ABSTRACT

BOBEN, RAISA ROSE. Study of the Jet Diffusion Flames Exposed to Moderate-Strength Gradient Magnetic Field. (Under the direction of Dr. Kevin M. Lyons).

The behavior of laminar jet propane diffusion flames in the presence of moderate-strength permanent magnets has been investigated and the results of this experimental study are presented. It has been previously recognized that the gradient magnetic field can influence laminar diffusion flames because of paramagnetic and diamagnetic components of the reaction zone of the flame. Using a magnet assembly of moderate-strength neodymium iron boron magnets mounted on an iron yoke, a non-uniform magnetic field was applied to the laminar flame. Propane/air flames with different flow velocities were produced by a 0.81 mm burner port and subjected to gradient magnetic field.

The experimental results show that the flame showed significant increase in local temperature under the influence of a decreasing magnetic gradient field. Compared with the case without magnetic fields applied, the flame temperature increases by an average of 40 K. In an increasing magnetic gradient field, the local temperature is expected to be decreased, but it was found to increase slightly relative to zero magnetic field case. It was found to be lower than the decreasing gradient field condition. It appears that the impact of the magnetic field is independent of the burner tip position in the magnetic gradient.

Because the magnetic force is expected to induce greater entertainment of oxidizer towards the flame, dimensionless parameters like magnetic Froude number and magnetic Grashof number were studied to determine when the magnetic field will impact the diffusion flame. At relatively low Reynolds numbers, a region of magnetic influence on flames was found over which the flames gradually transition from gravity-controlled to magnetic field-controlled.
Study of the Jet Diffusion Flames Exposed to Moderate-Strength Gradient Magnetic Field

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DEDICATION

First and foremost, I would like to dedicate this thesis to the God, the Almighty, for his showers of blessings throughout my research work to complete the research successfully. I want to also dedicate it to my family and friends for their love, prayers and never-ending support.
BIOGRAPHY

The author was born and raised in India. She graduated with a bachelor’s degree in Mechanical and Automation Engineering from Indira Gandhi Institute of Technology, Delhi in the year 2014. She worked as a Design Engineer in the Powertrain department of General Motors Technical Center India, Bengaluru for two years. She started her study at NC State University in 2016 for Master of Science in Mechanical Engineering, where she joined the Lyons Research Group and started working on the effect of magnetism on diffusion flames.
I would like to thank Dr. Kevin M. Lyons, my advisor, for guiding me throughout my graduate education. This work would have been impossible without the suggestions and advice that I received from him.

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INTRODUCTION

1.1 Applications of Magnetic Field

The energy associated with the magnetic influence on flame behavior is generally several orders of magnitude smaller than the kinetic energy of molecules at room temperature. Nevertheless, recent studies have shown that an inhomogeneous magnetic field provide a means to control combustion behavior. Gaseous combustion comprises of not only a chemical reaction, but also of physical processes of heat transfer and mass diffusion. These processes can be manipulated using magnetic forces applied on paramagnetic gas flows to the flame. This potential ability of magnetic control of gas flow and combustion is a new research area and needs further data to investigate it in detail.

Applications of controlling the behavior of gas flows and combustion by magnetic fields can be important in many aspects of research and practical applications. Most research has recently been carried out to gain an understanding of its mechanism, to apply it to industrial situations and to bio-magnetics to support chemical reactions and physical processes in cells and tissues. If the behavior of oxygen and other radicals can be controlled by magnetic fields, a new type of cancer therapy might be contrived.

From the view point of industrial application of magnetic effects on combustion, increasing combustion temperature and controlling combustion processes will be widely useful. Natural gas, is widely used for heating, cooking, electricity generation and transportation. Over the past century, the need to reduce emissions by developing micro-power devices to enhance combustion efficiency of fuels has become crucial. A possible means to achieve this could be the application of magnetic fields to gas flows and combustion flames. There have been studies done earlier on
interactions of magnetic fields and electrically conducting fluids. However, this interaction is not limited to electrically charged particles, but magnetic field can affect even gases that exhibit paramagnetic and diamagnetic behavior.

1.2 Paramagnetism & Diamagnetism

Magnetic fields are known to affect flame behavior and gas flows because of the paramagnetic and diamagnetic nature of the constituent gases. Paramagnetism is a form of magnetism whereby certain materials are weakly attracted by an externally applied magnetic field, and form internal, induced magnetic fields in the direction of the applied magnetic field. In contrast with this behavior, diamagnetic materials are repelled by magnetic fields and form induced magnetic fields in the direction opposite to that of the applied magnetic field. [1] Paramagnetism is due to the presence of unpaired electrons in the material. Due to their spin, unpaired electrons have a magnetic dipole moment and act like tiny magnets. An external magnetic field causes the electrons' spins to align parallel to the field, and thus paramagnetic materials are drawn toward the direction of increasing magnetic field strength. Paramagnetic materials include aluminum, oxygen, titanium, and iron oxide. On the contrary, if the electrons are already paired, the atoms oppose the applied field, and this induces a net dipole moment that causes the atoms to move in the direction of decreasing magnetic field strength. Nitrogen, CO$_2$, and most hydrocarbon fuels are examples of diamagnetic materials and experience a weak repulsion to the applied magnetic field.

The magnetic susceptibility, the ratio of the magnetization to the magnetic field strength [2], is the parameter that characterizes this behavior. Since the magnetic forces associated with the dipole moments in a paramagnetic material must compete with the randomizing effects of temperature, the magnetic susceptibility for a paramagnetic material is a function of temperature. All materials, to some degree, display diamagnetic behavior. For materials whose atoms possess
permanent dipole moments, the associated paramagnetic forces are typically orders of magnitude larger and the diamagnetic behavior for these materials is thus negligible [3]. The magnetic susceptibility for a diamagnetic material is not a strong function of temperature and is negative in sign while a paramagnetic material has a positive magnetic susceptibility.

1.3 Theory of Diffusion Flames

A diffusion flame is used as a test subject to study the effect of magnetic field, since it simulates combustion characteristics found in various industrial applications. 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 condensed medium (either solid or liquid) or in the gaseous form of a gaseous fuel jet, and the oxidizer may be a flowing gas stream or the quiescent atmosphere. It is the diffusion rate of the fresh mixture into the flame zone which sustains combustion and hence the name. These processes can be altered by the magnetic forces, as is evident from earlier studies. 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 [4]. The description of a non-reacting fuel jet issuing into an infinite reservoir of air helps in better understanding the diffusion flame. Figure 1.1 [5] shows the various regions of a laminar fuel jet issuing from a burner of radius “r” in to quiescent air. In a region between the potential core and jet edge, fuel properties such as the velocity and the fuel concentration decrease monotonically till they become zero at the jet edge.

