ABSTRACT

KRIBS, JAMES DAVID. Effects of Diluents and High Potential Electric Fields on Flame Stabilization and Liftoff. (Under the direction of Dr. Kevin Lyons.)

The focus of this study is to investigate the influences of additives and electric fields to traditional lifted hydrocarbon jet flames, as well as experiments into electrohydrodynamic devices using ambient air. These additives can take the form of nitrogen dilution or hydrogen enrichment of the central fuel jet, or coflowing air. Nitrogen dilution provides a method to increase the fuel jet velocity, while not adding either fuel or oxidizer. Hydrogen enrichment is the addition of small amounts of hydrogen to the fuel stream, which greatly increases the overall flame speed and flame temperature. Early investigations into the application of electric fields has shown that the high potential electric fields can create air flows using the ionic wind, but also has a possible influence on the chemical kinetics and overall chemical structure of the flame, influencing the interactions between ions within the flame or creating new ions. The influence, of the diluents, enrichment agents, or electric fields, on the downstream stabilization point was observed at different levels, either flow rates for the diluents/enrichment agents or potential for the electric fields, as well as the changes to flame structure and luminosity. Experimental models have drawn comparisons to existing models and theories, and understanding of known phenomena, and provided useful insight into overall mechanisms occurring within jet flames. Further experiments will focus on optimization of electrohydrodynamic devices and electric fields.
Effects of Diluents and High Potential Electric Fields on Flame Stabilization and Liftoff

by
James David Kribs

A dissertation submitted to the Graduate Faculty of
North Carolina State University
in partial fulfillment of the
requirements for the degree of
Doctor of Philosophy

Mechanical Engineering

Raleigh, North Carolina

2013

APPROVED BY:

_______________________________  ______________________________
Dr. Kevin Lyons                Dr. Alexei Saveliev
Chair of Advisory Committee

_______________________________  ______________________________
Dr. Tiegang Fang               Dr. Stephen Terry
DEDICATION

To My Parents for All Their Support and Guidance
BIOGRAPHY

James Kribs is a graduate research assistant in the Reacting Flows and Turbulent Jets Laboratory at North Carolina State University's Department of Mechanical and Aerospace Engineering. His research focuses on the stabilization of diluted, lifted jet flames, effects of high potential electric fields, and electrohydrodynamics.
ACKNOWLEDGMENTS

I would like to say thank you to Dr. Kevin Lyons for this opportunity to, as well as Dr. Alexei Saveliev, Dr. Tiegang Fang, Dr. Thomas Ward, Dr. Tarek Echekki, Dr. Nancy Moore, Dr. M. Sean June, and Dr. William Boettcher for their sound advice.

I greatly appreciate all the assistance from my thesis editor, Heather Thompson, who helped, more than I can ever express, with this dissertation.

I would also like to thank the graduate students that I have worked with, Andrew Hutchins, Parth Shah, Jon Gomes, and Jennifer McCraw, as well as the undergraduate students, who helped along the way, William Reach, Richard Muncey, and Tamir Hasan, and the staff of the MAE department, specifically Skip Richardson, Mike Breedlove, and Lance Mangum, for their advice and humor, without which this would not have been as much fun.

The research reported in this dissertation has been supported by the U.S. Army Research Office (Contracts W911NF0510045, W911NF0810142, and W911NF1210140) Dr. Ralph Anthenien, Technical Monitor, ARO.
# TABLE OF CONTENTS

LIST OF TABLES ........................................................................................................ vii

LIST OF FIGURES ..................................................................................................... viii

CHAPTER 1: INTRODUCTION .................................................................................. 1

1.1 Rationale and Focus of Research ..................................................................... 1
1.2 The Lifted Jet Flame ......................................................................................... 3
1.3 The Ionic Wind ................................................................................................. 3
1.4 Electrohydrodynamic Forces Applied to Jet Flames ......................................... 4

CHAPTER 2: BACKGROUND .................................................................................. 6

2.1 A Review of Stabilization Mechanisms in Lifted, Jet Flames and Combustion Theory 6
2.2 A Review of Mechanisms in Electrohydrodynamic (EHD) Flows .................... 19
2.3 Lifted Jet Flame Stabilization and Manipulation Using High Potential Electric Fields 26

CHAPTER 3- EXPERIMENTS IN NITROGEN DILUTION OF METHANE JET FLAMES
....................................................................................................................................... 30

3.1 Experimental Setup .......................................................................................... 31
3.2 Results and Discussion ..................................................................................... 33
3.3 Conclusions ....................................................................................................... 51

CHAPTER 4- EXPERIMENTS IN HYDROGEN ENRICHMENT OF METHANE JET FLAMES .......................................................... 54

4.1 Experimental Procedure .................................................................................... 55
4.2 Results and Discussion ..................................................................................... 58
4.3 Conclusions ....................................................................................................... 66
CHAPTER 5- COMPARISON OF INFLUENCES OF DILUTION IN ETHYLENE AND
METHANE JET FLAMES............................................................................................................ 68

5.1 Experimental Procedure ................................................................................................................. 69
5.2 Results and Discussion ......................................................................................................................... 70
5.3 Conclusion ........................................................................................................................................ 78

CHAPTER 6- ELECTROHYDRODYNAMICS FLOWS FOR COOLING APPLICATIONS
......................................................................................................................................................... 79

6.1 Methodology ...................................................................................................................................... 80
6.2 Results and Discussion ......................................................................................................................... 81
6.3 Conclusion ........................................................................................................................................ 90

CHAPTER 7- USE OF ELECTROHYDRODYNAMIC FORCES TO INDUCE STABILITY
OR INSTABILITY IN JET FLAMES....................................................................................................... 91

7.1 Rationale of Study .............................................................................................................................. 91
7.2 Experimental Apparatus ..................................................................................................................... 98
7.3 Results and Discussion ......................................................................................................................... 102
7.4 Conclusions ....................................................................................................................................... 125

CHAPTER 8- FUTURE INVESTIGATIONS AND CONCLUSIONS.............................................. 127

8.1 Open Questions Remaining in Jet Flame Combustion in Electric Fields ....................... 127
8.2 Application of Hugh Potential Electric Fields to Lifted Spray Combustion.................... 137
8.3 Final Investigations into Optimization of Ionic Air Moving Devices ......................... 141
8.4 Overall Conclusions ............................................................................................................................ 143

REFERENCES .................................................................................................................................... 147
LIST OF TABLES

Table 1- Composition of Blended Gaseous Fuels Used in Industry ........................................ 17
Table 2 -Fuel- Diluent Combinations For Near Field Experiments ........................................ 34
Table 3- Data for Diluted Methane Jet Flames with Coflow in the Far Field ....................... 40
Table 4- Axial and Radial Position of Far Field Experiments................................................. 44
Table 5- Experiments in Comparing Flames with Equivalent Effective Velocities ............... 49
Table 6- Critical Parameters ...................................................................................................... 58
Table 7- Stabilization Position of Enriched, Methane Jet Flames .......................................... 62
Table 8- Experimental Levels Measured for Ethylene and Methane ...................................... 72
Table 9- Electrode Configurations and Applied Voltages for Partially Premixed Flame
Experiments .................................................................................................................................. 111
Table 10- Adopted Ionic Reactions from Yamashita et al. [4] ................................................. 131
LIST OF FIGURES

Figure 1 - Image of Flame Liftoff for Methane Jet Flame.......................................................... 8

Figure 2 - Diagram of Triple Flame Structure .................................................................................. 9

Figure 3 - Stability Diagram of Lifted Jet Flames ............................................................................. 13

Figure 4 - Formation of the Ionic Wind Resulting From a Positively Charged Corona Discharge ................................................................................................................................. 21

Figure 5 - Formation of the Ionic Wind Resulting From a Negatively Charged Corona Discharge ................................................................................................................................. 22

Figure 6 - Secondary Ionization Forming on a Ring Resulting from a Corona Discharge on the 5 Needles [47]........................................................................................................................................ 24

Figure 7 - Fuel Dilution Burner Setup with Coflowing Annulus ................................................. 31

Figure 8 - Flame Location v. Flammable Region Approximation (Trial 1) ..................................... 35

Figure 9a-g - Comparison of Experimental Data to Flammable Limit Approximation for Trials 1-7 ............................................................................................................................................ 36

Figure 10 - Comparison of Axial Difference and Reynolds Number for Near Field Dilution Experiments (Re<4000) .................................................................................................. 38

Figure 11 - Comparison of Axial Difference and Mass Fraction for Near Field Dilution Experiments (Re<4000) .......................................................................................................... 39

Figure 12 - Axial Position of the Flame Base for Far Field Experiments (Re>5000) ............... 41

Figure 13 - Radial Position of the Flame Base for Far Field Experiments (Re>5000) ............ 43
Figure 14- Variation of Downstream Stabilized Position Due to Effect of Coflowing Air for Far Field Experiments (Re>5000) ................................................................. 45
Figure 15- Ratio of Axial to Radial Positions (r/z) of Stabilized Flame Base for Far Field Experiments (Re>5000) ................................................................. 46
Figure 16- Flammable Limit Approximation for Pure Jet Cases in Comparison to Peak Radial Expansion ................................................................. 47
Figure 17- Nitrogen Dilution over Flow Regime for Both Near and Far Flow Field Experiments ................................................................. 50
Figure 18- Experimental Setup ................................................................................. 56
Figure 19- Comparison of Flowrates and Liftoff Height .................................................. 59
Figure 20- Flame Luminosity ................................................................................. 60
Figure 21- Comparison of Jet Velocity to Hydrogen Mass Fraction .................................. 61
Figure 22- Flame Stability as a Function of Enrichment Level ........................................... 63
Figure 23- Comparison of Chemiluminescence of Hydrogen and Methane Jet Flames ...... 65
Figure 24- Experimental Apparatus ................................................................................. 70
Figure 25- Lifted Flame Height Versus Ethylene Flow Rate ............................................... 73
Figure 26- Ethylene Jet Flames with Various Nitrogen Dilution Levels .......................... 74
Figure 27- Comparison of Methane Lifted Flame Heights to Ethylene Lifted Flame Heights ................................................................................................. 76
Figure 28- Non-Dimensional Height versus Fuel Flow Rate for Various Nitrogen Dilution Levels of Ethylene ............................................................................................. 76
Figure 29- Lifted Flame Heights for Methane and Ethylene by Mass Fraction .................. 77
Figure 30- Electrode Setup ............................................................................................... 81
Figure 31- Ring Comparison at 11000V ........................................................................ 83
Figure 32- Ring Comparison at 13000 V ....................................................................... 84
Figure 33- Ring Comparison at 17000 V ....................................................................... 85
Figure 34- Voltage to Flow rate ...................................................................................... 86
Figure 35- Ionic AMD (4 mm Ring) and Fan ................................................................. 88
Figure 36- Ionic AMD (10 mm Ring) and Fan ............................................................... 89
Figure 37- Comparison of Dominant Influences Resulting from the Application of Electric Fields to Lifted Jet Propane Flames ......................................................... 92
Figure 38- Formation of Ionic Wind for the Negatively Charged Corona Discharges .... 95
Figure 40- Candle Flame Experimental Apparatus with Dual Electrodes ..................... 98
Figure 41- Multi-Electrode Setup for Jet Flame Experiments ......................................... 100
Figure 42- High Potential Electric Field Burner Configuration ..................................... 101
Figure 43- Comparison of Flame Behavior of Attached Diffusion as a Function of Applied High Voltage ............................................................................................................. 102
Figure 44- Attraction of Soot Resulting from Applied Electric Field ............................. 104
Figure 45 - Soot Attracted to Negatively Charged Electrodes for Small-Scale Candle Flame Experiments ................................................................. 105

Figure 46 - OH Mole Fraction for Premixed Flame Simulations ...................................................... 107

Figure 47 - Laminar Flame Speed and Peak OH Mole Fraction as a Function of O3 Concentration in the Reactants of a Premixed C3H8 Flame .................................................... 108

Figure 48 - Sample Stabilized, Partially Premixed Jet Flame at 1.14 slpm and 4000 V (Liftoff Height=1.78 cm) ......................................................................................................................... 110

Figure 49 - Location of the Leading Edge of the Flame for Applied Voltage (Propane Flow Rate = 1.14 slpm) ........................................................................................................... 112

Figure 50 - Location of the Leading Edge of the Flame for Applied Voltage (Propane Flow Rate = 1.23 slpm) ........................................................................................................... 113

Figure 51 - Location of the Leading Edge of the Flame for Applied Voltage (Propane Flow Rate = 1.30 slpm) ........................................................................................................... 114

Figure 52 - Location of the Leading Edge of the Flame for Applied Voltage (Propane Flow Rate = 1.38 slpm) ........................................................................................................... 115

Figure 53 - Location of the Leading Edge of the Flame for Applied Voltage (Propane Flow Rate = 1.46 slpm) ........................................................................................................... 116

Figure 54 - Location of the Leading Edge of the Flame for Applied Voltage (Propane Flow Rate = 1.53 slpm) ........................................................................................................... 117
Figure 55- Characterization of Flame Stabilization Points for Partially Premixed Flames as a Function of Applied Voltage. Negative Configurations are Shown as the Solid Curve, and Positive Configurations are Shown as the Dashed Curve................................. 119

Figure 56- Local Extinction Resulting from High Potential Electric Fields at Approximately 6950 V with the Negative Polarity, Single Electrode Configuration at 1.30 slpm......... 122

Figure 57- Abnormal Flame Structure of the Trailing Diffusion Flame at 11000 V at 1.30 slpm.................................................................................................................. 124

Figure 58- Characterization of Flame Stabilization Points for Partially Premixed Flames as a Function of Applied Voltage. Negative Configurations are Shown as the Solid Curve, and Positive Configurations are Shown as the Dashed Curve.............................................. 134

Figure 59- Influences of Positive and Negative Corona Discharges on the Ionic Wind and Flame Ions for Lifted Jet Combustion.............................................................................. 136

Figure 60- Flow Bench Setup for Ionic AMD Experiments............................................. 142
CHAPTER 1: INTRODUCTION

1.1 Rationale and Focus of Research

Even though the discovery of fire was one of humankind's earliest discoveries, there are many area of investigation with open questions that still remain in the field of combustion, from the fluid dynamics of a reacting flow, and unsteady convective and radiative heat transfer, to the chemical kinetics and resulting chemiluminescence, with all of these problems coupled together forming extremely complex problems. Even with modern research capabilities, there are so many open questions that remain. The focus of this work is to investigate the results of external influences, beyond the conventional fuel-air mixing studies, on the stabilization mechanisms of lifted jet flames, beginning with work in the dilution of flames with nitrogen and flame enrichment with hydrogen, as well as research into electrohydrodynamics in neutral flows, and electrohydrodynamic control of jet flames. With the increase in demand for alternative fuels, emissions control, and increased energy efficiency, all of these issues and phenomena have relevant practical applications.

The first research thrust focused on experiments performed on nitrogen and hydrogen blends with other fuels effectively simulating naturally occurring fuels, such as natural gas (mixture of methane and nitrogen) and biogas (mixture of methane and carbon dioxide), and synthesized fuels, such as syngas (mixture of hydrogen, nitrogen, carbon monoxide, and carbon dioxide). This work is to compliment previous work in dilution of pure jets, conducted by David Wilson [1, 2] and Dr. Nancy Moore [3]. As the stabilization
mechanisms of these mixed gases are relatively unknown, as compared to pure gases, such as methane, it is necessary to investigate and understand how diluted fuels stabilize, and the resulting changes in heat transfer and chemiluminescence.

The secondary research focus was on electrohydrodynamic flows, or the creation of a flow using high potential electric fields, flows which had been previously accomplished through mechanical devices, such as conventional fans or pumps. Devices using this concept are already in use, such as The Sharper Image® Ionic Breeze™, called an Ionic Air Moving Device (or Ionic AMD). These devices were investigated, in conjunction with Dr. M. Sean June [4], to see the feasibility of using an ionic AMD to create a bulk flow for heat transfer applications and to characterize the influences of variables, such as the polarity and magnitude of the applied electric field, as well as the electrode surface area, on the resulting volumetric flow rates and the efficiency of the device.

The final investigations combine both of these research interests focusing on the effects of a high potential electric field in lifted jet combustion. High potentials are already in use as an after process treatment for combustion devices in electrostatic precipitators, which remove particulates from the exhaust stream. By applying the electric fields directly to the flame, rather than to the exhaust stream, the high potential electric field provides the ability to stabilize lifted jet flames, as well as removing or reducing pollutant emissions, such as soot, NO\textsubscript{x}, and SO\textsubscript{2}.
1.2 The Lifted Jet Flame

While most household devices that burn hydrocarbon fuels use either premixed flames, similar in structure to those created by Bunsen burners, where the air and fuel are mixed prior to the combustion event, or non-premixed flames, such as candle flames, some industrial devices use jets of hydrocarbons released into air, much like flaring towers in petroleum drilling and refining facilities or in industrial burners. As the flow rate of fuel issuing from this jet increases beyond a critical value, the flame lifts off the burner, and either stabilizes at a downstream location, or becomes unstable and eventually reaches the flammable limits of the combustible mixture, and extinguishing itself. The advantage of using jet flames is the reduction in thermal stresses acting on the burner, as the fuel jet remains at a relatively cool temperature, when compared to the high temperatures seen in combustion. The mechanisms behind the stabilization and other phenomena of the lifted flame are explained further in section 2.1. While these flames have been studied in the past, the effects of diluents, nitrogen for example, and enrichment agents, such as hydrogen, have not been as extensively studied, as pure jets of methane, propane, or ethylene.

1.3 The Ionic Wind

The ionic wind is the formation of an air flow resulting from the application of high voltage electric fields in an open circuit configuration, where the air flow closes the circuit.
The ionic wind is the basis for electrohydrodynamic devices, and is given a more thorough treatment in section 2.2. As mentioned above, electrohydrodynamic devices are already in use for air filtration, and have begun to see use in heat transfer applications [5]. The advantages of these devices is that ionic AMD's can achieve efficiencies on the same order as traditional fans, and the ionic AMD's can use the existing structure of a complex geometry, such as a heat sink or, where the secondary electrode is used to drive the flow, instead of acting as an impedance, when acting in the conventional fan/heat sink setup.

