2008

**Magnetic field effects on diffusion flames**

Diego F. Gonzalez

*Louisiana State University and Agricultural and Mechanical College, diego.gonzalez.j@gmail.com*

Follow this and additional works at: [https://digitalcommons.lsu.edu/gradschool_theses](https://digitalcommons.lsu.edu/gradschool_theses)

Part of the Mechanical Engineering Commons

**Recommended Citation**


[https://digitalcommons.lsu.edu/gradschool_theses/2936](https://digitalcommons.lsu.edu/gradschool_theses/2936)

This Thesis is brought to you for free and open access by the Graduate School at LSU Digital Commons. It has been accepted for inclusion in LSU Master’s Theses by an authorized graduate school editor of LSU Digital Commons. For more information, please contact gradetd@lsu.edu.
MAGNETIC FIELD EFFECTS ON DIFFUSION FLAMES

A Thesis

Submitted to the Graduate Faculty of the Louisiana State University and Agricultural and Mechanical College in partial fulfillment of the requirements for the degree of Master of Science in Mechanical Engineering

in

The Department of Mechanical Engineering

by

Diego F. Gonzalez
B.S., Louisiana State University, 2008
December 2008
Dedicated to my parents

Dario & Ana Maria
ACKNOWLEDGEMENTS

I would like to first acknowledge my advisor, Dr. Tryfon T. Charalampopoulos, for his assistance and guidance during this project and my academic career. Dr. Charalampopoulos served as my mentor throughout my time as an undergraduate and graduate student at Louisiana State University and he was an integral part of my development as an engineer both in and out of the classroom. This project would not have been possible without his innovative ideas and any future graduate student should feel extremely proud to be under his supervision.

I extend my sincere thanks to my examining committee, Dr. Ernest Mendrela and Dr. Muhammad Wahab, for taking their time to evaluate this thesis. Moreover, Dr. Mendrela’s expertise in magnetism provided a significant help during the development of this project and his aid in using Finite Element Method Magnetics is greatly appreciated. Also, the assistance of James Dupree and Morgan Dias during the experimental process of this project was extremely valuable.

I would also like to express my deep gratitude towards my parents, Dario Gonzalez and Ana Maria de Gonzalez, for their efforts in giving me the high-quality education that I received at LSU. I would not have been able to become the engineer that I am today without their unconditional love and support. Finally, I would like to acknowledge the love of my life and my inspiration, Emily David, for motivating me to be a better person and encouraging me to pursue a higher-level education.
# TABLE OF CONTENTS

ACKNOWLEDGEMENTS........................................................................................................ iii

LIST OF TABLES.................................................................................................................. vi

LIST OF FIGURES............................................................................................................... vii

ABSTRACT............................................................................................................................ x

CHAPTER 1- INTRODUCTION............................................................................................... 1
  1.1 Proposed Study and Methodology.............................................................................. 2
  1.2 Thesis Organization................................................................................................. 3

CHAPTER 2- BACKGROUND INFORMATION.................................................................... 5
  2.1 Magnetism Terminology......................................................................................... 5
  2.2 Magnetism Types.................................................................................................... 6
  2.3 Magnetic Materials................................................................................................. 8
  2.4 Laminar Diffusion Flames...................................................................................... 9
  2.5 Soot Formation........................................................................................................ 12
  2.6 Magnetic Effects on Gases..................................................................................... 14

CHAPTER 3- LITERATURE SURVEY................................................................................. 16

CHAPTER 4- HOMOGENEOUS MAGNETIC FIELDS......................................................... 22
  4.1 Equilibrium Mole Fraction and Homogeneous Magnetic Fields......................... 22
  4.2 Nomenclature.......................................................................................................... 23
  4.3 Formulation of Equations....................................................................................... 24
  4.4 Results and Discussion............................................................................................ 26

CHAPTER 5- GRADIENT MAGNETIC FIELDS.................................................................. 30
  5.1 Finite Element Magnetics: Numerical Study......................................................... 30
  5.2 Experimental Data Analysis.................................................................................... 37
    5.2.1 Oxygen Mole Fraction Estimation for Decreasing Gradient Magnetic Fields... 38
    5.2.2 Soot Agglomeration Reduction....................................................................... 41

CHAPTER 6- OSCILLATING MAGNETIC FIELDS: NUMERICAL STUDY..................... 47
  6.1 Experimental Setup for Time Varying Magnetic Field........................................... 47
  6.2 Magnetic Piston-Cylinder System.......................................................................... 51

CHAPTER 7- OSCILLATING MAGNETIC FIELDS EXPERIMENT.................................. 55
  7.1 Methodology and Experimental Setup.................................................................... 57
  7.2 Results and Discussion............................................................................................ 59
  7.3 Conclusions.............................................................................................................. 64
CHAPTER 8- COMBUSTION OF MAGNETIZED GAS ........................................ 66
  8.1 Methodology and Experimental Setup ........................................... 66
  8.2 Results and Discussion .............................................................. 69
  8.3 Conclusions ............................................................................. 74

CHAPTER 9- SUMMARY OF RESULTS AND RECOMMENDATIONS ............ 76
  9.1 Summary of Results and Discussion ............................................. 76
  9.2 Recommendations for Future Work ............................................. 79

REFERENCES .................................................................................... 80

APPENDIX A- CLASSICAL THEORY OF DIAMAGNETIC AND
PARAMAGNETIC MATERIALS ............................................................. 83

APPENDIX B- DETAILED DERIVATION OF EQUATIONS AND SOLUTION OF
SYSTEM FOR HOMOGENEOUS MAGNETIC FIELD EFFECTS ON
COMBUSTION .................................................................................. 85

APPENDIX C- FLAME HEIGHT AND TEMPERATURE DATA OBTAINED BY
SWAMINATHAN IN REFERENCE [5] ..................................................... 90

APPENDIX D- IMAGE ANALYSIS MATLAB CODE .............................. 93

APPENDIX E- FOURIER TRANSFORM MATLAB CODE ....................... 95

APPENDIX F- FINITE ELEMENT METHOD MAGNETICS OVERVIEW [34] .... 96

VITA .................................................................................................. 97
LIST OF TABLES

4.1: Percent difference between estimates provided by GASEQ and Excel……………… 26

5.1: Curve-fit results for each magnetic type and correlation coefficient of equations…….. 35

5.2: Maximum magnetic force on oxygen for different configurations………………… 36

5.3: Oxygen mole fraction for decreasing magnetic field gradient versus case of no applied magnetic field at different velocities…………………………………………………….. 39

5.4: Soot agglomerate properties for no magnetic field and applied magnetic field…….. 46

7.1: Statistical analysis of flame length data at different magnet rotation speeds………… 63

7.2: Comparison between magnet rotating frequency (blue) and magnetic field frequency (green) to the fundamental frequencies of the FFT spectrum…………………………………………………….. 64

A.1: Volumetric Magnetic Susceptibility values for different species [16]……………… 88

C.1: Measured flame height data for different propane speeds [5]………………………… 90

C.2: Axial temperature measurements for a flow speed of 0.9 cm./sec [5]………………… 91

C.3: Axial temperature measurements for a flow speed of 2.6 cm./sec [5]………………… 92
LIST OF FIGURES

2.1: Magnetic gradients formed by attracting magnet geometries and effects on oxygen........  7

2.2: Relative strength and cost of different magnetic materials [27]..............................................  9

2.3: Axial velocity profile, mass fraction of fuel and oxygen, and mixing layer of a diffusion flame [20]......................................................................................................................... 11

2.4: Regions of soot formation in a diffusion flame................................................................. 13

4.1: Mole fractions of product species under a homogeneous magnetic field (B=0.5T)........  27

5.1: Experimental electromagnet configuration............................................................................. 31

5.2: Modified solenoid to form a gradient field (left), homogeneous field of a solenoid (right).............................................................................................................................. 31

5.3: Simulation results of magnetic flux around circular permanent magnets......................... 32

5.4: Simulation results of magnetic flux around experimental electromagnet......................... 33

5.5: Validation of numerical results by comparison to experimental measurements of magnetic flux density along the vertical central axis of the electromagnet........................ 33

5.6: Magnetic flux density for electromagnets along the central axis......................................... 34

5.7: Magnetic flux density for circular Neodymium magnets along the central axis............... 34

5.8: Magnetic flux density for rectangular Neodymium magnets along the central axis......... 34

5.9: Magnetic flux density at the center of the gradient solenoid along the radial direction...  35

5.10: Magnetic force on oxygen for different magnetic configurations...................................... 36

5.11: Comparison of forces- Ratio of buoyancy to momentum forces acting along a diffusion flame, Re=15 [5]................................................................................................................. 40

5.12: Comparison of forces- Ratio of magnetic to buoyancy forces acting along a diffusion flame, Re=15 [5]............................................................................................................. 40

5.13: Soot images under no applied magnetic field [5]............................................................ 41

5.14: Soot images under decreasing gradient magnetic field [5]............................................ 42

5.15: Surface Area Intensity plot for no applied magnetic field............................................. 42
5.16: Surface Area Intensity plot for decreasing gradient magnetic field................................. 43
5.17: Size distribution for no applied magnetic field............................................................... 44
5.18: Size distribution for decreasing gradient magnetic field.............................................. 44
5.19: Binary image conversion of soot particle agglomeration.............................................. 45
5.20: Color indexed images of continuous objects in soot agglomerates.............................. 46
6.1: Magnetic flux lines for rotating spheres at different alignment angles with respect to the horizontal: (a) 0 degrees, (b) 45 degrees, (c) 90 degrees, and (d) 135 degrees......................... 48
6.2: Magnetic flux density along centerline of rotating sphere at different angles of rotation... 50
6.3: Magnetic flux density at center point as a function of angle of rotation.......................... 51
6.4: Internal combustion engine cycle and representation of piston-cylinder system [33]..... 52
6.5: Magnetic flux density at center point 1 mm below the head as a function of crank angle of IC engine (left) and flux lines in flat-type piston and head system (right).................... 53
6.6: Magnetic flux density at center point 1 mm below the head as a function of crank angle of IC engine (left) and flux lines in dish-type piston and head system (right)............. 53
7.1: Expected magnetic force field variations as a function of sphere rotation for magnetic alignments of (a) 0 degrees, (b) 45 degrees, (c) 90 degrees, and (d) 135 degrees............. 55
7.2: Magnetic spheres mounted on aluminum brackets (top) and spherical rotation of spheres during experimental run (bottom)................................................................. 58
7.3: Magnetic field strength of static Neodymium grade 40 spheres with a 1.5” air-gap.......... 59
7.4: Standardized length change ($\Delta L$) of flame as a function of time and FFT frequency spectrum for function for a magnet rotation speed of 160 RPMs........................................... 60
7.5: Standardized length change ($\Delta L$) of flame as a function of time and FFT frequency spectrum for function for a magnet rotation speed of 220 RPMs........................................... 61
7.6: Standardized length change ($\Delta L$) of flame as a function of time and FFT frequency spectrum for function for a magnet rotation speed of 335 RPMs........................................... 61
7.7: Standardized length change ($\Delta L$) of flame as a function of time and FFT frequency spectrum for function for a magnet rotation speed of 460 RPMs........................................... 62
7.8: Standardized length change (ΔL) of flame as a function of time and FFT frequency spectrum for function for a magnet rotation speed of 620 RPMs………………………………………………. 62

8.1: Experimental setup for magnetic fields on fuel line and flame……………………………... 68

8.2: Diffusion flame images for jet exit velocity of 2.5 cm/sec for cases: (a) No magnetic field, (b) Magnetic field on propane fuel line, (c) Spherical magnetic field on diffusion flame, and (d) Both magnetic field on fuel line and diffusion flame ………………………………………….. 70

8.3: Enhanced flame images for jet exit velocity of 2.5 cm/sec for cases: (a) No magnetic field, (b) Magnetic field on propane fuel line, (c) Spherical magnetic field on diffusion flame, and (d) Both magnetic fields on fuel line and diffusion flame…………………………………...……. 71

8.4: Axial flame temperature comparison between no applied magnetic field and pre-combustion magnetic field for average jet exit speed of 1.3 cm./sec…………………………………….. 72

8.5: Axial flame temperature comparison between no applied magnetic field and pre-combustion magnetic field for average jet exit speed of 2.0 cm./sec……………………………………….. 73

8.6: Axial flame temperature comparison between no applied magnetic field and pre-combustion magnetic field for average jet exit speed of 2.5 cm./sec…………………………………….. 73

A.1: (a) Loop model for electron orbiting an atom under a non-homogeneous magnetic field. (b) Charge –e moves counterclockwise and current moves clockwise. (c) Magnetic Forces on the loop. (d) Charge –e moves clockwise and current moves counterclockwise. (e) Magnetic forces on loop [28]……………………………………………………………………………. 83
ABSTRACT

Magnetic field effects in combustion is an area of study that has previously been overlooked. The influence of magnetic fields on flames has only recently been explored and is of interest both from a scientific and a practical standpoint. This study provides theoretical, numerical and experimental evidence that combustion can be affected with the use of suitable magnetic fields. This thesis focuses on four different types of magnetic fields: homogeneous, gradient, oscillating and pre-combustion.

For the homogeneous field case, the Gibbs Free Energy method was used to determine the mole fraction of product species. It was found that homogeneous fields have negligible effects on combustion characteristics. Different magnetic gradient configurations were then tested using Finite Element Methods to obtain the force field profile on paramagnetic oxygen. Numerical simulations showed that high magnetic field gradients at high magnetic strengths, such as those exerted by spherical permanent magnets, are most suitable to enhance oxygen entrainment into a reaction zone. Also, from experimental data, it was shown that the concentration of oxygen around a diffusion flame has a higher increase if the momentum of the flame jet exit is low. Furthermore, a digital imagery study quantitatively demonstrated that soot particle agglomeration is decreased with the use of gradient magnetic fields.

Experimentations with oscillating magnetic fields confirmed that an alternating magnetic field produces a varying force field around a diffusion flame, which enhances mixing between fuel and oxidizer. Finally, pre-combustion magnetic fields increased the temperature on the lower portion of a diffusion flame suggesting possible dissociation of the fuel molecules resulting in more complete combustion.
CHAPTER 1- INTRODUCTION

The recently increasing worldwide focus on emission reduction caused by the combustion of fossil fuels has veered researchers into the investigation and development of alternative fuels. This intense focus on alternative fuel research has limited the scope of investigators and could arguably have turned the face of science away from more viable and short-term solutions. Widespread recommendations to reduce emissions and slow global warming involve small changes in the daily lifestyle of society such as switching to efficient light bulbs, adjusting household thermostats and taking shorter showers. Transferring the idea of “baby-steps” towards a better environment and applying it to the improvement of combustion of fossil fuels could potentially generate groundbreaking advancements in the reduction of emissions. A possible answer to this calling could be the use of magnetic fields in combustion processes. Although little research has been conducted in this area, results have demonstrated improvements in emission reduction and combustion efficiency [1-6, 9, 11-12].

Since the time of Faraday, there have been few studies specifically focused on the effects of magnetic fields on flames. Faraday, in his original investigation, realized that the application of certain magnetic field configurations to a burning candle resulted in an equatorial elongation of the combustion zone [7]. More recently, researchers have confirmed what Faraday observed over a century earlier by demonstrating that flames bend to escape magnetic fields of higher intensities. The present study is an attempt to demonstrate the effects of different types of magnetic fields on diffusion flames, thus finding an optimum magnetic configuration that can positively affect combustion characteristics. Before undertaking an extensive discussion on the phenomena that mediates the magnetic effects on combustion, an overview of the proposed study will be given as well as background information on the subject.
1.1 Proposed Study and Methodology

As it was previously stated, the main focus of this study is to investigate how different types of magnetic fields affect combustion. Homogeneous, gradient and oscillating magnetic fields will be analyzed in order to determine a configuration that best promotes the mixing of fuel and oxidizer in a diffusion flame. Additionally, an investigation of effects of magnetic fields on gas flows prior to combustion will be performed. The study will consist of theoretical, numerical and experimental research.

