, was set to 5. This ratio was determined based on the ratio of the experimentally measured currents for the two voltage half-cycles. The numerical process used to solve the above equations is beyond the scope of the current discussion, but can be found within reference 164.
The plasma body force was obtained by solving Poisson’s equation at each time step of the lumped-element circuit model. The solution of Poisson’s equation is a boundary value problem where the boundary conditions are obtained from the lumped-element circuit model. This requires two boundary conditions. The first is the applied voltage, which is known, and the second is the voltage on the dielectric surface, which is obtained. The plasma body force is then given as

\[ \vec{f}_b^* = \rho_e \vec{E} = -\left( \frac{\varepsilon_0}{\lambda_D^*} \right) \varphi \vec{E} \]  

(2.2.1.6)

where \( \varphi \) is the electric potential, \( \lambda_D^* \) is the Debye length and \( \vec{E} \) is the electric field.

The lumped-element circuit model, as will be discussed, successfully reproduced some experimental observations; however, there are some inherent problems with this model. The model does not account for various physical events, such as surface charging, ionization, dissociation and other chemical reactions, occurring within the DBD from a first principles formulation. Because of this many of the circuit element values used were selected based on experimentally derived quantities for a particular applied time-dependent voltage. Therefore, this model in its current formulation cannot be used to predict the behavior of voltage waveforms different from the one measured to determine circuit element values.

The lumped-element circuit model was able to accurately determine the plasma extent and plasma sweep velocity, as a function of voltage and frequency. In addition, the model accurately predicts that the power dissipated by a DBD, as shown by experiments, has the following relationship

\[ P \propto V^{7/2}, \]  

(2.2.1.7)

Where \( P \) is power and \( V \) is voltage. Also it is shown that each AC cycle results in two push-push force producing mechanisms. That is forces produced during the negative and positive voltage half-cycles are in the induced flow direction. In view of these successes, the model was used to determine the momentum and heat source terms needed as inputs for a computational fluid dynamic code. It was then used to study the effect SDBD actuators have on flow separation over an airfoil.
2.2.2 The Particle-In-Cell Direct Simulation Monty Carlo Model

The particle-in-cell, direct simulation Monte Carlo model (PIC-DSMC), which has been described in detail in reference 268, involves recasting the appropriate species of the discharge as weighted computational particles. Each computational particle typically represents millions to trillions of real particles. The PIC portion of the method updates the trajectory of each particle along with the electric field at each time step. The electric field is computed by taking the gradient of the potential which is found by solving Poisson’s equation for the charge distribution. The charge distribution is updated at each time step by tracking the trajectories of the charged particles so that the position of the particles is known. This is done by computing the force exerted on each charged particle by the electric field and backing out the corresponding velocity using kinematic equations of motion. The DSMC portion of the model is used to handle the chemical reactions and momentum transfer associated with particle interactions via collisions. The details associated with the physics are obtained after a statistically sufficient number of collisions have occurred such that the different distributions of each computational species is periodic with respect to time. This modeling scheme has been used to model many types of discharges including SDBD’s. 167-169,170,171

In Font’s work, two different discharges were studied, namely an SDBD operated in pure nitrogen167 and an SDBD operated in pure oxygen.168 The thickness of the dielectric barrier and exposed electrode was 0.5 mm, which in the case of the exposed electrode, is substantially different from the typical value of 0.1 mm used in experiments. The height and width of the computational domain was 1.5 mm by 2.0 mm, respectively. A typical width used in experiments is on the order of 12 mm which makes the computational width of 2.0 mm an artificial value. The grid size was reduced from 25 by 25 micrometers to 4 by 4 micrometers in the hope that the induced body force would converge; however, this did not occur. The fact that the solution did not converge shows that the results presented are not independent of the grid. Another significant difference between the model and experiment is the use of an unrealistic dielectric constant of 1.0 which corresponds to a vacuum. In experiments, the dielectric constant typically ranges from 2.0 to 10.0. The use of 1.0 will result in differences between the computed electric fields and the electric fields in experiments. The discharge has several different boundaries, such as the edge of the plasma, the dielectric surface, the edges of the exposed
electrode and the edges of the encapsulated electrode. In the model, the edge of the plasma, which propagates across the encapsulated electrode, is represented as having a potential gradient of zero. The surface charge accumulation on the dielectric is included by assigning a velocity of 0 to any charged particle drifting onto the surface. Charged particles that drift into the exposed electrode are instantaneously neutralized. Finally, the exposed electrode was held at a constant value of 5000 volts, which represents the positive voltage half-cycle, and a constant value of -5000 volts, which represents the negative voltage half-cycle. The encapsulated electrode was held at 0 volts. The negative voltage half-cycle was run for 60 ns and then the positive voltage half-cycle immediately followed for an additional 60 ns, resulting in an effective frequency of 8 MHz. Again, this is substantially different from the typical experimental values of 1 to 10 kHz which ultimately alters the surface charge accumulation because the amount of time allocated for charge recombination in the model is much less than in experiments. The simulation is started using seed electrons. The number of seed electrons used was decreased until the solution no longer depended on the number of seed electrons.

During the negative voltage half-cycle, for the pure nitrogen case, results show that breakdown occurs when the electric field is at a maximum on the exposed electrode, resulting in electrons avalanching towards the dielectric barrier. The electrons, being significantly lighter than the ions, separate forming a negative sheath. When the electrons reach the dielectric surface, they eliminate the vertical component of the electric field, resulting in electrons landing farther away from the exposed electrode. Arrival of the negative sheath upon the dielectric surface occurs in 30 ns. At this time, when the discharge is expanding across the dielectric, very little ionization occurs. The predicted results show that momentum is transferred to the neutrals by the positive ions, resulting in a body force pointing downstream.

During the positive voltage half-cycle, similar events occur except initially electrons that accumulated on the dielectric surface avalanche back towards the exposed electrode resulting in ionization of neutral particles. The faster moving electrons again will separate from the positive ions resulting in a positive sheath which propagates across the dielectric surface transferring momentum to neutral molecules. The force produced during the positive voltage half-cycle is found to be much greater and in the opposite direction than the force produced during the negative voltage half-cycle. The level at which this occurs is dependent on the fact that production of positive ions is substantially enhanced during the positive voltage half-cycle due to the electrons stored on the dielectric surface. Computations show that this can occur independently of surface
charge because during the negative voltage half-cycle, electrons travel from larger electric fields near the exposed electrode to weaker electric fields whereas during the positive voltage half-cycle, electrons travel from weaker electric fields to stronger electric fields. This asymmetry leads to an enhancement of the avalanche process during the positive voltage half-cycle, resulting in a larger production of ions.\textsuperscript{169}

In the PIC-DSMC simulations of SDBD’s in pure oxygen, the particles tracked are electrons, positive ions and negative ions. The reactions included in the model are dissociation, meta-stable excitation, ionization, dissociative attachment, dissociative recombination, elastic collisions and secondary electron emission at the walls. All other parameters used are identical to those used for the PIC-DSMC simulations of SDBD’s in pure nitrogen. Results showed that the presence of negative oxygen ions do not noticeably change the characteristics of force production because the level of negative oxygen ions generated in the air plasma are not sufficient to reverse the direction of the induced body force. The time average force was found to be given as the result of a large push in the induced flow direction during the positive voltage half-cycle and a small pull, against the direction of induced flow, during the negative voltage half-cycle. The presence of negative oxygen ions was shown to have a significant, beneficial effect on the efficiency of the SDBD. Results showed that a negative sheath composed of negative ions propagated across the encapsulated electrode during the negative voltage half-cycle imparting momentum to neutrals.

A time-dependent momentum source term, which was used to determine the induced flow field of the SDBD by a Navier-Stokes code, was qualitatively pieced together based on experimental results and the PIC-DSMC results presented above.\textsuperscript{172} In particular, Font et al.\textsuperscript{172} noted from their PIC-DSMC results that the magnitude of the force during the positive voltage half-cycle was 20 times greater than the force during the negative voltage half-cycle. The computational results also showed that the force was directed in the direction of the induced flow during the positive voltage half-cycle and against the induced flow during the negative voltage half-cycle. This information was used to set the amplitude of a sinusoidal-like waveform shown in Figure 2.33. The justification of selecting a sinusoidal momentum source was not given; however, questionable experimental results have shown that the induced momentum follows the voltage waveform\textsuperscript{93}. Unfortunately though, experiments have shown that the negative voltage half-cycle produces the driving force which means that the proposed source term is still incorrect. Observations from experimentally determined current and voltage profiles were used to determine the amplitude of the sinusoid.
Typical measured current profiles show larger amplitude current spikes occurring during the positive voltage half-cycle than negative voltage half-cycle. It is interesting to note that the current waveform given in Figure 2.33, by Font et al.\textsuperscript{172}, appears to be out-of-phase by 180 degrees with respect to the voltage waveform. At any rate, the amplitude of their proposed sinusoidal-like momentum source term during the positive voltage half-cycle (denoted as the backward discharge by their group) and the negative voltage half-cycle (denoted as the forward discharge by their group) was determined based on the amplitude of the current pulses occurring during the appropriate voltage half-cycle. The functional dependence of the momentum source term, on time, was determined from the measured current profile. Font et al.\textsuperscript{172} assumed, based on their PIC-DSMC results, that the induced body force is present only when the plasma is present (when there is conductive current) and not during the afterglow. For this reason, the momentum source term has nonzero values only at times when conductive current is present. It is not surprising given the nature of how the momentum source term was “guessed” that the computed flow field matches reasonably well with experimentally measured flow fields.

Figure 2.33: (a) Experimental current profile. (b) Momentum source term (it is really a force source term) used as an input to a Navier-Stokes code. Taken from Font et al.\textsuperscript{172}.
2.2.3 The Drift-Diffusion Model

Many different forms of the drift-diffusion model have been applied to model the SDBD actuator\textsuperscript{173-214}. Each variant contains the same fundamental approach which is outlined below. The dynamics of an arbitrary species, designated as \( i \), are given as

\[
\frac{\partial n_i}{\partial t} + \nabla \cdot \vec{J}_i = S_i
\]  

(2.2.3.1)

where \( n_i \) is the number density of species \( i \), \( S_i \) is the source term of species \( i \) and \( \vec{J}_i \) is given as

\[
\vec{J}_i = -\nabla(D_i n_i) - n_i K_i \vec{E}.
\]  

(2.2.3.2)

In Equation 2.2.3.2, \( D_i \) is the diffusion coefficient of species \( i \), \( K_i \) is the mobility of species \( i \) and \( \vec{E} \) is the electric field. Note that the diffusion coefficient is inside the gradient. It was found necessary to treat the diffusion coefficient for electrons as a function of the electric field in regions where large field gradients exist, such as along the dielectric surface\textsuperscript{175}. Treating the diffusion coefficient for electrons as a constant with respect to the field resulted in unrealistic charge densities at the dielectric surface. The electric field is obtained by solving

\[
\vec{E} = -\nabla V
\]  

(2.2.3.3)

where \( V \), the electric potential, is determined by solving

\[
\nabla^2 V = \begin{cases} \frac{-\rho}{\varepsilon_0} & \text{gas region} \\ 0 & \text{dielectric region} \end{cases}.
\]  

(2.2.3.4)

In Equation 2.2.3.4, \( \rho \) is the net charge density. The solution of Equations 2.2.3.1 through 2.2.3.4, which are coupled together, depend on the boundary conditions and source terms used. These vary between the different researchers and are given below for each model discussed.

In the modeling work done by Soloviev et al\textsuperscript{173-175}, Equations 2.2.3.1 through 2.2.3.4 were solved for positive ions, negative ions and electrons. The inclusion of three species results in the use of Equation 2.2.3.1 three times, once for each species. Both terms in the flux vector, \( \vec{J}_i \), are used to describe the motion of electrons; however, the diffusion term is neglected for positive and negative ions. In the framework that follows the subscript \( p \) is used to designate positive ions, the subscript \( n \) is used to designate negative ions and the subscript \( e \) is used to designate electrons. The initial condition and boundary conditions imposed on Equation 2.2.3.1 for electrons are
\[ n_e(t = 0) = n_{in}, \quad (2.2.3.5) \]
\[ n_e \mid \text{at exposed electrode} = \begin{cases} 0 & V_0 < 0 \\ \gamma_s I_{p,\perp} & V_0 < 0 \end{cases} \quad (2.2.3.6) \]

and

\[ n_e \mid \text{at dielectric barrier} \rightarrow -K_e n_e E_{\perp} - \frac{\partial (D_e n_e)}{\partial y} = a(E_{\perp}) \frac{n_e V_T}{4} + f_{out} \quad (2.2.3.7) \]

where

\[ a(E_{\perp}) = \begin{cases} (1 - r) \exp \left( \frac{K_e E_{\perp} \lambda}{T_e} \right) & \text{for } E_{\perp} < 0 \\ (1 - r) \left[ \exp \left( -\frac{K_e E_{\perp} \lambda}{T_e} \right) + 4 \left( 1 - \exp \left( \frac{K_e E_{\perp} \lambda}{T_e} \right) \right) \right] & \text{for } E_{\perp} > 0 \end{cases} \quad (2.2.3.8) \]

In Equations 2.2.3.5 through 2.2.3.8, \( n_{in} \) is the number of electrons in air produced by cosmic rays and natural radioactivity, \( \gamma_s \) is the secondary emission coefficient, \( \lambda \) is the electron mean free path, \( r \) is the surface reflection coefficient for electrons, \( T_e \) is the electron temperature and \( f_{out} \) is the electron flux from the surface and is given as

\[ f_{out} = \begin{cases} 0 & V > 0 \\ -\gamma_s I_{p,\perp} & V < 0 \end{cases} \quad (2.2.3.9) \]

When the applied voltage is independent of time, electron production via desorption at the dielectric surface is 0. The initial conditions and boundary conditions imposed on Equation 2.2.3.1 for positive ions and negative ions are

\[ n_p \mid \text{at exposed electrode and dielectric barrier} = 0. \quad (2.2.3.11) \]
\[ n_n(t = 0) = 0 \quad (2.2.3.12) \]

and

\[ n_n \mid \text{at exposed electrode and dielectric barrier} = 0. \quad (2.2.3.13) \]

The boundary conditions imposed on the electric field for the tangential and perpendicular component at the gas-dielectric interface are given as

\[ E_{T,\text{above}} = E_{T,\text{below}} \quad (2.2.3.14) \]

and

\[ E_{\perp,\text{above}} = \varepsilon E_{\perp,\text{below}} - 4\pi \sigma(x, t) \quad (2.2.3.15) \]

where \( \varepsilon \) is the permittivity of the dielectric barrier and \( \sigma(x, t) \) is the surface charge density given as

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\[ \sigma(x, t) = e \int_0^t (f_{p, \perp} - f_{n, \perp} - f_{e, \perp}) dt. \]  
(2.2.3.16)

The boundary conditions applied to the electric potential are given as

\[ V_{\text{encapsulated electrode}} = 0. \]  
(2.2.3.17)
\[ V_{\text{exposed electrode}} = \begin{cases} -V_0 \\ V_0 \end{cases} \]  
(2.2.3.18)

and

\[ V_{\text{far field}} = V_0 \left[ \frac{1}{2} - \frac{1}{\pi} \tan^{-1} \left( \frac{V_0}{V} \right) \right]. \]  
(2.2.3.19)

Equation (2.2.3.19) is an analytical solution obtained by solving \( \nabla^2 V = 0 \) in the limit of the dielectric thickness and the exposed electrode height go to 0 and the spatial dimensions approach infinity. It is used to set the boundary condition on the outer edges of the computational domain. The surface charge densities of electrons and positive ions on the surface of the dielectric barrier are described by

\[ \frac{\partial \sigma_e}{\partial t} = -f_{e, \perp} - \alpha_{rw} \sigma_e \sigma_p \cong -f_{e, \perp} \]  
(2.2.3.20)

and

\[ \frac{\partial \sigma_p}{\partial t} = -f_{p, \perp} - \alpha_{rw} \sigma_e \sigma_p \cong -f_{p, \perp} \]  
(2.2.3.21)

where \( \alpha_{rw} \) is the electron-positive ion recombination coefficient at the surface and is a tabulated constant. Recombination in the above equations drops out when the applied voltage is constant. These terms need to be included when the applied voltage has time-dependence. The initial condition for Equations 2.2.3.20 and 2.2.3.21 are

\[ \sigma_e(t = 0) = \sigma_p(t = 0) = 0. \]  
(2.2.3.22)

The source terms for positive ions, negative ions and electrons are given as

\[ S_p = k_i N n_e - k_{dr} n_e n_p - k_{at} n_n n_p. \]  
(2.2.3.23)
\[ S_n = k_{dt} N n_e - k_{at} n_n n_p \]  
(2.2.3.24)

and

\[ S_e = k_i N n_e - k_{dr} n_e n_p - k_{at} N n_e \]  
(2.2.3.25)

where \( k_i, k_{dr}, k_{at} \) and \( k_r \) are the rate constants for ionization, dissociative recombination, attachment and ion-ion recombination. The chemical reactions participating in the production of the species included within the model are given as
The photoionization source term is obtained by using the model proposed by Zheleznyak \(^{213}\) and is given as

\[
S_{ph}(x, y) = 30 \int n_e a_{ex} Q_{ph} N_0 N_k \frac{\tau^* \tan^{-1}(h_{str}/\rho_{st})}{\pi \rho_{st}} d\alpha_a dy_a
\]  

where \(Q_{ph}\) is the mean photoionization cross-section, \(h_{str}\) is the characteristic dimension of the streamer head, \(\frac{\tau^*}{\tau_R}\) is the ratio of time constants and is given as

\[
\frac{\tau^*}{\tau_R} = \frac{30}{\rho(\text{torr}) + 30}
\]

where \(\rho_{st}\) is

\[
\rho_{st} = \sqrt{(x - x_a)^2 + (y - y_a)^2}.
\]

The model, described by Equations 2.2.3.1 through 2.2.3.35, was solved with \(V_o = 4.2\) kV, \(\varepsilon = 8\) and a dielectric thickness of 1.0 mm, for the positive voltage half-cycle and \(V_o = -4.5\) kV, \(\varepsilon = 8\) and a dielectric thickness of 1.0 mm, for the negative voltage half-cycle. Results show that during the negative voltage half-cycle a small cathode fall region is formed at the exposed electrode with a high electron-ion density of \(10^{15}\) cm\(^{-3}\) with severe charge separation. The large field gradient results in substantial ionization in this region. The electrons produced in this region, drift to the dielectric surface whereas the ions drift towards the exposed electrode. The seeding of electrons upon the dielectric surface continues until the perpendicular component of the electric field changes direction, resulting in the electrons to switch directions and drift towards the exposed electrode. At this point the net flux of electrons goes to zero and the vertical component of the electric field is negative due to the negative surface charge. The surface
charge obtained agrees well with experimental results presented in reference 269. The electric fields along the region near the dielectric surface are found to always be large, resulting in ionization for both directions of the field (before and after the direction change due to surface charging). This result indicates that while the dominate production of the plasma species occurs in the cathode region (cathode spots), there is some volume ionization along the region near the surface. This indicates that the discharge regime during the negative voltage half-cycle is a diffusive discharge, which agrees with experimental observations by Gibalov and Pietsch.\textsuperscript{269} The number densities of electrons and ions, within this region, is $5 \times 10^{13} \text{ cm}^{-3}$. The electron-ion concentrations were found to be a maximum at the inner-electrode gap and then decrease smoothly as you go across the dielectric barrier. The thickness of this layer was found to be 0.02 mm at the inner electrode gap and decreased down to 0.01 mm.

When the discharge starts to relax, the plasma species diffuse outward to around 0.2 to 0.3 mm above the dielectric surface. During this time period, which lasts for several microseconds, the net charge is negative due to the large amount of negative ions and the resulting body force is in the direction of flow. It is interesting to note that the body force responsible for inducing flow is shown to occur during the relaxation period instead of during the discharge period, which lasts for $\sim$ 30 nanoseconds. The result was explained in terms of the amount of time associated with these two different regimes. It was argued that a period of 30 nanoseconds was not sufficiently long for significant momentum transfer to occur, whereas several microseconds during the plasma relaxation period was.

During the positive voltage half-cycle, a positive ion cloud is produced at the inner-electrode gap and is then followed by a volumetric streamer. This occurs only if the applied voltage is large enough. In atmospheric air the voltage requirement for streamer production is on the order of 4.2 kV. For applied voltages lower than 4.2 kV, the discharge exists as a small glow around the inner-electrode gap. The plasma regime dependence on voltage was demonstrated by the model and agreed well with experiments. Results show that the streamer was found to propagate parallel to the dielectric surface at a velocity of $\sim 2.8 \times 10^6 \text{ m/s}$. It should be noted that the streamer never touched the surface but ion drift resulted in positive surface charge. The predicted surface charge compares well with experiment\textsuperscript{269}, as did the plasma extent.
During the relaxation phase of the positive voltage half-cycle, the electron density and ion density are approximately the same. The negative ion density is three orders of magnitude less than the electron density and, in this phase, does not play a factor in the induced body force. The net charge within the region that was once the streamer head is positive, whereas the net charge within the region which was once the streamer tail is negative. The resulting momentum transfer to the neutrals is a small contribution to the overall body force by the ions in the direction of flow. The net force is an order of magnitude smaller than during the negative voltage half-cycle which agrees with experiment\textsuperscript{121,122}.

The time-averaged heat and momentum source terms, as a function of space, are obtained from this solution and are used as inputs to determine the flow field around a high-speed delta wing using a Navier-Stokes code\textsuperscript{214}. The tangential and perpendicular component of the time-averaged force source term, designated as \( F_t \) and \( F_\perp \), is given as

\[
F_t = F_0 \exp \left[ -\frac{(y-y_0)^2}{y_0^2} \right] \tag{2.2.3.36}
\]

and

\[
F_\perp = -0.3F_0f(y) \tag{2.2.3.37}
\]

where

\[
f(y) = \begin{cases} 
\frac{y(y-2y_0)}{y_0^2}, & 0 \leq y \leq 2y_0, \\
0, & y < 2y_0
\end{cases} \tag{2.2.3.38}
\]

In Equations 2.2.3.36 through 2.2.3.38, \( F_0 = 10^4 \text{N/m}^3 \) and \( y_0 = 3 \times 10^{-5} \text{m} \). The time-averaged heat source term, \( Q \) is given as

\[
Q = Q_0 \exp \left[ -\frac{(y-y_0)^2}{y_0^2} \right] \tag{2.2.3.39}
\]

where \( Q_0 = 2 \times 10^9 \text{W/m}^3 \). Note these source terms are determined by Soloviev et al\textsuperscript{175}; however, they were published in reference 214.

The flow field around a delta wing was determined for laminar flow at Mach 1.5, angles of attack ranging from 0 to 30 degrees, with a corresponding Reynolds number of \( 2 \times 10^6 \) with and without the presence of an SDBD. Three different placements of the SDBD onto the delta wing, shown in Figure 2.34, were investigated. Results show that the location of the vortex burst can be controlled using an SDBD; however, this resulted in little change of the aerodynamic loads. In particular, only a 3\% change in the lift
and drag coefficients were observed suggesting that the aerodynamic loads are not overly sensitive to the vortex burst locus. An example of the influence of the SDBD on the vortex burst is shown in Figure 2.35. As the figure shows, the flow field is influenced by the presence of the SDBD. The corresponding lift and drag coefficients are shown in Figure 2.36. The figure shows that the lift and drag coefficients are barely changed even though the flow field is.

**Figure 2.34:** Red lines show SDBD location (a) wing-apex actuator, (b) leading-edge actuator, (c) multi-element actuator. Taken from Fedorov and Soudakov\textsuperscript{214}.