1.4 Electrohydrodynamic Forces Applied to Jet Flames

The development of combustion devices with applied high potential electric fields to influence the combustion event is relatively new, with few devices in existence, as the understanding behind the forces within these devices is relatively limited. The difficulty with these devices is in the addition of another coupled physics problem, the electric field, into the complexity of a jet flame, which causes numerous changes within the flame. Some of the literature on this is reviewed in section 2.3. One of the few devices used in a commercial setting is the Electrohydrodynamic Combustion Control™ developed by ClearSign© [6], which is designed to control flame shape and combustion chemistry. With further investigation, these devices could become more feasible as a method of flame and pollutant control. The purpose of the investigation, described later in this dissertation, is to better
catalogue the influences of electric fields on the leading edge stabilization of a propane jet flame.
CHAPTER 2: BACKGROUND

2.1 A Review of Stabilization Mechanisms in Lifted, Jet Flames and Combustion Theory

While considered to be one of the first scientific discoveries of humankind, the number of open questions, remaining in combustion and the scientific understanding of flames, leaves an expansive amount of inquiry still to be investigated. The basic definition of combustion is the oxidation of a fuel, such as a hydrocarbon, generally perceived as an exothermic reaction. The traditional representation of combustion is a single forward reaction, with fuel and oxidizer on one side and the products of combustion on the other, as shown below for methane in air.

\[ CH_4 + 2O_2 \rightarrow CO_2 + 2 \cdot H_2O \]  

(1)

This reaction uses pure oxygen as the oxidizer, which does not traditionally occur, except in laboratory settings. The most common oxidizer is air, which consists of a combination of nitrogen, oxygen, argon, and traces of other species. By changing the chemical make-up of the oxidizer, the overall chemical reaction changes to:

\[ CH_4 + 2(O_2 + 3.76N_2) \rightarrow CO_2 + 2 \cdot H_2O + 7.52N_2 \]  

(2)
Yet, as complex as this reaction may seem to be, it is actually over 325 reactions, including both forwards and reverse reactions, and 53 intermediate species, which only accounts for the addition of nitrogen into the oxidizer stream [7].

By changing the overall structure of the combustion event, from a fully premixed flame to an issuing jet of fuel into oxidizer, the problem increases from just a function of chemistry to a coupled system between the chemistry, the fluid dynamics, and heat transfer. As the fuel jet mixes with the air, the flame will stabilize at the stoichiometric mixture line (where the fuel is completely burned without any excess air), this phenomenon is shown below.
In laminar flow rates, the stabilized flame will show characteristics of three separate flames; a premixed lean, a premixed rich, and a trailing diffusion flame. This structure, called a triple or tribrachial flame, allows for the propagation against an incoming jet of fuel, and the complete burning of the fuel. The triple flame, as shown in Figure 2, has been extensively studied by S.H. Chung [8], using small diameter nozzles, with propane, where
the partially premixed portions of the flame burn against the incoming reactants, and the trailing diffusion flame burns in flammable mixture regions, designated by the dashed lines in the figure.

It is also possible to observe bibrachial flames [8], where one of the premixed branches is missing, merging with the diffusion flame, but the partial premixing, at the flame base allows for the flame to propagate against the incoming reactants, which allows for the stabilization of the flame. Also of note, is the inability of some fuels to produce stabilized, laminar, lifted
jet flames, which has been found to be a function of the Schmidt number of the fuel (ratio of momentum diffusivity to mass diffusivity),

\[ Sc = \frac{\nu}{D} \]  \hspace{1cm} (3)

where \( \nu \) is the kinematic viscosity, and \( D \) is the mass diffusivity [8]. For fuels with a Schmidt number greater than 1.0, a laminar jet flame can stabilize, such as for propane (\( Sc = 1.3 \)), but cannot stabilize for Schmidt numbers between 0.5 and 1.0, such as methane (\( Sc = 0.7 \)) [9].

With the increase in velocity, and the transition to turbulence, the question of flame stability expands. The addition of turbulence allows for the stabilization of lifted flames of methane and other fuels with Schmidt numbers between 0.5 and 1.0 [9]. The stabilization mechanisms at these higher flow rates have been extensively debated and reviewed [9, 10, 11], focusing around 5 different theories; the premixed theory [12], turbulent intensity theory [13], scalar dissipation theory [14], the large eddy concept [15], and the flame edge concept [16].

- **The Premixed Theory**, as postulated by Vanquickenborne and Van Tiggelen [12], states that partial premixing of the reactants with the ambient air controls flame stabilization. Experiments performed by Vanquickenborne and Van Tiggelen on methane-air lifted flames, assumed that there was a balance between the lifting forces of the incoming jet and downward acting turbulent
burning velocity, comparing the influence of turbulent fluctuations to the propagation velocity [12]. The premixed model states that the flame base will stabilize along the stoichiometric contour, resulting from the mixing of the fuel jet into the ambient oxidizer [12].

- **The Turbulent Intensity Theory**, proposed by Kalghatgi et al. [13], theorized that the flame speed is enhanced by the presence of turbulence, creating a turbulent burning velocity, roughly equivalent to the local flow velocity at the leading edge of the flame. It was also theorized that the location of the flame base, in relation to the stoichiometric contours is linked to the eventual blowout of a lifted flame [13].

- **The Critical Scalar Dissipation Theory** explains that flame stabilization, specifically focusing around diffusion flamelets, occurs at a point downstream of the issuing nozzle, where the scalar dissipation rate falls below a specific value, relating to flame stretch and strain [14].

- **The Large Eddy Concept** focuses on the recirculation of the hot products of combustion through turbulent eddies, in order to preheat the incoming reactants [15]. This investigation focused on flame blowout, highlighting the blowout parameter, $\varepsilon$, for methane and other hydrocarbons [15].

- **The Edge Flame Concept**, much like the triple flames described above, focuses on the stabilization due to partial premixing of the fuel and oxidizer at
the flame base [16]. This partial premixing allows the flame base to propagate against the incoming reactants [16].

As referenced in the turbulent intensity theory, the transition from laminar to turbulent nozzle velocities results in a marked increase in the flame speed from a laminar flame speed, \( S_L \), to the turbulent flame speed, \( S_T \). The calculation of flame speed, shown below, from a study by Gülder [17], calculates the turbulent flame speed as a function of the laminar flame speed, the local time-varying velocity, \( u' \), the integral length scale, \( L_T \), and the kinematic viscosity, \( \nu \) [18].

\[
S_T = S_L + 0.62 \cdot \frac{S_L^2}{L_T} \cdot \left( \frac{u'}{\nu} \right)^{\frac{3}{2}}
\]  

As shown above, the turbulent flame speed is not a fixed quantity, unlike the laminar flame speed, as the turbulent flame speed is a function of downstream position (based on the integral length scale), as well as local flow speeds.

To predict the flammable region from the issuing nozzle, a relation proposed by Tieszen et al. [19], was used, where the mass fraction, \( Y \), the downstream position, \( z \), based upon the mass fraction of fuel, \( Y \), the density of the ambient air, \( \rho_a \), the density of the jet stream \( \rho_0 \), the radius of the nozzle, \( r_0 \), the radial position of the flame from the centerline of the nozzle, \( r \).
While liftoff is a primary concern within jet flame research, another phenomenon, hysteresis, which is observed in a regime found after liftoff, and prior to reattachment, shown in the figure below, has been of interest to combustion science.

\[
Y = 10 \left( \frac{\rho_0}{\rho_{\infty}} \right)^{\frac{3}{2}} \left( \frac{r_0}{x} \right) \exp \left( -57 \left( \frac{r}{x} \right)^2 \right)
\]  

(5)

Figure 3- Stability Diagram of Lifted Jet Flames
As shown above, the liftoff velocity for a jet flame is higher than the reattachment velocity, resulting in a region where the flame could be either lifted or attached to the nozzle. In experiments by Tummers et al. [20], the stabilization of the flame in the hysteresis regime could be a result of the smaller scalar dissipation levels and the local flow velocities, as well as a result of rotating structures within the flame.

Also shown in the figure above, as the nozzle velocity increases after liftoff, the lifted height increases until it reaches a critical value. At this point, the flame becomes "meta-stable", where a small perturbation is all that is necessary to cause the flame to blowout. One observation of a jet flame, as it approaches blowout, is a shortening of the trailing diffusion flame, as shown in Moore et al. [21], which postulates the diffusion flame disappearance is an indicator of blowout. In a study of Broadwell et al. [15], the mechanism behind flame blowout is the insufficient time necessary to mix the hot products of combustion with the oncoming stream, therefore not creating the combustible mixture necessary to continue flame propagation. Further study into the blowout mechanism, showed that a calculated value, $\varepsilon$, the blowout parameter, is a function of

$$\varepsilon = \frac{dS^2 \psi^2 (\rho_0)^{1/2}}{u \kappa}$$

(6)

the nozzle diameter, $d$, the stoichiometric air to fuel ratio, $\psi$, the local axial velocity, $u$, and the thermal diffusivity, $\kappa$ [15].
In order to observe the effects of the entrainment of oxidizer into the fuel jet stream, various experiments have been performed on setups with the ambient oxidizer, conventionally air, flowing in various configurations, when compared to the direction of the fuel jet. The air moving in the same direction as the fuel jet is referred to as coflowing air, or coflow [22, 23, 24, 25], flowing opposite to the fuel jet is counterflowing [26], and perpendicular to the fuel jet is cross flow. Other experiments have been performed on air flow acting on fuel jets from other angles, commonly referred to as oblique flows [27]. Experiments performed in this study focused on a coflowing annulus of air around a central issuing jet, and in order to compare these flames in coflow to jets into stagnant air, a relation, proposed by Kumar et al. [28], using an effective velocity, $U_{\text{eff}}$, was applied, shown in equation below,

$$U_{\text{eff}} = U_0 + C \sqrt{\frac{\rho_{\text{cf}}}{\rho_o}} U_{\text{cf}}$$  \hspace{1cm} (7)$$

where $U_0$ is the central nozzle velocity, $U_{\text{cf}}$ is the velocity of the coflowing air, $\rho_{\text{cf}}$ is the density of the coflowing air, $\rho_o$ is the density of the issuing jet, and $C$ is a constant, assumed to be 40, from experimental results.

Other experiments into the effects of coflowing air have produced an increased understanding of the resulting mixing and instabilities. In an investigation by Ferraris and Wen [29], it was found that it is possible using Large Eddy Simulations (LES) to predict the
mixture profiles and liftoff heights of flames in coflow, which matched with previous experimental results. The investigation also provided insight into internal structures not observable in experiments, such as the patterns within the rich premixed branch of the flame [29]. Maczynski [30] conducted a study into the flow of a jet into coflowing air, not specifically a jet flame, but the results are directly related to flame stability and propagation, where the eddy viscosity is not directly related to the width of the jet or the downstream position. In experiments by Demare and Baillot [31], on methane jet flames, using Particle Image Velocimetry (PIV), to observe the localized flow field within the flame, showed the role of Kelvin-Helmholtz instabilities in flame stabilization, specifically how the instabilities improve mixing. Terry and Lyons [25] conducted experiments into flame hysteresis in coflowing air and found that the variation of lifted and reattachment velocities are affected by coflows, as well as local stoichiometry. The study by Moore and Lyons [32], on the leading edge fluctuations of turbulent flames in coflow, found that downstream fluctuations are directly affected by the Reynolds number at the nozzle and that normalizing the height fluctuations shows consistency at most stabilization points in the mid-field, past liftoff but prior to blowout.

While the combustion of pure fuels does provide some unique insight into the stabilization mechanisms, most fuels used in industry are a mixture of various fuels and diluents, as shown in the table below.
Table 1- Composition of Blended Gaseous Fuels Used in Industry

<table>
<thead>
<tr>
<th>Component</th>
<th>Natural Gas [33]</th>
<th>Biogas [34]</th>
<th>Syngas [35]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methane</td>
<td>87-96%</td>
<td>50-60%</td>
<td>3.0%</td>
</tr>
<tr>
<td>Ethane</td>
<td>1.8-5.1%</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>1.3-5.6%</td>
<td>-</td>
<td>50.9%</td>
</tr>
<tr>
<td>Carbon Dioxide</td>
<td>0.1-1.0%</td>
<td>38-48%</td>
<td>4.5%</td>
</tr>
<tr>
<td>Carbon Monoxide</td>
<td>-</td>
<td>-</td>
<td>27.0%</td>
</tr>
<tr>
<td>Oxygen</td>
<td>0.01-0.1%</td>
<td>-</td>
<td>0.6%</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>&lt;0.02%</td>
<td>Trace</td>
<td>18%</td>
</tr>
</tbody>
</table>

With the inclusion of diluents in the fuel stream, overall combustion mechanisms within jet flames are affected. Previous studies have compared the stabilization mechanisms of diluted jet flames to those of pure jet flames. In experiments performed by Gollahalli et al. [36] on propane jets with and without dilution, it was found that the mass fraction of fuel decreased with the presence of diluents, resulting in a decrease in both the liftoff and reattachment velocities of diluted jets. Donnerback and Peters [37] conducted a study comparing the scalar dissipation rates on nitrogen diluted methane flames and found that the residence time of the jet flame, the ratio of jet velocity to nozzle diameter ($U_o/d$ [1/s]), increased as the mole fraction of oxidizer decreased, maintaining a constant non-dimensionalized height ($h/d$) downstream of the nozzle. The study went further, showing the trend of the instantaneous scalar dissipation rate at quenching, $\chi_q$, is constant between different mole fractions of oxygen, when compared between the same non-dimensionalized height [37].
Direct Numerical Simulations (DNS), run by Chun et al. [38], when compared to experiments on highly-diluted propane, showed that the turbulent fluctuations of the leading edge of the flame reduced as the amount of nitrogen within the fuel stream increased, for the same overall jet velocity, allowing for a more stable, less transient liftoff height. It was also found that the influence of nitrogen dilution on the stagnation region of the flame was small [38].

Other experiments have been conducted on the dilution of pure jets to create "surrogate" fuels, such as the dilution of methane with nitrogen to create a natural gas "surrogate". Wilson and Lyons [1, 2] conducted experiments on biogas and natural gas surrogates to observe the influence of higher levels of dilution in the fuel jet, since there is a range of compositions that are considered biogas and natural gas. It was found that the laminar flame speed is inversely proportional to the amount of nitrogen diluent added to the gas, with a decrease from a laminar flame speed for methane from 35 cm/s to 15 cm/s, with the change in diluent from 3.76 moles to 5.25 moles [2]. In experiments into carbon dioxide dilution of hydrogen jets, creating syngas surrogates, Dam et al. [39] found that there was a non-linear increase in the laminar flame speed as the amount of hydrogen in the fuel stream increased.

In the far flow field, the study of Karbasi and Weirzba [40] on flames near blowout, using diluted, coflowing air, found that the addition of dilution in the coflow was more influential on flame stabilization than the diluent in the fuel stream. In another investigation into dilution at blowout, Moore et al. [3] showed that the lean flammability limit was
effective in calculating the upper limits of flame stabilization and that, calculating the blowout parameter, \( \varepsilon \), could be accomplished, as long as the calculation of the velocity took the dilution into account.

Due to the large discrepancy between the burning velocities of most gaseous hydrocarbons, like methane, and the burning velocity of pure hydrogen, which is much higher, it is possible to stabilize a jet flame at higher velocities than normal, if hydrogen is added to the fuel stream. Choi and Chung [41] conducted a study into auto-ignited, laminar flames of methane and hydrogen and were able to show that as the amount of hydrogen present in the fuel stream increased, the liftoff height of the flame decreased and observed a more distinct triple flame. With respect to other fuels, such as biogas, it has been shown that an increase in the mixture fraction of hydrogen in the fuel causes the blowout velocity to increase [42]. This observation is similar to Kalghatgi's [43] previous work in methane/hydrogen, propane/hydrogen, and hydrogen jets, where it was found that the liftoff velocity decreased as the amount of hydrogen in fuel stream decreased.

2.2 A Review of Mechanisms in Electrohydrodynamic (EHD) Flows

The ionic wind, the force behind electrohydrodynamic flows, was recorded as early as 1890, by A.P. Chattock [44], and was reviewed by Robinson [45], and is created through the application of high potential electric fields on sharply curved electrodes, shown in the Figure 4 and Figure 5.
For an electric field formed by negative potentials, there are three distinct regions between the charged electrodes and the grounded electrode downstream; the ionizing plasma region, the non-ionizing plasma region, and the unipolar region. For an electric field resulting from a negative potential, the non-ionizing plasma region is absent. A characterization of the resulting flow is shown in the figures below.
Figure 4- Formation of the Ionic Wind Resulting From a Positively Charged Corona Discharge
Figure 5- Formation of the Ionic Wind Resulting From a Negatively Charged Corona Discharge
At the charged electrode, a corona discharge forms, which in turn, generates charged ions around the electrode (shown in the first pane of Figure 4 and Figure 5). The charged ions are repelled and travel towards the grounded electrode, impacting neutral molecules along the path, imparting momentum, resulting in the formation of a bulk flow towards the grounded electrode (shown in panes 2 and 3).