To further understand the effects of homogeneous fields, a theoretical thermodynamic analysis will be performed on a reacting system. This will allow the determination of the product mole fractions of different species under the application of homogeneous magnetic fields. This analysis is aimed towards confirming that homogeneous magnetic fields do no affect combustion characteristics [4, 5, 8-9].

The analysis of gradient magnetic fields involves numerical analysis of the fields produced by different magnet geometries and using these results to find a geometry that can produce the best oxygen attraction towards a combustion reaction zone. Also, data from previous experiments are used to quantify the amount of oxygen entrainment in a diffusion flame. Soot imagery will then be digitally enhanced and segmented to determine the amount of soot reduction under the application of gradient fields.

Experimental investigations will be performed on the effects of oscillating magnetic fields on a propane diffusion flame. The oscillating fields will be produced by mechanically rotating permanent magnets. Flame imagery and temperature measurements will be obtained to determine the effects of these fields. Finally, magnetic fields will be applied to the propane gas prior to combustion and the results will be compared to the case of no applied fields.
1.2 Thesis Organization

This thesis is organized into nine different chapters, each covering different topics on the subject at hand. Chapter 2 provides background information on magnetism and diffusion flames including introductions to magnetic materials and magnetic gas dynamics.

Chapter 3 is a detailed literature survey that reviews previous studies conducted on the effects of magnetism in combustion. Several short comes in the studies are discussed and constitute the impetus for the present study.

In Chapter 4, the effects of homogeneous magnetic fields in combustion processes are theoretically derived. Using a thermodynamic approach, the mole fractions of product species are solved numerically for the chemical reaction occurring at different temperatures.

After discussing the effects of homogeneous fields, the focus shifts towards gradient magnetic fields. Chapter 5 begins by analyzing different magnetic configurations using finite element methods to determine the type of magnetic field that could best promote combustion. Previous experimental data is then analyzed to better understand the underlying phenomena of gradient magnetic fields on diffusion flames.

In Chapter 6, finite element methods are again used to find possible magnetic fields that could vary sinusoidaly at prescribed frequencies. This investigation is then used to design an experimental setup for oscillating fields around a propane diffusion flame. The methodology, experimental setup and a discussion of results of this experiment are provided in Chapter 7.

In Chapter 8, experiments are performed on diffusion flames in which the fuel is magnetized prior to combustion. This includes the application of homogeneous magnetic fields in a propane gas line and how combustion characteristics can be altered in this process. The
experiment also examines how the application of two simultaneous magnetic fields can affect a diffusion flame.

Finally, Chapter 9 summarizes the results from all the different studies and provides a discussion of their importance. Also, recommendations of future work are addressed and areas of main focus are mentioned.
CHAPTER 2- BACKGROUND INFORMATION

The aim of this chapter is to provide the reader with information on magnetism fundamentals including commonly used terms, magnetic relations and magnetic materials. Also, a detailed description of the physics of a diffusion flame is included to better understand the phenomena behind the effects of magnetism on diffusion flames.

2.1 Magnetism Terminology

The following definitions of terms are included to aid the reader in understanding the terminology used throughout this thesis. The definitions were obtained from a variety of sources [5, 10, 14, 16-17].

**Air Gap**: A low permeability gap in the flux path of a magnetic circuit.

**Curie Temperature**: The temperature at which the parallel alignment of elementary magnetic moments completely disappears and the material is no longer able to hold magnetization.

**Magnetic Gradient**: Refers to the spatial change of magnetic induction at any point within a magnetic field.

**Magnetic Induction, \( B \)**: The magnetic flux per unit area of a section normal to the direction of flux. Magnetic induction is also referred to as magnetic flux density. Usually measured in Tesla (SI units), which is equivalent to Newtons per Ampere meter or volt seconds per square meter.

**Magnetic Force, \( H \)**: The magnetic force per unit length at any point in a magnetic circuit. Also referred to as the magnetic field strength. Measured in Oersteds or in Amperes per meter.

**Magnetic Susceptibility, \( \chi \)**: The receptiveness of a material to react to an applied magnetic field. It is a unitless quantity when referred to as the volume magnetic susceptibility, but it can be alternatively represented as a mass magnetic susceptibility measured in cubic meters per
kilogram (SI) or molar magnetic susceptibility measured in cubic meters per mole (SI). This thesis will use the volume magnetic susceptibility in all pertaining calculations.

**Magnetization,** $M$: quantity of magnetic dipole moments per unit volume measured in Amperes per meter.

**Orientation Direction:** The direction in which a magnet should be magnetized in order to achieve optimum magnetic properties.

**Permeability of free space,** $\mu_0$: Magnetic constant defined with a value of $4\pi \times 10^{-7}$ Henrys per meter.

Mathematically, some of the above terms can be related to each other. The magnetic induction is related to the magnetic force as:

$$B = \mu_0 (H + M) \quad (2.1)$$

where the volumetric magnetization, $M$, is defined by the relationship,

$$M = \chi_v H \quad (2.2)$$

### 2.2 Magnetism Types

There are three different types of magnetism: diamagnetism, paramagnetism, and ferromagnetism. The first two types are of special interest to gas dynamics and will be discussed due to their importance in this study. Diamagnetism can be found in almost all common materials but it is so weak that it is sometimes negligible if the material also exhibits magnetism of either of the other two types [5,11,17]. In this type of magnetism, a weak magnetic dipole is produced when the atom is placed in an external magnetic field. This gives the material a weak net magnetic field that disappears as soon as the field is removed. If the field is non-uniform, the
diamagnetic material is repelled from a region of greater magnetic field towards a region of lesser magnetic field [5, 28].

In paramagnetic materials, the magnetic dipole moments of the material line up with the external magnetic field to produce a net magnetic dipole moment. If no magnetic field is present, these atomic dipole moments are randomly oriented and the net magnetic dipole moment is zero [28]. When placed in a non-uniform field, the opposite of what is seen in diamagnetic materials happens: paramagnetic materials are attracted toward a region of greater magnetic from a region of lesser field [3-5, 28]. The physical explanation of diamagnetism and paramagnetism is discussed in detail in Appendix A.

The strength of the magnetic dipole moments is defined by the magnetic susceptibility of a material. Paramagnetic materials have positive magnetic susceptibility while diamagnetic materials have a negative susceptibility. Carbon dioxide, nitrogen and most products of combustion are diamagnetic while oxygen is paramagnetic in nature [3-5]. This means that by applying an external inhomogeneous magnetic field, oxygen can be attracted towards one area while the combustion products are repelled from this area. However, at relatively low magnetic field strengths, the enhancement in combustion is accredited to the oxygen’s paramagnetic characteristics since diamagnetic materials only form a weak magnetic dipole moment [11].

Figure 2.1: Magnetic gradients formed by attracting magnet geometries and effects on oxygen
Figure 2.1 shows how different magnetic field configurations affect the convective flow of oxygen to enhance combustion characteristics. The effects depend on the direction of flow of the fuel. In the case depicted in Figure 2.1, the fuel flows in a vertically upward direction, which means that for the vertically decreasing field, the oxygen flow will be forced downward opposing the direction of fuel flow. On the other hand, the vertically increasing field will cause oxygen to flow upward along with the gas flow thus, repelling it from the reaction zone. This implies that during combustion, the oxygen concentration around the reaction zone will be increased with the use of vertically decreasing gradients thus allowing more fuel molecules to react with oxygen molecules, leading to more complete combustion.

2.3 Magnetic Materials

Magnetic fields can be created with the use of electromagnets or permanent magnetic materials. Electromagnets can be formed by passing current through a conducting wire. To concentrate the magnetic field in an area, the wire can be wound into a coil called a solenoid. Introducing a ferromagnetic core, such as soft iron, inside the solenoid can produce even stronger magnetic fields. The magnetic domains within the core are aligned when exposed to the magnetic field thus, increasing the strength of the electromagnet. The magnetic field created is linearly proportional to the current passed as well as to the windings in the coil. The strength of the field can be increased until the core reaches a saturation point where all the magnetic domains become aligned and any increase in current will produce little increase in magnetic strength [28, 32].

Permanent magnets are readily available in different alloys, each designed for different objectives. There are four types of permanent magnet materials: Flexible, Ceramic, Alnico, and
Rare Earth magnets [27]. Flexible magnets are very low cost and commonly used since they can be magnetized in multiple directions. Ceramic magnets are the most widely used magnets since they provide a relatively high strength at a low cost. Alnico magnets are used for high temperature applications and can withstand up 1,000 degrees Fahrenheit. These are relatively costly and require careful handling to avoid demagnetization. Rare Earth magnets are of two kinds, Neodymium and Samarium Cobalt. Neodymium magnets are the strongest class of magnets available. They are relatively costly and should not be used at temperatures higher than 300 degrees Fahrenheit. Samarium Cobalt magnets are the most expensive magnets due to their high strength and the fact that they can maintain their properties up to temperatures of 600 degrees Fahrenheit. Figure 2.2 summarizes the relative strength and cost of the different magnetic materials.

![Figure 2.2: Relative strength and cost of different magnetic materials [27]](image)

**2.4 Laminar Diffusion Flames**

A diffusion flame may be defined as any flame in which the fuel and oxidizer are originally separated or non-premixed. Fuels may be in solid, liquid or gaseous states. Examples
of these may include lighted candles, fuel droplets burning in oxygen, and solid fuels burning in a ramjet engine. In a technical sense, diffusion flames can be described as non-premixed, nearly isobaric flames in which most of the reaction occurs in a narrow zone that can be approximated as a surface [17]. Diffusion flames can either be laminar or turbulent; in this thesis, focus will only be given to laminar flames. Specifically, this study will deal with unconstrained configurations or free jets, issued from a circular burner port into a quiescent environment.

The fuel and oxygen in a diffusion flame mix to create a combustible mixture, which once ignited, forms a flame at the border between the fuel and oxygen zones. Combustion products created by the flame spread to both sides and fuel and oxygen have to diffuse against those streams in order to mix and react. Diffusion in a flame follows Fick’s law [11, 20].

Flames can be classified into two categories, overventilated and underventilated. If more air is available than what is required for complete combustion, then an overventilated flame is formed. If the oxidizer is less than the stoichiometric amount, the flame extends further outward due to diffusion from fuel to oxygen and the flame is referred to as underventilated. In this case, all the oxygen is consumed and complete combustion is not obtained. Underventilated flames mostly occur in constrained environments [17].

The physical description of a diffusion flame allows for better understanding of the basic flow and chemical process. If it is assumed that the velocity profile is uniform at the tube exit, close to this area there is a region called the potential core where the effects of viscous shear and diffusion have not been felt [11]. Considering momentum, the velocity profiles are almost flat within the potential core. The maximum velocity of the flow is unchanged until the flow reaches a point called the potential core length, which is the point where the viscous effects have reached
the entire flow regime. Inside the potential core, there are no significant gradients or transfer of heat or mass [11, 20].

As the jet mixes with surrounding quiescent air, it transfers momentum, which causes more air to be entrained into the jet. This results in a decrease in jet velocity or momentum for positions higher than the potential core length. The velocity profile within a flame appears as shown in Figure 2.3. The mixing layer thickness \( y_m \) can be plotted for values where \( V_x = 0.01V_{x,max} \) where \( x \) refers to the vertical position along the axis of the flame [20]. The mixing layer is a function of \( x \), and starts at the edge of the port. If the jet is in quiescent air, the velocity is zero outside the mixing layer [17, 20].

![Figure 2.3: Axial velocity profile, mass fraction of fuel and oxygen, and mixing layer of a diffusion flame [20]](image)

When gaseous fuel passes through the jet port, mixing between air and fuel occurs as air is entrained. This mixture causes fuel and oxygen mass fractions to change as a function of axial and radial position within the flame. Due to diffusion and mixing, the fuel is dispersed radially and the flame boundary moves outward. Since fuel is consumed axially, the concentration of
fuel decreases along the axis and the flame shape moves radially inward until converging at the center of the axis. The total length of the flame is referred to as the flame height and is of important interest in combustion research. Early theoretical descriptions of flame shapes started with Burke and Schumann [21], where several assumptions and simplifications were made to obtain important information of the structure of a diffusion flame. Later, Roper published a new approach [22] that relaxed the requirement of constant velocity and provided estimates of flame lengths for both circular and non-circular nozzles. Roper’s correlations will be explained further in Chapter 5 and will be used to estimate the amount of oxygen entrainment in a diffusion flame under a gradient magnetic field.

Buoyant forces on a flame become important at upper regions of a flame where the temperatures are highest. Buoyancy causes the flow to accelerate and this narrows the flame since conservation of mass requires that the streamlines come close together as the velocity increases. The narrowing of the flame increases the fuel concentration gradients and enhances diffusion as stated by Fick’s law [11]. Effective diffusion of a flame from the fuel outward and oxidizer inward is important to ensure a proper amount of ventilation in the process.

2.5 Soot Formation

Laminar diffusion flames are commonly used in fundamental research and have been used to better understand the formation and development of soot [18-19]. Soot commonly occurs in hydrocarbon flames and is what gives the flame a yellow-orange appearance. Soot mainly consists of carbon and small amounts of hydrogen, typically in the ratio 9:1 by mass. In addition, polycyclic aromatic hydrocarbons (PAHs) are also trapped in the soot aggregates. It appears as finely divided carbon particles and it is formed at temperatures greater than 1000 K
[20]. With sufficient amount of time, soot is formed in the fuel side of the reaction zone and is consumed when it flows into an oxidizing region. Depending on the fuel type and residence time, not all the soot is oxidized in the oxidizing region and escapes the flame as smoke. The different regions of soot formation in a diffusion flame can be seen in Figure 2.4.

Figure 2.4: Regions of soot formation in a diffusion flame

Soot can be commonly observed in the exhaust of diesel trucks appearing as smoke. These solid particles are known as carcinogens and are produced by the cracking of hydrocarbons [20]. In the soot development process, PAHs become important intermediates between the original fuel molecule and the soot particles. In the first step of soot formation, ring structures are formed and begin to grow due to reactions with acetylene. The second step of the process involves particle inception, or the formation of small particles by chemical means and coagulation. As the particles travel through the flame, they are exposed to an array of broken down molecules and radicals and thus, the particles experience growth and agglomeration. These agglomerates are formed primarily from spherical particles measuring 10 to 40 nm [23]. At the flame tip, the particles reach the oxidizing region. If the particles are oxidized completely, the flame is referred to as non-sooting. On the other hand, if the particles are not completely oxidized, sooting conditions are created [11]. This is the reason why pre-mixed
flames are less likely to form soot due to the oxygen availability. Since most practical flame systems are of diffusion type, it is critical to reduce soot emissions in such flames to control toxic carcinogens in the atmosphere and minimize global warming effects.

2.6 Magnetic Effects on Gases

As it was discussed in Section 2.2, gases are either diamagnetic or paramagnetic in nature. Due to the magnetic susceptibility of gases, a magnetic body force can be applied to these with the use of gradient magnetic fields. The magnitude and direction of the magnetic body force follows Kelvin’s equation [4, 5, 24-25]:

$$ F_{mag} = \frac{1}{2} \frac{\chi_i}{\mu_o} \nabla \vec{B}^2 $$

(2.3)

where the direction is dependent on the sign of the magnetic susceptibility of gas species $i$ ($\chi$) as well as the direction of the gradient magnetic flux density. The force acts on a volumetric basis and can be simplified to a one-dimensional case yielding,

$$ F_{mag} = \frac{1}{2} \frac{\chi_i}{\mu_o} \frac{d\vec{B}}{dz} $$

(2.4)

where $z$ refers to the direction in which the magnetic field changes. In the case of a gas within another medium, the net force acting on the system is proportional to the difference in magnetic susceptibilities of the participating materials:

$$ F_{mag} = \frac{1}{2} \frac{\chi_i - \chi_m}{\mu_o} \nabla \vec{B}^2 $$

(2.5)

For diamagnetic species, the magnetic susceptibility has an order of magnitude of $-10^{-9}$ while the susceptibility for paramagnetic species has an order of magnitude of $+10^6$ [5, 16, 26]. Being that the order of magnitude of paramagnetic materials is significantly larger than that of
diamagnetic ones, the magnetic force acting on a diffusion flame is mainly attributed to the effects on paramagnetic oxygen.

