ABSTRACT

RAMNATH, VIKRAM. Investigation of the Impact of Low Strength Gradient Magnetic Fields on Jet Diffusion Flames. (Under the direction of Dr. Kevin M. Lyons).

A method to manipulate propane diffusion flame using low strength permanent magnets has been studied in this work. It involves determining the impact of increasing and decreasing gradient magnetic fields on flame structure and liftoff height as a possible route towards flame stabilization and combustion control.

A non-uniform magnetic field was produced by using two low strength permanent magnets mounted on an iron yoke. Propane/air flames with different flow velocities corresponding to an attached (diffusion or non-premixed) and lifted flame (partially premixed) produced by two different burners were subject to the non-uniform field. To extract only the impact of the magnetic force on flames from the buoyance force generated due to the presence of the yoke, a yoke made of aluminum possessing the exact geometry of the magnetic yoke is fabricated and all the baseline investigations are done in the presence of this yoke, called "false magnet".

The direction of the gradient field, type of flame and fuel jet velocities were identified as the key parameters that would affect the flame structure. Flames attached to the burner lip were fist studied. For an increasing gradient field from the burner lip, it was observed that, an increasing field increased the height of the flame and this effect was more pronounced at higher flow rates. A decrease in the flame height was observed in the presence of a decreasing gradient field. The presence of the yoke rendered flame width measurements inaccurate.

The impact of the gradient field on lifted flames was also studied. It was observed that the liftoff height was decreased in the presence of an increasing and a decreasing gradient field; this effect appeared to be independent of the burner size. This observation can be attributed due to the two effects caused due to the presence of the yoke – the aerodynamics effect and the magnetic field effect. The liftoff height is appeared to be reduced by both these effects.

Investigations of the Impact of Low Strength Gradient Magnetic Fields on Jet Diffusion Flames

by
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DEDICATION

To my mother and father for their never-ending support.

BIOGRAPHY

The author was born and raised in India. He graduated with a Bachelor's degree in Aeronautical Engineering from Anna University in the year 2015. He started his study at NC State in 2016 for Masters of Science in Mechanical Engineering, where he joined the Lyons Research Group and started working on effect of magnetism on diffusion flames.

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I would like to thank all my friends and lab mates who helped me overcome difficulties at every step in this project and supported me in running the experiments.

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1. INTRODUCTION

Ever since the discovery of fire, understanding its uses has fueled mankind's progress and propelled us to where we stand at present. Developing uses for the energy obtained from the combustion of fossil fuels has been key to technological advancements over the centuries. The development of every modern combustor has been the result of several years of research, and there is still ongoing experimental and computational research aimed towards improving our understanding of complex combustion phenomena. The impact of combustion has never diminished and it continues to be a phenomenon that plays a significant role in our daily lives – predominantly in transportation and energy. The combustion process has several benefits but fossil fuel combustion also brings with it some environmental hazards. Over the past quarter century, with a large increase in the demand for energy, the attention of scientists, engineers and policymakers has been directed towards reducing pollution. Therefore, from the age when the first combustion researcher confirmed that rubbing two stones to obtain a spark was a repeatable experiment, we have come a long way to the 21st century, where the focus is on goals such as minimizing pollutant emissions and maximizing combustion efficiency. 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.

1.1 Laminar Diffusion Flames

A diffusion flame is a flame in which fuel and oxidizer come together in a reaction zone through molecular and turbulent diffusion. The fuel may be in the form of a gaseous fuel jet or a condensed medium (either solid or liquid), and the oxidizer may be a flowing gas stream or the quiescent atmosphere. The distinctive characteristic of a diffusion flame is that the burning rate is determined by the rate at which the fuel and oxidizer are brought together in proper proportions for reaction. 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 [1].

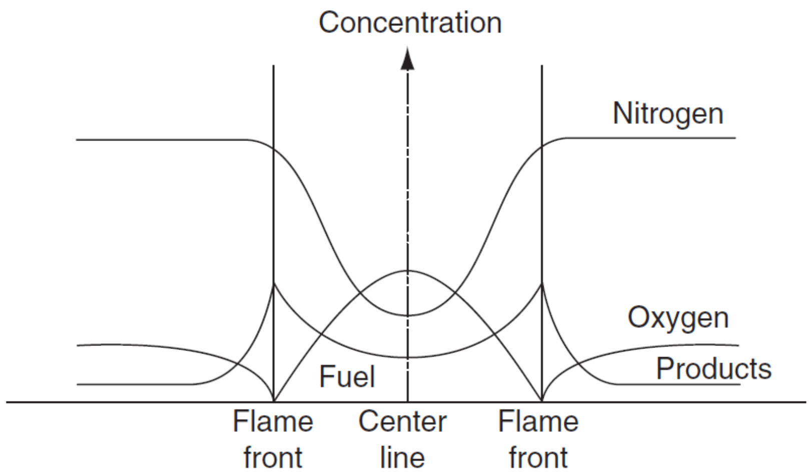

Figure 1.1: Species variations through a gaseous fuel–air diffusion flame

Diffusion flames can either be laminar or turbulent. 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 [1].

Flames can be classified into two categories, over ventilated and under ventilated. If the volume of air required for combustion is in excess of the stoichiometric amount required, the flame is classified as overventilated or fuel lean. If the volume of air is reduced below an initial mixture strength corresponding to the stoichiometric required amount, an underventilated or fuel rich flame is produced. In this case, all the oxygen is consumed and complete combustion is not obtained. Under ventilated flames mostly occur in constrained environments [1].

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. Effective diffusion of a flame from the fuel outward and oxidizer inward is important to ensure a proper amount of ventilation in the process.

When the fuel mass flow rate exceeds a critical value, the base of the diffusion flame leaves the burner tip and remains suspended above the burner exit section as shown in Figure 1.2. The phenomenon is known as liftoff. This flame is not strictly a diffusion flame now, since air entrained at the leading edge produced some premixing. Such flames are often referred to as "partially-premixed" flames. When the mass flow rate increases further, the liftoff height increases until the flame becomes flat and then blows out.

Figure 1.2: Lifted Diffusion Flame

A lifted flame is stabilized through the triple flame mechanism. A triple flame is a flame structure that has been observed in partially premixed regimes. In fact, just upstream the flame, premixing occurs and the flame front is formed of two branches, a fuel rich branch develops in the direction of the fuel stream and a fuel lean branch on the air side. Behind these two branches, hot fuel and oxidizer burn in a trailing diffusion flame along a stoichiometric surface forming the third part of the triple flame. The flame is said to be stabilized where the flame propagation speed with respect to the fuel-oxidizer matches the local flow velocity on the stoichiometric line.

In this study, the focus will only be laminar unconstrained configurations or free jets, issued from a circular burner port into a quiescent environment and it is assumed that gas velocity was constant and parallel to the flame axis [2].

1.2 Magnetism

Magnetism is a physical phenomenon produced by the motion of electric charge, resulting in attractive and repulsive forces between objects. 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. In this study, we will be using low strength permanent magnets.

1.2.1 Magnetic Materials

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. 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 expensive 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 moderately expensive 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.

1.2.2 Types of Magnetism

There are three main 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.

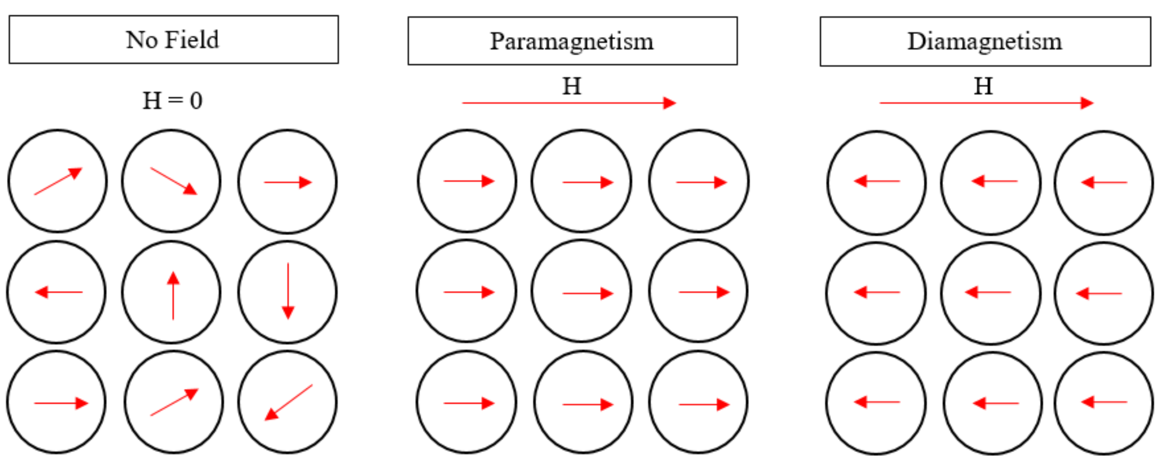

Figure 1.3: Types of magnetism

Paramagnetism is a result of unpaired electrons within an atom that can cause a magnetic dipole to form in the presence of a magnetic field [3]. In the presence of a magnetic field this effect causes the fluid to be drawn in the direction of increasing magnetic field strength. Paramagnetic materials such as molecular oxygen, possess randomly oriented dipole moments that align with the applied magnetic field and thus experience a weak attraction towards the applied field.

On the contrary, if the electrons are already paired, the atoms resist the formation of a dipole and this resistance causes the atoms to move in the direction of decreasing magnetic field strength, known as diamagnetism [3]. Diamagnetic materials develop a net dipole moment in the presence of an external magnetic field which opposes the applied field and the degree of repulsion increases with the strength of the applied magnetic field.

Paramagnetic behavior is about three orders of magnitude larger than the diamagnetic behavior [3]. Most gases such as carbon dioxide, nitrogen, hydrocarbons such as methane, butane, propane and the products of combustion are diamagnetic in nature and are repelled by an applied magnetic field while oxygen and air being paramagnetic in nature are attracted towards the applied magnetic field.

1.3 Magnetic Effects on Flames

The effect of electric fields on combustion is well established [4]. However, few studies have been conducted about the effect of magnetic fields on combustion, and the fact that magnetic fields can influence combustion was first realized over one hundred and fifty years ago. As early as 1846, Faraday applied a magnetic field to a flame on a wax taper and observed its tendency to form an equatorial disc [5]. He also found that the flames were more luminous when placed in an external magnetic field. Faraday attributed the change in the flame shape to the presence of charged particles in the flames interacting with the magnetic fields. Later, researchers found that the interaction between flame ions and the magnetic fields were much too small to cause the flame deflection. It was showed that the change in the flame shape could be attributed to the diamagnetic flame gases in the paramagnetic atmosphere.

Recently, there has been a renewed interest in this area. A majority of the research on the relation between combustion and magnetic fields has taken place in Japan and France. The nature of the studies has varied over a wide range, such as the influence of the magnetic fields on advancing gas flows, combustion reactions in premixed and diffusion flames, emission intensities of various radicals observed in flames, material synthesis and separation, and an extension of similar studies on these systems under a micro-gravity environment.

Ueno, S. and Harada, K. [6] observed that the flow of gases such as carbon dioxide, nitrogen and argon were observed to be blocked or perturbed when they traveled in the direction of a magnetic field of increasing strength, while a mixture of oxygen and aqueous aerosol has been found to be attracted towards a stronger field and behave as a magnetic fluid. Despite various theories that were proposed, the authors have primarily attributed this behavior to the diamagnetic and paramagnetic nature of the gases involved.