This force, $F$, has been investigated by Rickard et al. [46], showing that,

$$\vec{F} = \vec{E}e(n_+ + n_-)$$

where $E$ is the electric field vector, $e$ is the fundamental charge, and $n$ is the number density of positive or negative ions, as denoted by the subscript. The local current density, $j$, is related to the resulting force as,

$$\vec{j} = j_+ + j_- = F \ast K = (K_+n_+ + K_-n_-)\vec{E}e$$

where $K$ is the electron mobility [46]. The maximum force is restricted by the breakdown of the dielectric, air, causing the secondary electrode to ionize, causing a negation of the bulk flow. The maximum current density permitted is shown to be,

$$j_{max} = (E_b^2 - E_0^2)\epsilon_oK/2x$$
where $E_b$ is the breakdown electric field at the electrode, $E_0$ is the electric field at the corona source, $\varepsilon_0$ is the permittivity of free space, and $x$ is the distance coordinate [46]. Once the maximum current density is surpassed, the dielectric (in most cases air) begins to conduct the charge, resulting in secondary ionization, where the second (grounded) electrode begins to form a charge. The formation of the charge at the secondary electrode generates a bulk flow of ions away from the secondary electrode, towards the primary electrodes, negating the main flow from the primary electrode. This phenomenon is shown in the figure below, where the sewing needles are acting as the primary electrode, and the ring is the secondary electrode.

Figure 6- Secondary Ionization Forming on a Ring Resulting from a Corona Discharge on the 5 Needles [47]
One major application of EHD devices is for improved heat transfer, specifically the creation of a bulk flow to increase convective heat transfer. Yue et al. [48] conducted a series of experiments comparing the increases in convective heat transfer between an electrohydrodynamic flow and natural convection, and found that the maximum heat transfer coefficient resulting from a negative DC charge was approximately 12 times larger than for natural convection. The study went further, comparing the effectiveness of three different types of discharges; corona discharges, dielectric barrier discharges, and DC glow discharges [48].

Go et al. [49] also conducted a study on the ionic wind and heat transfer applications, using flows over a heat flat plate, and found that using a corona discharge changed the overall flow pattern, changing and reducing the boundary layer. The study observed an increase in the overall heat transfer coefficient, as well as, a change in velocity vectors along the flat plate, which were manipulated using the ionic wind over a conventional bulk flow device [49].

Chen and Davidson [50] conducted a study on current densities resulting from negative and positive corona discharges, using wire electrodes and found that the temperature of the gaseous medium was directly related to the electron number density and that the electron number density was much higher for positive coronas near the electrode, but the negative corona had a higher value downstream from the electrode. The parametric study also showed an increase in electron number density for larger wire surface areas, but the
smaller wires had a sharper rise in electron number density in the near field, around the corona [50].

2.3 Lifted Jet Flame Stabilization and Manipulation Using High Potential Electric Fields

Acknowledgement of the effects of electric fields on flames goes back to W.T. Brande [51] who in 1814, observed the manipulation of flame shape of a candle flame between two electrodes. It was shown that the make-up of the combustion event, specifically when the flame was changed from a candle to a phosphorus flame, changed the effect of the applied electric field. Further observations on the influence of electric fields on flame shape showed that, using electric fields, it is possible to simulate flames in microgravity, creating the signature dome shape observed in microgravity situations [52].

Weinberg and Carleton [53] showed that the application of electric fields could result in similar flame shapes to those seen in high altitude drop tests, creating a relationship between the applied electric field and the equivalent gravitational forces, shown below, where J is the drawn current, A is the cross sectional area, N is the number of "gees" (the relative strength of the gravitational field, non-dimensionalized against normal earth gravity, g, 9.81 m/s²), k is the ion mobility, and ρ is the ambient air density.

\[
J = ANk\rho g
\]  

(11)
Weinberg et al. [54] showed that the same electric fields used to manipulate flame shape and behavior could be used to control the dispersal of extinguishants, such as water and sodium bicarbonate, for use in microgravity situations, which focused on the control of the sprays, using high potential, low power systems.

Further studies by Lawton et al. [55] and Weinberg et al. [56] focused on the use of high potentials in industrial burner systems. Lawton et al. [55] found that electric fields could be used to improve the recirculation or aeration of flames, whereas Weinberg et al. [56] focused on the use of electric fields to induce flows of fuel. Further investigations by Lee et al. [57], on turbulent, nonpremixed flames, showed that high potential electric fields (~4 kV) could influence the liftoff height of the flame, noting that AC electric fields were more effective than DC fields. In experiments on the use of plasma excitation, created by an electric pulse generator, on combustion, Kim et al. [58] found that the plasmas created by ultra-short repetitive pulsed discharges (USRD) had a higher influence on liftoff height than dielectric barrier discharges (DBD) or single electrode AC corona discharges (SECD). Similarly, Pilla et al. [59] found that using nanosecond repetitively pulsed discharges the heat transfer and temperatures increased, observing that the flame could stabilize beyond the normal lean regimes for the flame. Comparing the influence of AC and DC pulsed high voltage discharges, Criner et al. [60] found that, using DBD's the dielectric properties have an influence on the time-scale of the interaction between the plasma and flame. In comparisons on the effects of low frequency AC electric fields on flame stabilization, Ryu et al. [61] showed that the oscillations of the flame height were influenced by the frequency of
the applied electric field, specifically finding three separate oscillation modes; a small scale oscillation mode (at frequencies below 1 Hz), a large scale (at frequencies above 10 Hz), and a combination of the small scale and large scale oscillations (at frequencies between 1 and 3 Hz).

It has also been shown that the application of electric fields has an influence on the chemical kinetics and chemical mobility in combustion, including a focus on the manipulation of pollutant emissions, such as particulates or NO\textsubscript{x}. Early observations on the effects of electric fields on soot mobility, by Bowser and Weinberg [62], found that soot suppression is possible if an electric field is applied to the soot formation region of the diffusion flame. Imamura et al. [63] showed that, for droplets of liquid fuels, such as ethanol, n-octane, and toluene, the increase in current density from the natural charge of soot particles, weakened the influence of the applied electric field. It has also been found that using DC electric fields to manipulate flame luminosity and soot formation for acetylene-air flames, for both premixed and non-premixed flames, higher frequency pulses had a smaller influence on soot formation, than lower frequencies, and that flame luminosity could be increased or decreased [64]. Further investigation into the formation of NO\textsubscript{x} and SO\textsubscript{2}, showed that pollutant formation from flames, in applied electric fields, were a function of the oxidizer availability and the presence of water vapor and ammonia within the jet stream [65]. Saito et al. [66] and Vatazhin et al. [67] linked the applied electric field to soot production, flame shape, and peak flame temperature.
Using these studies, into combustion and electric fields, to formulate a basis understanding of these areas of investigation, the following studies were performed, to further this understanding.
Abstract

With the increased utilization of multicomponent fuels, such as natural gas and biogas, in industrial applications, there is a need to be able to effectively model and predict the properties of jet flames for mixed fuels. In addition, the interaction of these diluted fuels with outside influences (such as differing levels of coflow air) is a primary consideration. Experiments were performed on methane jet flames under the influence of varying levels of nitrogen dilution, from low Reynolds number lifted regimes to blowout, observing the influence of the nitrogen on lifted flame height and flame chemiluminescence images. These findings were analyzed and compared to existing lifted jet flame relations, such as the flammable region approximation proposed by Tieszen et al., as well as to undiluted flames. The influence of nitrogen dilution was seen to have an effect on the liftoff height of the flame, as well as the blowout velocity of the flame, but was seen to have a less pronounced effect compared to flames with coflowing air.
3.1 Experimental Setup

For experiments in both the near flow field and the far flow field, the same apparatus was used, shown in Figure 7 below. In the near field experiments, the coflow section of the burner was not used, but was used in the far flow field setup.

Figure 7- Fuel Dilution Burner Setup with Coflowing Annulus
The central fuel nozzle is 3.5 mm in diameter with an inward taper, and an overall length such that the length to diameter ratio is high enough to ensure a fully developed and mixed flow. At the base of the nozzle, there is a mixing chamber that will combine the fuel and nitrogen from separate supply lines. The fuel gas, which is CP Grade methane (99% Pure), and the compressed nitrogen flow rates are measured through separate Advanced Specialty Gas Equipment Series 150 Flowmeters. The methane supply tank is controlled through a MicroLine UHP Gas Panel controller, and the nitrogen supply tank is controlled through an ESAB R 72-75-580 Regulator.

The coflowing air is supplied through a Magnetek model 9467 centrifugal blower into the lower section of the burner, where the air flows through the various sections and screens, shown in Figure 7, in order to create a top hat profile for the coflowing annulus, with a diameter of 150 mm. The coflowing air velocity was measured with a TSI Veloci-calc model 8345 hot-wire anemometer, which provides a 0.01 m/s accurate reading with a ± 3% error.

The jet flames are created with a butane lighter, and are lit from a downstream position. All images are taken through a Nikon D80 digital SLR camera with an 18-135 mm Nikkor Lens. These images were processed through Adobe® Photoshop®, in order to determine the lowest flammable region, as indicated by chemiluminescence. Using a known length, within each photo, it was possible to measure the distances from the center of the nozzle exit to the earliest chemiluminescent zone, at the furthest radial positions, in order to discern the true radial position of the flame.
3.2 Results and Discussion

Near Flow Field

Initial observations were made on flames just after liftoff commenced, with varying levels of dilution, to show the influence of non-reactive diluents on the stabilization of lifted jet flames. The different fuel-diluent combinations that were investigated are shown in Table 2. All near field stabilization investigations were conducted on flames with Reynolds numbers at the nozzle between 1800 and 3750. The diluent-fuel combinations were chosen to create lifted flames, just after liftoff occurs, with turbulent characteristics, specifically the absence of distinct premixed branches near the flame base. While these Reynolds numbers occur in the transition region between laminar and turbulent flows, no observable changes in the flame structure were observed during the tests, with flames from trials 1 and 7 appearing similar. The lifted flame heights were found after flame liftoff, without adjusting the fuel velocity after liftoff in order to insure that the flame did not enter the hysteresis regime, as documented by Terry and Lyons [25]. As shown in the table below, the Reynolds numbers of the overall flow exiting the nozzle of the burner were near transition regime levels, using mass weighted averages for the overall density and the combined velocity. Using a sequence of images for each dilution level, an average lifted height of the flame and the radial position of lowest flammable region was calculated, as shown in Table 2.
Table 2 - Fuel- Diluent Combinations For Near Field Experiments

<table>
<thead>
<tr>
<th>Trial</th>
<th>U(CH4) (m/s)</th>
<th>U(N2) (m/s)</th>
<th>Re</th>
<th>Avg Axial (cm)</th>
<th>Avg Radial (cm)</th>
<th>Ratio (A/R)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10.63</td>
<td>2.71</td>
<td>1839</td>
<td>3.54</td>
<td>0.77</td>
<td>4.60</td>
</tr>
<tr>
<td>2</td>
<td>11.20</td>
<td>1.78</td>
<td>2035</td>
<td>2.32</td>
<td>0.62</td>
<td>3.76</td>
</tr>
<tr>
<td>3</td>
<td>12.35</td>
<td>1.05</td>
<td>2397</td>
<td>1.82</td>
<td>0.39</td>
<td>4.70</td>
</tr>
<tr>
<td>4</td>
<td>14.15</td>
<td>0.68</td>
<td>2866</td>
<td>1.65</td>
<td>0.47</td>
<td>3.52</td>
</tr>
<tr>
<td>5</td>
<td>15.94</td>
<td>1.42</td>
<td>3082</td>
<td>2.99</td>
<td>0.65</td>
<td>4.63</td>
</tr>
<tr>
<td>6</td>
<td>15.37</td>
<td>0.00</td>
<td>3326</td>
<td>1.74</td>
<td>0.44</td>
<td>3.96</td>
</tr>
<tr>
<td>7</td>
<td>18.97</td>
<td>1.42</td>
<td>3724</td>
<td>4.10</td>
<td>0.91</td>
<td>4.50</td>
</tr>
</tbody>
</table>

In order to predict the stabilization point of flames after the initial liftoff occurs, the lowest flammable regions were compared to existing turbulent flame approximations, mainly the flammable limit approximation proposed by Tieszen et al. [19]. The flammable limit approximation, as proposed by Tieszen et al. [19], was used on turbulent jet flames of ethane and ethylene, but in previous studies by Moore et al. [68], has been used on studies of methane jet flames, in the same burner configuration as this study. Tieszen et al. [19] highlighted this equation was created from values from Dowling and Dimotakis [69], as well as Chen and Rodi [70]. While this study focuses on near field areas, outside the self-similarity of the model, the experiment focused on this area due to possible effects resulting from the dilution, specifically the decreased concentration of the fuel at the nozzle and further downstream. Using the flammable limit approximation, assuming combustion of methane where the combustible region is between Y=0.05 and Y=0.15, the flammable regions were plotted for each set of data and were compared to data points taken from the
still photos. An example of one of the trials, for trial 1, is shown below in Figure 8. As expected, most of the values for the experimental data appear around the flammable region base, near the nozzle exit between an attached position and 6 centimeters. In order to show more detail, the plots were restricted to axial positions between the nozzle base and the furthest observed downstream position, shown in Figure 9a-g, which correspond with trials 1-7, respectively.

![Flame Location v. Flammable Region Approximation (Trial 1)](image)

*Figure 8- Flame Location v. Flammable Region Approximation (Trial 1)*
Figure 9a-g: Comparison of Experimental Data to Flammable Limit Approximation for Trials 1-7
The observed location was within expected limits, with most of the observed lowest flammable regions occurring around the lean flammability limit of methane. The closest comparison occurs in trial 6, demonstrated by Figure 9f, which is the pure methane jet flame with no dilution. A comparison of this data set to the approximation shows that the average position occurs just outside the $Y=0.05$ line. Of all the datasets, trials 3 and 5, with Reynolds numbers of 2397 and 3082 respectively, showed the best agreement with and were the most accurate to the predicted flammability limits. Trials 3 and 5 both had a moderate amount of dilution, with the mass fraction of nitrogen at approximately 0.13 for both cases. The cases with the most deviation from the predicted flammability limits, trials 2 and 4, both of which had no data points within the lean limit for methane, had mass fractions of 0.22 and 0.08 and Reynolds numbers of 2035 and 2866 respectively, showing that the influences of nitrogen dilution did not have a pronounced effect on the flames stabilized position, when compared to those of a pure jet flame.

All of the other data sets, shown in Figure 9, displayed similar trends. The overall flame shape was maintained between the varying levels of dilution, showing that the flame base occurred at the same ratio of axial to radial positions, between 3.52 and 4.70, as shown in Table 2. In order to show the effectiveness of the flammable region approximation for diluted flames, it was necessary to compare the modeled position to the observed position. The percent difference between the expected axial position and the average axial position (assuming a constant radial position) compared to the observed Reynolds number, is shown below in Figure 10.
As Figure 10 shows, the flammable region approximation is more accurate in mid-range Reynolds numbers, but begins to lose its effectiveness at higher and lower Reynolds numbers, which would be assumed to be a result of the higher levels of dilution for these trials. Based upon this comparison, the accuracy of the flammable region approximation for a flame under dilution is in question, as is any error resulting from the dilution level. In a comparison with the mass fraction of nitrogen in the fuel jet stream, shown in figure 11, it is apparent that discrepancies between the observed axial location and the estimated axial location (assuming a fixed radial location) are random with respect to the speed of the flow. As discussed above for the cases with moderate dilution, trials 3 and 5 remain relatively
accurate to the flammable region approximation for the diluted cases, but trial 7, with a mass fraction of 0.12, was the most inaccurate with a deviation of approximately 1.33 cm from the expected stabilization point.

![Figure 11- Comparison of Axial Difference and Mass Fraction for Near Field Dilution Experiments (Re<4000)](image)

Based upon this observation, the difference between the model and observed positions is not a result of the level of dilution, but the result of other influences, such as instabilities due to turbulence or the unsteadiness of the eddies at the lower Reynolds numbers. Overall, the flammable region approximation provides an acceptable
approximation for flames under low levels of dilution, even at near transition regime Reynolds numbers.

Far Flow Field

The effects of dilution in high Reynolds number flows were also studied, where flames near blowout show the highest level of turbulence. In order to achieve flames at near blowout conditions, a combination of dilution and coflowing air were added to the methane jets. To take into account the addition of the coflow into the velocity of the jet, an effective velocity was calculated for each trial, shown below in Table 3. Each combination was observed with a sequence of 12 images, with an average calculated from each sequence.

### Table 3- Data for Diluted Methane Jet Flames with Coflow in the Far Field

<table>
<thead>
<tr>
<th>Case</th>
<th>U(CH4) (m/s)</th>
<th>U(N2) (m/s)</th>
<th>U(Cf) (m/s)</th>
<th>U(Eff) (m/s)</th>
<th>Re</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>25.75</td>
<td>0.00</td>
<td>0.00</td>
<td>25.75</td>
<td>5571</td>
</tr>
<tr>
<td>2</td>
<td>25.75</td>
<td>1.42</td>
<td>0.00</td>
<td>26.50</td>
<td>5172</td>
</tr>
<tr>
<td>3</td>
<td>25.75</td>
<td>1.42</td>
<td>0.22</td>
<td>50.90</td>
<td>5172</td>
</tr>
<tr>
<td>4</td>
<td>25.75</td>
<td>0.00</td>
<td>0.22</td>
<td>50.93</td>
<td>5571</td>
</tr>
<tr>
<td>5</td>
<td>25.75</td>
<td>0.00</td>
<td>0.44</td>
<td>61.36</td>
<td>5571</td>
</tr>
<tr>
<td>6</td>
<td>25.75</td>
<td>1.42</td>
<td>0.44</td>
<td>61.01</td>
<td>5172</td>
</tr>
<tr>
<td>7</td>
<td>35.56</td>
<td>0.00</td>
<td>0.00</td>
<td>35.56</td>
<td>7694</td>
</tr>
<tr>
<td>8</td>
<td>35.56</td>
<td>1.42</td>
<td>0.00</td>
<td>36.28</td>
<td>7279</td>
</tr>
<tr>
<td>9</td>
<td>35.56</td>
<td>1.42</td>
<td>0.22</td>
<td>60.88</td>
<td>7279</td>
</tr>
<tr>
<td>10</td>
<td>35.56</td>
<td>0.00</td>
<td>0.22</td>
<td>60.74</td>
<td>7694</td>
</tr>
<tr>
<td>11</td>
<td>35.56</td>
<td>0.00</td>
<td>0.44</td>
<td>71.17</td>
<td>7694</td>
</tr>
<tr>
<td>12</td>
<td>35.56</td>
<td>1.42</td>
<td>0.44</td>
<td>71.06</td>
<td>7279</td>
</tr>
</tbody>
</table>
For each case, the lowest flammable region was determined using the same method as the near flow field trials. As expected, maintaining a constant fuel velocity for any case with nitrogen dilution or the addition of coflow caused the axial location of the flame to increase to a further downstream position, as shown in Figure 12. Accounting for each addition, through coflow, dilution, and fuel jet velocities, the effective velocity has a fairly linear relationship with the flames’ lifted position. Each effective velocity occurs at a value above the liftoff velocity for methane, as shown in Terry and Lyons [25]. Of interest are the shifts that occur with the addition of coflow at 50 m/s. This discontinuity occurs for both cases 3 and 4, as well as cases 9 and 10 for the higher velocity fuel jet, with and without dilution.

