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Analysis of LPG diffusion flame in tube type burner

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ABSTRACT

The present research aims to analyse diffusion flame in a tube type burner with Liquefied petroleum gas (LPG) as a fuel. An experimental investigation is performed to study flame appearance, flame stability, Soot free length fraction (SFLF) and CO emission of LPG diffusion flame. Effects of varying air and fuel velocities are analysed to understand the physical process involved in combustion. SFLF is measured to estimate the reduction of soot. Stability limits of the diffusion flame are characterized by the blowoff velocity. Emission characteristic in terms of CO level is measured at different equivalence ratios. Experimental results show that the air and fuel velocity strongly influences the appearance of LPG diffusion flame. At a constant fuel velocity, blue zone increases and the luminous zone decreases with the increase in air velocity. It is observed that the SFLF increases with increasing air velocity at a constant fuel velocity. It is observed that the blowoff velocity of the diffusion flame increases as fuel velocity increases. Comparison of emission for flame with and without swirl indicates that swirl results in low emission of CO and higher flame stability. Swirler with 45° vanes achieved the lowest CO emission of 30 ppm at $\Phi = 1.3$.

Keywords: Diffusion flame; flame appearance; flame stability; soot free length fraction; CO emission.

INTRODUCTION

Turbulent nonpremixed flames are used in the most practical combustion systems because of the ease with which such flames can be controlled. LPG is a popular fuel for domestic and commercial applications [1]. However, the pollutant emitted by the LPG flame is of great concern because of its direct effect on human health. Flame stability, soot formation and emissions associated with the diffusion flame are a matter of concern when deciding its application [2].

Flame stability is one of the important features to be considered while designing the combustion systems. In a practical device, a stable flame is desired which anchors to the burner outlet with resistance to liftoff and blowoff in the operating range. At a higher fuel flow, the flame liftoff from the burner outlet [3-5]. Mishra and Kiran used [6] a bluff-body as a flame holder. They claimed that the bluff-body generates a recirculation zone, which helps to improve flame stability. The liftoff characteristic is influenced by the fuel jet velocity [7-11]. Kang et al. [12] reported that methane diffusion flame has higher blowout velocity compared to dimethyl ether and LPG. Mishra and Rahman [13] investigated flammability limits for LPG-air mixtures. Laphirattanakul et al. [14] studied the combustion stability of the LPG porous burner. They revealed that convection and flame speed control the stability of flame. Chen et al. [15] found that the flame stability is highly sensitive to the standing waves. Sawarkar et al. [16] explored the influence of external pulsations on LPG diffusion flame at different fuel flow rates.

In view of indoor air pollution, the formation of soot and CO is a matter of great concern for its direct impact on public health. Moderate or intensive combustion with low oxygen (MILD) is a new combustion technology that generates low pollutant combustion [17]. Noor et al. [18] numerically studied the effect of exhaust gas recirculation, air and fuel velocity on accomplishing MILD combustion in the open furnace. They designed and developed the combustion furnace for the MILD combustion successfully [19]. Gulder and Snelling [20] observed that the addition of inert gas plays a significant role in the formation of soot. Aravind et al. [21] presented a study of the influence of hydrogen enrichment on combustion characteristics of LPG-air mixtures. They found the improved burning ability of the LPG-air mixture. Gulder [22] studied the influence of flame temperature on the formation of soot, using propylene, ethylene, and isooctane as a fuel. Frenklach and Wang [23] modeled the nucleation and growth of soot particles in premixed hydrocarbon flames. Wang et al. [24] investigated numerically and experimentally the formation of soot in a counterflow diffusion flames. Saini and De [25] attempted to quantify the formation of soot in the turbulent diffusion flame. Naccarato et al. [26] measured soot volume fraction using Laser-Induced-Incandescence and Two-Color technique in LPG flame. Liu et al. [27] carried out experimental investigations of the characteristic of soot distribution in the laminar diffusion flame. Soussi et al. [28] numerically investigated the influence of soot aging on soot formation.

The degree of soot formation can be quantified in terms of SFLF [29]. Wu et al. [30] found increased SFLF from a co-axial burner that incorporates a methane diffusion flame. Mishra and Kumar [31] concluded that the addition of nitrogen in LPG diffusion flame improves SFLF. Hou et al. [32] compared the performance of swirl flow burner with conventional radial flow burner. They observed a marginally higher level of CO emission in the swirl flow burner. Li et al. [33] reported that the equivalence ratio has a strong influence on CO emission in the cooker-top burner. Kang et al. [34] examined the emission characteristic of CO emission of dimethyl ether/air jet diffusion flame.

