On the effect of repulsive magnetic field on partially premixed flames

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Abstract. The premixed flames are important with wide range of applications from burners, gas turbine combustor, mixing studies to practical, functional, engineering and scientific research applications. One of the interesting cases of premixed flames is partially premixed flames which has redirected the attention of the scientific community. The partially premixed flames represent incomplete burning, safety hazards, heterogeneous heat and mass transfer. The flame stability of premixed flames comprises an integral role in most of the propulsion applications. For efficient combustion operations and applications, flame stability is mandatory and different approaches have been tried. However, the complexity of the problem has prevented a thorough understanding. One aspect of transitional energy interaction which is yet to be tried is the interaction of magnetic energy with the thermal energy in partially premixed flames. The energy interactions are likely to alter the high energy field supporting flame stabilization and control. The major application includes, enhancement of fundamental understanding and optimization of potential gas turbine combustors, spacecrafts and magnetic nozzles etc. Thorough experimental investigation was carried out utilizing Bunsen burner and designated magnets for varying number of external energy sources, continual variation in interspace distances, and different configurations in repulsion fields. The magnetic effect on the flames is characterized in terms of geometric flame classification viz., Blue flame length (BFL), Yellow flame length (YFL) and Gross flame length (GFL) along with the visible structural changes in the flames. Results clearly state that presence of magnetic energy in the immediate vicinity significantly affect the flame behaviour. With systematic reduction in the separation distance, a non-monotonous drop in the BFL is observed for the cases of 2,3,4 magnet configuration(s) with reduction in the interspace distance.

1. Introduction
A flame is a self-sustained propagation of chemical reaction. The flaming combustion is broadly classified as diffusion flames and premixed flames and this classification is based on the region and characteristics of the flame (figure 1). In diffusion flame, the fuel diffuses from higher concentration to lower concentration and mix with air. Whereas in premixed flames, the air and the fuel mix before the combustion process takes place at the reaction front. Generally, the laboratory flames such as Bunsen burner are premixed with inner premixed cone and outer diffusion cone. Flame stability imparts a vital role in the in many of the aero propulsion applications. The effect of the external energy interactions with the flames play a vital role in the flame stability studies. One of the special cases of flaming combustion is partially premixed flames. They represent incomplete combustion with heterogeneous heat and mass transfer.
Flame stabilization have initiated studies based on the interaction with the electrical, thermal, and acoustic energies. Magnetic energy interaction in the vicinity of a thermal source is well known to affect the resultant energy field (Figure 2). The magnetic properties of the substances play an important role in the outcome. Magnetic fields arise due to the orderly arrangement of the small regions called as magnetic domains. A domain is a region consisting of group of molecules possessing a same magnetic dipole moment. Thus, the magnetic materials are classified into three types viz., diamagnetic, paramagnetic and ferromagnetic. The diamagnetic materials have the tendency to repel i.e. move from stronger to weaker magnetic fields when placed in external magnetic field like nitrogen, hydrogen etc. The paramagnetic materials attract weakly, when placed in external magnetic fields like oxygen, carbon dioxide etc. The ferromagnetic materials are strongly attracted when placed in external magnetic fields like iron, iron oxide and nickel, cobalt etc. Substantial work had been done on the direct interaction of the magnetic fields with the premixed and diffusion flames, but the interaction of the partially premixed flames with magnetic fields is an aspect of combustion yet to be explored. In partially premixed flames, these energy interactions are likely to alter the high energy field supporting flame stabilization and control.

![Figure 1: Pictorial representation of flame classification.](image)

Following the classical work on the effect of a magnetic field on the electrical conductivity of flame by Wilson [1], researchers had examined the effect of magnetism on flames in diverse possibilities. Ueno and Harada [2], investigated effects of magnetic field on combustion and gas flow. Methane, propane and hydrogen gases were utilized and their flames were exposed to the gradient
magnetic fields of 1.6 T and 220 T/m. Apart from the combustion experiments, flows of gases such as carbon dioxide and oxygen were exposed to magnetic fields up to 2.2 T and 300 T/m. The work notified that the flames bent so as to escape from magnetic fields of higher intensities. It was noted that the flows of gases with a velocity 20-140 ml/min was blocked by the magnetic fields. The corresponding changes of flame-shape and gas-flow by magnetic fields was attributed to be the result of the role of oxygen. The work concluded that under varying intensities of magnetic fields, oxygen gases as paramagnetic molecules are aligned so as to make a ‘wall of oxygen’. The oxygen presses back flames and other gases. Aoki [3], carried out experiments to explore the effect of upward-decreasing magnetic fields on diffusion flame of non-premixed butane gas. The study detailed increase in flame temperature, emission intensities of OH, CH and C2 radical transitions and decrease in the flame dimension with a bluing tendency of the flame. The Lorentz force was configured to bear no significant effect on flame shape changes. Magnetic forces originating from the magnetic gradients accelerated, stretched and squeezed the flame, resulting in a change in the flame shape. The results stated that the emission intensity of a continuous spectrum decreased drastically with increasing magnetic gradient field. Exploration by Wakayama [4], inscribed the relationship between the direction of a fuel-gas flow and the steepest gradient of the magnetic field to determine how the reaction was promoted. The results suggested that, when a fuel gas flows in the direction of a magnetic field of decreasing strength, a combustion reaction is activated. Furthermore, the chemical reaction involving a change in the magnetic susceptibilities of component species can be controlled by application of a gradient magnetic field. Utilization of permanent magnets was proliferated to be very important industrially, as they offer wide range of applications including combustion [5]. In continuation of work on magnetic advancement of combustion in diffusion flames, Wakayama and Sugie [6], noted that with fuel gas flow in the direction of a decreasing field strength, inhomogeneous magnetic fields promote combustion in diffusion flames. The flame temperature was found to increase with the flame became shorter and more brilliant on the application of a magnetic field gradient. The supply of air to the flame front was found to be increased because of the magnetic attractive force. Following which, the magnetic promotion of combustion was explained by the two kinds of air flow caused by the magnetic force. The results suggested the possibility of magnetic control of combustion and air flows. Work by Lovatt and Watterson [7], provided the correct formulation, under both normal operation and partial demagnetization, and discussed the physical meaning of stored energy in a permanent magnet. Campbell [8], disagreed technically with Lovatt and Watterson [7], on the energy stored in permanent magnets and stated that the work was based upon some erroneous assumptions. He presented valuable comments in an effort to explain some aspects about the energy exchanges in a magnetic circuit containing a permanent magnet. Mizutani et.al., [9], explored the direct effects of an almost uniform magnetic field on Bunsen flames. The work addressed issues pertaining to the influences acting directly on chemical kinetics, indirect effects generated by the interaction between the non-uniform magnetic fields, the combustion-derived gradient in oxygen concentration and the Lorenz force which works on moving charged particles. Baker et.al., [10] experimented laminar diffusion flames in the presence of non-uniform upward decreasing magnetic fields. The study was directed to obtain a symmetric magnetic field around a circular flame and visually record the flame height and shape along the burner axis. The study reported that non-uniform magnetic fields affect laminar diffusion flames as a result of the paramagnetic and diamagnetic properties of the products and reactants. Para-magnetism is the weak attraction to a magnetic field a material exhibits and Diamagnetism is the weak repulsion to a magnetic field exhibited by a material. Using a scaling analysis, it was shown that for laminar diffusion flames the magnetic field/ionized gas interaction was insignificant to the paramagnetic and diamagnetic influences.

