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Experimental Study on Combustion Performance of Diffusion Jet Flames Using Developed Flame Holder

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Abstract: In this study, a newly developed flame holder was investigated experimentally in the presence of two air sources applied to the combustion zone. The flame holder is a double cone holder with three fuel ports in the top cone to convey fuel to the combustion zone. Three coaxial pipes were used to transport air and fuel to the combustion zone. The outer pipe conveyed the secondary air with a velocity $(\mathbf{V_1})$ of 6.34 m/s while the primary air was conveyed with the middle pipe with a velocity $(\mathbf{V_2})$ of 7.1 m/s, 15.3 m/s, and 19.9 m/s. The inner pipe was used to convey fuel to the flame holder and hence to the combustion zone. The experiment was carried out using the diffusion flame principle in a still air environment at atmospheric conditions. The flame temperature, length, width, and emissions were first studied in the presence of primary air only, and then in the presence of both primary and secondary air. The results showed that the flame temperature, flame length, flame width, and emissions were all affected when secondary air was applied to the combustion zone alongside primary air.

Keywords: diffusion jet flame, Flame holder, Flame length, flame width, concentric pipes, emissions.

1. INTRODUCTION

In our everyday lives, combustion is a significant source of energy. The energy released by combustion can be used for a wide range of applications including transportation, power generation, and manufacturing [1]. Premixed flame and diffusion flame are two types of combustion, but diffusion flame is more relevant and connected to industrial and domestic life. Diffusion flame is a kind of flame where the oxidizer and fuel are reacted directly in the combustion zone [2] [3].

Many researchers investigated premixed flames using various techniques [4], [5], [6], [7], [8], [9]. Non-premixed flames have also been investigated in terms of flame holder geometry, flame length, emissions, and so on.

The flame holder geometry has been shown in numerous studies to have a significant impact on combustion characteristics, and it has the potential to improve combustion characteristics [10] [11] [12] [13].

[10] stated that the burner geometry has an effect on the flame stability, flame height, and flame lift off distance. [12] investigated the effect of nozzle geometry by varying the diameter of the spouting nozzle. It was found that the nozzle exit diameter could improve the length of the jet flame.

[14] used a circular nozzle with various diameters to investigate a hydrogen jet diffusion flame and found that the size of the flame was affected by the nozzle's aspect ratio.

Flame length and lift off distance were studied by many researchers as well. Many studies were performed in still air [15] [16] [17] [18] and other studies were performed in moving air.

[20] investigated the impact of the outer vortex of jet diffusion flames and the fuel jet on the flame structure over a wide range of Reynolds numbers and three different diameters of 6 mm, 8 mm, and 10 mm. [21] investigated the size and trajectory of mixed jet diffusion flames in cross wind conditions. The flame trajectory length initially decreased and then increased with increasing cross air flow speed for the same fuel jet velocity. [19] used four different circular nozzle diameters to investigate the flame blowout limits of the flame jet at atmospheric and sub-atmospheric pressures. In both cases, the blowout limit increased and then decreased as the fuel jet velocity increased.

[22] investigated the soot and flame stabilization of methane jet flames and found that increasing the fuel flow rate and pressure increased soot emissions. [23] investigated the effects of five different nozzle geometries with equivalent diameters on flame stability and found that the asymmetric nozzle reduced liftoff height and improved flame stability.

Based on previous researches, it can be shown that the flame holder shape has a significant impact on flame stability, so a new flame holder with three fuel exit ports was designed and used here to ensure the most complete distribution of fuel in the combustion zone as possible with the turbulent air from the concentric pipe.

2. EXPERIMENTAL SETUP

The experimental work was carried out on a bluff-body burner (Figure 1). Three coaxial pipes carried air and fuel to the combustion zone. The inner pipe has a 3 mm inner diameter and is used to transport fuel to the flame holder and hence to the combustion zone. The middle pipe, with a 30 mm inner diameter, transported primary air to the combustion zone, while the outer pipe, with a 52 mm inner diameter, transported secondary air to the combustion zone. To provide turbulent air to the combustion zone, a conversion-diversion path was installed on top of the middle pipe. The flame holder is a double cone with a diameter of 21 mm and three circular 3 mm diameter fuel ports that were mounted with the fuel pipe and centered at the top of the conversion-diversion path as shown in Figure 1 (a), (b). The experiments were carried out in still air without an enclosure and the fuel used in all experiments was natural gas and its volumetric composition and properties is shown in table 1.