Several researchers had studied the effect of swirl on combustion. The swirling flow develops a low-pressure region at the swirler outlet [35, 36]. This results in recirculation of the fuel-air mixture in the form of a toroidal vortex, which improves the mixing of combustion products [37, 38]. Chen and Driscoll [39] investigated the role of swirling motion in the fuel-air mixing process with a swirl stabilised the flame. Raj and Ganesan [40] experimentally demonstrated that the size of the recirculation zone strongly depends on the amount of turbulence generated by swirler. Samantaray and Mohanta [41] analysed different kinds of flame in a swirl burner using an image processing technique.

In the diffusion flame, flame stabilization, flame appearance, and pollutant emission may depend on the fuel velocity and equivalence ratio. The above survey shows that there is a limited study on the characterization of the flame in a tube type burner, used in cooking stoves in India. The present study is therefore intended to experimentally investigate the combustion characteristics of the LPG diffusion flame in the tube type burner. The objective of this study is to analyse flame appearance, flame stability, SFLF and CO emission of LPG diffusion flame. The potential of CO emission reduction of LPG combustion using swirler is discussed.

TUBE TYPE BURNER AND EXPERIMENTAL FACILITY

Figure 1(a) demonstrates the schematic drawing of the tube type burner. It contains a fuel jet located at the bottom of the burner. The diameter of the fuel jet hole is 0.8 mm. The fuel jet has a conical shape with an included angle of 60^0. The height of the tube type burner is 63 mm and the internal diameter is 28 mm. The tube type burner has four holes of 9 mm diameter, through which air is supplied. The holes are located on the cylindrical surface with a centre height of 20 mm from the bottom of the tube type burner. Photographic views of tube type burner and fuel jet are shown in Figure 1(b) and (c) respectively. To investigate the effect of swirl flow on diffusion flame, three swirlers with 8 flat vanes are produced (Figure 1(d), (e) and (f)). The vane angles vary from 15° to 45° in the step of 15°. Figure 2 shows the schematic diagram of the experimental setup. A blower supplies the necessary air flow. A calibrated rotameter (accuracy ± 2.0 % of full scale) is used to measure the air flow rate. LPG is employed as fuel for present studies. The fuel flow rate is controlled by a needle valve installed near the tube type burner in the fuel supply line. The LPG flow rate is metered through the calibrated rotameter (accuracy ± 2.0 % of full scale). To avoid disturbance from the surroundings, the burner is confined by a 55 x 55 x 90 cm^3 enclosure with a glass windowat the front side to provide optical access for the camera.