Ueno, S. [7] studied the impact of magnetic fields on flames and jets of diamagnetic and paramagnetic gases. In their study, gases such as carbon dioxide, nitrogen, argon, oxygen and methane were subjected to magnetic fields of 2.2 T. The flow of these gases were blocked or modified by the magnetic fields. It was suggested that the magnetic field's influence on the paramagnetic oxygen was the cause for the observed behavior. They proposed that oxygen concentrated in the region of highest magnetic field gradient, and exerted a magnetic pressure on other component gases due to its molecules forming a magnetic curtain that blocked the movement of the other gases.

Ueno, S. [7] also examined the ability of the magnetic field to quench flames. A candle flame between two columnar electromagnets, hollowed out, to enclose the flame was exposed to a field of 1.5 T in an air gap of 5-10 *mm*. The flame was quenched soon after the application of the magnetic field. It was even noticed that the flame life time increased with decreasing magnetic fields and fields below a critical value of 0.9 T would no longer quench the flame.

In a subsequent study by Ueno, S. and Iwasaka, M. [8] the effect of the above mentioned magnetic curtain were classified into three regimes. In the first regime, it was found that low flow velocities allowed the gas to diffuse through the magnetic curtain. In the second regime, as the flow rates were increased, the diffusion decreased till the flow was blocked from passing through the region of the steepest magnetic field gradient. And lastly in the third regime, it was observed that for higher flow rates beyond those in regime two, the gas diffused through the curtain once again though it was clearly pinched in the regions of highest field strength. This penetration in the third regime was due to the increased momentum of the gas molecules, and it was also noted that the specific effects in each of these regimes is a function of field strength, diamagnetic nature of the gases studied, physical dimensions of the air gap and the surrounding air.

Ueno et al. [9] studied slow combustion of gasoline as an analogy to cellular respiration in biological systems. Here, to simulate the biological processes, the fuel was burnt on the surface of platinum catalysts instead of direct burning. It showed a sinusoidal response in its burning velocity for increasing magnetic field strengths. The reasons for this behavior were not explained.

Wakayama, N.I. [10] studied the relationship between the direction of fuel flow and the steepest gradient of the magnetic field to determine the promotion of the combustion reaction on diffision and premixed flames. For the flames experiencing a decreasing magnetic field, it was observed that they became shorter and sharper. The temperature of the flames and its brightness was also observed to rise sharply during the application of the field. For the flames experiencing an increasing magnetic field, it was observed that they became flattened and combustion reaction appeared quenched. No significant changes were observed when they were exposed to uniform field gradients. The author inferred that combustion reaction was altered due to paramagnetic oxygen gas being attracted towards a stronger field, while the reaction products and fuel vapors are diamagnetic and flow towards a weaker field.

Aoki, T. [11] investigated butane diffusion flames within upward decreasing magnetic fields and found that the presence of the magnetic field caused an increase in the emission intensities of radicals OH*, CH* and C2* transitions, flame temperature and also a bluing tendency of the flame. The increase in the bluing tendency of the flame was attributed to a decrease in soot generation within the flame.

Similar experiments conducted by the author [12] determined that a reversal of the above observed effects compared to the previous study. The author inferred that, these observations depicts the magnetic field influence and the specific way it affects the diamagnetic fuel, hot gases and the paramagnetic oxidizer. A change in the diffusion and mixing patterns due to the applied field were found to be the cause of increased soot formation.

Gillon, P. et al. [13] studied the behaviour and stability of a laminar methane air flame with an air coflow for anchored and lifted conditions for different flow regimes. It was observed that application of the magnetic field reduces liftoff height and that it was dependent on the coflow air velocity. For the flame and coflow experiencing an upward increasing magnetic field gradient, it was observed that there was a decrease in the liftoff height. The author attributed the observation to the action of the magnetic gradient which blocked the ambient air at the entrance of the magnet. This reduced the entrainment by the air co-jet, resulting in the reduction of the flame lift height.

Mizutani, Y. et al. [14] studied the effect of a uniform magnetic field on premixed laminar flames. The structure of the flame was observed using a schlieren system. It was observed that the presence or absence of a magnetic field had no perceptable influence on the flame structure. They inferred that the magnetic field, even ones as high as 5 T had no effect on the burning veloity as it was dominated by high-speed chemical reactions.

Gilard, V. et al. [15] studied the behavior of a lifted diffusion flame with a central methane jet and surrounding air coflow under the influence of a non uniform magnetic field. They used an axi-symmetric burner that was surrounded by an air coflow. In their investigation, the velocity of the fuel jet was kept constant while the air coflow velociy was varied. The authors observed that the liftoff height and the behavior of the flame was dependent on the coflow velocity. They observed two different regimes of lifted flame behavior – lifted and stable flame that had a smooth flame base, and a noisy and oscillating flame with an instable front. They observed that the value of the air velocity where the lifted flame becomes unstable is delayed in the presence of an upward degreasing gradient field than in the no field case. They proposed that the liftoff height for a fixed fuel exit velocity depends on the air coflow velocity

Gilard, V. et al. [16] studied the influence of magnetic fields on the stability and blow out properties of a lifted methane/air co-flow diffusion flame. They introduced a “false magnet” to extract only the influence of magnetic field on the flow field. They observed that liftoff height was purely dependent on thee coflow air velocity. The authors concluded that magnetic gradients were able to increase flow rates above which blow off occurred.

Faris, A. et al. [17] investigated to effectiveness of magnetic fields in reducing fuel consumption and emissions on a two-stroke gasoline engine. They observed that under the influence of high magnetic fields, the percentage of carbon monoxide in the emissions was reduced slightly at the cost of an increase in carbon dioxide production. They also reported a 9% saving in the fuel consumption under certain conditions. They attributed these results to the ability of strong magnetic fields to alter the molecular structure of the hydrocarbon fuels.

1.4 Summary

Since the time of Faraday, there have been few studies specifically focused on the effects of magnetic fields on flames. Earlier studies had suggested the use of prohibitively high magnetic fields of about 5 Tesla for this effect to be noticeable. Recent studies using lower strength electromagnets studied the properties of lifted flames using an air coflow. The use of electromagnets is a major drawback of these investigations because they require significant energy to produce the magnetic fields. Also, the direct impact of these gradient fields on the flames and the hydrocarbon fuel is greatly diminished due to the paramagnetic nature of the co-flowing air that forms a shield around the diamagnetic combustion products. In order to fully understand the complex nature of the impact of magnetic fields on flame behavior, the effects of magnetic fields produced by permanent magnets of relatively low strengths are studied as a stepping stone to a possible route towards combustion control and flame stabilization by magnetism.

The objective of the current investigation is to determine if gradient magnetic fields produced by relatively low strength permanent magnets could effectively alter the combustion characteristics of a small laminar flame. The study anticipates to determine if these low strength magnetic fields can impact a flame outside a relatively narrow sphere of influence. The different properties of the flame such as liftoff height, flame structure of a propane jet flame is investigated and the work carried out in the course of this study is organized as follows.

In Chapter 2, the components of the experimental setup are described. The relevance of the components, methodology of the investigation and analysis is presented.

In Chapter 3, a summary of the observations, highlighting the significant findings are discussed.

In Chapter 4, the conclusions, and the recommendations for the future work about the possible areas that need to be addressed further along with improvisations that would enhance the findings of the current study are discussed.

2. EXPERIMENTATION

2.1 Experimental Setup

The investigation was conducted at the Reacting Flow and Turbulent Jets laboratory in the MAE department of NC State University. The description of the various components and the general setup used in this investigation is described in the following paragraphs. A picture of the experimental setup is shown in Figure 2.1. The experimental setup consists of the burner, yoke with the magnets, illuminated scale and the image capture device.

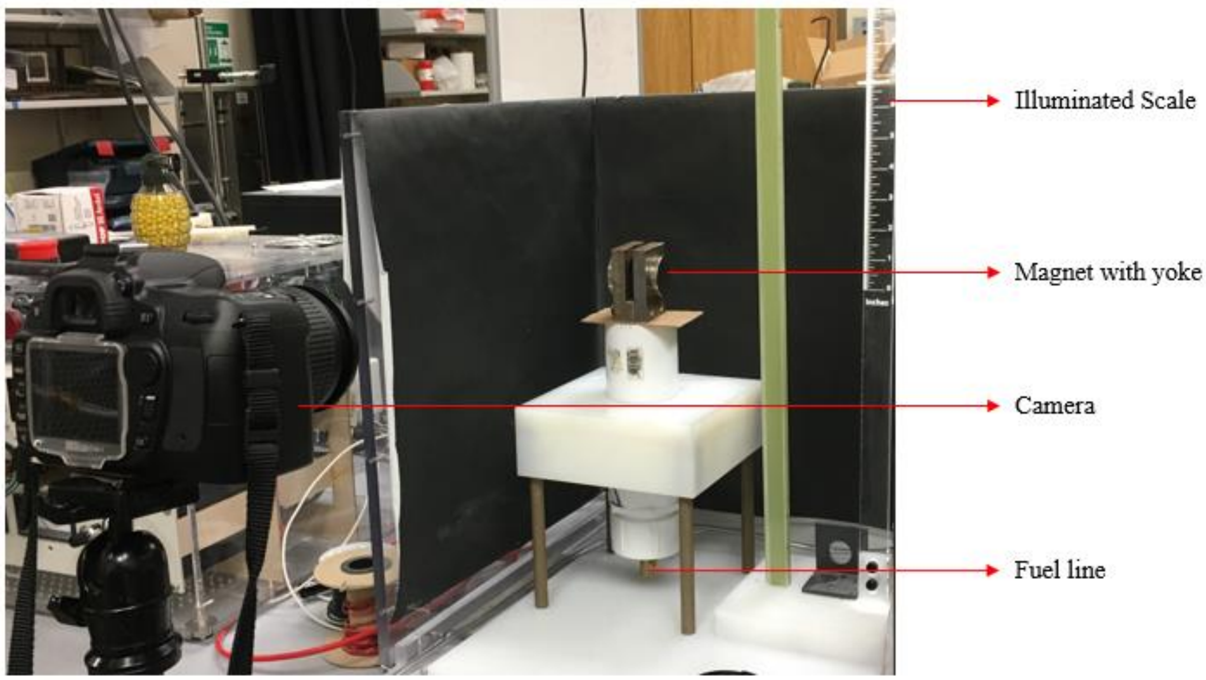

Figure 2.1: Experimental Setup

2.1.1 Burner

A schematic representation of the burner is shown in Figure 2.2. The burner consists of a cylindrical base set on a stand through which a series of PVC fittings have been configured. A gaseous fuel supply line is attached to the central fuel jet. The fuel jet, having an outer diameter of 1.57 *mm* is made of stainless steel and extends from the bottom of the apparatus through the center of the PVC fittings and ending outside the concentric PVC casing.