**Figure 2.35:** The vortex flow fields corresponding to the multi-element SDBD arranged delta wing with the discharge off and on for an angle of attack of 20 degrees. Note SBD in the figure has the same meaning as SDBD. Taken from Fedorov and Soudakov\textsuperscript{214}. 
Boeuf et al.\textsuperscript{176-184} have included electrons, negative ions and positive ions within a drift-diffusion model of an SDBD. There are several key differences between the model used by Boeuf and Solovev, which include, the voltage of the exposed electrode, photoionization is not accounted for, diffusion of both ion species is included during the active and relaxation period of the discharge and the diffusion coefficient for electrons is treated as a constant. According to Solovev, treating the diffusion coefficient as a constant resulted in the charge particle density going towards infinity when the cathode-directed streamer came in contact with the dielectric, this was not observed in Boeuf’s model. The voltage waveform applied to the exposed electrode is a linearly increasing voltage with a slope of 100 V/\(\mu\)s which is equivalent to the traditional sinusoidal voltage of 5-20 kV and 1-10 kHz used in experiments. The source terms in Equation 2.2.3.1 for electrons, positive ions and negative ions are, in this model, given as

\[ S_e = (\alpha - \eta) |I_e'| - r_{ep} n_e n_p, \]  
\[ S_p = \alpha |I_e'| - r_{ep} n_e n_p - r_{in} n_p n_n \]  
\[ S_n = \eta |I_e'| - r_{in} n_p n_n. \]  

The permittivity of the dielectric was set at 5.

Results indicate that during the positive voltage half-cycle, a positive ion cloud forms at the tip of the exposed electrode and slowly expands along the surface of the dielectric barrier. The development of

\[ C_L \]  
\[ C_D \]

\[ \alpha \]  
\[ r_{ep} \]  
\[ r_{in} \]  
\[ \eta \]  
\[ n_e \]  
\[ n_p \]  
\[ n_n \]
the discharge, along with the currents associated with this ion cloud, is similar to a Townsend discharge; however, the presence of a large geometric field distortion at the tip is similar to a corona discharge. The term corona-like was introduced to describe the dual nature of the discharge. During this phase, the expansion of the ion cloud is aided by secondary emission processes due to ion bombardment of the surface and volume ionization until an upper limit is reached. At this point, which is approximately 26 microseconds from the start of the corona-like regime, breakdown occurs and is associated with a large current spike. During breakdown, the electric field obtained is similar to the field of a cathode-directed streamer. They show that the field in the streamer head is large, whereas the field within the streamer tail is much weaker. The propagating velocity of the discharge was found to be $2 \times 10^5$ m/s which is similar to a cathode-directed streamer; however, electron production required for the development of a cathode-directed streamer is typically accomplished by photoionization, which is not included in the model. It is shown that the ability of the dielectric surface to store electrons, produced during the negative voltage half-cycle, is a sufficient source for the development of a cathode-directed streamer. Eventually, due to the self-limiting nature of the SDBD, the cathode-directed streamer stops and a relaxation period begins. During this period, some electrons attach to oxygen forming negative ions which occurs predominantly within the volume once occupied by the streamer tail. The volume once occupied by the streamer head is characterized as having a net positive charge during the relaxation period. Note, this is substantially different from the results obtained by Solovev, which showed the negative ion concentrations were negligible compared to electron and positive ion concentrations during this period.

During the negative voltage half-cycle, the current profile is characterized by many small amplitude current pulses, with a lifetime of 100 nanoseconds, occurring at around 1 MHz. The time between pulses was too short to allow full quenching of the plasma species resulting in leftover negative and positive ions from the previous current pulse. In contrast, electron concentrations at the beginning and the end of the current pulse were found to be effectively zero due to the formation of negative ions. The amount of net negative ions is significantly more than the amount of net positive ions resulting in a net negative charge. This net amount of negative ions, after each successive current pulse, results in the growth of a large negative space cloud over the dielectric surface. The velocity of this expanding negative ion cloud was found to be around 100 m/s and is linearly proportional to the applied voltage slope. In terms of
plasma regime, the model indicates that the plasma is behaving as a diffuse discharge. The surface charge, as mentioned in the previous paragraph, is negative and is at a maximum near the inner-electrode gap. The electric field, as a function of distance from the inner-electrode gap, is found to be at a maximum of 60 kV/cm at the inner-electrode gap and then decreases rapidly to a minimum value of 18 kV/cm. It then increases to a local maximum of 30 kV/cm and finally decreases asymptotically. The location within the discharge of the local maximum was found to sweep across the dielectric surface. It is interesting to note that the magnitude of the field corresponding to the local maximum point was around the breakdown voltage for atmospheric pressure air. The breakdown voltage in air is when ionization balances attachment which shows that negative ion production is large for the DBD because most of the volume occupied by the discharge is below the breakdown voltage.

The time-history of the EHD force over the course of the various discharge phenomena, occurring during the positive and negative voltage half-cycle, is now discussed. The EHD force produced during the corona-like phase of the positive voltage half-cycle is small but lasts for several microseconds. The force then spikes to a maximum when the corona-like phase gives way to streamer breakdown; however, because the streamer discharge phase is so short, the time average force is completely dominated by the much smaller, longer lasting corona-like discharge. The steady state, time averaged force produced during the positive voltage half-cycle was found to be 0.12 mN/m and was not overly sensitive to the voltage slope or the ratio of the permittivity of the dielectric barrier and dielectric thickness. These parameters did have a significant effect of the spatial distribution of the EHD force. The EHD force produced during the negative voltage half-cycle is caused by the large negatively charged cloud. The expansion of the negative space charge above the surface is continuous and, unlike the positive voltage half-cycle, not interrupted by high current breakdown. This has a pronounced effect on the EHD force because the length of the negative ion cloud is not limited by breakdown but rather the duration of the negative phase. This is a fundamental difference between the EHD force produced during the two half-cycles and results in greater force generation during the negative voltage half-cycle. Finally, it was also found that the force produced during the negative voltage half-cycle was only weakly dependent on the dielectric layer and increases with increasing voltage slope. The induced body force was shown to be caused by a push-push mechanism, i.e. a push during the positive voltage half-cycle, followed by a push during the negative voltage half-cycle.
Another possibility is a push-pull mechanism which is characterized by a push during the positive voltage half-cycle and a pull during the negative voltage half-cycle.

In the work done by Likhanskii et al.\textsuperscript{185-190}, the source terms for Equation 2.2.3.1 are identical to those used by Solovev. There are; however, some noticeable differences between the two models, such as treating the drift coefficient for electrons as a constant, assuming the ion temperature is the same as the gas temperature, and using the Edgington approximation to handle the photoionization term. The permittivity of the dielectric was set to a value of 5. The first set of results to be discussed is for a sinusoidal voltage at 1500 volts and an unrealistic frequency of 1 MHz which is way out of the range of typical experimental values of 1 to 20 kHz. In the sinusoidal voltage work, the model does not include photoionization. The second set of results is for a nano-pulsed applied voltage and takes into account everything mentioned.

For a sinusoidal voltage, they show that during the negative voltage half-cycle electrons in the air interact with the strong electric field and cause some ionization. More electrons are produced from secondary emission, due to ion bombardment, until a critical value is reached causing electron avalanches. During the avalanches the lighter and faster electrons separate from the ions and charge the dielectric surface leaving behind an ion cloud. The ion cloud expands in size from further secondary emission and volume ionization until the presence of a large geometric field distortion, at the tip, causes the ions to propagate across the dielectric surface restoring neutrality. The avalanches stop after only a fraction of the time of the negative half cycle. During the rest of the time, negative ions formed at the front and upper edges of the plasma, push the flow downstream while the positive ions push the flow upstream. It should be noted that the ions are decreasing the performance during this period. Which mechanism is dominant, negative ions or positive ions, was shown to depend on the frequency, applied voltage and size of the discharge. They show that when the frequency is high (1000 kHz), the voltage low (1500 volts) and the size of the discharge small (encapsulated electrode width of 1 mm), the flow is directed in the negative y-direction (Figure 1.1a gives the coordinate system), towards the exposed electrode. At larger size (encapsulated electrode width of 7 mm), frequency (100 kHz) and voltage (3500 volts), the flow moves in the positive direction. This gives some indication of the scaling associated with a sinusoidal SDBD. Namely, the backward-directed force, caused by the positive ions, remained almost constant with scaling, whereas the downstream-directed force, caused by negative ions, increases with increasing plasma size and
voltage amplitude. This could lead to a push-push force production mechanism for larger sized SDBD’s and push-pull force production for smaller sized SDBD’s and explain the existence of experimental evidence for both force production mechanisms. During the positive voltage half-cycle, two different plasma regimes are possible and depend on the frequency. For low frequency (2-3 kHz), the period is long enough that almost complete quenching of the electrons by recombination occurs. Therefore the plasma around the exposed electrode can only exist as a positive corona. The positive ions at the tip of the cathode partially shield the electric field, preventing avalanches. Once the ions drift away, shielding stops and breakdown can start again. The second regime corresponds to higher frequencies (at least 5-10 kHz). In this case the period is much shorter and the recombination rate is not fast enough to quench all the electrons on the dielectric surface from the negative voltage half-cycle. The remaining electrons are then pulled from the surface by secondary emission during the positive voltage half-cycle, aiding electron avalanches.

Likhanskii’s findings showed that the sinusoidal voltage waveform was not the most efficient because of the long time period during the negative voltage half-cycle in which positive ions are working against the induced flow. Based on this, he suggested a waveform utilizing high voltage nanosecond pulses superimposed on a positive DC bias. The temporal and spatial heating rate and imparted momentum, for this waveform, were used as source inputs for a 2D Navier-Stokes code and solved for the flow field. Results indicated that an increase in imparted momentum by a factor of 3 could be obtained. His results also indicated a flow field similar to the sinusoid, but with the addition of two vortices produced during each burst of the single-pulsed burst mode SDBD. The first vortex has a positive curl ($\nabla \times \vec{v} > 0$) and is produced from the buoyancy associated with the plasma heated surface, whereas the second vortex, which lags behind the first, has a negative curl ($\nabla \times \vec{v} < 0$) and is produced from the EHD wall jet. The first vortex associated with buoyancy has a density gradient, whereas the second vortex associated with the EHD phenomena does not. This allowed Opaits et al. to image the flow using Schlieren imaging techniques, and as expected he was only able to image the first vortex produced by thermal buoyancy. Opaits showed that the voltage waveform suggested by Likhanskii did not produce the predicted enhancement of the SDBD because of the positive charge build up on the dielectric surface which effectively shielded the DC voltage. They suggested that nanosecond pulses should be superimposed onto a 60 Hz sinusoid instead of a DC bias. This waveform then gave results similar to those predicted by
Likhanskii. It was shown that, during the positive voltage half-cycle, a slow moving vortex is generated (0.4 m/s) and propagates only a small distance away from the gap before a faster moving wall jet produced during the negative half cycle catches it. The merging of this vortex with the wall jet produced a faster moving vortex (1.5 to 2 m/s). A new SDBD arrangement was suggested to eliminate the shielding and involved placing a second exposed grounded electrode downstream of the encapsulated electrode. The waveform originally suggested by Likhanskii was used again and obtained results similar to those predicted by his model.

Bogdanov et al.\textsuperscript{193} took account of the chemical processes occurring (576 total reactions) within the SDBD; however, very little is given on how the model is setup and solved. The following conclusions were obtained assuming the work was done correctly. Results show that the spatial distributions of plasma actuator parameters strongly depend on the choice of the plasma-chemical model. It was found that a large part of the energy input into the discharge was deposited during the current pulse, corresponding to when the space charge and EHD force are at a maximum. The influence of negative ions was shown to not noticeably affect the outcome of the EHD interaction. Finally, they indicated that the dominant positive ion is O\textsubscript{4}\textsuperscript{+} and the dominant negative ion is O\textsubscript{3}.\textsuperscript{−}

As indicated, other researchers have also applied the drift-diffusion model to SDBD actuators. Shang\textsuperscript{191} and Shang et al.\textsuperscript{192} have shown detailed analysis on the electromagnetic field and show the majority of the force production occurs during the positive voltage half-cycle. Roy et al.\textsuperscript{207,208,210-213} model an SDBD actuator operating in helium which, for obvious reasons, does not match the chemistry produced in air. The results from these studies are not discussed here because of the obvious discrepancy. More recent work from this group does investigate air; however, they achieve breakdown in atmospheric pressure air at voltage amplitude of 500 volts and a frequency of 5000 Hz. These values are not realistic and are substantially different than experiment, which shows breakdown occurs at around 3,000 volts for similar conditions.
2.3 The Applications of Surface-Discharge-Mode, Dielectric Barrier Discharge Actuators

The capabilities of SDBD actuators, for flow control applications, have been demonstrated in the form of proof-of-concept experiments. These type of experiments have been conducted for a large range of flow fields produced by turbine blades, landing gear, jet engines, windmills, microairvehicles (MAV), unmanned air vehicles, rotorcrafts and commercial jets. In general, successful implementation relies on the strength of the momentum associated with the perturbation induced upon the flow field and, even more so, on the local flow instabilities surrounding the actuator. Unfortunately, the strong dependence upon flow instabilities is a direct result of how weak the momentum of the perturbation is. As already mentioned, this perturbation is in the form of a wall jet and typically the momentum transferred is completely contained within the boundary layer which has dire consequences. For example, from boundary layer theory the pressure gradient normal to the surface within the boundary layer is zero, which means the SDBD actuator acting alone is unable to alter the surface pressure distribution along an aerodynamic surface. For obvious reasons, this is detrimental for application because if the surface pressure distribution does not change, then the forces of lift and drag, acting on the aerodynamic body, are unaffected. This can be alleviated by the use of a flow instability, which allows the momentum of the perturbation to propagate beyond the boundary layer and ultimately alter lift and drag. This is the very reason that successful use of SDBD actuators has so far relied on strategic placement of the actuator near flow instabilities. In this sense the flow instability can be thought of as a lever providing mechanical advantage.

Another useful technique, used to increase the effectiveness of an SDBD actuator, relies on how it is operated. In general, it has been shown that unsteady operation leads to greater effectiveness; however, not enough to eliminate the need for flow instabilities. Unsteady actuation of the SDBD simply means operating the device at a particular duty cycle. For example, a duty cycle of 30% means the device is operated for 30% of the time within a single period of the driving waveform. Reasons why this occurs are given later in this section. For now the focus of the discussion is switched to specific examples illustrating the applicability of the SDBD actuator along with appropriate definitions.
The classification of a flow field as being either laminar or turbulent is completely dependent on the flow structures present, and is best illustrated by the injection of dye. For laminar flow, the dye would appear as a single line because adjacent fluid layers do not mix, with the exception of random thermal motion of the molecules. In contrast, for turbulent flow the dye will be dispersed throughout the fluid immediately due to strong swirling vortices which enhance mixing. The region where laminar flow changes to turbulent flow is called transition flow, and is a natural occurring instability. An example of utilizing this instability region can be found in the work by Jacob et al. and verified by Porter et al. In this work, the SDBD actuator was placed within the region where laminar-to-turbulent transition takes place. The use of this instability was shown to be sufficient in allowing the SDBD actuator to first trip and then control the boundary layer resulting in changes to the surface pressure distribution. This result, at first glance, seems encouraging; however, the problem is that the SDBD actuator required a flow instability for a free-stream flow velocity of 4.5 m/s, further illustrating the need to increase the induced momentum.

Another example was provided by Balcer et al. who used an SDBD actuator to reattach separated laminar flow to a Pak B low-pressure turbine blade. In this example, the bifurcation is flow separation which occurs when the flow within the boundary layer does not have enough momentum to remain attached to the surface. The flow speeds used in this study ranged from 3 to 10 m/s with corresponding chord Reynolds numbers of 50,000 and 100,000, respectively. It should be mentioned that typical Reynolds numbers for high-altitude flight encountered by low pressure turbine blades are on the order of 25,000. The resultant flow field was measured using PIV and showed that the presence of the SDBD actuator increased the near-wall-layer velocities by as much as 40%, effectively reenergizing the boundary layer, and delaying flow separation. A similar attempt was made for turbulent flow with turbulence levels of 3.3 and 5.4%; however, the induced momentum of the SDBD actuator was insufficient.

These results motivated Boxx et al., a member of the same group, to try and correlate the phase of the driving voltage of the SDBD actuator with observable perturbations induced within the flow field, thereby determining when momentum transfer occurs. The goal was to use this information to increase the SDBD effectiveness so that turbulent flows could be reattached. The flow field used in this study was produced by a flat plate. It was selected because the flow field is well known, easy to characterize and measure, and does a reasonable job simulating the flow field produced by a generic low-pressure turbine blade. The results...
reported demonstrated many errors. First, there was an obvious error with the measured discharge currents. The cause was likely due to placing the SDBD wire in the wrong direction through the current probe, which would result in the measured current appearing 180 degrees out of phase. Second, the bulk of the reported momentum transfer was found to occur when the driving voltage is positive, opposite of other reported results. This may stem from trying to correlate plasma events occurring with characteristic times on the order of nanoseconds using visual flow perturbations having a characteristic time scale of milliseconds. Also one would expect some sort of delay between the plasma event(s) and the observable flow perturbation. In this work, these events are treated as occurring simultaneously, which, as shown in Section 2.1.1, is not correct.

The above results were obtained for a steady, sinusoidally driven SDBD actuator. Similar results were reported by Wall et al.\textsuperscript{220} using an SDBD actuator driven with DC pulses. The pulses had a full width at half maximum (FWHM) of 250 nanoseconds and the corresponding Reynolds number was 23,500. The flow field was measured using phased-locked PIV and showed that the separated flow was reattached on the suction surface side of a highly loaded turbine blade. A comparison study between steady and unsteady actuation was conducted by Huang et al.\textsuperscript{221} for a Reynolds number of 25,000. Results showed that unsteady actuation was more effective at suppressing flow separation. Their results showed that the effectiveness of unsteady actuation was dependent on the Strouhal number which is a nondimensional frequency characteristic of the flow. Based on flow visualization results, they speculated that steady actuation suppressed flow separation because of turbulence tripping, whereas the mechanism for unsteady actuation was a train of spanwise structures promoting mixing.

The use of SDBD actuators on improving the efficiency of low pressure turbine blades has also been extended to controlling secondary flows, such as tip leakage\textsuperscript{222}. A secondary flow is defined as unintentionally diverted flow from the main passage flow within an air breathing gas-turbine engine and constitutes the majority of the overall penalty to efficiency. In this case, tip leakage exits over the suction side of the blade forming a small jet at an angle with the main passage flow. The shearing of the leakage flow with the main passage flow takes the form of a wall jet in cross flow, causing substantial mixing and loss. Results showed that the SDBD actuator was successful at reducing the momentum of the leakage flow, thereby reducing losses. These results were obtained for Reynolds numbers of 100,000 and 500,000.
The flow field produced within the exhaust of a jet gives rise to another instability in the form of a mixing layer between two fluids. The use of this instability, by an SDBD actuator, has been shown by Benard et al.\textsuperscript{223} to enhance the laminar-to-turbulent transition, thereby increasing the mixing rate. This is useful for increasing the rate at which the temperature of the exhaust decreases, reducing infrared radiation and increasing the burning rate of fuel. The perturbed flow field was measured using stereo PIV and LDV for flow velocities at the center line of 10 to 40 m/s which correspond to Reynolds numbers ranging from 33,000 to 128,000. Results show significant enhancement of jet spreading, a jet core length reduction and turbulent kinetic energy increase for steady and unsteady actuation for flow velocities below 40 m/s with little enhancement for jet velocities greater than 40 m/s. In particular, unsteady actuation led to the production of a Strouhal number ranging from 0.25-0.32 which was found to be particularly effective at enhancing the turbulent kinetic energy in the flow field. A further study by Benard et al.\textsuperscript{224} focused on applying multiple SDBD actuators operated in phase and 90 degrees out-of-phase. PIV results showed that in-phase operation resulted in little control of the exhaust, whereas out-of-phase operation resulted in a significant enhancement of mixing with an increase in jet flow entrainment of 180%. In a similar study, Labergue et al.\textsuperscript{225} used an SDBD actuator to separate flow along the lower hinged base-plate of a rectangular cross-section, turbulent jet to enhance mixing. PIV results were obtained for a flow velocity of 30 m/s and showed some increase in mixing.

Another area of potential application is for a stalled wing. In this situation, two different flow instabilities occur. The first is a local instability produced from a separating shear layer and the second results in the production of large-scale vertical structures that propagate into the wake. The maximum lift and stall characteristics of a wing affect many performance aspects of an aircraft such as takeoff and landing distance, maximum sustained turn rates, climb and glide rates and flight ceiling\textsuperscript{226}. Traditionally, leading-edge separation is handled using a slotted leading-edge flap (slot) which works by allowing air from the high pressure, lower surface to flow to the upper surface adding momentum to the boundary layer, suppressing flow separation. Some examples demonstrating the use of SDBD actuators for these instabilities can be found in the work by Maslov et al.\textsuperscript{227}, Post and Corke\textsuperscript{228}, Bernard et al.\textsuperscript{229,230} and Patel et al.\textsuperscript{231} Specifically, Maslov et al.\textsuperscript{227} delayed separation for a model RAE5212 transonic airfoil by placing an SDBD actuator slightly upstream of the separation line at the leading edge. This was accomplished for free-stream velocities up to 50
Post and Corke\textsuperscript{227} achieved similar results for a free-stream velocity of 30 m/s with corresponding Reynolds number of 333,000. Their results showed that reattaching the flow generated a full pressure recovery accompanied with a 400\% increase to the lift-to-drag ratio. Bernard et al.\textsuperscript{229,230} also showed that the SDBD actuator was able to suppress flow separation for a NACA 0015 airfoil. This was accomplished for a free-stream velocity of 20 m/s with corresponding Reynolds number of 260,000.

Based upon the positive results for suppressing flow separation at stall conditions, Patel et al.\textsuperscript{231} have put forth the idea of a self-governing smart plasma slat for active control of separation and incipient wing stall. The design uses plasma actuators on the leading edge of a NACA 0015 airfoil in such a way that they mimic the effect of a movable leading-edge slat of a conventional high-lift system. Adjustment of the actuator was accomplished with a feedback controller utilizing a high bandwidth pressure sensor. Results showed that stall hysteresis was eliminated and the stall angle was delayed by 7 degrees. They also showed a significant improvement in the lift-to-drag ratio for a large range of angles of attack for free-stream velocities of 21 m/s and Reynolds number of 180,000. The use of feedback control provided a means to reduce power requirements, increasing the efficiency for unsteady plasma actuator.

Another area of interest is in controlling the wake behind cylinders, which would correspond to similar conditions for flow fields produced by landing gear. These flow fields are characterized with alternately shedding vortices within the wake, called Karman vortex sheets, which produce undesirable effects such as fluid structure interaction, increased drag and large oscillatory lift. To put it in perspective, the greatest source of airframe noise is produced by this interaction. This is an undesirable effect of commercial aircrafts landing or taking off in airports; particularly near residential areas. Current flow actuators used to reduce this problem have low bandwidths and are unable to control the wake beyond 20 to 30 Hz, which is insufficient since the bandwidth of the shedding can be as high as 100 Hz. With this in mind, McLaughlin et al.\textsuperscript{232,233} utilized the SDBD actuator to control the wake behind the cylinder at a Reynolds number of 300,000 for bandwidths up to 500 Hz. Results showed that the SDBD actuator was able to lock-in the shedding frequency and delay separation beyond the cylinder rear stagnation point. They concluded that these devices would be useable for this application if the induced momentum was significantly increased. Similar results were reported by Thomas et al.\textsuperscript{234,235} for a Reynolds number of 33,000. Results showed that both unsteady
and steady actuation led to the elimination of Karman shedding. Specifically, unsteady actuation, with a duty cycle of 25%, led to identical results produced by steady actuation. This is important because the power requirements in this case is reduced by 75%. Also worth noting is the turbulence in the wake was significantly reduced, resulting in a 13.3 dB reduction of the near-field sound pressure. The reduction in turbulence within the wake is best observed from Figure 2.37.