Figure 12- Axial Position of the Flame Base for Far Field Experiments (Re>5000)
In this comparison of the lifted flame base location to the effective velocity of the flame, it is apparent that the addition of diluent to the jet has a small effect on the overall stabilization point, but any addition of coflowing air has a much larger influence. Also demonstrated in Figure 12, the addition of diluent at higher fuel velocities has a more pronounced effect than the same amount of diluent added at the lower velocity. At the same effective velocity (about 61 m/s), four separate cases have approximately the same lifted position.

A similar comparison of the influence of effective velocity on the radial position of the flame base, shown in Figure 13, yields some similar results. This growth of the flame base shows the radial expansion of the leading edge of the flame from the center point of the nozzle. The addition of diluent to the fuel jet has a much smaller influence than an increase in fuel velocity or the addition of coflowing air. Of interest is the change between the positioning at an effective velocity of 61 m/s; the no dilution and low coflow cases are similar in their radial position, but at the diluted, high coflow case, the radial position of the flame increases significantly. This shows, once again, that the flame is more influenced by nitrogen dilution at higher velocities.
Further investigation, shown in Table 4, indicates that calculating a ratio of the axial to radial position of the flame shows some changes in the overall flame shape, with the flame base changing at a rate not linearly to the upstream position, with the ratio of axial to radial position varying randomly between the cases. The axial position of the flame increases at a higher rate for flames with coflow, than for flames under the influence of dilution. Between cases 7 and 8, the upstream location of the flame increases at much higher rate, with little change in the average radial position meaning the spread of the flame base did not change while the flame is at a further downstream position.
### Table 4- Axial and Radial Position of Far Field Experiments

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>25.75</td>
<td>3.57</td>
<td>0.69</td>
<td>5.17</td>
<td>0.71</td>
</tr>
<tr>
<td>2</td>
<td>26.50</td>
<td>4.84</td>
<td>0.85</td>
<td>5.69</td>
<td>1.42</td>
</tr>
<tr>
<td>3</td>
<td>50.90</td>
<td>7.85</td>
<td>1.27</td>
<td>6.18</td>
<td>1.44</td>
</tr>
<tr>
<td>4</td>
<td>50.93</td>
<td>7.15</td>
<td>1.05</td>
<td>6.81</td>
<td>1.72</td>
</tr>
<tr>
<td>5</td>
<td>61.36</td>
<td>10.15</td>
<td>1.37</td>
<td>7.41</td>
<td>3.25</td>
</tr>
<tr>
<td>6</td>
<td>61.01</td>
<td>11.72</td>
<td>1.95</td>
<td>6.01</td>
<td>1.01</td>
</tr>
<tr>
<td>7</td>
<td>35.56</td>
<td>7.38</td>
<td>1.18</td>
<td>6.25</td>
<td>1.98</td>
</tr>
<tr>
<td>8</td>
<td>36.28</td>
<td>7.65</td>
<td>1.24</td>
<td>6.17</td>
<td>0.98</td>
</tr>
<tr>
<td>9</td>
<td>60.88</td>
<td>11.38</td>
<td>1.44</td>
<td>7.90</td>
<td>4.08</td>
</tr>
<tr>
<td>10</td>
<td>60.74</td>
<td>10.18</td>
<td>1.56</td>
<td>6.53</td>
<td>0.8</td>
</tr>
<tr>
<td>11</td>
<td>71.17</td>
<td>15.56</td>
<td>2.18</td>
<td>7.14</td>
<td>1.42</td>
</tr>
<tr>
<td>12</td>
<td>71.06</td>
<td>18.04</td>
<td>2.63</td>
<td>6.86</td>
<td>1.64</td>
</tr>
</tbody>
</table>

Figure 14 shows the change between the axial and radial positions of the flame as the coflow velocity is increased. Of note, the variation between the no coflow cases, and the low coflow cases, (U_{cf}=0.22 \text{ m/s}), showed a similar variation between the axial and radial positions between cases with and without dilution (cases 1-4 and cases 7-10). The variation and values of axial position change at a higher rate than that of the radial position for cases with the highest amount of coflow, which means that a flame under coflow behaves differently than a pure jet flame or diluted flame at the same effective velocity. A direct comparison does not account for decreases in turbulent eddy mixing or other turbulent effects.
In a further comparison of the changes in flame shape to the change in effective velocity, Figure 15 shows that for two cases, the no dilution, low and high coflow cases, the flame shape decreases in size, as the effective velocity increases. This observation requires more investigation into the effects of coflow on the turbulent mixing within the flame. In a previous study into the effects of coflowing air on flames approaching blowout the effect of coflow is seen to dominate a pure jet flame reaction resulting in the stable position of the flame moving downstream. It should be noted that in this study with a coflow velocity of approximately 0.4 m/s, flame blowout occurred at jet velocities as low as 36.0 m/s [21].

Figure 14- Variation of Downstream Stabilized Position Due to Effect of Coflowing Air for Far Field Experiments (Re>5000)
In order to ensure that the decrease in flame shape as denoted by the A/R ratio used in Figure 15 was not a result of passing the apex of the flammable regions of a turbulent methane flame, where the flame base would shrink, as the flame reaches the flammable limit, approaching blowout, a comparison of the two pure jet cases was made to the existing approximation technique proposed by Tieszen et al. [19], shown in Figure 16, below. Both plotted cases were shown to be well below the apex value for a pure jet, occurring at approximately 15.8 cm downstream of the nozzle, for a methane mass fraction of 0.05,
meaning that any contraction towards the nozzle was caused by the influence of either nitrogen or coflowing air.

Figure 16- Flammable Limit Approximation for Pure Jet Cases in Comparison to Peak Radial Expansion

Based upon the above observations, a second comparison was made for three separate setups with the same effective velocity, with a pure jet, a diluted jet and a jet under coflow. Each case was tested at approximately 35 m/s, and the flame base was observed for each case. These results indicate that, in general, flames under dilution and coflow were thinner
than a pure fuel jet flame. Similar to the earlier data (cases trials 1-12), the flame is more influenced by the addition of a small amount of coflow, than a much larger amount of dilution. These results indicate that, in general, flames under dilution and coflow were thinner than a pure fuel jet flame, with the flame base occurring at a lower axial to radial position ratio than for the pure jet case. These results were contrary to the conventional wisdom on this issue. With the addition of a large amount of diluent, at the same nozzle velocity, it would be expected that the flame expand radially, and to shift further downstream, in order to increase the reaction zone and ensure proper mixing between the fuel and the ambient oxidizer, yet it was observed that the flame constricted radially, and burned at an upstream location than a pure jet of methane. This leads to the inference that the influence of dilution is small, and that flame stability is mainly a function of the momentum and mixing of the fuel and air, even at the high levels of diluent seen in case 2 from table 5. This data can also explain the discontinuity that occurs for cases 3 and 4, as well as for cases 9 and 10, where the addition of coflow increased the effective velocity, without much addition to the liftoff height, since a comparison between cases 1 and 3 from Table 5, shows that for the same effective velocity the downstream position of the flame was lower with coflow than for a pure jet. This conclusion is supported by the earlier data that the coflow changes the fluid dynamics and the mixing of the fuel and oxidizer more than the addition of a diluent. The overall flame shape appears to be relatively unaffected by the presence of a small amount of diluent, even with increase in the effective velocity change for the central nozzle velocity.
Overall Flow Regime

Combining the observations of the dilution effects in both the near and far flow fields, it is possible to draw some distinct conclusions on the nature of the influence of dilution. As shown in Figure 17, a comparison of each test case from the near field and far field experiments, with any cases including coflowing air omitted, shows that there is a shift between the effects of the dilution on the lifted position of the jet flame. When compared to the effect in the far field, dilution in the near flow field has a much greater bearing on the downstream position of the flame. At velocities below 15 m/s, the flame would stabilize at a higher height, than it would for a pure jet flame, whereas for higher fuel velocities, shown at 35.56 m/s, the lifted height is less than 3% higher than it would be for the pure jet case. Based upon these observations, it can be concluded that the effects of dilution at lower flow rates, even at the same proportion as at the higher flow rates, are more effective at manipulating the lifted position of the flame.

<table>
<thead>
<tr>
<th>Case</th>
<th>U(CH4) (m/s)</th>
<th>U(N2) (m/s)</th>
<th>U(CF) (m/s)</th>
<th>Avg. Height (cm)</th>
<th>Avg. Radial (cm)</th>
<th>Ratio of Axial to Radial</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>35.56</td>
<td>0</td>
<td>0</td>
<td>7.58</td>
<td>1.30</td>
<td>5.83</td>
</tr>
<tr>
<td>2</td>
<td>33.85</td>
<td>36.38</td>
<td>0</td>
<td>5.90</td>
<td>1.02</td>
<td>5.78</td>
</tr>
<tr>
<td>3</td>
<td>23.71</td>
<td>0</td>
<td>0.22</td>
<td>6.34</td>
<td>0.98</td>
<td>6.47</td>
</tr>
</tbody>
</table>
When considered, in conjunction with the conclusions from Moore and Lyons [27], which investigated the fluctuations of the leading edge of the flame at various flow rates of fuel and coflow, it can be concluded that the liftoff trends for nitrogen diluted jet flames is similar for those under the influence of coflowing air. The slope of the liftoff height to nozzle velocity is consistent between the diluted cases and the cases of a pure jet of methane.
in coflowing air, including the cases from Moore and Lyons [27]. Based upon these observations, the stabilization mechanisms for both cases are influenced similarly.

While the near field data is in the transition from laminar to turbulent flow, in a similar regime to that of Lee et al. [71], the liftoff characteristics of the data appeared in to only be in the turbulent region, where both liftoff and blowout would occur at turbulent Reynolds numbers. The correlation between the quantity of the nozzle jet velocity divided fuel mass fraction at the nozzle \(U_{0, F,0}\) to the liftoff height of the flame was observed [71], but did not provide any further insight into the contribution of the dilution to the stabilization mechanisms of the methane jet.

3.3 Conclusions

In order to more accurately predict the stable, lifted height for natural gas flames, diluted methane flames were observed and compared to existing turbulent flame models. The flames were observed at low and high Reynolds numbers, just after liftoff and prior to blowout. Based upon observations in the near field of lifted methane jet flames under low levels of nitrogen dilution, it was found that

1. When compared with the flammable limit model, proposed by Tieszen et al. [19], images taken of the diluted flames showed the flame base for all levels of dilution was observed outside the lean limit for methane, regardless of the level of dilution, or the Reynolds number of the central jet.
2. With the addition of nitrogen to the fuel jet, the flame base maintained a ratio of the axial position to radial position of approximately 3.5 to 4.7, remaining invariant when compared to the amount of dilution present, meaning that the flame base appeared in a similar region when compared to the downstream position.

When taking into account the addition of coflowing air to the lifted position of diluted methane flames at higher Reynolds numbers, as jet flames approach blowout, the following observations were made:

1. The downstream stabilized position of the flame is a greater function of the mixing of the fuel jet with ambient air, than adjustments made to the fuel jet. For multiple trials, the stabilized position of the flame base was influenced by the presence of a small amount of coflowing air in the surrounding annulus, more than by the addition of a much larger amount of nitrogen to the issuing nozzle. For all cases, the axial to radial position of the flame was found to be consistent, maintaining a value of 5.17 to 7.40 and remaining invariant to the addition of coflowing air or dilution, or a combination of the two.

2. In order to compare cases with the addition of coflow to those without coflow, the effective velocity was calculated. While maintaining the effective velocity as a constant, it was found that for cases with dilution or for cases with no dilution, the flame stabilized at a further downstream position than for pure methane jets.
Based upon these observations, while the amount of diluent needed to change the overall lifted position of the flame is much higher than the amount of coflowing air necessary, the overall structure of the flame, as well as the stabilization mechanisms, are similar between the two cases.
CHAPTER 4- EXPERIMENTS IN HYDROGEN ENRICHMENT OF METHANE JET FLAMES

Excerpts from: James Kribs, Andrew Hutchins, William Reach, Tamir Hasan, Kevin Lyons, Effects of Hydrogen Enrichment on the Reattachment and Hysteresis of Lifted Methane Flames, ASME 2013 Power Conference (Accepted, Peer Reviewed) ©ASME 2013

Abstract

The purpose of this study is to observe the effects of hydrogen enrichment on the stability of lifted, partially premixed, methane flames. Due to the relatively large burning velocity of hydrogen-air flames when compared to that of typical hydrocarbon-air flames, hydrogen enriched hydrocarbon flames are able to create stable lifted flames at higher velocities. In order to assess the impact of hydrogen enrichment, a selection of studies in lifted and attached flames were initiated. Experiments were performed that focused on the amount of hydrogen needed to reattach a stable, lifted methane jet flame above the nozzle. Although high fuel velocities strain the flame and cause it to stabilize away from the nozzle, the high burning velocity of hydrogen is clearly a dominant factor, where as the lifted position of the flame increased, the amount of hydrogen needed to reattach the flame increased at the same rate. In addition, it was observed that as the amount of hydrogen in the central jet increased, the change in flame liftoff height increased and hysteresis became more pronounced. It was found that the hysteresis regime, where the flame could either be
stabilized at the nozzle or in air, shifted considerably due to the presence of a small amount of hydrogen in the fuel stream. The effects of the hydrogen enrichment, however small the amount of hydrogen compared to the overall jet velocity, was the major factor in the flame stabilization, even showing discernible effects on the flame structure.

4.1 Experimental Procedure

This experiment was conducted on jet flames as part of the Turbulent Jets and Reacting Flows Laboratory of the Mechanical and Aerospace Engineering Department at North Carolina State University. Observations were conducted on methane (CP Grade, 99% Pure) and hydrogen (High Purity, 99.99% Pure) issuing from a central nozzle, 3.5 mm in diameter, with a length over 10 times the nozzle diameter, in order to ensure a fully developed flow. Each gas was controlled and metered through a separate Advanced Specialty Gas Equipment Series 150 Flowmeters. The experimental setup is shown in Figure 18.
All lifted flame heights were determined from still photographs taken by a Nikon D80 digital SLR camera using an 18-105mm Nikkor lens. These images were processed through Adobe Photoshop, where the length scale was determined by known lengths within the image plane. The images were taken to determine the flame’s lowest flammable region, indicating the lowest position of combustion for that fuel combination and jet velocity. The lowest flammable region had to be at the edges of the flame since the images were 2-dimensional, and therefore any radial positions could not be determined along the flame’s centerline.

Each iteration of the experiment began with a lifted, turbulent methane flame. After the flame’s lifted height and radial position of the earliest point of chemiluminescence was
determined, hydrogen was then added to the fuel mixture in order to reattach the flame to the central nozzle. The flow rates of the methane and hydrogen were recorded.

Using the images taken of the flame at its original lifted height, as well as its reattached position, other observations on the flame structure and appearance were recorded.

Further investigation into the lifted, hydrogen-enriched flames, used sequences of images of attached, lifted, and unstable flames, of hydrogen and methane mixtures. These stable and unstable flames were observed to see the stabilized position of the flame, as well as the variation of the position.
4.2 Results and Discussion

Analysis on the reattachment of flames under hydrogen enrichment started with the recording of critical liftoff and reattachment parameters, such as the methane velocity, original lifted height of the flame, the radial position of the first flammable region, and the hydrogen velocity required to reattach the flame to the nozzle. These parameters are listed in Table 6.

<table>
<thead>
<tr>
<th>Methane Jet Speed (m/s)</th>
<th>Liftoff Height (cm)</th>
<th>Liftoff Radial Position (cm)</th>
<th>Hydrogen Supply Speed Needed for Reattachment (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>18.40</td>
<td>1.45</td>
<td>0.45</td>
<td>2.34</td>
</tr>
<tr>
<td>21.42</td>
<td>1.82</td>
<td>0.45</td>
<td>2.81</td>
</tr>
<tr>
<td>24.45</td>
<td>2.28</td>
<td>0.56</td>
<td>4.22</td>
</tr>
<tr>
<td>27.63</td>
<td>3.55</td>
<td>0.67</td>
<td>5.76</td>
</tr>
<tr>
<td>30.90</td>
<td>4.35</td>
<td>0.38</td>
<td>9.09</td>
</tr>
<tr>
<td>34.25</td>
<td>6.39</td>
<td>0.88</td>
<td>31.44</td>
</tr>
<tr>
<td>37.88</td>
<td>8.79</td>
<td>1.16</td>
<td>59.76</td>
</tr>
</tbody>
</table>
As expected from previous studies, the amount of hydrogen required to reattach a lifted jet flame increases with increasing methane velocities, as well as for increasing lifted heights. A comparison of these variables is shown in Figure 19. Figure 19 shows that the amount of hydrogen needed to reattach the lifted methane flame and the amount of methane needed to cause flame liftoff vary by magnitudes. Overall, the exponential growth of the
hydrogen flow rate would be expected as the lowest flammable limit shifts upwards at higher jet velocities.