A standard pitot tube was used to measure air velocity in each pipe, and a mass flow controller was used to control the fuel flow rate. Throughout the experiment, the fuel flow rate (Q_f) was kept constant at $2.398 \times 10^{-5}\ m^3/s$ and the primary air velocity (V_2) was set to 7.1 m/s, 15.3 m/s, and 19.9 m/s respectively. To investigate the impact of adding a secondary air on the combustion process, the secondary air velocity (V_1) was initially set to 0 and then increased to 6.34 m/s.

Thermocouples S-Type (Platinum – Platinum Radium 10 %) with a diameter of 0.5 mm were used to measure the flame temperatures. As shown in Figure 2, the vertical difference between each level is 15 mm, and the horizontal distance between every two measuring points is 10 mm.

To determine the length and width of the flame, the imaging system used a digital camera and computer software (MATLAB and AutoCAD). Photo processing was done in MATLAB to determine the edges of the flames in each photo, and then the flame length and width were measured in AutoCAD.

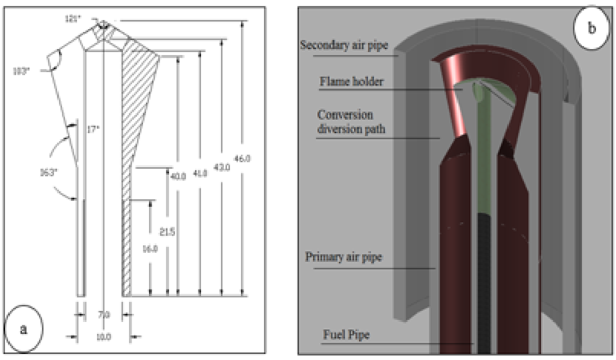


Figure 1. Burner schematic (a) Flame holder dimensions (dimensions in mm) (b) A 3D section for pipes and flame holder arrangement.

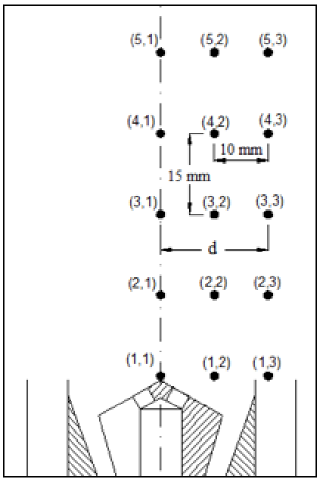


Figure 2. Thermocouples measuring positions.

Table 1: the volumetric composition of Natural gas

	Component	Formula	Volume %
Composition	Methane	CH_4	84.9 – 94.82
	Ethane	C_2H_6	3.12 – 7.1
	Propane	C_3H_8	1.09 – 2.6
	Iso-Butane	C_4H_{10}	0.04 – 0.5
	n-Butane	C_4H_{10}	0.02 – 0.65
	Iso-Pentane	C_5H_{12}	0.01 – 0.2
	n-Pentane	C_5H_{12}	0.02 – 0.14
	Hexane's plus	C_6H_{14}	0.04 – 0.11
	Nitrogen	N_2	0.11 – 0.3
	Carbon dioxide	CO_2	0.7 – 3.5
Properties	Calorific Value		42852 kJ/kg
	Density		0.754 kg/m^3
	Correct (A/F)		17.2
	Molecular weight		18.87

3. RESULTS AND DISCUSSION

3.1 FLAME TEMPERATURES

As previously stated, primary air was only applied to the combustion zone with velocities of 7.1 m/s, 15.3 m/s, and 19.9 m/s and then secondary air was applied to the combustion zone with a velocity of 6.34 m/s along with the primary air. Figure 3 shows the distribution of flame temperatures when only primary air was applied to the combustion zone while Figure 4 shows the distribution of flame temperatures when both primary and secondary air was applied to the combustion zone. The flame temperatures were measured from the center of the flames along the distance (d) as shown in Figure 2.

When only the primary air velocity (V_2) = 7.1 m/s was applied to the combustion zone, the flame temperatures were 254.2 °C at $T_{1,1}$, 583.1 °C at $T_{2,1}$, and 423.6 °C at $T_{2,2}$. After secondary air of (V_1) = 6.34 m/s was applied to the combustion zone along with primary air (V_2) = 7.1 m/s, the flame temperatures were 360.8 °C at $T_{1,1}$, 610.3 °C at $T_{2,1}$, and 444.5 °C at $T_{2,2}$. Applying secondary air to the combustion zone improved air-fuel mixing which resulted in raising the temperature of the flames.