For a typical diffusion flame used in this study and with magnetic field of flux density of 0.4 Tesla, the magnetic forces acting on the system may vary in the range of 0-4 N/m$^3$. More specifics on this aspect are provided in reference [5] and in Chapter 5 of this thesis.
CHAPTER 3- LITERATURE SURVEY

Extensive investigations on the effects of magnetic fields on combustion have been conducted since 1985. Most of these studies have taken place in Japan and have mainly focused on diffusion flames, pre-mixed flames and catalysis. Ueno and Esaki [1] pioneered these studies by observing temperature changes and combustion speeds of methanol catalysis under a magnetic field. They observed that the combustion temperature varied heavily in frequency and amplitude when magnetic fields exceeded strengths of 0.9 T. This suggested that magnetic fields indeed altered combustion but the authors had no explanation for the phenomena. That same year, the authors continued their studies and published another report. In that paper [2], three experiments were conducted to analyze the effects of magnetic fields on the combustion of gasoline and alcohol. Experiment (a) consisted of low gradient magnetic fields from 0.1 T to 1.0 T. Experiment (b) involved exposing evaporating gas before combustion to different magnetic field types. Experiment (c) entailed a homogeneous magnetic field exposed to the combustion zone. In the results, there was an undulant phenomenon in the curve of combustion velocity versus magnetic field. Under the same type of gradient, different magnetic field strengths sometimes made combustion velocity faster and sometimes slower. The magnetic field effects were explained by a principle of superposition of pure fuels, which have their own resonance in magnetic fields.

In 1987, Ueno and Kosuke [3] began experimenting with diffusion flames. As Faraday had observed, the flames bent away from magnetic fields of decreasing gradients. After this was observed, the authors proceeded to test gas flows without a diffusion flame. All gases analyzed were blocked or modified by the gradient magnetic fields. Oxygen concentration was continuously measured and was increased in all of the different gas flows. They concluded that
oxygen is aligned so as to form a “wall of oxygen”. They tested different velocity flows to test
the strength of the “wall of oxygen”. This air curtain extended between magnetic poles in areas
were both magnetic fields and gradients were high enough. It was observed by the authors that
the wall was strong enough to press back on flames and gas flows. They attributed these results
to the paramagnetic nature of oxygen and to the forces that were produced on air by the
introduction of a magnetic field. Later studies contradicted the “wall of oxygen” theory by
instead proving the presence of an oxygen convective flow through the gradient magnetic field
[4-6, 11].

Wakayama [4] conducted magnetic experiments on methane diffusion flames. The
author observed the effects of inhomogeneous magnetic fields by both measuring temperature
differences and observing variations in flame shape, color and size. Under a homogeneous
magnetic field, no change was observed. On the other hand, a decreasing magnetic gradient in
the direction of the flow, the flame became shorter, sharper and more brilliant. The velocity of
air into the flame front under decreasing magnetic field was calculated using energy conservation
and was about three orders larger than the rate of diffusion. Several researchers confirmed this
results in similar experiments [5, 8, 9]. Ruan [6] used digital particle velocimetry (DIPV)
techniques to measure the velocity distribution of gas flows around diffusion flames under
magnetic fields. The author quantitatively verified the existence of flows of oxygen induced by
gradient magnetic fields. All of these experiments concluded that the flow of oxygen promotes
combustion in diffusion flames.

Swaminathan [5] determined that low Reynolds number flames could be affected by
relatively low strength gradient magnetic fields (~0.27 T). In her study, the applied magnetic
forces are compared to the momentum forces at different Reynolds number and it is determined
that magnetic forces are dominant only for low Reynolds number flows, typically in the range of 10-100. Structure and shape of flames were experimentally analyzed and perceivable changes were easily observed in low-velocity flames. This study expanded results by other researchers by observing that the flames became shorter and more brilliant under decreasing magnetic field strength and the opposite occurred for increasing magnetic fields in the direction of the flow. In addition, thermophoretic soot sampling results qualitatively demonstrated the decrease of soot formation and agglomeration with the application of decreasing gradient magnetic fields.

The idea of induced convection flows attracted the space industry since diffusion flames cannot be maintained in microgravity environments. Fujita et al [9] observed the effects on combustion using various magnetic field intensities in the Japan Microgravity Center. At field strengths higher then 85.9 mT, the flame was maintained but it was extinguished at strengths below this point. This indicated that there is a critical field strength above which steady flames can be maintained. Altering the equation for the Grashof number, this publication introduced a non-dimensional magnetic Grashof ($Gr_m$) number that related the magnetic convective forces to the viscous forces. The authors concluded that a flame under a microgravity environment can be sustained with $Gr_m$ larger that $10^2 - 10^3$.

The most recent studies have focused on numerical simulations to investigate the effects on combustion due to magnetic fields. In 2000, Baker [10] performed a thermodynamic analysis of magnetic combustion by modifying the Gibbs free energy equation to include a magnetic field term. A methane flame in air was modeled under a uniform magnetic field. Plots were shown for equilibrium mole fractions as a function of temperature and magnetic induction for all product species. Results showed that within certain temperature ranges, a homogeneous magnetic field decreases the mole fraction of major product species and increases the mole
fraction of minor product species. At high temperatures, the application of a magnetic field greatly decreased the equilibrium composition of NO. Even though this study suggests that NO emissions can be reduced, this happens at temperatures that are higher than most practical engineering applications.

Yamada et al [11] performed an experimental and numerical analyses of magnetic effects on OH radical distribution in a hydrogen-oxygen diffusion flame. Numerical simulations were used to solve the equations of reactive gas dynamics and magnetism. Neodymium (NdFeB) permanent magnets were modeled with decreasing gradient on a co-axial type burner. The common tendency between the experiment and the numerical simulations was that OH radicals migrated towards the central axis of the flame as it had been observed in previous experiments. Again, numerical simulations confirmed that the main reason for increase in the OH concentration was from the magnetic body forces in the momentum equation.

Numerical simulations of diffusion flames with and without magnetic field were performed by Kinoshita et al [12]. Axis-symmetric laminar jet diffusion flames under normal and microgravity environments were studied. The fundamental equations considered were conservation of mass, axial momentum, radial momentum, species and energy. Velocity vectors and temperature contours were plotted for gradient magnetic fields under microgravity and normal gravity. It was observed that convection around the diffusion flame is induced by magnetic buoyancy forces. The flow under microgravity with a gradient magnetic field is similar to the one under normal gravity without magnetic fields. This study again confirms that a magnetic flow of oxygen promotes combustion in diffusion flames.

Recently, several commercial products in the market have claimed that applying a magnetic field to ionizing fuel prior to combustion can lead to better fuel economy and reducing
polluting emissions [29, 30]. They posit that hydrocarbon molecules can be decomposed and ionized prior to combustion with the application of magnetic force from a magnet. According to them, the resultant conditioned fuel/air mixture burns more completely, producing higher engine output, better fuel economy, more power and most importantly reduces the amount of hydrocarbons, carbon monoxide and oxides of nitrogen in the exhaust.

Very few research papers can be found to back up this argument. One of the only studies found on this subject did not involve the combustion of hydrocarbons and investigated the effects of homogeneous fields on a hydrogen gas line prior to combustion. Yamada, et al [31] applied a 1.5 T magnetic flux to hydrogen fuel and digitally photographed the flames that were produced. The spectral emissions of OH radicals were analyzed in the pictures and qualitative results showed the intensity to be altered. The polarity of the magnets had no effects on the spectral intensity. This study also measured NO concentration in the emissions of the flame. No perceivable difference in NO was observed during the application of the magnetic field. Although no reductions of NO emissions were seen, temperature changes in the flame were recognizable as soon as the magnetic field was applied. The investigation demonstrated that the flame temperature increased immediately in response to the step input of the electromagnet. The author attributed these results to the change in flow velocity caused by magnetic forces and not to the ionization of the fuel.

In summary, few studies have been performed on the effects of magnetic fields in combustion and the most important ones have been discussed in this Chapter. Throughout the literature survey, the importance of the proposed experiment has been re-emphasized. Thus, it can be noted that none of the studies reviewed have investigated optimum magnetic configurations for best combustion. Although it has been determined that magnetic fields can
positively affect combustion, there is no information on what types of field produce the most perceivable effects. More importantly, there have been no studies on the effect of an oscillating magnetic field on combustion. The physics of magnetic gas dynamics suggest that oscillating magnetic fields could produce a mixing effect between fuel and oxidizer thus, further improving combustion characteristics. Additionally, due to the lack of research in the area of magnetized fuels prior to combustion, it was deemed important to investigate the effects of these fields on hydrocarbon fuels.
CHAPTER 4- HOMOGENEOUS MAGNETIC FIELDS

The study of magnetic field effects on diffusion flames begins with the simplest type of magnetic field, that is, homogeneous magnetic fields. This chapter will provide a theoretical investigation of how the magnetic work of a magnetic field may affect combustion characteristics. Specifically, it will focus on the changes in product mole fractions under an applied homogeneous field.

4.1 Equilibrium Mole Fraction under Homogeneous Magnetic Fields

Equilibrium composition characteristics are important in high-temperature combustion processes. As opposed to other chemical reactions, combustion reactions do not produce simple mixtures of ideal products. Species tend to dissociate into minor species which consequent in a wide array of combustion products. Several techniques can be used to compute their mole fractions. Methods used include using the equilibrium-constant approach and the minimization of the changes in the Gibbs free energy [13]. In this section, the latter method is modified to determine the combustion characteristics of a combustion reaction affected by a homogeneous magnetic field.

Although the magnetic force on paramagnetic oxygen is zero in a homogeneous field (i.e. $\frac{dB}{dz}=0$), there is still magnetic work performed on the system [14]. Using the method outlined by Baker and Saito [10], the Gibbs free energy formulation was modified to include magnetic field work effects. A method of Lagrange multipliers was used to obtain a solvable system of non-linear equations. The Newton-Raphson method was then used to determine the mole fractions of product species on a methane and air flame. Plots of mole fractions of ten different product species were derived for the combustion flame in the temperature range of
1500-5000 K. The plots were compared with the results obtained by the equilibrium combustion software package GASEQ [15].

4.2 Nomenclature

\( a_{ij} \) = atoms of element \( j \) in product \( i \)

\( \mathbf{B} \) = magnetic flux density

\( b_j \) = atoms of element \( j \) in reactants

\( G \) = Gibbs free energy

\( \overline{\gamma}_i^s \) = molar specific reference Gibbs free energy

\( H \) = magnetic field strength

\( I \) = enthalpy

\( L \) = objective function

\( M \) = intensity of magnetization

\( n \) = number of moles

\( n_e \) = number of constituent elements

\( n_s \) = number of product species

\( P \) = pressure

\( R_u \) = universal gas constant

\( S \) = entropy

\( T \) = temperature

\( U \) = internal energy

\( V \) = volume

\( W \) = work

\( x_i \) = mole fraction of species \( i \)

\( \lambda_i \) = Lagrange multiplier corresponding to species \( i \)

\( \mu_0 \) = permeability of free space

\( \chi_i \) = magnetic susceptibility of species \( i \)
4.3 Formulation of Equations

The magnetic work contribution in a homogeneous, isotropic system was derived by Rosenweig [14] and is described as,

\[ \delta W_{mag} = d(V \int \mu_o H dM) \]  
(4.1)

The total work on the system can then be represented by (A detailed derivation is provided in Appendix B)

\[ \delta W_{system} = -PdV + \mu_o H^2 \chi dV + V\mu_o H \chi dH + V\mu_o H^2 d\chi \]  
(4.2)

where the boundary work on the system has been included and the relation \( M=\chi H \) was used for the expansion of the terms.

The change in internal energy of the system is thermodynamically described as,

\[ dU = TdS - dW_{sys} \]  
(4.3)

and the Gibbs free energy equation \( (G=I+TS) \) along with the definition of enthalpy \( (I=U+pV) \) can be used to find the Gibbs free energy of the system as:

\[ dG = \mu_o H^2 \chi dV + V\mu_o H \chi dH + V\mu_o H^2 d\chi + VdP - sdT \]  
(4.4)

The following assumptions were made to simplify the Gibbs Free Energy equation. The magnetic field is constant \( (dH=0) \), the system is isothermal \( (dT=0) \), the magnetic susceptibility obeys the Curie-Weiss law and is only a function of temperature, thus, \( d\chi=0 \), and the mixture of gases consists of only ideal gases \( (PV=nR_u T) \). Simplifying equation (4.4) and integrating from a reference state to a specified state for a mixture of ideal gases yields,

\[ \frac{G}{R_u T} = \sum_{i=1}^{n} n_i \left[ \frac{\overline{\mu}_i^p}{R_u T} + \ln \left( \frac{n_i}{n_{tot}} \right) + \ln(p) + \frac{H^2 \mu_o \chi_i}{n_i} - \frac{H^2 \mu_o \chi_i}{P_o} \right] \]  
(4.5)
At equilibrium, $G/R_uT$ is at a minimum, subject to the elemental composition being fixed.

The conservation of mass of the constituent elements in a chemical reaction is defined as

$$\sum_{i=1}^{n_i} a_{ij} n_i - b_j = 0 \quad (4.6)$$

where $G/R_uT$ needs to be minimized subject to the constraints of equation (4.6). This can be accomplished with the use of Lagrangian multipliers [12] by defining the objective function $L$ as,

$$L = \sum_{i=1}^{n_e} \left[ \frac{\bar{g}_i}{R_u T} + \ln \left( \frac{n_i}{n_{tot}} \right) + \ln(p) + \frac{H^2 \mu_i \chi_i}{p} - \frac{H^2 \mu_o \chi_i}{p_o} \right] - \sum_{j=1}^{n_s} \lambda_j \sum_{i=1}^{n_i} (a_{ij} n_i - b_j) \quad (4.7)$$

where the required solution will occur when $L$ is a minimum i.e. $\partial L / \partial n_i = 0$. The derivative of $L$ is calculated to be,

$$\frac{\partial L}{\partial n_i} = \frac{\bar{g}_i}{R_u T} + \ln \left( \frac{n_i}{n_{tot}} \right) + \ln(p) + \sum_{i=1}^{n_e} \frac{H^2 \mu_i \chi_i}{p} - \frac{H^2 \mu_o \chi_i}{p_o} - \sum_{j=1}^{n_s} \lambda_j a_{ij} = 0 \quad (4.8)$$

This results in a system of equations where there are $n_e$ equations of type (4.6) and $n_s$ equations of type (4.8). The unknowns are $n_s$ values of the mole numbers $n_i$ and $n_e$ Lagrangian multipliers $\lambda_i$.

Because of the logarithmic terms, the system of equations is non-linear and therefore needs to be solved iteratively. The method used by Baker and Saito involved a pseudoalgorithm developed by Morley [12]. A simpler method was used in this study where the equations were solved using Newton-Raphson method for non-linear systems of equations. To ensure that the iterations did not produce complex solutions, the absolute value of the terms within the logarithms were used for the iteration process. Also, if the solutions resulted in a negative number of moles, the absolute value of these results were calculated and a new iteration process
was started until the solution converged to a positive value. The process is iterated until the changes in the solution satisfied the convergence criterion of $10^{-8}$.