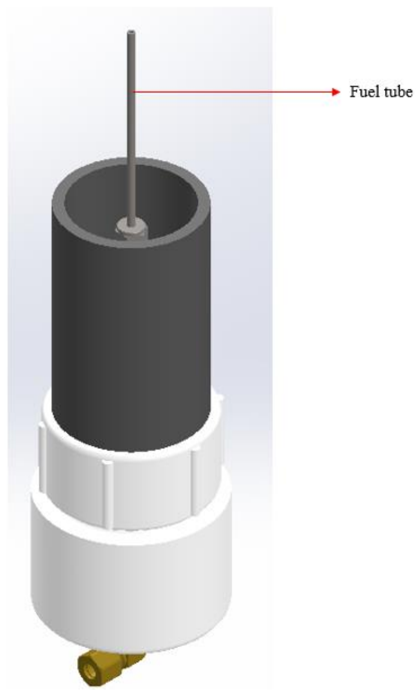

Figure 2.2: Burner CAD diagram

Two different fuel jets as shown in Figure 2.3, having a 0.81 *mm* and 0.55 *mm* inner diameter are selected for this investigation. Due to a burner length of 125 *mm*, the gas flow is assumed to be fully developed at the exit of the burner, with a Poiseuille-type velocity distribution.

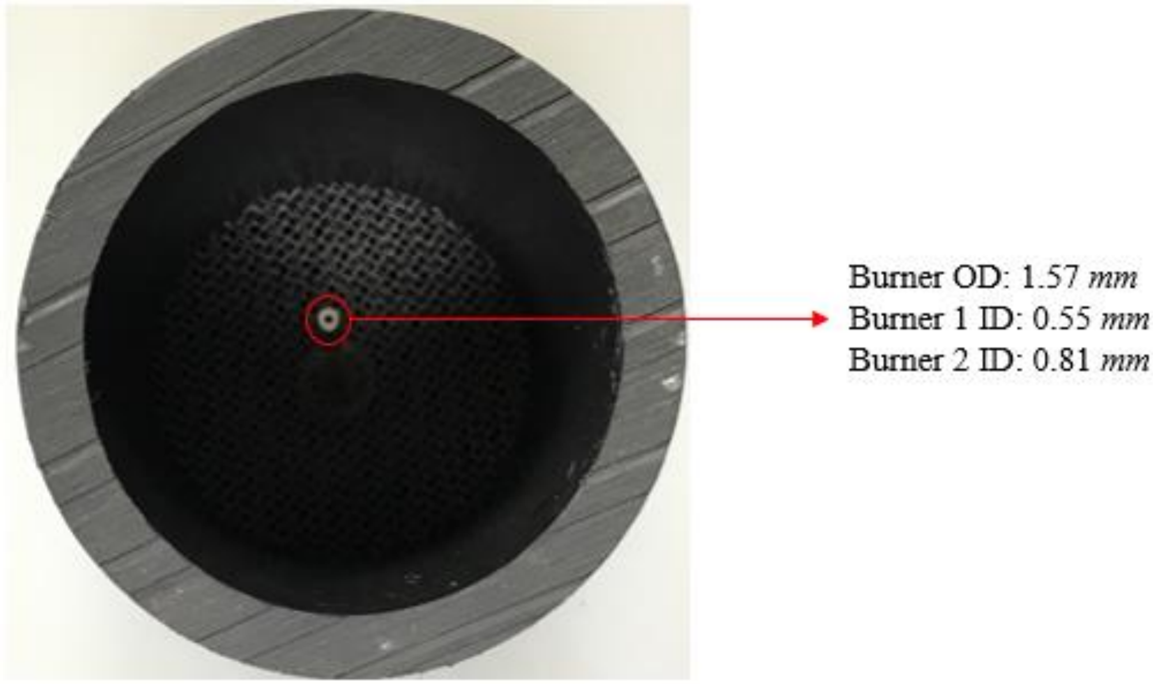

Figure 2.3: Burner top view

2.1.2 Fuel Supply

The fuel used, 99.0% pure CP grade propane (C_3H_8) was supplied from the cylinder. It flows through a Yor-Lok precision flow adjustment needle valve and was monitored using volumetric flow meter (OMEGA, FMA-A2309) having a range of 0-50 SLPM. The readings were estimated to be accurate within 5%. This range is sufficient for experiments to be performed over a wide range of jet velocities. A schematic of the laboratory fuel supply line is shown in Figure 2.4. Propane is injected at ambient temperature (i.e. 293 K)

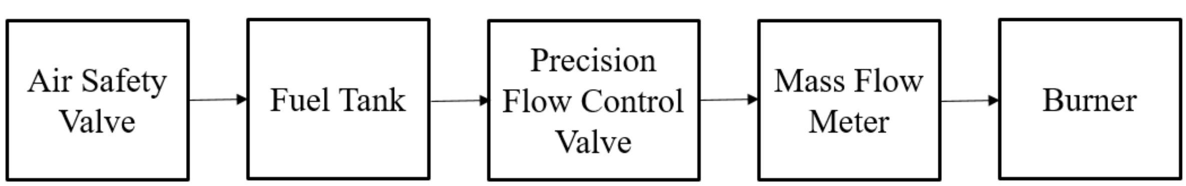

Figure 2.4: Fuel supply line schematic

2.1.3 Magnets

In this investigation, N52 grade permanent magnets (DX8C-N52) having a diameter of 37.6 *mm* and a depth of 19.05 *mm* is used to generate the gradient magnetic field. Two magnets, each of which could produce a pull force of 52.3 Kg towards a steel plate are used in the current investigation. Placing two of these magnets in an iron yoke completes a path for the magnetic flux which enables a magnetic field whose strength is stronger than the individual strength of the magnets, to be formed between the poles of the magnet. Two standard yoke designs that could be used to increase the magnetic field strength were considered:

i. Plain iron yoke

ii. Iron yoke with prisms

The predicted magnetic field strengths in obtained from the various yoke configurations are compared and shown in Figure 2.5.

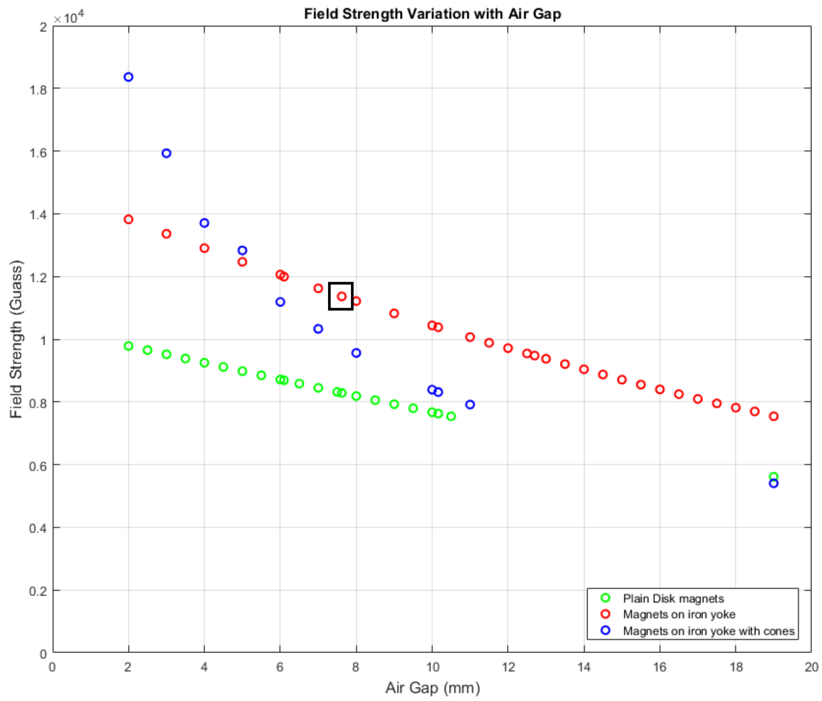

Figure 2.5: Yoke Selection

It is observed that in theory, magnets on the iron yoke with a 7.62 *mm* air gap produces a high field of ~1.1 T. This design is selected for its combination of a sufficiently high field and a reasonably big air gap and is fabricated. The yoke with the magnets is shown in Figure 2.6.

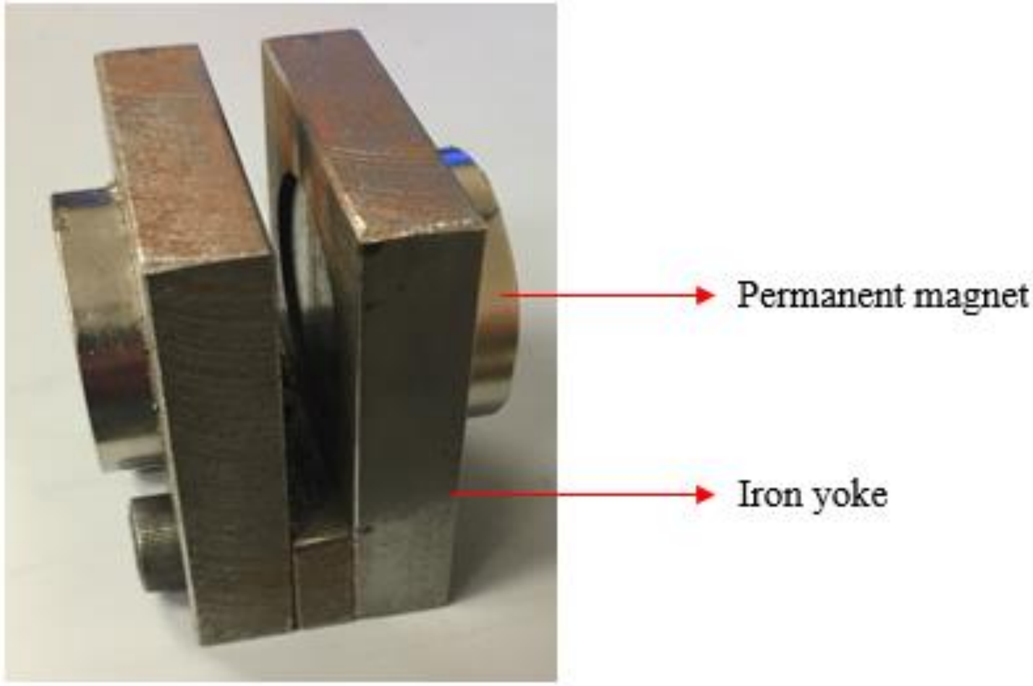

Figure 2.6: Iron yoke with magnets

The magnetic field induction was measured along the vertical z-axis position using a gauss meter with a transverse probe where the uncertainty of measurement was 1% and is shown in Figure 2.7.

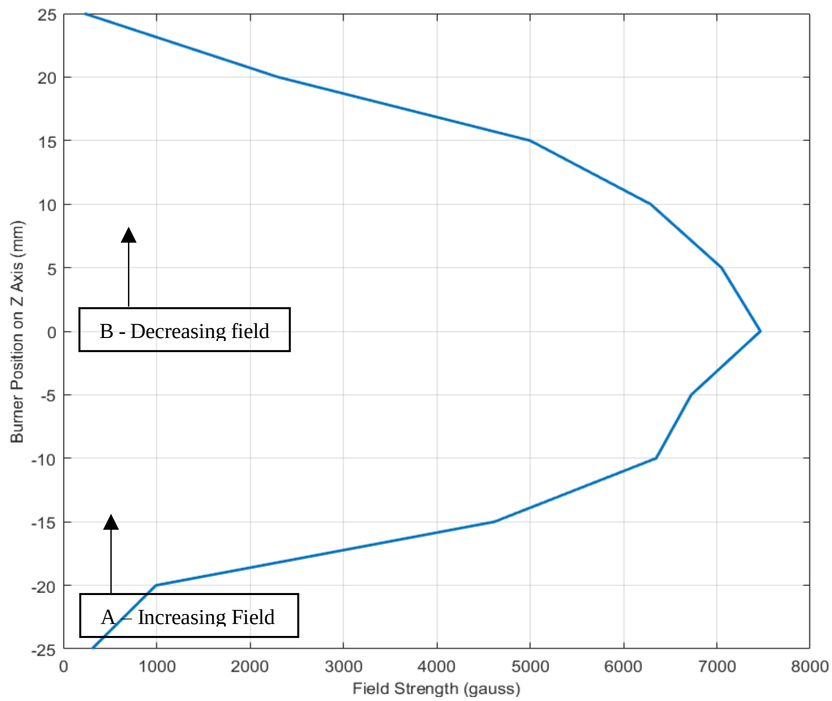

Figure 2.7: Actual magnet field strength variation

The yoke with the magnets is set to be mounted on the fuel jet as shown in Figure 2.8. The height of the fuel jet is adjusted to be in two vertical positions A and B in a manner that ensures the flame experiences an increasing gradient magnetic field when the burner is set at position A and a decreasing gradient magnetic field when it is set at position B. This arrangement is oriented in a manner that is best for image capture.