Shinoda et. al., [11], experimented the mechanism of magnetic field effect on OH density distribution in a methane-air premixed jet flame by means of PLIF measurement and numerical simulation. In the experiment, magnetically induced change in the OH density profile in the flame in a N2 atmosphere was much smaller than that in air and phenomenon was qualitatively reproduced by solving the equations for reactive gas dynamics and magnetism in the numerical simulation. N2 was
Swaminathan [12], studied the effect of a gradient magnetic field on a diffusion micro flame i.e. C₃H₈/air flame. A non-uniform magnetic field was produced in the air gap of an electromagnet and the C₃H₈/air flame corresponding to various flow velocities. The work reported the influence of the operating conditions on the fundamental characteristics of the diffusion flame, such as the flame structure, temperature distribution and the morphology of the soot produced. It was found that the flame structure and its luminosity was influenced and the flame length decreased with the application of the vertically decreasing gradient magnetic field. The agglomeration of the soot particles decreased on the application of the decreasing magnetic field around the flame. Grimaldi [13], explored the effects of magnetic fields on the combustion velocities of gasoline and alcohol with platinum catalysis. The place of combustion reaction of gasoline on platinum catalyst was exposed to D.C. magnetic fields with field intensities from 0.1 T to 1.0 T. The study stated that the combustion velocity was influenced by the magnetic fields and the magnetic field effect on the combustion velocity of alcohol was observed to show a minimum at a specific magnetic field. Garanin and Chudnovsky [14], developed the theory of magnetic deflagration in crystals of molecular magnets. The analytical and numerical solutions for criteria of the ignition of magnetic deflagration was worked upon to compute the ignition rate and the speed of the developed deflagration front. The results advocated that the phenomenon resembles the burning of a chemical substance, with the Zeeman energy playing the role of the chemical energy. Besides, the non-destructive reversible character of magnetic deflagration, as well as the possibility to continuously tune the flammability of the crystal by changing the magnetic field, make molecular magnets an attractive system for a detailed study of the burning process. Gonzalez [15], reported aggregated spreads on the magnetic field effects on diffusion flames.

The work focused on four different types of magnetic fields viz., homogenous, gradient, oscillating and pre-combustion and provided theoretical, numerical and experimental insight into magnetic field effects on combustion. Whereas results, showed little effect of homogenous fields for gradient magnetic fields, different magnet geometry was used in for finite-element methods and numerical simulations to show the enhanced oxygen entrainment into the reaction zone. Digital imagery stated that soot particle agglomeration decreases with the use of gradient magnetic fields. Oscillating field results conveyed enhancement in mixing of fuel and oxidizer while pre-combustion magnetic fields resulted into more complete combustion. In the last decade, Gilard et. al., [16], carried out an experimental investigation on the behaviour of a lifted diffusion flame with a methane jet and air. Different regimes of flame stability were described from an anchored flame to a stable lifted flame which is destabilized before extinction. The results showed that the flame lift-off height decreases in presence of the magnetic gradient. The effects were attributed to the magnetic force which develops on air via its action on the paramagnetic oxygen. Ugare et. al., [17], investigated the effect of magnetic field on the performance of single cylinder four stroke spark ignition engine. The study focused on the effect of magnetic field the engine performance parameters viz., fuel consumption, break thermal efficiency and exhaust emissions. The magnetic field was applied along the fuel line immediately before carburettor with the help of strong permanent magnets. The exhaust gas emissions such as CO, CO₂, HC and NOX were measured by using an exhaust gas analyser. The results indicated that with the application of magnetic field, the fuel consumption reduced along with HC and CO respectively. The NOx and CO₂ emissions level in engine was noted to increase with the application of magnetic field. In recently, Agarwal et. al., [14], investigated magnetic field effect on temperature profile of diffusion flame using circular grating Talbot interferometer. Experiments were carried out for both upward decreasing and upward increasing non-uniform and uniform magnetic fields. The results conformed to the preceding research outputs.

The present work attempts to investigate the stabilization behaviour of partially premixed flames by utilizing the uniform repulsive magnetic field as an external energy field. The visible changes are captured and useful physical insight for enhanced understanding of the governing physics is drawn.
The work is motivated by the need to enhance fundamentally understanding of the partially premixed flame behaviour and stabilization utilizing an alternate energy source for wide range of applications viz., testing, validating and designing efficient combustion chambers, industrial furnaces, thermal power plants, household application including burners, and stoves and enhanced fire safety. The specific objective of the work is to explore the effect of the repulsive magnetic field on the destabilized combustion process and to investigate the role of key controlling parameters.

2. Experimental setup and Solution Methodology

A simple experimental setup was upraised for experimentation as shown in figure 3. The apparatus consists of the wooden plank of dimensions 90×90 cm in dimensions and four neodymium magnets with the dimensions 12×12×1 cm of strength 0.1 tesla was used as external energy source, whose influence on the flame needed to be observed. Each magnet is graded (ND32). A hall effect sensor was used to measure the variation of the magnetic field strength for a distance of 15.5 cm equatorially and 8.5 cm poloidal. The magnetic field strength varied from 986 gauss at a distance of 1 cm on the equatorial side to almost zero at a distance of 15 cm, while on the poloidal side it varied from 255 gauss to almost zero at a distance of 7 cm. The magnets are arranged such that their centers are at a height of 14.3 cm from the plank. The magnets are fixed to roller channels. Depending on the kind of the experimental run the angles with which they are arranged are varied. Three configurations were used with \( \frac{2 \pi}{3} \) rad, of variation in the angles as shown in the figure. The flame source is a Bunsen burner, which was attached to a butane canister. The Bunsen burner is 13.8 cm in height with a hole of 1cm on the top. The air holes on the sides having dimensions of 0. 7 cm. A video of the flames was taken, with camera placed at a distance of 32 cm from the flame. The readings were taken on the black background graph, with the dimensions of 0.5 cm per block. An optical setup was made to obtain shadowgraph of the ignition front which was digitally video graphed. Mobile phones were used to capture videos which were processed to images at 60 fps (frame per second) to measure the distinct flame length(s).

The experimentation was carried out with fixed mass flow rate and an anemometer was used to measure the velocity of the butane gas by holding it at the mouth of the nozzle. At a selected value, the nozzle knob was marked for fixed flow rates. For every reading, the nozzle knob was set at selected mass flow rate and the burner was ignited using a lighter. A stopwatch was used to measure time intervals in which readings were taken. With the help of a stopwatch, the videography was carried out for 60 seconds from the instant the flame was ignited.

![Figure 3: Schematic of the experimental setup.](image)
Figure 4: Schematic of the partially premixed flame length classifications.

Ignition is primarily transition from a non-reactive material decomposition to a self-sustained reactive combustion. This transition is owing to an imbalance between the heat production and heat loss which relates to the energy stored in a volume as:

\[ \text{Net energy change} = \text{Energy Production} - \text{Energy loss} \]  

The energy production is based on an Arrhenius approximation as:

\[ \rho \cdot C_v \cdot V \cdot \frac{dT}{dt} = q_p - q_L \]  

\[ q_p = \Delta H_c \cdot V \cdot C_i \cdot A^* \cdot e^{-\frac{E_a}{RT}} \]  

\[ q_L = hA(T - T_e) \]

Where, ‘\( q_p \)’ is the Energy production, ‘\( q_L \)’ represents Energy loss, ‘\( V \)’ is the volume, ‘\( T \)’ is the temperature and ‘\( t \)’ represents time, ‘\( \Delta H_c \)’ is the heat of combustion, ‘\( C_i \)’ represents the Concentration of reactants, ‘\( A^* \)’ is the Pre-exponential factor, ‘\( E_a \)’ is the Activation energy, ‘\( R \)’ is the Universal gas constant., ‘\( h \)’ is the convection factor.

During experimentation, special care was taken to avoid external disturbances and normalcy of the ambient conditions was maintained for every run. Every reading was taken after a window of 2 minutes to allow the setup to cool off before re-using it. It is important to note that thorough environmental normalcy was maintained in experimentation and data represents repeatability and reproducibility of the order three.