4.4 Results and Discussion

An Excel spreadsheet was used to solve the system of equations and the validity of the solution was tested against the values found by the program GASEQ. Combustion of methane and air with a fuel equivalence ratio of 0.8 and ten product species for the case of no magnetic field were modeled in Excel and in GASEQ. The magnetic field was set to zero to verify that the formulation of the equations was correct. The numbers of moles for product species were recorded for both methods and the results are shown in Table 4.1. The estimates reflect gas properties at a pressure of 1 atm and a temperature of 2300 K. The third column then captures the percent difference between these two estimates. As shown here, there is very little difference between the two sets of estimates, signifying the accuracy of the excel formulae. The most extreme difference occurs for $N_2$ at a 4.265% difference. The least discrepancy is found with $H_2O$ at 0.033% difference. Similar comparisons were made for different fuel types, temperatures and pressures. All cases produced similar results.

**Table 4.1:** Percent difference between estimates provided by GASEQ and Excel

<table>
<thead>
<tr>
<th>Gas</th>
<th>Present Estimate</th>
<th>GASEQ Estimate</th>
<th>Percent Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>$CO_2$</td>
<td>0.944</td>
<td>0.943</td>
<td>0.089</td>
</tr>
<tr>
<td>$H_2O$</td>
<td>1.939</td>
<td>1.938</td>
<td>0.033</td>
</tr>
<tr>
<td>$CO$</td>
<td>0.056</td>
<td>0.057</td>
<td>1.483</td>
</tr>
<tr>
<td>$N_2$</td>
<td>8.958</td>
<td>9.357</td>
<td>4.265</td>
</tr>
<tr>
<td>$O_2$</td>
<td>0.473</td>
<td>0.472</td>
<td>0.108</td>
</tr>
<tr>
<td>$OH$</td>
<td>0.076</td>
<td>0.076</td>
<td>0.716</td>
</tr>
<tr>
<td>$H$</td>
<td>0.005</td>
<td>0.005</td>
<td>2.222</td>
</tr>
<tr>
<td>$O$</td>
<td>0.012</td>
<td>0.012</td>
<td>1.501</td>
</tr>
<tr>
<td>$H_2$</td>
<td>0.021</td>
<td>0.021</td>
<td>1.542</td>
</tr>
<tr>
<td>NO</td>
<td>0.084</td>
<td>0.085</td>
<td>2.089</td>
</tr>
</tbody>
</table>
For the simulation with the presence of a magnetic field, a magnetic induction of 0.5 Tesla was used in the model since this field strength is easily obtainable experimentally using relatively small magnets. The susceptibilities of products were obtained from the CRC Handbook of Chemistry and Physics [16] for each of the elements and the values are provided in Appendix B. The model was tested at a pressure of 1 atm for a temperature range of 1500 K to 5000 K.

The solution resulted in negligible differences between the applied magnetic field to the case of no magnetic field. When using the Excel spreadsheet to model both cases, the plots were coincident and no difference was perceived. The magnetic field model was then plotted with the results of no magnetic field given by GASEQ (Figure 4.1). The plots follow the same trends and are very close to within 3% in values. Differences can be attributed to the numerical methods used to solve the equations and were not credited to the application of a magnetic field.

Figure 4.1: Mole fractions of product species under a homogeneous magnetic field (B=0.5T)
An order of magnitude analysis on the governing equations (Eq. (4.8)) was performed to further assess the reason for the negligible effects on combustion characteristics. The magnetic contributions in these equations are dependent on the magnetic field strength, magnetic susceptibility of the species and inversely related to the pressure. For the case modeled in this experiment ($B=0.5 \, T$), the magnetic contributions have an order of magnitude of $\sim 10^{-9}$. Note
that the units in the numerator of the fraction are N/m² and therefore the pressure has to be expressed in these units as opposed to atmospheres (atmospheres are used in the non-magnetic terms). The remaining terms in the equation have a significantly higher order of magnitude. The reference Gibbs energy term has an order of magnitude of \(~10^1\) and the mole fraction term has a magnitude of \(~10^0\). Thus, any variation in the magnetic term will have negligible effect on the net result. From these results, it can be confirmed that homogeneous magnetic fields have negligible effects on combustion reactions for the investigated temperatures and pressures.
CHAPTER 5- GRADIENT MAGNETIC FIELDS

As stated earlier in this thesis, gradient magnetic fields can be used to promote combustion in diffusion flames. This chapter focuses on determining the type of magnetic field that would be most suitable to better enhance oxygen entrainment in a combustion zone. Also, the extent of combustion enhancement with the use of gradient magnetic fields is quantitatively analyzed.

5.1 Finite Element Magnetics: Numerical Study

Once it was determined that homogeneous fields produce no significant effects of diffusion flames, a numerical study was performed on inhomogeneous fields. The numerical study focuses on analyzing four different types of magnetic fields to find a type of magnetic configuration that can positively affect combustion characteristics. Main focus is given to the effects of the fields on paramagnetic oxygen. The Finite Element Method Magnetics software package was used to find the flux density profile along the central axis of four different types of magnetic configurations. The gap in between magnetic surfaces was kept constant (3 cm air gap) for all the simulations. Convergence was checked in the numerical analysis by reducing the mesh size until no perceivable changes in the results were obtained. Also, the results were validated by experimental measurements using a Gauss meter (Lakeshore 420). The simulations were performed in the following magnetic configurations:

1. **Experimental Electromagnet**: Electromagnet configuration used in previous combustion studies [5, 12] (Figure 5.1).

2. **Gradient Solenoid**: Copper solenoid modified to induce a gradient magnetic field by coiling the wire at a slope of 30° with respect to the vertical direction (Figure 5.2).
3. **Circular Permanent Magnets:** Common Neodymium grade 40 permanent magnets with a circular, 5 cm diameter cross-section and a horizontal magnetic alignment.

4. **Rectangular Permanent Magnets:** Common Neodymium grade 40 permanent magnets with a rectangular cross-section (5 X 4 cm). To form a gradient field, the magnets were oriented at 45° with respect to the vertical direction.

![Experimental electromagnet configuration](image)

**Figure 5.1:** Experimental electromagnet configuration

![Modified solenoid to form a gradient field (left), homogeneous field of a solenoid (right)](image)

**Figure 5.2:** Modified solenoid to form a gradient field (left), homogeneous field of a solenoid (right)

Once the magnetic flux density profile was obtained, curve fitting was performed to generate an analytical expression for the profile. As discussed in Chapter 2, the magnetic force on gas species is governed by equation (5.1),

\[
F_i = \frac{1}{2} \frac{\mu_0}{\mu} \frac{d\vec{B}}{dz} \quad (5.1)
\]
where $\chi_i$ is the magnetic susceptibility of species $i$, $\mu_0$ is the permeability of free space, $\bar{B}$ is the magnetic flux density and $d\bar{B}/dz$ is the magnetic flux gradient. As it may be seen from equation (5.1), the magnetic force on a gas species is proportional to both the magnetic flux density and the magnetic flux gradient. MATLAB was used to calculate the force profile on paramagnetic oxygen as a function of vertical position for each of the magnetic configurations.

The magnetic flux density profile around the cross-section of the different magnetic configurations was found with a convergence criteria of $10^{-8}$. Figures 5.3 and 5.4 show the results obtained from the simulations. To validate the numerical results, experimental measurements were taken in the air-gap region of the electromagnet (Figure 5.5). In comparison, the results exhibit the same trends although the experimental maximum value is 0.09 T lower than the numerical. These differences may be attributed to geometrical discrepancies between the model and the electromagnet, material differences (pure iron versus cast iron) and a 2% experimental error in the measurements due to the difficulties in the placement of the probe.

![Simulation results of magnetic flux around circular permanent magnets](image)

**Figure 5.3:** Simulation results of magnetic flux around circular permanent magnets
Figure 5.4: Simulation results of magnetic flux around experimental electromagnet

Figure 5.5: Validation of numerical results by comparison to experimental measurements of magnetic flux density along the vertical central axis of the electromagnet

Plots of magnetic flux density with respect to the vertical position were obtained for the electromagnet, the circular permanent magnets and the rectangular permanent magnet configurations (Figures 5.6-5.9). Since the solenoid is on an axis-symmetric plot, the magnetic gradients occur on the radial direction. Plots for the solenoid were obtained at the center of
solenoid in the radial direction. The appropriate polynomial curve fit was found for all configurations by using the equation that had a Pearson’s correlation coefficient of around ~0.999. All of the analytical expressions are described by the polynomials shown in Table 5.1.

**Figure 5.6:** Magnetic flux density for electromagnets along the central axis

**Figure 5.7:** Magnetic flux density for circular Neodymium magnets along the central axis

**Figure 5.8:** Magnetic flux density for rectangular Neodymium magnets along the central axis
Figure 5.9: Magnetic flux density at the center of the gradient solenoid along the radial direction

Table 5.1: Curve-fit results for each magnetic type and correlation coefficient of equations

<table>
<thead>
<tr>
<th>MAGNET TYPE</th>
<th>CURVE-FIT RESULT</th>
<th>R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experimental</td>
<td>$y = -2E-05x^6 - 8E-07x^3 + 0.0011x^4 - 5E-06x^2 - 0.0275x - 6E-05x + 0.364$</td>
<td>0.99903</td>
</tr>
<tr>
<td>Circular</td>
<td>$y = -0.0003x^6 + 2E-05x^3 + 0.0076x^2 - 0.0001x - 0.09x + 0.0025x + 0.3872$</td>
<td>0.99995</td>
</tr>
<tr>
<td>Rectangular</td>
<td>$y = 8E-05x^6 - 0.0033x^3 + 0.0507x^2 - 0.3929x^1 + 1.5525x^1 - 2.7967x + 1.7948$</td>
<td>0.99946</td>
</tr>
<tr>
<td>Solenoid</td>
<td>$y = 0.007x^2 + 0.0003x + 0.1703$</td>
<td>0.99989</td>
</tr>
</tbody>
</table>

The curve-fitted polynomials were used to calculate the magnetic flux gradients ($d\vec{B}/dz$). Using equation (5.1) and the magnetic susceptibility data from [16], the magnetic force on oxygen as a function of position for each of the configurations was plotted (Figure 5.10).

For all cases except the solenoid, the force on oxygen changes direction from positive to negative. To enhance combustion characteristics, the direction of the force has to oppose the direction of the fuel flow. For example, if the burner flows in the positive vertical direction, the force on paramagnetic oxygen should be in the negative vertical direction so that oxygen is forced into the flame. It can be seen from the plots that the circular permanent magnets exert the maximum force mainly due to the large gradients formed by its geometry. The rectangular
magnets have a larger maximum force in the positive than in the negative direction. The electromagnets are third on the maximum force followed by the solenoid, which has rather negligible forces on oxygen. For comparison purposes, the magnitude and direction of the maximum force exerted by each of the magnetic configurations is shown in Table 5.2.

![Figure 5.10: Magnetic force on oxygen for different magnetic configurations](image)

**Table 5.2: Maximum magnetic force on oxygen for different configurations**

<table>
<thead>
<tr>
<th>Magnetic Configuration</th>
<th>Force (N/m^3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electromagnet</td>
<td>-1.59</td>
</tr>
<tr>
<td>Circular Permanent</td>
<td>-3.36</td>
</tr>
<tr>
<td>Rectangular Permanent</td>
<td>+2.34</td>
</tr>
<tr>
<td>Solenoid</td>
<td>+0.074</td>
</tr>
</tbody>
</table>

In conclusion, circular permanent magnets should be used to better enhance combustion in diffusion flames. It was shown by this study that the force of these types of magnets more than doubles the force of previously used experimental electromagnets. It is also suggested by this study that magnets with complex geometries can produce steep gradients and this is
anticipated that it may enhance combustion. Future work of magnetic field effects on combustion should focus on developing magnetic configurations that can provide for even higher forces on paramagnetic oxygen.

5.2 Experimental Data Analysis

The experimental data previously obtained by Swaminathan [5] was used to quantitatively analyze the effects of gradient magnetic fields. The system consisted of a diffusion type propane/air flame centered on a stainless steel burner tube (1/4 inch in diameter). Regulated fuel was supplied to the burner. The electromagnet used (Figure 5.1) was set-up by using a permanent magnet with a cast iron core and magnetic wire winding connected to a DC power supply. The magnetic flux density along the central axis of the electromagnet was previously shown in Figure 5.5. The study was carried out in two flow regimes. Firstly, in the non-sooting regime corresponding to flow rates ranging from 17 cc/min-105 cc/min were studied for the influence on the flame structure/height. The flame structure was captured using a digital camera. In the sooting regime, soot particles produced in the flame were collected through a thermophoretic sampling system and deposited on to a 200-mesh copper grid coated with carbon film that is stable under electron beam exposure for subsequent transmission electron microscopy (TEM).

The results of these experiments confirmed an increase in oxygen presence around the combustion reaction zone. These conclusions were derived from the qualitative data of flame structure images and soot agglomeration analysis. In this section, further investigations are performed on the data in order to quantitatively estimate the increase of oxygen in the flame and calculate the decrease in soot agglomeration of the products.
5.2.1 Oxygen Mole Fraction Estimation for Decreasing Gradient Magnetic Fields

As it was mentioned in chapter 2, a widely used expression to predict laminar jet flame lengths for circular burner ports was derived by Roper [22]. The expression applies to flames regardless of whether or not buoyancy is important in the reaction and is applicable for fuel jets emerging into a quiescent oxidizer or a co-flowing stream. Given that magnetic forces are similar to buoyant forces (both act on a volumetric basis) it may be assumed that the expression developed by Roper applies for laminar flames under the application of a magnetic field. Roper’s expression for the flame length in a circular port is as follows:

\[ L_f = 1330 \frac{Q_f (T_\infty / T_f)}{\ln(1 + 1/S)} \]  \hspace{1cm} (5.2)

where \( Q_f \) is the volumetric flow rate of fuel from the nozzle (\( \text{m}^3/\text{sec} \)), \( T_\infty \) is the ambient oxidizer temperature (K), \( T_f \) is the mean flame temperature at the burner exit (K), and \( S \) is the molar-stoichiometric oxidizer-fuel ratio. For a generic hydrocarbon, \( \text{C}_x\text{H}_y \), the stoichiometric ratio can be expressed as

\[ S = \frac{x + y/4}{\chi_{O_2}} \]  \hspace{1cm} (5.3)

where \( \chi_{O_2} \) is the mole fraction of oxygen in air.

Substituing Equation (5.3) into (5.2) and solving for the mole fraction of oxygen in air results in:

\[ \chi_{O_2} = \left( x + \frac{y}{4} \right) \exp \left( 1330 \frac{Q_f (T_\infty / T_f)}{\ln(1 + 1/S)} - 1 \right) \]  \hspace{1cm} (5.4)

Using the experimental data (Appendix C) for flame length and flame temperature for the combustion of propane (\( \text{C}_3\text{H}_8 \)), the changes in mole fraction of oxygen for the case of an applied magnetic field can be compared to the no magnetic field case. Flame temperature data was taken
for jet velocities of 0.9 cm/sec and 2.6 cm/sec. For these same speeds, flame lengths were measured for the cases of applied magnetic field (magnetic strength of 0.27 Tesla at a gradient of -240 T/m) and no applied magnetic field. By averaging the temperature measurements and using the measured flame lengths, the increase in oxygen concentration was found and summarized in the Table 5.3.

**Table 5.3**: Oxygen mole fraction for decreasing magnetic field gradient versus case of no applied magnetic field at different velocities

<table>
<thead>
<tr>
<th>Velocity (cm./sec)</th>
<th>Flame Length (cm)</th>
<th>Average Flame Temp. (K)</th>
<th>Oxygen Mole Fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No Field</td>
<td>Dec. Field</td>
<td>No Field</td>
</tr>
<tr>
<td>0.9</td>
<td>1.02</td>
<td>0.80</td>
<td>1255</td>
</tr>
<tr>
<td>2.6</td>
<td>2.62</td>
<td>2.43</td>
<td>1214</td>
</tr>
</tbody>
</table>

For the case of 0.9 cm/sec velocity, the increase in oxygen concentration was of 20.3% while the case of 2.6 cm/sec jet velocity only produced an increase of 2.68%. The lower velocity case has a larger increase in oxygen entrainment since the momentum is lower in the axial direction. As velocity increases in the jet flow, the momentum force becomes dominant and the effects of the magnetic force on paramagnetic oxygen are reduced.