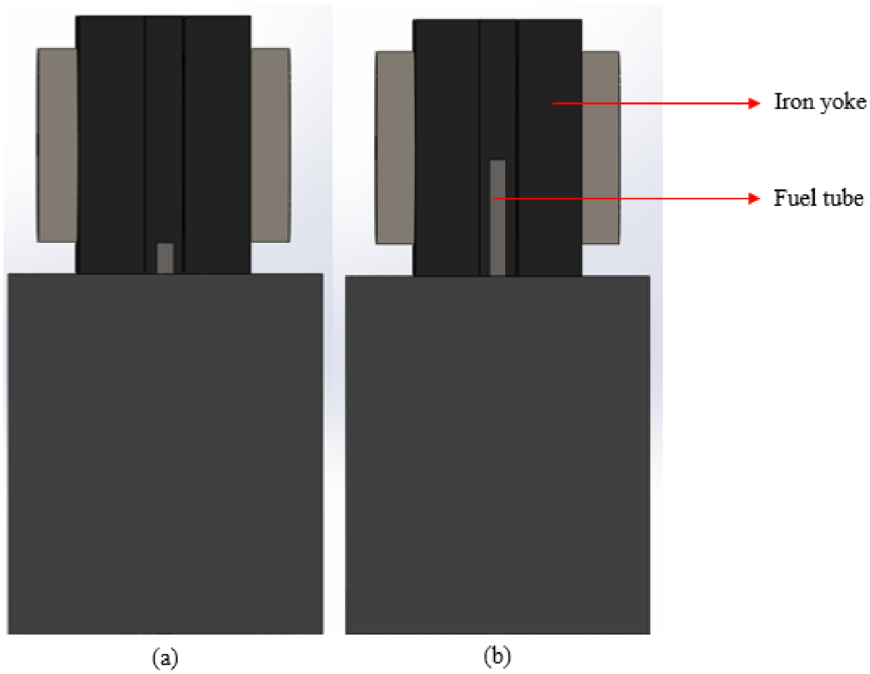

Figure 2.8: Comparison of fuel tube position for (a) increasing or (b) decreasing magnetic field

An active cooling arrangement for the magnets was deemed unnecessary as the duration of the individual experimental runs were short which ensured that the temperature of the yoke and the magnets did not reach the Curie temperature. The individual experiments were sufficiently spaced out to ensure this condition. A series analysis of the strength of the magnets after each successive test revealed no significant loss of magnetic strength and thus the assumption that the magnetic field strength remained constant throughout the investigation is supported.

2.3 Tests Performed

A set of experiments were carried out to determine the flame structure, liftoff height and the minimum flow required to sustain a lifted flame. The flame structure test is conducted to determine the impact of magnetic field gradients on the height of the diffusion flame. For a circular-port flame, the flame length does not depend on initial velocity or diameter but, rather, on the initial volumetric flow rate [4] so, the propane flow rate is varied to produce a flame whose height is within the influence of the magnetic field. The variation of the flame liftoff height under the influence of gradient fields is studied. The lifted flame investigation is conducted by varying the propane flow rate as required. The test matrix is shown in Table 2.1.

Table 2.1: Test matrix

	Increasing Gradient Field	Decreasing Gradient Field
0.55 *mm* Burner	Flame Structure Flame Liftoff height	Flame Structure Flame Liftoff height
0.81 *mm* Burner	Flame Structure Flame Liftoff height	Flame Structure Flame Liftoff Height

2.4 Post Processing

The flame images were captured using a digital single-lens reflex camera (Nikon Corp, Model: D80), and the flame images were analyzed using in house codes. The camera is mounted on a tripod and is positioned to accurately capture the flame. An illuminated scale is placed in the field of view. MATLAB is used to read and analyze the flame structure and liftoff height. The uncertainty of flame measurements for the structure and liftoff height determination are reduced by capturing multiple flame images and averaging them. In house codes are used to crop the image, sobel filter is used to obtain the flame outline as shown in Figure 2.9, and subsequently determine the flame structure and the liftoff height. The illuminated scale is used to calibrate the length measuring function of the code. The results of the code is used to plot the variation and is exported as a spreadsheet.

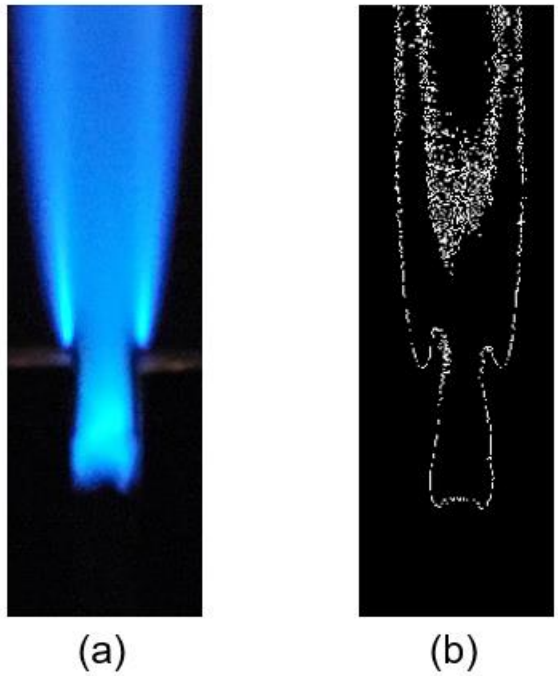

Figure 2.9: Comparison of (a) raw image obtained from camera and (b) corresponding image of the flame edge

3. RESULTS AND DISCUSSION

The behavior of laminar jet diffusion flames in the presence of gradient magnetic fields has been investigated for two different burners and the results of this experimental study are presented. Two different flame properties were studied as a part of this investigation – flame height and liftoff height. The flame height test was to determine the height of the flame which was considered to be the distance from the burner rim to the visible tip of the flame. The width of the flame width was unable to be captured due to the presence of the yoke which made width measurements highly inaccurate. The flame liftoff height analysis involved the determination of the distance between the visible flame base and the tip of the fuel jet. These measurements were determined using in house codes and were plotted along as a function of the fuel jet velocity.

Using a yoke to hold the magnets in place gives rise to two different impacts – a dynamic impact on the flow field and a magnetic impact. In this investigation, we consider only the magnetic impact on the flow field. To extract only the impact of the magnetic force on flames from the buoyance force generated due to the presence of the yoke, a yoke made of aluminum possessing the exact geometry of the magnetic yoke is fabricated and all the baseline investigations are done in the presence of the aluminum yoke. This aluminum yoke is called the “false magnet”.

3.1 Increasing Gradient Field

The variation in flame height and flame liftoff height in the presence of a gradient magnetic field whose strength was increasing from the burner lip is studied and is shown in Figure 3.1. This data is compared to measurements studied in the absence of a magnetic field.

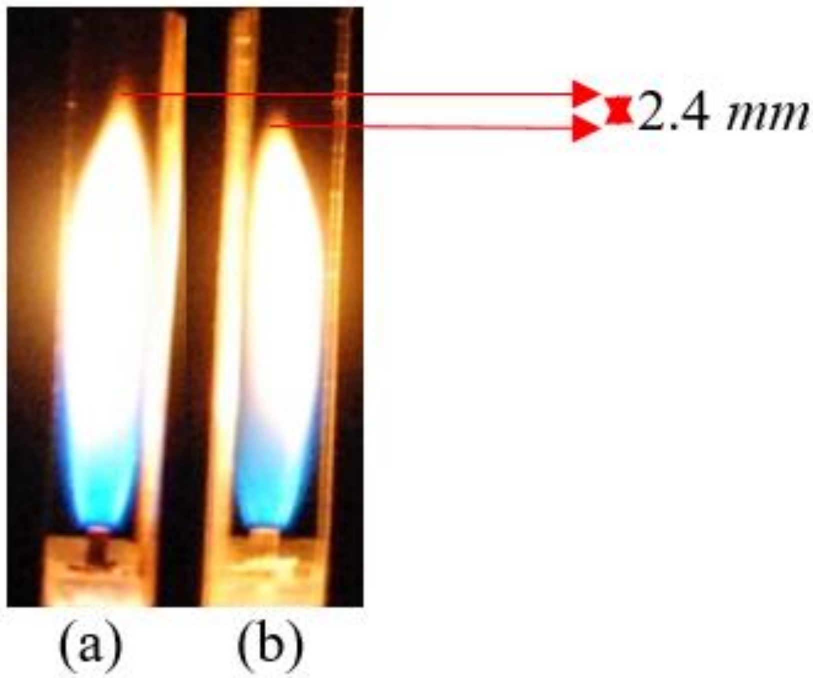

Figure 3.1: Flame height comparison (a) Increasing gradient field (b) No field

3.1.1 Flame Height

The variation of the flame height in the presence and absence of the gradient magnetic field were used to determine if it had a significant impact on the flame height. Figure 3.2 and Figure 3.3 show the variation in flame height for two different burner sizes and is compared to the flame height measured in the absence of a magnetic field.