3. Result and Discussions

Prior to the main study, systematic experimentation was carried out on partially premixed flame without external influence (magnets). This was done in order to establish the base condition. The videos were converted to 1800 frames with 30 FPS rate for a period of 60 sec. The parameters such as the GFL, YFL and BFL were tabulated and plotted. Figure 5 shows the behaviour of the flame at 25°C without any external magnetic influence e.g. the base case. This forms the primary condition with which all the other conditions under the influence of the external magnetic field was compared.
Thus, the magnets were placed such that their faces arranged at 180°, 120°, 90° respectively. The percentage increase in the GFL was found to be 13.82%, while the YFL had a decrement of 22.4 %, and BFL had marginal change while comparing the flame characteristics at ‘t=0’ sec. At ‘t=40’ seconds the GFL, YFL, BFL are found to be 50.5 cm, 48 cm and 2.5 cm respectively. The percentage decrement in the GFL was found to be 5.6%, while the YFL had an increment of 39.13% and no change in the BFL was noted while comparing with the flame at ‘t=20’ sec. At ‘t=60’ seconds the GFL, YFL, BFL were found to be 39 cm, 36.5 cm and 2.5 cm respectively. The GFL had a percentage decrement of 22.7%, while the YFL had a percentage decrement of 23.9% and consistent no change in the BFL values was observed, while comparing with the flame at ‘t=40’ sec. The changes in the flame length substantiates the sensitivity of the experimental setup in predicting the flame length variation reasonably well (figure 6). Thus, the experimental setup is likely to offer good physical insight into the effect of magnetic repulsive forces effect on partially premixed flame. The main experimentation was carried out with 2, 3 and 4 magnet(s) arranged at 180°, 120°, 90° respectively. The magnets were placed such that their faces having same poles faced opposite to each other. This was done in order to establish repulsion field. The interspace distance between each magnet was varied in a constant manner and the experiment is repeated for every case mentioned above. Three zones were defined depending on the interspace distance between the flame and the magnet. They are near zone comprising till 3.5 cm distance, intermediate zone comprising the distance till 9.5cm, and far zone till 15.5cm. The case with the 2

Figure 5: Variation of BFL, YFL, GFL with time without magnetic influence.

Figure 6: Pictorial representation of the experimentation without magnets, (a) t = 0 sec, (b) t = 20 sec, (c) t = 40 sec, (d) t = 60 sec.
Magnets represents the validation of the response of the flame when placed in the vicinity of the repulsion magnetic field. While the other two cases viz., 3 and 4 magnets represent the optimization parameters.

3.1 Two-Magnet Configuration

The two-magnet configuration apparatus is as shown in the figure 7. The two magnets configuration was arranged at 180° with each other. The readings were taken for nearby zone viz., 1.5 cm, 3.5 cm, intermediate zone viz., 5.5 cm, 7.5 cm, 9.5 cm, and faraway zone at 11.5 cm, 13.5 cm, 15.5 cm.

**Figure 7:** Pictorial representation of the Two-magnet experimental setup configuration(top-view).

![Two-magnet experimental setup configuration](image)

**Figure 8:** Variation of flame length(s) (BFL, YFL, GFL) with separation distance in Two-magnet configurations for nearby zone (a) d = 1.5 cm, (b) d = 3.5 cm.

![Flame length variation](image)
3.1.1 Flame Characteristics in Nearby Zone (1.5 cm and 3.5 cm)

Figure 8 shows the variation of GFL, YFL and BFL in the nearby zone for a Two-Magnet flame configuration in the nearby zone. Figure 9 shows the pictorial representations of the corresponding flames. At ‘t=0’ seconds the GFL, YFL, BFL were found to be 38 cm, 35 cm and 3 cm respectively. At ‘t=20’ sec the GFL, YFL, BFL values shifted to 37.5 cm, 34 cm and 3 cm respectively. The percentage decrement in the GFL was found to be 1.31\%, while the YFL had a decrement of 2.85\%, and BFL had no change while comparing with the flame characteristics at ‘t=0’ sec. At ‘t=40’ seconds the GFL, YFL, BFL were found to be 25.5 cm, 22 cm and 3.5 cm respectively. The percentage decrement in the GFL was found to be 32\%, while the YFL had a decrement of 35.2\% and the BFL had an increment of 16.6 \%, while comparing with the flame at ‘t=20’ sec. At ‘t=60’ seconds the GFL, YFL, BFL were found to be 29.5 cm, 26.5 cm and 3 cm respectively. The GFL had a percentage increment of 15.68\%, while the YFL had a percentage increment of 20.4\% and the BFL had a decrement of 14.28 \%, while comparing the flame at ‘t=40’ sec. In comparison to the base flame (without magnetic repulsive force effect), at time ‘t=0’ sec the GFL had a percentage decrement of 19.14\% while YFL had a percentage decrement of 21.31\% and BFL had a percentage increment of 20 \% while comparing with the flame at the base case. At time ‘t=20’ sec the GFL had a percentage decrement of 29.90\% while the YFL had a percentage decrease of 1.44\% and BFL had an increment of 20\% when compared to the base case. At time ‘t=40’ sec the GFL had a percentage decrease of 49.50\% while YFL had a percentage decrease of 54.26\% and BFL had a percentage increase of 40\%, when compared to the base flame. At time ‘t=60’ sec the GFL had a percentage decrease of 24.37\% while the YFL had a percentage decrease of 27.39\% and BFL had an increment of 20\% while compared to the flame at base case. Looking at the plots one can note that, at a location of 3.5 cm, at ‘t=0’ seconds the GFL, YFL, BFL were 35.5 cm, 32 cm and 3.5 cm respectively. At ‘t=20’ sec the GFL, YFL, BFL values were found to be 31.5 cm, 28.5 cm and 3 cm with the percentage decrement in the GFL as 11.26\%, while the YFL had a decrement of 10.93\%, and BFL had a decrement of 14.28\%, in comparison with the flame characteristics at t=0 sec. At ‘t=40’ seconds the GFL, YFL, BFL were found to be 33.5 cm, 30.5 cm and 3 cm respectively. The percentage decrement in the GFL was found to be 6.34\%, while the YFL had an increment of 7.01\% and the BFL had no change comparing with the flame at ‘t=20’ sec. At ‘t=60’ seconds the GFL, YFL, BFL were found to be 40 cm, 37 cm and 3 cm. The GFL had a percentage increment of 19.40\%, while the YFL had a percentage increment of 21.31\% and the BFL had no change, while comparing with the flame at ‘t=40 sec’. In comparison with the base flame, at time ‘t=0’ sec the GFL had a percentage decrement of 24.46\% while YFL had a percentage decrement of 28.08\% and BFL had a percentage decrement of 40 \%. At ‘t=20’ sec the GFL had a percentage decrement of 41.12\% while the YFL had a percentage decrease of 17.39\% and BFL had an increment of 20\%. At ‘t=40’ sec the GFL had a percentage decrease of 33.63\% while YFL had a percentage decrease of 36.45\% and BFL had a percentage increase of 20\%. At ‘t=60’ sec the GFL had a percentage increment of 2.56\% while the YFL had a
percentage increase of 1.36% and BFL had an increment of 20% while compared to the base case flame.

3.1.2 Flame Characteristics in Intermediate zone (5.5 cm, 7.5 cm, 9.5 cm)

Figure 10 shows the variation of GFL, YFL and BFL in the intermediate zone for a Two-Magnet flame configuration in the nearby zone. Figure 11 shows the pictorial representations of the corresponding flames. For 5.5 cm, at ‘t=0’ seconds the GFL, YFL, BFL are found to be 45 cm, 26 cm and 3.5 cm respectively. At ‘t=20’ sec the GFL, YFL, BFL values were found to be 32.5 cm, 29.5 cm and 3 cm with the percentage decrement in the GFL to be 27.7%, while the YFL had an increment of 13.46%, and BFL had a decrement of 14.28%. At ‘t=40’ seconds the GFL, YFL, BFL are found to be 46.5 cm, 43 cm and 3.5 cm respectively, and the percentage increment in the GFL was found to be 43.07%, while the YFL had an increment of 45.26%, and the BFL had a decrement of 14.28% change comparing with the flame at ‘t=20’ sec. At ‘t=60’ seconds the GFL, YFL, BFL were found to be 41.5 cm, 38 cm and 3.5 cm, besides the GFL had a percentage decrement of 10.7%, while the YFL had a percentage decrement of 11.62% and the BFL had no change, while comparing with the flame at ‘t=40’ sec.