These results agree to the ones reported by Swaminathan, which state that magnetic fields of low strengths only have significant effects for low Reynolds number flows in the range of 10-100 [5]. In her study, she reports that as long as buoyancy forces as opposed to momentum forces control the flame, the magnetic field enhances flame behavior. Figures 5.11 and 5.12 show the ratio of buoyancy forces to momentum forces and magnetic forces to buoyancy forces, respectively for a Reynolds number of 15. The plots show that the diffusion flame at this Reynolds number is buoyancy controlled since the buoyancy forces are 10^4 orders of magnitude larger than the momentum forces. It is also concluded that magnetic forces are of comparative magnitude to the buoyancy forces thus, enhancing flame behavior.
Figure 5.11: Comparison of forces- Ratio of buoyancy to momentum forces acting along a diffusion flame, Re=15 [5]

Figure 5.12: Comparison of forces- Ratio of magnetic to buoyancy forces acting along a diffusion flame, Re=15 [5]
5.2.2 Soot Agglomeration Reduction

Images of soot agglomeration can be used to infer the size distribution of individual particles without explicitly detecting each object first. Granulometry, in MATLAB can be used to estimate the intensity surface area distribution of particles as a function of size. Granulometry likens image objects to stones whose sizes can be determined by sifting them through screens of increasing size and collecting what remains after each pass. Objects are sifted by opening the image with a structuring element of increasing size and counting the remaining intensity surface area (summation of pixel values in the image) after each opening. Soot images of a diffusion flame under no magnetic field and a decreasing gradient magnetic field were obtained using transmission electron microscopy (Figures 5.13- 5.14) [5]. The intensity surface area distribution was determined from these images and plotted in Figures 5.15 and 5.16.

![Figure 5.13: Soot images under no applied magnetic field [5]](image)
Figure 5.14: Soot images under decreasing gradient magnetic field [5]

Figure 5.15: Surface Area Intensity plot for no applied magnetic field
A significant drop in intensity surface area between two consecutive openings indicates that the image contains objects of comparable size to the smaller opening. This is equivalent to the first derivative of the intensity surface area array, which contains the size distribution of the particles in the image. The derivative of the size distribution of particles can then be plotted (Figures 5.17-5.18). The minima in the plots determine the radii of the particles in the image. The more negative the minimum point, the higher the particles’ cumulative intensity at that radius.

It can be noticed that the minima occurs at a radius of 6 pixels for the case of no applied magnetic field while it occurs at a radius of 5 pixels for an applied magnetic field. Being that in these images 1 micrometer is equal to 220 pixels, the radius of the most occurring particles are 27.3 nanometers and 22.7 nanometers for the case of no applied magnetic field and applied magnetic field, respectively. These values are consistent with the ones in the literature, which
suggest that agglomerates are formed from spherical particles measuring approximately 10-40 nm. See for example, reference [20] amongst others. The sizes of the particles are similar in value suggesting that the application of magnetic field does not appreciably decrease the soot particle size.

Figure 5.17: Size distribution for no applied magnetic field

Figure 5.18: Size distribution for decreasing gradient magnetic field
Although the size of the particles might have not changed much, it is clear from the images that the quantity of the agglomerates certainly decreased. In order to quantify the decrease of particle agglomeration, another image processing technique can be used. The method used involves enhancing the image to correct for non-uniform illumination and then use the enhanced image to identify individual particle agglomerates. This first requires that the background of the image be removed and then the image be converted to binary (Figure 5.19). This allows the labeling of connected components in the binary images. Each distinct object is labeled with an individual integer value and can be easily visualized in a color-indexed image (Figure 5.20).

![Binary image conversion of soot particle agglomeration](image1.png)

**Figure 5.19:** Binary image conversion of soot particle agglomeration

Once the regions in the image are labeled, MATLAB can measure object or region properties such as area, centroids and eccentricity in an image. In the case of soot agglomeration, area is the main interest. Table 5.4 summarizes the properties found from the two images analyzed.
Figure 5.20: Color indexed images of continuous objects in soot agglomerates

Table 5.4: Soot agglomerate properties for no magnetic field and applied magnetic field

<table>
<thead>
<tr>
<th>Property</th>
<th>No magnetic field</th>
<th>Grad. magnetic field</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of agglomerates</td>
<td>84</td>
<td>141</td>
</tr>
<tr>
<td>Max area</td>
<td>0.261 μm²</td>
<td>0.0796 μm²</td>
</tr>
<tr>
<td>Agglomerates with max area</td>
<td>58</td>
<td>37</td>
</tr>
<tr>
<td>Mean area</td>
<td>9.56 X 10⁻³ μm²</td>
<td>2.97 X 10⁻³ μm²</td>
</tr>
</tbody>
</table>

Although the number of agglomerates is larger for the gradient magnetic field, the maximum area of these agglomerates is about 69.4% smaller than the case of no magnetic field. Also, the mean area for the agglomerates decreased by 68.9% when a magnetic field is used. This results show that even though the size of the particles formed in the soot based on the present data analysis change by approximately 17%, the formation of long chains of agglomerates is significantly decreased with the use of magnetic fields. These results suggest that the agglomerate particles are oxidized further in the flame tip. Mainly, this is caused by the increase in oxygen concentration due to paramagnetic attraction. This increase in oxygen causes enhanced diffusion from the outside of the flame into the reaction zone since oxygen concentration gradients are higher.
CHAPTER 6- OSCILLATING MAGNETIC FIELDS: NUMERICAL STUDY

As previously noted, it has been well established that gradient magnetic fields can be used to promote combustion in diffusion flames. A question that may arise from these conclusions is, which other magnetic field types may promote combustion? The study of time-varying magnetic fields may provide useful insight into this question. It is clear from the literature survey that previous studies have not dealt with the effects of these types of fields on diffusion flames. The underlying physics affecting paramagnetic oxygen suggests that the aforementioned fields would form a time varying force field around the flame, thus enhancing mixing between fuel and oxidizer. This could lead to even more complete combustion and further reduction in emissions than that obtained with the use of gradient fields. The focus of this chapter is to determine a way to experimentally test the effects of time varying magnetic fields on diffusion flames. Also, the feasibility of a potentially groundbreaking “magnetic” internal combustion engine is discussed by analyzing possible ways to mix fuel and oxygen in the reaction zone inside a piston-cylinder system.

6.1 Experimental Setup for Time Varying Magnetic Field

Finite element magnetic methods were used to obtain a configuration that would generate an oscillating magnetic field with the use of permanent magnets. Since it was found in the previous chapter that a circular surface provides the largest magnetic force on paramagnetic oxygen, it was deemed appropriate that the rotation of magnetic spheres could be used to generate a time varying magnetic field. Two 1.5 inch diameter Neodymium grade 40 circular cross-sections were modeled using FEMM with a one inch air-gap and rotating magnetic orientation direction. Different snapshots were taken for the magnetic field created around the
spheres. The spheres were rotated at the same rate so that the magnetic orientation direction was parallel at all times and so that the spheres were in attraction mode every half-cycle. If the spheres were to rotate in opposite directions, the magnetic field created would oppose the entrainment of oxygen due to the formation of a field of no strength along the centerline. Figure 6.1 shows representations of the magnetic flux lines and how the magnetic field changes as the spheres rotate.

Figure 6.1: Magnetic flux lines for rotating spheres at different alignment angles with respect to the horizontal: (a) 0 degrees, (b) 45 degrees, (c) 90 degrees, and (d) 135 degrees
Figure 6.2 shows magnetic flux density along the centerline for different magnetic orientation angles. It is clear that a diffusion flame placed along the centerline would experience a continuously changing magnetic field. As the spheres rotate, the magnetic field changes from a minimum of 0 Tesla to a maximum of 0.37 Tesla. Also, these changes of magnetic flux density
occur along steep positional gradients, which, as discussed earlier, exert larger forces on paramagnetic oxygen.

Along the centerline, any point can be traced to obtain the magnetic flux change as a function of angle of rotation. Figure 6.3 shows the changes in flux density at the center point of the central axis. It can be seen that the rotation of the spheres forms an approximately sinusoidal change of magnetic flux density, which reaches a maximum every 180 degrees or at the position of magnetic alignment between the two spheres. As expected, the frequency of the time-varying magnetic flux density is directly proportional to the frequency of rotation of the spheres. These results demonstrate that the rotation of spherical permanent magnets provides an effective way to experiment on the effects of oscillating magnetic fields on diffusion flames.

![Figure 6.2: Magnetic flux density along centerline of rotating sphere at different angles of rotation](image-url)
Simulations were performed to replicate the combustion process of an internal combustion engine in which a piston translates inside a cylinder as shown in Figure 6.4. Both the piston and head of the cylinder were modeled as Alnico permanent magnets. Alnico 5 was chosen for these simulations since this is the magnetic material with the highest Curie temperatures (approximately 1100 Kelvin) [27]. Temperatures inside an IC engine may be higher than the Curie temperature of Alnico 5. Accordingly, although the magnetic simulations performed in this section were designed to simulate the magnetic fields created by the motion inside an engine, they are not meant to be part of a design of such a system.

A point 1 mm below the head in the center of the cylinder was chosen to trace the changing magnetic flux density in the simulation. Two different geometries for the piston were
used in the simulations in order to create different magnetic gradients. The first simulation involved a flat piston with a hemispherical head and the second involved both a hemispherical piston and head. The two permanent magnets were modeled with a vertically upward magnetic orientation. The stroke of the engine was modeled to be 63 mm and the piston diameter was kept constant for both simulations.

![Four-stroke cycle](image)

**Figure 6.4:** Internal combustion engine cycle and representation of piston-cylinder system [33]

Figures 6.5 and 6.6 show snapshots of the translating piston as well as the changes in magnetic flux at the center point. The magnetic flux density plots show a spike near top dead center (TDC) for both models. The main difference between the plots is that the flat-piston produces a larger maximum flux density of 0.29 Tesla compared to 0.24 Tesla of the hemispherical piston. This difference is attributed to the larger thickness of the flat magnet. Although the field in the models does not oscillate as that of the rotating spheres, large magnetic gradients are present as the piston approaches TDC.
The results from these two models show that a magnetic piston-cylinder system could be designed to promote combustion. The magnetic field formed by the permanent magnets produces steep gradients near TDC, which is where combustion occurs in an engine. If the magnetic attraction of oxygen is timed appropriately with the ignition time of the engine, it is
anticipated that the reaction rate would increase thus combustion would be enhanced. These simulations provide important insight into the possibilities of magnetic combustion and should serve as motivation for future research on the subject.
CHAPTER 7- OSCILLATING MAGNETIC FIELDS EXPERIMENT

Experimenting on oscillating fields may provide significant insight into the effects of magnetic fields on diffusion flames. From the literature survey, it was concluded that such fields have never been tested on diffusion flames. Clearly, this area of study is ripe for future research and thus, an experiment investigating these processes may have important implications. As discussed in Chapter 6, oscillating magnetic fields are expected to produce a varying force field that may enhance mixing between fuel and oxidizer during combustion. Mixing of fuel and oxidizer has been an extensive area of research in combustion since better mixing results in more complete combustion, increased thermal efficiency and emission reduction [20]. The purpose of this experiment is to visualize the effects of oscillating magnetic fields on diffusion flames and investigate if mixing is indeed promoted. From the knowledge gained of magnetic effects on diffusion flames in previous experiments, it is expected that the constantly changing gradients of the magnetic spheres mentioned in Chapter 6 will produce forces in which the magnitudes will change with magnetic gradient. Figure 7.1 may be used to qualitatively represent the expected magnetic force field during the rotations of the magnetic spheres.

Figure 7.1: Expected magnetic force field variations as a function of sphere rotation for magnetic alignments of (a) 0 degrees, (b) 45 degrees, (c) 90 degrees, and (d) 135 degrees
(Figure 7.1 continued)
Case (a) in Figure 7.1 shows the expected force field on the flames due to the magnets being aligned at 0 degrees from the horizontal in an attracting position (North and South poles aligned with each other). The force field is symmetric due to the symmetry of the magnetic field with respect to the vertical axis. The resultant force acts vertically downward on the diffusion flame, thus shortening its overall length. As the magnets rotate, the force field is expected to move with the gradient as it is shown in Figure 7.1 (b) and (d), where the resultant force is now at an angle diagonal to the flame length and the downward component of the force is decreased. When the magnetic alignment reaches a 90-degree angle with the horizontal (Figure 7.1 (c)), the magnetic force in the central axis approximates zero and the forces on the flame vanish. This allows the flame to return to its normal length. This variation of magnetic force acting on the flame is expected to cause the length of the flame to vary as the field changes. Such variations in flame lengths due to oscillating magnetic fields are expected to enhance mixing in this type of flame.

7.1 Methodology and Experimental Setup

The oscillating magnetic field was created by mounting two 1.5 inch diameter Neodymium grade 40 spherical magnets into a pair of aluminum brackets that can be individually rotated. Figure 7.2 (top) shows the experimental setup where the magnets are mounted 3 inches apart from center-to-center, resulting in a 1.5 inch air-gap between them. The magnets rotate in the same direction (Figure 7.2 (bottom)) so that they were always in attraction mode creating an oscillating field in the central axis. The brackets were connected to shafts, which were fastened to two separate gears. A third gear connected to an electric drill with variable speeds (Black & Decker Cordless Drill rated at 750 rpm) was used to drive the
remaining gears. All gear ratios were 1:1 to ensure that the spheres were rotating at the same speed as the drill. Aluminum foil was placed between the brackets and the flame to prevent the convection of air from the rotation of the spheres to affect the structure of the diffusion flame. A tachometer was used to measure the rotational speed of the drill. A Sony Cybershot DSC-T50 digital camera was used to record video at 30 frames per second of a diffusion flame at a fuel jet exit velocity of approximately 2 cm/sec. Five-second video recordings were made for five different speeds, which were measured during each experimental run. The Matlab image processing toolbox was then used to process each video and measure the changes of length in the flame structure using each individual frame.

Figure 7.2: Magnetic spheres mounted on aluminum brackets (top) and spherical rotation of spheres during experimental run (bottom)
Experimental measurements of magnetic field strength were taken with the use of a Gaussmeter for the two Neodymium grade 40 spheres at a 1.5 inch air-gap. The measurements were made when the spheres were static, with a parallel magnetic orientation of 0-degrees with the horizontal. The highest possible magnetic strength achieved by the field was found with these measurements. As shown in the Figure 7.3, the field has a maximum strength of 0.28 Tesla.

![Figure 7.3: Magnetic field strength of static Neodymium grade 40 spheres with a 1.5” air-gap](image)

7.2 Results and Discussion

Video recordings at 30 frames per second were taken for five different rotational speeds: 160, 220, 335, 460 and 620 RPMs. The video recordings were imported into Matlab and reduced to one-second time frames. Each video was then separated into 30 different images in order to process each image individually. The Matlab image processing toolbox was used to measure the length of the flame in pixels resulting in 30 pixel data points for each speed. In order to observe the length variation of the flames, the average flame length was calculated for each speed, and the data points were standardized by taking the difference of each measurement with respect to
the mean \((\Delta L = L_r - L_{mean})\). To analyze the fundamental frequencies of the flame length change, the Discrete Fourier Transform of the data was performed using the FFT Matlab algorithm (Appendix D). Plots of the frequency spectrum were obtained for each rotation speed of the magnets. It is important to note that the frequency of oscillations of the magnetic flux density is not the same as the frequency of rotations of the magnets. As it was discussed in Chapter 6, the magnetic field flux density completes two cycles for every 360-degree rotation of the spheres. This is due to the fact that the magnetic orientation aligns every 180 degrees thus completing a period. The magnetic field flux density frequency is therefore twice the rotational frequency of the magnets. Figure 7.4 – 7.8 show the standardized length change \((\Delta L)\) of the flames with time as well as the magnetic flux density at the prescribed frequency and the frequency spectrum of \(\Delta L\) for each case.