Another source of noise is airflow over an open cavity. The generation of noise, for this structure, occurs by the so called Rossiter mode which comes about in the following manner: vortices in the shear layer shed periodically from the leading edge of the cavity and convect downstream to the rear wall. Acoustic disturbances are generated from an interaction between the vortices and the rear wall. This acoustic disturbance then propagates back upstream to the leading edge of the cavity and disturbs the shear layer, producing new vortices, thus creating a feedback loop. The tonal frequencies produced by this phenomenon can be predicted using a semi-empirical formula developed by Rossiter. It has been shown by Chan et al.\textsuperscript{236} that the noise level produced can be controlled by an SDBD actuator for free-stream velocities up to 20 m/s with corresponding Reynolds number of 71,000. The characteristic dimension used to compute this Reynolds number is the depth of the cavity. Specifically, results demonstrated that the dominant cavity mode, along with its harmonics, was attenuated to the broadband level. This came about because the plasma actuator produced vortices, which altered the development of the vortices in the cavity shear layer, ultimately disrupting the feedback mechanism.
Figure 2.37: Smoke visualization of the flow field demonstrating the ability of the SDBD actuator to reduce the turbulence within the wake. Taken from Thomas et al.\textsuperscript{234}

The above examples of potential applications introduced several key flow instabilities utilized by SDBD actuators. With these introduced, it is now possible to discuss the potential application of flight control via SDBD actuators. For this application, the actuators are required to control rolling, steering and changes in
elevation. Many of these studies have focused on comparisons between the capabilities of preexisting actuators and the SDBD actuator. For example, according to a report from Corke et al., steady and unsteady actuation of an SDBD actuator is capable of controlling separation on a separation ramp, at the trailing edge of an HSNLF(1)-0213 airfoil, resulting in a production of lift comparable to that of a moving plane flap. These results appear significant for the potential use of flight control; except that the free-stream velocity was 21 m/s with a corresponding chord Reynolds number of 215,000. Patel et al. applied an SDBD actuator to the leeward side of an airfoil for angles of attack ranging from -10 to 26 degrees and a free-stream velocity of 15 m/s. Results showed that the SDBD actuator was insufficient to alter the flow field at angles of attack below 15 degrees. The work by Patel et al. was further explored by Nelson et al. who determined from flow visualization that the windward surface is characterized with a small cross-flow component and is potentially more susceptible to the actuation of an SDBD. In light of this, the SDBD actuator was located at the leading edge. This enabled the SDBD actuator to control flows for angles of attack greater than 15 degrees, along with substantial improvement to the overall performance. The enhancement was sufficient enough that Nelson et al. concluded that the SDBD actuator was as effective for roll control as a conventional trailing edge aileron. These results were obtained for free-stream velocities as high as 30 m/s with corresponding Reynolds numbers up to 450,000. Another example is provided by Lopera et al., who applied an SDBD actuator to alter flow past an aft separation ramp on a scaled-1303 unmanned air vehicle, producing changes in lift sufficient for maneuvering at Reynolds numbers of 433,000. In a similar study, Post et al. investigated the use of an SDBD actuator on an HSNLF(1)-0213 airfoil at Mach 0.1 and 0.2 with corresponding Reynolds numbers of 292,000 and 584,000. The objective was to use the SDBD as an aileron-up or trailing-edge flap. Experiments were performed for angles of attack ranging from -2 degrees to 16 degrees. Results showed a 2% increase in lift coefficient and an 8% increase in drag coefficient at Mach 0.2. They concluded that the steady plasma actuator with an upstream oriented body force was able to trip the boundary layer, causing a delay in separation or possibly a turbulent reattachment of the flow.

Vorobiev et al. studied SDBD actuators applied as near-trailing-edge actuators, on an NACA0009 airfoil, for the improvement of lift and roll-control. Roll was induced by placing SDBD actuators across the length of the airfoil and only operating those located on one side. Results showed an increase in lift and proof of concept for generating moments strong enough to induce rolling motion of an air vehicle for a
free-stream velocity of 40 m/s. Patel et al.\textsuperscript{,245} investigated the use of an SDBD actuator for hingeless flow control over a 47 degree, 1303 unmanned air vehicle. Actuation was performed on the lee side, at the leading edge for a chord Reynolds number of 412,000 and angles of attack ranging from 15 to 35 degrees. When compared to the conventional trailing-edge actuator devices, the plasma actuators greatly improved the lift-to-drag ratio, and demonstrated significant improvement in control authority for angles of attack ranging from 15 to 35 degrees. Results demonstrated that plasma actuators are able to perform well for highly swept wings at high angles of attack in which conventional flaps and ailerons are ineffective.

The above studies give positive results for controlling flight; however, the work of Mabe et al.\textsuperscript{,246} demonstrated that the SDBD actuator was insufficient for this purpose. In this study, the effect of an SDBD actuator on the lift and drag of an NACA0021 airfoil is reported. For angles of attack ranging from -4 to 20 degrees, results demonstrate that the induced momentum was insufficient at preventing flow separation for chord Reynolds numbers greater than 100,000. His final conclusion was that they “may” be useful for microairvehicles (MAV), but otherwise SDBD’s are less effective when compared to other aerodynamic actuators.

When comparing the free-stream velocities of the above studies, with take-off and landing velocities of around 100 m/s and cruising velocities of 250 m/s\textsuperscript{,247}, one can conclude that flight control of larger aircraft, using SDBD actuators, is currently not possible; however, there is a very real possibility of controlling smaller air vehicles, such as MAV’s. These air vehicles are defined as having a characteristic length of 8 cm and mass of 30 g\textsuperscript{,248}. Their small size and low flight speeds of 5 to 6 m/s gives rise to many inherent problems, such as the production of lift. This occurs because conventional airfoils are not effective at producing lift for low flight speeds. For this purpose, SDBD actuators have been investigated to provide aid. The applicable range of Reynolds numbers, for MAV’s, is 30,000 to 100,000\textsuperscript{,248}. An example of increasing the lift of an MAV can be found in the work by Goksel et al.\textsuperscript{,248}. In this work, they employed unsteady actuation at a duty cycle as small as 0.66% which resulted in effective flow field control with power inputs of only 1.2 milliwatts per centimeter. A significant increase to lift, by as much as a factor of 2, was reported for the whole range of applicable MAV Reynolds numbers. In a similar study, Greenblatt et al.\textsuperscript{,249,250} also reported an increase in lift for a Eppler E338 airfoil over the applicable range of Reynolds numbers. Their results showed that the increased lift was insensitive to the duty cycle of unsteady actuation.
The SDBD actuator has also been used for several other applications, such as control of leading-edge flow separation and dynamic stall of blades used by rotorcraft\textsuperscript{251}, and to improve the efficiency for turbine blades used for windmills\textsuperscript{252}. The blades used by rotorcraft typically have in flight conditions of Mach 0.3 to 0.5 with a chord Reynolds number of 4,000,000, which is well beyond the abilities of an SDBD actuator. The situation is more favorable for the turbine blades used for windmills. In this case, the Reynolds number has a significantly large range depending on wind speeds, with a range from 30,000 to 3,000,000\textsuperscript{253}. The applicability of the SDBD actuator, for low end conditions, is possible. The objective of applying an SDBD actuator is to control leading-edge flow separation, thereby increasing blade loading and energy capture along with decreasing noise. The decrease in noise could be beneficial for windmills located near residential areas. Nelson et al.\textsuperscript{252} controlled blade loading by changing the effective pitch distribution across the turbine blade using SDBD actuators. The S8727 and the S822 airfoils were used in this study. The S827 airfoil was used to examine circulation control, thereby increasing the effective camber and leading-edge separation control, thereby increasing the coefficient of lift. The S827 airfoil was used to demonstrate geometric changes that promote local flow separations which can be easily manipulated by SDBD actuators to control lift. Both approaches produced controlled changes in the lift coefficients, equivalent to trailing-edge flaps or leading-edge slats, for free-stream velocities of 20 m/s with corresponding chord Reynolds number of 400,000. These results were shown to be obtainable with unsteady actuation, reducing the power consumed by the SDBD actuator by 90%.

The studies presented were conducted within controlled environments on models depicting real devices. A typical question that naturally arises when trying to apply results from controlled laboratory experiments to real applications is how will these results scale from controlled experiments to real applications? Attempts to address this problem have been discussed in the works by Asghar et al.\textsuperscript{254}, Corke et al.\textsuperscript{255} and Patel et al.\textsuperscript{256}. So far two different approaches have been applied to answer this question. The first relies on a theoretical analysis of the governing flow equations, whereas the second depends on a combination of experimental and computational results. The first approach has been demonstrated in the work by Asghar et al.\textsuperscript{254} who develop scaling parameters from nondimensional analysis of the governing flow equations. The governing equations required are the incompressible, steady, and laminar continuity and momentum equations for a boundary layer. The presence of the perturbation produced by an SDBD actuator is accounted
for by first quantifying the functionality of the induced body force, followed by nondimensionalizing it, and finally by inserting this result into the governing equations. In this work, the induced body force is approximated as the average force over the active plasma volume and is given as

\[ F_x = \frac{F_x}{\eta x_p s} \]  

(2.1.1.1)

where \( F_x \) is the maximum induced force in the \( x \)-direction, \( x_p \) is the plasma extent, \( \eta \) is the height of the plasma volume and \( s \) is the span of the electrode. The dimensional analysis indicates that the Reynolds number, along with how the induced body force changes per unit span, is required for scaling. The work by Corke et al.\textsuperscript{255} determined scaling parameters based on the second approach. They show that for unsteady actuation, scaling requires the Reynolds number along with another quantity describing the unsteady frequency. It was demonstrated that the unsteady frequency scales with the length of the separation zone and local velocity in the following manner

\[ F = \frac{f L_{sep}}{U_\infty} \]  

(2.1.1.2)

where \( f \) is the unsteady frequency, \( L_{sep} \) is the separation length and \( U_\infty \) is the free-stream velocity. Optimum results were shown to occur for an \( F \) value of unity. This result was further supported by the work of Patel et al.\textsuperscript{256}.

So far, in this section, proof-of-concept experiments have been discussed along with how they might scale to real life conditions. This provides a natural background for the final discussion of this section dedicated to the results of real flight data, along with conditions encountered in real flight, such as humidity and varying pressure for SDBD actuators.

Sidorenko et al.\textsuperscript{257} performed flight tests with SDBD actuators mounted onto the leading edge of a sailplane wing, as shown in Figure 2.38. The SDBD actuators were utilized in an effort to try and control flow separation for pre-stall and post-stall flight conditions. Data showed that the SDBD actuator had some effect on flow separation; however, little information, such as the flight speed and corresponding Reynolds number, was given. Another problem with the results is that the effect on flow separation was not clearly quantified.
The effect of humidity and varying pressure on the application of the SDBD actuator has been studied by Benard et al. In their study, the relative humidity ranged from 40 to 85%. Results showed that the presence of humidity reduces the induced momentum but that this loss can be made up by increasing the amplitude of the applied voltage. They note that the humidity appears to have an effect on the current, namely that at higher relative humidity, the number of current pulses delivered during the negative voltage half-cycle decreased. In contrast, the number of current pulses during the positive voltage half-cycle was found to first decrease with increasing relative humidity until 85% and then increase; however, this observation appears to be difficult to measure accurately. According to this study, actuation by plasma can be performed even in extreme humidity without damaging the dielectric layer or the electrodes. Also, unsteady actuation was applicable over the range of relative humidity studied. For the situation of altering pressure, a velocity is induced for low pressures of 0.2 atmospheres, so long as the encapsulated electrode width is increased for the increasing plasma extent. They also noted that the maximum induced velocity occurs at a pressure of 0.6 atmospheres. Finally, Segawa et al. showed that the performance of an SDBD actuator deteriorated with increasing temperature. This occurred when the temperature rises above 200 degrees Celsius.
CHAPTER 3: Equipment Description

3.1 The Surface-Discharge-Mode, Dielectric Barrier Discharge

The SDBD configuration and dimensions, used in this study, are shown in Figure 3.1. The exposed and encapsulated electrode are made out of copper and have an overlap length of 54.0 mm, 100 μm thick, and have widths of 4.4 and 10.7 mm, respectively. The copper tape used has glue on the backside enabling it to stick to the dielectric barrier, which is made from a VWR Pyrex micro slide. The dimensions of the dielectric barrier are 76.2 mm wide, 25.4 mm long and 1.0 mm thick. The dielectric constant of the effective dielectric layer, consisting of contributions from glue and Pyrex, was measured because, at this time, the material was unknown, and because the effective dielectric layer consists of two different materials. The measured dielectric constant was found to be 5.9 and is reasonably close to the tabulated value of 5.6 for Pyrex. The discrepancy between values is most likely due to edge field effects and/or the glue. The details associated with measuring the dielectric constant can be found in Appendix A.

A discharge is established over the encapsulated electrode by placing an oscillating voltage of sufficient strength between the two electrodes. A schematic of the system used to supply power to the SDBD is shown in Figure 3.2. The initial signal is produced by an Agilent 33220A function generator. The output voltage waveform from the function generator is sent to a Crown CE1000 power amplifier via a BNC connection. The voltage output from the amplifier is increased with a Corona Magnetics Inc CMI-5012 step-up transformer. The transformer is designed to operate at a frequency of 5 kHz, is directly attached to the SDBD, and is capable of delivering up to 20kV at 5 kHz. The power amplifier and function generator are shown in Figure 3.3.
A copper oxide layer on the surface of the electrodes was found to have an effect on the measured currents and therefore was removed using steel wool. The surface of the SDBD was then cleaned using methanol. The encapsulated electrode was insulated with RTV silicon to prevent breakdown on the backside. The significance of breakdown on both sides is shown in the voltage-current traces of Figures 3.4 and 3.5. Comparison between the current profiles in these figures show that the larger amplitude, positive current pulses, delivered during the negative voltage half-cycle, are greatly reduced by eliminating breakdown on the encapsulated electrode side. This occurs because the discharge structures produced at the exposed electrode correspond to the glow-like structures, as shown in Figure 2.23a, whereas the discharge structures produced by the encapsulated electrode correspond to the cathode-directed streamers, as shown in Figure 2.23b.
Figure 3.2: Schematic of the system used to supply power to the SDBD.

Figure 3.3: Power amplifier and function generator used to power the SDBD.
Figure 3.4: Voltage-current profiles for an SDBD with breakdown on the exposed electrode side only.

Figure 3.5: Voltage-current profiles for an SDBD with breakdown on both sides.
### 3.2 The Electrical Measurement Set-Up

The measured voltages and currents of the SDBD are recorded with a Tektronix TDS 3034B oscilloscope, having a bandwidth and rise time of 350 MHz and 1 nanosecond, respectively. The voltage waveform is measured using a Tektronix P6015A high voltage probe, capable of measuring peak-to-peak voltages up to 20kV, and has a bandwidth and rise time of 75 MHz and 4.7 nanoseconds, respectively. This is a passive probe; therefore, the ground lead has to be attached to the circuit ground. The discharge current is obtained by measuring the voltage drop across a 100 Ohm resistor, in series with the SDBD, using a Tektronix P6139A passive probe. Figure 3.2 shows the system schematic used for this procedure. The dissipated power could be obtained using the measured voltage and currents; however, an easier way, along with additional information, can be obtained using a Lissajous chart. The details of this method are presented in Appendix B. The use of a Lissajous chart requires the measured charge of a capacitor in series with the SDBD. The schematic is similar to Figure 3.2, except that the resistor is replaced with a 4.57 nF capacitor. The charge is obtained by measuring the voltage drop across the capacitor using a Tektronix P6139A probe, and multiplying the voltage by the capacitance. The capacitance of the capacitor was obtained by measurement; the procedures to do so are outlined shortly. Both probes are designed for the oscilloscope and have been properly compensated.

The proper use of these probes was verified by measuring the currents of the simple circuits shown in Figures 3.6 and 3.7. The voltages associated with the circuit given in Figure 3.6, from Kirchhoff’s voltage law, are given as

\[ V(t) = I(t)[R_1 + R_2] \]  \hspace{1cm} (3.2.1)

where \( V \) is voltage, \( I \) is current, and \( R \) is resistance. The voltage drop across the resistor \( R_2 \) is given as

\[ V_{R_2}(t) = I(t)R_2 = V(t) \frac{R_2}{R_1 + R_2} \]  \hspace{1cm} (3.2.2)

where the current is obtained from Equation 3.2.1. The measured value of the voltage across \( R_2 \) was found to be

\[ V_{R_2}(t) = 2.45 \sin(2\pi5000t) \text{ (volts)} \]  \hspace{1cm} (3.2.3)

which has an uncertainty of 0.8%. 

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The current for the circuit shown in Figure 3.7 is given as
\[
I(t) = C \frac{dV_C}{dt} = \frac{V_{R_1}(t)}{R_1} \tag{3.2.4}
\]
where \(V_C\) is the voltage drop across the capacitor, and \(V_R\) is the voltage drop across the resistor. The capacitance is obtained by rearranging Equation 3.2.4 and is given as
\[
C = \frac{V_{R_1}(t)}{R_1 \frac{dV_C}{dt}} \tag{3.2.5}
\]
where the voltage drop across the capacitor is given as
\[
V_C(t) = V(t) - V_R(t) \equiv V(t). \tag{3.2.5}
\]
The measured capacitance was found to be 567 pF and has a deviation of 1.2% from the manufacture’s reported value of 560 pF. The tolerance reported by the manufacture was 15%. The capacitance was found with and without using the assumption implied in Equation 3.2.5, which resulted in a difference of 0.02% for the measured capacitance. The use of a simple RC circuit is used for determining the capacitance of any capacitors used in the SDBD system because the measured value is typically more accurate than the value reported by the manufacturer.

Figure 3.6: A simple resistive circuit.
Figure 3.7: A simple RC circuit.

\[ V(t) = 2.47 \sin(2\pi 5000t) \]

\[ R_1 = 93.9 \]

\[ C_1 = 560 \, \text{nF} \]
3.3 SDBD Force Measurement Experimental Set-Up

The body force applied to the SDBD is equal in magnitude and opposite in direction of the induced thrust. Thus the induced thrust can be implied from measurements of the body force. The system shown in Figure 3.8 measures the displacement of the SDBD due to the applied body force. The system consists of an SDBD mounted with monofilament line and a laser displacement meter. As Figure 3.8 shows, the force measurement system is housed in an enclosure. This was done because the natural air flow within the room is sufficient to disturb the measurement. The laser displacement meter has a working distance of 150 mm and is capable of measuring displacements as small as 10 µm. Standard masses made by Ohaus, model number 210-01 were placed on top of the SDBD, producing the calibration curve shown in Figure 3.9. Each measured point on the calibration curve was obtained by taking the average of 65,000 displacement measurements over the course of five minutes. This was done before and after the addition of the standard masses. Prior to measurement the system was allowed time to damp out. The linear least squares fit of the measured force versus displacement along with the residual is shown in Figure 3.9.
The reported empirical relationship between average thrust and voltage was found to be well approximated using a power fit \(^{75,119}\), given as

\[
\overline{F} = a V^b
\]  \hspace{1cm} (3.3.1)

where \(a\) and \(b\) are fitting parameters. The objective behind this experiment is to determine the actual strength of the induced thrust and to determine the reported discrepancy between the empirical relationship of voltage and thrust. In reference 75, the dependence of force was found to be proportional to voltage raised to the 3.5 power, whereas, in reference 119, force was shown to be proportional to voltage raised to the 6 power. The possibility of how force multipliers such as the mechanical advantage of a lever arm, and additive forces affect the power fit is analyzed to aid in understanding measurements reported in the literature and in designing the experiment proposed in this section. For a mechanical advantage, designated as \(r\), the measured forces are given as

\[
r \overline{F} = a V^b.
\]  \hspace{1cm} (3.3.2)

Taking the natural logarithm of Equation 3.3.2 gives

\[
\ln(r \overline{F}) = \ln(r) + \ln(\overline{F}) = \ln(a V^b) = b [\ln(a) + \ln(V)].
\]  \hspace{1cm} (3.3.3)
Rearranging Equation 3.3.3 results in

\[
\ln( F) = b \ln(V) + b \ln(a) - \ln(r) \tag{3.3.4}
\]

which is simply an equation of a line with slope \( b \), and offset \( b\ln(a) - \ln(r) \). Equation 3.3.4 demonstrates that the use of a mechanical lever does not affect the exponential fitting parameter, only the intercept term in the linear equation.

The effect on the fit, assuming a power fit, due to multiple, linear forces acting on the SDBD, can be determined by considering

\[
\vec{F}_{\text{tot}} = \vec{F}_1 + \vec{F}_2 = aV^b. \tag{3.3.5}
\]

Again, taking the natural logarithm and rearranging yields

\[
\ln(\vec{F}_1 + \vec{F}_2) = b \ln(V) + b\ln(a), \tag{3.3.6}
\]

an equation of a line. The exponent and proportionality fitting parameters are changed by the presence of additional forces. From this analysis, the contribution of forces other than the induced thrust such as friction, incorrect calibration, buoyancy, or forces associated with the wires must be negligible when compared to the thrust or else an incorrect dependence will be observed. These factors were included in the development of the measurement system. The effect of the wires was reduced by using conductive carbon fibers. The buoyancy force, due to heating, was determined from

\[
F_b = [\rho(T_1) - \rho(T_2)] \forall \ V g \tag{3.3.7}
\]

where \( \rho \) is the density evaluated at \( T_1 \) and \( T_2 \), \( \forall \) is the volume, and \( g \) is the acceleration of gravity. The force calculated was \( 3.5 \times 10^{-4} \) mN which is several orders of magnitude smaller than the thrust.
3.4 The Spectroscopic Experimental Set-Up

The experimental set-up for the spectroscopic measurements is shown in Figure 3.10 and is housed within a ventilated wooden box. Each of the individual components of the set-up is discussed individually.

Figure 3.10: Left: Experimental set-up. Right: Close up image of the equipment within box.

The SDBD model is mounted vertically, as shown in Figure 3.10, on a $xy$ translating stage. The translating stage consists of two Newport M-443 series, linear stages connected together with a Newport 360-90 bracket. The desired positioning is obtained, in both directions, by adjusting a Newport SM-50 micrometer with maximum travel of 50.8 mm.

The collection optics system and schematics are shown in Figures 3.10b and 3.11, respectively, and consists of 2 plano-convex lenses and a fiber optic bundle. The emitted radiation is collected and collimated with a Thorlabs LA4148 fused silica plano-convex lens, having diameter and effective focal length of 25.4 and 50 mm, respectively. The collimated beam is focused onto a Roper Scientific LG-455-020-1 fiber optic bundle with a Thorlabs LA4158 fused silica plano-convex lens, having a diameter and effective focal length of 25.4 and 250 mm, respectively. The resulting magnification is 5 and has a corresponding collection volume with dimensions $A = 0.2$ mm and $B = 0.7$ mm, for a plasma thickness of 1 mm. The front lens is mounted within a Thorlabs SM1V10 focusing element, which is attached to a Thorlabs SM1L30 lens tube. The back lens is mounted within the lens tube and is attached to a Thorlabs
SM1E34-200 lens tube extension. The fiber optic cable is attached to a Thorlabs SM1SMA fiber adapter mounted on the back of the lens tube extension.

![Schematics of collection optics.](image)

**Figure 3.11**: Schematics of collection optics.

The fiber optic bundle channels the collected radiation into an Acton 2756 - ¾ meter Czerny-Turner configuration spectrometer where it is diffracted and focused onto an Andor DU 440-BU CCD camera. The spectrometer has a resolution of 0.023 nm at 435.8 nm using a grating of 1200 grooves per mm and 0.010 nm at 380.415 nm using a holographic grating with 3600 grooves per mm. The aperture ratio is f/9.7, and was properly under filled with an f-number of 9.84, corresponding to the back lens shown in Figure 3.11. The slit height and width, for all measurements presented, were 4 mm and 15 μm, respectively. The 1200 groove per mm grating was calibrated for wavelength using hydrogen lines at 383.5484, 388.9049, 397.0072, 410.174, 434.047, 486.133, 656.272, 954.597, 1004.94, and 1093.81 nm.
produced by a SP200 spectrum tube. Comparison between the measured and NIST tabulated lines are shown in Table 3.1.