![image](image1.png)

**Figure 10:** Variation of flame length(s) (BFL, YFL, GFL) with separation distance in two magnet configurations for intermediate zone (a) d = 5.5 cm, (b) d = 7.5 cm, (c) = 9.5 cm
Figure 11: Pictorial representation of the two magnet configurations experimentation for intermediate zone (i = 5.5 cm, ii = 7.5 cm, and iii = 9.5 cm), (a) t = 0 sec, (b) t = 20 sec, (c) t = 40 sec, (d) t = 60 sec.

In comparison to the base case flame, at time ‘t=0’ see the GFL had a percentage decrement of 4.25\% while YFL had a percentage decrement of 41.17\% and BFL had a percentage increment of 40\%. At time ‘t=20’ sec the GFL had a percentage decrement of 39.25\% while the YFL had a percentage decrease of 14.49\% and BFL had an increment of 20\%. At time ‘t=40’ sec the GFL had a percentage decrease of 7.92\% while YFL had a percentage decrease of 10.41\% and BFL had a percentage increase of 40\%. At time ‘t=60’ sec the GFL had a percentage increment of 6.41\% while the YFL had a percentage increase of 4.19\% and BFL had an increment of 40\% while compared to the base case flame (refer figure 10(a) & figure 11(i)).

For intermediate distance of 7.5 cm, at ‘t=0’ seconds the GFL, YFL, BFL were found to be 31.7 cm, 28.2 cm and 3.5 cm. At ‘t=20’ sec the GFL, YFL, BFL values were found to be 40 cm, 36.5 cm and 3.5 cm respectively, with the percentage increment in the GFL to be 26.18\%, while the YFL had an increment of 29.43\%, and BFL had no change while comparing with the flame characteristics at ‘t=0’ sec. At ‘t=40’ seconds the GFL, YFL, BFL were found to be 29.5 cm, 26.5 cm and 3cm, besides the percentage decrement in the GFL as 26.25\%, while the YFL had a decrement of 27.39\% and the BFL had a decrement of 14.28\% comparing with the flame at ‘t=20’ sec. At ‘t=60’ seconds the GFL,
YFL, BFL were found to be 34.5 cm, 32 cm and 2.5 cm, and the GFL had a percentage increment of 16.94%, while the YFL had a percentage increment of 20.78% and the BFL had a decrement of 16.66% while comparing the flame at t=40’ sec. In comparison to the base case flame, at time ‘t=0’ sec the GFL had a percentage decrement of 35.53% while YFL had a percentage decrement of 36.62% and BFL had a percentage increment of 40% . At time ‘t=20’ sec the GFL had a percentage decrement of 25.23% while the YFL had a percentage increase of 5.79% and BFL had an increment of 40%. At time ‘t=40’ sec the GFL had a percentage decrease of 41.58% while YFL had a percentage decrease of 44.79% and BFL had a percentage increase of 20%. At time ‘t=60’ sec the GFL had a percentage decrement of 11.53% while the YFL had a percentage decrease of 12.32% and BFL had no change while compared to the base case flame (refer figure 10(b) & figure 11(ii)).

For intermediate distance of 9.5 cm, at ‘t=0’ seconds the GFL, YFL, BFL were found to be 28.5 cm, 25.5 cm and 3 cm. At ‘t=20’ sec the GFL, YFL, BFL values were 34.5 cm, 31 cm and 3.5 cm respectively, and the percentage increment in the GFL was found to be 21.05%, while the YFL had an increment of 21.56%, and BFL had an increment of 16.66%, while comparing with the flame characteristics at t=0 sec. At ‘t=40’ seconds the GFL, YFL, BFL were found to be 41 cm, 25 cm and 3.5 cm respectively, along with the percentage increment in the GFL to be 18.84%, while the YFL had a decrement of 19.35% and the BFL had no change comparing with the flame at ‘t=20’ sec. At ‘t=60’ seconds the GFL, YFL, BFL were found to be 35.5 cm, 32 cm and 3.5 cm, besides the GFL had a percentage decrement of 13.41%, while the YFL had a percentage increment of 28% and the BFL had no change, while compared to the flame at ‘t=40’ sec. In comparison to the base case flame, at time ‘t=0’ sec the GFL had a percentage decrement of 39.36% while YFL had a percentage decrement of 42.69% and BFL had a percentage increment of 20%. At time ‘t=20’ sec the GFL had a percentage decrement of 35.51% while the YFL had a percentage decrease of 10.14% and BFL had an increment of 40%. At time ‘t=40’ sec the GFL had a percentage decrease of 18.81% while YFL had a percentage decrease of 47.91% and BFL had a percentage increase of 40%. At time ‘t=60’ sec the GFL had a percentage decrement of 8.97% while the YFL had a percentage decrease of 12.32% and BFL had an increment of 40% while compared to the base case flame (refer figure 10(c) & figure 11(iii)).

3.1.3 Flame Characteristics in Faraway zone (11.5 cm, 13.5 cm, 15.5 cm)

Figure 12 shows the variation of GFL, YFL and BFL in the intermediate zone for a Two-Magnet flame configuration in the faraway zone. Figure 13 shows the pictorial representations of the corresponding flames. For faraway distance of 11.5 cm, at ‘t=0’ seconds the GFL, YFL, BFL were found to be 38 cm, 35 cm and 3 cm. At ‘t=20’ sec the GFL, YFL, BFL values were observed to be 43 cm, 39.5 cm and 3.5 cm respectively, along with the percentage increment in the GFL as 13.15%, while the YFL had a decrement of 12.85%, and BFL had an increment of 16.66%, while comparing the flame characteristics at t=0 sec. At ‘t=40’ seconds the GFL, YFL, BFL were found to be 35.5 cm, 37 cm and 3.5 cm respectively, and the percentage decrement in the GFL was found to be 17.44%, while the YFL had a decrement of 6.23% and the BFL exhibited no change in comparing with the flame at ‘t=20’ sec.

At ‘t=60’ seconds the GFL, YFL, BFL were 42.5 cm, 39 cm and 3.5 cm, besides the GFL had a percentage increment of 19.71%, the YFL had a percentage increment of 5.40% and the BFL showed no change, while comparing with the flame at ‘t=40’ sec. In comparison to the base case flame, at time ‘t=0’ sec the GFL had a percentage decrement of 19.14%, the YFL had a percentage decrement of 21.64% and BFL had a percentage increment of 20%. At ‘t=20’ sec the GFL had a percentage decrement of 19.62%, the YFL had a percentage increase of 14.49% and BFL had an increment of 40%. At ‘t=40’ sec the GFL had a percentage decrease of 29.70%, the YFL had a percentage decrease of 22.91% and BFL had a percentage increase of 40%. At ‘t=60’ sec the GFL had a percentage increment of 8.97%, the YFL had a percentage increase of 6.84% and BFL had an increment of 40% when compared to the base case flame (refer figure 12(a) & figure 13(i)).
For 13.5 cm in a two-magnet configuration, at ‘t=0’ seconds the GFL, YFL, BFL were found to be 36.5 cm, 33 cm and 3.5 cm. At ‘t=20’ see the GFL, YFL, BFL values were found to be 28.5 cm, 25.5 cm and 3 cm respectively, and the percentage decrement in the GFL was found to be 21.91%, the YFL had a decrement of 22.72%, and BFL had a decrement of 14.28%, while comparing with the flame characteristics at ‘t=0’ sec. At ‘t=40’ sec the GFL, YFL, BFL were found to be 40.5 cm, 37 cm and 3.5 cm, alongside the percentage increase in the GFL to be 42.10%, the YFL had an increment of 45.09% and the BFL had an increment of 16.66%, as compared with the flame at ‘t=20’ sec. At ‘t=60’ sec the GFL, YFL, BFL values are 38.5 cm, 35 cm and 3.5 cm, besides the GFL had a percentage decrement of 4.93%, the YFL had a percentage decrement of 5.40% and the BFL showed no change, while comparing the flame at ‘t=40’ sec. In comparison to the base case flame, at time ‘t=0’ sec the GFL had a percentage decrement of 22.34%, the YFL had a percentage decrement of 25.84% and BFL had a percentage increment of 40%. At ‘t=20’ sec the GFL had a percentage decrement of 46.72%, the YFL had a percentage decrease of 26.08% and BFL had an increment of 20%. At ‘t=40’ sec the GFL had a percentage decrease of 19.80%, the YFL had a percentage decrease of 22.91% and BFL had a percentage increase of 40%. At time ‘t=60’ sec the GFL had a percentage decrement of 1.28%, the YFL had a percentage decrease of 4.10% and BFL had an increment of 40% when compared to the base case flame (refer figure 12(b) & figure 13(ii)).