![Flame Length Change and Magnetic Field Intensity](image)

**Figure 7.4:** Standardized length change \((\Delta L)\) of flame as a function of time and FFT frequency spectrum for function for a magnet rotation speed of 160 RPMs
Figure 7.5: Standardized length change ($\Delta L$) of flame as a function of time and FFT frequency spectrum for function for a magnet rotation speed of 220 RPMs

Figure 7.6: Standardized length change ($\Delta L$) of flame as a function of time and FFT frequency spectrum for function for a magnet rotation speed of 335 RPMs
Figure 7.7: Standardized length change (ΔL) of flame as a function of time and FFT frequency spectrum for function for a magnet rotation speed of 460 RPMs.

Figure 7.8: Standardized length change (ΔL) of flame as a function of time and FFT frequency spectrum for function for a magnet rotation speed of 620 RPMs.
As it was expected, the plots show that the diffusion flames indeed change in length as the magnetic field oscillates. It is important to note that the magnitude of oscillations increases with speed. The standard deviation of each data set was calculated to quantify the variations in length at each of the rotational speeds. Table 7.1 summarizes the results of the statistical analysis of the data. The results show that both the maximum $\Delta L$ and the standard deviation increase as the frequency of magnet rotation increases.

<table>
<thead>
<tr>
<th>Rotating Speed (RPM)</th>
<th>Maximum $\Delta L$ (pixels)</th>
<th>Standard Deviation (pixels)</th>
</tr>
</thead>
<tbody>
<tr>
<td>160</td>
<td>1.09</td>
<td>1.22</td>
</tr>
<tr>
<td>220</td>
<td>5</td>
<td>2.25</td>
</tr>
<tr>
<td>335</td>
<td>7.94</td>
<td>3.51</td>
</tr>
<tr>
<td>460</td>
<td>8.03</td>
<td>4.18</td>
</tr>
<tr>
<td>620</td>
<td>11.03</td>
<td>5.56</td>
</tr>
</tbody>
</table>

The frequency of magnetic field oscillations was compared with the frequency of $\Delta L$ by analyzing the peaks in the frequency spectrum. Being that the data is not entirely pure and may contain external noise, the peaks that were considered were those that are close to the oscillation frequency of the magnetic field. Table 7.2 compares the fundamental frequencies from the data to the frequency of oscillations of the magnetic field as well as the frequency of the rotating spheres. The frequencies in blue represent the fundamental frequencies that are close in value to the frequency of the rotation of the magnets. These frequencies are important since they represent variations in the flame that may be induced by vibration from the motion of the spheres. Moreover, the frequencies in green represent the fundamental frequencies that are close in value to the frequency of oscillations of the magnetic field. Since the frequency spectrum is limited by the sampling speed of the camera (30 fps), the spectrum only provides information for frequencies up to 15 Hz. Being that the rotation speeds of 460 and 620 RPM result in magnetic
oscillation frequencies of 15.24 and 20.66 Hz, respectively, the frequency spectrum does not provide results for these speeds. A high-speed camera would be required to obtain this information.

**Table 7.2:** Comparison between magnet rotating frequency (blue) and magnetic field frequency (green) to the fundamental frequencies of the FFT spectrum

<table>
<thead>
<tr>
<th>Rotating Speed (RPM)</th>
<th>Rotating Frequency (Hz)</th>
<th>Magnetic Field Frequency (Hz)</th>
<th>δL Fundamental Frequencies (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>160</td>
<td>2.67</td>
<td>5.34</td>
<td>0.63, <strong>3.13, 6.25, 8.75</strong></td>
</tr>
<tr>
<td>220</td>
<td>3.67</td>
<td>7.34</td>
<td>1.41, <strong>3.75, 6.56, 8.44</strong></td>
</tr>
<tr>
<td>335</td>
<td>5.58</td>
<td>11.16</td>
<td>0.093, <strong>5.62, 9.38, 11.25, 13.13</strong></td>
</tr>
<tr>
<td>460</td>
<td>7.67</td>
<td>15.34</td>
<td>1.88, 4.69, <strong>8.45, 10.3, 12.19</strong></td>
</tr>
<tr>
<td>620</td>
<td>10.33</td>
<td>20.66</td>
<td>1.88, 6.56, <strong>9.38</strong></td>
</tr>
</tbody>
</table>

The magnetic field frequencies for the speeds of 160, 220 and 335 RPM appear in the spectrum, which confirms that the flame changes in length from oscillations of the magnetic field. Also, the frequencies of the rotating spheres appear in the frequency spectrum of the data meaning that some vibrations are in fact also inducing changes in length of the flame. For rotational speeds higher than 450 RPM, a camera with sampling rate higher than 30 fps would be needed to obtain frequency results.

**7.3 Conclusions**

The effects of oscillating magnetic fields at different frequencies were investigated. The mechanical rotation of spherical permanent magnets was used to create a sinusoidal field in the central axis of the air-gap. Video recordings at five different speeds were taken to analyze the flame structure at a constant fuel flow rate. Statistical analysis showed that the magnitude of the changes in length of the diffusion flame increase with the frequency of the oscillating field. These results suggest that fields of higher frequency may significantly enhance mixing in a
combustion process due to the varying force field induced on the diffusion flame. Frequency spectrum analysis for the rotational speeds of 160, 220 and 335 RPM demonstrated that the oscillation of the magnetic fields was in fact affecting the length of the flame. It was also seen that the rotation of the magnetic spheres induced vibrations in the flame, which also had an effect of the length of the flame.

Due to flame instability caused by the magnetic field rotation, temperature measurements are difficult to perform accurately in such systems. It is recommended that measurements be taken in flames of higher jet exit velocity since these are more stable against external forces due to their higher momentum. Also, the noise in the recorded data caused by the vibrations induced by the rotation of the spheres should be prevented in future experimentations.
CHAPTER 8- COMBUSTION OF MAGNETIZED GAS

In previous chapters, it has been noted that a magnetic flux has the capability to affect flame reactions. However, these studies have only dealt with the application of magnetic fields on the flame itself. The purpose of this chapter is to present a study where magnetic fields are applied to the gas before combustion occurs. Furthermore, the study will involve the application of two magnetic fields, that is, a magnetic field on the gas as well as the flame itself. From the literature survey in Chapter 3, it can be concluded that a study as such has not previously been conducted and it could very well lead to improved thermal efficiency and pollution characteristics in a diffusion flame. This study could also confirm claims of several commercial products that state that pollution emissions in automobile engines can be reduced by applying a homogeneous magnetic field to the gas line [29-30].

8.1 Methodology and Experimental Setup

An important factor in the combustion of diffusion flames is flame structure, which is usually investigated using digital imagery. In order to better understand the effects of magnetic fields on diffusion flames, computer image processing can be used to segment, enhance and analyze digital photographs. With the use of the Matlab Image Processing Toolbox, different areas of a flame can be segmented for analysis on flame shape, length and intensity.

Color segmentation can be performed in an automated fashion with the use of color recognition and statistical analysis. For example, an image of a diffusion flame can be loaded into Matlab and converted into what is called the L*a*b color space. The L*a*b space consists of a luminosity layer ‘L*’, chromaticity layer ‘a*’ indicating where a color falls along a red-green axis, and chromaticity layer ‘b’ indicating where the color falls along the blue-yellow axis.
All of the color information is in the ‘a*’ and ‘b*’ layers. The differences between two colors can be measured and clustered into groups of objects. Using the K-means clustering technique, each object is treated as having a location in space. This statistical analysis then finds partitions such that objects within each cluster are as close to each other as possible, and as far from other objects in other clusters as possible. K-means clustering requires that the number of clusters to be partitioned be specified and the distance of how close two objects are to each other.

In the image of a diffusion flame, three colors can be recognized, white, yellow and blue. Once the K-means clustering takes place, each group of colors can be separated from the image and visualized in different photographs. In this experiment, the flame structure of a propane and air flame was captured using a digital camera and the type of analysis previously described was performed for flame images in four different cases:

1. Diffusion flame under no magnetic field.
2. Diffusion flame with magnetized gas (magnets placed 5 inches below jet exit).
3. Spherical magnets around a diffusion flame (1 inch air-gap).
4. Magnetic fields of case 2 and case 3 simultaneously.

The flow rate of propane was measured using a Singer American dry test flow meter model 115 and kept constant to provide a jet exit velocity of approximately 2.5 cm/sec while the digital pictures were acquired. Two rectangular Neodymium grade 40 rectangular magnets with dimensions of 2x1x1 inches formed the magnetic field applied on the gas. These magnets were placed directly on the burner, 5 inches below the jet exit and this configuration provided a ¼ inch gap between magnets as shown in Figure 8.1. The magnetic field formed by these rectangular magnets had a maximum strength of approximately 0.5 Tesla. Neodymium grade 40, 1.5 inch diameter magnetic spheres were used to apply the magnetic field on the diffusion flame. The
magnets were aligned in a way that the center of the spheres was in-line with the exit nozzle of the burner. The burner central axis was placed in the center of the air gap, which was kept at 1 inch. This placed the combustion reaction zone approximately 1 mm above the center of the field under a vertically decreasing magnetic gradient, which is the prescribed condition for combustion enhancement. This configuration resulted in a maximum magnetic field strength of 0.37 Tesla, which was measured with a Gauss meter using a transverse probe. The complete experimental setup for the case of the simultaneous fields is shown in Figure 8.1.

**Figure 8.1:** Experimental setup for magnetic fields on fuel line and flame

Temperature measurements were taken for the case of no applied magnetic field and the case of magnetized gas combustion for three different jet exit velocities: 1.3, 2.0 and 2.5 cm./sec. A Platinum versus Rhodium Type-S thermocouple with a bead diameter of 0.2 mm was used to
measure the temperature. Temperature measurements were taken from the nozzle exit to the tip of the flames. Five temperature measurements were taken at each position and then averaged to provide a mean flame temperature. The thermocouple was mounted on a vertically displacing platform that allowed measurements within a 0.1 mm margin of error.

8.2 Results and Discussion

Flame images were taken at a constant flow rate for the four different cases analyzed. The flow rate was chosen because the size of the flame at this preset speed allowed ease of visualization of the changing flame structure. The unedited digital images are shown in Figure 8.2. These images were imported into Matlab and digitally enhanced as described in the previous section. The background in the images was removed and the flames were segmented into three different colors: yellow, blue and white. The yellow color was the area of focus since it provides an accurate representation of the flame sheet structure. The digitally enhanced images are shown in Figure 8.3.

Changes in the flame structure that are not visually clear in the unedited images can be clearly seen after color segmentation. It can be seen from the photographs that no perceivable difference in the flame structure occurs with the addition of a magnetic field to the fuel line. Furthermore, it is clear that the case of no applied magnetic field and the case of applied magnetic field on the fuel line produce the same bowing arc near the jet exit and are of similar length and width. On the other hand, the application of the magnetic field on the diffusion flame produces a shorter narrower flame due to the applied pressure of paramagnetic oxygen. This confirms observations seen by previous researchers [3-9]. An interesting feature that can be visualized in Figure 8.3 (c) and (d) is the elimination of the arc formed near the exit of the flame.
The arc is formed in the first two cases due to the parabolic velocity distribution of the fuel at the jet exit. The elimination of this arc suggests that the downward magnetic convection of oxygen slows down the fuel velocity, thus changing the shape of the velocity distribution. By reducing the jet velocity, the fuel and oxidizer have more time to mix and more complete combustion can be achieved. Again, both magnetic fields applied simultaneously showed no perceivable differences in the flame structure.

**Figure 8.2:** Diffusion flame images for jet exit velocity of 2.5 cm/sec for cases: (a) No magnetic field, (b) Magnetic field on propane fuel line, (c) Spherical magnetic field on diffusion flame, and (d) Both magnetic field on fuel line and diffusion flame
Figure 8.3: Enhanced flame images for jet exit velocity of 2.5 cm/sec for cases: (a) No magnetic field, (b) Magnetic field on propane fuel line, (c) Spherical magnetic field on diffusion flame, and (d) Both magnetic fields on fuel line and diffusion flame
Temperature comparisons were made between the case of no magnetic field and applied magnetic field at different flow rates. The temperature measurements were not corrected for radiation losses since the measurements were made for comparison purposes between the two cases and the relation between the measurements would have remained unchanged after the temperature correction. Figures 8.4-8.6 show the plots of temperature as a function of vertical position above the burner.

As it can be seen from Figure 8.4, no significant changes in axial temperatures are seen with the application of a magnetic field at low speeds. Relatively larger variations in temperature appeared for a jet exit speed of 2.0 cm./sec where a temperature increase of approximately 30 °C occurs at positions close to the burner exit. For this speed, the temperature of the magnetized fuel case becomes lower than the case of no field in the soot formation region, which for this speed occurs between 5-15 mm above the burner exit.

![Figure 8.4: Axial flame temperature comparison between no applied magnetic field and pre-combustion magnetic field for average jet exit speed of 1.3 cm./sec](image)
Figure 8.5: Axial flame temperature comparison between no applied magnetic field and pre-combustion magnetic field for average jet exit speed of 2.0 cm./sec

Figure 8.6: Axial flame temperature comparison between no applied magnetic field and pre-combustion magnetic field for average jet exit speed of 2.5 cm./sec
The trends exhibited by the medium speed flame were also seen for a jet exit velocity of 2.5 cm/sec. In this case, temperature differences were also observed near the jet exit with the magnetized fuel case having temperatures up to 100 °C higher than the no applied field case. Again, the temperatures for the flame with no applied field were higher in the soot formation region, which in this case occurred between 10-15 mm above the burner. Moreover, the temperatures at the tip of the flame were higher for the case of magnetized fuel at all measured velocities.

Since the temperature measurements were taken from the jet exit to the tip of the flame, the measurements also serve as a way to measure the length of the flame. From the plots, it can be observed that the flame length did not change with the application of a magnetic field on the fuel line for any of the speeds. Also, during temperature measurements, carbon formation on the thermocouple probe occurred faster and in narrower regions of the flame when a magnetic field was applied to the fuel line. This was particularly perceivable in the higher velocity measurements. This particulate formation in the flame might be the main reason for the decrease in temperature gradient inside the sooting region since the particulates may discourage heat transfer between the flame and the thermocouple probe.

8.3 Conclusions

Structural effects of magnetized fuel on diffusion flames were studied for four different setups: (1) No magnetic field, (2) Magnetic field applied to propane fuel, (3) Magnetic field applied to diffusion flame, and (4) Both magnetic fields applied simultaneously. Results showed that the magnetized fuel did not result in any perceivable change in flame structure for case (2) and (4). The magnetic field applied to the diffusion flame confirmed results seen by previous
researchers [3-9], showing a decrease in flame size. Digitally enhanced imagery showed that applying a magnetic field to the flame redistributes the parabolic velocity distribution of the fuel jet. This is attributed to the downward force of paramagnetic oxygen, which opposes the direction of fuel flow.