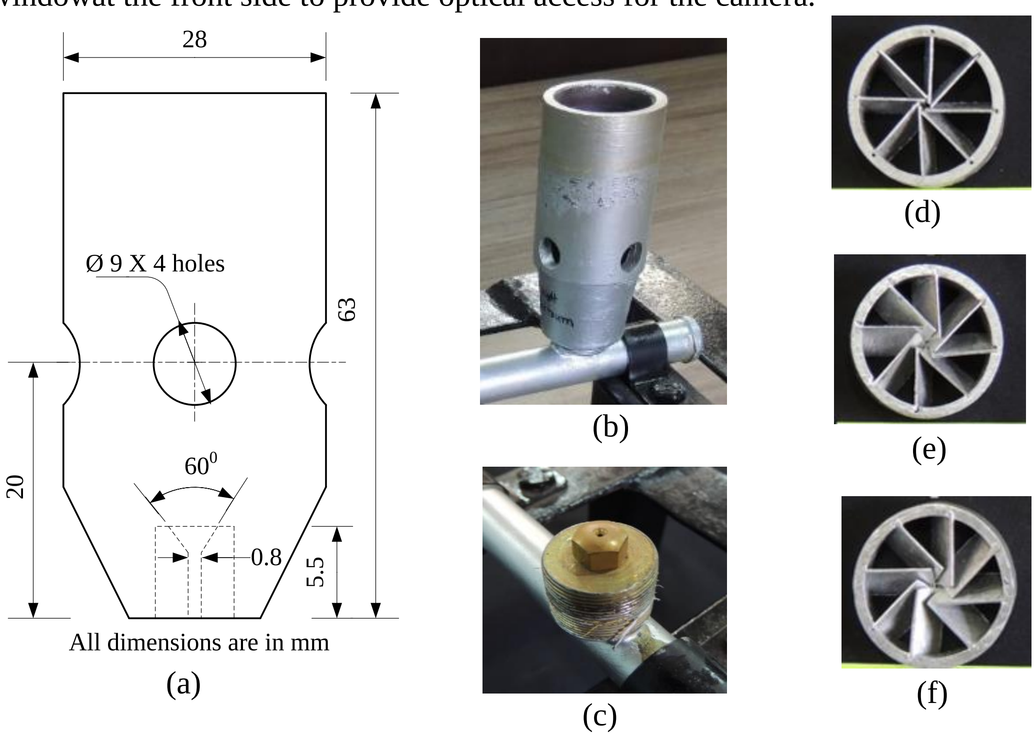


Figure 1. Details of tube type burner (a) Schematic diagram (b) Tube type burner (c) Fuel jet (d) 15° swirler (e) 30° swirler (f) 45°swirler.

CO emission level in the exhaust gases is measured using flue gas analyser (accuracy ±2 ppm). For measuring CO emission in the exhaust gas, a probe of flue gas analyser is mounted at the duct as shown in Figure 2. The flame sizes and shapes are recorded with a high-resolution camera (24.2 megapixels, ISO sensitivity 12800). The fuel used in this study is standard LPG available in India containing 30% C_3H_8, 69% C_4H_{10} and other trace of gases by volume. Burner stand is made of mild steel square tube and strip. The burner stand is designed so that the burner outlet is 205 mm above the lower surface of the enclosure. The flame length is defined as the vertical distance from the base of the flame to the tip of the flame along the centreline. The flame length is determined by using ImageJ software. The average of the flame length is determined from 10 photos of the same condition. The equivalence ratio, Φ is defined as

$$\phi = \left(M_a/M_f\right)_{stoich} \Big/ \left(M_a/M_f\right)_{actual} \tag{1}$$

where $\left(M_a/M_f\right)_{actual}$ is the actual air-fuel ratio, $\left(M_a/M_f\right)_{stoich}$ is stoichiometric air-fuel ratio, M_a is the mass flow of air (kg/s) and M_f is mass flow of air (kg/s).

The experiments are conducted to investigate the effects of fuel and air velocities on flame appearance, SFLF and flame stability. CO emission is also measured for comparison with the swirling diffusion flame. The operational conditions for the flames is chosen to be at fuel velocity $V_f = 39.81$ m/s while air velocity V_a increases from 0.66 m/s to 3.28 m/s; at $V_a = 1.57$ m/s while V_f increases from 13.27 m/s to 39.81 m/s. CO emission of the diffusion flame with and without swirl is measured at different equivalence ratio (Φ = 0.53 to 2.66). To ensure experimental repeatability, each experiment is repeated three times and the averaged data of these tests are reported.

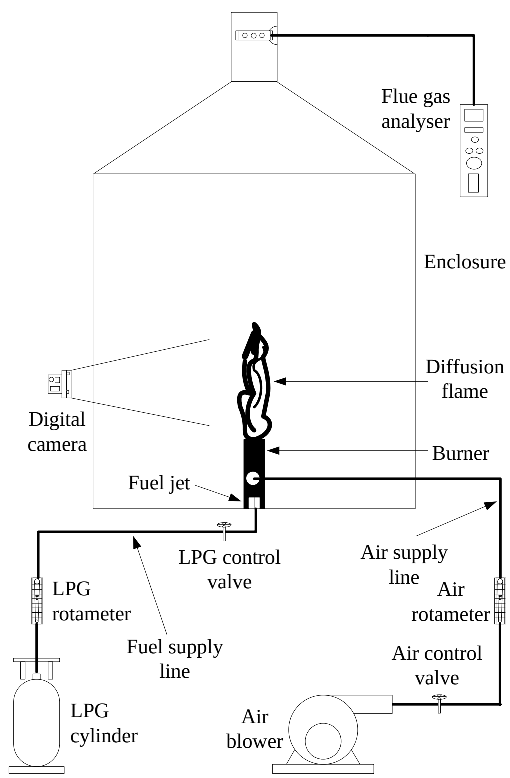
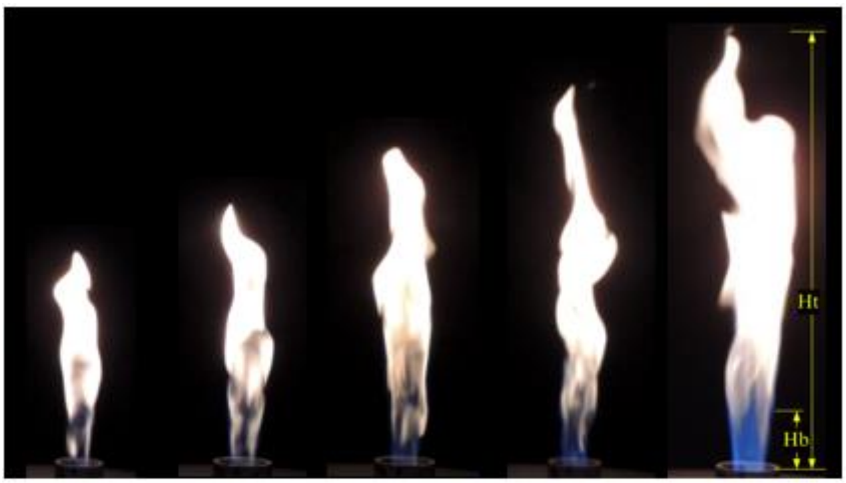