The focus of the proposed study is to understand the interaction of laminar diffusion flame and magnetic forces originating from the gradient magnetic field. In diffusion flames, one of the key parameters needed to continue combustion is the convective air flow induced by buoyancy, which affects the heat and mass transport processes. An application of magnetic field enhances this air flow to the flame reaction zone, as quiescent air being paramagnetic would be drawn towards higher magnetic field strengths.

In diffusion flames, hydrocarbon fuels, nitrogen, carbon dioxide are diamagnetic; oxygen is the principal paramagnetic gas. As the paramagnetic susceptibility of oxygen is orders of magnitude larger, the diamagnetic behavior is considered as negligible. A gas containing more O₂, such as air, tends to move towards the stronger magnetic field and a gas with less O₂ such as fuel or combustion gas tends to move towards the weaker magnetic field. Based on this, it may be possible to utilize a magnetic field to control the flow field of combustion region to improve combustion characteristics. A key parameter to characterize the laminar diffusion flame behavior is the flame height under the influence of magnetic field [7]. The flame height (L_f) is defined as
the vertical distance between the burner surface and the point along the flame axis where the fuel is consumed in stoichiometric proportions [5].

1.4 Flow Characterization Parameters

Fujita et al. [6] identified a parameter like the Grashof Number that could be used to identify when magnetically induced convection would occur. They found that increase in the magnetic field intensity and the oxygen concentration caused a decrease in flame “redness”, indicating an increase in local temperature. Dimensionless numbers such as Reynolds number, Grashof number and Froude number can be used to define regimes where non-uniform magnetic fields impact flame behavior. They are evaluated at average local temperature and atmospheric pressure to study hot gas flow conditions.

1.4.1 Reynolds Number

Reynolds number of the hot gases is determined by eqn. 1. It is ratio of the momentum forces to the viscous forces and is used to characterize the fuel flow as being laminar or turbulent.

\[
Re = \frac{v_F l F_{stoic} L_f}{v}
\]
1.4.2  Grashof Number

The Grashof number (Gr) is a dimensionless number in fluid dynamics and heat transfer which approximates the ratio of the buoyancy to viscous force acting on a fluid. It frequently arises in the study of situations involving natural convection and is analogous to the Reynolds number.

\[ Gr = g \beta (T_f - T_0) d^3 / v^2 \]

1.4.3  Magnetic Grashof Number

Fujita et al. [6] defined a magnetic Grashof number analogous to the gravitational field, the criterion to maintain a steady flame with magnetic field. The magnetic Grashof number was defined as the ratio of magnetic-buoyancy forces to viscous forces [7]. Thus, \( Gr_m \) shows a buoyancy-like force caused by differences between the magnetic forces acting on the combustion gas and surrounding air.

\[ Gr_m = \frac{(\chi_f - \chi_{ox}) B \frac{dB}{dz} L_f^3}{\mu_0 \rho v^2} \approx \frac{\chi_{ox} B \frac{dB}{dz} L_f^3}{\mu_0 \rho v^2} \]

Fujita, et al., [6] concluded that in a manner like buoyancy induced flow because of the acceleration due to gravity, the presence of magnetic force should induce flow for a value of \( Gr_m \) in the order of \( 10^2 \cdot 10^3 \). For flames with \( Gr_m \) greater than the critical value, flames were observed to burn brighter, and the tips of the flames were observed to close with increasing magnetic field intensity. Both of these observations were attributed to the increased motion due to the application of upward decreasing magnetic field.

1.4.4  Froude’s Number

For diffusion flames in gravitational flow field, depending on the magnitude of Froude number, these flames may be either buoyancy controlled (\( Fr << 1 \)) or momentum controlled (\( Fr >> 1 \)) or in a transition region (\( Fr \approx 1 \)) [7].
Here, the mean buoyant acceleration is determined as [7]

\[ \alpha \approx 0.6g \left( \frac{T_f}{T_{ox}} - 1 \right) \]

### 1.4.5 Magnetic Froude Number

Magnetic Froude number is defined to compare the magnitude of the magnetically generated buoyancy forces to the momentum forces. Magnetic field acts along the length of the flame and so the flame height is kept as the characteristic dimension. By using this analogy, Fujita et. al established that if \( Fr_m < 0.1 \), then the behavior of the flame should be dominated by the magnetic field interaction [6].

\[
Fr_m = \frac{\rho \mu_0 (v_FY_F)^2}{(\chi_f - \chi_{ox})B \frac{dB}{dz} L_f} \approx \frac{\rho \mu_0 (v_FY_F)^2}{\chi_{ox}B \frac{dB}{dz} L_f}
\]

It can also be written in terms of \( Re \) and \( Gr_m \) of the flame as:

\[
Fr_m = \frac{Re^2}{Gr_m}
\]

In this manner, it is again reasonable to compare the magnetically induced behavior to that associated with a gravitationally generated buoyancy induced flow. To define regimes where the non-uniform magnetic field impacts flame behavior, we can determine a ratio of the body forces associated with gravity to those associated with magnetic force by examining the ratio of \( Fr_m \) to the traditionally defined \( Fr \) [7]:

\[
N_{gm} = \frac{Fr_m}{Fr} = \frac{-\rho \mu_0 a}{\chi_{ox}B \frac{dB}{dz}}
\]
1.5 Motivation and Research Goal

In this study, a laminar diffusion propane flame produced using 0.81 mm burner port in the presence of an increasing and decreasing magnetic field is used to gain insight into the magneto-combustion behavior. Previous studies had suggested the use of prohibitively high magnetic fields of about 5 Tesla for this effect to be noticeable. However, recent studies have indicated that fields of the order of 1 Tesla could exhibit similar interaction [13, 16, 22]. Most research on effect of magnetic field is performed using electromagnets to study the flame behavior within 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. The motivation for this study is to look at the effects produced by magnetic field of moderate-strength. The aim is to study if such fields can alter combustion behavior. The benefits of using permanent magnets also includes negating the need for external energy sources to produce high magnetic field strengths. At present, magnetic control of combustion and gas flow is a new scope of research and further experimental study is required to establish the mechanism for this interaction. The specific objectives of study are:

a.) To design an experimental set-up to measure the local temperature in order to study the influence of magnetic forces to promote combustion compared to the normal buoyancy forces induced by gravity in diffusion flames.

b.) To identify dimensionless parameters that can be used to predict the regimes where application of non-uniform magnetic field can significantly influence flame characteristics.
LITERATURE SUMMARY

A large assembly of research has recently been carried out to study the effects of magnetic field on the behavior of flames to understand its mechanism. The effect was first recognized in 1847, when Michael Faraday [9] held a flame of a wax taper with the magnetic field and observed its tendency to move into an equatorial position. He also observed that the flames were more luminous when placed with the magnetic field. He theorized that the changes were due to the presence of “magnetic” and “diamagnetic” gases in the flames.