<table>
<thead>
<tr>
<th>1200 groove/mm</th>
<th>NIST Wavelength (nm)</th>
<th>Measured Wavelength (nm)</th>
<th>Error (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>383.5484</td>
<td>383.67</td>
<td>-0.13</td>
<td></td>
</tr>
<tr>
<td>388.9049</td>
<td>388.98</td>
<td>-0.08</td>
<td></td>
</tr>
<tr>
<td>397.0072</td>
<td>397.05</td>
<td>-0.04</td>
<td></td>
</tr>
<tr>
<td>410.174</td>
<td>410.17</td>
<td>0.004</td>
<td></td>
</tr>
<tr>
<td>434.047</td>
<td>434.20</td>
<td>-0.15</td>
<td></td>
</tr>
<tr>
<td>486.133</td>
<td>486.25</td>
<td>-0.12</td>
<td></td>
</tr>
<tr>
<td>656.272</td>
<td>656.29</td>
<td>-0.02</td>
<td></td>
</tr>
<tr>
<td>954.597</td>
<td>954.64</td>
<td>-0.04</td>
<td></td>
</tr>
<tr>
<td>1004.94</td>
<td>1005.00</td>
<td>-0.06</td>
<td></td>
</tr>
<tr>
<td>1093.81</td>
<td>1093.90</td>
<td>-0.09</td>
<td></td>
</tr>
</tbody>
</table>

**Table 3.1:** Comparison between measured and NIST tabulated transitions of hydrogen for the 1200 groove/mm grating.

The above procedure correctly determines the wavelength at the center pixel; however, the grating equations for a Czerny-Turner configuration spectrometer have to be used in order to obtain the correct wavelength at the off-center pixels. The procedure is handled with a small code that reads in the measured spectra scan and outputs the corrected data. The wavelength at a particular pixel in the exit plane of the spectrometer can be written, in terms of the geometry, as

\[
\lambda' = \frac{d}{m} \left\{ \sin \left( \frac{\psi - \frac{\pi}{2}}{2} \right) + \sin \left( \psi - \frac{\pi}{2} + \xi \right) \right\}
\]  \hspace{1cm} (3.4.1)

where \( \lambda' \) is wavelength, \( d \) is length between grooves, \( m \) is the grating order, and \( \psi \) is the inclusion angle. The angles \( \psi \) and \( \xi \) represent the angle of rotation for the grating and the incident radiation, respectively, and are defined below as

\[
\psi = \sin^{-1} \left( \frac{m \lambda_{\text{Center Pixel}}}{2d \cos(\frac{\pi}{2})} \right) \hspace{1cm} (3.4.2)
\]

and

\[
\xi = \tan^{-1} \left( \frac{n x \cos(\delta)}{f + nx \sin(\delta)} \right) \hspace{1cm} (3.4.3)
\]

Where \( x \) is the pixel width, \( n \) is the number of pixels away from the center pixel, \( f \) is the focal length, and \( \delta \) is the detector angle. Figure 3.12 shows the measured 0-2, 1-3, 2-4 and 3-5 vibrational transitions of the
$N_2(C^3Π_u → B^3Π_g)$ band overlaid with the calculated spectrum. The figure shows that wavelength is correctly calibrated for the off-center pixels. The wavelength at the center pixel, as shown in Table 3.1, is well known; however, in the case of known transitions this quantity can be iterated upon until the measured wavelength of the transitions match the tabulated, resulting in near perfect agreement. The spectra data displayed throughout this document were obtained in this manner unless otherwise specified.

![Figure 3.12](image.png)

**Figure 3.12:** Comparison between measured and calculated spectra of 0-2, 1-3, 2-4 and 3-5 vibrational transitions of $N_2(C^3Π_u → B^3Π_g)$.

The spectral response of the system was calibrated using a Newport 63976 tungsten halogen lamp. The signal due to stray light inside the spectrometer, caused from the imperfections of the internal optical components of the spectrometer, was obtained by using a filter that blocks the wavelength range over which the calibration curve is being obtained. The use of a filter blocks the actual signal so that any intensity measured corresponds with stray light and can then be subtracted from the lamp spectra. The calibration curve is given by
The calibrated data is given by

\[
\text{Calibrated Data} (\lambda) = \frac{\text{Raw Data} (\lambda)}{\text{Calibration Curve} (\lambda)}.
\]  

(3.4.5)

An optical chopper is used to block radiation from either the positive voltage or negative voltage half-cycle, allowing radiation from the opposite voltage half-cycle. The size of the slit of the chopper blade has to be as close as possible to the size of the opening of the fiber optic bundle. Also, it is important that the space between the blade and optic bundle be as small as possible. A laser and a voltage cell, placed at the bottom end of the chopper, determine whether the open slit is passing through the optical line of sight. A voltage of zero corresponds to when the blade blocks the laser from the sensor, and a voltage of four volts corresponds to when the laser passes through the slit of the blade. The chopper voltage, applied voltage, and discharge current are measured and shown in Figures 3.13 and 3.14 for the positive and negative voltage half-cycle, respectively. The optical chopper is used to trigger the function generator and the phase of the function generator was set to determine which voltage half-cycle was blocked.

**Figure 3.13:** Voltage and current characteristics of the SDBD. Chopper is blocking the negative voltage half-cycle. The chopper voltage was multiplied by a constant factor for display purposes.
Figure 3.14: Voltage and current characteristics of the SDBD. Chopper is blocking the positive half-cycle. The chopper voltage was multiplied by a constant factor for display purposes.

The use of an optical chopper to separate radiation from each voltage half-cycle was verified by comparing the measured spectra of each voltage half-cycle with spectra measured with a PI Max ICCD camera. In this experiment, the ICCD was triggered with the Agilent function generator. The ICCD has a minimum offset of 26 nanoseconds which is much shorter than the 60 microseconds current is delivered. Also, the radiative lifetime of the excited states, in an atmospheric pressure air discharge, is on the order of 1 nanosecond. Spectra emitted during three different regions within the discharge were measured with the ICCD camera, as indicated in Figure 3.15. Region 1 corresponds to the positive voltage half-cycle, region 3 corresponds to the negative voltage half-cycle, and region 2 corresponds to the region between the two voltage half-cycles. The spectra obtained for these three regions are shown in Figure 3.16. The spectra obtained for region 2 indicates that the phase correlation is correct for the current, voltage, and spectra data. The spectra collected from region 2 lies on the horizontal axis because the emission is essentially zero. There is no significant emission when there is no current through the discharge. The asymmetry of the
spectra for the two voltage half-cycles is also apparent. The negative voltage half-cycle is characterized by lower intensities for all emitting species. The spectra from the positive voltage half-cycle are dominated by the $N_2^+ (B^2 \Sigma_u^+ \rightarrow X^2 \Sigma_g^+)$ electronic band system around the band head of this system. The intensity of the $N_2 (\Omega^3 \Pi_u \rightarrow \Omega^3 \Pi_g)$ electronic band system is also greater for this half-cycle.

The spectra from both voltage half-cycles, measured with the optical chopper, are overlaid in Figure 3.17. The same qualitative tendencies, observed with the ICCD, are present. In Figure 3.18, a comparison between spectra, obtained with the chopper blade in an open and closed position, is given. This figure shows that no signal is obtained for the closed position, whereas a signal of 15,000 counts is obtained for the open position. It was concluded that the optical chopper is functioning as intended from these two figures.

Figure 3.15: Voltage and current characteristics of the SDBD from ICCD measurements.
Figure 3.16: Top: spectra for regions 1-3 with an ICCD. Bottom: spectra measured in regions 1 and 3 with an ICCD’s. Vibrational transitions marked with red numbers indicate vibrational bands for $N_2^+ (B^2 \Sigma_u^+ \rightarrow X^2 \Sigma_g^+)$ electronic band system and vibrational transitions marked with blue numbers indicate vibrational bands for $N_2 (C^3 \Pi_u \rightarrow B^3 \Pi_g)$. 
Figure 3.17: (a.) The measured and fit spectra for the negative voltage half-cycle. (b.) The measured and fit spectra for the positive voltage half-cycle. Vibrational transitions marked with red numbers indicate vibrational bands for $N_2^+$ ($B^2\Sigma_u ^+ \rightarrow X^2\Sigma_g ^+$) electronic band system and vibrational transitions marked with blue numbers indicate vibrational bands for $N_2(C^3\Pi_u \rightarrow B^3\Pi_g)$.

Figure 3.18: Comparison of the spectra measured with the optical chopper in the open and closed position.
CHAPTER 4: Results

4.1 Measured Forces of the SDBD

The discussion from Chapter 2.3 demonstrated that the induced flow produced by an SDBD was very weak and unable to effectively alter flow fields for real flight conditions. In this section, the thrust is measured to demonstrate exactly how weak, providing justification for the proposed fundamental study. Also, how the force changes as a function of dissipated power and voltage is presented. This was done to try and understand why results presented within reference 75 do not match results presented within reference 119. Finally, the produced thrust of the SDBD is the most important quantity for aerodynamic flow control. Therefore, one way to quantify the effectiveness of the SDBD is to measure the reaction force produced by the induced thrust. This is also a good way to gage research progress in developing the SDBD for application. The approach is to measure the induced thrust using a technique that is different than the technique used in references 75 and 119.

In this section, the force produced by an SDBD is measured using the system shown in Figure 3.8. The calibration curve, relating deflection with force is given in Figure 3.9. A mass balance was also used to measure the body force; however, the technique was found to have several problems and was abandoned.

The applied voltage amplitude and the discharge current were measured along with the force using the laser displacement meter. The force is plotted versus dissipated power and applied voltage amplitude; however, it is felt that plotting the force versus dissipated power is the more appropriate parameter. The justification being that two different forces can be obtained for the same applied voltage amplitude. This can happen because the discharge current can change due to heating and due to changes in the surface via chemical reactions. The dissipated power would be sensitive to any physical change of the discharge, making it less likely for two different forces to occur for the same dissipated power. In the results given, force is plotted versus both voltage and dissipated power because most groups only plot it versus voltage.

The measured forces versus voltage are given in Figure 4.1. The measured thrust was found to be directly proportional to the applied voltage amplitude. The empirical relationship along with the residual is
shown on the figure. It is interesting to note that the empirical relationship has a y-offset of -33.1 mN/m, which should have a value of zero. It is believed that force is not linear outside the voltage range measured which is why the offset is -33.1 mN/m. The trend is also found to differ from those reported by Abe et al.\textsuperscript{119} and Enloe et al.\textsuperscript{75} In the results reported by Enloe et al., the force was found proportional to $V^{7/2}$. It is plausible that the results reported in Figure 4.1 have a similar dependence but is not observable because the force was not measured with large enough applied voltage amplitudes. Also, the measured forces range from 2 mN/m at a voltage of 5400 volts and 23 mN/m at a voltage of 8600, demonstrating how weak the induced thrust is.

![Graph showing thrust force of an SDBD versus applied voltage amplitude.](image)

**Figure 4.1:** Thrust force of an SDBD versus applied voltage amplitude.
The measured power versus applied voltage amplitude is given in Figure 4.2 and is best represented using a power fit with an exponent of 3. The empirical equation and residual is shown on the figure. It should be mentioned that the measured power agrees with those reported by Enloe et al.\textsuperscript{75}. The measured force per unit length versus power dissipated is shown in Figure 4.3. The empirical relationship between force per unit length and dissipated power is obtained by solving the system of equations shown on Figure 4.1 and 4.2, is given as

\[ F(P) = 0.0064 \left( \frac{p}{4 \times 10^{-13}} \right)^{\frac{1}{3}} - 33.13 \quad 5280 \leq V \leq 8600 \quad (4.1.1) \]
In this section, thrust was measured as a function of applied voltage amplitude and power dissipated. The forces produced as a function of applied voltage amplitude and dissipated power were presented. The force appeared to increase with respect to dissipated power cubed and linearly with the applied voltage amplitude. This is close to what other investigators have reported. The deviation most likely is caused by the limited voltage range studied which was not wide enough to show a nonlinear dependence. It could also be the published results are incorrect. Finally, the magnitude of the produced thrust was shown to range from 2 to 23 mN/m for applied voltages of 5400 to 8600 volts, demonstrating the need for improvement via a fundamental study.
4.2 Electrical Measurements of an SDBD

The discussion presented in Chapter 2, dedicated to the background of SDBD’s, demonstrated that the various effects produced by an SDBD such as an induced flow, a chemically active environment, and the emission of radiation are the byproducts of an electrical interaction with the surrounding environment. Therefore, understanding the electrical nature of an SDBD is essential to understanding measurements associated with these byproducts. In addition, the SDBD is fundamentally an electrical device which means that any serious model of the SDBD must satisfy Maxwell’s electromagnetic equations. The solution of Maxwell’s equations requires appropriate boundary conditions. One of these boundary conditions, the voltage potential at the exposed electrode, is already known. Another boundary condition which is not known is the surface potential along the dielectric surface due to free charge build-up. Based on this, an initial study was conducted to determine some of the electrical properties including the surface charge potential, effective capacitance of the SDBD and dissipated power associated with the specific SDBD used in this study. The intention behind measuring the surface charge potential is to aid computational models. The discussion that follows first lays the necessary groundwork required for obtaining each of the electrical parameters measured, concluding with the measured surface charge potential along the dielectric surface.

The first experiment was dedicated to investigating the relationship between average current and average voltage, the results of which are shown in Figure 4.4. An average is obtained by averaging over 512 current-voltage waveforms. These results are easily interpreted based on the equivalent circuit shown in Figure 2.32. When the applied voltage is less than the breakdown voltage, the measured current is entirely displacement current and is given by the linear equation

\[ I(t) = C_{die} \frac{dv(t)}{dt}. \]  

(4.2.1)

The average current in this regime is given as a straight line and corresponds to the pink line, designated as “no breakdown”, in Figure 4.4. This line was obtained from a least squares fit of the linearly dependent portion of the measured current and is used to determine the onset of breakdown. For breakdown, the applied voltage is greater than the breakdown voltage, and the current is given as the superposition of a
displacement current and a conductive current. The conductive current is delivered in short duration bursts, lasting for approximately 10 nanoseconds, and shows up as large spikes superimposed on top of the much smaller displacement current. In the case of currents averaged over 512 waveforms, as shown in Figures 4.5 through 4.7, the large spikes are averaged out, resulting in a smoothed profile. This suggests that the difference between the linear line and the measured current in Figure 4.4 is the conduction current; however, this is not correct because the displacement current contributes at a rate greater than suggested by the pink line after breakdown. This can more easily be seen from the equivalent circuit model which shows that the gas capacitance is a function of the plasma extent and changes during the course of breakdown. The point of deviation between the measured current and the pink line corresponds to the breakdown voltage and was found to be ~2800 volts for a 5000 Hz, sinusoidal voltage. This turns out to not be the most accurate method for determining breakdown voltage because sensitivity is lost when detecting breakdown events by averaging the current-voltage waveforms. This point will be discussed in a greater detail later on in this section.

![Figure 4.4](image)

**Figure 4.4**: Average current versus average applied voltage for an SDBD. The breakdown voltage corresponds to the point of deviation between the line labeled as “no breakdown” and the measured current.
When taking the data, it was noted that the shape of the average current waveform was distorted as the contribution of the conductive current increased. Initially the current waveform, at a voltage below breakdown, is a cosine, as shown in Figure 4.5. The waveform starts to distort at voltages greater than the breakdown voltage, as shown in Figures 4.6 and 4.7, for applied voltage amplitudes of 4290 and 5980 volts, respectively. For an applied voltage amplitude of 4290 volts, the distortion is small because the contribution from the average conductive current is small with respect to the contribution from the average displacement current. As shown in Figure 4.7, the distortion increases significantly for an applied voltage amplitude of 5980 volts, even for the portion of the current corresponding to no breakdown, designated as the passive phase. The distortion during this phase is due to the charging and discharging of the dielectric surface.

Figure 4.5: Voltage-current trace at an applied voltage amplitude of 2800 volts.
Figure 4.6: Voltage-current trace for an applied voltage amplitude of 4290 volts. The current waveform shows slight distortion due to the contribution of the conductive current.

Figure 4.7: Voltage-current trace for an applied voltage amplitude of 6000 volts. The current waveform is significantly distorted, even in the passive region corresponding to no breakdown.
Another interesting observation, demonstrated with a large applied voltage, is that the active phase of the negative voltage half-cycle, constituting the period of breakdown, starts when the applied voltage is positively biased. In a similar manner, the active phase of the positive voltage half-cycle starts when the applied voltage is negatively biased. This is more easily seen in the current-voltage profiles, shown in Figures 4.8 and 4.9, depicting the negative and positive voltage half-cycles, respectively. The current-voltage waveforms shown in these figures are not averaged, clearly showing the conductive current spikes. For now, it is hypothesized that the early onset of breakdown occurs because of surface charge build-up from the previous discharge events. The basic idea is that free charged particles, produced during the previous active phase, coat the dielectric surface, altering the effective voltage across the gas, which results in early breakdown. Due to this, the definition of positive and negative voltage half-cycle is truly meaningful and correct when interpreted as the potential difference between the exposed electrode and the dielectric surface. The positive voltage half-cycle refers to a positive potential difference between the exposed electrode and dielectric surface; whereas the negative voltage half-cycle refers to a negative potential difference between the exposed electrode and dielectric surface.

The question remains as to whether surface charge is responsible for the observable, early onset of breakdown. The answer is separated into an initial qualitative discussion, which lays down the necessary framework and a quantitative discussion based on experiment. First, in Figure 4.8, the discharge regime during the region $t_3.5 \leq t \leq t_0$ is the same as that during the region $t_0 \leq t \leq t_1$ because the measured currents, high-speed photographs, and photomultiplier emission measurements, as shown in Figures 2.22 and 2.23, respectively, are the same. Similarly, in Figure 4.9, the discharge regime during the regions $t_1.5 \leq t \leq t_2$ and $t_2 \leq t \leq t_3$, are the same. This is important because these discharge regimes, occurring during the negative and positive voltage half-cycle, occur only when the potential difference is negative or positive, respectively. The fact that the applied voltage switches sign and the discharge regime remains the same indicates that the sign of the potential difference remains unchanged. This could be explained because during the active phase of the negative voltage half cycle, region $t_3.5 \leq t \leq t_1$, free electrons are driven to the dielectric surface resulting in a negative voltage. The surface potential at the dielectric surface, produced by these events, decreases during the passive phase of the negative voltage half-cycle from $t_1 \leq t \leq t_{1.5}$; however, it never reaches zero. During this time, the applied voltage decreases at a greater rate, becoming
less positive until the potential difference between the exposed electrode and the dielectric surface is greater than the breakdown voltage, resulting in the initiation of breakdown at time $t = t_{1.5}$. The potential difference across the gas, given at this time, is

$$\Delta V = V_E - V_D = V_B. \tag{4.2.2}$$

where $V_E$ is the exposed electrode voltage, $V_D$ is the dielectric surface voltage, and $V_B$ is the breakdown voltage. In a similar manner, positive charge is driven towards the dielectric surface during the active phase of the positive voltage half-cycle, resulting in a positively charged surface. The surface potential produced by these events, at the dielectric surface, decreases during the passive phase of the positive voltage half-cycle from $t_3 \leq t \leq t_{3.5}$; however, it never reaches zero. During this time, the applied voltage decreases at a greater rate, becoming less negative until the potential difference between the exposed electrode and the dielectric surface is greater than the breakdown voltage, resulting in the initiation of breakdown at time $t = t_{3.5}$. The potential difference is also given by Equation 4.2.2. At this time, it is imperative to emphasize the first big assumption made when using Equation 4.2.2. Equation 4.2.2 assumes the potential difference across the gas is the breakdown voltage only at the instant when a passive phase gives way to an active phase or when an active phase gives way to a passive phase. At any other time, Equation 4.2.2 is not valid.

As mentioned, for this to be plausible the surface charge produced during the active phases of the discharge has to persist throughout the passive phases of the discharge, which last approximately 30 to 35 microseconds at the frequency and voltage used in Figures 4.8 and 4.9. Measurements by Opaits\textsuperscript{108} indicate that surface charge persists for up to 15 minutes providing some support that surface charge will remain throughout the passive phases of the discharge.
Figure 4.8: Current-voltage trace for the negative voltage half-cycle with an applied 6000 volt amplitude sinusoid. The current-voltage trace shown is not averaged. The large current spikes represent conductive current superimposed on top of a displacement current.

Figure 4.9: Current-voltage trace for the positive voltage half-cycle of an applied 6000 volt amplitude sinusoid. The current-voltage trace shown is not averaged. The large current spikes represent conductive current superimposed on top of a displacement current.
An experiment aimed at investigating the surface charge phenomenon was performed. First, the breakdown voltage is measured for both voltage half-cycles and is assumed to remain constant for every applied voltage amplitude investigated. The subtleties associated with this assumption simply imply that the breakdown voltage is insensitive to the time rate of change of the applied voltage. From Paschen’s law, which states the breakdown voltage is a function of pressure and the effective distance between the applied potential. In Paschen’s law, pressure indicates the particle number density. The breakdown of a gas is fundamentally a function of $E/n$ where $E$ is the electric field strength and $n$ is the particle number density. Thus the breakdown voltage of a gas can change with temperature even though the pressure remains constant. The temperature change causes the particle number density to change. This means the breakdown voltage of air will change slightly during the passive and active phases for each voltage half-cycle of the SDBD due to a slight temperature increase during the active phase. The amount of temperature increase is dependent on the applied voltage, but only increases slightly with increasing voltage. The second requirement for constant breakdown voltage is a constant effective length between two voltages, which is dependent on the surface charge distribution, requiring it to be similar for all peak voltages measured. Second, the evidence for this assumption must be measured. Third, the exposed electrode voltage at times $t_{1.5}$ and $t_{3.5}$, in Figures 4.8 and 4.9, are measured as a function of the voltage amplitude applied to the exposed electrode. Lastly, the voltage at the dielectric surface is determined from Equation 4.2.2, and plotted versus the applied voltage amplitude, resulting in two different profiles. The locations of the $x$-intercepts correspond to the absolute value of the breakdown voltage.

Initially, the breakdown voltage obtained from the average current-voltage profile, shown in Figure 4.4, was used for both voltage half-cycles. The exposed electrode voltage at times $t_{1.5}$ and $t_{3.5}$ were obtained from average current-voltage profiles, similar to those shown in Figures 4.5 through 4.7. The results showed an apparent trend, but were difficult to interpret. A more accurate and concise approach was instead used, which determined the desired quantities from unaveraged current-voltage profiles shown in Figures 4.8 and 4.9. A problem with using averaged current/voltage traces occurred because conductive current contributions, which are random in time, are washed out by averaging, resulting in an inaccurate
measurement of the breakdown voltage. Before these details are shown, the assumption of a similar surface charge distribution, occurring for each applied voltage amplitude, during the negative and positive voltage half-cycle, is shown. This is done by comparing the effective capacitances at time $t_{1.5}$ for each peak voltage with a similar procedure done for time $t_{3.5}$, using a Lissajous chart.

The development of an ideal Lissajous chart is given in Appendix B and is obtained in practice by measuring the charge accumulated on a capacitor in series with the SDBD. This capacitance is selected so that it is much greater than the capacitance of the SDBD, resulting in an insignificant voltage drop across the capacitor. In this work, the capacitance used is 4.57 nF, which is significantly greater than the SDBD capacitance of 4.4 pF, without breakdown. A measured Lissajous chart is given in Figure 4.10; the corresponding voltage-current profiles are given in Figures 4.8 and 4.9. The times indicated in Figures 4.8 and 4.9 correspond directly to those indicated in Figure 4.10. The slope of the Lissajous chart is simply a capacitance and is given as $\Delta Q/\Delta V$; thus the capacitances corresponding to the onset of the active phases at times $t_{1.5}$ and $t_{3.5}$, can be determined. The importance of this is that the capacitance is a function of the material and the geometry, and therefore, changes depending on the surface charge distribution. The effective capacitance of an SDBD, obtained using Lissajous charts for the positive and negative voltage half-cycle, as a function of the applied voltage for both active and passive phases are given in Figures 4.11 and 4.12, respectively.
Figure 4.10: Measured Lissajous chart for an SDBD driven by a sinusoidal voltage with amplitude of 6000 volts.

Figure 4.11: Effective capacitance of an SDBD as a function of applied voltage for the active and passive phases of the positive voltage half-cycle. The x-axis corresponds to the applied voltage as a function of time, whereas the voltages in the legend refer to the voltage amplitude of the sinusoidal voltage.
Figure 4.12: Effective capacitance of an SDBD as a function of applied voltage for the active and passive phases of the negative voltage half-cycle. The x-axis corresponds to the applied voltage as a function of time, whereas the voltages in the legend refer to the voltage amplitude of the sinusoidal voltage.

The effective capacitance, for all applied voltage amplitudes during the passive phases before breakdown, at times $t_{1.5}$ and $t_{3.5}$ are nearly the same at 5 pF. Closer inspection shows that the effective capacitance values, right at the onset of breakdown, are slightly less at the onset of the positive voltage half-cycle. The capacitance being similar for each applied voltage amplitude at the on-set of breakdown suggests that the normalized charge distribution on the dielectric surface does not noticeably change. It should be mentioned that the plasma extent increases linearly with respect to the applied voltage, and therefore, the surface charge on the dielectric extends further in the x-direction with increasing applied voltage (coordinate system is given in Figure 3.8). According to the capacitances measured at the onset of breakdown, the effect the surface charge from these distant regions has on the potential of the dielectric surface is negligible.