Figure 2. Schematic of the experimental setup.

RESULTS AND DISCUSSION

Flame Appearance

The diffusion flame can be characterised by its visible appearance. The flame appearance of LPG diffusion flame at different air-fuel velocities is studied. The appearance of the flame with the increased velocity of fuel is shown in Figure 3. The velocity of fuel, V_f varies from 13.27 m/s to 39. 81 m/s. The burner is partially aerated by entrainment of air naturally from the air holes due to the momentum produced by the high velocity of fuel. The flame length is considered from the fuel jet outlet. The burner outlet is 57.5 mm from the fuel jet outlet. The length of the flame is denoted by H_t, and the blue zone length is denoted by H_b (Figure 3 (e)).



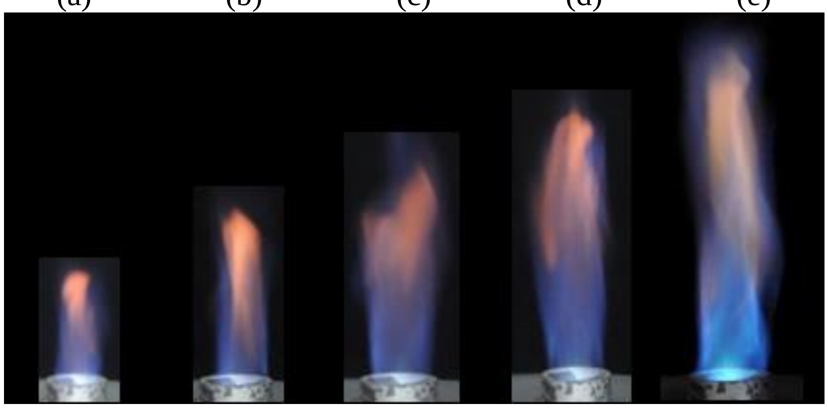
(a) V_f =13.27 m/s (b) V_f =19.9 m/s (c) V_f =26.54 m/s (d) V_f =33.17 m/s (e) V_f =39.81 m/s

Figure 3. Flame appearance with increasing fuel velocity.

It is observed from Figure 3 that the diffusion flame has a blue zone at the bottom, which is covered by a luminous zone. As the fuel velocity increases, both the blue zone and the luminous zone in the diffusion flame are increased. It should also be noted that as the fuel velocity increases, the flame length increases. An increase in the fuel velocity leads to a fuel-rich regime. Moreover, it improves the mixing process between fuel and air, which forms a larger flame length.

The flame appearance with increasing air velocity (V_a = 0.66 m/s to 3.28 m/s) with a constant fuel velocity (V_f = 39.81 m/s) is shown in Figure 4 (a) to (e). It is observed that increasing air velocity increases the length of the blue zone and reduces the length of the luminous zone of the diffusion flame. At the air velocity V_a = 1.97 m/s (Figure 4 (c)), the luminous zone of the diffusion flame changes from yellow to orange with a small intense blue zone in the core of the flame near the burner outlet. A further increase in the air velocity from 2.62 m/s to 3.28 m/s, gives a shorter and narrower diffusion flame with a large intense blue zone near the burner outlet, as shown in Figure 4 (d) and (e). At V_f = 39.81 m/s, as the air velocity increases, the mixing process between the air and fuel is enhanced, resulting in an improved combustion process. Therefore, the diffusion flame becomes shorter in length with a larger blue zone and smaller luminous zone.