Temperature measurements were taken for different flow speeds for the case of no applied magnetic field, and the case of magnetized fuel. Results showed a variation in temperature at higher speeds with a maximum increase in temperature of 22.5% for the magnetized fuel case at the lower portions of the flame. Carbon build-up in the thermocouple probe was observed to occur faster and in narrower regions of the flame when a magnetic field was applied to the fuel. This is a possible reason for the observed decrease in temperature gradient inside the soot formation region since heat transfer is blocked between the flame and the thermocouple probe. The temperature increase in the flame can be explained by dissociation caused by the magnetic force on the molecules. The temperature increase does not occur for the flame at low speeds since molecules have sufficient time to recombine. Further experimentation with higher flow rates and different fuel types could lead to more conclusive evidence.
CHAPTER 9- SUMMARY OF RESULTS AND RECOMMENDATIONS

9.1 Summary of Results and Discussion

The effects of different types of magnetic fields on combustion characteristics have been explored. Theoretical, numerical and experimental studies were carried out for combustion in a diffusion flame. The magnetic fields types investigated included, homogeneous, gradient oscillating and pre-combustion magnetic fields. The specific findings for each part of the study may be summarized as follows:

1. Using a modified Gibbs Free Energy approach, it was theoretically shown that homogeneous magnetic fields have no significant effects on combustion characteristics. Plots of mole fractions of ten product species depicted no significant change in the case of an applied magnetic field in comparison to the case of no applied magnetic field. To have any significant effects on the mole fractions, the strength of the homogeneous magnetic fields would have to be of unattainable magnitudes.

2. The numerical study of different magnetic configurations focused on determining the position of highest magnetic force exerted on paramagnetic oxygen for four different magnetic configurations. It was determined that magnets with high magnetic flux gradients at high magnetic strengths are more suitable to affect oxygen flow in a combustion process. In particular, circular permanent magnets with a horizontal magnetic alignment exerted the highest force due to the gradients that can be formed by having a curved surface.

3. The effects of paramagnetic oxygen flow in a diffusion flame were tested experimentally by previous researchers in both decreasing and increasing magnetic gradients. It was shown that increasing oxygen flow with the use of magnetic gradients altered the flame...
structure and shape of a diffusion flame. Furthermore, it was qualitatively shown that soot agglomeration is decreased with the use of decreasing gradient magnetic fields. It is important to note that to enhance combustion characteristics of diffusion flames, the direction of the magnetic force on paramagnetic oxygen has to oppose the direction of the fuel flow so as to act as a buoyancy force that attracts oxygen towards the reaction zone.

4. By using the expression to predict laminar jet flame lengths derived by Roper [22] and with the use of temperature and flame length data previously found by Swaminathan [5], the oxygen concentration was estimated for different jet velocities of a diffusion flame under a gradient magnetic field. It was found that for the lower fuel jet velocity, oxygen concentration increases up to 20.3% around the diffusion flame. A mere 2.68% increase was estimated for the higher jet velocity. The difference in concentration was attributed to the higher momentum dominating the flow in the latter case. These conclusions agree with ones previously reported, which mentioned that low strength gradient magnetic fields can be used to affect only low Reynolds number flames.

5. Computer processing of digital images of soot agglomeration allowed the estimation of the diameter of soot particulates collected under a gradient magnetic field versus ones collected under no applied magnetic field. The particle diameter decreased by 17% under the application of a magnetic field and the calculated average diameters were within the range of values reported in the literature (10-40 nm [20]). Also, the formation of long chains of agglomerates was decreased by 68.9% with the use of a decreasing gradient magnetic field in the direction of the flow.

6. The magnetic field created by the rotation of magnetic spheres was numerically analyzed to demonstrate that an oscillating, time varying field could be formed. The magnetic
spheres rotating at different speeds were tested experimentally on a diffusion flame at a constant flow rate. A varying force field on the diffusion flame was formed by the varying magnetic gradients, which resulted in a change of length in the diffusion flame as the spheres rotated. The variation in flame length increased as a function of rotation speed of the spheres. The changes in flame structure suggest that oscillating fields may be used to enhance mixing between fuel and oxidizer.

7. The magnetic field created by the translation of a piston in a magnetic piston-cylinder system was analyzed numerically. It was seen that steep magnetic gradients are created as the piston approaches top dead center, which suggests that, if timed appropriately, the concentration of oxygen may be increased before combustion occurs in an engine.

8. Experiments were performed on a diffusion flame under an oscillating magnetic field. The alternating magnetic field induced changes in the length of the flame, which were recorded with a digital camera. Statistical analysis of the measurements demonstrated that higher magnetic oscillating frequencies result in increased length changes of the flame. The results suggest that better mixing can be obtained in a combustion process with the use of oscillating magnetic fields.

9. Finally, results showed that no perceivable changes in structure are observed when a magnetic field is exerted on the fuel line prior to combustion. On the other hand, the magnetic force exerted by magnetic spheres on the diffusion flame itself results in the redistribution of parabolic velocity profile formed by the fuel jet. This is mainly due to the downward force on oxygen, which opposes the direction of the fuel flow. Moreover, an applied magnetic field on the fuel line resulted in an increase in temperature of about 22.5% in the lower portions of the flame for the higher fuel flow rates measured. A
decrease in temperature gradient in the mid-section of the flame was observed during the application of the magnetic field before combustion. This was attributed to the higher soot agglomeration rate observed on the probe, which, in turn, blocked heat transfer between the flame and the thermocouple.

9.2 Recommendations for Future Work

Due to the limited amount of research that has been performed in the area of magnetic effects on combustion, there are vast possibilities available for future research. Given that both previous studies and this thesis have established that magnetic fields indeed have positive effects on combustion, it is recommended that future research take this investigation to the next level. Since there is a global need for an urgent solution to harmful emissions from the combustion of fossil fuels, it is imperative that investigators look into this area as a possible solution to this worldwide problem.

Now that the effects of magnetic fields on diffusion flames are known, the next step is to investigate the effects of magnetic fields on droplet evaporation. Primary focus should be given to both gradient and oscillating magnetic fields and how these may be used to alter the rate of evaporation of a fuel droplet. Future work should also focus on developing magnetic configurations that can provide for higher forces on paramagnetic oxygen. Complex magnet shapes and magnetic fields could be used to promote oxygen entrainment and mixing in combustion processes.
REFERENCES


15. Morley, C. *GASEQ* <http://www.arcl02.dsl.pipex.com>


APPENDIX A- CLASSICAL THEORY OF DIAMAGNETIC AND PARAMAGNETIC MATERIALS

Although much of the physical explanation of diamagnetism and paramagnetism comes from quantum physics, a classical explanation can be provided as outlined in [28]. The loop model for electron orbits assumes that an electron moves along a circular path with a radius that is much larger than an atomic radius (Figure A.1(a)). It can also be assumed that in a diamagnetic material, an electron can orbit only counterclockwise (Figure A.1(b)) or clockwise (Figure A.1(d)). A non-uniform magnetic field $B_{ext}$ directed upward can then be applied to the system as shown in Figure A.1(a) with decreasing strength in the vertically upward direction as noted by the magnetic flux lines. As the magnitude of the magnetic field increased from zero to its maximum value, a clockwise electric field is formed in the electron’s orbital loop as stated by Faraday’s law and Lenz’s law.

Figure A.1: (a) Loop model for electron orbiting an atom under a non-homogeneous magnetic field. (b) Charge $-e$ moves counterclockwise and current moves clockwise. (c) Magnetic Forces on the loop. (d) Charge $-e$ moves clockwise and current moves counterclockwise. (e) Magnetic forces on loop [28]

In Figure A.1(b) the orbiting electron is accelerated by the clockwise electric field formed by the magnetic field. This means that the conventional current $i$ and the magnetic dipole moment $\mu_{orb}$ are also increased. The opposite occurs in Figure A.1(d) where the electron is
decelerated. In Figure A.1(c) and (d) a length element \( dL \) is shown from the plane of orbit. The resulting magnetic force due to the current along an element \( dL \) in a magnetic field is described by equation A.1:

\[
d\vec{F} = id\vec{L} \times \vec{B}_{\text{ext}}
\]

(A.1)

This means that depending on the direction of the current through the orbital, the resulting force can be either vertically up or down (Note that the horizontal components of the force cancel out). Since the current in Figure A.1(b) increases, the upward magnetic force also increases. In an opposite manner, the current \( i \) in Figure A.1(d) is decreased by the magnetic field and the downward magnetic force is also decreased. This results in a net upward force on the current loop where the force is directed away from the region of greater magnetic field thus, explaining why diamagnetic materials act as such.

In paramagnetic materials, the spin and orbital magnetic dipole moments of the electron in each atom do not cancel out but add vectorially. In the absence of an external magnetic field, the dipole moments are randomly oriented and the net magnetic dipole moment is zero. However, if a magnetic field is applied, the dipole moments tend to align with the external magnetic field as shown in Figure A.1(d) where \( \mu_{\text{orb}} \) is in the direction of \( B_{\text{ext}} \). This alignment produces a net force downward towards the region of increasing magnetic field.
The following is an explicit derivation for the equations used in the theoretical analysis in Chapter 4 (See Chapter 4 for Nomenclature). The magnetic work contribution in a homogeneous, isotropic system was derived by Rosenweig [14] and is described as,

\[ dW_{\text{mag}} = d(V \int \mu_o HdM) \]  

\text{(B.1)}

Expanding the derivative results in,

\[ dW_{\text{mag}} = dV \mu_o HdM + V \mu_o HdM \]  

\text{(B.2)}

where \( dM \) can be expanded as \( dM = d(\chi H) = Hd\chi + \chi dH \). Substituting into equation B.2, expanding and simplifying gives,

\[ dW_{\text{mag}} = H^2 \mu_o \chi dV + VH \mu_o \chi dH + VH^2 \mu_o d\chi \]  

\text{(B.3)}

Including the boundary work on the system, the total work can be written as,

\[ dW = -pdV + H^2 \mu_o \chi dV + VH \mu_o \chi dH + VH^2 \mu_o d\chi \]  

\text{(B.4)}

The definition of internal energy \( U \) (B.5), the definition for enthalpy \( I \) (B.6) and the Gibbs free energy \( G \) (B.7) are,

\[ dU = TdS + dW \]  

\text{(B.5)}

\[ dI = d(U + pV) = dU + pdV + Vdp \]  

\text{(B.6)}

\[ dG = dI - d(TS) = dU + pdV + Vdp - TdS - SdT \]  

\text{(B.7)}

Substituting B.4 and B.5 into B.7 and simplifying, the change of Gibbs free energy for the system results in,

\[ dG = H^2 \mu_o \chi dV + VH \mu_o \chi dH + VH^2 \mu_o d\chi + Vdp - sdT \]  

\text{(B.8)}
Assuming that the magnetic field is constant \((dH=0)\), the system is isothermal \((dT=0)\), the magnetic susceptibility obeys the Curie-Weiss law and is only a function of temperature, thus, \(d\chi=0\), the change in Gibbs free energy may be simplified to,

\[
dG = H^2 \mu_o \chi dV + V dp \quad \text{(B.9)}
\]

If the mixture of gases consists of only ideal gases which follow the ideal gas law, \(PV=nR_uT\) then equation B.9 may be written as,

\[
d\left(\frac{G}{R_uT}\right) = n \left[ \frac{dp}{p} - H^2 \mu_o \chi \left( \frac{1}{p} \right) \right] \quad \text{(B.10)}
\]

Integrating equation B.10 from a reference state to a specified state yields,

\[
\frac{G}{R_uT} = n \left[ \frac{\bar{p}^0}{R_uT} + \ln \left( \frac{p}{p_o} \right) + H^2 \mu_o \chi \left( \frac{1}{p} - \frac{1}{p_o} \right) \right] \quad \text{(B.11)}
\]

which for a mixture of \(n_s\) species, it can be written as,

\[
\frac{G_{mix}}{R_uT} = \sum_{i=1}^{n_s} n_i \left[ \frac{\bar{p}^0}{R_uT} + \ln \left( \frac{p_i}{p_o} \right) + H^2 \mu_o \chi_i \left( \frac{1}{p_i} - \frac{1}{p_o} \right) \right] \quad \text{(B.12)}
\]

for a mixture of ideal gases, the partial pressure can be written as \(p_i=(n_i/n_{tot})p\) where \(n_{tot}\) is the total number of moles.

\[
\frac{G}{R_uT} = \sum_{i=1}^{n_s} n_i \left[ \frac{\bar{p}^0}{R_uT} + \ln \left( \frac{n_i}{n_{tot}} \right) + \ln(p) + \frac{H^2 \mu_o \chi_i}{n_i} \left( \frac{n_i}{n_{tot}} - \frac{1}{p_o} \right) \right] \quad \text{(B.13)}
\]

At equilibrium, \(G/R_uT\) is at a minimum, subject to the elemental composition being fixed.

The conservation of mass of the constituent elements in a chemical reaction is defined as

\[
\sum_{i=1}^{n_s} a_{ij} n_i - b_j = 0 \quad \text{(B.14)}
\]
where $G/R_u T$ needs to be minimized subject to the constraints of equation (B.14). This can be accomplished with the use of Lagrangian multipliers \cite{12} by defining the objective function $L$ as,

$$L = \sum_{i=1}^{n_s} \left[ \frac{\bar{g}_i^o}{R_u T} + \ln \left( \frac{n_i}{n_{tot}} \right) + \ln(p) + \frac{H^2 \mu_o \chi_i}{n_i p_{o}} \right] - \sum_{j=1}^{n_v} \lambda_j \sum_{i=1}^{n_s} (a_{ij} n_i - b_j) \quad (B.15)$$

where the required solution will occur when $L$ is a minimum. The derivative of $L$ is calculated to be,

$$\frac{\partial L}{\partial n_i} = \frac{\bar{g}_i^o}{R_u T} + \frac{\partial}{\partial n_i} \left( n_i \ln(n_i) - n_i \ln(n_{tot}) \right) + \ln(p) + \sum_{i=1}^{n_s} \frac{H^2 \mu_o \chi_i}{n_i p_{o}} - \sum_{j=1}^{n_v} \lambda_j a_{ij} \quad (B.16)$$

where,

$$\frac{\partial}{\partial n_i} \left( n_i \ln(n_i) - n_i \ln(n_{tot}) \right) = \ln(n_i) + n_i \frac{\partial}{\partial n_i} \left( \ln(n_i) - \ln(n_{tot}) \right) - n_i \frac{\partial}{\partial n_i} \left( \ln(n_{tot}) \right) = \ln \left( \frac{n_i}{n_{tot}} \right) \quad (B.17)$$

Substituting B.17 into B.16 results in the objective function,

$$\frac{\partial L}{\partial n_i} = \frac{\bar{g}_i^o}{R_u T} + \ln \left( \frac{n_i}{n_{tot}} \right) + \ln(p) + \sum_{i=1}^{n_s} \frac{H^2 \mu_o \chi_i}{p_{o}} - \sum_{j=1}^{n_v} \lambda_j a_{ij} = 0 \quad (B.18)$$

This results in a system of equations where there are $n_v$ equations of type (B.14) and $n_s$ equations of type (B.18). The unknowns are $n_s$ values of the mole numbers $n_i$ and $n_v$ Lagrangian multipliers $\lambda_i$. This set of non-linear equations can be solved iteratively using the Newton-Raphson method.

The values used for the volumetric susceptibility of each of the ten species involved in the analysis are listed in Table A.1 and were obtained from reference \cite{16}. In the analysis, it was assumed that the magnetic susceptibility of the species remained constant with temperature.

A Matlab code is also included in this Appendix, which is equivalent to the code used in Excel to solve the system of equations. Since the code in Excel is a built-in function, it cannot
be included. Nonetheless, the Matlab code uses the same process to solve the equations and was tested to give the same results.