Over the past 30 years, there has been a renewed interest in the impact of magnetic field on combustion behavior. Hayashi [10] investigated magnetic field effects on the emission intensities of intermediate species in premixed flames. He found that magnetic field is seen to increase the combustion efficiency through the increase in the population of OH* radicals. He thought that this change in combustion process in terms of the magnetically induced change of singlet-triplet conversion rate agreed with the radical pair theory [11].

Ueno et al. [12] measured combustion velocities of gasoline and alcohol with platinum catalysis as an analogy to cellular respirations in biological systems. They found the increase in the applied magnetic field gradient caused a sinusoidal response in gasoline combustion velocity. In alcohol, it was found that the combustion rates exhibited a minimum at a specific field strength. They attributed this effect to radical reactions through hydrogen-bonded species on the surface of platinum catalyst. However, the detailed mechanisms for this phenomenon were still unknown. Combustion consists of many radical reactions. As in the case of chemical reactions in solution, the magnetic field changes the singlet-triplet (S-T) conversion rates of intermediate radical pairs through hyperfine interactions. Aoki, T. [13] rejected the radical pair theory for gaseous combustion process, since in a gaseous phase, the lifetimes of a radical pair disappear before
inversing the spins of excited states by S-T conversions. Ueno, S. and Harada, K. [14] continued his investigations by examining the behavior of candle flames. It was noted that the presence of an increasing magnetic gradient caused the flame to deflect in the direction of decreasing magnetic field strength. They came up with two reasons for this behavior; first, the charged particles in flame plasma made a current loop that tended to reduce the external magnetic field. Thus, flames escape from magnetic field of higher intensity. Second, paramagnetic O\textsubscript{2} gases could be gathered by a gradient magnetic field and create a magnetically induced pressure to press back other diamagnetic gases and particles. To clarify this behavior, Ueno, S. and Harada, K. [15] expanded their research to study flames and jets of gas flow. Since the gas flow was also impacted by the magnetic field, the first hypothesis of charged particle theory was rejected. He also concluded that the presence of a strong magnetic gradient did not concentrate oxygen but aligned or trapped the molecules to make a “wall of oxygen” under the influence of magnetic gradient like an “air curtain” that pressed back flames and other gases. Ueno, S. [16] devised a new experiment to study the strength of this wall of oxygen. He used a candle placed between two columnar electromagnets that extinguished the flame shortly after application of the field and there was no increase in air pressure. He used an incense smoke to trace the curved surface of this magnetic air curtain. It indicated that instead of concentrating the O\textsubscript{2} molecules and dispersing the N\textsubscript{2} molecules, air was trapped in the region of highest gradient strength.

In 1990, Ueno, S. and Iwasaka, M. [17] studied the properties of air curtain and observed that the flow of CO\textsubscript{2} gas wasn’t blocked by magnetic field in N\textsubscript{2} atmosphere, which emphasizes the importance of O\textsubscript{2} as a paramagnetic gas in the formation of a magnetic curtain. They further classified this effect in to three regimes depending on the flow velocities. In the first and third regime with slow and fast flow velocities respectively, the gas could pass through the magnetic
curtain, while in the second regime with medium flow velocities, the gas flow was blocked. This mechanism of magnetic curtain was also simulated numerically to explain the behavior of gas flows using collision of O₂ molecules model.

Aoki, T. [13] was the first one to investigate the effect of an inhomogeneous magnetic field under increasing, decreasing and uniform magnetic field gradients. In case of an upward decreasing field generated by electromagnets, he found that the presence of a magnetic field caused an increase in the flame temperature, emission intensities of radicals OH*, CH₈ and C₂* transitions and a bluing tendency of the flames. The author used a simplified diffusion model to explain the increase in flame temperature and flame dimensions in a diffusion flame; that they were mainly because of the effect of magnetic force. This magnetic force acting on the paramagnetic species changes the gas flow which affects the mixing and diffusion process conditions that increase the combustion velocity. Therefore, it is the changes in the actual physical processes that change the combustion state and not the chemical reaction itself.

On the other hand, the upward-increasing magnetic fields [18] increased the flame dimensions, they decreased radical emissions, temperatures and the bluing tendency. These phenomena were contrary to those observed in previous studies. The upward-increasing magnetic fields caused inverse burning where the positions of blue and yellow-orange regions were reversed, and the highest temperature of the flame appeared at the flame surfaces distant from the flame top. He also investigated butane combustion under a uniform magnetic field encircled by magnetic field [19]. He observed no effect on combustion state, except for some changes that can be ascribed to the magnetic gradient produced by pole fringes. This exists for most of the magnets and is unavoidable. He showed that the velocities of electrons and ions produced by the combustion reaction are very low in the diffusive flame where the flow is dominated by buoyant force. Hence,
the effect of Lorentz forces on the deformation of the flame was insufficient to cause any appreciable changes in flame within the magnetic field. Yamada [20] supported this, as the amount of ionic species is negligibly small, and the influence of the Lorentz force can be ignored in ordinary flames.

This explanation of magnetic force theory was also supported by Wakayama, N.I. [21] when she conducted experiments on O₂, N₂, mixture of the two and air. The behavior of gas flow can be explained by the difference between the magnetic force acting on the gas group and the air surrounding it.

\[
F = (\chi - \chi_0)H \frac{\partial H}{\partial R}
\]

She explained that the air was attracted to the magnetic field which displaced the nitrogen gas from a magnetic field of relatively high intensity. This explanation also applies to the escape of flames from a high magnetic field gradient or magnetic quenching of flames observed by Ueno, S. [16]. Thus, the study demonstrates that it is the magnetic susceptibility of gas groups which exerts a net magnetic force that blocks gas flow, rejecting the “wall of oxygen” theory as suggested earlier.

