Experimental study of Partially Premixed-Diffusion Turbulent Flame with Circular Plate Bluff Body

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Abstract This Study presents a parametric study on flame stabilization of partially premixed-diffusion turbulent flame behind the circular bluff body. The effects of the premixing and equivalence fuel ratios on flame temperature distribution and emission variation along the flame axis are investigated. The results indicate that as the premixing ratio increases the residence time and the recirculation zone length increase while the flame length decreases. The axial temperature distribution enhancements at the recirculation zone, and then a decrease towards the flame tip. As the premixed ratio increases the flame average temperature increase while emission measurements indicate a decrease in CO concentration with a slight increase in NO\textsubscript{x} production along the flame axis.

1. Introduction

Partially premixed flames are those with regions of varying mixture composition ranging from fuel rich to stoichiometric and fuel-lean. Partially premixed flames have a wide range of applications since they are often more stable than both the premixed and diffusion flames [1–4]. The stabilization of the partial premixed-diffusion flame attracts more research. Oftentimes, the use of bluff bodies for flame stabilization. Such bodies by design induce separation of the flow leeward side of the body [5].

Lee et al [1] the investigation of characteristics of partially premixed turbulent flames, found that the ratio of the inner to outer jet velocities has the most dominant effect on the flame characteristics. In addition, they found that the flame height decreased with a relatively small increase in the inner jet flow rate. They mentioned that controlling both flame length and stability can be achieved by varying the velocity ratios and the inner tube recess to the inner diameter ratio, respectively.

The simulated lifted turbulent methane/air and propane/air jet flames are presented by Chen et al [6] by the changing fuel exit velocities and nozzle diameters. Two cases of partially premixed swirling flames were experimentally studied by Chao et al. [7]. The first one is with a constant fuel exit velocity and the other with an increased exit velocity at different equivalence ratios. They found in both cases that the flame length decreases significantly with increasing premixing. The flame color changes from the sooty orange-yellow to the soot-free blue indicating a higher level of premixing. The NO\textsubscript{x} and CO emission indices decreased at first with increasing premixing, and then increased with the equivalence ratio $\Phi$ increase.
Mansour [8] visualized and measured the structure of partially premixed lifted turbulent methane flames at various jet equivalence ratios and Reynolds numbers. The structure of the stabilization mechanism was investigated in Li et al. [9] for a partially premixed methane/air flame on a conical jet burner. Which concluded that close to the inside wall of the cone founded a reversal flow towards the nozzle. The high-speed premixed flow from the nozzle forms a shear layer where large scale vortices exist. Elbaz [2] assessed the influence of burner-nozzle conical angle, jet velocity, and equivalence ratio on the flame structure for a constant partial premixed ratio. He concluded that the effect of jet velocity was more pronounced at higher velocities, where higher air pockets were entrained in the reaction zone, which may cause flame extinction. Mansour et al. [8,10] studied the stabilization mechanism in a concentric flow conic burner jet and concluded that the stabilization mechanism is mainly controlled by the flow pattern inside the cone. With study the mean temperature, they could recognize two distinctive regions near the nozzle, first is the lower central flame temperature and the second region is higher flame temperature. In conjunction with these two regions, there were four special fluctuated temperature regions. Finally, the jet equivalence ratio had a restrictive effect on flow fields and a relatively soft effect on the temperature field.

Kumar and Mishra [11] had an investigation on effects of bluff body lip thickness on the LPG-H2 jet diffusion flame. This indicates the addition of hydrogen to the LPG fuel stream resulted in reducing the flame length. The above-mentioned reaction zone was shifted toward the bluff body and fulfill flame length reduction. In another investigation, Kumar and Mishra [12] investigate the experiment LPG-H2 hybrid fuel jet diffusion flame. They studied the effect of H2 addition on the flame length and emission level. This indicated the raise ratio of H2 up to 20% does not exhibit any change in flame length. However, increasing H2 to 40% resulted in a reduction in CO2, NOx, and flame length while CO increased. They concluded that these results were due to the decrease in residence time caused by two factors. First increase the flame temperature and diffusivity with H2 addition, second is the increase the gas velocity. In another experimental work, Kumar and Mishra [9] investigated LPG-H2 jet diffusion flame for two cases. These are preheated only air or preheated air and fuel. Two bluff bodies with lip shape and different lip thickness were employed for each case They concluded that the flame length for all cases and all lip thickness got reduced with the addition of H2, which resulted in decrease due to the enhanced flame temperature.

Zhen et al. [13] studied the effect of hydrogen concentration on the emissions and heat transfer characteristics of a laminar premixed LPG-H2 flame, the varying H2 in the fuel mixture at fixed mixture jet Reynolds number and kept the equivalence ratio at stoichiometry. They concluded that at a higher level of hydrogen and the flame temperature and the NOx emissions increased the height of the inner reaction cone and the CO emissions decreased.