Unfortunately, the breakdown voltage for the negative voltage half-cycle is not the same as it is for the positive voltage half-cycle, creating some difficulty with the measurement. The breakdown voltage for the negative voltage half-cycle was obtained by slowly increasing the amplitude of an applied voltage amplitude, initially below breakdown. When the voltage was increased to 1900 volts, a single conductive
current spike occurring at the same time as the peak voltage was observed. At this voltage no conductive current was observed for the positive voltage half-cycle. Slowly increasing the applied voltage amplitude to 2100 volts resulted in conductive current pulses during the positive voltage half-cycle, which lined up with the peak positive voltage. The surface charge potential at the end of the negative voltage half-cycle was obtained using Equation 4.2.2 for a breakdown voltage of -1900 volts. This surface charge potential was then assumed to remain constant until the start of the positive voltage half-cycle so that the breakdown voltage of 2350 volts, for the positive voltage half-cycle, could be obtained. It should be noted that this value represents an upper range on this quantity, and therefore, is bounded between 1900 to 2350 volts. One way to measure the breakdown voltage directly, for the positive voltage half-cycle, would be to input a sinusoidal voltage with a positive DC offset so that breakdown would occur during the positive voltage half-cycle before the negative voltage half-cycle. Unfortunately, the use of a step-up transformer to power the SDBD does not permit the passage of a DC voltage.

The measured surface charge voltage at times $t_{1.5}$ and $t_{3.5}$, averaged over a sample size of 30, versus the applied voltage amplitude is shown in Figure 4.13. Times $t_{1.5}$ and $t_{3.5}$ change as a function of the applied voltage amplitude. The error bars represent the precision uncertainty of the sample at a 95% confidence interval. The surface charge potential is shown to be linearly proportional to the applied voltage amplitude over the voltage range measured. The absolute value of the breakdown voltage is obtained from the empirical equations by setting the surface charge voltage, represented by $y$ in the empirical equations shown in Figure 4.13, to zero and then solving for $x$. The breakdown voltages of the negative and positive voltage half-cycles, found using the linear least squares fit in Figure 4.13, are 2026 and 2323 volts, which match well with the measured values of 1900 and 2350 volts. The magnitude of the measured surface charge voltages compare well with results from references 77, 125, and 108 providing some support for these results.
Figure 4.13: Measured surface charge voltage, at time $t_{1.5}$ and $t_{3.5}$, versus the applied voltage amplitude of a sinusoidal voltage at a frequency of 5000 Hz.

The Lissajous charts are also a useful technique for obtaining the power dissipated by the discharge. The energy deposited per cycle is obtained by determining the area enclosed in Figure 4.10, and the corresponding power is determined by multiplying this quantity by the driving frequency. The power obtained versus the applied voltage amplitude is shown in Figure 4.14.
In this section, information about the surface charge potential on the dielectric surface is presented. The measured surface potential is for at the onset of breakdown only and for a single length i.e. the surface potential has no spacial dependence at this particular time; however, this quantity is in general a function of time and space. To measure the functional dependence of the dielectric surface potential on time and space requires a more sophisticated technique and was not available. The presented results of the dielectric potential still demonstrated that the surface charge can be significantly large depending on the applied voltage amplitude. In particular, it was shown that the dielectric surface potential increased linearly with respect to the applied voltage amplitude over a voltage range of 1900 to 6000 volts for both the positive and negative voltage half-cycle. Moreover, the measured potential along the dielectric surface is useful for understanding one of the required boundary conditions needed to solve Maxwell’s equations of electromagnetics.
4.3 Emission Measurements of an SDBD

In this section, optical emission spectroscopy is utilized to study some of the chemical kinetics of the SDBD. It was discussed throughout Section 2.1 and 2.2 that the induced flow is a product of momentum transfer between the ions and neutrals. The ions are produced within the chemically active plasma; therefore, a study dedicated to the production and spatial distribution of the ions within the plasma would be useful information. Other details associated with the chemical kinetics of the plasma are investigated within the rest of this chapter. This particular study is geared towards aiding the development of the essential physics needed in computational models.

Initially, optical emission spectroscopy measurements for an SDBD operating in atmospheric air at an ambient temperature of 295 K are temporally averaged over both voltage half-cycles. Results include spatially resolved rotational and vibrational temperatures. The temperatures are obtained from the $^3Π_u \rightarrow B^3Π_g$ electronic band system of $N_2$ and from the $B^2Σ^+_u \rightarrow X^2Σ^+_g$ electronic band system of $N_2^+$. The translational temperature is inferred from the measured $N_2$ rotational temperature by assuming the rotational and translational temperatures are in equilibrium. This is a valid assumption at the temperatures and pressure involved in this work because the rotational energy levels are closely spaced and allow for rapid energy transfer between the two energy modes.\(^{271}\)

The rotational temperatures are obtained from a two-temperature fit by numerically comparing the measured spectra of the 0-1, 0-2, 1-3, 2-4, 3-5, 0-3, 1-4, 2-5, 3-6, 4-7, and 4-8 vibrational transitions of $N_2$ and the 0-0 and 1-1 vibrational transitions of $N_2^+$ to a calculated spectrum. The comparison was done quantitatively using the statistical parameter $\chi^2_\nu$, which was minimized iteratively by adjusting the fitting parameters using a program called N2SPECFIT.\(^{272,273}\) The two rotational temperatures obtained, one for $N_2$ and one for $N_2^+$, corresponds to the calculated spectra that best matches the measured spectra. Figure 4.15 shows the excellent agreement between the measured spectra scan with the calculated spectra. This method has been used successfully in the past to determine the temperature profile within the thermal boundary layer of a DC glow discharge on top of a flat plate in a Mach 5 flow.\(^{273}\) The vibrational temperature was obtained from a Boltzmann plot of the relative, upper vibrational state number densities for $N_2$, determined...
by N2SPECFIT. The methods used to obtain the rotational and vibrational temperature are discussed in detail in Appendix C and D, respectively.

Figure 4.15: Example of measured $N_2$ and $N_2^+$ spectra overlaid with the fitted spectrum generated by N2SPECFIT. The transitions of $N_2^+$ are labeled and all other transitions are for $N_2$. The transitions are labeled as $v'-v''$ above the band heads.

The SDBD was powered with a sinusoidal voltage for voltage amplitudes of 4000, 4800, 5600, and 6400 volts at a frequency of 5000 Hz. The optical line-of-sight, as indicated in Figure 4.16, was perpendicular to the electrodes, providing spatial resolution in the $x$- and $y$-directions of the SDBD. The measurements were taken after the SDBD ran for 30 minutes in order to reach a periodic operational state.

Figure 4.16 shows the measured rotational and vibrational temperatures for the $N_2(C^3Π_u \rightarrow B^3Π_g)$ electronic band system, corresponding to an applied voltage amplitude of 6400 volts. The rectangle with a dashed white perimeter indicates the region in the discharge where temperatures were measured. This region and the corresponding temperature contour profiles are one-to-one images. Each contour profile contains 152 measured points, with spacing between points of 0.14 mm in the $y$-direction out to 1.10 mm from the edge of the exposed electrode, after which the spacing is increased to 0.28 mm. The spacing in the $x$-direction is 3.17 mm. The rotational temperature results show the rotational temperature is greatest at the intersection where the exposed and encapsulated electrodes meet; $465 \pm 10$ K, and then decreases to a minimum of $345 \pm 10$ K going across the encapsulated electrode to the edge of the discharge. The vibrational temperature profile in Figure 4.16 shows that the maximum vibrational temperature of 3250 K corresponds to the same spatial location as the maximum rotational temperature. The vibrational
temperature is seen to decrease from the maximum value in the gap down to a minimum of 2850 K at the edge of the discharge.

![Figure 4.16](image)

**Figure 4.16:** The rotational temperature profile (top) and vibrational temperature profile (bottom) for the region of the discharge within the dashed box as indicated with the white dashed line in the SDBD picture above. The boxed region of the discharge and the contour plots are one-to-one images. The line-of-sight of the measurements is perpendicular to the electrodes.

Figure 4.17 shows a comparison between the best-fit Boltzmann distribution and the actual measured relative distribution of the vibrational energy levels for the $C^3\Pi_u$ electronic state of N$_2$. It is shown that the actual distribution deviates from the Boltzmann distribution; however, this deviation is small and the vibrational distribution of the $C^3\Pi_u$ state can be approximated by a Boltzmann distribution.
These rotational and vibrational results also show non-uniform temperatures with large fluctuations in the $x$-direction. This is emphasized in the line profile plots in Figures 4.18 through 4.20. Each line represents the rotational temperature, given in the left figure, and vibrational temperature, given in the right figure, at a constant $y$-coordinate, as a function of $x$-position. Figure 4.18 shows these fluctuations have a maximum rotational and vibrational temperature of 465 and 3250 K, at a $y$-location of 0 mm, corresponding to the edge of the exposed electrode, and then damp out in the $y$-direction. A prominent temperature peak occurs in the profiles between $0.14 \leq y \leq 0.82$ mm. It is also shown that the extreme value of the rotational and vibrational temperature profiles correspond to the same location. Figure 4.19 shows the fluctuations for $y$-coordinates from 1.0-2.5 mm. In this figure it is demonstrated that the fluctuations are beginning to dampen. In Figure 4.20, which shows the rotational and vibrational temperature line plots with
y-coordinates between 2.5-4.0 mm, the fluctuations are completely gone as is the temperature gradient in the y-direction.

**Figure 4.18:** Line plots of the rotational temperatures as a function of x and y-directions for the first 1.0 mm across the encapsulated electrode. The uncertainty of each measured rotational and vibrational temperature is ± 10 K and ± 300 K, respectively. All positional locations are given in mm.

**Figure 4.19:** Line plots of the rotational temperatures as a function of x and y-directions for the 1.0-2.5 mm range across the encapsulated electrode. The uncertainty of each measured rotational and vibrational temperature is ± 10 K and ± 300 K, respectively. All positional locations are given in mm.
Figure 4.20: Line plots of the rotational temperatures as a function of x and y-directions for 2.73-3.82 mm range across the encapsulated electrode. The uncertainty of each measured rotational and vibrational temperature is ± 10 K and ± 300 K, respectively. All positional locations are given in mm.

An explanation of the spatial variation of the rotational and vibrational temperatures can be obtained by visual observation of the discharge, as shown in Figure 4.21. This figure shows four successive images of the SDBD separated in time by 30 seconds. Note, the attachment points of the microdischarges within the plasma, bright spots located between the encapsulated and exposed electrode, remain approximately fixed spatially, but do change with respect to time. While the pictures show a time frame of 90 seconds, the experimental measurements shown in Figures 4.17 through 4.20 were taken over a period of weeks. The figure and data presented later in this chapter suggest that the attachment points are actually cathode spots and will be referenced as such hereafter. Figures 4.17 through 4.20 show the rotational temperature peak at $x = 14.1$ mm, corresponding with a cathode spot in Figure 4.21. Other local temperature maxima, in the x-direction, correlate less strongly with the cathode spots. This is probably due to spot movement. It should also be noted that the resolution of the measured data in the x-direction causes many spots to be missed.
Figure 4.21: Images of the SDBD taken in 30 second intervals. The dimensions given in the x-direction are in mm.

These microdischarges, associated with the cathode spots, may have some effect on the flow structure. Figure 2.1 shows PIV measurements from a similar SDBD experiment, showing spanwise periodic regions of higher and lower velocity within the induced flow. These PIV results were obtained from a 2000 Hz square wave, but were also evident for a 5000 Hz sine wave. In this experiment, the velocity fluctuations could not conclusively be correlated with the cathode spots in the discharge. The possibility remains that they may be due to fluid dynamic instabilities in the induced flow or other inherent problems associated with using PIV in plasmas.

The next set of results, shown in Figures 4.22 through 4.24, is for the same optical line of sight as the previously presented results. The rotational and vibrational temperatures are still obtained from the \( C^3\Pi_u \rightarrow B^3\Pi_g \) band system of \( N_2 \), and temperatures for \( N_2^+ \) are obtained from the \( B^2\Sigma_u^+ \rightarrow X^2\Sigma_g^+ \) electronic band system. In these results, only the profile at \( y = 0 \) mm is measured. In addition, a new SDBD had to be built, but it was made so that the dimensions were the same as the first model. Even
though the dimensions were kept the same, the cathode spots changed locations. It was observed that the location of the cathode spots remained approximately in the same location as a function of time, as was the case with the first SDBD. However, using new electrodes resulted in the observed fluctuations in temperature shifting to new locations.

Figure 4.22 shows the rotational temperatures for N\textsubscript{2} as a function of voltage. It is shown that the rotational temperature increases from a minimum of 320 ± 10 K to a maximum of 390 ± 10 K as the voltage is increased. The measurements again show fluctuations in the x-direction. Figure 4.23 shows the corresponding rotational temperatures for N\textsubscript{2}\textsuperscript{+} for all four applied voltages at the same y-coordinate of 0 mm. The rotational temperature of N\textsubscript{2}\textsuperscript{+} also increases with increasing applied voltage from a minimum of 430 ± 15 K to a maximum of 760 ± 15 K. Figure 4.24 gives the corresponding vibrational temperatures of N\textsubscript{2}, which range between 2380-2540 K.

![Figure 4.22: Line plots of the N\textsubscript{2} rotational temperatures as a function of voltage at a y-coordinate of 0 mm.](image-url)
Figure 4.23: Line plots of the N$_2^+$ rotational temperatures as a function of voltage at a y-coordinate of 0 mm.

Figure 4.24: Line plots of the vibrational temperatures as a function of voltage at a y-coordinate of 0 mm for the vibrational energy levels of the $C^3II_u$ electronic state of N$_2$. The uncertainty of each measured temperature is ±300 K.
The rotational temperature of \( \text{N}_2 \) and \( \text{N}_2^+ \) are determined to be drastically different from one another. The deviation in rotational temperatures increases as the applied voltage is increased and was observed by obtaining the average temperature of each species, for each applied voltage amplitude and taking the difference. Figure 4.25 shows the relationship between the average temperature differences versus the applied voltage amplitude. It should be noted that the rotational distribution of each species is well approximated by the Boltzmann distribution as is shown in Figure 4.17.

![Figure 4.25](image)

**Figure 4.25:** The average rotational temperature difference between \( \text{N}_2 \) and \( \text{N}_2^+ \) versus the applied voltage amplitude. It can be seen that the difference increases as the applied voltage amplitude is increased.

Stefanovic et al.\(^{147}\) found the same deviation in rotational temperature between \( \text{N}_2(C^3\Pi_u \rightarrow B^3\Pi_g) \) and \( \text{N}_2^+(B^2\Sigma_u^+ \rightarrow X^2\Sigma_g^+) \) for a PDBD operating in dry air at atmospheric pressure. The mechanism responsible, according to Stefanovic, is related to the populating kinetics. Stefanovic argued that the lifetime of \( \text{N}_2^+(B^2\Sigma_u^+) \) is approximately 0.1 ns and since the main production mechanism is
the spontaneous emission of \( N_2 \left( X^1 \Sigma_g^+ \right) + e \rightarrow N_2 \left( B^2 \Sigma_u^+ \right) + 2e \). \hspace{1cm} (4.3.1)

emission only occurs during the active time of the microdischarge. The main production mechanism of \( N_2 \left( C^3 \Pi_u \right) \), identified by Stefanovic, occurs from direct electron impact of the ground state and the energy pooling reaction given as

\[
N_2 \left( X^1 \Sigma_g^+ \right) + e \rightarrow N_2 \left( C^3 \Pi_u \right) + e
\]

and

\[
N_2 \left( A^3 \Sigma_u^+ \right) + N_2 \left( A^3 \Sigma_u^+ \right) \rightarrow N_2 \left( C^3 \Pi_u \right) + N_2 \left( X^1 \Sigma_g^+ \right).
\] (4.3.3)

According to Stefanovic, the production of the metastable specie \( N_2 \left( A^3 \Sigma_u^+ \right) \), is predominantly produced by recombination reactions, effectively delaying the emission of the \( C^3 \Pi_u \rightarrow B^3 \Pi_g \) transition of \( N_2 \). This means that the emissions of these two electronic band systems occur at different times within the discharge.

They performed a computational study, utilizing the Navier-Stokes equations, to see if the gas temperature could change during this time and found that after the current pulse, a rapid jump in temperature and pressure occurred. They showed that the temperature change causes the gas to expand radially outward from the microdischarge, on a time scale of 0.1-1 μs. This expansion process causes the gas temperature to drop. Stefanovic argued that the deviation in temperature between the two emitting species occurs because spontaneous emission from the \( N_2 \left( B^2 \Sigma_u^+ \rightarrow X^2 \Sigma_g^+ \right) \) electronic band system occurs predominantly before this expansion process, when the gas temperature is hot; whereas, the \( N_2 \left( C^3 \Pi_u \rightarrow B^3 \Pi_g \right) \) band system lags behind and emits after the expansion, when the gas temperature is cooler. One problem with this explanation comes from Kozlov et al., who shows that the spontaneous emission from \( N_2 \left( B^2 \Sigma_u^+ \rightarrow X^2 \Sigma_g^+ \right) \) lags the emission from \( N_2 \left( C^3 \Pi_u \rightarrow B^3 \Pi_g \right) \) within an atmospheric pressure, air PDBD by several nanoseconds. This is significantly smaller than the characteristic time of expansion and does not appear to be enough time for the microdischarge region to cool noticeably. Also, the emission of both transitions occurs at the same time that current is flowing through the microdischarge. This would indicate that the microdischarge region is still heating when emission from \( N_2 \left( C^3 \Pi_u \rightarrow B^3 \Pi_g \right) \) is occurring. As will be discussed later in this chapter, there is another more plausible explanation of the temperature deviation.
The above results were taken along the inner-electrode gap at $y = 0$. The final results of this section are shown in Figure 4.26 and correspond to the rotational temperatures of $N_2$ and $N_2^+$ in the $y$-direction, as a function of the applied voltage amplitude. Results show the rotational temperatures of both species decrease in the $y$-direction and are, again, different from one another. The difference in temperature decreases slightly for each applied voltage amplitude as a function of increasing $y$-coordinate.

![Figure 4.26](image)

Figure 4.26: Line plots of the rotational temperatures for $N_2$ (top) and $N_2^+$ (bottom), as a function of the applied voltage amplitude, in the $y$-direction.

At this point, measurements have been averaged over the negative and positive voltage half-cycle where the discharge regime has been shown to be different. In the next section, measurements will be for only emission from the positive or negative voltage half-cycle but not both. In this section, measurements have shown the rotational and vibrational temperatures are at a maximum within the inner-electrode gap and decrease in the induced flow direction. Spanwise fluctuations within the rotational and vibrational
temperatures were also shown and attributed to the cathode spots of the plasma. It was also shown that the rotational temperature of the ions is significantly greater than the rotational temperature of the neutrals, with the deviation increasing with increasing voltage. These initial results will be expanded upon in later sections.
4.4 Emission Measurements of the Positive and Negative Voltage Half-Cycle of an SDBD

In the previous section, emission measurements from the SDBD were averaged over the positive and negative voltage half-cycle. In this section, emissions from the two voltage half-cycles are separated using an optical chopper, resulting in average measurements over only the negative or positive voltage half-cycle. These results provide more evidence for some of the observations made in the last section and clearly show some of the differences between the plasma regimes of the two voltage half-cycles.

The SDBD was again run for 20 minutes for each voltage setting of 4450 and 5900 volts before any data was taken to ensure a quasi-steady operational state. The largest electronic upper state number density measured was used to normalize all the concentration data. This included the concentrations measured for both voltage settings and both electronic band systems. The region of interest within the SDBD was limited to the interior region, eliminating end effects. The optical line of sight for all measurements was in the $z$-direction of Figure 3.1, going into the page. The data points of each profile were taken as a single set and each set was taken twenty times. The data displayed is the average over the twenty samples for a given position. The error bars on all figures in this section are the precision uncertainty of the sample with a 95% confidence interval.

Figure 4.27 shows the measured distribution of the $N_2(C^3Π_u)$ vibrational manifold versus the linear least squares fit for the positive and negative voltage half-cycle. The distributions for both voltage half-cycles deviate approximately the same amount from a Boltzmann distribution; however, the deviation is small and the vibrational manifold of $N_2(C^3Π_u)$ can be approximated by a Boltzmann distribution, enabling the use of a vibrational temperature.

The vibrational temperature profiles, for the negative and positive voltage half-cycles, versus the $y$-coordinate at a voltage of 5900 volts are shown in Figure 4.28. Results show that during the negative voltage half-cycle, the vibrational temperature starts out at a maximum of 2600 K, within the inner-electrode gap, and then decreases to a minimum of 2530 K in the $y$-direction. This gives some indication to how the electron energy distribution function (EEDF) behaves as a function of the $y$-coordinate. Basically,
the EEDF will be at a maximum at the inner-electrode gap, and then decrease in the positive \( y \)-direction. The vibrational temperature, during the positive voltage half-cycle, has a minimum value of 2860 K at the inner-electrode gap, then increases to a maximum of 2930 K at \( y \approx 0.5 \), and finally remains constant. Note that the behavior of the vibrational temperature during the two voltage half-cycles is inversely related, providing some evidence for different plasma regimes occurring during the positive and negative voltage half-cycles.

![Graph](image)

**Figure 4.27**: The best-fit Boltzmann distribution of the measured vibrational manifold of the \( N_2(C^3Π_u) \) vibrational energy levels for the positive and negative voltage half-cycle. The vibrational quantum number is indicated above the measured point.
Figure 4.28: Vibrational temperature profiles for the positive and negative voltage half-cycles versus y-direction.

The rotational temperatures of $N_2(C_3)$ and $N_2^+(B_2)$ as a function of y-coordinate and voltage half-cycle for two different applied voltages are given in Figures 4.29 and 4.30, respectively. In Figure 4.29, the rotational temperature of $N_2(C_3)$ starts at a maximum at $y = 0$ and decreases in the positive y-direction during the positive voltage half-cycle and decreases and then increases during the negative voltage half-cycle. The rotational temperature corresponding to the larger applied voltage is greater than the smaller applied voltage, as is expected. In Figure 4.30, the rotational temperature of $N_2^+(B_2)$ is significantly greater during the negative voltage half-cycle at $y = 0$ and then quickly drops for increasing y-coordinate until it is equivalent with the rotational temperature during the positive voltage half-cycle. It is also shown that the rotational temperature of $N_2^+(B_2)$ is greater than the rotational temperature of $N_2(C_3)$ with the largest deviation of 265 K occurring during the negative voltage half-cycle at $y = 0$. 
Figure 4.29: Rotational temperature of \( N_2(C^3) \) state in the y-direction.

Figure 4.30: Rotational temperatures of \( N_2^+(B^2) \) state in the y-direction.
The relative concentrations of $N_2(C^3Π_u)$ and $N_2^+(B^2Σ^+_u)$ versus y-coordinate, for the positive voltage half-cycle, are shown in Figure 4.31 for voltages of 4450 and 5900 volts. In Figure 4.31b, the relative concentration of $N_2(C^3Π_u)$ is on the left axis and $N_2^+(B^2Σ^+_u)$ is on the right axis. The relative concentrations of the measured excited states are at a maximum at the inner-electrode gap, and then decrease in the y-direction. The profiles for $N_2(C^3Π_u)$ and $N_2^+(B^2Σ^+_u)$ at 5900 volts vary from one another; however, they are very similar for the 4450 volt case. In particular, for the higher voltage case, the figure indicates that the relative concentration of $N_2(C^3Π_u)$ decreases much slower than $N_2^+(B^2Σ^+_u)$. This is due to the difference in excitation energies of the two states.