When only the primary air velocity (V_2) = 15.3 m/s was applied to the combustion zone, the flame temperatures were 279.3 °C at $T_{1,1}$, 198.9 °C at $T_{2,1}$ and 161.8 °C at $T_{2,2}$. After secondary air V_1= 6.34 m/s was applied to the combustion zone along with primary air (V_2) = 15.3 m/s, the flame temperatures were 430.4 °C at $T_{1,1}$, 405.6 °C at $T_{2,1}$, and 256.8 °C at $T_{2,2}$. Applying secondary air to the combustion zone improved air-fuel mixing which resulted in raising the temperature of the flames.

When only the primary air velocity (V_2) = 19.9 m/s was applied to the combustion zone, the flame temperatures were 323.3 °C at $T_{1,1}$, 320.9 °C at $T_{2,1}$ and 82.7 °C at $T_{2,2}$. After secondary air V_1= 6.34 m/s was applied to the combustion zone along with primary air (V_2) = 19.9 m/s, the flame temperatures were 279.1 °C at $T_{1,1}$, 213.8 °C at $T_{2,1}$, and 162.6 °C at $T_{2,2}$. Adding secondary air to the combustion zone enhanced air-fuel mixing, but the temperature reduced because the secondary air was delivered to the combustion zone at high velocity, which resulted in heat dissipation from the flames and reduced the flame temperature.

3.2 FLAME LENGTH AND WIDTH

The effect of adding a secondary air to the primary air on flame length and width is shown in Figure 5 and Figure 6 respectively. The flame height was 7.14 cm and the flame width was 2.71 cm when only primary air velocity V_2 = 7.1 m/s was applied; however, when secondary air velocity V_1 was increased to 6.34 m/s, the flame height was reduced to 6.72 cm and the flame width increased to 3.22 cm.

Also, the flame height was 5.7 cm and the flame width was 2.75 cm when only primary air velocity V_2 = 15.3 m/s was applied however, when secondary air velocity V_1 was increased to 6.34 m/s, the flame height was increased to 8.38 cm and the flame width as well increased to 2.98 cm. Also, the flame height was 7.13 cm and the flame width was 2.74 cm when only primary air velocity V_2 = 19.9 m/s was applied however, when secondary air velocity V_1 was increased to 6.34 m/s, the flame height was decreased to 6.14 cm and the flame width as well decreased to 2.57 cm.

The maximum flame height was 8.38 cm at secondary air velocity V_1= 6.34 and primary air velocity V_2= 15.3 m/s while the maximum flame width was 3.22 cm at primary air velocity V_2= 7.10 m/s and secondary air velocity V_1= 6.34 m/s.

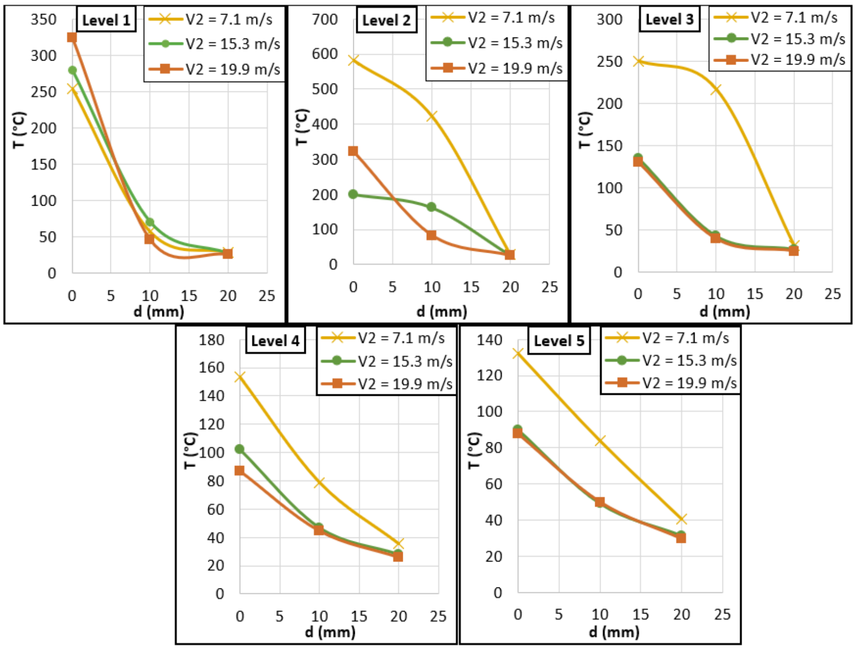


Figure 3: The flame temperature distribution at secondary air velocity (V_1 = 0.0 m/s) with the variation of primary air velocity (V_2).