Later, Wakayama, N. I. [22,23] studied methane premixed, partially-premixed and diffusion flames within the magnetic field gradients. The results of these experiments brought to light a distinct thought process for interaction of flames with magnetic fields. It was observed that a decreasing magnetic field along the flame caused its shape to be more elongated and slender, while an increasing magnetic field produced shorter and thicker flames. It was also observed that the temperature and luminosity of the flame increased with increasing gradient strength. These observations were attributed to the paramagnetic nature of oxygen and the diamagnetic properties of the products of combustion. She suggested two reasons for magnetic promotion of combustion
in diffusion flames. First, when fuel gas flows in the direction of decreasing field strength, the paramagnetic nature of oxygen increases the diffusion rate of air to the reaction zone and diamagnetic reaction products reject out efficiently. Accordingly, the burning velocity increases with increasing strength. Secondly, magnetic convection of air is also magnetically promoted because the gradient of temperatures causes the gradient of magnetic susceptibilities. The latter effect is less than the former one, comparing the difference of the magnetic susceptibilities in both cases.

However, no significant changes were observed for partially premixed flames and no effects on premixed flames, in either increasing or decreasing magnetic fields. Also, when the flames were moved to a homogenous field, the flames did not appear to be affected. Again in 2000, Mizutani, Y. [23] found that premixed flames were hardly affected by a uniform magnetic field as intense as 5T. He also concluded that the direct effects of the magnetic field on the chemical kinetics of flame propagations are negligible. This suggested the convection of oxygen into the regions of increasing strength was the most dominant factor in affecting the combustion behavior.

Hence, a diffusion flame is best suited to study the effect of a non-uniform magnetic field, as this combustion reaction occurs in the interface where the oxidizer and air react in stoichiometric

Figure 2.1: Direction of entrainment of air to flame under decreasing magnetic field (A). [17]
proportions. Diffusion flames are mainly governed by physical processes of mixing and diffusion of fuel gas and oxidizer. The rate of combustion is altered by magnetic field modifying the transport phenomena of oxidizer to the reaction zones of such flames. Wakayama, N.I. and Sugie, M. [24] suggested two kinds of air flow that promoted combustion in methane diffusion flames within 2 cm gap of electromagnets. Air was magnetically attracted along the steepest gradient (solid lines) and supplied to flame front. This makes flame front velocity three orders larger than the diffusion rate by natural physical processes. Furthermore, magnetic convective air flow occurred along y axis (dotted lines) feeding oxidizer to the leading edge of the flame because magnetic susceptibility of air is proportional to $P_0^2/T^2$. Accordingly, the direction of magnetic force in decreasing magnetic field facilitates this combined movement of involved species to promote combustion in diffusion flames.

Yamada et al. [20] performed numerical analysis of OH radical distributions in H$_2$/O$_2$ diffusion flames. It was observed that the magnetic gradient induced changes in the repartition of OH density in the flame. The effect is due to the enhancement of the entrainment gas flow around the flame base. This increases the mass density and then the magnetic susceptibility of oxygen in the peripheral region of the flame. To explore the possibility of combustion control by magnetic force, they [25] performed experiments using a co-axial type burner set between permanent magnets. Using spectroscopic techniques, they measured radial migration of OH towards the central axis of the flame as predicted numerically. Numerical simulations based on gas dynamics and magnetism showed that the magnetic force acts on the mean velocity of gas mixture and not on the diffusion velocity of OH radicals. Hence, the magnetic effect is essentially due to magnetic force acting on O$_2$ and not directly on OH itself.
Baker et al. [7] studied the characteristics of slotted laminar jet diffusion flames in the presence of upward decreasing magnetic field, using an assembly of prisms in permanent magnets. The magnetic field decreased the flame height, prevented the flame from attaching to the prisms, increased the intensity of the flame, reduced the flow rate for which visible soot inception occurred, and increased the flow rate below which the flame extinguished. They provided a power-law fit between the experimental data and dimensionless parameters, which shows an inverse relation between magnetic body force and flame height.

Khaldi, F. [26] investigated the phenomenon of thermos-magnetic convection due to the dependence of the O$_2$ magnetic susceptibility on temperature. They redefined the Rayleigh number as the results showed that heat transfer driven by a magneto-gravity buoyancy is like that driven by gravity alone. Gillon, P. [27] did extensive research on lift-off height of methane co-flow diffusion flames. Flame lift-off is referred to as the phenomenon in which the fuel mass flow rate exceeds a critical value and the flame and burner become separated. When the mass flow rate increases further, the lift-off height increases until the flame becomes flat and then blows out. The flame is said to be stabilized where the flame propagation speed with respect to the fuel/oxidizer matches the local flow velocity.

Under the influence of an upward decreasing magnetic field, Gilard, V. [28] observed a reduction in lift-off height. Magnetic force acting downwards on paramagnetic oxygen molecules decreases the air velocity locally. This modification of external air mixing layer, enhances the radial diffusion of methane and drops the stoichiometric line moving the flame front to a lower position.

Kumar, M. et al. [29] used Digital Speckle Pattern Interferometry to study the behavior of butane diffusion flames under the influence of a magnetic field. The maximum flame temperature
increased under an upward-decreasing magnetic gradient and decreased under an upward-increasing magnetic gradient, while a negligible effect on temperature was noted in a uniform magnetic field.
EXPERIMENTAL APPROACH

In this chapter, the various components of the experimental setup used in this study are described. The components are designed and fabricated in a way to produce a laminar propane/air diffusion flame which is convenient for accurate temperature measurements. The experiments were carried out in the presence of magnetic gradient field created by a permanent magnet placed around the burner system and the results are compared to a case of zero magnetic field created using false magnets. All the components were made using non-magnetic materials to avoid any unwarranted attractions by the application of the magnetic field on the setup used.

1.6 Experimental Set-up

The whole experimental device is installed at the Reacting Flow and Turbulent Jets laboratory in the MAE department of NC State University. A picture of the experimental setup is shown in Figure 3.1. The experimental setup is placed where the surrounding air remains relatively static, is mainly composed of the propane-air diffusion burner, yoke with the magnets, flow meter along with provisions for local temperature measurements.
1.7 Burner System

The burner system is required to produce laminar flow conditions for the fuel gas issuing into ambient air and to maintain a stable flame environment for temperature measurement required for this system. The fuel flow rate was regulated using a metering valve to ensure accurate results reproducible over multiple tests under similar conditions. A schematic representation of the burner is shown in Figure 3.2. The burner consists of a cylindrical base set on a stand through which a series of PVC fittings have been configured. The burner setup consists of fuel supply system and the diffusion burner. 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.