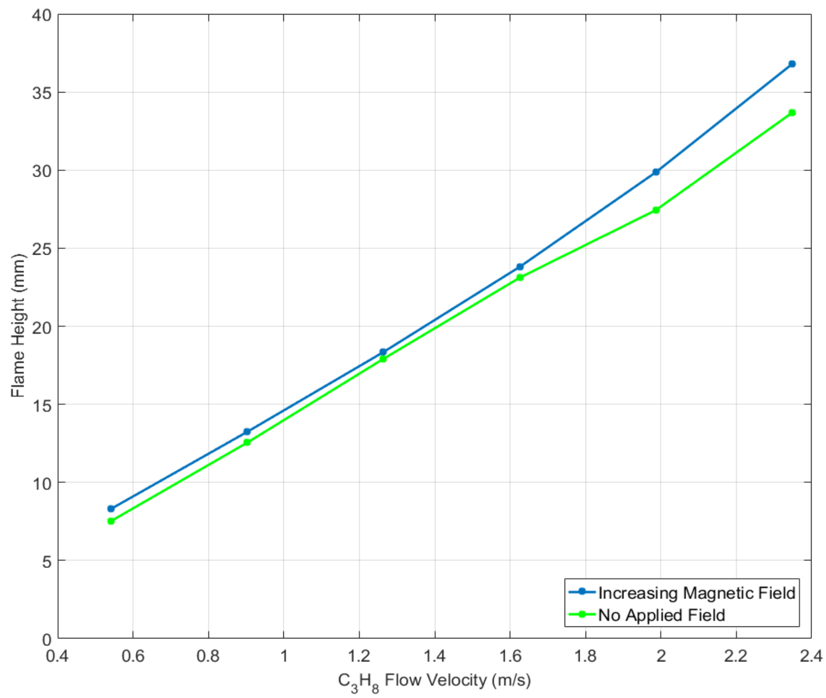

Figure 3.2: Flame height variation in an increasing gradient field for the 0.55 *mm* burner

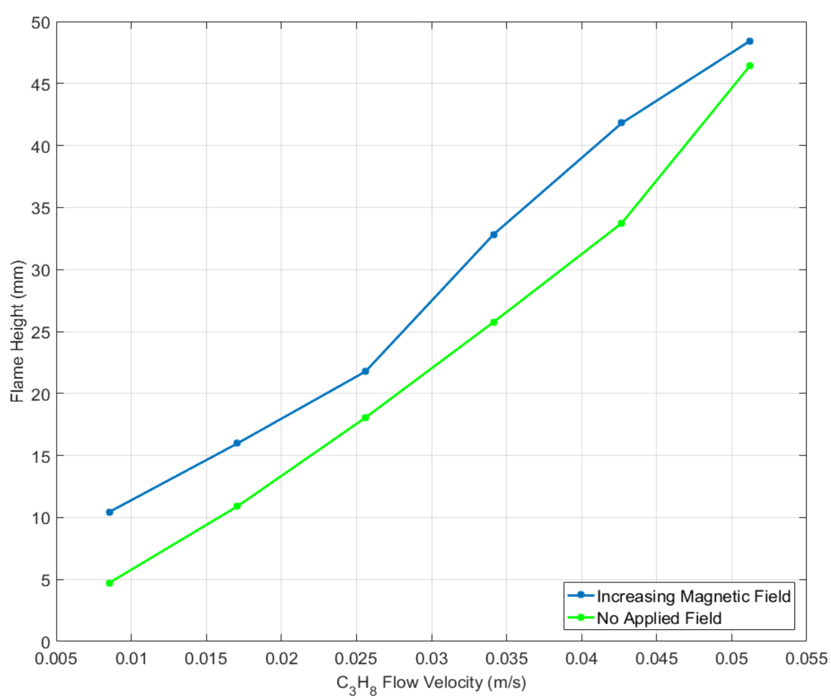

Figure 3.3: Flame height variation in an increasing gradient field for the 0.81 *mm* burner

It is observed that the presence of an increasing gradient magnetic causes an increase in the flame height compared to the no field applied case for both the burners. For the 0.55 *mm* burner, it is observed that the increase in height is more pronounced for the high flow rates. Also, it can be noted that an overall larger increase in height can be noted for the flame produced by the larger burner. This shows that this effect is dependent of the burner size. This observation is in contrast to the conclusions of Gilard, V. et al [16].

3.1.2 Flame Liftoff Height

Figure 3.4 shows the variation in flame liftoff height for the burner with a 0.81 *mm* diameter. It is compared to the flame liftoff height measured in the absence of a magnetic field.

It is observed that an increasing field decreases the liftoff height of the flame when compared to the no field applied case. Also, a lifted flame could not be obtained for the low flow rates. This test could not be performed on the 0.55 *mm* burner due to the limitations of the experimental setup.

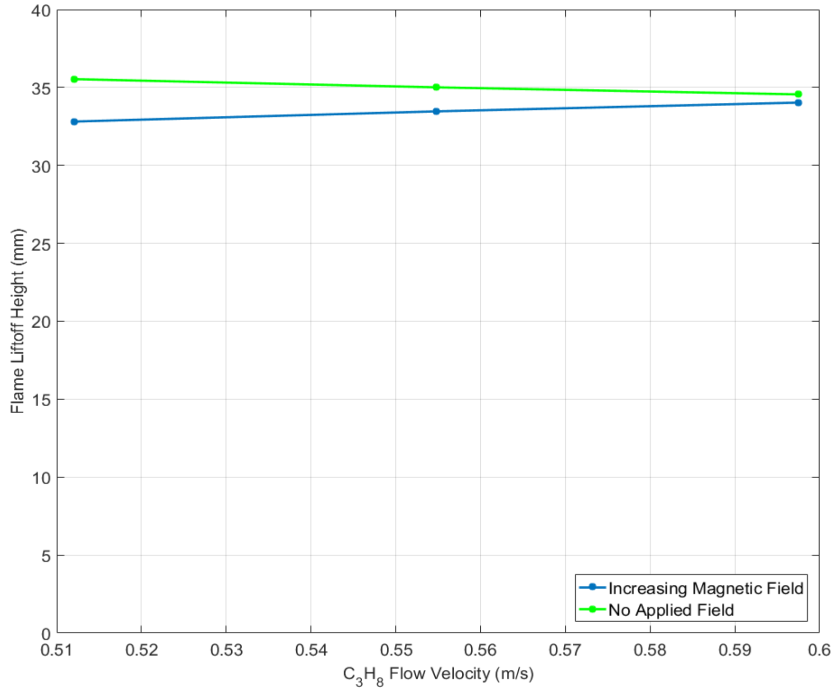

Figure 3.4: Liftoff height comparison for the 0.81 *mm* burner

3.2 Decreasing Gradient Field

The variation in flame height and flame liftoff height in the presence of a gradient magnetic field whose strength was decreasing from the burner lip is studied and is shown in Figure 3.5. This data is compared to measurements studied in the absence of a magnetic field.

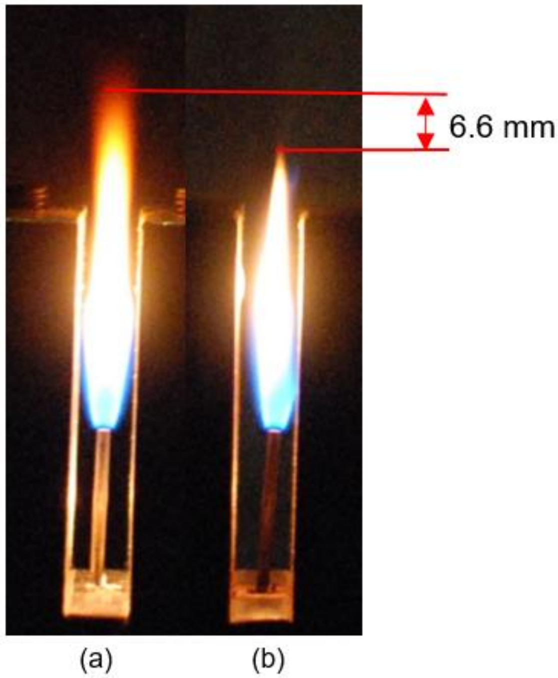

Figure 3.5: Flame height comparison (a) No field (b) Decreasing gradient field

3.2.1 Flame Height

The variation of the flame height in the presence and absence of the gradient magnetic field were used to determine if it had a significant impact on the flame height. Figure 3.6 and Figure 3.7 show the variation in flame height for two different burner sizes and is compared to the flame height measured in the absence of a magnetic field.

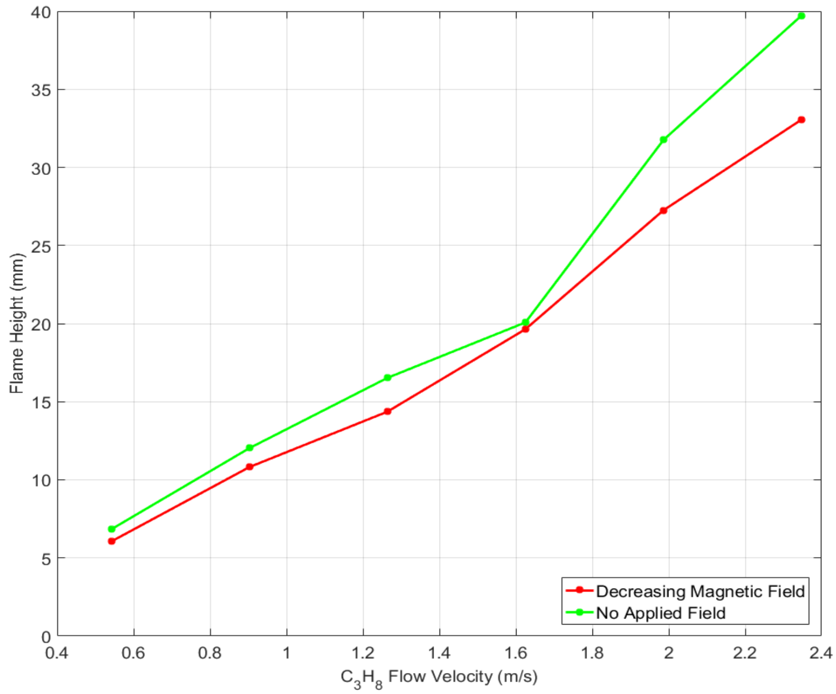

Figure 3.6: Flame height variation in a decreasing gradient field for the 0.55 *mm* burner

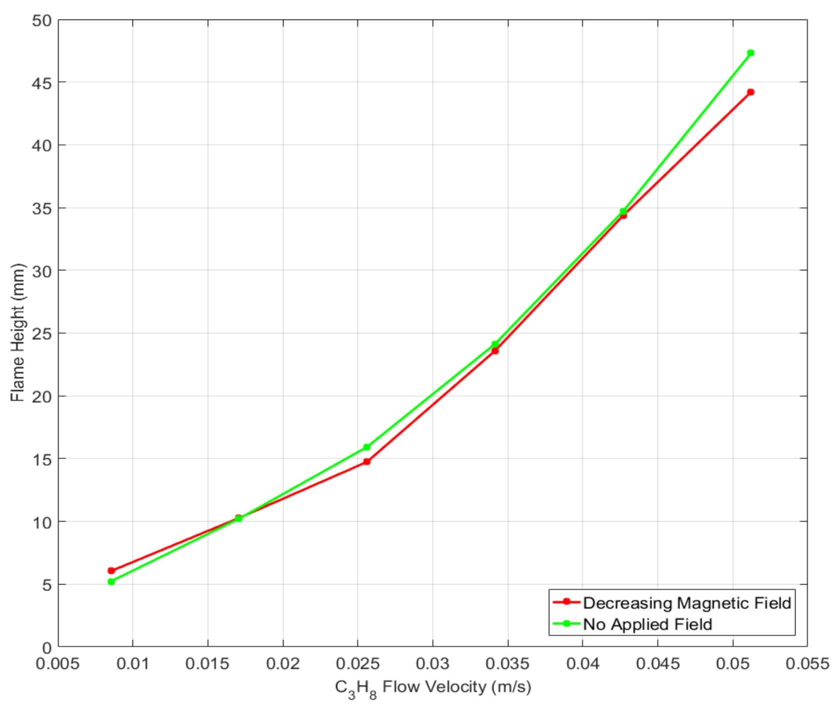

Figure 3.7: Flame height variation in a decreasing gradient field for the 0.81 *mm* burner

It is observed that the presence of a decreasing gradient magnetic causes a decrease in the flame height compared to the no field applied case for the 0.55 *mm* burner. It has a negligible impact on the larger burner. It is observed that a change in burner size influences the change in flame height. This shows that the impact of decreasing gradient field on flame height is dependent of the burner size.

3.2.2 Flame Liftoff Height

Figure 3.8 shows the flame liftoff height variation for the burner with a 0.55 *mm* diameter. It is compared to the flame liftoff height measured in the absence of a magnetic field.