**Figure 12:** Variation of flame length(s) (BFL, YFL, GFL) with separation distance in two magnet configurations for faraway zone (a) d = 11.5 cm, (b) d = 13.5 cm, (c) = 15.5 cm.
For 15.5 cm in a two-magnet configuration, at ‘t=0’ seconds the GFL, YFL, BFL were found to be 37 cm, 33.5 cm and 3.5 cm. At ‘t=20’ sec the GFL, YFL, BFL values were 41 cm, 37 cm and 4 cm, alongside the percentage increment in the GFL was found to be 10.8%, the YFL had an increment of 10.44%, and BFL had an increment of 14.28%, while comparing with the flame characteristics at ‘t=0’ sec. At ‘t=40’ sec the GFL, YFL, BFL were 38.5 cm, 35 cm and 3.5 cm, the percentage decrement in the GFL was found to be 6.09%, the YFL had a decrement of 5.40% and the BFL had a decrement of 12.5% change, comparing with the flame at ‘t=20’ sec. At ‘t=60’ sec the GFL, YFL, BFL were found to be 42 cm, 38.5 cm and 3.5 cm, besides the GFL had a percentage increment of 9.09%, the YFL had a percentage increment of 10% and the BFL highlighted no change, when compared to the flame at ‘t=40’ sec. In comparison to the base case flame, at time ‘t=0’ sec the GFL had a percentage decrement of 21.27%, the YFL had a percentage decrement of 24.79% and BFL had a percentage increment of 40%. At ‘t=20’ sec the GFL had a percentage decrement of 23.36%, the YFL had a percentage increase of 7.24% and BFL had an increment of 60%. At ‘t=40’ sec the GFL had a percentage decrease of 23.76%, the YFL had a percentage decrease of 27.08% and BFL had a percentage increase of 40%. At ‘t=60’ sec the GFL had a percentage increment of 7.69%, the YFL had a percentage increase of 5.47% and BFL had an increment of 40%, when compared to the flame at base case (refer figure 12(c) & figure 13(iii)).

![Figure 13: Pictorial representation of the two magnet configurations experimentation for faraway zone (i = 11.5 cm, ii = 13.5 cm, and iii = 15.5 cm), (a) t = 0 sec, (b) t = 20 sec, (c) t = 40 sec, (d) t = 60 sec.](image-url)
3.2 Three-Magnet Configuration

The Three-magnet configuration apparatus is as shown in the figure 14. The three magnet(s) configuration was arranged at 120° with each other. The readings were taken for nearby zone at 3.5 cm, for intermediate zone at 5.5 cm, 7.5 cm, 9.5 cm, and faraway zone at 11.5 cm, 13.5 cm, 15.5 cm.

![Image](image.png)

**Figure 14:** Pictorial representation of the Three-magnet experimental setup configuration (top-view).

3.2.1 Flame Characteristics in Nearby Zone (3.5 cm)

For Three-Magnet configuration, in the nearby zone, the minimum applicable distance starts at 3.5 cm, at t=0 seconds the GFL, YFL, BFL were found to be 51 cm, 49 cm and 2 cm. At ‘t=20’ sec the GFL, YFL, BFL values were 49 cm, 47 cm and 2 cm, and the percentage decrement in the GFL was found to be 3.92%, the YFL had a decrement of 4.08%, and BFL exhibited no change, when compared with the flame characteristics at ‘t=0’ sec. At ‘t=40’ sec the GFL, YFL, BFL were found to be 37 cm, 35 cm and 2 cm, alongside the percentage decrement in the GFL to be 24.48%, the YFL had a decrement of 25.83% and the BFL showed no change, while comparing with the flame at ‘t=20’ sec. At ‘t=60’ sec the GFL, YFL, BFL were found to be 47.5 cm, 45.5 cm and 2cm, besides the GFL had a percentage increment of 28.37%, the YFL had a percentage increment of 30% and the BFL showed no change, while comparing with the flame at ‘t=40’ sec. In comparison to the base case flame, at time ‘t=0’ sec the GFL had a percentage increment of 8.51%, the YFL had a percentage increment of 10.11% and BFL had a percentage decrement of 20 %. At ‘t=20’ sec the GFL had a percentage decrement of 8.41%, the YFL had a percentage increase of 36.23%, and BFL had a decrement of 20%. At ‘t=40’ sec the GFL had a percentage decrease of 26.73%, the YFL had a percentage decrease of 27.10%, and BFL had a percentage decrease of 20%. At time ‘t=60’ sec the GFL had a percentage increment of 21.79%, the YFL had a percentage increase of 24.65%, and BFL had a decrement of 20% while compared to the base case flame (refer figure 15 & figure 16).

![Graph](graph.png)

**Figure 15:** Variation of flame length(s) (BFL, YFL, GFL) with separation distance (d = 3.5 cm) in three magnet configurations for nearby zone.
3.2.2 Flame Characteristics in Intermediate zone (5.5 cm, 7.5 cm, 9.5 cm)

For Three-Magnet configuration, at intermediate location of 5.5 cm, at ‘t=0’ seconds the GFL, YFL, BFL were found to be 44.5 cm, 43 cm and 1.5 cm respectively. At ‘t=20’ sec the GFL, YFL, BFL values were 40 cm, 28 cm and 2 cm, and the percentage decrement in the GFL was found to be 10.11%, the YFL had an increment of 34.88%, and BFL had an increment of 33.33%, when compared with the flame characteristics at t=0 sec. At ‘t=40’ seconds the YFL, BFL were found to be 48 cm, 46 cm and 2 cm, besides the percentage increase in the GFL to be 20%, the YFL had an increment of 64.28% and the BFL showed no change while comparing with the flame at ‘t=20’ sec. At ‘t=60’ see the GFL, YFL, BFL were observed to be 43 cm, 41 cm and 2 cm, alongside the GFL had a percentage decrement of 10.41%, the YFL had a percentage decrement of 10.86% and the BFL exhibited no change, while comparing with the flame at ‘t=40’ sec. In comparison to the base case flame, at time ‘t=0’ sec the GFL had a percentage decrement of 5.31%, the YFL had a percentage decrement of 3.37% and BFL had a percentage decrement of 40%. At ‘t=20’ sec the GFL had a percentage decrement of 25.23%, the YFL had a percentage decrease of 18.84% and BFL had a decrement of 20%. At ‘t=40’ see the GFL had a percentage decrease of 4.90%, the YFL had a percentage reduction of 4.11% and BFL had a percentage decrease of 20%. At time ‘t=60’ sec the GFL had a percentage increment of 10.25%, the YFL had a percentage increase of 12.32% and BFL had a decrement of 20%, while compared to the base case flame (refer figure 17(a) & figure 18(i)).

Figure 16: Pictorial representation of the Three magnet configurations experimentation for nearby zone (d = 3.5 cm), (a) t = 0 sec, (b) t = 20 sec, (c) t = 40 sec, (d) t = 60 sec.

For intermediate distance of 7.5 cm, at t=0 seconds the GFL, YFL, BFL were found to be 45.5 cm, 43.5 cm and 2 cm. At ‘t=20’ see the GFL, YFL, BFL values were 44.5 cm, 43 cm and 1.5 cm, and the percentage decrement in the GFL was found to be 2.19%, the YFL had a decrement of 1.14%, and BFL had a decrement of 25%, while comparing with the flame characteristics at ‘t=0’ sec. At ‘t=40’ see the GFL, YFL, BFL were found to be 47.5 cm, 32 cm and 2 cm, besides the percentage increase in the GFL was found to be 6.74%, the YFL had a decrement of 25.58% and the BFL had an increment of 33.33%, when compared with the flame at ‘t=20’ sec. At ‘t=60’ see the GFL, YFL, BFL were found to be 53 cm, 51.5 cm and 1.5 cm, alongside the GFL had a percentage increment of 11.57%, the YFL had a percentage increment of 60.93%, and the BFL had a percentage decrement of 25%, while comparing with the flame at ‘t=40’ sec.