Fuel gas of propane was fed into the inner tube of 0.81 mm inner diameter is 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. This stainless steel (type 316) burner produces nearly conical flame and can be vertically translated to different positions within the magnetic field.
1.8 Fuel Supply

The main purpose of fuel supply system is to supply the combustion gases to the burner in controlled proportions. This supply system consists of compressed gas cylinders, flow meters, valves and tubing, and can supply the fuel gases, oxidizer and others such as purge gases, both to a premixed and a diffusion burner configuration, present in the lab. The line supplying gases issues 99.0% pure CP grade propane (C\textsubscript{3}H\textsubscript{8}) was supplied from the cylinder to the diffusion burner. It flows through a Yor-Lok precision flow adjustment needle valve to govern the passage of the fuel gases and was monitored using volumetric flow meter (OMEGA, FMA-A2309) having a range of 0-10 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 3.3. Propane is injected at ambient temperature (i.e. 292.7 K)

1.9 Magnet Design

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. Plain Iron Yoke design was selected on the basis of prior study done by R,Vikram [25] in the lab. 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 3.4.

![Iron Yoke with Magnets](image)

Figure 3.3: 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 3.4. The influence of magnetic field along the flame length is studied and hence the field distribution in the vertical direction is emphasized.

![Actual Magnetic Field Strength Variation](image)

Figure 3.4: Actual Magnetic Field Strength Variation
Figure 3.4 also shows the specific locations of study employed in this experiment. The burner nose is positioned to be in two vertical positions A and B so that 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. The measurements of these cases were compared to a case of no applied magnetic field (NAMF).

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.

1.10 Temperature Measurements

The most critical element to this study is to identify the effect of non-uniform magnetic fields on the combustion processes occurring in the diffusion flame. The local temperature was monitored with a high-temperature Type K thermocouple probe, enclosed in a protection tube. Type K thermocouple has been chosen since it can accommodate temperatures up to 1523 K. The temperature is measured at the highest point on flame tip along the z axis for a given configuration. The thermocouple translation mechanism facilitates this movement for the different axial positions of flame tip for a given flow velocity as shown in Figure 3.1.
The thermocouple is connected to the digital temperature reader (CL3515R), which is a portable thermometer with a 4-digit LCD. It is designed to be used with an external K Type thermocouple as temperature sensors. It has an accuracy of ± (0.05% rdg + 0.5 K) -223 to 1645 K. It includes a DAQ (Data Acquisition) software to record the measurements and export the data in excel format.

![Digital Temperature Reader](image)

**Figure 3.6: Digital Temperature Reader**

### 1.11 Tests Performed

A set of experiments were carried out to determine the temperature distribution as a function of propane flow velocity within the flame. A propane/air diffusion flame was established for various fuel flow rates and the measured local temperatures were corrected for radiation losses. The measurements were carried for three different cases; increasing magnetic field gradient, decreasing magnetic field gradient and when no magnetic field was applied. The temperatures were measured at the flame tip for each of the above cases. This represents the peak local temperature value along the central axis of the flame length. The thermocouple was positioned along the flames’ central axis and gradually positioned at the flame tip on the z axis. 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 fluid flow behavior under the application of non-uniform magnetic field is characterized using various dimensionless parameters, as discussed earlier. To gauge whether the magnetic field enhances the combustion processes occurring in the flame, we use the experimental data for flame height obtained by previous research conducted in the lab by Ramnath, V. [30]. He studied the effect of gradient magnetic field on flame structure. 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 variation of the local temperature is studied using the same apparatus as Ramnath, V. under the same flow conditions. The tabulated data for flame height [30] and local temperatures measured are used to experimentally examine the dimensionless parameters. The test matrix is given in Table 3.1.

<table>
<thead>
<tr>
<th>Flow Velocity of $\text{C}_3\text{H}_8$ (m/s)</th>
<th>Increasing Magnetic Field Gradient</th>
<th>Decreasing Magnetic Field Gradient</th>
<th>NAMF (No Applied Magnetic Field)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.009 T$_f$</td>
<td>T$_f$</td>
<td>T$_f$</td>
<td>T$_f$</td>
</tr>
<tr>
<td>0.017 T$_f$</td>
<td>T$_f$</td>
<td>T$_f$</td>
<td>T$_f$</td>
</tr>
<tr>
<td>0.026 T$_f$</td>
<td>T$_f$</td>
<td>T$_f$</td>
<td>T$_f$</td>
</tr>
<tr>
<td>0.034 T$_f$</td>
<td>T$_f$</td>
<td>T$_f$</td>
<td>T$_f$</td>
</tr>
<tr>
<td>0.043 T$_f$</td>
<td>T$_f$</td>
<td>T$_f$</td>
<td>T$_f$</td>
</tr>
<tr>
<td>0.051 T$_f$</td>
<td>T$_f$</td>
<td>T$_f$</td>
<td>T$_f$</td>
</tr>
</tbody>
</table>
RESULTS AND DISCUSSION

The behavior of laminar jet diffusion flames in the presence of gradient magnetic fields has been investigated for different flow velocities of fuel and the results of this experimental study are presented. The local temperature test was to determine the variation of temperature at flame tip location with respect to propane flow rate. This chapter deals with the experimental run conditions, the data obtained, and the analysis of the relevant non-dimensional numbers used to characterize the flow regimes of flame gases under the effect of magnetic field.

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”. The results are comprehended in a manner to provide a better understanding of the flame-magnetic field interaction.

1.12 Case A: No Applied Magnetic Field (NAMF)

The variation in local temperature as function of flow velocity is measured at the flame tip for the case of no applied magnetic field. This is done using aluminum yoke instead of the magnetic yoke. The results are collected for flow velocities varying from 0.009 m/s to 0.051 m/s.

The values represent the average of ten measurements at each flow velocity with an estimated experimental error of ±(0.05% rdg + 0.5 K). Further, the measured thermocouple
temperature is corrected for radiation losses. This shows that local temperatures are underestimated by approximately 43.5 K due to radiation losses from the thermocouple tip.

Table 4.1: Axial local temperature variation in the absence of gradient magnetic field

<table>
<thead>
<tr>
<th>Flow Velocity (m/s)</th>
<th>Average $T_m$ (K)</th>
<th>Corrected $T_r$ (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.009</td>
<td>876.7</td>
<td>920.8</td>
</tr>
<tr>
<td>0.017</td>
<td>991.3</td>
<td>1048.5</td>
</tr>
<tr>
<td>0.026</td>
<td>1025.0</td>
<td>1082.1</td>
</tr>
<tr>
<td>0.034</td>
<td>994.2</td>
<td>1039.8</td>
</tr>
<tr>
<td>0.043</td>
<td>922.2</td>
<td>953.4</td>
</tr>
<tr>
<td>0.051</td>
<td>900.4</td>
<td>926.2</td>
</tr>
</tbody>
</table>

Figure 4.1: Variation of measured and corrected local temperature with flow velocity when no applied magnetic field
1.13 Case B: Increasing Gradient Field

The variation in highest local temperature with flow velocities in the presence of a gradient magnetic field whose strength was increasing from the burner lip is studied and is shown in Figure 4.2. It is observed that the local temperatures are underestimated by approximately 52 K due to辐射 losses from the thermocouple tip.