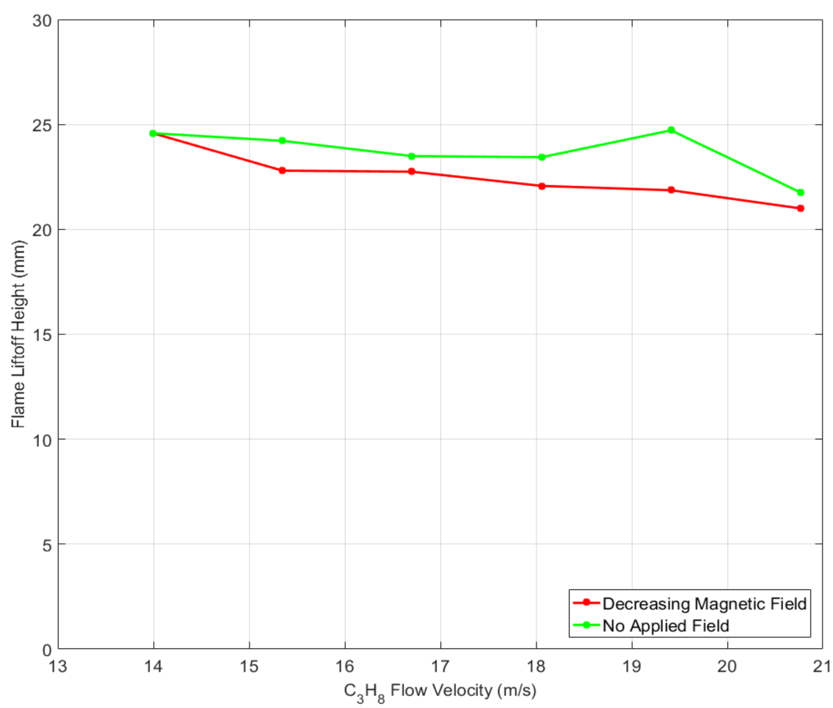

Figure 3.8: Liftoff height comparison for the 0.55 *mm* burner

It is observed that the presence of a decreasing gradient magnetic causes a decrease in the flame height. Increase in flow velocity increases the reduction in liftoff height. The reduction in height appears dependent on the fuel flow velocity.

Figure 3.9 shows the variation in flame liftoff height for the burner with a 0.81 *mm* diameter. It is compared to the flame liftoff height measured in the absence of a magnetic field. It is observed that a decreasing gradient magnetic causes a decrease in the flame liftoff height. The reduction in height appears to be fairly constant which shows that this effect is independent of the fuel flow velocity for the larger burner.

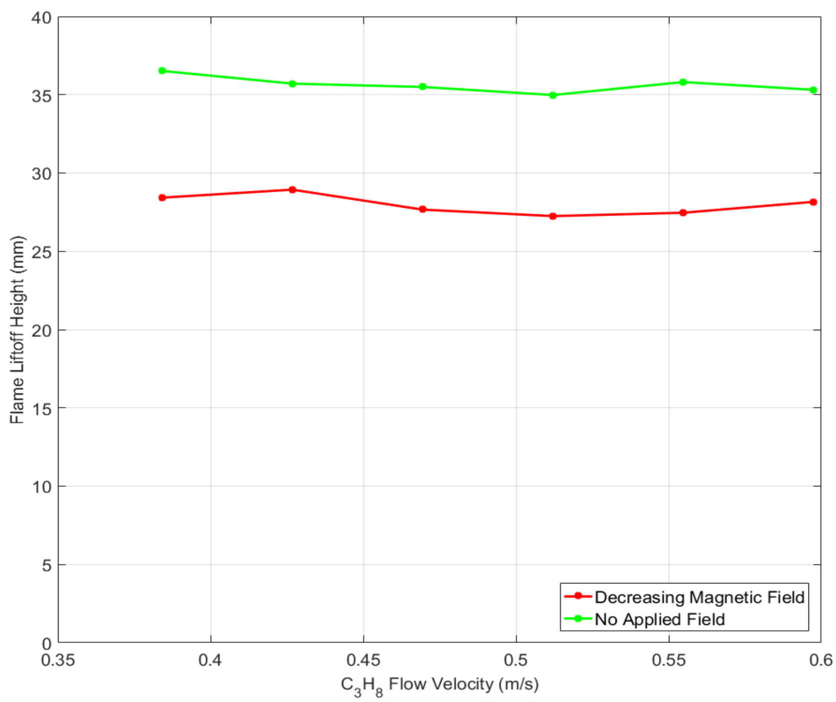

Figure 3.9: Liftoff height comparison for the 0.81 *mm* burner

3.3 Summary

Figure 3.10 and Figure 3.11 shows the impact of the gradient magnetic field on flame height for two different burners. The values of the flame height under the influence of an increasing and decreasing gradient magnetic field for the 0.55 *mm* burner can be found in Table 3.1, and for the 0.81 *mm* burner in Table 3.2.

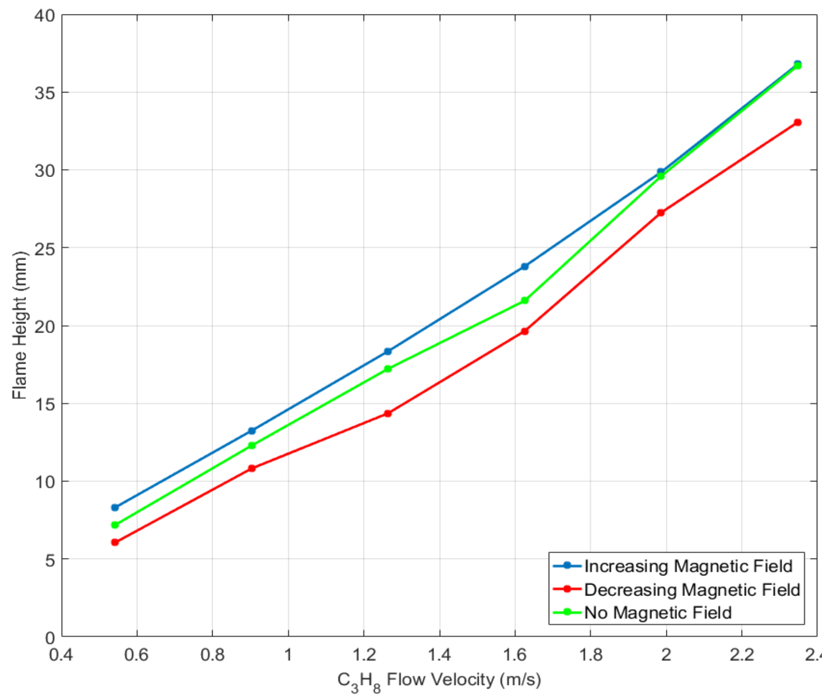

Figure 3.10: Flame height variation in the presence of gradient magnetic fields for the 0.55 *mm* burner

Table 3.1: Flame height variation for the 0.55 *mm* burner

Flow Velocity of C3H8 (*m/s*)	Increasing Magnetic Field (*mm*)	Decreasing Magnetic Field (*mm*)
0.54	8.31	6.05
0.90	13.24	10.81
1.26	18.35	14.36
1.63	23.80	19.64
1.99	29.86	27.26
2.35	36.78	33.06

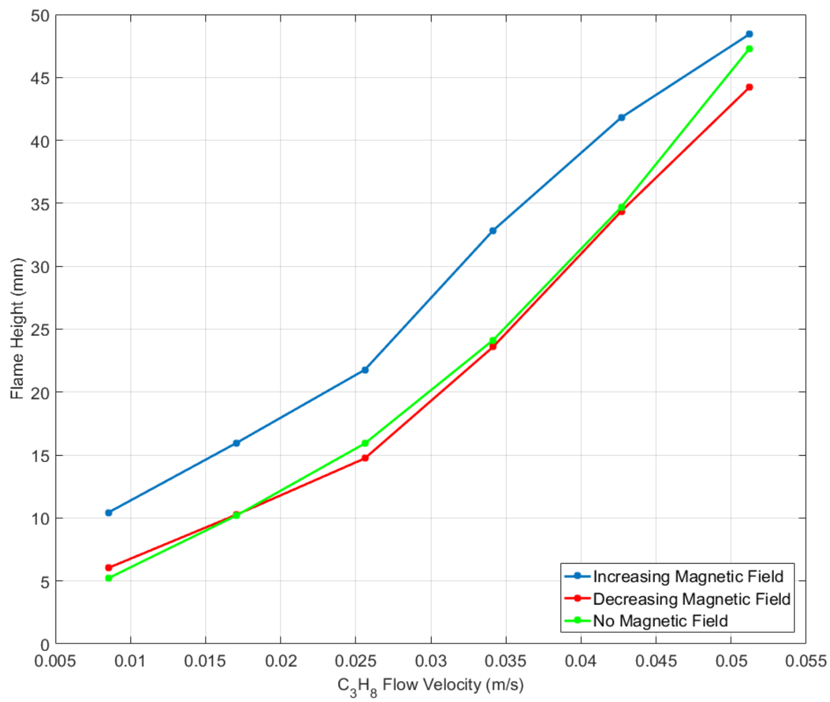

Figure 3.11: Flame height variation in the presence of gradient magnetic fields for the 0.81 *mm* burner

Table 3.2: Flame height variation for the 0.81 *mm* burner

Flow Velocity of C3H8 (*mm*)	Increasing Magnetic Field (*mm*)	Decreasing Magnetic Field (*mm*)
0.009	10.44	6.04
0.017	15.97	10.27
0.026	21.78	14.74
0.034	32.84	23.59
0.043	41.81	34.36
0.051	48.43	44.21

It was observed that the presence of an increasing gradient field caused the flame height to increase, causing the shape to be more elongated and slender while the flame became shorter under the influence of a decreasing gradient field. Their variation is plotted along a flame whose height is measured in the absence of a magnetic field. Wakayama [10] explained that this observation may be attributed to the paramagnetic nature of oxygen and the diamagnetic nature of the combustion products which cause a promotion of the combustion reaction when the fuel gas experiences a decreasing gradient field and the reverse effects in an increasing magnetic field. These observations suggests the possibility that a chemical reaction involving a change in the magnetic susceptibilities of component species could be controlled by application of inhomogeneous magnetic fields.