![Image of flame luminosity comparison]

Figure 20- Flame Luminosity

Also of note were the changes in flame luminosity as the flame anchored to the jet nozzle. This change is demonstrated in Figure 20, showing that as the flame anchors to the nozzle, the overall brightness of the flame, and in particular the trailing diffusion flame, increase. The diffusion flame luminosity is directly linked to soot production, but without an increase in the methane flow rate, the amount of carbon supplied to the flame on the reactants side did not increase. Soot production is linked to changes in temperature within the flame; therefore, it could be assumed that the flame's temperature increased above the value for the lifted flame.
Further investigation into the nozzle velocity, $U_0$, versus the attached flame's hydrogen mass fraction showed a relationship, as described in Figure 21.

![Figure 21- Comparison of Jet Velocity to Hydrogen Mass Fraction](image)

As the mass fraction of hydrogen increases, the ratio of the velocity at reattachment to the velocity at liftoff increases linearly. While the mass flow rate of hydrogen increased exponentially as the methane flow rate increased, the mass fraction growth within the reattachment velocity remained linear.
Further investigation into the effects of hydrogen enrichment into liftoff, blowout, and reattachment, were conducted while maintaining the mass fraction, $Y$, as a constant between trials, while increasing the flow rates of methane and hydrogen. The three levels of hydrogen enrichment are shown below in Table 7; at 5, 7, and 12 percent by mass.

The stability of each trial was observed, whether the jet flame was lifted, attached, or reached blowout. While the mass fraction of hydrogen in these trials remains low, each trial maintained below 15%, the observed effect on the stability and the lifted position of the flame is easily discernible.

### Table 7- Stabilization Position of Enriched, Methane Jet Flames

<table>
<thead>
<tr>
<th>Trial</th>
<th>Methane Flow Rate (m/s)</th>
<th>Hydrogen Flow Rate (m/s)</th>
<th>Methane Mass Fraction</th>
<th>Average Lifted Height (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>84.18</td>
<td>30.14</td>
<td>0.95</td>
<td>Blowout</td>
</tr>
<tr>
<td>2</td>
<td>74.27</td>
<td>26.68</td>
<td>0.95</td>
<td>Blowout</td>
</tr>
<tr>
<td>3</td>
<td>51.96</td>
<td>18.71</td>
<td>0.95</td>
<td>7.18</td>
</tr>
<tr>
<td>4</td>
<td>27.87</td>
<td>10.05</td>
<td>0.95</td>
<td>Attached</td>
</tr>
<tr>
<td>5</td>
<td>18.12</td>
<td>6.58</td>
<td>0.95</td>
<td>Attached</td>
</tr>
<tr>
<td>6</td>
<td>96.66</td>
<td>51.97</td>
<td>0.93</td>
<td>Blowout</td>
</tr>
<tr>
<td>7</td>
<td>72.74</td>
<td>38.98</td>
<td>0.93</td>
<td>12.55</td>
</tr>
<tr>
<td>8</td>
<td>59.37</td>
<td>31.87</td>
<td>0.93</td>
<td>8.34</td>
</tr>
<tr>
<td>9</td>
<td>40.44</td>
<td>21.65</td>
<td>0.93</td>
<td>2.88</td>
</tr>
<tr>
<td>10</td>
<td>29.80</td>
<td>15.94</td>
<td>0.93</td>
<td>0.56</td>
</tr>
<tr>
<td>11</td>
<td>62.75</td>
<td>67.21</td>
<td>0.88</td>
<td>6.43</td>
</tr>
<tr>
<td>12</td>
<td>58.00</td>
<td>62.36</td>
<td>0.88</td>
<td>5.16</td>
</tr>
<tr>
<td>13</td>
<td>39.71</td>
<td>42.44</td>
<td>0.88</td>
<td>Attached</td>
</tr>
<tr>
<td>14</td>
<td>26.58</td>
<td>28.41</td>
<td>0.88</td>
<td>Attached</td>
</tr>
<tr>
<td>15</td>
<td>18.69</td>
<td>20.09</td>
<td>0.88</td>
<td>Attached</td>
</tr>
</tbody>
</table>
Each trial is compared based upon the flow rate and the mass fraction of methane, shown above in Figure 22. As shown in the figure below, as the mass fraction of hydrogen is increased, the flame becomes more stable, lifting off at a higher methane flow rate. When compared to previous data collected on flame liftoff, from Kribs et al. [72], where flame liftoff was observed at jet speeds of approximately 15 m/s for a pure jet of methane, it is apparent that the addition of hydrogen has a pronounced effect. For methane jet speeds
approaching 40 m/s, the flame remained attached to the nozzle for the highest level of hydrogen enrichment, Y=0.88. Even for the initial reattachment trials, from Table 6, the flame was able to reattach from a downstream distance of over 8 cm, to the nozzle, with a methane mass fraction of 0.84.

When compared to the original non-enriched trials, the enriched cases are attached at the nozzle, for higher methane flow rates, and did not blowout until further downstream. The hydrogen enhancement causes the flame to be stable, and at times remain attached, well beyond the flow rates that would cause a pure jet to liftoff, as well as cause a flame that would reach blowout to remain stable at the same methane flow rate, extending not only the attached regimes, but also the lifted regimes beyond that of a pure jet. This concept is exemplified by the change between trials 2 and 6, where an increase in 2% flow by mass of hydrogen was able to stabilize the flame.

When compared to previous studies into blowout of lifted jet flames, specifically Moore et al. [3], it was found that for this burner configuration that a pure methane jet flame reaches a meta-stable position at approximately 60 m/s, or 0.0004 kg/s. When compared to these previous results, the addition of a small amount of hydrogen permitted extension of the stable region of the flame by approximately 20%, from the pure jet's methane velocity of approximately 60 m/s to a methane flow rate of 72.74 m/s for a methane mass fraction of 0.93. If the increased speed resulting from the hydrogen flow is used to calculate a new jet speed, the flame is stable above the expected meta-stable position for a pure jet, for each of the tests, with the Y=0.95 test having stable positions at 63.3 m/s.
Of note, as the level of hydrogen enrichment increases, there is a decrease in the turbulent fluctuations in the stabilization of the flame, with the discontinuities or the shift in flame lift-off observed for the non-enriched trial being absent for the enriched cases. This increase in steadiness of the flame, or reduced effect of turbulence would result from the increase in burning velocity at the flame front.

The chemiluminescent effect of hydrogen enrichment was observed in these trials as well, with a noticeable increase in the flame chemiluminescence for trials with increasing hydrogen enrichment. This increase in chemiluminescence is of interest, since hydrogen jets burn with little observable fluorescence, shown below in Figure 23.

![Figure 23- Comparison of Chemiluminescence of Hydrogen and Methane Jet Flames](image)
In the low light environment, shown above, it was possible to discern some fluorescence for pure hydrogen flames, in higher light environments, the flame luminescence is not as apparent, at times not being discernible at all. Yet, with the addition of hydrogen to an existing methane jet flame, the amount of chemiluminescence increases. In direct contrast to Figure 23, the flames observed in Figure 20 have an increased chemiluminescent effect, which furthers the conclusion that combustion is occurring at a much higher temperature than previously observed for a pure methane flame.

Additional observations were made about the qualitative properties of the flame, specifically that the amount of branching that occurred downstream from the flame front increased as the flame reattached, causing the flame to expand radially downstream from the leading-edge. The reasons for the increased presence of "flamelets" with the addition of such a small amount of hydrogen could be a result of the burning of hydrogen left in the fuel stream after the flame front.

4.3 Conclusions

Observing the influences of hydrogen enrichment on the reattachment of lifted methane flames, it was shown that,

1. As the methane flow rate increases, the amount of hydrogen needed to reattach the flame increases exponentially
2. As the flame reattaches to the nozzle, the flame luminosity increases leading to the assumption that the overall flame temperature increases

3. The mass fraction of hydrogen in the fuel mixture increases linearly as the ratio of the final velocity to the initial velocity

4. The overall stability regions, specifically the attached and lifted regions for jet flames, are expanded, allowing for increased stability

5. Hydrogen addition decreased the turbulent fluctuations in the flame height.

While this study had some purview into flame blowout, the study did not have extensive focus on the transition to blowout, and the liftoff fluctuations as a hydrogen-methane mixture reaches a meta-stable position. Further experiments will focus on hydrogen enrichment on methane jet flame blowout and liquid-hydrogen mixtures.
CHAPTER 5- COMPARISON OF INFLUENCES OF DILUTION IN ETHYLENE AND METHANE JET FLAMES


Abstract

While the liftoff mechanisms of nitrogen-diluted methane jet flames have been well documented, higher order fuels, such as ethylene, have not been studied as extensively with regards to flame stabilization and behavior. Higher order fuels burn with more intensity, and thus produce much different stabilization patterns than those of simple hydrocarbon fuels, such as methane. The purpose of this study was to observe the effects of nitrogen dilution on ethylene combustion and compare to typical methane jet flames; specifically, the influence on the liftoff height, blowout, and flame chemiluminescence. Liftoff and blowout velocities were compared for various mixtures of ethylene without nitrogen. It was observed that the reason behind the varying stabilization patterns is due to the higher thermal diffusivity of ethylene as well the higher flame speeds that are characterized in the combustion of ethylene. Using a sequence of images from each mixture, the flame liftoff heights were recorded. Due to the strong chemiluminescence of ethylene flames, little offset was observed; however, there was a significant effect on the liftoff height. Blowout for fuel mixtures was much more difficult to achieve due to the higher thermal diffusivity of ethylene, meaning the flame
would stabilize at positions much farther downstream than those of simple hydrocarbon fuels.

5.1 Experimental Procedure

This experiment was conducted at the Reacting Flows and Turbulent Jets Laboratory in the Department of Mechanical and Aerospace Engineering at North Carolina State University. The fuel used during testing was ethylene (CP Grade, 99.5% Pure) and was run through a 3.5-millimeter diameter nozzle. The ethylene flame was diluted with compressed nitrogen and was premixed with the ethylene fuel upstream from the nozzle exit. The length to diameter ratio is greater than 10, meaning the flow is fully developed for each of the trials. Figure 24 has an illustration of the ethylene and nitrogen burner apparatus.

The images that were analyzed were taken with a Nikon D80 Digital SLR camera with an 18-105 millimeter Nikkor Lens. The volumetric flow rate of the fuel and nitrogen were varied for each trial, using separate Advanced Specialty Gas Equipment Series 150 Flowmeters for each gas to measure the flow rates, MicroLine UHP Gas Panel controller for controlling the flow rates of fuel gases, and a ESAB R 72-75-580 Regulator to control the nitrogen flow rate. For each trial, 10 images were taken and an average liftoff height was recorded. Each of the volumetric flow rates of the nitrogen and methane were then converted to a volume fraction in order to separate various trials. The liftoff heights were analyzed using Adobe Photoshop by converting pixels to a distance. The stability point was
determined to be at the lowest level of chemiluminescence determining the leading edge of the flame.

5.2 Results and Discussion

For experiments into the effects of nitrogen dilution of lifted methane and ethylene jet flames, qualitative and quantitative observations were cataloged on six-fuel flow rates under three levels of dilution, shown in Table 8. For each iteration, the lifted position of the leading edge of the flame was determined. For each trial, a set of mixtures of nitrogen and
fuel were combined upstream of the nozzle, to maintain the volume fraction, $X$, as a constant, with four different cases of each fuel flow rate, a pure jet case ($X_{\text{Fuel}}=1$), and three dilution cases. For each of the various flow rate and nitrogen level combinations, an average liftoff height was recorded from the ten images that were taken. It can be seen that a majority of the methane trials resulted in blowout; therefore, no liftoff height could be recorded.
### Table 8- Experimental Levels Measured for Ethylene and Methane

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Fuel Flow Rate (slpm)</th>
<th>H(X(Fuel)=1) (cm)</th>
<th>H(X(Fuel)=0.91) (cm)</th>
<th>H(X(Fuel)=0.83) (cm)</th>
<th>H(X(Fuel)=0.77) (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ethylene</td>
<td>18.95</td>
<td>0.64</td>
<td>0.98</td>
<td>1.44</td>
<td>1.78</td>
</tr>
<tr>
<td>Ethylene</td>
<td>22.14</td>
<td>0.86</td>
<td>1.41</td>
<td>2.05</td>
<td>3.45</td>
</tr>
<tr>
<td>Ethylene</td>
<td>25.6</td>
<td>1.21</td>
<td>1.89</td>
<td>3.42</td>
<td>5.45</td>
</tr>
<tr>
<td>Ethylene</td>
<td>28.71</td>
<td>1.64</td>
<td>3.01</td>
<td>4.82</td>
<td>6.14</td>
</tr>
<tr>
<td>Ethylene</td>
<td>31.85</td>
<td>2.63</td>
<td>4.4</td>
<td>6.03</td>
<td>8.08</td>
</tr>
<tr>
<td>Ethylene</td>
<td>35.34</td>
<td>3.14</td>
<td>5.33</td>
<td>7.06</td>
<td>9.38</td>
</tr>
<tr>
<td>Methane</td>
<td>18.95</td>
<td>4.29</td>
<td>9.45</td>
<td>Blowout</td>
<td>Blowout</td>
</tr>
<tr>
<td>Methane</td>
<td>22.14</td>
<td>8.17</td>
<td>12.74</td>
<td>Blowout</td>
<td>Blowout</td>
</tr>
<tr>
<td>Methane</td>
<td>25.6</td>
<td>9.99</td>
<td>Blowout</td>
<td>Blowout</td>
<td>Blowout</td>
</tr>
<tr>
<td>Methane</td>
<td>28.71</td>
<td>12.95</td>
<td>Blowout</td>
<td>Blowout</td>
<td>Blowout</td>
</tr>
<tr>
<td>Methane</td>
<td>31.85</td>
<td>14.42</td>
<td>Blowout</td>
<td>Blowout</td>
<td>Blowout</td>
</tr>
<tr>
<td>Methane</td>
<td>35.34</td>
<td>Blowout</td>
<td>Blowout</td>
<td>Blowout</td>
<td>Blowout</td>
</tr>
</tbody>
</table>

While most of the trails for methane resulted in the flame blowing out, due to the smaller flammability limits of methane (5-15% by volume), when compared to the flammability limits of ethylene (2.75-36% by volume), the ethylene mixtures were able to stabilize, even at the higher levels of dilution. The averages of the lifted heights were plotted for the ethylene trials, shown in Figure 25 below.
The liftoff progression of the diluted cases followed expected trends, with each higher level of dilution stabilizing at a higher position than lower levels of dilution or the pure jet case. The increase in velocity of the central jet, without the increase in the amount of fuel supplied would push the leading edge of the flame further downstream. This expected linear trend was noted for both the pure fuel jet trials and all of the nitrogen diluted trials. The differences in liftoff heights between varying levels of dilution, even at the same fuel flow rate, were not proportional to the amount of diluent added to the fuel stream. The deviation of the liftoff heights between each level of dilution increases with increasing fuel flow rates.

**Figure 25- Lifted Flame Height Versus Ethylene Flow Rate**

Other observations on the chemiluminescence of the diluted ethylene flames were made, specifically that while ethylene has a much higher chemiluminescence than other fuels, such as methane or propane, the amount of chemiluminescence decreases as the level of dilution
increases, maintaining the fuel supply speed as a constant, as shown in Figure 26 below, with each photo being at the same ethylene flow rate (22.14 slpm).

![Figure 26- Ethylene Jet Flames with Various Nitrogen Dilution Levels](image)

When comparing the stabilization of the diluted ethylene flames, to that of diluted methane flames, it was observed that maintaining the volume fraction and fuel flow rate as a constant, jets of methane were much more sensitive to dilution, than jets of ethylene, shown in Figure 27 below, as the change in liftoff height between the pure jet and diluted cases was much higher for methane, than for ethylene, at times resulting in a 220% increase in liftoff height. This large difference in liftoff heights between ethylene and methane flame can be explained by the chemical composition of both molecules. Being a lower order hydrocarbon, the methane experiences many fewer chain-branching/propagation reactions during the combustion process. This, in addition, to the higher flame temperature of ethylene and
higher flame speed, results in ethylene experiencing a lower liftoff height even with nitrogen acting as a diluent.

As a result of methane being more sensitive to nitrogen dilution than ethylene, the methane jets reached blowout much more rapidly than the ethylene flames. This can be noted by comparing the liftoff progression of the two fuels, as shown in Figure 29. With the addition of the nitrogen diluent, the rate of change in the liftoff height increases more for methane than for ethylene, as the fuel flow rate increases.

As seen in Figure 28, non-dimensionalizing the liftoff height of the diluted cases to the pure jet cases shows that the effect of dilution is much weaker at the extremes of flame stabilization, in the near field and approaching blowout, but increases in strength in the mid field, peaking at 4.5 at 25.6 slpm, for X(Fuel)=0.77. It is interesting that ethylene non-dimensional liftoff height is affected by the nitrogen dilution the greatest at the mid-range of the stability region for ethylene (slightly after near field). This trend is quite curious in that the typical steadily increasing liftoff height with increasing fuel flow rate is not present (when considering non-dimensional liftoff height), specifically the expectation that the influence of the nitrogen dilution would become stronger in the far field, approaching blowout, where the stabilization mechanisms are becoming weaker.
Figure 27- Comparison of Methane Lifted Flame Heights to Ethylene Lifted Flame Heights

Figure 28- Non-Dimensional Height versus Fuel Flow Rate for Various Nitrogen Dilution Levels of Ethylene
In order to further document the effects of nitrogen dilution on the stabilization mechanisms of jet flames, the overall central jet velocity at the nozzle was calculated, and the ethylene cases were plotted using a mass fraction, rather than a volume fraction, as in Figure 29 above. This is to ensure that the increase in liftoff was not just a result in the increase in jet speed at the nozzle. From Figure 29, it is discernible that the liftoff height is not only a function of the change in central jet velocity, as the diluted cases are further downstream than the undiluted cases.