Table 4.2: Axial local temperature in case of increasing gradient magnetic field

<table>
<thead>
<tr>
<th>Flow Velocity (m/s)</th>
<th>Average T_m (K)</th>
<th>Corrected T_r (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.009</td>
<td>948.0</td>
<td>1005.2</td>
</tr>
<tr>
<td>0.017</td>
<td>1028.7</td>
<td>1093.6</td>
</tr>
<tr>
<td>0.026</td>
<td>1037.2</td>
<td>1096.3</td>
</tr>
<tr>
<td>0.034</td>
<td>1031.6</td>
<td>1083.9</td>
</tr>
<tr>
<td>0.043</td>
<td>1023.8</td>
<td>1070.2</td>
</tr>
<tr>
<td>0.051</td>
<td>957.8</td>
<td>990.6</td>
</tr>
</tbody>
</table>

Figure 4.2: Variation of measured and corrected local temperature with flow velocity under increasing magnetic field gradient
1.14 Case C: Decreasing Gradient Field

The variation in local temperature in the presence of a gradient magnetic field whose strength was decreasing from the burner lip is studied and is shown in Figure 4.3. It is observed that the local temperatures are underestimated by approximately 52 K due to radiation losses from the thermocouple tip.

<table>
<thead>
<tr>
<th>Flow Velocity (m/s)</th>
<th>Average $T_m$ (K)</th>
<th>Corrected $T_f$ (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.009</td>
<td>912.9</td>
<td>963.5</td>
</tr>
<tr>
<td>0.017</td>
<td>986.9</td>
<td>1043.4</td>
</tr>
<tr>
<td>0.026</td>
<td>1038.5</td>
<td>1097.6</td>
</tr>
<tr>
<td>0.034</td>
<td>1053.9</td>
<td>1110.6</td>
</tr>
<tr>
<td>0.043</td>
<td>1068.3</td>
<td>1122.3</td>
</tr>
<tr>
<td>0.051</td>
<td>974.6</td>
<td>1009.9</td>
</tr>
</tbody>
</table>

Figure 4.3: Variation of measured and corrected local temperature with flow velocity under decreasing magnetic field gradient
1.15 Flame Gas Flow Behavior Characterization

The flame gas flow behavior is characterized with the help of previously defined magnetic Froude number, magnetic Grashof number and the ratio of gravitationally induced buoyancy forces to the magnetically induced body forces. They are identified as the key parameters to determine the regime where the magnetic field will affect the diffusion flame behavior. To examine the physical processes responsible for the observed flame behavior, the magnitude of these dimensionless numbers is compared for the different flow velocities of propane gas. Table 4.4 shows the baseline parameters used to perform these calculations.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean Buoyant Acceleration (m/s²)</td>
<td>α</td>
<td>23.73</td>
</tr>
<tr>
<td>Mass Diffusivity (m²/s)</td>
<td>D</td>
<td>7.62 × 10⁻⁵</td>
</tr>
<tr>
<td>Ratio of actual Initial Momentum to that</td>
<td>I</td>
<td>1.0</td>
</tr>
<tr>
<td>of Uniform Flow</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ambient Temperature (K)</td>
<td>Tᵢ</td>
<td>297.2</td>
</tr>
<tr>
<td>Fuel Mass Fraction</td>
<td>Yᵢ,stoic</td>
<td>0.0601</td>
</tr>
<tr>
<td>Permeability of free space (kg.m/s²A²)</td>
<td>μ₀</td>
<td>1.26 × 10⁻⁶</td>
</tr>
<tr>
<td>Magnetic Susceptibility of Oxygen</td>
<td>χₐ₀</td>
<td>2.0 × 10⁻⁶</td>
</tr>
<tr>
<td>Density of fuel (kg/m³)</td>
<td>ρ</td>
<td>0.4</td>
</tr>
</tbody>
</table>

As can also be seen from Figure 4.3, the application of a non-uniform decreasing magnetic field produced the most significant increase in the local temperature. Thus, in this condition the interaction of flame with magnetic field enhanced the combustion processes occurring in the flame. To examine the extent of this interaction, the dimensionless parameters characterizing the forces acting on the diffusion flame are tabulated for the case of a vertically decreasing gradient field. The mean buoyant acceleration was calculated using the local temperature for each flow velocities,
to determine if the buoyancy force associated with the magnetic field increases the oxygen transport to the diffusion flames.

Table 4.5: Parameters characterizing flame behavior in a decreasing gradient magnetic field

<table>
<thead>
<tr>
<th>Flow velocity (m/s)</th>
<th>$T_f$ (K)</th>
<th>$v$ (m$^2$/s)</th>
<th>$L_f$ (m) [30]</th>
<th>$\alpha$ (m/s$^2$)</th>
<th>Dimensionless numbers to characterize flame behavior</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Re</td>
</tr>
<tr>
<td>0.009</td>
<td>963.48</td>
<td>1.79E-05</td>
<td>0.00604</td>
<td>13.20</td>
<td>0.17</td>
</tr>
<tr>
<td>0.017</td>
<td>1043.37</td>
<td>2.00E-05</td>
<td>0.01027</td>
<td>14.78</td>
<td>0.26</td>
</tr>
<tr>
<td>0.026</td>
<td>1097.62</td>
<td>2.14E-05</td>
<td>0.01474</td>
<td>15.85</td>
<td>0.35</td>
</tr>
<tr>
<td>0.034</td>
<td>1110.61</td>
<td>2.19E-05</td>
<td>0.02359</td>
<td>16.11</td>
<td>0.55</td>
</tr>
<tr>
<td>0.043</td>
<td>1122.31</td>
<td>2.23E-05</td>
<td>0.03436</td>
<td>16.34</td>
<td>0.79</td>
</tr>
<tr>
<td>0.051</td>
<td>1009.89</td>
<td>1.96E-05</td>
<td>0.04421</td>
<td>14.11</td>
<td>1.16</td>
</tr>
</tbody>
</table>

1.16 Important Observations

The values of the local temperatures under the influence of an increasing and decreasing gradient magnetic field and no applied magnetic field for the 0.81 mm burner can be found in Table 4.6.