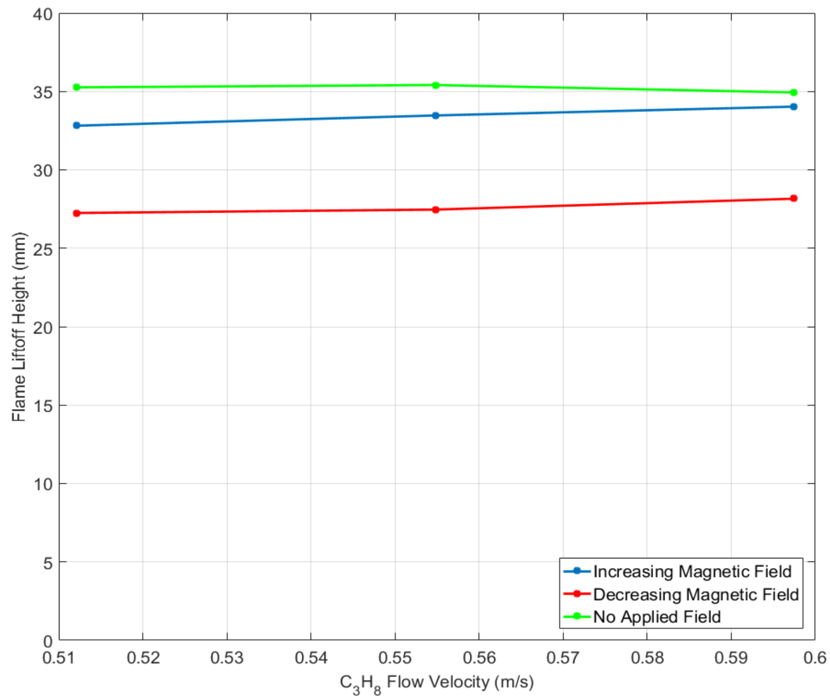

Figure 3.12: Liftoff height comparison for the 0.81 *mm* burner

Figure 3.12 shows the impact of the gradient magnetic field on flame liftoff height for the 0.81 mm burner. It was observed that the presence of gradient field caused the flame liftoff height to decrease irrespective of the direction of the gradient field. The observations can be dissociated into two effects due to the yoke – the aerodynamics effect and the magnetic effect. The lift is appeared to be reduced by both these effects. The attached flame region for the increasing field test was maybe to the presence of the yoke. The variation is plotted along a flame whose liftoff height is measured in the absence of a magnetic field. It can be concluded that the reduction in height due to the application of gradient field appears to be independent of the fuel flow rates. The values of the flame liftoff height under the influence of an increasing and decreasing gradient magnetic field for the 0.81 *mm* burner can be found in Table 3.3.

Table 3.3: Flame liftoff height variation for the 0.81 *mm* burner

Flow Velocity of C3H8 (*m/s*)	Increasing Magnetic Field (*mm*)	Decreasing Magnetic Field (*mm*)
0.51	32.81	27.25
0.55	33.47	27.46
0.60	34.03	28.16

4. CONCLUSION AND FUTURE WORK

4.1 Conclusion

The aim of this thesis was to study the effectiveness of low strength permanent magnets in manipulating diffusion flames towards a goal of achieving combustion control through magnetism. The direction of gradient magnetic fields, along with the rate of flow of fuel was identified to be affecting the structure and liftoff height of the flame. Experimental studies have been conducted on the existing burner setup to understand the effect of the above parameters on flame properties.

- Initial experiments were conducted in the presence of gradient magnetic fields whose maximum strength was observed as 0.75T. The flame structure and the liftoff height was studied for two different burner having an inner diameter of 0.55 *mm* and 0.81 *mm*. The burner position was varied so that the flame experiences an upward increasing and subsequently an upward decreasing gradient magnetic field
- The height of the flame increased in the presence of an increasing gradient field compared to the no field applied case. This increase in height was found to be dependent on the burner size
- A decrease in the liftoff height was observed for the 0.81 *mm* diameter burner at high flow rates. Low flow rates caused the flame to attach to the burner lip. This may be due to the aerodynamic effect of the yoke. This test could not be conducted for the 0.55 *mm* diameter burner due to the limitations of the experimental setup

- The height of the flame was reduced in the presence of a decreasing gradient field case compared to the no field applied case. This effect was found to be independent on the burner size although it was more pronounced on the 0.55 *mm* diameter burner
- A decrease in the liftoff height was observed for both the burners under the influence of a decreasing gradient field. The reduction in liftoff height appeared to be independent of the fuel flow rates
- The impact of the gradient fields on flame width was unable to be captured due to the presence of the iron yoke which made width measurements highly inaccurate

4.2 Future Work

There is scope for a lot of work that can be conducted further in this area of research in order to fully understand the complex nature of the interactions between magnetism and combustion.

- The presence of the yoke greatly reduces the range on flow rates that can be used in this investigation. The yoke cannot be eliminated because it is required to augment the field strength produced by the low strength permanent magnets. Future investigations should be carried out by employing permanent magnets that whose strength are an order of magnitude greater than the ones used in the current investigation so that it would negate the need for a yoke which in turn would provide a greater flexibility in choosing flow rates.
- The current investigation uses a yoke with magnets mounted on the axis of the burner. Future experiments can investigate the impact of the orientation of the magnets on the flame and gas flow.

- Flame structure and liftoff height variations can also be investigated in the presence of both electric and magnetic fields.
- An electromagnet with the capability to vary field strengths in real time can be used to determine the rate of change of properties of the flame and gas flow

REFERENCES

[1] I. Glassman and R. A. Yetter, Combustion, Elsevier, 2008.

[2] Roper, F G;, "The Prediction of Laminar Jet Diffusion Flame Sizes," *Combustion and Flame,* pp. 219-226, 1977.

[3] B. B. Laud, Electromagnetics, John Wiley & Sons, 1983.

[4] J. Lawton and F. J. Weinberg, Electrical Aspects of Combustion, Clarendon Press, 1969.

[5] M. Faraday, "On the Diamagnetic Conditions of Flame and Gases," *The London, Edinburgh and Dublin Philosophical Magazine and Journal of Science,* vol. 31, no. 210, pp. 401-421, 1847.

[6] S. Ueno and K. Harada, "Effects of Magnetic Fields on Flames and Gas Flow," *IEEE Transactions on Magnetics,* pp. 2752-2754, 1987.

[7] S. Ueno, "Quenching of Flames by Magnetic Fields," *Journal of Applied Physics,* pp. 1243-1245, 1989.

[8] S. Ueno and M. Iwasaka, "Properties of Magnetic Curtain Produced by Magnetic Fields," *Journal of Applied Physics*, vol. 67, no. 9, pp. 5901-5903, 1990.

[9] S. Ueno, H. Esaki and K. Harada, "Combustion Processes in Strong DC Magnetic Fields," *IEEE Transactions on Magnetics,* vol. 5, pp. 2077-2079, 1985.

[10] N. I. Wakayama, "Effect of a Gradient Magnetic Field on the Combustion Reaction of Methane in Air," *Chemical Physics Letters,* pp. 279-281, 1992.

[11] T. Aoki, "Radicals' Emissions and Butane Diffusion Flames Exposed to Upward-Decreasing Magnetic," *Japanese Journal of Applied Physics,* pp. 776-785, 1989.

[12] T. Aoki, "Radical Emissions and Anomalous Reverse Flames Appearing in Upward-Increasing," *Japanese journal of Applied Physics,* pp. 181-190, 1990.

[13] P. Gillon, J. Blanchard and V. Gilard, "Methane/Air-Lifted Flames in Magnetic Gradients," *Combustion Science and Technology,* pp. 1805-1819, 2010.

[14] Y. Mizutani, M. Fuchihata and Y. Ohkura, "Pre-Mixed Laminar Flames in a Uniform Magnetic Field," *Combustion and Flame,* pp. 1071-1073, 2001.

[15] V. Gilard, P. Gillon and C. J. N. Blanchard, "Effects of magnetic Field on the Stabilization of a Lifted Diffusion Flame," in *Proceedings of the European Combustion Meeting*, 2009.

[16] V. Gilard, P. Gillon, J. Blanchard and B. Sarh, "Influence of a Horizontal Magnetic Field on a Co-Flow Methane/Air Diffusion Flame," *Combustion Science and Technology,* pp. 1920-1935, 2008.

[17] A. Faris, S. Al-Naserib, N. Jamal, R. Isse, M. Abed, Z. Fouad, A. Kazim, N. Reheem, A. Chaloob, H. Mohammad, H. Jasim, J. Sadeq, A. Salim and A. Abas, "Effects of Magnetic Field on Fuel Consumption and Exhaust Emissions in Two-Stroke Engine," in *Energy Procedia,* 2012.

[18] S. R. Turns, An Introduction to Combustion, McGraw Hill Education, 2012.

[19] N. Wakayama, "Magnetic Promotion of Combustion in Diffusion Flames," *Combustion and Flame,* pp. 207-214, 1993.

[20] T. Aoki, "Radical Emissions and Butane Diffusion Flames Exposed to Uniform Magnetic Fields," *Japanese Journal of Applied Physics,* pp. 952-957, 1990.

[21] J. Baker and M. Calvert, "A Study of the Characteristics of Slotted Laminar Jet Diffusion Flames in the Presence of Non-Uniform Magnetic Fields," *Combustion and Flame,* pp. 345-357, 2003.

[22] "Gasoline Combustion Process Under Strong DC Magnetic Field," in *International Conference on Electromagnetic Fields, Health and Environment*, Wroclaw, Poland, 2007.

[23] "Magnetically Induced Flame Flickering," in *Proceedings of the Combustion Institute*, 2010.

[24] T. Aoki, "A Magnetically Induced Anomalous Ring Flame and Quenching Characteristics of Butane," *Japanese Journal of Applied Physics,* pp. 864-867, 1990.

[25] P. Gillon, W. Badat, V. Gilard and B. Sarh, "Magnetic Effects on Flickering Methane/Air," *Combustion Science and Technology,* pp. 1972-1982, 2016.

[26] A. Jocher, H. Pitsch, T. Gomez, J. Bonnety and G. Legros, "Impact of Magnetic Fields on the Stability of Non-Premixed Flames," in *Proceedings of the European Combustion Meeting*, 2015.

[27] A. Jocher, H. Pitsch, T. Gomez and G. Legros, "Modification of Sooting Tendency by Magnetic Effects," in *Proceedings of the Combustion Institute,* 2014.

[28] F. Khaldi, K. Messadek and A. Benselama, "Isolation of Gravity Effects on Diffusion Flames," *Microgravity Science and Technology*, pp. 1-5, 2008.