Figure 29- Lifted Flame Heights for Methane and Ethylene by Mass Fraction
5.3 Conclusion

Observing the effects of diatomic nitrogen on the ethylene jet flame resulted in the following:

1. Ethylene burns with much more intensity than that of methane (brighter chemiluminescence due to higher adiabatic flame temperature, as well as more black body radiation resulting from the higher soot production)
2. The ethylene jet flame stabilized at much lower liftoff heights than that of methane
3. For ethylene flames, nitrogen dilution effects are more prevalent in the mid-range liftoff heights, rather than in the near or far fields
4. Nitrogen diluted methane jet flames reached blowout much quicker (with respect to liftoff heights) than nitrogen diluted ethylene jet flames
5. Nitrogen dilution influences methane flames at much higher rates than it does to similar ethylene flames

The study described primarily focuses on the comparison of nitrogen diluted methane flames to nitrogen diluted ethylene flames. The trends observed are described, as well as illustrated by various figures. Further studies should involve comparing other higher order hydrocarbons (such as propane) to the nitrogen diluted ethylene data described above.
CHAPTER 6- ELECTROHYDRODYNAMICS FLOWS FOR COOLING

APPLICATIONS

Excerpts from: James Kribs, M. Sean June, K. M. Lyons, Utilizing Multiple Corona Discharges as an Ionic Air Moving Device, AUISHEM 2009 Interdisciplinary Conference in Chemical, Mechanical and Materials Engineering, January 2010

Abstract

As a new prospect for inducing forced convection, ionic air moving devices have been found as possible replacements to conventional fans. Ionic air moving devices apply high potentials over sharp curves to impart electric energy to the surrounding air, which, due to potential gradients, is forced away from the electrode. The collisions with other air molecules, and the associated momentum transferred, creates an overall flow away from the electrode. This effect, noted as far back as 1889, has seen recent application as a cooling mechanism. In this study, an ionic air moving device, using the pin and ring configuration, is investigated. Applying voltages between 7-25 kV, the efficiency of the ionic air moving device is observed. This efficiency, which is in the order of .01-.1%, is compared to the efficiency of a conventional fan, of a similar physical size.
6.1 Methodology

An Acopian 20kV power source was used to generate the high-voltage and was attached to a Hewlett Packard HP3466A DMM voltmeter. The ionization sites, which were 5 x 1.3 mm diameter common sewing needles, were monitored through the needle holder, to insure that the same voltage and polarity was reaching each of the ionization sites. The voltages, volumetric flow rates, and pressure combinations were observed and recorded as voltage was varied. All measurements of flow and pressure were conducted on a flow bench, with a MKS model 698A11TRD differential manometer to measure static pressure, a Meriam model 50MC2-2F linear flow element to measure air flow, and Meriam model LFS-1180E-99SP-5-31-1-99 to measure ambient conditions (temperature, relative humidity, and ambient pressure). All measurements were obtained in 26°-28°C temperatures, with the relative humidity ranging from 31-38%, as it has been noted that humidity affects the breakdown voltage of air.

Rather than utilizing a series formation for each pin setup, the pins were placed in a holder in a parallel formation with a single grounded, secondary electrode. Each needle holder was built from aluminum, designed to hold a number of needles (3-5 needles) in a polar array, keeping each needle 5.08 mm from a common center point. 5 separate secondary electrodes were used, varying the thickness from 2-10 mm, while the diameter was maintained at 25.4 mm.
Figure 30- Electrode Setup

The purpose of this setup is to test the effects of multiple ionization sites within a small area, in order to observe any interference effects, as well as maximize the volume affected by the electric fields, to maximize the volumetric flow rate. For the comparison, a traditional 2.54 cm commercially available fan from a major vendor was used. The conventional fan was compared to the ionic air moving device on the same flow bench.

6.2 Results and Discussion

Initial Observations of the Ionic Air Moving Device

The focus of the experimental results was to observe the effects of multiple corona discharges within close proximity, as well as test to influence of the secondary grounded ring
on the flow parameters and testing the viability of an ionic air moving device as a substitute to traditional cooling fans. The intent was to test the efficiency of the ionic air moving devices to convert the electrical power into pumping work against the surrounding air.

In the initial investigations into effects of the parallel setup for the primary electrodes and the effect of multiple corona discharges in the parallel configuration, with the voltage held constant multiple ring sizes were tested. The intent was to see the limits of the flow created by the ionic air moving device and observe the impact of the surface area of the secondary electrode, specifically the maximum flow rates and static pressures the flow can act against. For these experiments, efficiency is,

$$\eta = \frac{\rho g H Q}{V I}$$

(10)

, where $\rho$ is the density of air, $g$ is the acceleration due to gravity, $H$ is the static pressure, $Q$ is the volumetric flow rate, $V$ is the applied voltage, and $I$ is the applied current. Comparisons of ring sizes were run at 3 separate voltages 11000, 13000, and 17000 V. At 11000 V applied to the needles, there exists a sizable difference between the 4 mm ring, and the larger rings, as displayed in Figure 31-Ring Comparison at 11000V.
Initial observations hinted that the smaller rings, while providing lower peak flow, and could not act at larger static pressures as well as larger rings, the smaller rings provided a much higher efficiency. More peculiar was the operation of the 6 mm ring to the 10 mm ring. At 13000 V, the same trends were observed, as demonstrated in Figure 32- Ring Comparison at 13000 V.
As it is evident in Figure 32- Ring Comparison at 13000 V, the 6 mm ring and the 10 mm ring follow the same approximate trend, never reaching above 0.2% efficiency, whereas the 4 mm ring pushes above 0.3% efficiency at its peak. The difference in size would result in assumptions that the 6 mm ring would perform near the 4 mm ring rather than the 10 mm ring. This trend disappears at 17000 V, but is replaced with a far more unexpected result.
In Figure 33- Ring Comparison at 17000 V, while the trend of the 4 mm ring performing better than the 2 larger sizes, the functioning of the 10 mm at higher efficiencies and peak parameters than the 6 mm ring does not conform to the previous trends. Further comparison of how the voltages affect the relative trends, taking into account the ring sizes, resulted in observations that the 6 mm ring faced a different rate of change between the flow rate and the static pressure. In Figure 34- Voltage to Flow rate, the 6 mm ring performs as
well as the 10 mm ring at lower voltages, but quickly loses much of the flow as the voltage increases.

Figure 34- Voltage to Flow rate
Evaluation against a Traditional Fan

As an efficient forced convection method, the ionic air moving device is mainly used in independent fabricators. The traditional fan utilizes electrical energy to create mechanical work and impart energy to create a flow, whereas the ionic AMD imparts electrical energy (the electric potential), without performing direct mechanical work. The key for the development of ionic AMDs is designing and developing them so they perform as well as a traditional fan. In the comparison to a traditional fan, the ionic AMD performed more efficiently in most cases, as demonstrated by Figure 35- Ionic AMD (4 mm Ring) and Fan.
While the fan does not perform as efficiently as the ionic AMD, the fan does have higher peak flow rates than the 4 mm rings, as demonstrated in Figure 36- Ionic AMD (10 mm Ring) and Fan, the 10 mm rings can provide much higher peak flow rates.
Figure 36- Ionic AMD (10 mm Ring) and Fan
6.3 Conclusion

In observations made of an ionic AMD and a comparably sized traditional fan, it was found the ionic AMD could provide an alternative as a method of creating a forced convection current. The ionic AMD demonstrated that larger rings can provide the necessary peak flow values, while the smaller rings can provide higher efficiencies than a traditional fan. Continued investigations are needed to map out the effects of the secondary ring geometry, specifically the effects observed in intermediary sizes between the 4 mm ring and 10 mm ring, as well as the effects of an ionic AMD in confined environments.
CHAPTER 7 - USE OF ELECTROHYDRODYNAMIC FORCES TO INDUCE STABILITY OR INSTABILITY IN JET FLAMES


7.1 Rationale of Study

The previous investigations provided the framework for the study of the dominant jet flame stabilization mechanisms resulting from the application of high potential electric fields, specifically, it permits investigation of which of the observed influences, among the thermal, ionic, or chemical mechanisms (resulting from the electric fields), results in changes in flame stabilization. The chemical mechanism results from the changes in chemical kinetics and species present resulting from the high potential electric fields, such as the creation of ozone in ambient air in electric fields or the changes in pollutant emissions discussed above. This mechanism was investigated through premixed flame simulations below on propane-air flames with increasing amounts of ozone addition in the oxidizer. The thermal mechanism, where the electric field provides resistive heat transfer from the current passing through the flame, has been extensively investigated as part of previous jet flame studies, and is highlighted below. The ionic mechanisms, such as the ionic wind, are caused by the

91
electrohydrodynamic forces acting within the flame, in conjunction with the applied electric field. The ionic wind has been observed and documented in previous research, shown in the discussion of the ionic wind shown later in the study. The ionic wind has been observed and documented in previous research, shown in the discussion of the ionic wind shown later in the study. A graphic illustrating the effects of each mechanism is shown below in Figure 37.

Figure 37- Comparison of Dominant Influences Resulting from the Application of Electric Fields to Lifted Jet Propane Flames
Prior investigations into the stabilization mechanisms of jet flames, both laminar and turbulent, have provided useful insight into the understanding of non-premixed flame propagation into an oncoming fuel stream. These stabilization mechanisms have been reviewed by Lyons [9], Pitts [11], and Lawn [10]. As part of this study, the effects of increased heat release resulting from the applied electric field are investigated. Previous work into the influence of heat release on partially premixed flames, have been documented by Ruetsch et al. [73], showed that accounting for the increase in heat release at the flame front resulted in changes of the mixture fraction gradient, improving the overall stabilization of the lifted flame. The relation between the laminar flame speed and temperature have been well documented, and have shown that an increase in flame temperature would result in an increase in laminar flame speed [74]. These studies provide necessary understanding of the stabilization mechanisms resulting from temperature changes or increases in heat transfer within the flame.

The location of the leading edge of the flame, or liftoff height, can be influenced by the addition of external influences, such as the dilution of the fuel with inert species, such as nitrogen [72, 3], or dilution with enhancing combustible species, such as hydrogen [42], the changing of the conditions of the ambient oxidizer, such as coflowing [75], crossflowing, or counterflowing air [27], or the preheating of the fuel and oxidizers [76]. These previous investigations show that the mechanisms behind jet flame stabilization have been thoroughly
investigated in many different regimes and configurations, but the influences of high potential electric fields leave many open questions, which have yet to be answered. In order to understand the influences of electric fields within combustion, it is necessary to review the mechanisms within the ionic wind, in neutral fluids, and then within combustion.

Influences of the Ionic Wind

Early investigations into the phenomenon known as the ionic wind, conducted as far back as 1899 by A.P. Chattock [44] and reviewed by Robinson [45], focused on the formation of bulk flow between two high potential electrodes. The main requirement, for the ionic wind, was that the electrode needed to be a sharply curved surface, as demonstrated in Figure 38, which outlines the process for negatively charged corona discharges.
It is important to note that the ionic wind can be formed by positive or negative potentials applied to the sharply curved, primary electrode, the difference between the polarities of the applied potentials is that for positive potentials, the non-ionizing plasma region is absent, with only the ionizing plasma and the unipolar region. The setup, shown in Figure 38, uses a combination of a single sharply curved electrode, such as a common sewing needle, and a flat secondary electrode, or a thin wire combined with a plate or a pin electrode paired with a ring. The secondary electrode is flat, or with blunted curves, in order to prevent secondary ionization, where after a corona discharge forms on the primary electrode, a second set of coronas, as shown in Figure 39, of opposite charge may form on the secondary electrode,
which in turn creates a bulk flow in the opposite direction of that created from the primary ionization.


In an investigation by Rickard et al. [46], it was shown that the local body force, $F$, created by primary ionization can be shown to be

$$
\vec{F} = \vec{E} e(n_+ + n_-)
$$

(11)
where \( \mathbf{E} \) is the electric field vector, \( e \) is the fundamental charge, and \( n \) is the number density of positive and negative ions, as denoted by the subscript. The local current density, \( j \), can be calculated as

\[
\mathbf{j} = j_+ \mathbf{j}_+ + j_- \mathbf{j}_- = (K_+n_+ + K_-n_-) \mathbf{E} e
\]

where \( K \) is the electron mobility [46]. The maximum current density that can be achieved prior to secondary ionization has been shown to be

\[
\mathbf{j}_{\text{max}} = (E_b^2 - E_0^2) \varepsilon_0 \frac{K}{2x}
\]

where \( E_b \) is the breakdown electric field at the electrode, \( E_0 \) is the electric field at the corona source, \( \varepsilon_0 \) is the permittivity of free space, and \( x \) is the distance coordinate.

The purpose of this study is to investigate the influences of high potential, steady DC electric fields on the flame shape, chemiluminescence, and leading edge stabilization of stable, non-premixed, solid fuel flames, in the form of candle flames, as well as attached and lifted partially premixed flames. Experiments center on the variation of applied voltage, current, application method, and jet velocity, in the case of the partially premixed flames.
7.2 Experimental Apparatus

All experiments were conducted in the Reacting Flows and Turbulent Jets Laboratory in the Department of Mechanical and Aerospace Engineering at North Carolina State University, in conjunction with simulations run by the High Pressure and Laser Diagnostics Laboratory. Initial experiments were conducted on candle flames, focusing on the local enhancement or suppression of the flame, with the setup shown in the figure below.

![Candle Flame Experimental Apparatus with Dual Electrodes](image)

**Figure 40- Candle Flame Experimental Apparatus with Dual Electrodes**

The applied voltage was created using an Acopian Positive High Voltage Power Supply (PO30HP2), using voltage control to adjust the power of the electric fields, while allowing the applied current to vary freely. The voltage and current were monitored using dual Agilent Technologies U3401A Multimeters. The electrodes used were ring electrodes, with the grounded electrode having a diameter of 3.5 inches (88.9 mm), and the positively
charged electrode, with a diameter of 2.5 inches (63.5 mm), with a common sewing needle soldered to it, such that the point of the needle was directed at the center of the ring, in order to create a corona discharge.

Further experiments on partially premixed flames used propane (CP Grade, 99.0% Pure) issuing from a central nozzle with an inner diameter of 0.0325 (0.8255 mm). The flow rate of the propane was measured through a King 7430 flowmeter and controlled through a MicroLine UHP Gas Panel controller. The electric field was created using the same power supply as the candle flame experiment, and the current and voltage were monitored using the same multimeters used in the first experiments, with the primary electrode consisting of a delrin plastic case surrounding a 10 AWG solid core copper wire charging up to 12 needle electrodes on the same loop, though only the one and two needle electrode setup was used in this experiment, as shown in the figure below, and the secondary electrode was the nozzle for the issuing jet. The copper wire is inlaid within the electrode case at a diameter of 11.43 cm (4.5 inches) and the internal diameter of the case is 9.60 cm (3.78 inches).
The electrode polarity of the jet flame experiments was varied, switching between a positively charged primary electrode, and the primary electrode acting as the negatively charged ground. The position of the electrode, relative to the issuing nozzle was held constant at 2.53" (64.262 mm) above the nozzle and 0.93" (23.622 mm) radially from center of the nozzle to the tip of the needles. The setup of the burner is shown below in Figure 42. The images of the jet flames were taken using a Nikon D80 digital SLR camera with an 18-135 mm Nikkor Lens, in order to observe the downstream location of the leading edge of the flame, as well as changes in chemiluminescence. The downstream location was determined using Adobe® Photoshop® using the ruler attached to the burner to determine a comparable length scale.
The experimental apparatus above is electrically insulated at the base to prevent accidental grounding, and all experiments were conducted with a shroud placed over the device to isolate the influences of external air flows, while providing access to outside oxidizer, as well as providing protection from electrical arching during the experiment.

Numerical simulations of premixed propane flames were conducted using the C3 Mechanism from Qin et al. [77], which covers the reaction mechanisms for propane-air combustion. The flame speeds and OH concentrations, as well as the concentrations of other major species of combustion, including transient species, were determined for premixed propane flames with and without the addition of ozone into the oxidizer, using the constants for ozone creation, as referenced by Ombrello et al. [36].
7.3 Results and Discussion

Diffusion Flame Experiments

Initial observations, made on candle flames, from the experimental apparatus shown in Figure 40, were made to prove the effectiveness of high potentials to adjust flame shape, chemiluminescence, and the possibility of flame suppression. Using paraffin candles, the experiments focused on qualitative observations made at observed voltages. During the initial testing, the flame behavior, shown in the figure below, was observed.

![Comparison of Flame Behavior of Attached Diffusion as a Function of Applied High Voltage](image)

**Figure 43- Comparison of Flame Behavior of Attached Diffusion as a Function of Applied High Voltage**
In this single needle electrode configuration, it was observed that the flame was repelled by the presence of the high potential. This effect became more pronounced at higher voltages. The experiment was limited to 20,000 V, as the air surrounding the electrodes would begin to carry a charge and cease acting as a dielectric, creating sparks, which would travel between the clamp for the candle and the grounded ring. While the candle flame responded in a similar way as though there were a counterflowing air acting on the system, the intermittent flickering that would be expected from a diffusion flame in a flow of air was not present, but rather the flame maintained a consistent shape at each applied voltage.

Further observation of the results of the candle flame experiment has shown that not only is the flame shape influenced by the electric field, but also, the products of combustion, specifically soot accumulation. Figure 44 is a still image taken after the experiment was concluded.
As shown in Figure 44, there is a pronounced buildup of soot on the grounded electrode, away from the needle. This effect has been observed in other experiments, specifically the repulsion of soot by positive electrodes, or attraction of soot by negative electrodes. In the case below, using a negatively charged power supply, the soot and flame would appear on the electrode, with the effect becoming more pronounced as the electrode approached the diffusion flame.
These experiments brought up serious questions into which mechanism of flame manipulation using electric fields dominates and controls the stabilization of the flame. The main observations on the attraction of soot and the flame shape manipulation, similar to counterflowing air experiments, brought into question whether certain influences were more significant than other forces. By applying an outside electric field, there are three major factors that must be accounted for, specifically the thermal effects resulting from the resistive heating within the flame, the introduction of new chemical species to the reactants, such as ozone formation from corona discharges, and the ionization effects, such as the ionic wind and the attraction and repulsion of charged species. The thermal effects, specifically the influence of increased temperature on factors, such as flame speed have been well documented in past tests [37, 38], and the ionic influences have been reviewed above, while the influence of chemical species expected results need to be compared to a partially premixed flame under an electric field. For this reason, a premixed flame simulation was run with the addition of ozone to the oxidizer stream, in order to compare the influence of ozone creation to the experimental observations on the partially premixed flame.