Table 4.6: Local temperature variation with and without magnetic gradient field

<table>
<thead>
<tr>
<th>Flow Velocity (m/s)</th>
<th>NAMF (K)</th>
<th>Increasing Field (K)</th>
<th>Decreasing Field (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.009</td>
<td>920.8</td>
<td>1005.2</td>
<td>963.5</td>
</tr>
<tr>
<td>0.017</td>
<td>1048.5</td>
<td>1093.6</td>
<td>1043.4</td>
</tr>
<tr>
<td>0.026</td>
<td>1082.1</td>
<td>1096.3</td>
<td>1097.6</td>
</tr>
<tr>
<td>0.034</td>
<td>1039.8</td>
<td>1083.9</td>
<td>1110.6</td>
</tr>
<tr>
<td>0.043</td>
<td>953.4</td>
<td>1070.2</td>
<td>1122.3</td>
</tr>
<tr>
<td>0.051</td>
<td>926.2</td>
<td>990.6</td>
<td>1009.9</td>
</tr>
</tbody>
</table>
Figure 4.4 shows the impact of the gradient magnetic field on local temperature as a function of flow velocity.

We can see from figure 4.4 that the trend of local temperature with the variation of fuel flow velocity can be roughly divided into three regions.

- **Region I**: This is distinguished by an increasing behavior in the local temperature at the flame tip when the propane flow velocity is increased in all the three cases. It is noted that in this region the local temperature peaks for case B when flame is under increasing magnetic gradient field.

- **Region II**: This region represents a change in the trend of local temperature vs. propane flow velocity for each case. For the last cases when a gradient magnetic field is applied the rate of temperature rise slows down to almost approaching a flat line. However, for the case A: NAMF, the temperature starts to drop sharply after peaking to 1082.1 K at 0.26 m/s.
- Region III: This region expresses similar behavior for all the three cases, where the local temperature starts decreasing with any more increase in the propane flow velocity. It is in this region we observe the highest increase in the local temperature of all the three cases reaching up to 1122.3 K at 0.043 m/s, which is +40 K increase compared to the peak temperature in case A: NAMF. The local temperature behaves in a manner that is most favorable for the combustion of propane/air diffusion flame in case C when the flame is inside a decreasing magnetic gradient field.

It is well observed that the application of decreasing magnetic gradient field is accompanied by an increase in temperature. These results are consistent with earlier studies. In case C, by subjecting the flame to a decreasing magnetic gradient field, oxygen from the surrounding gas is drawn towards the flame via the magnetic force exerted. Thus, better utilization of the oxidizer implies better combustion. This aids enhanced burning conditions by replenishing reactants and removing hot product gases from the flame zone and thus leading to higher temperatures.

A reverse effect is expected in the case B, when the increasing magnetic gradient field is applied as the magnetic forces are in the direction that quenches the combustion processes in diffusion flame. Although the peak temperature in this case B was lower than that compared to case C, the local temperatures measured are still higher than the corresponding values for the case A of NAMF. This behavior was not consistent with previously published theory for magnetic promotion of combustion [29]. However, similar anomaly was observed by Gillon, P. [31] where he observed that the magnetic action on the flame lift-off height is independent of the burner position in the magnetic gradient field.
The experimentally examined Reynolds number indicates that the flame gases were laminar in nature and the Froude number shows that they were buoyancy controlled as \( Fr \ll 1 \). As stated earlier, since the magnetic Froude number is in the order of \( 10^{-6} \), the behavior of the flame should be dominated by the magnetic field interaction. By examining another important parameter, i.e. the ratio of the body forces associated with gravity to those associated with the application of decreasing gradient magnetic field, it was observed that the buoyancy of flames in this experiment is, dominated by gravitational force, since \( N_{gm} < 1 \). It should be noted that the value of \( N_{gm} \) increased up to 0.4 with an increase in flow velocity and thus we observed a higher local temperature in this region. Further, the values of magnetic Grashof number suggest a magnetic field influence on the propane/air diffusion flame. Thus, an examination of \( Fr_m \), \( Gr_m \) and \( N_{gm} \) shows that the flames examined in this study span a range over which the flames transition from buoyancy-controlled to magnetic-field controlled.
CONCLUSION AND FUTURE WORK

1.17 Conclusion

This study examined the behavior of the propane jet diffusion flames exposed to low strength gradient magnetic field. Based upon the results of this investigation, the following conclusions have been drawn:

1. The experimental data can be cast into three regions and is found to exhibit similar behavior within the regions for all the three conditions examined. When the propane flow velocity is low (region I), the local temperature shows an increasing behavior. As the velocity is increased (region II), the rise of local temperature slows down until it peaks and starts to decrease when the velocity is further increased (region III).

2. When the laminar propane/air diffusion flame corresponding to flow rates 0.009 m/s – 0.051 m/s were studied, a non-uniform upward decreasing magnetic field was observed to have the most significant impact on combustion processes in the flame. For this condition, compared to flames with no applied magnetic field, the local temperature increased by an average of 40 K. Here, the magnetic force enhanced the supply of paramagnetic oxygen to the bottom and efficiently pushed the diamagnetic gases out the reaction zone. This behavior was consistent with previously published results.

3. In the case of increasing magnetic field, reverse effects were expected but the local temperature showed a slight increase, by 15 degrees, relative to the case with no applied magnetic field but this was still lower than the case of decreasing magnetic field. This anomaly in flame behavior indicates a more complex interaction with magnetic field or it could be an artifact of the small investigation area of the magnet assembly. When the
burner tip is positioned for this case, there is still a possibility of decreasing magnetic gradient acting on the flame length from the upper half of the magnet assembly.

4. The tabulated data of dimensionless numbers clearly indicates that the momentum forces are small for the investigated Reynolds number flow. In addition, the Froude number calculations being very less than unity, it can be said that these flames are buoyancy controlled. The experimentally observed magnetic Froude number were of the order of $10^{-6}$. This would indicate that buoyancy in flames are caused by the magnetic force relative to inertial effects in a diffusion flame.

5. Further, the values of magnetic Grashof number suggest that a low strength magnetic gradient field of 0.75 T can impact combustion in propane diffusion flames. Thus, an examination of $F_{m}$, $G_{m}$ and $N_{gm}$ shows that the flames examined in this study span a range over which the flames transition from gravity-controlled to magnetic-field controlled. This observation can be attributed to the increased motion of air to the reaction zone due to the application of decreasing magnetic gradient field.

**1.18 Future Work**

There is scope for much work that can be conducted further in this area of research to fully understand the complex nature of the interactions between magnetism and combustion. The following suggestions might be useful in delving further in this area.

1. To study the effect of different strengths of magnetic field to identify the transition in flame behavior on the application of varying external field. This can be done by employing compact permanent magnets of higher field strength compared to the one used in current investigation to see a pronounced effect of magnetic field.
2. The current investigation area was limited to the size of the magnet assembly employed. This can be expanded to extend the experiments as the current investigation was limited by the maximum flow velocity required to maintain the flame top inside the magnet assembly.