APPENDIX

MATLAB Codes

```
%-----------------------------------------------------------------------
%Plot for selecting the best yoke design
%-----------------------------------------------------------------------
cd 'C:\Users\vramnat\Dropbox\NC State\Effect of Magnetic Field on Flames\Working
Folder\Spreadsheets'
filename = 'yoke_selection.xlsx';
sheet = 1;
xlrange = 'C4:C42'; %air gap
gap = xlsread(filename,sheet,xlrange)
%-----------------------------------------------------------------------
xlrange = 'E4:E42'; %disk magnets
diskmag = xlsread(filename,sheet,xlrange)
%-----------------------------------------------------------------------
xlrange = 'F4:F42'; %disk magnets with yoke
yoke = xlsread(filename,sheet,xlrange)
%-----------------------------------------------------------------------
xlrange = 'G4:G42'; %disk magnets with yoke & cones
cones = xlsread(filename,sheet,xlrange)
%-----------------------------------------------------------------------
%plotting
%-----------------------------------------------------------------------
plot(gap,diskmag,'go');
axis([0 20 0 20000])
hold on;
plot(gap,yoke,'ro')
axis([0 20 0 20000])
hold on;
plot(gap,cones,'bo')
axis([0 20 0 20000])
hold on;
xlabel('Air Gap (mm)'), ylabel('Field Strength (Guass)')
title('Field Strength Variation with Air Gap')
legend('Plain Disk magnets','Magnets on iron yoke','Magnets on iron yoke with cones')
grid on;
```

```matlab
%-----------------------------------------------------------------
%Image outline for Flames with holder at Lower Marker
%-----------------------------------------------------------------
clear all
%-------Read and crop images-------------------------------------
cd 'C:\Users\vramnat\Dropbox\NC State\Effect of Magnetic Field on Flames\Experiments\0
032in_ID\E10_structure_al_lwr_mkr'
n = 9
for i = 9:n
    I = im2double(imread(sprintf('Pic_%d.jpg',i)));
    %figure, imshow(I)
    %a = imdistline(gca)
    %1" = 230 pixels for dec, 210 for inc
    I2 = imcrop(I,[1550 900 400 1025]);
    %crop borders>> 1600-left,900-top, 400-right, 1025-bottom
    I2 = imrotate(I2,1);
    figure, imshow(I2)
    title(sprintf('Cropped Image # %d',i));
    %[x1,y1]=ginput();
    %base(i) = y1
    %base=760 lwr , 610 mid
%-----------------------------------------------------------------
%%
%----Convert image to grayscale and binary-----------------------
    I3 = rgb2gray(I2);
    I4 = imadjust(I3,[0.1 1],[]);
    %imadjust(I3,[0.95 1],[]) // attached flames
    %imadjust(I3,[0.3 1],[]) // lifted flames
    figure, imshow(I4)
    title(sprintf('Grayscale Image # %d',i'));
    bw = im2bw(I4,0.95);
    figure, imshow(bw)
    title(sprintf('Binary Image # %d',i'));
%-----------------------------------------------------------------
%%
%---Determine edge of flame--------------------------------------
    BW1 = edge(bw,'sobel');
    figure, imshow(BW1)
    title(sprintf('Flame # %d Edge',i));
%-----------------------------------------------------------------
%%
%---Determine height of flame----------------------------
    BW1 = imcomplement(BW1)
    figure, imshow(BW1)
    [x1,y1]=ginput();
    l = 610 - y1;
    disp('Height in pixels is: ')
    disp(l)
    lin = l * (1/210) * 25.4;
    lift(i) = lin;
    disp('Height of flame in mm is: ')
```

```
    disp(lin)
    pause()
    close all
end
plot (lift)
title('Flame Height')
%-----------------------------------------------------------------
%Notes:
%1. Crop dimensions has to be adjusted for different expts
%2. Camera position should not be moved during experiments
%3. Flame structure can be calculated if image cropped to burner lip
%4. Base at y=795
%5. Base at y=785 for attached flame with magnet
```

```
%----------------------------------------------------------------------
%Matlab plots for data
%----------------------------------------------------------------------
cd 'C:\Users\vramnat\Dropbox\NC State\Effect of Magnetic Field on Flames\Working
Folder\Spreadsheets'
filename = 'experiment_data.xlsx';  %spreadsheet containing the plot data
%----------------------------------------------------------------------
%Selecting the plots to display
%----------------------------------------------------------------------
disp('Choose Option:');
prompt = '1. 0.022" Burner   2. 0.032" Burner';
x = input(prompt)
%----------------------------------------------------------------------
switch (x)
    case 1
        %----------------------------------------------------------------------
        %Selecting Plots to display for flame height comparison
        %----------------------------------------------------------------------
        sheet = 3;
        xlrange = 'S11:S16'; %Gas Flow Velocity
        gas = xlsread(filename,sheet,xlrange)
        %----------------------------------------------------------------------
        %Plot for Flame Height Comparison in Inc vs Dec Mag Field
        %----------------------------------------------------------------------
        xlrange = 'T11:T16'; %Inc mag field flame height data
        htinc = xlsread(filename,sheet,xlrange)
        plot(gas,htinc,'-*'),
        hold on
        xlrange = 'T45:T50'; %Dec Field Flame Height
        htdec = xlsread(filename,sheet,xlrange)
        plot(gas,htdec,'-*'),
        xlrange = 'T28:T33'; %No Field Flame Height
        htno = xlsread(filename,sheet,xlrange)
        plot(gas,htno,'g-*'),
        hold on
        grid on
        legend('Increasing Magnetic Field','Decreasing Magnetic Field','No Magnetic
Field')
        xlabel('C3H8 Flow Velocity (m/s)'), ylabel('Flame Height (mm)')
        title('Flame Height Variation')
        pause()
        close all
        %----------------------------------------------------------------------
        %Plot for Flame Height Comparison in Inc Field vs Al holder
        %----------------------------------------------------------------------
        xlrange = 'T11:T16'; %Inc mag field flame height data
        ht4 = xlsread(filename,sheet,xlrange)
        plot(gas,ht4,'-*'),
        hold on
        xlrange = 'T28:T33'; %Al holder, lwr marker flame height data
        ht10 = xlsread(filename,sheet,xlrange)
```

```
    plot(gas,ht10,'-*'),
    hold on
    grid on
    legend('Increasing Magnetic Field','False Magnet')
    xlabel('C3H8 Flow Velocity (m/s)'), ylabel('Flame Height (mm)')
    title('Flame Height Variation')
    pause()
    close all
    %-----------------------------------------------------------------------
    %Plot for Flame Height Comparison in Dec Field vs Al holder
    %-----------------------------------------------------------------------
    xlrange = 'T45:T50'; %Dec Field Flame Height
    ht7 = xlsread(filename,sheet,xlrange)
    plot(gas,ht7,'-*'),
    hold on
    xlrange = 'T62:T67'; %Al holder, mid marker flame height data
    ht13 = xlsread(filename,sheet,xlrange)
    plot(gas,ht13,'-*'),
    hold on
    grid on
    legend('Decreasing Magnetic Field','False Magnet')
    xlabel('C3H8 Flow Velocity (m/s)'), ylabel('Flame Height (mm)')
    title('Flame Height Variation')
    pause()
    close all
    %-----------------------------------------------------------------------
    %Liftoff Heights
    %-----------------------------------------------------------------------
    sheet = 4;
    xlrange = 'U64:U69'; %Gas Flow Velocity
    gas = xlsread(filename,sheet,xlrange)
    %-----------------------------------------------------------------------
    %Plot for Flame Liftoff Height Comparison in Dec Field vs Al holder
    %-----------------------------------------------------------------------
    xlrange = 'V64:V69'; %Dec mag field lifted averaged data points
    ht4 = xlsread(filename,sheet,xlrange)
    plot(gas,ht4,'-*')
    hold on
    xlrange = 'V91:V96'; %Al holder, mid marker averaged data points
    ht10 = xlsread(filename,sheet,xlrange)
    plot(gas,ht10,'-*'),
    hold on
    grid on
    legend('Decreasing Magnetic Field','False Magnet')
    xlabel('C3H8 Flow Velocity (m/s)'), ylabel('Flame Height (mm)')
    title('Flame Liftoff Height Variation')
    pause()
    close all
case 2
    %-----------------------------------------------------------------------
    %Selecting Plots to display for flame height comparison
```

```
%--------------------------------------------------------------------------
sheet = 3;
xlrange = 'D11:D16'; %Gas Flow Velocity
gas = xlsread(filename,sheet,xlrange)
%--------------------------------------------------------------------------
%Plot for Flame Height Comparison in Inc vs Dec Mag Field
%--------------------------------------------------------------------------
xlrange = 'E11:E16'; %Inc mag field flame height data
htinc = xlsread(filename,sheet,xlrange)
plot(gas,htinc,'-*'),
hold on
xlrange = 'E45:E50'; %Dec Field Flame Height
htdec = xlsread(filename,sheet,xlrange)
plot(gas,htdec,'-*'),
xlrange = 'F73:F78'; %No Field Flame Height
htno = xlsread(filename,sheet,xlrange)
plot(gas,htno,'g-*'),
hold on
grid on
legend('Increasing Magnetic Field','Decreasing Magnetic Field','No Magnetic↙
Field')
xlabel('C3H8 Flow Velocity (m/s)'), ylabel('Flame Height (mm)')
title('Flame Height Variation')
pause()
close all
%--------------------------------------------------------------------------
%Plot for Flame Height Comparison in Inc Field vs Al holder
%--------------------------------------------------------------------------
xlrange = 'E11:E16'; %Inc mag field flame height data
ht4 = xlsread(filename,sheet,xlrange)
plot(gas,ht4,'-*'),
hold on
xlrange = 'E28:E33'; %Al holder, lwr marker flame height data
ht10 = xlsread(filename,sheet,xlrange)
plot(gas,ht10,'-*'),
hold on
grid on
legend('Increasing Magnetic Field','False Magnet')
xlabel('C3H8 Flow Velocity (m/s)'), ylabel('Flame Height (mm)')
title('Flame Height Variation')
pause()
close all
%--------------------------------------------------------------------------
%Plot for Flame Height Comparison in Dec Field vs Al holder
%--------------------------------------------------------------------------
xlrange = 'E45:E50'; %Dec Field Flame Height
ht7 = xlsread(filename,sheet,xlrange)
plot(gas,ht7,'-*'),
hold on
xlrange = 'E62:E67'; %Al holder, mid marker flame height data
ht13 = xlsread(filename,sheet,xlrange)
```

```
plot(gas,ht13,'-*'),
hold on
grid on
legend('Decreasing Magnetic Field','False Magnet')
xlabel('C3H8 Flow Velocity (m/s)'), ylabel('Flame Height (mm)')
title('Flame Height Variation')
pause()
close all
%-----------------------------------------------------------------------
%Liftoff Heights
%-----------------------------------------------------------------------
sheet = 4;
xlrange = 'D10:D15'; %Gas Flow Velocity
gas = xlsread(filename,sheet,xlrange)
%-----------------------------------------------------------------------
%Plot for Flame Liftoff Height Comparison in Inc Field vs Dec Field
%-----------------------------------------------------------------------
xlrange = 'E10:E15'; %Inc mag field lifted averaged data points
ht4 = xlsread(filename,sheet,xlrange)
plot(gas,ht4,'-*')
hold on
xlrange = 'E64:E69'; %Dec mag field lifted averaged data points
ht10 = xlsread(filename,sheet,xlrange)
plot(gas,ht10,'-*'),
hold on
xlrange = 'E115:E120'; %No mag field lifted averaged data points
ht10 = xlsread(filename,sheet,xlrange)
plot(gas,ht10,'g-*'),
hold on
grid on
legend('Increasing Magnetic Field','Decreasing Magnetic Field','No Field')
xlabel('C3H8 Flow Velocity (m/s)'), ylabel('Flame Height (mm)')
title('Flame Liftoff Height Variation')
pause()
close all
%-----------------------------------------------------------------------
%Plot for Flame Liftoff Height Comparison in Inc Field vs Al holder
%-----------------------------------------------------------------------
xlrange = 'E10:E15'; %Inc mag field lifted averaged data points
ht4 = xlsread(filename,sheet,xlrange)
plot(gas,ht4,'-*')
hold on
xlrange = 'E37:E42'; %Al holder lifted averaged data points
ht10 = xlsread(filename,sheet,xlrange)
plot(gas,ht10,'-*'),
hold on
grid on
legend('Increasing Magnetic Field','False Magnet')
xlabel('C3H8 Flow Velocity (m/s)'), ylabel('Flame Height (mm)')
title('Flame Liftoff Height Variation')
pause()
```

```
        close all
        %-----------------------------------------------------------------------
        %Plot for Flame Liftoff Height Comparison in Dec Field vs Al holder
        %-----------------------------------------------------------------------
        xlrange = 'E64:E69'; %Dec mag field lifted averaged data points
        ht4 = xlsread(filename,sheet,xlrange)
        plot(gas,ht4,'-*')
        hold on
        xlrange = 'E91:E96'; %Al holder lifted averaged data points
        ht10 = xlsread(filename,sheet,xlrange)
        plot(gas,ht10,'-*'),
        hold on
        grid on
        legend('Decreasing Magnetic Field','False Magnet')
        xlabel('C3H8 Flow Velocity (m/s)'), ylabel('Flame Height (mm)')
        title('Flame Liftoff Height Variation')
        pause()
        close all
end
```