In comparison to the base case flame, at time ‘t=0’ sec the GFL had a percentage decrement of 3.19%, the YFL had a percentage decrement of 2.24%, and BFL had a percentage decrement of 20%. At ‘t=20’ sec the GFL had a percentage decrease of 16.82%, the YFL had a percentage increase of 24.63% and BFL had a decrement of 40%. At ‘t=40’ see the GFL had a percentage reduction of 5.94%, the YFL had a percentage decrease of 33.33%, and BFL had a percentage drop of 20%. At time ‘t=60’ see the GFL had a percentage increment of 35.89%, the YFL had a percentage increase of 41.09% and BFL had a decrement of 40%, when compared to the base case flame (refer figure 17(b) & figure 18(ii)).
For intermediate location of 9.5 cm, at ‘t=0’ seconds the GFL, YFL, BFL were found to be 28 cm, 26 cm and 2 cm. At ‘t=20’ see the GFL, YFL, BFL values were 38.5 cm, 37 cm and 1.5 cm, with the percentage increment in the GFL as 37.5%, the YFL had an increment of 42.30%, and BFL had a decrement of 25%, while comparing with the flame characteristics at ‘t=0’ sec. At ‘t=40’ see the GFL, YFL, BFL were found to be 45 cm, 43.5 cm and 1.5 cm, and the percentage increment in the GFL was found to be 16.88%, the YFL had an increment of 17.56%, and the BFL showed no change, when compared with the flame at ‘t=20’ sec. At ‘t=60’ seconds the GFL, YFL, BFL were observed to be 39.5 cm, 37.5 cm and 2 cm, besides the GFL had a percentage decrement of 12.22%, the YFL had a percentage decrement of 13.74%, and the BFL had an increment of 33.33%, when compared with the flame at ‘t=40’ sec. In comparison to the base case flame, at time ‘t=0’ see the GFL had a percentage decrement of 40.42%, the YFL had a percentage decrement of 41.57%, and the BFL had a percentage decrement of 20%. At ‘t=20’ see the GFL had a percentage decrement of 28.03%, the YFL had a percentage increase of 7.24%, and the BFL had a decrement of 40%. At ‘t=40’ see the GFL had a percentage decrease of 10.89%, the YFL had a percentage decrease of 9.37%, and the BFL had a percentage decrease of 40%. At time ‘t=60’ see the GFL had a percentage increment of 1.28%, the YFL had a percentage increase of 2.73%, and the BFL had a decrement of 20%, while compared to the base case flame (refer figure 17(c) & figure 18(iii)).

![Figure 17](image_url)
3.2.3 Flame Characteristics in Faraway zone (11.5 cm, 13.5 cm, 15.5 cm)

Systematic experimentation was carried out in faraway zone at 11.5 cm, 13.5 cm and 15.5 cm. For a Three-Magnet configuration, in faraway zone at 11.5 cm, at ‘t=0’ seconds the GFL, YFL, BFL were found to be 40.5 cm, 37.5 cm and 2.5 cm respectively. At ‘t=20’ sec the GFL, YFL, BFL values were 35 cm, 33.5 cm and 1.5 cm, and the percentage decrement in the GFL was found to be 13.58%, the YFL had a decrement of 10.66%, and the BFL had a decrement of 40%, while comparing with the flame characteristics at ‘t=0’ sec. At ‘t=40’ sec the GFL, YFL, BFL were found to be 42 cm, 40 cm and 2 cm, besides the percentage increment in the GFL as 20%, the YFL had an increment of 19.40%, and the BFL had an increment of 33.33%, while comparing with the flame at ‘t=20’ sec. At ‘t=60’ sec the GFL, YFL, BFL were 42 cm, 45 cm and 2 cm, with the GFL exhibiting no change, the YFL had a percentage increment of 12.5% and the BFL showed no change, while comparing the flame at ‘t=40’ sec.

In comparison to the base case flame, at time ‘t=0’ sec the GFL had a percentage decrement of 13.82%, the YFL had a percentage decrement of 15.73%, and the BFL showed no change. At ‘t=20’ sec the GFL had a percentage decrement of 34.57%, the YFL had a percentage decrease of 2.89% and
the BFL had a decrement of 40%. At ‘t=40’ see the GFL had a percentage decrease of 16.83%, the YFL had a percentage drop of 16.66%, and the BFL had a percentage drop of 20%. At time ‘t=60’ see the GFL had a percentage increment of 7.69%, the YFL showed a percentage increase of 23.28% and the BFL had a decrement of 20%, when compared with the base case flame (refer figure 19(a) & figure 20(i)).

![Variation of flame length(s) (BFL, YFL, GFL) with separation distance in three magnet configurations for faraway zone](image)

Figure 19: Variation of flame length(s) (BFL, YFL, GFL) with separation distance in three magnet configurations for faraway zone (a) d = 11.5 cm, (b) d = 13.5 cm, (c) = 15.5 cm.

At a location of 13.5 cm, at t=0 seconds the GFL, YFL, BFL were found to be 43.5 cm, 41.5 cm and 2 cm. At ‘t=20’ sec the GFL, YFL, BFL values were 45 cm, 42.5 cm and 2 cm, along with the percentage increment in the GFL as 3.44%, the YFL had an increment of 2.40%, and the BFL showed no change, while comparing with the flame characteristics at ‘t=0’ sec. At ‘t=40’ sec the GFL, YFL, BFL were found to be 39 cm, 37 cm and 2 cm, and the percentage decrement in the GFL was found to be 13.33%, the YFL had a decrement of 12.94%, and the BFL highlighted no change, while comparing with the flame at ‘t=20’ sec. At ‘t=60’ see the GFL, YFL, BFL were found to be 34.5 cm, 32.5 cm and 2 cm, alongside the GFL had a percentage decrement of 11.53%, the YFL had a percentage decrement of 12.16% and the BFL showed no change, while comparing the flame at ‘t=40’ sec. However, in comparison to the base case flame, at time ‘t=0’ see the GFL had a percentage decrement of 7.44%, the YFL had a percentage decrement of 6.74%, and the BFL had a percentage decrement of 20%. At ‘t=20’ see the GFL had a percentage decrement of 15.88%, the YFL had a percentage increase of 23.18%, and the BFL had a decrement of 20%. At ‘t=40’ see the GFL had a percentage decrease of 22.77%, the YFL had a percentage decrease of 22.91%, and the BFL had a
percentage drop of 20%. At time ‘t=60’ sec the GFL had a percentage decrements of 11.53%, the YFL had a percentage drop of 10.95%, and the BFL showed a decrement of 20%, while comparing to the base case flame (refer figure 19(b) & figure 20(ii)).

![Figure 20](image)

**Figure 20:** Pictorial representation of the three magnet configurations experimentation for faraway zone (i = 11.5 cm, ii = 13.5 cm, and iii = 15.5 cm), (a) t = 0 sec, (b) t = 20 sec, (c) t = 40 sec, (d) t = 60 sec.

For faraway location of 15.5 cm, at ‘t=0’ seconds the GFL, YFL, BFL were found to be 41.5 cm, 38.5 cm and 3 cm. At ‘t=20’ sec the GFL, YFL, BFL values were found to be 30.5 cm, 21 cm and 2.5 cm, and the percentage decrements in the GFL was found to be 26.50%, the YFL had a decrement of 45.45%, and the BFL had a decrements of 16.66%, while comparing with the flame characteristics at t=0 sec. At ‘t=40’ sec the GFL, YFL, BFL were 39 cm, 36.5 cm and 2.5 cm, besides the percentage increment in the GFL was found to be 21.79%, the YFL had an increment of 73.80%, and the BFL showed no change, when compared with the flame at ‘t=20’ sec. At ‘t=60’ sec the GFL, YFL, BFL were observed to be 47.5 cm, 45 cm and 2.5cm, alongside the GFL had a percentage increment of 21.79%, the YFL had a percentage increment of 23.28%, and the BFL showed no change, when compared to the flame at ‘t=40’ sec. Similarly, in comparison to the base case flame, at time ‘t=0’ sec the GFL had a percentage decrements of 11.70%, the YFL had a percentage decrements of 13.48%, and the BFL showed a percentage increment of 20%. At ‘t=20’ sec the GFL had a percentage decrements
of 42.99%, the YFL had a percentage decrease of 39.13%, and the BFL showed no change. At ‘t=40’ sec the GFL had a percentage decrease of 22.77%, the YFL had a percentage decrease of 23.95%, and the BFL exhibited no change. At time ‘t=60’ sec the GFL had a percentage increment of 21.79%, the YFL had a percentage increase of 23.28%, and the BFL showed no change, when compared to the base case flame (refer figure 19(c) & figure 20(iii)).