The previous work deals with either partial premixed-diffusion flame or bluff body stabilization. Methane or H2 were added as combustion enhancement fuels. It is the aim of this work to use dual combustion mechanisms; diffusion and premixed while burning fixed mass flow rate of nonhazardous and commercially available fuel, such as LPG, employing bluff body stabilizer technique. The study covers the effect of varying the equivalence ratio, partial premixing ratio (the ratio of premixing mass flow rate to the total fuel mass flow rate, α), and blockage ratio on the temperature and flame characteristics.

![Figure 1. Schematic assembly drawing for the experimental setup.](image_url)
2. **Experimental setup**

The schematic of the burner setup used in this study shown in Figure 1. It contains gas and air supply lines with installation of the necessary measuring and controlling devices. Using 12 thermocouples type K to measure the temperatures the flame centerline. Using the digital camera to visualize the flame shape and size. The flame length ($L_f$) and recirculation length ($L_r$) were measured using a measuring-board (scale board) of 2.5 m height and 1 m width as shown in figure 2.

The commercial buttle of LPG-gas supplies the fuel to common rail lines. The gas line was divided into two streams as shown in figure 3, the first line is the diffusion-fuel supply system at its end installed a fuel nozzle and a bluff body stabilizer. The second line is the premixed-fuel supply line coaxially fixed to the diffusion line. Midway of premixed-fuel line, there was a ring with 6 outlet-nozzles discharging the fuel into the air stream as shown in figure 1. The premixing ratio was calculated according to Eq. 1.

$$\alpha = \frac{m_{pr}}{m_{diff}+m_{pr}} \times 100\%$$

where $m_{pr}$ and $m_{diff}$ are the diffusion and premixing mass flow rates.

Uncertainty in air and fuel flow rate measurements were ±0.34%. The bluff body dimensions and characteristics are given in table 1. Bluff bodies used in the work are simply circular plates made of 3 mm thick steel plate with a 10 mm inner diameter and blockage ratio of 13.1%.

![Figure 2. Method of measuring flame characteristics.](image)

**Table 1. Bluff body characteristics.**

| Blockage ratio%, | $D_s$, mm | Re number of co-flow air | $D_p$, mm | Flow rate, L/s | Air mass flow rate, kg/s | $V_p$, m/s |
|-----------------|-----------|--------------------------|-----------|---------------|-------------------------|-----------|
| 13.1%           | 38        | 2.23*10^4                | 105       | 18.51         | 0.022                   | 5.25      |

3. **Results and discussion**

3.1. **Residence time**

It is the fact that as the residence time is increased, the combustion process is well promoted and its efficiency is increased. Residence time $\tau$ can be calculated from Eq. (2) [14]:

$$\tau = c \frac{L_r}{V_j}$$

where $L_r$ is the recirculation zone length, $V_j$ is the jet velocity, and $c$ is the proportionality constant. The variations of the residence time with the premixing ratio described in Figure 4, as shown $\alpha$ increases forward residence time gets longer at a higher rate at lean mixture but it slows down as $\Phi$ is increased. This refer to increases premixed jet velocity when $\alpha$ increases. When the fuel mixture changed from lean to rich, these results, the reaction rate increases, which means the residence time decreases. In general, the increase the recirculation zone length cause the increase of $\tau$.

3.2. **Non-Dimensional flame length**

Figure 5 shown the effect of the premixed ratio $\alpha$ on non-dimensional flame length ($L_f/D_p$) at different equivalence ratios $\Phi$. As shown, as $\alpha$ increases the dimensionless flame length decreases, this refers to a decrease of the diffusion-fuel velocity and the increase of the premixed jet velocity. As long as, the
flame length becomes shorter with increases residence time. On another hand, at constant premixed ratio $\alpha$, it is shown as $\Phi$ increases, the non-dimensional flame length increases. This refers to the increase of fuel jet velocity as fuel mass flow rate increases. And then, the premixed fuel jet increase in the flow field, which turns to the flame length becomes longer [11,15].

3.3. Recirculation zone

The effect of the premixing ratio on the recirculation zone characteristic at different $\Phi$ is shown in Figure 6. The recirculation zone length is increased due to Increases the premixing ratio $\alpha$, so the jet velocity in diffusion decreases. The recirculation length continues to increase until it becomes the whole flame. Also, in figure 6 shows as $\Phi$ is increased, the fuel mass is increased too. These results rise to the jet velocity and the intensity of the recirculation zone behind the bluff body lift higher reaction rate, and then reduction in the residence time as well as that of the recirculation zone characteristic parameter $L_f/D_p$.