Another important detail of Figure 4.31b is the difference in the profiles for $N_2^+(B^2Σ^+_u)$ at 4450 volts versus 5900 volts. The figure shows that the relative concentration at 5900 volts is substantially higher, and more importantly, the dependence in the y-direction is different near the inner-electrode gap. This difference can be explained because “strong” cathode spots are present during the 5900 volt case, whereas “weak” cathode spots occur during the 4450 volt case. The presence of strong cathode spots during the 5900 volt case results in an elevated production of electrons via ion bombardment of the electrode. As Equations 4.2.1 and 4.2.2 indicate, more electrons increases the number density of the two measured excited states. This alternative production mechanism of electrons could have a profound effect on the cathode directed streamers produced during the positive voltage half-cycle because, at high frequencies, electrons produced during the negative voltage half-cycle will not have enough time to recombine, resulting in some fraction of produced electrons left near the dielectric surface during the positive voltage half-cycle. The dependence of streamer radius and propagation velocity of cathode-directed streamers on the number of seed electrons have been demonstrated by Pancheshnyi et al.\textsuperscript{264}
Figure 4.31: Relative concentration of $N_2^+ (B^2 \Sigma_u^+)$ and $N_2 (C^3 \Pi_u)$ versus y-coordinate for the negative voltage half-cycle. In Figure 4.31a, the relative concentrations of both excited species are on the same axis, whereas in Figure 4.31b, the relative concentration of $N_2 (C^3 \Pi_u)$ is on the left vertical axis and $N_2^+ (B^2 \Sigma_u^+)$ is on the right vertical axis. Relative concentration is the measured number density divided by the maximum number density.

The effect on the discharge, produced by the presence of strong and weak cathode spots, can also be observed by plotting the ratio of the relative concentrations of $N_2^+ (B^2 \Sigma_u^+)$ and $N_2 (C^3 \Pi_u)$, which, as will be shown, is only a function of the reduced electric field. To show this dependence, it is assumed that the
dominant production channel for \( N_2(C^3 \Pi_u, \nu' = 0) \) and \( N_2^+(B^2 \Sigma_u^+, \nu' = 0) \), for this type of discharge, along with their respective excitation energies, are given as

\[
N_2(X^1 \Sigma_g^+) + e \rightarrow N_2(C^3 \Pi_u, \nu' = 0) + e \quad \Delta E = 11.2 \text{ eV} \tag{4.4.1}
\]

and

\[
N_2(X^1 \Sigma_g^+) + e \rightarrow N_2^+(B^2 \Sigma_u^+, \nu' = 0) + 2e \quad \Delta E = 18.6 \text{ eV}. \tag{4.4.2}
\]

The plausibility of this mechanism dominating the production of these states seems intuitive given that the ratio of the number of excited species to ground state species is on the order of \( 10^4 \), resulting in a much higher probability of an electron colliding with ground state nitrogen than with an excited state. The quenching of these excited states via collisions with the surrounding background gas and radiation is given by

\[
N_2(C^3 \Pi_u, \nu' = 0) + N_2 \rightarrow \text{products} \quad K_c^{N_2} = 9 \times 10^{-13} \left( \text{cm}^3 \text{s}^{-1} \right) \tag{4.4.3}
\]

\[
N_2(C^3 \Pi_u, \nu' = 0) + O_2 \rightarrow \text{products} \quad K_c^{O_2} = 2.7 \times 10^{-10} \left( \text{cm}^3 \text{s}^{-1} \right) \tag{4.4.4}
\]

\[
N_2(C^3 \Pi_u, \nu' = 0) \rightarrow N_2(B^3 \Pi_g) + h\nu. \tag{4.4.5}
\]

\[
N_2^+(B^2 \Sigma_u^+, \nu' = 0) + N_2 \rightarrow \text{products} \quad K_B^{N_2} = 2.1 \times 10^{-10} \left( \text{cm}^3 \text{s}^{-1} \right) \tag{4.4.6}
\]

\[
N_2^+(B^2 \Sigma_u^+, \nu' = 0) + O_2 \rightarrow \text{products} \quad K_B^{O_2} = 5.1 \times 10^{-10} \left( \text{cm}^3 \text{s}^{-1} \right) \tag{4.4.7}
\]

\[
N_2^+(B^2 \Sigma_u^+, \nu' = 0) + N_2 + M \rightarrow N_4^+ + M \quad K_B^{M} = 5 \times 10^{-29} \left( \text{cm}^6 \text{s}^{-1} \right) \tag{4.4.8}
\]

and

\[
N_2^+(B^2 \Sigma_u^+, \nu' = 0) \rightarrow N_2^+(B^2 \Sigma_u^+) + h\nu. \tag{4.4.9}
\]

The rate equations for the \( N_2^+(B^2 \Sigma_u^+) \) and \( N_2(C^3 \Pi_u) \) states, correspond to the difference of the sum of the production and quenching mechanisms, are given as

\[
\frac{d}{dt}N_2^+(B^2 \Sigma_u^+, \nu' = 0) = K_c^{N_2}n_eN_2(X^1 \Sigma_g^+) - \frac{N_2^+(B^2 \Sigma_u^+, \nu' = 0)}{\tau_B} \tag{4.4.10}
\]

and

\[
\frac{d}{dt}N_2(C^3 \Pi_u, \nu' = 0) = K_c^{N_2}n_eN_2(X^1 \Sigma_g^+) - \frac{N_2(C^3 \Pi_u, \nu' = 0)}{\tau_C} \tag{4.4.11}
\]

where \( n_e \) is the electron number density, \( K_c^{CB} \) are rate constants, and \( \tau_B \) and \( \tau_C \) are given as

\[
\tau_B = \left[ \frac{1}{\tau_B^0} + K_B^{N_2}N_2(X^1 \Sigma_g^+) + K_B^{O_2}N_2(X^3 \Sigma_g^+) + K_B^{M}N_2(X^1 \Sigma_g^+)M \right]^{-1} \tag{4.4.12}
\]
and

\[ \tau_c = \left[ \frac{1}{\tau_0^N} + K_c^N N_2 (X^1 \Sigma_g^+) + K_c^O_2 O_2 (X^3 \Sigma_g^-) \right]^{-1}. \]  \tag{4.4.13}

In Equations 4.4.12 and 4.4.13, \( \tau_0^N \) and \( \tau_0^O \) are the radiative lifetimes of the \( N_2 (C^3 \Pi_u, \nu' = 0) \) and \( N_2^+ (B^2 \Sigma_u^+, \nu' = 0) \) states and have reported values of 37 and 62 nanoseconds, respectively.\(^{263}\)

The development of Equations 4.4.1 through 4.4.13 is the same as what has been given in reference 263; however, the following has never been documented to the author’s knowledge. In reference 263, the use of photomultiplier tubes allows for fast sampling of the emission, quick enough so that the upper state number density is assumed constant, resulting in the time derivative terms in Equations 4.4.10 and 4.4.11 being equal to zero. A short enough exposure time was not possible with the equipment available. Instead, the time averages of Equations 4.4.10 and 4.4.11 are taken. The time average of Equations 4.4.10 and 4.4.11 are given as

\[
\frac{1}{b-a} \int_a^b \left\{ \frac{d}{dt} N_2 (B^2 \Sigma_u^+, \nu' = 0) \right\} dt = \frac{1}{b-a} \int_a^b K_c^N N_2 (X^1 \Sigma_g^+) dt - \frac{1}{b-a} \int_a^b \frac{N_2^+ (B^2 \Sigma_u^+, \nu' = 0)}{\tau_c} dt
\]  \tag{4.4.14}

and

\[
\frac{1}{b-a} \int_a^b \left\{ \frac{d}{dt} N_2 (C^3 \Pi_u, \nu' = 0) \right\} dt = \frac{1}{b-a} \int_a^b K_c^N N_2 (X^1 \Sigma_g^+) dt - \frac{1}{b-a} \int_a^b \frac{N_2 (C^3 \Pi_u, \nu' = 0)}{\tau_c} dt \]  \tag{4.4.15}

Evaluating the left hand sides of Equations 4.4.14 and 4.4.15 gives

\[
\frac{1}{b-a} \int_a^b \left\{ \frac{d}{dt} N_2 (B^2 \Sigma_u^+, \nu' = 0) \right\} dt = \frac{1}{b-a} \left\{ N_2 (B^2 \Sigma_u^+, \nu' = 0) \right\}_{t=b} - N_2^+ (B^2 \Sigma_u^+, \nu' = 0) \right\}_{t=a} \]  \tag{4.4.16}

and

\[
\frac{1}{b-a} \int_a^b \left\{ \frac{d}{dt} N_2 (C^3 \Pi_u, \nu' = 0) \right\} dt = \frac{1}{b-a} \left\{ N_2 (C^3 \Pi_u, \nu' = 0) \right\}_{t=b} - N_2 (C^3 \Pi_u, \nu' = 0) \right\}_{t=a}. \]  \tag{4.4.17}

The integration limits, \( a \) and \( b \), represent the start and end time of the measurement and were chosen to corresponded with the middle of the passive phase of the discharge, defined as having no conductive current; where it is known that the concentrations of the \( N_2 (C^3 \Pi_u, \nu' = 0) \) and \( N_2^+ (B^2 \Sigma_u^+, \nu' = 0) \) states are zero.\(^{24}\) Therefore, Equations 4.4.16 and 4.4.17 are equal to zero, and Equations 4.4.14 and 4.4.15 simplify to

\[
0 = \frac{K_c^N N_2 (X^1 \Sigma_g^+)}{\tau_c} - \frac{N_2^+ (B^2 \Sigma_u^+, \nu' = 0)}{\tau_c} \]  \tag{4.4.18}

and
where the over bar represents an average quantity. The quantities \( N_2 ^ \lambda \left( X^1 \Sigma_g ^ + \right) \), \( K_{ex} ^ B \), and \( \tau_{e,c} \) are constants resulting in

\[
K_{ex} ^ B N_2 ^ \lambda \left( X^1 \Sigma_g ^ + \right) \frac{1}{\tau_e} = \frac{1}{\tau_e} N_2 ^ \lambda \left( B^2 \Sigma_u ^ +, v' = 0 \right)
\]  

and

\[
K_{ex} ^ C N_2 ^ \lambda \left( X^1 \Sigma_g ^ + \right) \frac{1}{\tau_e} = \frac{1}{\tau_e} N_2 ^ \lambda \left( C^3 \Pi_u, v' = 0 \right)
\]

Dividing Equation 4.4.20 by 4.4.21 and solving for the concentration ratio gives

\[
\frac{N_2 ^ \lambda \left( B^2 \Sigma_u ^ +, v' = 0 \right)}{N_2 ^ \lambda \left( C^3 \Pi_u, v' = 0 \right)} = \frac{\tau_B K_{ex} ^ B}{\tau_C K_{ex} ^ C}
\]

which is the important result from the above derivation. The rate constants on the right hand side of Equation 4.4.22 are functionally dependent on the reduced electric field only. In particular, as the ratio of the relative concentration of \( N_2 ^ \lambda \left( B^2 \Sigma_u ^ +, v' = 0 \right) \) to \( N_2 ^ \lambda \left( C^3 \Pi_u, v' = 0 \right) \) increases, the reduced electric field increases.

As suggested by Equation 4.4.22, the effect on the discharge, produced by the presence of strong and weak cathode spots, can also be seen in Figure 4.30, which shows the ratio of the relative concentration of \( N_2 ^ \lambda \left( B^2 \Sigma_u ^ +, v' = 0 \right) \) to \( N_2 ^ \lambda \left( C^3 \Pi_u, v' = 0 \right) \) during the negative voltage half-cycle. For the 4450 volt case, the weak cathode spots result in the ratio decreasing linearly. The ratio for the 5900 volt case takes on a much different functional dependence near the inner-electrode gap. In particular, the presence of the positive sheath, which makes up the cathode spot, appears to produce a locally nonuniform electric field. The strength of the reduced electric field is clearly greater for the higher voltage case within the inner-electrode gap. Properties of the EEDF, in the presence of a nonuniform electric field, are given in reference 283. A pertinent result from this work is in the presence of a nonuniform electric field the electrons within the high energy tail of the EEDF are most affected and can be increased by as much as an order of magnitude. This relationship is easily seen, considering the electrons corresponding to the most probable energy of the EEDF are those which travel a distance of one mean free path between collisions. The electrons, which make up the high energy tail of the EEDF, travel a distance greater than one mean free path between collisions. It is these electrons which are affected the most by a nonuniform field because they have a longer distance to accelerate unhindered by collisions, and thus, reach greater velocities, which
indicate higher energies. The result of an increase in the population of high energy electrons results in an increase in production of excited states according to Equations 4.4.1 and 4.4.2, and is evident from the results.

**Figure 4.32:** Ratio of the concentration of $N_2^+(B^2 \Sigma_u^+, \nu' = 0)$ to $N_2(C^3 \Pi_u, \nu' = 0)$ versus y-coordinate during the negative voltage half-cycle for both voltages.

The relative concentrations of $N_2(C^3 \Pi_u)$ and $N_2^+(B^2 \Sigma_u^+)$ versus y-coordinate for the positive voltage half-cycle are shown in Figure 4.33 for voltages of 4450 and 5900 volts. Figure 4.33a shows the relative concentrations of both species on the same axis, whereas Figure 4.33b shows the relative concentration of $N_2(C^3 \Pi_u)$ on the left vertical axis, and $N_2^+(B^2 \Sigma_u^+)$ on the right vertical axis. The concentration of each excited state, excluding $N_2(C^3 \Pi_u)$ at 5900 volts, increases to a maximum, and then decreases linearly in the positive y-direction.

The relationship of the ratio of the relative concentrations of $N_2^+(B^2 \Sigma_u^+, \nu' = 0)$ to $N_2(C^3 \Pi_u, \nu' = 0)$ for the positive voltage half-cycle is given in Figure 4.34. The figure shows a larger concentration of
$N_2(C^3Π_u)$ compared to $N_2^+(B^2Σ^+_u)$. The amount of $N_2^+(B^2Σ^+_u)$ relative to $N_2(C^3Π_u)$ starts off low at the inter electrode gap, increases, and then decreases slowly in the positive $y$-direction.

Figure 4.33: Concentrations of $N_2(C^3Π_u)$ and $N_2^+(B^2Σ^+_u)$ versus $y$-coordinate for the positive voltage half-cycle. In Figure 4.33a, the relative concentrations of both excited species are on the same axis, whereas in Figure 4.33b, the relative concentration of $N_2(C^3Π_u)$ is on the left vertical axis and $N_2^+(B^2Σ^+_u)$ is on the right vertical axis. Relative concentration is the measured number density divided by the maximum number density.
Figure 4.34: Ratio of the concentration of $N_2^+(B^2\Sigma_u^+, \nu' = 0)$ to $N_2(C^3\Pi_u, \nu' = 0)$ versus y-coordinate during the positive voltage half-cycle for both voltages.

The relative concentration of $N_2(C^3\Pi_u)$ is shown for both voltage half-cycles and voltages in Figure 4.35. The figure shows that the relative concentration, in the inner-electrode gap, is greater during the negative voltage half-cycle than the positive voltage half-cycle for both voltages. This changes at greater y-coordinates because the relative concentration drops off much more rapidly during the negative voltage half-cycle. The location at which the change occurs, appears to be dependent on voltage. In particular, at 4450 volts the change occurs at 0.6 mm and at 5900 volts at 0.8 mm. The difference in the concentration profiles, for the two voltage half-cycles, is a direct indication of the difference in the structure of the discharge during the two voltage half-cycles. Finally, the extent of the discharge in the y-direction is greater during the positive voltage half-cycle than the negative voltage half-cycle. The ratios of the relative concentration of $N_2(C^3\Pi_u, \nu' = 0)$, during the negative voltage half-cycle and positive voltage half-cycle, as a function of y-coordinate, for both voltages are shown in Figure 4.36. The figure shows that the greatest difference in relative concentration of $N_2(C^3\Pi_u)$ occurs within the inner-electrode gap, and is as much as 3 times greater during the negative voltage half-cycle, as opposed to the positive voltage half-cycle.
Figure 4.35: Relative concentration of $N_2(C^3Π_u)$ versus y-coordinate for both positive and negative voltage half-cycles. Relative concentration is the measured number density divided by the maximum number density.

Figure 4.36: Ratio of the relative concentration of $N_2(C^3Π_u)$ during the negative voltage half-cycle over the positive voltage half-cycle as a function of y-coordinate for 4450 and 5900 volts.
The relative concentration of \( N_2^+ (B^2 \Sigma_u^+) \) is shown for both voltage half-cycles and voltages in Figure 4.37. In Figure 4.37b the relative concentration during the positive voltage half-cycle is on the left vertical axis, and the concentration during the negative voltage half-cycle is on the right vertical axis. During the positive voltage half-cycle, the relative concentration increases to a maximum, and then decreases linearly; whereas during the negative voltage half-cycle, it decreases rapidly due to the presence of a strong cathode spot, and linearly due to a weak cathode spot. The ratios of the relative concentration of \( N_2^+ (B^2 \Sigma_u^+) \) during the positive voltage half-cycle and negative voltage half-cycle, as a function of \( \gamma \)-coordinate for both voltages, are shown in Figure 4.38. The figure shows that there is more \( N_2^+ (B^2 \Sigma_u^+) \) during the positive voltage half-cycle, than during the negative half-cycle. The amount is seen to increase from 1.6 at the inner-electrode gap to ~100 at \( \gamma = 1.7 \) mm for the 5900 volt case; and from ~15 at the inner-electrode gap to ~48 at \( \gamma = 1 \) mm. The presence of the cathode spot is seen to drive the ratio from 15 for a weak cathode spot, down to 1.7 for a strong cathode spot at the inner-electrode gap.
Relative concentration is the measured number density divided by the maximum number density.
In this section, the radiant signal was separated according to voltage half-cycle, resulting in a clearer description of some of the initial measurements presented in Section 4.3. In particular, the vibrational temperature of the positive and negative voltage half-cycle was presented as a function of y-coordinate. The vibrational temperature profile was shown to be completely different depending on voltage half-cycle. During the positive voltage half-cycle, the vibrational temperature started at a minimum, increasing to a maximum and then remaining constant; whereas, during the negative voltage half-cycle, the vibrational temperature started at a maximum and then decreased exponentially. The voltage half-cycle dependence clearly illustrates the difference in discharge structure which was also evident in measured concentrations of $N_2^+(B^2\Sigma^+)$ and $N_2^+(C^3\Pi)$. During the negative voltage half-cycle, for a voltage amplitude of 4450 volts, the concentrations of both species decreased linearly; however, the concentration of both species decreased exponentially for an applied voltage of 5900 volts. The difference was shown to be caused by a significantly stronger electric field within the cathode fall. During the positive voltage half-cycle, the concentrations of $N_2(C^1\Pi)$ and $N_2^+(B^2\Pi)$ increased to a maximum and then decreased linearly with increasing y-coordinate.

**Figure 4.38**: Ratio of the relative concentration of $N_2^+(B^2\Sigma^+)$ during the positive voltage half-cycle over the negative voltage half-cycle as a function of y-coordinate for 4450 and 5900 volts.
4.5 Emission Measurements of a Single Microdischarge within an SDBD

Previous results, presented in Sections 4.3 and 4.4, established some of the structural differences between the discharge regime during the negative and positive voltage half-cycles. Currently, the spectroscopic results illustrate the discharge structure. In this section, the previous results are expanded upon, resulting in some appropriate chemical kinetics needed to accurately model a SDBD. To achieve these results, it was necessary to optimize the SDBD so that the cathode spots were spatially reproducible, enabling measurements from a single cathode spot. This was useful in explaining previous results presented in Section 4.1 which showed fluctuations in temperature that were weakly correlated to the cathode spots of the SDBD. The difficulties correlating the two come about because the cathode spots did not remain at the same location, even though the movement was not significant.

It was found that the cathode spots would remain almost completely stationary if the separation distance between the exposed and encapsulated electrode was increased, or if the applied voltage was increased. The voltages required were very large and resulted in the destruction of the dielectric barrier after brief run times. Therefore, quasi-stationary cathode spots were produced by adjusting the separation distance between the electrodes. The quasi-stationary cathode spots are demonstrated by viewing successive images in time, as shown in Figure 4.39. These images are for a separation distance of 0.5 mm. In Figure 4.39, the image designated at $t = 0$ was taken after the SDBD ran for 30 minutes. The SDBD was turned off at $t = 4$ minutes and turned back on 6 hours later where the cathode spots remained in the same location. In particular, the first two cathode spots from the left edge of Figure 4.39 remained spatially fixed. This property is used for spatially determining the rotational temperatures obtained from $N_2^+(B^3\Sigma_u^+ \rightarrow X^3\Sigma_g^+)$ and $N_2(C^3\Pi_u \rightarrow B^3\Pi_g)$, the vibrational temperature and the relative concentrations of $N_2(C^3\Pi_u)$ and $N_2^+(B^2\Sigma_u^+)$ within a single microdischarge for both voltage half-cycles. It is hypothesized that the location of the cathode spots is determined by surface effects and by electric field effects. It was observed that for low voltages the cathode spots appeared to be spatially random; however, for large voltages the cathode spots would remain spatially fixed. The electrical field effect is believed to cause the cathode spots
to stabilize spatially, whereas the surface effects are believed to cause the cathode spots to set-up randomly in space.

Figure 4.39: Successive images of the SDBD for an inner-electrode distance 1 mm.

The collection volume was adjusted so that the upper edge just touched the exposed electrode, as shown in Figure 4.40. This location was designated as \( y = 0 \), which remains constant for the measurements.
presented in this section. The step size between measurements is 0.1 mm in the $x$-direction. The applied voltage was a sinusoid with amplitude of 5800 volts and a frequency of 5000 Hz.

The results that follow were obtained from the 0-2, 1-3, 2-4 and 3-5 vibrational transitions of $N_2(C^3Π_u \rightarrow B^3Π_u)$. These transitions were selected instead of the 0-3, 1-4, 2-5, 3-6 vibrational transitions of $N_2(C^3Π_u \rightarrow B^3Π_u)$ and the 0-0 and 1-1 vibrational transitions of $N^+_2(B^2Σ^+_u \rightarrow X^2Σ^+_g)$ because of better signal-to-noise ratio, requiring shorter acquisition times. This significantly shortened the time required to obtain data, enabling quicker preliminary results. The signal-to-noise ratio for the latter transitions was sufficient and was used to verify the preliminary results, along with determining the properties of the $N^+_2(B^2Σ^+_u)$ state within the microdischarge.

![Figure 4.40: Alignment of collection optics.](image)

The rotational temperature, during the negative voltage half-cycle, along with the relative concentration of $N_2(C^3Π_u)$, are shown in Figure 4.41. The two large peaks correspond with the first two cathode spots from the left in Figure 4.38. The distance between the cathode spots, obtained from Figure 4.39, is 1.2 mm, and obtained from Figure 4.41, is 1.3 mm. In Figure 4.41, this distance corresponds to the
relatively low, flat region between the $x$-coordinates of 1.6 and 3.2 mm. The rotational temperature was observed to increase from 350 to 500 K within the microdischarge, and the production of $N_2(C^3Π_u)$ increased by a factor of 5 within the microdischarge. During the positive voltage half-cycle, the relative concentration of $N_2(C^3Π_u)$ and the rotational temperature, shown in Figure 4.42, are constant with respect to the $x$-direction. The rotational temperature obtained outside of the microdischarge, during the negative voltage half-cycle, is the same as the rotational temperature measured during the positive voltage half-cycle. The concentration of $N_2(C^3Π_u)$ obtained during the positive voltage half-cycle is a factor of 2 greater than the concentration outside of the microdischarge during the negative voltage half-cycle. However, the concentration during the negative voltage half-cycle, within the microdischarge, is a factor of 2.5 times greater than during the positive voltage half-cycle.

![Negative Voltage Half-Cycle](image)

**Figure 4.41:** Relative concentration of $N_2(C^3Π_u)$ and rotational temperature during the negative voltage half-cycle. The peaks in these quantities are due to cathode spots.
The corresponding vibrational temperatures during the negative voltage half-cycle, along with the relative concentration of $N_2(C^3Π_u)$, given for the purpose of a spatial reference, are shown in Figure 4.43. In the first microdischarge, the vibrational temperature was observed to increase from 2800 K outside of the microdischarge, up to 3500 K at the outer edge of the microdischarge and then decreased to 3000 K at the center of the microdischarge. This trend was repeated by the second microdischarge. It is speculated that the vibrational temperature is elevated at the edges of the microdischarge due to field effects produced by a sheath located at the outer edge of the microdischarge. Essentially, the presence of a sheath gives rise to a large, local reduced electric field resulting in an increased number of high energy electrons capable of populating the upper vibrational energy levels via collisions. During the positive voltage half-cycle, the vibrational temperature, shown in Figure 4.44, is constant with respect to the x-direction.
Figure 4.43: Vibrational temperature and concentration of \( N_2(\text{C}^3\Pi_u) \) during the negative voltage half-cycle.