3.3 Four-Magnet Configuration

The Four-magnet configuration apparatus is as shown in the figure 21. The four magnet(s) configuration was arranged at 90° with each other. The readings could be taken for intermediate zone at 5.5 cm, 7.5 cm, 9.5 cm, and faraway zone at 11.5 cm, 13.5 cm, 15.5 cm.

3.3.1 Flame Characteristics in Intermediate zone (5.5 cm, 7.5 cm, 9.5 cm).For Four-Magnet configuration located at 5.5 cm, at ‘t=0’ seconds the GFL, YFL, BFL were found to be 40 cm, 38.5 cm and 1.5 cm. At ‘t=20’ sec the GFL, YFL, BFL values were 41 cm, 39.5 cm and 1.5 cm, and the percentage increment in the GFL was found to be 2.5%, the YFL had a increment of 2.59%, and the BFL showed no change, while comparing with the flame characteristics at ‘t=0’ sec. At ‘t=40’ sec the GFL, YFL, BFL were 37.5 cm, 36 cm and 1.5cm, besides the percentage decrement in the GFL as 8.53%, the YFL had a decrement of 8.86% and the BFL exhibited no change, while comparing with the flame at ‘t=20’ sec. At ‘t=60’ sec the GFL, YFL, BFL were found to be 34.5 cm, 33 cm and 1.5 cm, alongside the GFL had a percentage decrement of 8%, the YFL had a percentage decrement of 8.33% and the BFL showed no change, while comparing with the flame at ‘t=40’ sec. However, in comparison to the base case flame, at time ‘t=0’ sec the GFL had a percentage decrement of 14.89%, the YFL had a percentage decrement of 13.48%, and the BFL had a percentage decrement of 40%. At ‘t=20’ sec the GFL had a percentage decrement of 29.36%, the YFL had a percentage increase of 14.49%, and the BFL had a decrement of 40%. At ‘t=40’ sec the GFL had a percentage drop of 25.74%, the YFL had a percentage drop of 25%, and the BFL had a percentage drop of 40%. At time ‘t=60’ sec the GFL had a percentage decrement of 11.53%, the YFL had a percentage drop of 9.58%, and the BFL had a decrement of 40%, when compared to the base case flame (refer figure 22(a) & figure 23(i)).

![Figure 21: Pictorial representation of the Four-magnet experimental setup configuration(top-view).](image-url)

For 7.5 cm separation distance, at ‘t=0’ seconds the GFL, YFL, BFL were found to be 36.5 cm, 34.5 cm and 2 cm. At ‘t=20’ sec the GFL, YFL, BFL values were 34 cm, 32.5 cm and 1.5 cm, and the percentage decrement in the GFL was found to be 6.84%, the YFL had a decrement of 5.79%, and the BFL had a decrement of 25%, while comparing with the flame characteristics at ‘t=0’ sec. At ‘t=40’ sec the GFL, YFL, BFL were found to be 45 cm, 43 cm and 2cm, besides the percentage increment in the GFL was found to be 32.35%, the YFL had an increment of 32.30%, and the BFL 33.33%, while comparing with the flame at ‘t=20’ sec. At ‘t=60’ sec the GFL, YFL, BFL were found to be 36 cm, 34.5 cm and 1.5 cm, alongside the GFL had a percentage decrement of 20%, the YFL had a percentage decrement of 19.76%, and the BFL had a decrement of 2.5%, while comparing the flame at ‘t=40’ sec. In comparison to the base case flame, at time ‘t=0’ sec the GFL had a percentage decrement of 22.30%, the YFL had a percentage decrement of 22.47%, and the BFL had a percentage decrement of 20%. At ‘t=20’ sec the GFL had a percentage decrement of 36.44%, the YFL had a
percentage decrease of 5.79%, and the BFL had a decrement of 40%. At ‘t=40’ sec the GFL had a percentage decrease of 10.89%, the YFL had a percentage decrease of 10.46%, and the BFL had a percentage decrease of 20%. At time ‘t=60’ sec the GFL had a percentage decrement of 7.92%, the YFL had a percentage decrease of 24.65%, and the BFL had a decrement of 40%, while compared to the base case flame (refer figure 22(b) & figure 23(ii)).

**Figure 22:** Variation of flame length(s) (BFL, YFL, GFL) with separation distance in Four magnet configurations for intermediate zone (a) d = 5.5 cm, (b) d = 7.5 cm, (c) = 9.5 cm.

For intermediate distance of 9.5 cm, at ‘t=0’ seconds the GFL, YFL, BFL were found to be 42 cm, 40.5 cm and 1.5 cm. At ‘t=20’ sec the GFL, YFL, BFL values becomes 36 cm, 34 cm and 2 cm, with the percentage decrement in the GFL as 14.28%, the YFL had a decrement of 16.04%, and the BFL had an increment of 33.33%, while comparing with the flame characteristics at ‘t=0’ sec. At ‘t=40’ sec the GFL, YFL, BFL values were 42 cm, 40 cm and 2 cm, and the percentage increment in the GFL was found to be 16.66%, the YFL had an increment of 17.64%, and the BFL showed no change, in comparison with the flame at ‘t=20’ sec. At ‘t=60’ sec the GFL, YFL, BFL were found to be 33 cm, 31 cm and 2 cm, besides the GFL had a percentage decrement of 21.42%, the YFL had a percentage decrement of 22.5%, and the BFL exhibited no change, while comparing the flame at ‘t=40’ sec. Similarly, in comparison to the base case flame, at time ‘t=0’ sec the GFL had a percentage decrement of 10.63%, the YFL had a percentage decrement of 8.98%, and the BFL had a percentage decrement
of 40%. At ‘t=20’ sec the GFL had a percentage decrement of 32.71%, the YFL had a percentage decrease of 1.44%, and the BFL had a decrement of 20%. At ‘t=40’ sec the GFL had a percentage decrease of 16.83%, the YFL had a percentage decrease of 16.66%, and the BFL had a percentage decrease of 20%. At time ‘t=60’ sec the GFL had a percentage decrement of 15.38%, the YFL had a percentage decrease of 15.06%, and the BFL had a decrement of 20%, while compared to the base case flame (refer figure 22(c) & figure 23(ii)).

![Figure 23: Pictorial representation of the Four magnet configurations experimentation for intermediate zone (i = 5.5 cm, ii = 7.5 cm, and iii = 9.5 cm), (a) t = 0 sec, (b) t = 20 sec, (c) t = 40 sec, (d) t = 60 sec.](image)

3.3.2 Flame Characteristics in Faraway zone (11.5 cm, 13.5 cm, 15.5 cm)
For Four-Magnet configuration located at 11.5 cm, at ‘t=0’ seconds the GFL, YFL, BFL were found to be 41 cm, 39 cm and 2 cm. At ‘t=20’ sec the GFL, YFL, BFL values were 31 cm, 29.5 cm and 1.5 cm, with the percentage decrement in the GFL to be 24.39%, the YFL had a decrement of 24.35%, and the BFL had a decrement of 25%, while comparing with the flame characteristics at ‘t=0’ sec. At ‘t=40’ sec the GFL, YFL, BFL were found to be 39.5 cm, 27.5 cm and 1.5 cm, besides the percentage increment in the GFL was found to be 27.41%, the YFL had a decrement of 6.77%, and the BFL showed no change, when comparing with the flame at ‘t=20’ sec. At ‘t=60’ seconds the GFL, YFL, BFL were found to be 41.5 cm, 40 cm and 1.5 cm, the GFL had a percentage increment of 5.06%, the
YFL had a percentage increment of 45.45%, and the BFL exhibited no change, while comparing the flame at ‘t=40’ sec. 