<table>
<thead>
<tr>
<th>Species</th>
<th>Volumetric Magnetic Susceptibility $\chi_v$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO$_2$</td>
<td>-1.12E-08</td>
</tr>
<tr>
<td>H$_2$O</td>
<td>-5.48E-09</td>
</tr>
<tr>
<td>CO</td>
<td>-6.27E-09</td>
</tr>
<tr>
<td>N$_2$</td>
<td>-6.38E-09</td>
</tr>
<tr>
<td>O$_2$</td>
<td>1.83E-06</td>
</tr>
<tr>
<td>OH</td>
<td>-3.87E-09</td>
</tr>
<tr>
<td>H</td>
<td>-3.28E-09</td>
</tr>
<tr>
<td>O</td>
<td>-5.17E-09</td>
</tr>
<tr>
<td>H$_2$</td>
<td>-2.11E-09</td>
</tr>
<tr>
<td>NO</td>
<td>7.77E-07</td>
</tr>
</tbody>
</table>

**Table A.1:** Volumetric Magnetic Susceptibility values for different species [16]

**MATLAB CODE**

```matlab
function f=nle(x)

Ru=8.315;                                  %Problem Properties
T=2500;
B=0.5;
mu=4*pi*10e-7;
H=B/mu;

GCO2=-396152;                             %Gibbs Energy of Formation
GH2O=-106555;
GCO=-327245;
GN2=0;
GO2=0;
GOH=2400;
GH=76672;
GO=88203;
GH2=0;
GNO=58711;
```

88
XCO2= -8.923e-10*4*pi;  
%Magnetic Susceptibilities
XH2O= -4.363e-10*4*pi;
XCO= -4.988e-10*4*pi;
XN2= -5.076e-10*4*pi;
XO2= 1.459e-7*4*pi;
XOH= 3.87e-9*4*pi;
XH= -2.61e-10*4*pi;
XO= -4.117e-10*4*pi;
XH2= -1.682e-10*4*pi;
XNO= 6.184e-8*4*pi;
S= 4.0172e-5*4*pi;

%Equations
f(1)=x(1)+x(3)-1;
f(2)=2*x(2)+x(6)+x(7)+2*x(9)-4;
f(3)=2*x(1)+x(2)+2*x(5)+x(6)+x(8)+x(10)-5;
f(4)=2*x(4)+x(10)-18;
f(5)={(GCO2/(Ru*T))+log(abs(x(1)/x(15)))+log(1)+(1*(x(11)/(Ru*T)))+(0*(x(12)/(Ru*T)))+(2*(x(13)/(Ru*T)))+(0*(x(14)/(Ru*T)))+S-(H*mu*XCO2/101325);
f(6)={(GH2O/(Ru*T))+log(abs(x(2)/x(15)))+log(1)+(0*(x(11)/(Ru*T)))+(2*(x(12)/(Ru*T)))+(1*(x(13)/(Ru*T)))+(0*(x(14)/(Ru*T)))+S-(H*mu*XH2O/101325);
f(7)={(GCO/(Ru*T))+log(abs(x(3)/x(15)))+log(1)+(1*(x(11)/(Ru*T)))+(0*(x(12)/(Ru*T)))+(1*(x(13)/(Ru*T)))+(0*(x(14)/(Ru*T)))+S-(H*mu*XCO/101325);
f(8)={(GN2/(Ru*T))+log(abs(x(4)/x(15)))+log(1)+(2*(x(14)/(Ru*T)))+S-(H*mu*XN2/101325);
f(9)={(GO2/(Ru*T))+log(abs(x(5)/x(15)))+log(1)+(2*(x(13)/(Ru*T)))+S-(H*mu*XO2/101325);
f(10)={(GOH/(Ru*T))+log(abs(x(6)/x(15)))+log(1)+(1*(x(12)/(Ru*T)))+(1*(x(13)/(Ru*T)))+S-(H*mu*XOH/101325);
f(11)={(GH/(Ru*T))+log(abs(x(7)/x(15)))+log(1)+(1*(x(12)/(Ru*T)))+S-(H*mu*HX/101325);
f(12)={(GO/(Ru*T))+log(abs(x(8)/x(15)))+log(1)+(1*(x(13)/(Ru*T)))+S-(H*mu*HXO/101325);
f(13)={(GH2/(Ru*T))+log(abs(x(9)/x(15)))+log(1)+(2*(x(12)/(Ru*T)))+S-(H*mu*HX2/101325);
f(14)={(GNO/(Ru*T))+log(abs(x(10)/x(15)))+log(1)+(1*(x(13)/(Ru*T)))+S-(H*mu*XNO/101325);
f(15)=x(15)-x(1)-x(2)-x(3)-x(4)-x(5)-x(6)-x(7)-x(8)-x(9)-x(10);

x0=[1 1 1 1 1 1 1 1 1 1 1 1 1 1 1]  %Initial Guess
x=fsolve(nle, x0)  %Solve the system of equations

89
APPENDIX C- FLAME HEIGHT AND TEMPERATURE DATA OBTAINED BY SWAMINATHAN IN REFERENCE [5]

The following table shows data obtained by Swaminathan [5] for flame height for three different cases: (1) No magnetic field, (2) Decreasing gradient magnetic field at a maximum flux density of 0.27 Tesla, and (3) Increasing gradient magnetic field at a maximum field flux density of 0.27 Tesla. Tables C.2 and C.3 show the axial temperature for these three different cases at speeds of 0.9 cm./sec and 2.6 cm./sec, respectively. The temperature measurements were corrected for radiation losses in the thermocouple. This information is used in Chapter 5 of this thesis to calculate the amount of oxygen concentration increase around a diffusion flame for the speeds in which temperature was measured.

<table>
<thead>
<tr>
<th>( \text{C}_3\text{H}_8 ) velocity (cm/sec)</th>
<th>Cold Flow Conditions</th>
<th>Measured Flame length(cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( \text{Re} )</td>
<td>( \text{Fr} )</td>
</tr>
<tr>
<td>5.2</td>
<td>74</td>
<td>0.043452</td>
</tr>
<tr>
<td>3.9</td>
<td>56</td>
<td>0.024442</td>
</tr>
<tr>
<td>2.6</td>
<td>37</td>
<td>0.010863</td>
</tr>
<tr>
<td>1.3</td>
<td>19</td>
<td>0.002716</td>
</tr>
<tr>
<td>1.2</td>
<td>17</td>
<td>0.002155</td>
</tr>
<tr>
<td>1.1</td>
<td>15</td>
<td>0.001782</td>
</tr>
<tr>
<td>0.9</td>
<td>12</td>
<td>0.001091</td>
</tr>
</tbody>
</table>

**Table C.1**: Measured flame height data for different propane speeds [5]
**Table C.2:** Axial temperature measurements for a flow speed of 0.9 cm./sec [5]

<table>
<thead>
<tr>
<th>Location above burner in mm</th>
<th>No Field</th>
<th>$B_z=2.77$ kGs</th>
<th>No field</th>
<th>$B_z=2.77$ kGs</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Uncorrected Temp, K</td>
<td>Uncorrected Temp, K</td>
<td>Corrected Temp, K</td>
<td>Corrected Temp, K</td>
</tr>
<tr>
<td>1</td>
<td>836</td>
<td>934</td>
<td>850</td>
<td>956</td>
</tr>
<tr>
<td>2</td>
<td>1073</td>
<td>1163</td>
<td>1111</td>
<td>1216</td>
</tr>
<tr>
<td>4</td>
<td>1241</td>
<td>1298</td>
<td>1310</td>
<td>1380</td>
</tr>
<tr>
<td>6</td>
<td>1287</td>
<td>1415</td>
<td>1367</td>
<td>1531</td>
</tr>
<tr>
<td>8</td>
<td>1325</td>
<td>478</td>
<td>1415</td>
<td>1617</td>
</tr>
<tr>
<td>10</td>
<td>1381</td>
<td>1327</td>
<td>1487</td>
<td>1417</td>
</tr>
<tr>
<td>12</td>
<td>1315</td>
<td>1152</td>
<td>1402</td>
<td>1202</td>
</tr>
<tr>
<td>15</td>
<td>1060</td>
<td>-</td>
<td>1096</td>
<td>-</td>
</tr>
</tbody>
</table>
Table C.3: Axial temperature measurements for a flow speed of 2.6 cm./sec [5]

<table>
<thead>
<tr>
<th>Location above burner in mm</th>
<th>No field Uncorrected Temp, K</th>
<th>B&lt;sub&gt;e&lt;/sub&gt;=2.77kGs Uncorrected Temp, K</th>
<th>No field Corrected Temp, K</th>
<th>B&lt;sub&gt;e&lt;/sub&gt;=2.77kGs Corrected Temp, K</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>618</td>
<td>786</td>
<td>622</td>
<td>797</td>
</tr>
<tr>
<td>3</td>
<td>950</td>
<td>1021</td>
<td>973</td>
<td>1052</td>
</tr>
<tr>
<td>6</td>
<td>1074</td>
<td>1151</td>
<td>1113</td>
<td>1202</td>
</tr>
<tr>
<td>9</td>
<td>1166</td>
<td>1213</td>
<td>1220</td>
<td>1276</td>
</tr>
<tr>
<td>12</td>
<td>1210</td>
<td>1268</td>
<td>1272</td>
<td>1343</td>
</tr>
<tr>
<td>15</td>
<td>1238</td>
<td>1318</td>
<td>1306</td>
<td>1406</td>
</tr>
<tr>
<td>18</td>
<td>1288</td>
<td>1376</td>
<td>1368</td>
<td>1480</td>
</tr>
<tr>
<td>21</td>
<td>1360</td>
<td>1447</td>
<td>1459</td>
<td>1574</td>
</tr>
<tr>
<td>24</td>
<td>1373</td>
<td>1355</td>
<td>1476</td>
<td>1453</td>
</tr>
<tr>
<td>27</td>
<td>1295</td>
<td>1129</td>
<td>1377</td>
<td>1176</td>
</tr>
<tr>
<td>30</td>
<td>1131</td>
<td>-</td>
<td>1178</td>
<td>-</td>
</tr>
</tbody>
</table>
APPENDIX D- IMAGE ANALYSIS MATLAB CODE

The Matlab image processing toolbox was used throughout this thesis to analyze structural features in both soot and flame images. The granulometry code in this appendix was used to obtain the results presented in Chapter 5 when estimating the size of the particles in each agglomerate. The color segmentation code was written to segment the flame images shown in Chapter 8 and it is useful to help visualize the structure of a flame. It is noted that Matlab requires the image processing toolbox to be installed in order to run both of these codes and the statistical toolbox is also required to run the color segmentation code.

GRANULOMETRY CODE

```matlab
J = imread('soot.png');
clahel = adapthisteq(J,'NumTiles',[10 10]); %Enhance Image
clahel = imadjust(clahel);
imshow(clahel);

for counter = 0:50 %Determine intensity distribution
    remain = imopen(clahel, strel('disk', counter));
    intensity_area(counter + 1) = sum(remain(:));
end

figure,plot(intensity_area, 'm-*'); %Plot surface area intensity
title('Sum of pixel values in opened image as a function of radius');
xlabel('Radius of opening (pixels)');
ylabel('Pixel value sum of opened objects (intensity)');

intensity_area_prime= diff(intensity_area); %Calculate first derivative
plot(intensity_area_prime, 'm-*');

figure,plot(intensity_area_prime, 'b-*'); %Plot results
set(gca, 'xtick', [0 2 4 6 8 10 12 14 16 18 20 22]);
xlabel('Radius of soot (pixels)');
ylabel('Sum of pixel values in soot as a function of radius');
```

93
COLOR SEGMENTATION CODE

I = imread('flame.png'); %Read Image

cform = makecform('srgb2lab');
lab_I = applycform(I,cform); % Convert image to L*a*b color space

ab = double(lab_I(:,:,2:3)); %Use k-means to classify the colors
nrows = size(ab,1);
ncols = size(ab,2);
ab = reshape(ab,nrows*ncols,2);

nColors = 3; %Select number of colors
[cluster_idx cluster_center] = kmeans(ab,nColors,'distance','sqEuclidean', 'Replicates',3);

pixel_labels = reshape(cluster_idx,nrows,ncols); %Label each color from k-means
segmented_images = cell(1,3);
rgb_label = repmat(pixel_labels,[1 1 3]);
for k = 1:nColors
    color = I;
    color(rgb_label ~= k) = 0;
    segmented_images{k} = color;
end

imshow(segmented_images{1}) %Display the segmented images
imshow(segmented_images{2})
imshow(segmented_images{3})
APPENDIX E- FOURIER TRANSFORM MATLAB CODE

The following is the code used to perform a Fast Fourier Transform (FFT) on the data for the change in length of a flame at different speeds in Chapter 7. The output gives a plot of the data as well as the calculated frequency spectrum.

clear all
load 160.txt
Fs = 30; % Sampling frequency
T = 1/Fs; % Sample time
L = 31; % Length of signal
t = (0:L-1)*T; % Time vector
y=X160(:,2);

subplot(2,1,1);
a=0:0.001:1;
B=0.185*sin(2*pi*(2*2.67*a))+0.185;
[AX,H1,H2]=plotyy(t,y,a,B);
title('Flame Length Change and Magnetic Field Flux Density')
set(get(AX(1),'Ylabel'), 'String','Change in Length (pixels)');
set(get(AX(2),'Ylabel'), 'String','Magnetic Field Flux Density B (Tesla)', 'Color','k');
set(AX(1),'ycolor','k');
set(AX(2),'ycolor','r');
set(AX(2),'Ylim', [0 0.5]);
set(AX(2),'YTick', [0:0.25:0.5]);
xlabel('Time (sec)');
ylabel('Change in Length (pixels)');
set(H1, 'Color','k');
set(H2, 'Color','r','Linestyle',':');

NFFT = 2^nextpow2(L); % Next power of 2 from length of y
Y = fft(y,NFFT)/L;
f = Fs/2*linspace(0,1,NFFT/2+1);

% Plot single-sided amplitude spectrum.
subplot(2,1,2);
plot(f,2*abs(Y(1:NFFT/2+1)),'Color','k')
title('Amplitude Spectrum of Flame Length Change')
xlabel('Frequency (Hz)')
ylabel('Amplitude')
APPENDIX F- FINITE ELEMENT METHOD MAGNETICS OVERVIEW [34]

Finite Element Method Magnetics (FEMM) is a finite element package for solving 2D planar and axisymmetric problems in low frequency magnetics and electrostatics. This software package was used extensively throughout this thesis for numerical calculations of magnetic flux density profiles. The program runs under Windows 95, 98, ME, NT, 2000 and XP. The program may be obtained via the FEMM home page at http://femm.foster-miller.com. Tutorials on how to use it maybe be found on the Documentation section of the website.

The package is composed of an interactive shell encompassing graphical pre- and post-processing, a mesh generator, and various solvers. A powerful scripting language, Lua 4.0, is integrated with the program. Lua allows users to create batch runs, describe geometries parametrically, perform optimizations, etc. Lua is also integrated into every edit box in the program so that formulas can be entered in lieu of numerical values, if desired. (Detailed information on Lua is available from http://www.lua.org.) There is no hard limit on problem size—maximum problem size is limited by the amount of available memory. Users commonly perform simulations with as many as one million elements [34].
VITA

Diego Felipe Gonzalez was born in Pasto, Colombia, to Dario and Ana Maria Gonzalez. He spent the first 7 years of his life living in Bogota, Colombia, but then moved with his family to Quito, Ecuador. He graduated from the American School of Quito in 2002 and began his undergraduate studies at Louisiana State University later that year. As an undergraduate, Diego obtained research experience in micro-technology where he assisted Dr. Michael Murphy in the design and fabrication of thermal micro-sensors. During this time, he worked on the fabrication of carbon X-ray masks used in the LIGA process and wrote an instruction manual to expedite their fabrication process. Diego then began his work with Dr. Tryfon Charalampopoulos in an independent research class, which focused on the understanding of the effects of magnetic fields on flames. Later that year, he enrolled in the Mechanical Engineering 3-2 Accelerated Masters Program with Dr. Charalampopoulos as his advisor. During this time, he became an Associate Editor for the Journal of Young Investigators in the Engineering and Technology Section. Diego obtained his Bachelor of Science in Mechanical Engineering, Magna Cum Laude, in May 2008. Presently, Diego is a candidate for the degree of Master of Science in Mechanical Engineering.