Figure 4.44: Vibrational temperature and concentration of \( N_2(\text{C}^3\Pi_u) \) during the positive voltage half-cycle.
The following results were obtained from the 0-3, 1-4, 2-5 and 3-6 vibrational transitions of \( N_2(C^3\Pi_u \rightarrow B^3\Pi_g) \) and the 0-0 and 1-1 vibrational transitions of \( N_2^+(B^2\Sigma^+_u \rightarrow X^2\Sigma^+_g) \), for the first microdischarge from the left in Figure 4.39. This is a different region of the spectrum where the signal is weaker but information about \( N_2^+ \) can be obtained. The previous results were taken several days prior to the results that follow and are obtained from different rovibrational bands of \( N_2(C^3\Pi_u \rightarrow B^3\Pi_g) \), illustrating the spatial reproducibility of this particular SDBD, the reproducibility of the data and the independence of the measured quantities with respect to the specific rovibrational bands used. The applied voltage was a sinusoid with amplitude of 5800 volts and frequency of 5000 Hz.

The relative concentrations of \( N_2(C^3\Pi_u) \) and \( N_2^+(B^2\Sigma^+_u) \), as a function of \( x \)-coordinate, are given in Figure 4.45 for the negative voltage half-cycle. The figure shows that the concentration of \( N_2(C^3\Pi_u) \) is a factor of 60 times larger than the concentration of \( N_2^+(B^2\Sigma^+_u) \). The figure also shows that the maximum of both species occurs at the center of the microdischarge.

**Figure 4.45**: Relative concentration of \( N_2(C^3\Pi_u) \) and \( N_2^+(B^2\Sigma^+_u) \) during the negative voltage half-cycle for a single microdischarge.
Vibrational temperatures as a function of the $x$-coordinate along with the ratio of relative concentrations of $N^+_2(B^2\Sigma_u^+, \nu' = 0)$ and $N_2(C^3\Pi_u, \nu' = 0)$ are given in Figure 4.46, for the negative voltage half-cycle. The figure shows that the vibrational temperature is at a maximum along the outer edges of the microdischarge. Specifically, the vibrational temperature was measured to be 2700 K outside the microdischarge, increasing to 3500 K at the outer edges, with the center of the microdischarge at 2900 K. The ratio of relative concentrations indicates that the reduced electric field is greatest at the outer edges of the microdischarge, corresponding with the maximum vibrational temperatures. Note that both the trend and the magnitude of the vibrational temperatures are in excellent agreement with measurements shown in Figure 4.43. The two measurements are separated by days and obtained from different rovibrational bands of $N_2(C^3\Pi_u \rightarrow B^3\Pi_u)$, illustrating the spatial reproducibility of this particular SDBD, the reproducibility of the data and the independence of the measured quantities with respect to the specific rovibrational bands used.

Figure 4.46: Vibrational temperature along with the ratio of the relative concentrations of $N^+_2(B^2\Sigma_u^+)$ and $N_2(C^3\Pi_u)$ during the negative voltage half-cycle for a single microdischarge.
The rotational temperature of $N_2(C^3Π_u)$ and $N_2^+(B^3Π_u^+)$, within a single microdischarge, for the positive voltage half-cycle is given in Figure 4.48. The figure shows that the temperature remains almost constant with respect to the x-coordinate. It also shows that the temperatures of $N_2(C^3Π_u)$ and $N_2^+(B^3Π_u^+)$ are within 50 K of one another. The rotational temperature obtained for $N_2(C^3Π_u)$, given in Figure 4.47, is around 380 K and nearly identical with that given in Figure 4.42 again illustrating the spatial reproducibility of this particular SDBD, the reproducibility of the data and the independence of the measured quantity with respect to the specific rovibrational bands used.

The rotational temperatures of $N_2(C^3Π_u)$ and $N_2^+(B^3Π_u^+)$, for the negative voltage half-cycle, are shown in Figure 4.48. This figure shows that the rotational temperature profile of $N_2^+(B^3Π_u^+)$ has a similar shape as the vibrational temperature profile given in Figure 4.45. In particular, the rotational temperature profile of $N_2^+(B^3Π_u^+)$ obtained is around 800 K outside of the microdischarge, increasing to a maximum of 1300 K at the outer edge of the microdischarge and is around 950 K within the center of the microdischarge. It is significantly higher than the rotational temperature of $N_2(C^3Π_u)$, demonstrating that the temperature deviation occurs almost entirely during the negative voltage half-cycle. Also, the rotational

![Figure 4.47](image-url)

**Figure 4.47**: Rotational temperature obtained from $N_2(C^3Π_u \rightarrow B^3Π_u)$ and $N_2^+(B^3Π_u^+ \rightarrow X^3Σ^+_g)$ during the positive voltage half-cycle for a single microdischarge.
temperature of $N_2(C^3Π_a)$ is at a maximum of 450 K at the center of the microdischarge and is in good agreement with the values and trend reported in Figure 4.41. Another observable difference between the spatial dependence of the two reported temperature profiles, within a microdischarge, is the difference in shape. It is for now hypothesized that the difference is caused by a contribution to the ions from the reduced electric field.

![Negative Voltage Half-Cycle Graph](image)

**Figure 4.48**: Rotational temperature obtained from $N_2(C^3Π_a → B^3Π_u)$ and $N_2^+(B^2Σ^+_u → X^2Σ^+_g^+)$ during the negative voltage half-cycle for a single microdischarge.

As mentioned earlier in Section 4.2, Stefanovic et al.\textsuperscript{147} provided an explanation for the mechanism responsible for the deviation in temperature between the ions and neutrals. The explanation given was shown to have serious problems and is likely incorrect. There is another possible explanation for the deviation in rotational temperatures between $N_2(C^3Π_u)$ and $N_2^+(B^2Σ^+_u)$. Some regions within the discharge, such as the sheath, are not effectively shielded by the discharge from the applied electric field. In these regions, ions can pick up extra energy from the electric field, and while some of the energy is transferred to the neutrals, it may be possible for the two species to have different rotational temperatures. The temperature deviation between the two species would require the ions to pick up more energy than is lost through collisions. An expression relating the translational temperature of the ions and the neutral gas
particles, known as the Wannier relationship, was derived in reference 280 using kinetic theory and is given as

\[ T_i = T_g + \frac{(m_i + m_a)(K_i E)^2}{3k_B} \]  

(4.4.1)

where \( T_i \) is the ion temperature, \( T_g \) is the neutral gas temperature, \( m_i \) is the mass of the ion, \( m_a \) is the mass of the neutral gas particle, \( K_i \) is the ion mobility, \( E \) is the electric field, and \( k_B \) is the Boltzmann constant. In this work the mass of \( N_2^+(B^2 \Sigma_u^+) \) and \( N_2(C^3 \Pi_u) \) are assumed to be the same. The value of the ion mobility of \( N_2^+(B^2 \Sigma_u^+) \) depends on the reduced electric field and was obtained from reference 281. A plot of the ion temperature versus the reduced electric field for a gas temperature of 320 K, using the Wannier relationship, is given in Figure 4.49.

![Figure 4.49: Ion temperature versus reduced electric field, for a gas temperature of 320 K, using the Wannier relation.](image)

The reduced electric field, as a function of x-coordinate, within a single microdischarge for the negative voltage half-cycle was obtained using two different methods. The first backs out the reduced electric field required for the observed temperature deviation between \( N_2(C^3 \Pi_u) \) and \( N_2^+(B^2 \Sigma_u^+) \) using the Wannier relationship. The second technique relies on comparing the ratio of relative concentrations of \( N_2^+(B^2 \Sigma_u^+, v' = 0) \) and \( N_2(C^3 \Pi_u, v' = 0) \) with tabulated values measured as a function of the reduced
electric field by Paris et al.\textsuperscript{282}. The reported empirical dependence of the ratio in intensity of \(N_2(C^3\Pi_u, \nu' = 0 \rightarrow B^3\Pi_u, \nu'' = 0)\) at 337 nm and \(N_2(B^3\Sigma_u^+, \nu' = 0 \rightarrow X^2\Sigma_g^+, \nu'' = 0)\) at 391.2 nm with the reduced electric field was reported as

\[
\frac{[N_2(C^3 \rightarrow B^3, 0 \rightarrow 0)]}{[N_2(B^3 \rightarrow B^3, 0 \rightarrow 0)]} = (3.6 \times 10^{-7}) \left( \frac{E}{N} \right)^2 \exp \left( -\frac{150}{E/N} \right) \tag{4.4.2}
\]

where \(E/N\) is in units of Td. The ratio of intensities was related back to a ratio of upper state number densities for the \(\nu' = 0\) levels of the \(C^3\) and \(B^3\) state of \(N_2\) and \(N_2^+\) by first considering the equation for intensity of the two transitions which are given as

\[
I_{0,0}(B^3) = N_0(B^3)A_{0-0}(B^3) \frac{hc}{\lambda_{0-0}(B^3)} \tag{4.4.3}
\]

and

\[
I_{0,0}(C^3) = N_0(C^3)A_{0-0}(C^3) \frac{hc}{\lambda_{0-0}(C^3)} \tag{4.4.4}
\]

Dividing Equation (4.4.3) by Equation (4.4.4) gives

\[
\frac{I_{0,0}(B^3)}{I_{0,0}(C^3)} = \frac{N_0(B^3)A_{0-0}(B^3)A_{0-0}(C^3)}{N_0(C^3)A_{0-0}(C^3)A_{0-0}(B^3)} \tag{4.4.5}
\]

Substituting Equation 4.4.5 into Equation 4.4.2 and rearranging gives

\[
\frac{N_0(B^3)}{N_0(C^3)} = (3.6 \times 10^{-7}) \left( \frac{A_{0-0}(B^3)A_{0-0}(C^3)}{A_{0-0}(B^3)A_{0-0}(C^3)} \right) \left( \frac{E}{N} \right)^2 \exp \left( -\frac{150}{E/N} \right) \tag{4.4.6}
\]

This method requires that the measured ratio is only a function of the reduced electric field which means that the chemical kinetics model presented in Section 4.3, spanning Equations 4.3.1 through 4.3.22, holds for the discharge produced during negative voltage half-cycle of the SDBD.

The reduced electric field as a function of the \(x\)-coordinate for a single microdischarge during the negative voltage half-cycle, is shown in Figure 4.50. Two curves are shown on this plot: one using the ratio of upper state number densities and Equation 4.4.6 and the other using the difference in temperature and Equation 4.4.1. Results show the same trend is obtained using both methods providing some support that the difference in temperature between \(N_2^+(B^3\Sigma_u^+)\) and \(N_2(C^3\Pi_u)\) is caused by the electric field.
Figure 4.50: Reduced electric fields for a single microdischarge during the negative voltage half-cycle. The blue curve was obtained from the Wannier relationship and the red curve was obtained from the ratio of relative concentrations of $N_2^+(B^2Σ_u^+)$ and $N_2(C^3Π_u)$.

The above discussion illustrates that the temperature of the ions and neutral species, within an SDBD, are different. The importance of this observation will now be addressed and is best illustrated by considering the drift-diffusion model of an SDBD. In this model, chemical reactions are handled using rate constants, and in the case of chemical reactions involving ions and neutrals, the rate constants are functions of the effective temperature, which is dependent on the ion temperature, and is given as

$$T_{eff} = \frac{m_iT_i + m_NT_N}{m_i + m_N}. \quad (4.4.7)$$

Some examples of chemical reactions, important for SDBD modeling, with rate constants dependent on the effective temperature, according to Solov’ev et al. \textsuperscript{173}, are

$$O_2^+ + O_2 + M \rightarrow O_4^+ + M \quad K = 2.4 \times 10^{-30} \left(\frac{300}{T_{eff}}\right)^{3.2} \left(\frac{cm^3}{s}\right). \quad (4.4.8)$$

$$N_2^+ + O_2 \rightarrow N_2 + O_2^+ \quad K = 6 \times 10^{-11} \left(\frac{300}{T_{eff}}\right)^{0.5} \left(\frac{cm^3}{s}\right). \quad (4.4.9)$$
Note that the reactions given involve ions and neutrals which are of specific interest because it is these collisions in which momentum is transferred from the ions to the neutrals. The percentage difference in the rate constants given in Equation 4.4.10, for equivalent ion and neutral temperatures and for the greatest deviation reported in Figure 4.48 is 98.1 percent, illustrating the potential importance of the deviation in temperatures.

In this section, the objective was to develop the details of some of the observations made in Sections 4.3 and 4.4. The first step in meeting this objective was to produce spatially stable cathode spots by increasing the voltage amplitude and inner-electrode gap spacing, enabling spatially resolved measurements within a single cathode spot. Measurements verified the attachment points of the discharge are indeed cathode spots, occurring only during the negative voltage half-cycle. It was also shown that the cathode spots are spatially stable. It was also determined that the fluctuations in rotational temperature, presented in Section 4.3, was caused by cathode spots. During the positive voltage half-cycle, it was shown that the microdischarges are still spatially random, resulting in constant plasma properties with respect to the \( x \)-coordinate. The plasma properties measured included the vibrational temperature, rotational temperature of \( \text{N}_2(C^3) \) and \( \text{N}_2^+(B^3) \), and relative concentration of \( \text{N}_2(C^3) \) and \( \text{N}_2^+(B^3) \). Measurements showed that the production of \( \text{N}_2(C^3) \) and \( \text{N}_2^+(B^3) \) occurred within the cathode spot. The vibrational temperature profile within a cathode spot was at a maximum along the outer edges, decreasing to a minimum in the center. The rotational temperature of \( \text{N}_2^+(B^3) \) was found to have the same profile within a cathode spot; however, the rotational temperature of \( \text{N}_2(C^3) \) was found to be at a minimum along the outer edges, increasing to a maximum in the center. The cause of the spatial discrepancy was attributed to the local electric field which was shown to be at a maximum along the outer edges, decreasing to a minimum at
the center of a cathode spot. Specifically, experimental evidence suggests that the outer edge of the microdischarge is a sheath where the electric field is at a maximum. Rotational temperature of N$_2$(C$^3$) and N$_2^+$(B$^2$) were shown to be nearly identical during the positive voltage half-cycle; however, deviated significantly during the negative voltage half-cycle. During the negative voltage half-cycle, the rotational temperature of N$_2^+$(B$^2$) ranged from 800 to 1300 K, whereas the rotational temperature of N$_2$(C$^3$) ranged from 350 to 450 K. The deviation in temperature between the ions and neutrals was explained in terms of the electric field. It was shown that the ion temperature consisted of contributions from the surrounding neutrals and the electric field.

At this point, the work done within this section has been summarized but not much has been said of how it is useful for the development of the SDBD. In the next chapter, the results from Chapter 4 are reviewed along with a thorough discussion on how it related with the SDBD.
CHAPTER 5: Conclusions

In this chapter, the motivation of the research and the research objectives are restated. The experimental results presented within Chapter 4 are reviewed and discussed. In Chapter 4, the focus was placed on presenting the results along with the details associated with how they were obtained. In this chapter, emphasis is placed on combining all the pieces in a coherent manner and directly stating how the results of Chapter 4 impact the current understanding of SDBD actuators.

Research conducted within the SDBD community, for the last ten years, has mostly been geared towards the adaptation of the SDBD actuator for application. Unfortunately, the current state of the SDBD is insufficient for application for flow control; however, the SDBD actuator has demonstrated potential to perform the desired application. The development of the SDBD actuator, in my opinion, requires fundamental research, dedicated to developing an understanding of the physics. The results obtained from a fundamental study should then be used in the development of a computational model. With this in mind, the research objectives of the work presented within this dissertation were to develop a quantitative understanding of some of the physics of an SDBD actuator. Initially, the measurement of thrust, electrical properties, and radiation via optical emission spectroscopy were selected to investigate the SDBD. Thrust measurements were done first to establish the small strength of the induced thrust produced by an SDBD, thus providing justification for the present study. Electrical measurements were done next because, fundamentally, the SDBD is an electrical device. The results obtained from electrical measurements provided details about the SDBD and gave insight into designing the spectroscopic experiments. Also, remember the electrical nature of the SDBD produces a chemically active plasma which generates charged particles. The charged particles collide with the background gas, imparting momentum and inducing a flow. Therefore, based on the desired application of flow control, it seems intuitive to study the chemical kinetics. The study of the chemical kinetics was done using the diagnostic tool of optical emission spectroscopy. The discussion that follows presents a brief summary of the results given in Chapter 4 along with their potential impact.

In Section 4.1, the induced thrust of the SDBD was measured as a function of the applied voltage amplitude and the dissipated power. The measured induced thrust was on the order of 10 mN/m which, as
discussed in Chapter 2, is incapable of controlling flow fields characterized with Reynolds numbers for real flight conditions. Based upon results of other investigators, as presented and discussed in Chapter 2, an induced thrust on the order of 100 mN/m is required for some of the intended aerospace applications. Since the measured thrust presented in Section 4.1 is so small, the research conducted within this document is warranted.

Electrical measurements of the SDBD were presented in Section 4.2. The main objective was to measure the potential along the dielectric surface. The motivation for measuring the potential along the dielectric surface is best illustrated by briefly discussing the electrical model of an SDBD and the importance of the potential along the dielectric surface. As mentioned throughout this document, the SDBD is an electrical device and is therefore governed by Maxwell’s electromagnetic equations. Any serious SDBD model must satisfy these partial differential equations. To do so requires various boundary conditions to be known. In particular, boundary conditions for the electric field include the potential along the exposed electrode, the potential along the encapsulated electrode and the potential far from the SDBD. Technically, magnetic field boundary conditions are also required to solve Maxwell's electromagnetic equations; however, the conductive current produced by the discharge is small, usually less than one tenth an ampere. Therefore, the boundary conditions associated with the magnetic field are not needed and the electromagnetic problem can be approximated as an electrostatic problem.

Similarly, the boundary conditions of the electrical model given for the SDBD can be simplified further. The justification is best illustrated by understanding the morphology of the SDBD. When a sufficiently large, oscillating potential is applied to the exposed electrode, the gas breaks down into a plasma. Charged particles produced by the plasma drift under the influence of the applied electric field, distributing themselves along the surface of the dielectric barrier. After a sufficient number of cycles of the applied, periodic voltage, the spatial and temporal distribution of accumulated charge along the dielectric surface will be periodic. A numerical solution of the electrostatic model described above, will determine what the periodic potential along the dielectric surface is; however, the computational cost is great. One way to reduce the computational cost is to redefine the required boundary conditions of the electrostatic model. In particular, the potential along the encapsulated electrode can be replaced by the potential along
the dielectric surface due to accumulated charge. Unfortunately, the potential along the dielectric surface is unknown; however, it can be measured and entered as a boundary condition in the numerical simulation.

There are some obvious advantages and disadvantages with replacing the potential of the encapsulated electrode with the potential upon the dielectric surface. The main advantage is the simulation now has to run for a single cycle of the applied voltage waveform; whereas before, it would have to run for many cycles. The computational savings achieved is best illustrated by understanding how many computational time steps are typically needed to complete a single applied voltage cycle. According to Likhanskii et al., the required computational time step, based upon the CFL condition, ranges from 5 to 10 picoseconds. The typical period of the applied voltage ranges from 0.2 to 1 millisecond, resulting in 20,000,000 to 200,000,000 time steps per cycle. The main disadvantage associated with replacing the potential of the encapsulated electrode with the potential upon the dielectric surface is that the former potential is known, whereas the latter potential is unknown.

Before moving forward, it should be mentioned that the electrostatic model given thus far is sufficient for small SDBD's where distributed loading of inductance, capacitance and resistance along the electrodes is negligible. The effects caused by distributed loading within the electrodes may not be negligible for large SDBD's. For this case, the electrostatic model given may not hold and the problem now requires solution of the full electromagnetic equations.

To summarize, the electrostatic model of the SDBD has three boundary conditions which include the potential of the exposed electrode, the potential of the dielectric surface, and the potential far from the SDBD. The potential of the exposed electrode is specified and is therefore known. The potential far from the SDBD is given by Equation 2.2.3.19 in Chapter 2. The potential along the dielectric surface is in general dependent on space and time; however, once the dielectric potential becomes periodic it is only dependent on space and phase of the applied voltage.

The potential along the dielectric surface was measured and presented within Section 4.2. The technique performed was unable to determine the phase or spatial dependence of the potential along the dielectric surface, but was able to determine the magnitude at a particular phase of the applied voltage. A more sophisticated technique using Pockels effect is required to determine the phase and space dependence.
In spite of the obvious limitations associated with the method used to measure surface charge, the measured potential along the dielectric surface, presented in Section 4.2, still provides useful insight. It was shown that, during the positive voltage half-cycle, breakdown started at an applied voltage amplitude of 2300 volts with a corresponding potential along the dielectric surface of 0. The dielectric potential increased linearly with increasing applied voltage amplitude, reaching 4100 volts at an applied voltage of 6000 volts. During the negative voltage half-cycle, breakdown started at an applied voltage amplitude of 1900 volts and the corresponding potential along the dielectric surface was 0. The dielectric potential increased linearly with increasing applied voltage amplitude, reaching 4000 volts at an applied voltage amplitude of 6000 volts.

Unfortunately, the measured potential along the dielectric surface cannot be used as an input to a computer simulation because it is an average over the space coordinates at a particular phase; however, it can be used as a check for other measurements of the dielectric surface potential which do resolve the spatial and phase dependence. The trends measured, namely linearly increasing surface potential with respect to the applied voltage amplitude at the on-set of breakdown, has to be present for other measurements of potential along the dielectric surface.

In Sections 4.3 through 4.5, the rotational temperature of \( N_2(C^3\Pi_u) \) and \( N_2^+(B^2\Sigma_u^+) \), the vibrational temperature for \( N_2(C^3\Pi_u) \), the relative upper state number densities of \( N_2(C^3\Pi_u) \) and \( N_2^+(B^2\Sigma_u^+) \), and the reduced electric field were measured to describe the chemically active plasma. In Section 4.3, the spectroscopic results were averaged over the entire discharge, providing direction for the development of other experiments. The results of which were presented in Sections 4.4 and 4.5. In Section 4.4, an optical chopper was used so that the radiant signal was separated in terms of voltage half-cycle, resulting in measurements averaged over either the positive or negative voltage half-cycle. In Section 4.5, the inner-electrode gap spacing was increased to 1 mm, resulting in spatially stable, periodic cathode spots, allowing detailed, spatially resolved measurements within a single cathode spot. This is the first time that spatially and phase resolved spectroscopic measurements have been made within an SDBD. Finally, the results from Section 4.5 are used to describe a model of the SDBD.

The spectroscopic quantities listed above, namely the rotational temperature of \( N_2(C^3\Pi_u) \) and \( N_2^+(B^2\Sigma_u^+) \), the vibrational temperature for \( N_2(C^3\Pi_u) \), the relative upper state number densities of
and were obtained directly by fitting the measured spectra using a code called N2SPECFIT. The reduced electric fields were obtained by developing a chemical kinetics model which demonstrated the quantity \( N_2^+(B^2\Sigma_u^+, \nu' = 0)/N_2(C^3\Pi_u, \nu' = 0) \) was a function of only the reduced electric field. The reduced electric field was then determined from tabulated results of \( N_2^+(B^2\Sigma_u^+, \nu' = 0)/N_2(C^3\Pi_u, \nu' = 0) \) versus the reduced electric field. The discussion that follows will summarize the results obtained from Sections 4.3, 4.4 and 4.5. A discussion about the impact of the results is given also.

In Section 4.3, measurements showed the rotational and vibrational temperatures are at a maximum within the inner-electrode gap and decreases in the induced flow direction. The rotational temperature of \( N_2(C^3\Pi_u) \) ranged from 460 K at the inner-electrode gap to 340 K at the outer edge of the discharge. The vibrational temperature ranged from 3200 K at the inner-electrode gap to 2850 K at the edge of the discharge. Spanwise fluctuations within the rotational and vibrational temperatures were shown. The cause of the fluctuations was attributed to the cathode spots of the plasma. The rotational temperature of \( N_2^+(B^2\Sigma_u^+) \) was also shown to be significantly greater than the rotational temperature of \( N_2(C^3\Pi_u) \). The difference in rotational temperatures between the two excited states ranged from 120 K at an applied voltage of 3900 volts to 200 K at an applied voltage of 6300 volts.