The flames were captured using a digital camera, and MATLAB was used to identify the flame edges as shown in Figure 5 and then AutoCAD was used to measure the length and width of the flames.

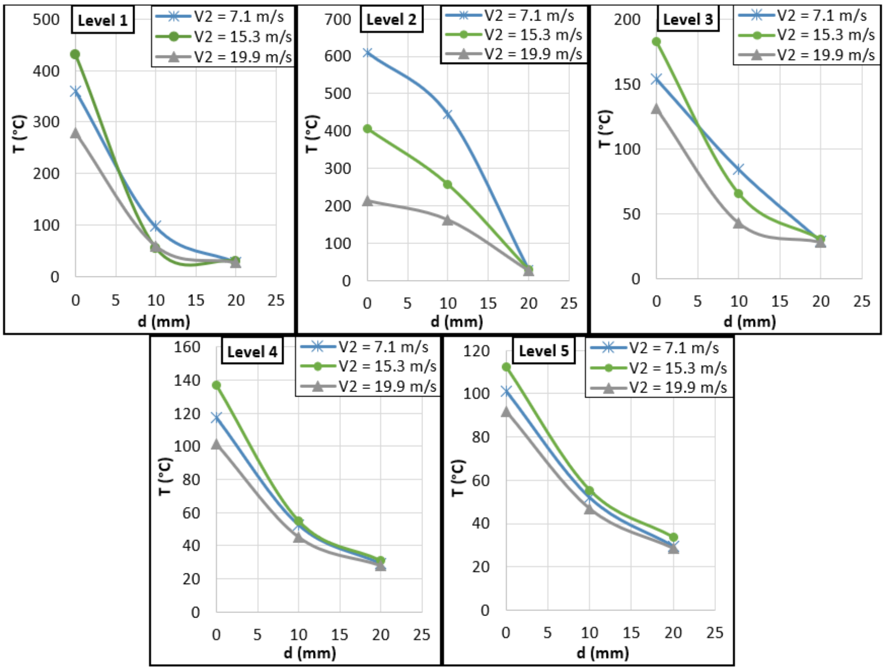


Figure 4: The flame temperature distribution at secondary air velocity (V_1 = 6.34 m/s) with the variation of primary air velocity (V_2).

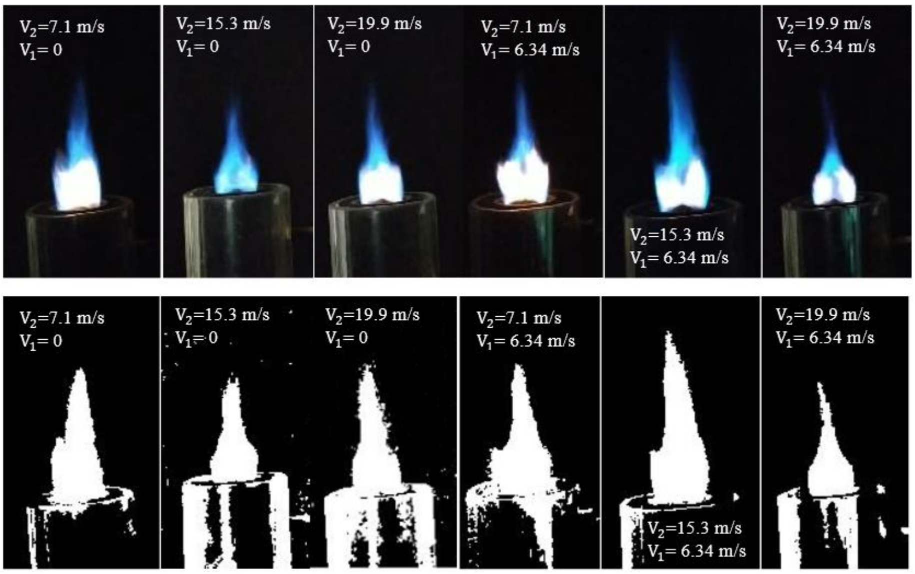


Figure 5. MATLAB Image processing summary.