Figure 45- Soot Attracted to Negatively Charged Electrodes for Small-Scale Candle Flame Experiments
Premixed Flame Simulations

Fully premixed flames provide useful insight into the basic mechanisms in flame liftoff, allowing for the calculations of laminar flame speeds. In order to investigate the influence of high potential electric fields resulting from corona discharges on premixed flames, a specific mechanism, the formation of ozone issuing from the corona was investigated. The formation of ozone was chosen as it is one of the major changes to the reactants resulting from an electric field. Previous studies into the effects of ozone addition to a flame have been conducted [78], but a wider range of ozone concentration was chosen for this study, in order to completely understand the impacts. In the investigation by Ombrello et al. [78], it was found that the addition of ozone did improve flame front stabilization with experiments adding ozone to a coflowing air, as well as numerical simulations. These simulations provided a necessary baseline for comparison, within the partially premixed experiments conducted later, on the effect of the ozone addition, and expected flame behavior. The simulations show how does ozone addition influence the stabilization of the leading edge of the flame, in the form of changes in laminar flame speed, and what changes in chemiluminescence would result from the addition of ozone, as these effects are not well documented.

The PREMIX package within chemical kinetic package, Cantera, was used to determine the OH concentration, as well as the laminar flame speed, $S_L$, for increasing concentrations of ozone addition in the oxidizer, from the flame front to a position 0.1m
downstream. The amount of $O_3$ was varied from 0 ppm to 10,000 ppm. The concentrations of OH for 3 concentrations of ozone (0, 5000, 10000 ppm) are shown below, in Figure 46.

![Figure 46- OH Mole Fraction for Premixed Flame Simulations](image)

The OH mole fraction peak value for the highest concentration of ozone ($O_3=10000$ ppm) was found to be approximately 20% more than for the standard case ($O_3=0$ ppm). This
marked increase in OH production is not supported by experimental results from Kim et al. [79], where using OH-PLIF (Planar Laser Induced Fluorescence) visualizations of a non-premixed laminar flame, where a change in the OH concentration was not observed in the experiment between cases with no applied voltage and at 3 kV.

Further investigation, showing a comparison of the change in OH concentration resulting from ozone addition, as well as the change in laminar flame speed, is shown below in Figure 47.

![Figure 47- Laminar Flame Speed and Peak OH Mole Fraction as a Function of O3 Concentration in the Reactants of a Premixed C3H8 Flame](image)
Based on these observations, it would be expected that as the amount of applied voltage increases, thereby increasing the amount of ozone formation from the resulting corona discharge, the laminar flame speed of a propane flame would increase, as well as the peak amount of OH production, an increase of approximately 20% for both the OH production and laminar flame speed when compared to the standard case. The increase in OH production, shown by OH chemiluminescence, would act as an indicator of the chemical mechanisms, specifically the O₃ production, resulting from the influence of electric fields, was the dominant mechanism affecting the stabilization mechanisms of a lifted jet flame.

Partially Premixed Flame Experiments

Unlike the diffusion flame experiments, where observations only focused on localized suppression or manipulation of flame shape, it is possible to adjust the lifted position of partially premixed flame, both upwards or downwards (axially) from the issuing jet. This localized enhancement or suppression of the flame front was investigated in positive and negative polarity configurations (referring to the polarity of the primary electrode, the ring), in a single and double needle setup, over 6 flow rates between 1.14 to 1.53 liters per minute (2.4-3.2 scfh). An example of the resulting flame is shown in the figure below.
The voltage applied to create the electric field was varied until either the flame reattached, which was found to be the result for the positive configurations, or blowout, for
the negative configurations, respectively. The flow rates were fixed between tests, and the voltage varied to witness the effect on the flame, with photos taken of the leading edge of the flame at approximately 1000V increments. The different configurations and applied voltages are shown below in Table 9.

Table 9- Electrode Configurations and Applied Voltages for Partially Premixed Flame Experiments

<table>
<thead>
<tr>
<th>Primary Electrode Polarity</th>
<th>Number of Primary Electrodes</th>
<th>Applied Voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Negative</td>
<td>1</td>
<td>0-12,000 V</td>
</tr>
<tr>
<td>Negative</td>
<td>2</td>
<td>0-12,000 V</td>
</tr>
<tr>
<td>Positive</td>
<td>1</td>
<td>0-5,000 V</td>
</tr>
<tr>
<td>Positive</td>
<td>2</td>
<td>0-5,000 V</td>
</tr>
</tbody>
</table>
The average lifted position of the flame was plotted against the applied voltage, shown in the figures below.

Figure 49- Location of the Leading Edge of the Flame for Applied Voltage (Propane Flow Rate = 1.14 slpm)
Figure 50- Location of the Leading Edge of the Flame for Applied Voltage (Propane Flow Rate = 1.23 slpm)
Figure 51- Location of the Leading Edge of the Flame for Applied Voltage (Propane Flow Rate = 1.30 slpm)
Figure 52- Location of the Leading Edge of the Flame for Applied Voltage (Propane Flow Rate = 1.38 slpm)
Figure 53- Location of the Leading Edge of the Flame for Applied Voltage (Propane Flow Rate = 1.46 slpm)
Figure 49 through 54 provide useful insight into the electric field effects within lifted flames. The overall trends with the same electrode configuration (positive or negative polarity) remained similar for each flow rate. The positive configurations, for both one and two electrode setups, saw a decrease in liftoff height until the flame reattached at approximately 4 kV, and remained attached at higher voltages. The reattachment for the
positive configuration occurred at the same voltage, independent of the number of electrodes, and while the trends for the two electrode setups were not the same, where it was observed that the two electrode setup was more effective for most flow rates, there was no definitive advantage to using multiple electrodes. The negative configurations saw a marked decrease in liftoff height following trends similar to the positive configurations, at low voltages (below 6 kV), where the flame would intermittently attach and liftoff after 3 kV at approximately 4.5 kV, then the leading edge shifted downstream, eventually blowing out at voltages above 10 kV. Much like the positive configuration, there was no marked difference between utilizing double electrode configuration, with both setups reattaching and then progressing to blowout in the same trends, with the applied voltage at blowout being approximately the same between the setups. The overall observations on the flame stability are shown in the figure below.
The overall trend for the negative configuration could have been a result of secondary ionization at the electrodes, where the maximum charge density, listed in Equation 3, was reached. This would be in agreement with previous studies, on neutral fluids, such as June et al. [4], where the influences of the ionic wind decreased as the electric field became too strong. The resulting corona discharge seen in Figure 39 was not observed, but it would have been masked by the chemiluminescence of the flame. Secondary ionization would have
occurred at a lower applied voltage than in previous studies into air flows [4, 47], as the number density of ions, $n$, would have been higher due to the number of ions produced in combustion.

Further observations into the influence of the current in the applied electric field provided little insight into the stabilization mechanisms. Using the experimental setup, with the current floating, resulted in a near constant current at approximately 0.013-0.016 mA for both configurations at voltages below 3,000 V. At voltages above 4,000 V, where the positive and negative configurations reattach, the current increased by an order of magnitude. While any further adjustment in the positive configuration has no influence, as the flame remained attached, adjusting the voltage, for the negative configuration causes the flame to liftoff further downstream, and the current increases to approximately 0.5 mA at blowout. Plotting the current against the liftoff height resulted in no discernible trends.

The major observation, the difference between the positive and negative configuration trends, provides unique insights into the major influences of electric fields in lifted flames and on the leading edge of the flame. The fact that changing the polarity of the primary electrode downstream has a distinct effect, going as far as causing the flame to blowout in one configuration and reattach in another, shows that the dominant mechanisms in flame stabilization in electric fields. The expected results were compared to observed flame behavior to study the overall dominant mechanisms. For the thermal mechanism, stating that the applied electric field provides resistive heating within the flame, increasing the flame temperature, resulting in an increase in flame velocity, or the speed at which the leading edge
of the flame propagates into the incoming stream of the fuel jet. If this were the dominant mechanism, the trends between the two polarities would have been the same, as resistive heating would provide the same amount of heat and therefore, the same increase in flame temperature, regardless of polarity. Specifically, the blowout, observed in the negative configurations, would not have been observed.

The main chemical mechanism considered in this study, the formation of ozone ($O_3$) resulting from the presence of high voltages, as shown in the numerical simulations, would have seen a marked increase in flame speed, as shown in the premixed numerical study above. Any increase in ozone formation would see the same increase in flame speed, but during an initial testing phase of the experiment, the ionization at the primary electrode caused a local extinction within the flame, shown in the figure below, at 1.30 slpm, contrary to the expected result, as shown in the numerical simulations, where the flame should see an increase in the flame speed at the electrode.
If the ozone formation were dominant in the stabilization mechanisms, it would be expected to see a localized enhancement of the flame with an increase in flame speed around the electrodes. It would also be expected that the flame would exhibit an increase in OH chemiluminescence, as from the numerical simulation, the ozone addition would cause an increase in the OH formation within the flame. The increase in OH chemiluminescence was
not observed in Kim et al [79], in experiments using OH-PLIF on laminar flames in electric fields. For these reasons, the ozone formation, and the chemical mechanisms resulting from the electric field application would not result in the decrease in liftoff height.

This extinction around the electrode provided evidence that the electromagnetic influences dominate the stabilization mechanisms of the leading edge of the flame. The influences of the ionic wind, especially with regards to an already ionized system, such as a partially premixed flame, were found to be the dominant flame control mechanism. The attraction or repulsion of chemical species, such as soot particles, would have had a direct influence on the chemical kinetics of the flame, as it would change the concentration of radicals within the flame front. Combining this influence with the ionic wind body forces, shown in Equation 1, which would have acted on the surrounding oxidizer, would explain the reattachment, even the intermittent reattachment and blowout observed for the negative configurations. Blowout could have been a result of the secondary ionization, due to the reaching of the maximum possible charge density, shown in Equation 3, for resulting in a negation of the ionic wind body forces, as well as, increased attraction and repulsion forces on the existing ions within the flame.

Also of note, the flame structure observed at higher voltages, as shown in the Figure 57 below at 11,000 V at 1.30 slpm for the single electrode, negative configuration, showed abnormal flow structure with intermittent flames, showing decreased chemiluminescence, but with the signature luminosity of a trailing diffusion flame. Previous studies have indicated that as flames approach blowout, resulting from the increases in central nozzle velocity, the
trailing diffusion flame disappearing as an indicator of blowout [21]. The presence of the diffusion flame, while not in the typical manner, indicates that the flame structure itself was not approaching the flammable limits of the flame, but implies that blowout was a result of the external influence of the electric field.

Figure 57- Abnormal Flame Structure of the Trailing Diffusion Flame at 11000 V at 1.30 slpm
7.4 Conclusions

Previous experiments on the impacts of high potential electric fields on combustion have shown the ability to manipulate the liftoff height of jet flames, remove pollutants, and alter flame structure and hence, chemiluminescence. The purpose of this study was to observe the dominant mechanisms within leading edge stabilization in the applications of electric fields in partially premixed, jet flames, comparing the influence of thermal, chemical, and ionic impacts. Numerical simulations of premixed propane flames with ozone formation resulting from a corona discharge showed an increase in OH formation, as well as laminar flame speed, with increasing ozone concentration in the reactants, in order to observe the expected influences of chemical mechanisms within the partially premixed flame. Further investigation into partially premixed, propane jet flames, showed:

1. With a positively charged electrode downstream of the leading edge of the flame, it was possible to reattach a lifted jet flame, while maintaining a constant fuel flow rate.
2. With a negatively charged electrode downstream of the leading edge, the liftoff height was shortened at voltages below 4000 V, after which the leading edge shifted downstream of the nozzle, and reached blowout at approximately 10000 V.
3. The ionizing influence of the applied electric field is the dominant influence of the high potentials, rather than thermal influences or changes to the chemical kinetics of the combustion event.
4. Blowout, in the negative configuration, did not show the expected markers of reaching the flammability limits of the fuel-air mixture, with the trailing diffusion flame remaining until blowout.

These conclusions show that jet flame behavior, with regard to the stabilization point of the flame at a set fuel velocity, was absent at high potentials, with regards to liftoff, reattachment, and blowout, which have been extensively investigated in the past. Further study is necessary in the concentrations, and flow directions, of ionic species within flames under electric fields.
CHAPTER 8-FUTURE INVESTIGATIONS AND CONCLUSIONS

8.1 Open Questions Remaining in Jet Flame Combustion in Electric Fields

While the study of electric fields in combustion has been investigated since Brade's [51] initial observations in 1814, the overall field has seen little progress until the recent developments in electric field studies by Felix Weinberg [55, 62, 53, 54, 56] at the Imperial College of London. As the understanding of mechanisms of combustion, without electric fields, has expanded with relevant studies and advances in observational methodology, such as Particle Image Velocimetry (PIV) and Planar Laser Induced Fluorescence (PLIF) of radical species, as well as computational modeling using Direct Numerical Simulations (DNS) or Large Eddy Simulations (LES). The studies, highlighted in Section 2.3, and the investigation shown in Chapter 7, provided useful insight into the physical mechanisms within jet flame stabilization and chemiluminescence, but have left open important questions of the interactions of the electric fields of the flame with those of the applied potentials. The current understanding of the influences of high potential electric fields on lifted jet flames shows major areas requiring study including:

- How does the electric field influence the ion mobility and internal chemistry of the combustion event?
- What is the optimum geometry of the electrodes to increase flame stability or other parameters, like flame temperature?
It has been observed in previous studies that during combustion, a range of chemical species and ions are created, all of which influence the internal physics of the flame. Boothman et al. [80] went on to measure the effects of common additives to the current density of flames, such as hydrogen, carbon monoxide, and carbon dioxide, as well as some uncommon additives, bromine, sodium, and lead. While the different additives could not be compared directly, as the burner configuration changed with each additive, the effects were compared to a baseline mixture without the additive [80]. With regards to hydrogen addition, the addition of hydrogen to the mixture caused a decrease in the current density, maintaining the flame temperature constant, and increase the current density as the equivalence ratio remains constant, finding that the current density becomes increasing negative as the temperature increases [80]. Further in the study it was shown that the addition of carbon monoxide, for a flame at the same temperature and pressure, caused the number of ion pairs created per carbon atom increased by a significant margin, maintaining the equivalence ratio constant [80]. The addition of carbon dioxide to the premixed flames was compared between C₂H₄/O₂ and C₂H₄/Air mixtures, where at a constant flame temperature, the pure oxygen flame saw a decrease in ion saturation, while the flame in air had an increase in ion saturation [80]. With respect to bromine addition, there was little effect, and any effects observed were deemed to be random [80]. The final additives to the flames, sodium and lead, were added through sprays of, sodium carbonate and lead nitrate, to a stabilized premixed flame, and it was found that the ionization of the metals was incomplete, but occurred, causing an increase in the current density within the flame [80].
Ions are not only formed within the flame, but can exist prior to the flame front or downstream of the flame. In a review of the structure of a methane flame, Fialkov [81] mentioned that, in a study on diffusion and premixed flames without the application of electric fields, while the overall structure upstream of the chemiluminescent zone is approximately neutral, there are a number of ions in this low temperature region, with up to $1.5 \times 10^{10}$ ions/cm$^3$. These upstream ions represent a large part of the total ions in a flame, with the maximum number of positive ions found within fuel rich flame (equivalence ratio of 2 and a pressure of 1 atmosphere) was observed to be $4 \times 10^{10}$ ions/cm$^3$ [81]. For fuel lean flames, one of the major ions found within the upstream zone is CH$_3$O$_2^+$, with the overall number of this ion peaking within the flame’s chemiluminescent zone, along with the ions CH$_3$OH$_2^+$ and HO$_2^+$ [81].

One of the ions that is the focus of investigation within many studies on the application of electric fields within combustion is soot, with approximately 30 % of the total soot production is charged, either negatively or positively [57]. The formation of soot particles and the ions generated through the process has been extensively studied and catalogued, as shown in Calcote et al. [82], which showed the formation of soot, starting with reactions creating propargylium ions (C$_3$H$_3$) that were formed directly or indirectly in the following reactions.