Assuming that the rotational temperature of \( N_2(C^3\Pi_u) \) is in equilibrium with the translational temperature then the rotational temperatures of \( N_2(C^3\Pi_u) \) represent thermal heating of the plasma. The importance of the maximum temperature of 460 K indicates the heating is too low to damage the various dielectric materials used for SDBD's. The rotational temperature of \( N_2^+(B^2\Sigma_u^+) \) was shown to not be in equilibrium with the rotational temperature of \( N_2(C^3\Pi_u) \) which suggests that \( N_2^+(B^2\Sigma_u^+) \) exchanges energy through collisions with the background species as well as some other mechanism. The net energy exchange of \( N_2^+(B^2\Sigma_u^+) \) over one mean-free-path must be greater than the net energy exchange of \( N_2(C^3\Pi_u) \) over one mean-free-path. The fact that the difference in temperature is a function of voltage and the higher energy species has a net charge, suggest the other energy transfer mechanism could be the local electric field. For the electric field to be the mechanism requires a large spatial gradient in the field, as is present in a sheath. Measurements showed the deviation in temperature persisted throughout the entire discharge region and was strongest within the cathode fall, suggesting that the SDBD is predominantly sheath if the electric field is the mechanism. The importance of the temperature deviation manifests itself not only in
debating the physical mechanism responsible, but also for accurately predicting the kinetics of the various species present in the discharge since the kinetics are a function of the energy of the particles. The importance of which is illustrated further when the experimental results of Section 4.5 are reviewed.

In Section 4.4, the radiant signal was separated according to voltage half-cycle, resulting in a clearer description of some of the initial measurements presented in Section 4.3. In particular, the vibrational temperatures of the positive and negative voltage half-cycles were presented as a function of y-coordinate. The vibrational temperature profile was shown to be completely different depending on voltage half-cycle; this was not possible to determine from the results presented in Section 4.3. During the positive voltage half-cycle, the vibrational temperature started at a minimum at the inner-electrode gap, increasing to a maximum and then remained constant; whereas, during the negative voltage half-cycle, the vibrational temperature started at a maximum at the inner-electrode gap and then decreased exponentially. The dependence of the vibrational temperature profile upon voltage half-cycle clearly illustrates the difference in discharge structure, which was also evident in measured concentrations of $N_2(C^3\Pi_u)$ and $N_2^+(B^2\Sigma^+_u)$. During the negative voltage half-cycle, for a voltage amplitude of 4450 volts, the concentrations of both species decreased linearly; however, during the positive voltage half-cycle, the concentrations of $N_2(C^3\Pi_u)$ and $N_2^+(B^2\Sigma^+_u)$ increased to a maximum and then decreased linearly with increasing y-coordinate. The profile of the concentrations of $N_2(C^3\Pi_u)$ and $N_2^+(B^2\Sigma^+_u)$ were also found to be dependent upon the applied voltage amplitude during the negative voltage half-cycle. It was shown that the concentration of both species, during the negative voltage half-cycle, decreased exponentially for an applied voltage of 5900 volts; however, as mentioned, both species decreased linearly for an applied voltage amplitude of 4450 volts. The difference was shown to be caused by a significantly stronger electric field within the cathode fall. It should be pointed out that the measurements were not resolved within the cathode fall, however, the measurements show the affects produced by the cathode fall.

The results presented in Section 4.4 are useful because they demonstrate the difference between the discharge produced during the positive and negative voltage half-cycle. Results obtained from numerical simulation can use these results as a check. In particular, results from a numerical simulation, for the negative voltage half-cycle, should have an excited particle density that decreases in the y-direction. For an applied voltage of 5900 volts, the excited particle density should decrease exponentially, whereas for an
applied voltage of 4450 volts, the excited particle density should decrease linearly. A difference in functional dependence, with respect to the y-coordinate for the two different applied voltages, should be present for species different than the species measured. The justification is based on the fundamental mechanism producing the difference which has everything to do with the difference is electric field strength for the two cases rather than the particular species. A similar argument holds for comparison of results obtained for the positive voltage half-cycle.

In Section 4.5, the objective was to develop the details of some of the observations made in Sections 4.3 and 4.4. The first step in meeting this objective was to produce spatially stable, periodic cathode spots by increasing the voltage amplitude and inner-electrode gap spacing, enabling spatially resolved measurements within a single cathode spot. Measurements verified the attachment points of the discharge are indeed cathode spots and occurred only during the negative voltage half-cycle. It was also shown that the cathode spots, generated using the arrangement described above, were spatially stable. It was also determined that the fluctuations in rotational temperature, presented in Section 4.3, was caused by the cathode spots. During the positive voltage half-cycle, it was shown that the microdischarges are spatially random for the spaced, inner-electrode gap arrangement, resulting in constant plasma properties with respect to the x-coordinate. The plasma properties measured shown are constant over a sufficiently long time including the vibrational temperature of \( N_2(C^3\Pi_u) \), rotational temperatures of \( N_2(C^3\Pi_u) \) and \( N_2^+(B^2\Sigma_u^+) \), and relative concentrations of \( N_2(C^3\Pi_u) \) and \( N_2^+(B^2\Sigma_u^+) \). Measurements showed that the production of \( N_2(C^3\Pi_u) \) and \( N_2^+(B^2\Sigma_u^+) \) occurred within the cathode spot. It was also shown that the vibrational temperature profile within a cathode spot was at a maximum along the outer edges, decreasing to a minimum in the center. The rotational temperature of \( N_2^+(B^2\Sigma_u^+) \) was found to have the same profile within a cathode spot; however, the rotational temperature of \( N_2(C^3\Pi_u) \) was found to be at a minimum along the outer edges, increasing to a maximum in the center. The cause of the spatial discrepancy between the rotational temperatures of \( N_2^+(B^2\Sigma_u^+) \) and \( N_2(C^3\Pi_u) \) was attributed to the local electric field. The average electric field was shown to be at a maximum along the outer edges, decreasing to a minimum at the center of a cathode spot which suggests that the outer edge of the microdischarge, during the negative voltage half-cycle, is a type of sheath where the electric field is at a maximum. Rotational temperatures of \( N_2(C^3\Pi_u) \) and \( N_2^+(B^2\Sigma_u^+) \) were shown to be nearly identical during the positive voltage half-cycle.
however, deviated significantly during the negative voltage half-cycle. During the negative voltage half-cycle, the rotational temperature of $N_2^+(B^2Σ_u^+)$ ranged from 800 to 1300 K, whereas the rotational temperature of $N_2(C^3Π_u)$ ranged from 350 to 450 K. The deviation in temperature between the ions and neutrals was explained in terms of the electric field. The use of the Wannier relationship showed that the ion temperature consisted of contributions from the surrounding neutrals and the electric field.

The consequences of the results reported in Section 4.5 should impact modeling work done on an SDBD and in the physics describing the discharge morphology. In the case of the latter, the reduced electric field was shown to be at a maximum at the outer edges of the microdischarge. The reduced field was also shown to change rapidly with respect to the $x$-direction. From Maxwell’s laws, the gradient of the electric field is proportional to the net charge, suggesting that the outer edges of the microdischarge have a net charge and are sheaths. It was not shown, but is speculated that the unshielded, reduced electric field at the outer edge of the various microdischarges of the SDBD could have influence on the spatial placement of the microdischarges of the SDBD. Supporting evidence for spatial placement via the reduced electric field can also be seen by how spatially stable the produced cathode spots are for the results presented within Section 4.5. It was shown that changing the electric field strength, by increasing the applied voltage or changing the gap spacing, resulted in spatially stable cathode spots.

As mentioned, the chemically active plasma produces charged particles which are responsible for inducing the flow via momentum transfer collisions with the surrounding neutrals. In order to determine the momentum transfer, a computational simulation has to accurately account for the production of charged particles and the number of momentum transfer collisions. Some of the momentum transferring collisions occurring in an air plasma, along with rate constants, are given by Equations 4.4.8 through 4.4.13 in Section 4.4. Almost all of the rate constants are a function of an average temperature between the participating ion and neutral. Not including the temperature deviation between the ion and neutral results in rate constants that are 90 to 100% different than if you include the temperature deviation. The large error in rate constants indicates that the temperature deviation must be accounted for, or the number of momentum transferring collisions will be significantly off, resulting in poor results. The work presented in Section 4.5 suggests that the ion temperature of each ion species must be calculated using the Wannier relationship and the local electric field at each time step. The updated ion temperature can then be used to calculate the rate
constants at each time step. A more accurate solution of the plasma problem should result by including proper rate constants. One of the results obtained is the spatially, temporally dependent momentum source term needed as an input for a Navier-Stokes solver which is used to determine the induced flow field.
Appendix A: Measuring the Dielectric Constant

The configuration, along with dimensions, used to measure the dielectric constant for the dielectric material used in the fabrication of the SDBD is shown in Figure A.1. The electric field, for an infinite two dimensional plate, was found using Gauss’s law and is given as

$$\vec{E} = \frac{Q}{2\epsilon_0 A} \hat{n}$$  \hspace{1cm} (A.1)

where $Q$ is the total charge on the plate, $A$ is the area, $\epsilon_0$ is the permittivity of free space and $\hat{n}$ is the unit normal vector. For two infinite parallel plates, held at an equal but opposite charge, the magnitude of the field between the plates is doubled and is zero everywhere else. The voltage is then given as

$$V = -\int_{\theta}^{d} \vec{E} \cdot d\vec{l} = \frac{Qd}{\epsilon_0 A}$$  \hspace{1cm} (A.2)

where $d$ is the distance between the two plates. The vacuum capacitance is then defined as

$$C_{vac} = \frac{Q}{V} = \frac{\epsilon_0 A}{d}$$  \hspace{1cm} (A.3)

The actual capacitance of the system is found by multiplying the capacitance of the vacuum by the dielectric constant $\kappa$ resulting in

$$C = \kappa C_{vac} = \kappa \frac{\epsilon_0 A}{d}$$  \hspace{1cm} (A.4)

The dielectric constant is then given as

$$\kappa = \frac{d}{\epsilon_0 A} C.$$  \hspace{1cm} (A.5)

The separation between plates is 1.0 mm, the area is $8.97 \times 10^{-4}$ m$^2$ and the permittivity of free space is given as $8.854 \times 10^{-12}$ C$^2$/Nm$^2$. 
Figure A.1: Dimensions and geometry used to measure the dielectric constant.

\[ V(t) = 500\sin(2\pi 5000t) \]

\[ R_2 = 94.9 \, \Omega \]

Figure A.2: Equivalent circuit used to measure dielectric constant.
The unknown capacitance was measured using the circuit shown in Figure A.2. The voltage drop across the resistor $R_2$, designated as $V_{R_2}$, and the input voltage $V(t)$ were measured. The voltage drop across the parallel capacitor is given as

$$V_{cap} = V(t) - V_{R_2}(t).$$  \hspace{1cm} (A.6)

The current through the parallel capacitor is given as

$$I = C \frac{dV_{cap}}{dt} = C \frac{d[V(t)-V_{R_2}(t)]}{dt} \approx C \frac{dV}{dt}. \hspace{1cm} (A.7)$$

The current through the resistor is obtained using Ohms law and is given as

$$I = \frac{V_{R_2}}{R_2} \hspace{1cm} (A.8)$$

Equating Equations A.7 and A.8 gives

$$C = \frac{V_{R_2}}{R_2 \frac{dV}{dt}}. \hspace{1cm} (A.9)$$

Substituting Equation A.9 into Equation A.5 gives

$$\kappa = \frac{V_{R_2} \frac{d}{dt}}{\kappa R_2 \frac{dV}{dt}}. \hspace{1cm} (A.10)$$

Approximating the voltage drop across the capacitor as the applied voltage resulted in a 0.04% difference.
Appendix B: Lissajous Charts

The power dissipated within the plasma, for the circuit given in Figure B.1, is given as

\[ P = fE = f \int_0^T V(t)I(t)\,dt \]  \hspace{1cm} (B.1)

where \( f \) is the frequency, \( E \) is the energy per cycle and \( I(t) \) is given as

\[ I(t) = C \frac{dV_C}{dt}. \]  \hspace{1cm} (B.2)

![Figure B.1: Equivalent circuit used to obtain a Lissajous chart for a DBD.](image)

In Equation B.2, the voltage \( V_C \) is the voltage drop across the capacitor. Substituting Equation B.2 into Equation B.1 gives

\[ P = f \int_0^T V(t)C \frac{dV_C}{dt} \,dt = f \int V(t)CdV_C. \]  \hspace{1cm} (B.3)

From the definition of capacitance, the product of \( CdV_C \) is the differential charge of the capacitor, designated as \( dQ \). Thus, dissipated power is given as

\[ P = f \int V(Q)dQ \]  \hspace{1cm} (B.4)

which is nothing more than the area under the curve of voltage versus charge, known as a Lissajous chart.

As will be demonstrated, the Lissajous chart is useful for understanding other important parameters of the DBD. It should also be mentioned that the capacitance \( C \) is strictly included for the purpose of measuring all the charge within the DBD. The voltage drop across \( C \) must be negligible for this to occur; therefore \( C \) has to be much greater than the capacitance of the DBD.
The idealized Lissajous chart, for the sinusoidal voltage shown in Figure B.2, is given in Figure B.3. In Figure B.2, the applied sinusoidal voltage is given as the black curve and the voltage across the gas is given as the red curve. The figure shows that the ideal voltage across the gas increases up to the breakdown voltage, \( V_D \) at time \( t_1 \), and then remains constant until breakdown ends at time \( t_2 \). This process then repeats for the negative voltage half-cycle. The first step to understanding the geometry of the Lissajous chart is realizing that any definable slope is given as \( \Delta Q/\Delta V \) which is nothing more than a capacitance. Therefore, the slopes between times \( t_1 \) and \( t_2 \), \( t_2 \) and \( t_3 \), \( t_3 \) and \( t_4 \), and \( t_4 \) and \( t_1 \) are the capacitances of the active phases and passive phases of the positive and negative voltage half-cycles. By assuming symmetry, the capacitances of both passive and active phases are the same. The capacitance of both passive phases is simply the capacitance of the dielectric; whereas, during the active phases, the total capacitance, \( C_{\text{tot}} \) is given as

\[
C_{\text{tot}} = \frac{C_D C_G}{C_D + C_G} \tag{B.5}
\]

where \( C_D \) and \( C_G \) are the dielectric and gas capacitances, respectively. For an applied peak voltage \( V_p \) less than the breakdown voltage, the total charge remains in phase with the applied voltage and the Lissajous chart consists of a straight line passing through the origin with slope \( C_D \).
Figure B.2: The blue curve is the applied voltage and the red curve is the ideal voltage drop across the gas.

Figure B.3: Idealized Lissajous chart for a sinusoidal voltage.
Appendix C: N2SPECFIT

The program N2SPECFIT is a line-by-line code used to analyze the measured spectra. It is capable of determining the rotational temperature for the 1st and 2nd positive electronic band systems of N\textsubscript{2} and the 1st negative electronic band system of N\textsubscript{2}+, along with the upper state number densities of the various bands within these band systems. The details of the theoretical equations used by N2SPECFIT are given below.

The intensity of a vibration-rotation line for an optically thin molecular gas is given as

\[ I_{\nu', J'}^{\nu'', J''} = N_{\nu', J'} A_{\nu', J'}^{\nu'', J''} \frac{hc}{\nu_{\nu', J'}^{\nu'', J''}} \quad (C.1) \]

where \( \nu' \) is the upper vibrational quantum number, \( \nu'' \) is the lower vibrational quantum number, \( J' \) is the upper rotational quantum number, \( J'' \) is the lower rotational quantum number, \( I_{\nu', J'}^{\nu'', J''} \) is the line intensity, \( N_{\nu', J'} \) is the number of upper-state molecules in the \( \nu' \) vibrational level and \( J' \) rotational level, \( A_{\nu', J'}^{\nu'', J''} \) is the Einstein coefficient, \( \nu_{\nu', J'}^{\nu'', J''} \) is the wavelength of the transition and \( hc \) is Planck’s constant times the speed of light.\(^{205}\) Assuming the rotational energy levels are in equilibrium, the distribution of molecules in the different energy levels is described by the Boltzmann distribution,

\[ N_{\nu', J'} = \frac{n_{\nu'}}{Q_{\nu'} g_{J'} e^{-F_{J'}/kT}} \quad (C.2) \]

where \( n_{\nu'} \) is the number of molecules in the upper vibrational level \( \nu' \), \( Q_{\nu'} \) is the rotational partition function, \( g_{J'} \) is the degeneracy of the \( J' \) upper rotational energy level, \( F_{J'} \) is the rotational energy of the \( J' \) upper rotational energy level, and \( kT \) is the Boltzmann constant times the rotational temperature. The Einstein coefficient of the vibration-rotation transition can be related to the Einstein coefficient of the vibrational transition through

\[ A_{\nu', J'}^{\nu'', J''} = A_{\nu'}^{\nu'', J''} \frac{g_{J'}}{g_{J'}}, \quad (C.3) \]

where \( A_{\nu'}^{\nu''} \) is the Einstein coefficient for the vibrational transition and \( S_{J'}^{J''} \) is the rotational line strength.\(^{206}\) Substituting Equations C.2 and C.3 into Equation C.1 gives the intensity of a vibration-rotation line as

\[ I_{\nu', J'}^{\nu'', J''} = \frac{n_{\nu'}}{Q_{\nu'}} S_{J'}^{J''} e^{-F_{J'}/kT} \frac{hc}{\nu_{\nu', J'}^{\nu'', J''}} \quad (C.4) \]
The intensity predicted in Equation C.4 is for a line without any width; however, a measured transition is spread over a small frequency band caused by various broadening mechanisms such as Doppler, pressure, and natural line broadening\(^{207}\). To account for the line shape, the line intensity is multiplied by the correct line shape function,

\[
I_{v',j'}^{''',j'''} = I_{v',j'}^{v'',j''} \Phi(\lambda, \lambda_{v',j'}^{v'',j''}).
\]  

In Equation C.5, \(I_{v',j'}^{v'',j''}\) is the spectral line and \(\Phi(\lambda, \lambda_{v',j'}^{v'',j''})\) is the line shape function. The line shape function is a normalized Voigt distribution and it is the convolution of the various broadening mechanisms listed above. Equation C.5 gives the spectral line for a single rotational transition within a vibration transition, but there are many rotational transitions within a single vibrational transition. Therefore all the rotational transitions within a single vibrational transition can be obtained by summing over all possible rotational quantum numbers. This is given as

\[
I_{v'}^{'''} = \sum_{j''} I_{v',j''}^{v'',j''}. \tag{C.6}
\]

where \(I_{v'}^{'''}\) is the intensity of the vibrational transition.

Equation C.6 gives the spectral lines for a perfect measuring device; real spectrometers, however, have error which causes the spectral line predicted in Equation C.6 to broaden even more. The error of the spectrometer is given by the instrumental line shape and the measured spectral line is obtained numerically by convolving Equation C.6 with the instrumental line shape. This is given as

\[
W_{v'}^{'''}(\lambda) = \int_0^\infty I_{v'}^{v'''}(\lambda')P(\lambda, \lambda')d\lambda'. \tag{C.7}
\]

where \(W_{v'}^{'''}(\lambda)\) is the spectral line and \(P(\lambda, \lambda')\) is the instrumental line shape. Substituting Equation C.5 into Equation C.7 gives

\[
W_{v'}^{'''}(\lambda) = \sum_{j''} \int_0^\infty I_{v',j''}^{v'''}(\lambda')P(\lambda, \lambda')d\lambda'. \tag{C.8}
\]

The different broadening mechanisms of the measured spectrum produce half-widths that are at least an order-of-magnitude smaller than the half-width of the instrumental line function in the environment being investigated. Therefore the half-widths of the different broadening mechanisms present in the measured spectrum can be approximated by a Dirac delta function with minimal error resulting in

\[
W_{v'}^{'''} = \int I_{v',j''}^{v'''}(\lambda, \lambda_{v',j'}^{v'',j''}). \tag{C.9}
\]
The final equation for the spectral line is obtained by substituting Equation C.4 into Equation C.9

\[ W_{\ell''} (\lambda) = \frac{hc N_{\ell''} S_{\ell''}}{q_r \gamma_{\ell'',j''}} \sum_{j',f''} e^{F_{j',f''}/kT} \frac{p(j',f'',j''')}{\gamma_{j',j''}}. \] (C.10)

The program N2SPECFIT uses Equation C.10 to calculate the numerical spectrum for a particular rotational temperature which is supplied as an initial guess and then iteratively changed until the measured spectrum matches the numerical. The spectroscopic constants used in Equation C.10 by N2SPECFIT are those tabulated by Gilmore et al.\textsuperscript{208} and Laher and Gilmore.\textsuperscript{209} Comparison between the measured and calculated spectrum is done statistically by

\[ \chi^2 = \frac{\chi^2}{n-N}. \] (C.11)

where \( n \) is the number of data points, \( N \) is the number of fitting parameters and \( \chi^2 \) is given as

\[ \chi^2 = \sum_{i=1}^{n} \frac{(y_i - y(x_i))^2}{\sigma_i^2}. \] (C.12)

In Equation C.12, \( y_i \) is the measured data point, \( y(x_i) \) is the calculated data point and \( \sigma_i \) is the standard deviation of the noise within the measured spectra scan. Convergence is achieved by iteratively changing the rotational temperature and upper state number density until \( \chi^2 \) is minimized. It is interesting to note that in the case of a good fit \( y_i - y(x_i) \approx \sigma_i^2 \) and Equation C.12 becomes

\[ \chi^2 = \sum_{i=1}^{n} \frac{\sigma_i^2}{\sigma_i^2} = n. \] (C.13)

From Equation C.13 it is seen that the number of data points is a good normalization parameter. Therefore convergence is achieved for \( \chi^2 \) values near 1.
Appendix D: Boltzmann Plot Method

The Boltzmann plot method can be used to obtain the rotational, vibrational and electronic temperature so long as the distribution of these energy levels is described with a Boltzmann distribution. The method is applied to the vibrational energy levels, but can easily be applied to the rotational and electronic. The Boltzmann distribution for the vibrational energy levels is given as

\[
\frac{N_{v'}}{N} = \frac{\exp\left(\frac{g(v')\hbar c}{kT_{\text{vib}}}\right)}{q_v}
\]  

(D.1)

where

\[
G(v') = \left(v' + \frac{1}{2}\right)\omega_e - \left(v' + \frac{1}{2}\right)^2\chi_e\omega_e + \left(v' + \frac{1}{2}\right)^3\gamma_e\omega_e ...
\]  

(D.2)

The spectral response of the spectroscopic system has been characterized by a relative calibration which means that the measured spectral transitions need to be taken relative to another measured transition. In this work the population distribution is relative to the \(v' = 0\) energy level. The fraction of \(N_{v'=0}\) is given as

\[
\frac{N_{v'=0}}{N} = \frac{\exp\left(-\frac{g(v'=0)\hbar c}{kT_{\text{vib}}}\right)}{q_v}
\]  

(D.3)

Dividing Equation D.1 by Equation D.3 gives

\[
\frac{N_{v'}}{N_{v'=0}} = \exp\left[G(v' = 0) - G(v')\frac{\hbar c}{kT_{\text{vib}}}\right].
\]  

(D.4)

Taking the natural logarithm of Eq. D.4 gives

\[
\ln\left(\frac{N_{v'}}{N_{v'=0}}\right) = \frac{1}{T_{\text{vib}}} \frac{\left(g(v'=0) - g(v')\right)\hbar c}{k}. \tag{D.5}
\]

Equation D.5 is an equation of a line with a slope of \(\frac{1}{T_{\text{vib}}}\). The slope is determined by plotting \(\ln\left(\frac{N_{v'}}{N_{v'=0}}\right)\) versus \(\frac{\left(g(v'=0) - g(v')\right)\hbar c}{k}\) and using a linear least squares fit. The vibrational temperature is obtained by setting the slope equal to \(\frac{1}{T_{\text{vib}}}\).
References