3. The study of flame-field interaction was altered by the intrusion of thermocouple tip that can manipulate the temperature at the flame tip location. Although the radiation loses were considered and corrected temperatures were calculated, to improve the accuracy of investigation, it would be helpful to use a non-contact type temperature measurement system.

4. To establish its commercial and industrial application, further design improvements can be performed. To ensure the temperature measurements are accurate and magnetic field are unaltered by the heating of the magnets, an active cooling arrangement for the magnets and thermocouple will ensure continuous working of the setup.

5. The current investigation can be taken further to study the behavior of flame in each of the three regions individually with respect to different base parameters like burner tip diameter, maximum field strength, co-flow air velocity and using different fuels etc.

6. It would be helpful to look into the effect of the flow rate on the soot produced by the diffusion flame under the effect of magnetic gradient flame to gauge whether the concentration of soot will be altered. Thus, enhancing the combustion processes to burn the fuel supplied more completely relative to when there is no applied magnetic field.
REFERENCES


[34] https://www.engineeringtoolbox.com/propane-d_1423.html
APPENDICES
APPENDIX A: Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \alpha )</td>
<td>Mean Buoyant Acceleration</td>
</tr>
<tr>
<td>AMF</td>
<td>Applied Magnetic Field</td>
</tr>
<tr>
<td>B</td>
<td>Magnetic Induction</td>
</tr>
<tr>
<td>D</td>
<td>Mass Diffusivity</td>
</tr>
<tr>
<td>Fr</td>
<td>Froude Number</td>
</tr>
<tr>
<td>( Fr_m )</td>
<td>Magnetic Froude Number</td>
</tr>
<tr>
<td>g</td>
<td>Acceleration due to gravity</td>
</tr>
<tr>
<td>Gr</td>
<td>Grashof Number</td>
</tr>
<tr>
<td>( Gr_m )</td>
<td>Magnetic Grashof Number</td>
</tr>
<tr>
<td>I</td>
<td>Ratio of the actual initial momentum to that for uniform flow</td>
</tr>
<tr>
<td>( L_f )</td>
<td>Flame Height</td>
</tr>
<tr>
<td>NAMF</td>
<td>No Applied Magnetic Field</td>
</tr>
<tr>
<td>( N_{gm} )</td>
<td>Ratio of Buoyancy to Magnetic Forces</td>
</tr>
<tr>
<td>Re</td>
<td>Reynolds Number</td>
</tr>
<tr>
<td>T</td>
<td>Temperature</td>
</tr>
<tr>
<td>( u )</td>
<td>Mean Burner Port Exit Velocity</td>
</tr>
<tr>
<td>( Y_f )</td>
<td>Fuel Mass Fraction</td>
</tr>
<tr>
<td>( z )</td>
<td>Distance Above Burner Port Exit</td>
</tr>
<tr>
<td>( \mu_0 )</td>
<td>Permeability of Free Space</td>
</tr>
<tr>
<td>( \nu )</td>
<td>Kinematic Viscosity</td>
</tr>
<tr>
<td>( \rho )</td>
<td>Density</td>
</tr>
<tr>
<td>( \chi )</td>
<td>Magnetic Susceptibility</td>
</tr>
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</table>

**Subscripts**

<table>
<thead>
<tr>
<th>Subscript</th>
<th>Description</th>
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</thead>
<tbody>
<tr>
<td>f</td>
<td>Flame</td>
</tr>
<tr>
<td>F</td>
<td>Fuel</td>
</tr>
<tr>
<td>OX</td>
<td>Oxidizer</td>
</tr>
<tr>
<td>Stoic</td>
<td>Stoichiometric Conditions</td>
</tr>
</tbody>
</table>
APPENDIX B: Thermocouple Radiation Correction

In a high-temperature environment, such as the hot-flame gases in the current burner arrangement, one major source of uncertainty in the measurement of local temperature is the correction for radiation. In the following, the various factors impacting the fidelity of the measured temperature to the true flame gas temperature are considered.

Under the assumption of steady-state temperature, an energy balance around the thermocouple bead may be written as the sum of conductive, convective, radiative and catalytic heat gain/loss:

\[ m_b c_{p,b} \frac{dT}{dt} = 0 = q_{\text{cond}} + q_{\text{conv}} + q_{\text{rad}} + q_{\text{cat}} \]

where \( m_b \) and \( c_{p,b} \) are the bead mass and the bead specific heat, respectively. Catalytic effects may be neglected a priori due to the choice of a K-type chromel/alumel thermocouple, whose materials can be considered non-reactive under the present conditions. Neglecting the conduction through thermocouple wires, the convective heat transfer between the thermocouple and the flame gases should be equal to net radiative heat exchange between the thermocouple bead and its ambient surroundings. Thus, the radiation correction has been considered. If \( T_m \), the thermocouple temperature is the same through the thermocouple probe and that steady condition prevails, the derivation for the temperature correction is as shown below:

\[ q_{\text{conv}} = h g A_{\text{sph}} (T_f - T_m) \]
\[ q_{\text{rad}} = \varepsilon A_{\text{sph}} \sigma (T_m^4 - T_\infty^4) \]

Where; \( T_f \) is the corrected local temperature (K), \( T_m \) is the measured temperature (K), \( \sigma \) is the Stefan Boltzmann constant \((\sigma = 5.67 \times 10^{-8} \text{ W/m}^2\text{K}^4)\), \( \varepsilon \) is the emissivity of the thermocouple
bead [32] and \( h_g \) is the convective heat transfer coefficient (W/m\(^2\)K). By equating the above two equations the corrected temperatures were calculated by using the relation:

\[
T_f = \frac{T_m}{h_g} + \frac{\sigma \varepsilon}{h_g} (T_m^4 - T_\infty^4)
\]

The value of the convective heat transfer coefficient \( h_g \) is approximated using the Nusselt number definition for a sphere immersed in a fluid [33] and given by the equations:

\[
h_g = \frac{k_g}{d} \left[ 2 + 0.6Pr^{\frac{1}{3}} \left[ \frac{ud}{v} \right] \right]
\]

Where; \( k_g \) is the thermal conductivity of the flame gases, \( Pr \) is the Prandtl number, \( v \) is the kinematic viscosity of the flame gases, all of which are evaluated at the film temperature \( (T_\infty + T_m)/2 \) [34], \( u \) is the flame velocity, \( d \) is the diameter of the thermocouple bead. This equation for \( h_g \) is valid for the case of forced convection from a sphere for Reynolds number \( (Re = \frac{ud}{v}) \) in the range 1-70,000 [33].