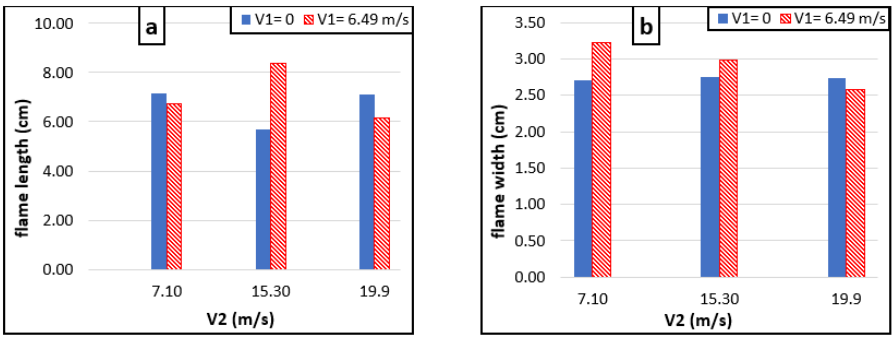
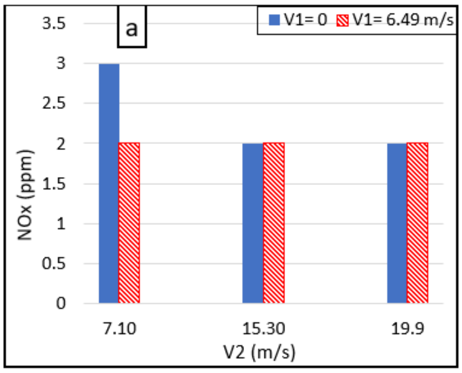


Figure 6. (a) flame length, (b) flame width for different secondary air velocities.

3.3 Emissions

Figure 7 shows the concentrations of CO, and NO_x that resulted from the combustion process which was measured by an exhaust analyzer (optima 7). The results show that when the primary air was only applied to the combustion zone, the CO values were 854 ppm at V_2= 7.1 m/s, 905 ppm at V_2=15.3 m/s and 942 ppm at V_2= 19.9 m/s. After secondary air V_1= 6.34 m/s was applied to the combustion zone along with primary air, the CO concentrations reduced to be 785 ppm at V_2= 7.1 m/s, 815 ppm at V_2=15.3 m/s and 853 ppm at V_2= 19.9 m/s. Also, the results show that NO_x concentrations did not exceed 3 ppm throughout the experiments as indicated in figure 7.



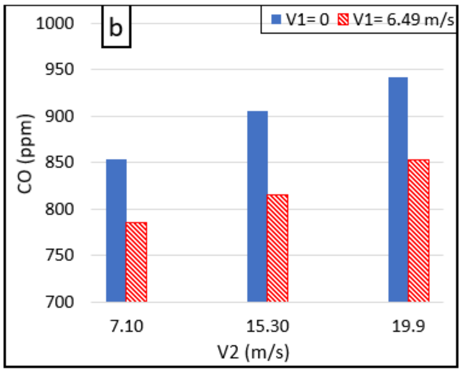


Figure 7: The emission concentrations at constant primary air velocities with different secondary air velocities for (a) CO, (b) NO_x.

4. Conclusions

- Flame temperatures were increased when secondary air velocity V_1 was applied to the combustion zone along with the primary air at V_2 = 7.1 m/s and V_2 = 15.3 m/s but it decreased at V_2 = 19.9 m/s.
- The flame length and flame width were affected by applying the secondary air to the combustion zone.
- Adding a secondary air source increased the flame length at V_2 = 15.3 m/s while the flame length decreased at V_2 = 7.1 m/s and V_2 = 19.9 m/s.
- Adding a secondary air source increased the flame width at V_2 = 7.1 m/s and V_2 = 15.3 m/s while it was decreased at V_2 = 19.9 m/s.
- Throughout the experiments, the concentrations of NO_x did not exceed 3 ppm.
- CO concentrations were decreased when secondary air velocity V_1 was applied to the combustion zone along with the primary air.

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