In comparison to the base case flame, at time ‘t=0’ sec the GFL had a percentage decrement of 12.77%, the YFL had a percentage decrement of 12.35%, and the BFL had a percentage decrement of 20%. At ‘t=20’ sec the GFL had a percentage decrement of 42.05%, the YFL had a percentage decrease of 14.49%, and the BFL had a decrement of 40%. At ‘t=40’ sec the GFL had a percentage decrease of 21.78%, the YFL had a percentage decrease of 42.70%, and the BFL had a percentage decrease of 40%. At time ‘t=60’ sec the GFL had a percentage increment of 6.41%, the YFL had a percentage increase of 9.58%, and the BFL had a decrement of 40%, when compared to the base case flame (refer figure 24(a) & figure 25(i)). For faraway location of 13.5 cm, at ‘t=0’ seconds the GFL, YFL, BFL were found to be 40.5 cm, 38 cm and 2.5 cm. At ‘t=20’ sec the GFL, YFL, BFL values were 42 cm, 39.5 cm and 2.5 cm, and the percentage increment in the GFL was found to be 3.70%, the YFL had a decrement of 3.94%, and the BFL showed no change, while comparing with the flame characteristics at ‘t=0’ sec. At ‘t=40’ sec the GFL, YFL, BFL were found to be 40 cm, 37.5 cm and 2.5cm, besides the percentage decrement in the GFL was found to be 4.76%, the YFL had a decrement of 5%, and the BFL exhibited no change, while comparing with the flame at ‘t=20’ sec. At ‘t=60’ sec the GFL, YFL, BFL were found to be 29 cm, 27 cm and 2 cm, the GFL had a percentage
decrement of 27.5%, the YFL had a percentage decrement of 28%, and the BFL had a decrement of 20%, when compared with the flame at ‘t=40’ sec. In comparison to the base case flame, at time ‘t=0’ sec the GFL had a percentage decrement of 13.82%, the YFL had a percentage decrement of 14.60%, and the BFL showed no change. At ‘t=20’ sec the GFL had a percentage decrement of 21.49%, the YFL had a percentage increase of 14.49%, and the BFL showed no change. At ‘t=40’ sec the GFL had a percentage decrease of 20.79%, the YFL had a percentage decrease of 21.87%, and the BFL exhibited no change. At time ‘t=60’ sec the GFL had a percentage decrement of 25.64%, the YFL had a percentage decrease of 26.02%, and the BFL had a decrement of 20%, when compared to the base case flame (refer figure 24(b) & figure 25(ii)).

![Image](image_url)

Figure 25: Pictorial representation of the Four magnet configurations experimentation for faraway zone (i = 11.5 cm, ii = 13.5 cm, and iii = 15.5 cm), (a) t = 0 sec, (b) t = 20 sec, (c) t = 40 sec, (d) t = 60 sec.

At 15.5 cm, at ‘t=0’ seconds the GFL, YFL, BFL were found to be 46 cm, 24.5 cm and 3 cm. At ‘t=20’ sec the GFL, YFL, BFL values were 41.5 cm, 38.5 cm and 3cm, with the percentage decrement in the GFL found to be 9.78%, the YFL had an increment of 57.14%, and the BFL showed no change, while comparing with the flame characteristics at ‘t=0’ sec. At ‘t=40’ sec the GFL, YFL, BFL were found to be 38.5 cm, 3.5 cm and 2cm, alongside the percentage decrement in the GFL was found to be 7.22%, the YFL had a decrement of 5.19%, and the BFL had a decrement of 33.33%, while comparing with
the flame at ‘t=20’ sec. At ‘t=60’ sec the GFL, YFL, BFL were found to be 39 cm, 36.5 cm and 2.5 cm, besides the GFL had a percentage increment of 1.29%, the YFL showed no change and the BFL had a percentage increase of 25%, while comparing with the flame at ‘t=40’ sec. In comparison to the base case flame, at time ‘t=0’ sec the GFL had a percentage decrement of 2.12%, the YFL had a percentage decrement of 44.92%, and the BFL had a percentage increment of 20%. At ‘t=20’ sec the GFL had a percentage decrement of 22.42%, the YFL had a percentage increase of 11.59%, and the BFL had an increment of 20%. At ‘t=40’ sec the GFL had a percentage decrease of 23.76%, the YFL had a percentage decrease of 23.95%, and the BFL had a percentage decrease of 20%. At time ‘t=60’ sec the GFL showed no change, YFL showed no change and BFL showed no change, when compared to the at base case flame (refer figure 24(c) & figure 25(iii)).

3.3.3 Coupled redundancy and Governing Mechanics
For 2, 3, 4 magnets at various interspace distance it was observed that the YFL values gets suppressed due to the presence of the external magnetic fields. This is due to the effect of the inter energy conversions taking place on the system boundaries. There is a continuous interaction of energies taking place between the, thermal energy fields formed by the flames and the magnetic field formed by the magnets, which is repulsive in nature. A favorable energy interaction happens when the flame length increases while, an unfavorable energy interaction happens when the flame length decreases. As a result, there is increment in the flame lengths in some conditions as shown in the tables given below. The percentage variation in between the GFL and YFL values at particular condition and the GFL and YFL values at the base case states how much amount of energy interaction is happening between the flames and the magnets.

![Figure 26: Schematic of inter-energy interaction and consequential conversion.](image)

In each configuration, the magnetic field strength around the flame changes and the structure of the magnetic field around the flame changes. As a result, the amount of interaction between the thermal fields and the magnetic fields also varies (refer figure 26). This results in the characteristic structure of the flame at that particular instant. The flame structure is also determined by the magnetic properties of the products formed due to incomplete combustion of the partially premixed flames as they interact with the surrounding magnetic the magnitude of percentage variation of the GFL and YFL when compared to the base case are taken, as explained the negative sign indicates the decrement in the flame length when compared to the base case. Similar to the above readings the values are taken at each instant and plotted as graphs as shown by the results. The graphs at each case determine the behavior of the flame and gives an information of the energy interaction taking place in between the flames and the magnets.
4. Conclusions

Thorough experimentation was carried out on the effect of repulsive magnetic field on partially premixed flames. Based on the effects and observations, following conclusions can be drawn:

1) The partially premixed flames respond to the presence of the repulsive magnetic field surrounding it.

2) The key controlling factors are, number of magnet(s) or type of configuration, the flame length(s) and effectiveness of energy transition.

3) The experimentation details flame stabilization as highly unsteady phenomenon and the repulsive field tends to suppress the flame.

4) For partially premixed flames, the variation in Yellow Flame Length (YFL), Blue Flame Length (BFL), and Gross Flame Length (GFL), were comprehensively studied for the cases of 2,3,4 Magnet configurations. Large part of repulsive magnetic field was noted to affect the YFL and thus the GFL. The BFL represented the small cases of significant changes in the flame length.

5) The effect and extent of the effect varied in terms of change in flame length(s) significantly in all the cases. This is due to the magnitude of energy interactions taking place between the thermal and the magnetic fields.

6) The work can be effectively utilized in the flame stabilization studies and enhancement of the fundamental understanding of the combustion process in the presence of the repulsive magnetic field.

7) The supplementary aspects of practical flame stabilization can be handled with the extension of the study to study the effects of the partially premixed flames in temporal variation of the repulsive magnetic fields.

8) Normalcy was maintained and external disturbance was avoided and all the readings represents repeatability of order 3.

9) Applications of the present work: Optimization of the power generation, development of significant fire safety equipments (figure 27).

Figure 27: Pictorial representation(s) of potential power generating applications (a) Can type combustion chambers, (b) Combustion chambers of blast furnaces, (c) Coal power plant combustion chambers, (d) Forced draft burners.
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