Direct Mechanism [82]

$$\text{CH} + \text{C}_2\text{H}_2 \rightarrow \text{C}_3\text{H}_3^+ + \text{e}^-$$  \hspace{1cm} (14)
Indirect Mechanism [82]

\[
\begin{align*}
CH + O & \rightarrow \text{CHO}^+ + e^- \quad (15) \\
\text{CHO}^+ + CH_2 & \rightarrow CH_3^+ + CO \quad (16) \\
CH_3^+ + C_2H_2 & \rightarrow C_3H_3^+ + H_2 \quad (17) \\
\text{CHO}^+ + H_2O & \rightarrow H_3O^+ + CO \quad (18) \\
H_3O^+ + C_3H_2 & \rightarrow C_3H_3^+ + H_2O \quad (19)
\end{align*}
\]

Investigations into the effects of electric fields into ionization mechanisms are limited. In a numerical study by Yamashita et al. [83], which attempted to predict the ion current within a methane jet flame flowing vertically downwards, in an applied electric field, a number of the ionic reactions were highlighted. The main reactions, 11 in total, covering 9 ionic species, are shown in a table below, along with their respective reaction constants.
Table 10- Adopted Ionic Reactions from Yamashita et al. [4]

<table>
<thead>
<tr>
<th>Index</th>
<th>Reaction formula</th>
<th>$k=A\times T^b\times \exp(-E/RT)$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$A$</td>
</tr>
<tr>
<td>1</td>
<td>CH + O $\Rightarrow$ HCO$^+$ + e$^-$</td>
<td>2.52E+11</td>
</tr>
<tr>
<td>2</td>
<td>HCO$^+$ + H$_2$O $\Rightarrow$ CO + H$_3$O$^+$</td>
<td>1.00E+16</td>
</tr>
<tr>
<td>3</td>
<td>H$_2$O$^+$ + e$^-$ $\Rightarrow$ H$_2$O + H</td>
<td>2.29E+18</td>
</tr>
<tr>
<td>4</td>
<td>CH* + O $\Rightarrow$ HCO$^+$ + e$^-$</td>
<td>5.04E+14</td>
</tr>
<tr>
<td>5</td>
<td>H$_2$O$^+$ + C$_2$H$_2$ $\Rightarrow$ C$_2$H$_3$O$^+$ + H$_2$</td>
<td>8.39E+15</td>
</tr>
<tr>
<td>6</td>
<td>HCO$^+$ + CH$_2$ $\Rightarrow$ CH$_3^+$ + CO</td>
<td>5.62E+14</td>
</tr>
<tr>
<td>7</td>
<td>H$_2$O$^+$ + CH$_2$ $\Rightarrow$ CH$_3^+$ + H$_2$O</td>
<td>6.17E+14</td>
</tr>
<tr>
<td>8</td>
<td>CH$_3^+$ + C$_2$H$_2$ $\Rightarrow$ C$_3$H$_5^+$ + H$_2$</td>
<td>7.24E+14</td>
</tr>
<tr>
<td>9</td>
<td>C$_3$H$_5^+$ + H$_2$O $\Rightarrow$ C$_2$H$_3$O$^+$ + CH$_2$</td>
<td>7.24E+14</td>
</tr>
<tr>
<td>10</td>
<td>CH$_3^+$ + CO$_2$ $\Rightarrow$ C$_2$H$_3$O$^+$ + O</td>
<td>7.24E+14</td>
</tr>
<tr>
<td>11</td>
<td>CH$_3^+$ + e$^-$ $\Rightarrow$ CH$_2$ + H</td>
<td>2.29E+18</td>
</tr>
</tbody>
</table>

It was observed that there was an increase in air entrainment, resulting from the electric field influence, which increased the partial premixing within the flame [83].

The study into premixed flame chemistry, conducted by Pederson and Brown [84], highlighted the need for a more detailed study into the motion of ions and neutral species within flames, citing that most previous studies focused on much smaller aspects of ion mobility or neutral species flow in electric fields. The study also showed that there are severe limitations on the understanding of flame-electric field interactions, on such topics as saturation currents and activation energies [84]. With such a lack of understanding within premixed flame chemistry, a much more detailed study is necessary into partially premixed flames.
The main issue with investigation of ion generation within flames is measurement techniques, where to study effects, such as current density changes, it is necessary to use electrodes, or to take samples using devices such as gas chromatographs. Within the investigation of jet flames, these probes have a pronounced effect on the flow profile, if used within the flame itself. The addition of the bluff body, the probe, would increase turbulent mixing, therefore changing the chemical influences within the flame, which would not provide a true understanding of the ionization mechanisms within jet combustion. Another issue is the limited residence time of unstable species observed in combustion, such as OH or CH, which are observable for a brief window of time. All of these methods would be affected by the high potential electric fields, which could interfere with the equipment, especially in precision equipment, such as a gas chromatograph.

The least intrusive method of observation would be a range of PLIF systems, used over multiple wavelengths, such as those for CH, HCO, H$_3$O, and OH to achieve a more complete view of ion formation in partially premixed jet flames, with and without the application of electric fields. This method also suffers the downside of providing limited quantifiable data on the flame, using a specific cross section of the flame, rather than the entire flame, limited to the resolution of the camera, the accuracy of the positioning of the laser sheet, especially between tests, and if the flame is turbulent, the natural variation between iterations.

For these reasons, future experiments should focus on using simultaneous OH, CH, and HCO PLIF systems on laminar jet flames to provide insight into chemical mechanisms
within the flame, in conjunction with, simulations combining all of the coupled physics, focusing on the ion mobility within the flame, as well as the formation and flow of major ionic species. OH, CH, and HCO systems would provide useful information on the ionic reactions used by the ionic reaction detailed above in Table 10, giving better insight into changes in concentration of these species. By comparing the experimental results to those of simulations, it would be possible to create a more complete understanding of the changes to lifted jet flames.

Other experiments should compare the strength of electrohydrodynamic forces to the natural buoyancy resulting from the temperature difference between the products of combustion and the ambient temperature. These forces have been shown, in previous experiments replicating flames in microgravity, to be comparable in magnitude, yet without complete information, such as the number density of ions within the lifted jet flame, any understanding of the forces resulting from the ionic wind, shown in equation 8, would be imperfect.

Final experiments, using the knowledge gained from the previous studies, should focus on optimization of electrode geometry and electric field application techniques (USRD v. DBD v. SECD) to achieve targeted results. Previous studies, highlighted in the review in Chapter 2, have shown that ultra-short repetitive discharges are most efficient at improving jet flame stabilization [58], but little investigation has gone into other factors such as peak flame temperature or optimization to decrease pollutant emissions.
As observed in the previous study, there is a deviation between the effects found resulting from a positive and negative corona, shown in Figure 58. These deviations could be a result of many influences, such as the impact of temperature on the formation of ions or the location of ions within the flame and the respective polarity of the ions.

Figure 58- Characterization of Flame Stabilization Points for Partially Premixed Flames as a Function of Applied Voltage. Negative Configurations are Shown as the Solid Curve, and Positive Configurations are Shown as the Dashed Curve
Of note is the types of ions formed in the flames, and the respective locations of ions within the flame structure. While it has been noted by Fialkov [81] that as a whole flames are charge neutral, Green and Sugden [85] noted the $\text{H}_2\text{O}^+$ is an important ion within internal hydrocarbon flame chemistry. With the formation of the positive corona downstream of the flame front acting as a repulsive force to these ions, as well as the eventual secondary ionization at the nozzle, forming a negative corona at the nozzle, attracting these ions, would explain the resulting difference to between the two trends. In the case of the negative corona downstream of the electrode, the ionic wind acted against the flow which would have caused the flame approach reattachment, until secondary ionization occurred, gradually negating the effect of the ionic wind. The difference between the two configurations is shown in Figure 59. This theory on the difference between the two trends needs significant testing to prove.
Providing a greater overall picture of the interaction between jet flames and electric fields would still only provide the necessary information for future study, but without this data, the overall understanding of the influences of high potential electric fields on jet flames will not progress, and estimations of the effects, rather than definitive proof, would continue to be used.
8.2 Application of Hugh Potential Electric Fields to Lifted Spray Combustion

As a non-premixed jet or spray expands from a central nozzle into atmospheric air, various mechanisms affect the stabilization point of the flame. The distance between the flame’s stabilization point and the central nozzle is the liftoff height. Throughout this liftoff height, various physical and chemical processes occur. Most theories behind spray flame stabilization are shared with gaseous jet flame stability. The overall structure of a lifted spray flame is similar to the structure of gaseous flames, where the spray flame shows triple flame behavior discussed in section 2.1. The main difference between spray and gaseous jet flame stabilization is that sprays are created from two different phases, the initial liquid phase of the fuel and the final gas phase of the oxidizer, whereas gaseous jet flames are formed by gaseous fuels and oxidizers.

In their investigation Stepowski, Cessou, and Goix [86], using methanol sprayed from a central nozzle, with a coflowing annulus of air to act as an atomizer, observed the flame’s OH radical profile through OH Planar Laser Induced Fluorescence (OH-PLIF). At low stokes number, \( S_t = \frac{\tau U_0}{d_c} < 1 \), where \( \tau \) is the flame time for spray injection, \( U_0 \) is the flow velocity, and \( d_c \) is a characteristic distance, in this case the Sauter mean diameter, the fuel droplet size is small enough to be recirculated by eddies formed through turbulence at the shear layer between the fuel jet and the oxidizer, yet the transfer of droplets between large to smaller scales does not occur within the stabilization zone [86]. The overall vaporization rate for this region, \( \omega_{vap} \), can be expressed as,
\(|\omega_{\text{vap}}| = \frac{3\rho K Y_{\text{fl}}^t}{2d^2}\) (20)

where \(\rho\) is the density, \(K\) is the evaporation constant, \(Y_{\text{fl}}^t\) is a function mass fraction of the fuel droplets, and \(d\) is the Sauter mean diameter [86]. Once the fuel has been vaporized, the oxidizer and fuel must be mixed to a combustible mass fraction for combustion to occur, which occurs between \(\tau_{\text{vap}}\) and \(\tau_{\text{mix}}\), where some fuel is vaporized, but no combustion occurs [86].

In a numerical study by Domingo, Vervisch, and Réveillon [87], using a two-dimensional direct numerical study (2-D DNS) for a single step chemistry, the main stabilization mechanism is characterized as the recirculation of hot products into the incoming reactants, as described by the large eddy dissipation theory, proposed by Broadwell, et al [15]. By recirculating the hot products into the reactants stream, the reactants are preheated, which allows for combustion to occur at a lower flame height.

In comparison to a gaseous jet flame, the flame height and flame of the spray flame are much larger, while the gaseous flame maintains a more consistent flame shape, without creating separation within the flame [87]. For spray flames, partially premixed flame structures have been observed, in the study by Stepowski, et al. [86], with the premixed lean and rich flames at the base and the diffusion flame propagating behind them, but there were diffusion flames tied to either type of premixed flame, either rich or lean, without the presence of the other premixed flame at the flame base [87]. Another consideration was that the spray flame was shown to have near consistent temperature, approximately 1.2 times the
reference temperatures. This increase in temperature is a result of the flamelets that occur at the centerline, at which the oxidizer is at a lower temperature than the oxidizer at the outer edges, whereas the temperature varies over the gaseous jet flame more as a function of the equivalence ratio [87].

Other investigations conducted by Marley and Lyons [88, 89] focused on the effects of nozzle geometry on flame structure, highlighting that the flow is heavily constrained on the sprayer, using an oil spraying nozzle, with ethanol as the fuel. In one study, using OH-PLIF and smoke visualizations, it was observed for flames under coflow that flames at higher liftoff heights showed more entrainment of oxidizers at the flame core, allowing for a flame to create an inner reaction zone [88]. The study further showed that the ambient air was pulled in as it approached the spray becoming entrained within the flow [88]. It is to be noted that for liquid sprays, this entrainment is not as effective as for gaseous fuels.

The overall structure of the flame is governed by the fluid dynamics of a fluid being sprayed into another stagnant fluid causing a shear layer to be formed, and the flame front is established at this shear layer [88]. The other investigation using OH-PLIF showed that the inner reaction zone does not immediately form as the flame lifts off, but rather forms at a specific lifted height [89].

To describe the breakup of the fuel prior to the flame front, Som and Aggarwal investigated the sprays on diesel engines [90]. The overall mechanisms behind the fuel breakdown are split into three separate mechanisms; a) Aerodynamically Induced, b) Turbulence Induced, and c) Cavitation Induced;
Each one of these mechanisms occur at different timescales, but do not occur separately, allowing for varying penetration lengths [90]. The study showed that the KH-ACT model was able to predict the penetration distance for diesel sprays [90]. This investigation showed that the fuel remained at the same temperature after injection, but prior to the flame front [90].

These studies have shown that the flame structure is a function of the fuel vaporization rate, the method of spraying, and the ambient conditions. Fuel vaporization is affected by the fluid dynamics of the upstream region, allowing for the localized mixing of the fuel and oxidizer. While the overall stabilization theories are similar for gaseous and spray flames, the localized physics vary.

By adding the influence of electric fields to spray flames, it is possible to achieve the similar results seen in gaseous flames, in the control of pollutant emissions and flame liftoff. Previous studies have shown the efficacy in improving the fuel atomization from sprays, showing an decrease in droplet diameter, as the potential of the applied electric fields increased, and observed that negative potentials were more effective [91].

Other studies have observed increase in the ion density resulting from the use of electrostatic (electrohydrodynamic) assisted sprays, including an increase in the amount of charged soot within the products of combustion [92]. This could result from the increase in flame temperature, changes in equivalence ratio, or the charging of soot molecules that would have been neutral.
Experiments should focus on the stability of lifted spray flames, similar to those conducted in Chapter 7, showing the overall trends of flame liftoff in the applied electric field, highlighting the transition towards blowout or other observed regimes. This combined with studies similar to those highlighted in the Section 8.1 on the ion mobility and electric field optimization would answer pivotal questions within the spray flame stabilization in electric fields.

8.3 Final Investigations into Optimization of Ionic Air Moving Devices

Based upon previous investigations into the formation of ionic air moving devices using single and multiple corona discharges [93], observing the influence of collector plate area on the efficiency of the resulting flow [47] and comparisons to existing air moving devices [4], future investigations will focus on comparing the effectiveness of applying high voltages to the secondary, flat electrodes, rather than the primary, sharply curved electrodes. This could improve the maximum flow achievable through the ionic wind.

By applying the voltage to the secondary electrode, it could be possible to achieve much higher efficiencies and flow rates prior to reaching secondary ionization, where both electrodes would be producing corona discharges, negating the overall flow. The planned investigation would mirror those in the past, using a flow bench, comprised of a Meriam laminar flow element (50MW20-1F) and a Dwyer 616C-20B differential manometer to measure the dynamic pressure, with a second differential manometer to measure the static
pressure, and recorded through a pair of Tenma 72-1055 benchtop digital multimeters. The air flow is driven by an Ametek 119349 low voltage blower, and the system is powered using a Tenma 72-7245 benchtop power supply. The system setup shown in the figure below.

Figure 60- Flow Bench Setup for Ionic AMD Experiments
8.4 Overall Conclusions

The scientific investigations conducted as part of this dissertation and outlined in the previous sections were meant to improve the understanding of phenomena in engineering devices focusing around ionic and combustible flows. Concerning the dilution of methane jet flames near the liftoff and hysteresis regime, it was found that

1. Utilizing the flammable limit approximation, proposed by Tieszen et al. [19], the flame base measurements appeared outside flammable regions from the model, no matter the level of dilution or Reynolds number

2. The axial to radial position ratio of all flames were found to be from 3.6 to 4.7, where the ratio was found to be insensitive to the amount of dilution, with the flame base stabilizing at a similar downstream position when compared to the liftoff height.

At the far field, as the flame approaches blowout, including the influences of coflowing air, it was observed that

1. Flame stabilization is highly dependent on the mixing of the air and the fuel, than to the increase in jet speed resulting from the addition of dilution, as shown by increased influence of coflowing air on the downstream position when compared to the level of dilution. When compared to the ratio of the axial to radial position of the leading edge, the ratio remained between 5.17 to 7.40, appearing to be insensitive to the coflow or nitrogen jet speed.
2. While maintaining the effective velocity as a constant, to compare jet flames with and without coflow, pure jet flames stabilize at a further upstream position.

In experiments on methane jet flames using hydrogen enrichment, it was observed that

1. The amount of hydrogen needed to reattach a lifted methane flame increases exponentially with the methane jet speed
2. The increase in luminosity of the flame, as it reattaches due to hydrogen enrichment, leads to the assumption that the flame temperature increases
3. When measuring the mass fraction of hydrogen in the reattached flame, the mass fraction increases linearly when compared to the ratio of final jet velocity to the initial jet velocity
4. The overall stability and flammability of the flame increases due to the presence of hydrogen
5. The turbulent fluctuations of the liftoff height decreased due to hydrogen enrichment.

Further experiments comparing the properties of diluted ethylene flames to those of methane found that

1. When comparing the luminosity of ethylene flame to those of methane, ethylene flames, even under dilution were much brighter
2. The stabilization point of ethylene flames was much lower than those of methane jet flames
3. The influence of nitrogen dilution of ethylene flames was more observable in the mid field, rather than near liftoff or approaching blowout
4. Due to the flammability limits of methane, methane jet flames reached blowout conditions at a lower jet velocity or dilution levels than for ethylene flames
5. Nitrogen dilution effects were more prevalent in methane flames than for ethylene flames.

These studies in the influences of diluents and enrichment agents in the fuel stream furthered the understanding of surrogate and naturally occurring fuels.

Another topic of study was the use of electrohydrodynamic devices for heat transfer applications, specifically the creation of Ionic AMD's, which found that

1. Higher efficiencies were possible using longer cylindrical electrodes, as the secondary electrode
2. Higher flow rates were observed for the smaller electrodes, in this setup.

Based upon these results, it would be necessary to optimize the geometry weighing increased flow rates against lower efficiencies.

The final investigation in this dissertation was into the stabilization of propane jet flames in the presence of a direct current, positive potential, corona discharges, creating an electric field that acted on the flames. During the investigation, it was observed that
1. If the positive polarity electrode was placed above the flame front, it was possible to reattach the flame to the nozzle, while maintaining the jet speed at the nozzle as a constant.

2. If the grounded electrode was downstream of the leading edge, the flame would approach reattachment, at voltages below 4000 V, then the leading edge would shift further downstream, eventually reaching blowout.

3. When comparing the three main effects resulting from the presence of the electric field, the ionizing influences were the dominant mechanism affecting the leading edge stabilization.

4. As the flame approached blowout in the negative configuration, with the grounded electrode downstream of the leading edge, the conventional markers of blowout, specifically the shrinking of the trailing diffusion flame was not observed.

Throughout these studies, the focus has been on both basic scientific observations and applied engineering, specifically the use of these studies for industrial or commercial applications. While not part of this dissertation, further study within these fields would provide more useful insight, and is necessary.
REFERENCES


[12] L. Vanquickenborne and A. Van Tiggelen, "The stabilization mechanism of lifted


[31] D. Demare and F. Baillot, "The role of secondary instabilities in the stabilization of a


[53] F. Carleton and F. Weinberg, "Electric field-induced flame convection in the absence of


[64] M. Kono, K. Iinuma and S. Kumagai, "Effect of DC to 10 Mhz Electric Field on Flame