3.4. Average flame temperature

Variations of the average flame temperature across the flame width at different heights with the increase of the premixed ratio are shown in figure 7. The average temperature for every case and every flame increase with increase the premixing ratio at all values of equivalence ratio $\Phi$. This refers to the increase of premier ratio $\alpha$ followed by a decrease in diffusion jet velocity, therefore, the residence time increases, which means better mixing and combustion, followed by an increase in average temperature. On another hand, with increase equivalence ratio $\Phi$, the average flame temperature little increases at a particular premixed ratio $\alpha$. This is due to the extra momentum to the coaxial-flow and results in better combustion. It can be concluded that the increase of $\Phi$ has a minor effect on the average flame temperature as compared with the effect of $\alpha$. 

![Figure 4](image1.png) **Figure 4.** The effect of premixed ratio on residence time at varied $\Phi$.  

![Figure 5](image2.png) **Figure 5.** The effect of premixed ratio on non-dimensional flame length $L_f/D_p$ at varied $\Phi$. 

1- Gas bottles
2- Common 3/4" pipe
3- Premixed-fuel line
4- Diffusion fuel line
5- Pressure gage
6- Regulating valve
7- Orifices
8- Premixed manometer inputs
9- Diffusion manometer inputs
10- To premixed-fuel ring
11- Diffusion-fuel pipe

**Figure 3.** Schematic of fuel lines.
Figure 6. The effect of premixed ratio $\alpha$ on recirculation zone parameter $L_r/D_p$ at $\Phi=0.8$ to 1.4.

Figure 7. The effect of the premixed ratio on the average flame temperature at $\Phi=0.8$ to 1.4.

3.5. Emission distributions

The CO and NOx emissions along the flame centerline are shown in figures 7-8. These curves summarize the effect of $\alpha$ and $\Phi$ on CO and NOx emissions. Figure 7 shows the CO concentration decreases as increases the distance along flame length $X/L_f$, this due to better CO oxidation. This better oxidation because of the continuous entrainment air from the surrounding, also increase residence time and the recirculation zone. The maximum CO values for pure diffusion flame, as a result of lower flame temperature. However, as $\alpha$ increases, the flame temperature increases so decrease CO concentration. This refers to better mixing and enhances the combustion process. On the other hand, increasing $\Phi$ increases CO production near the flame base due to incomplete combustion and then decreases it again at high values of $\Phi$ as the speed of the fuel jets becomes higher. Near the flame tip, CO concentration values are almost the same for all the cases studied.

Figure 8. The effect of premixed ratio $\alpha$ on CO distribution along flame length at different $\Phi$.

Figure 9. The effect of premixed ratio $\alpha$ on NOx distribution along flame length at different $\Phi$.

The examination of figure 8 shows that NOx concentration values are small for all tested values of $\alpha$ and $\phi$. The main controlling factor formation of NOx in flame is the temperature of the flame, as at flame temperature below 1100°C the NOx will appear. For that, the measured temperature in flames and the average values were below 1100°C as shown in figure 7. As mention in concentration CO the
effect of better oxidation because of the continuous entrainment air, also it help NOx concentration decreases with increasing X/Lf. As the NOx one of emission unwanted. Also, it can be seen in figure 7 that the diffusion flame exhibits the lowest temperatures and consequently the lowest NOx concentrations. However, as α increases and the flame behavior turns to the premixed, the average flame temperature exhibits a moderate increase resulting in a small increase of NOx production. Which agreement with the results described in [11,15,16]. However, increasing Φ results in a decrease of the NOx values near the flame base due to combustion enhancement then increases it again at higher values of Φ as the speed of the fuel jets becomes higher promoting better combustion and higher temperatures. Nevertheless, NOx values are almost the same near the flame end due to air entrainment.

4. Conclusions
This Study presents a parametric study on flame stabilization of partially premixed-diffusion turbulent flame behind the circular bluff body. The parameters changed from pure diffusion to partially premixed-diffusion with premixed ratios from 20 to 80% with increments of 10%, at four equivalence ratio 0.8, 1, 1.2, and 1.4.

The effect of the premixing ratio on flame length is higher than the equivalence ratio. As the premixed ratio increasing the flame length decreases and the recirculation zone length increases. The opposite trend is obtained for the equivalence ratio.

As the premixed ratio increases, the residence time is increased. Aso the axial temperature distribution along the flame centerline had effects as: it increases with increasing the premixing ratio in the recirculation zone followed by the further decrease upwards. With increasing premixed ratio, the average flame temperature is increased too. As the premixing ratio increases, CO concentration decreases while NOx production increases along with the flame central. The effect of increasing the fuel equivalence ratio is an increase of CO emission along with a decrease of NOx values for small and moderate Φ values. For the higher Φ values, NOx production is relatively higher.

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