V_a = 0.66 m/s	V_a = 1.31 m/s	V_a = 1.97 m/s	V_a = 2.62 m/s	V_a = 3.28 m/s
(a)	(b)	(c)	(d)	(e)



V_f =13.27 m/s	V_f = 19.9 m/s	V_f = 26.54 m/s	V_f = 33.17 m/s	V_f = 39.81 m/s
(f)	(g)	(h)	(i)	(j)

Figure 4. Flame appearance; (a) to (e) with increasing air velocity, V_f = 39.81 m/s, (f) to (j) with increasing fuel velocity, V_a =1.57 m/s.

The flame appearance of LPG diffusion flame with increasing fuel velocity from 13.27 m/s to 39.81 m/s at a constant air velocity of 1.57 m/s is shown in Figure 4 (f) to (j). It is observed that the length of flame, as well as the volume of the flame, are increased as the fuel velocity increases. It is noted that there is an increase in the luminous zone of the diffusion flame. As the fuel velocity increases, a fuel-rich regime in the diffusion flame is enhanced, resulting in increased flame volume and luminous zone. These observations show that the air and fuel velocities strongly influence the appearance of LPG diffusion flame.

In this work, the influence of swirl on flame appearance is examined. The effect of swirler with increased air velocity at constant fuel velocity on flame appearance is shown in Figure 5. The overall effect of 15°, 30° and 45° swirler on diffusion flame appearance is largely identical. It is seen that the flame length is shortened and the flame width is expanded with the use of swirler. It is also noted that as the air velocity increases, the colour of the luminous zone changes from yellow to lemon yellow. An intense blue zone at the burner outlet is also observed. Swirling flow helps to improve the air-fuel mixture by recirculating motion in the flow field. These effects lead to a reduction in the length and an increase in the width of the LPG diffusion flame [39].

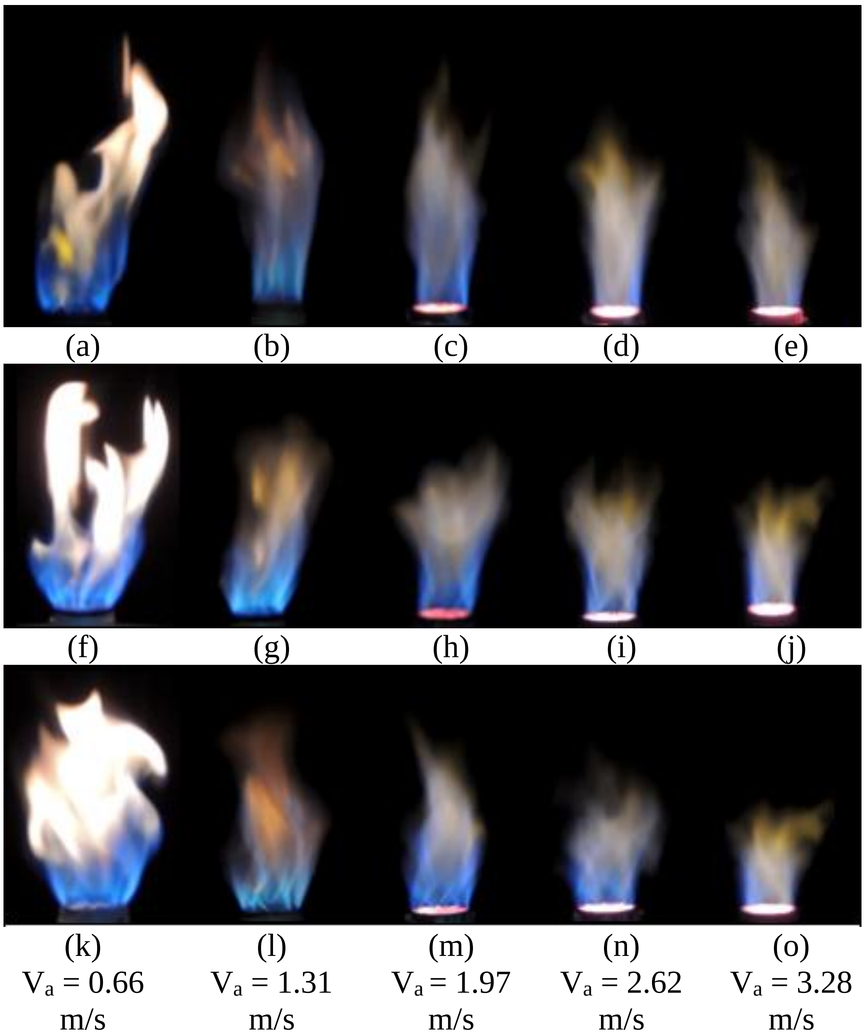
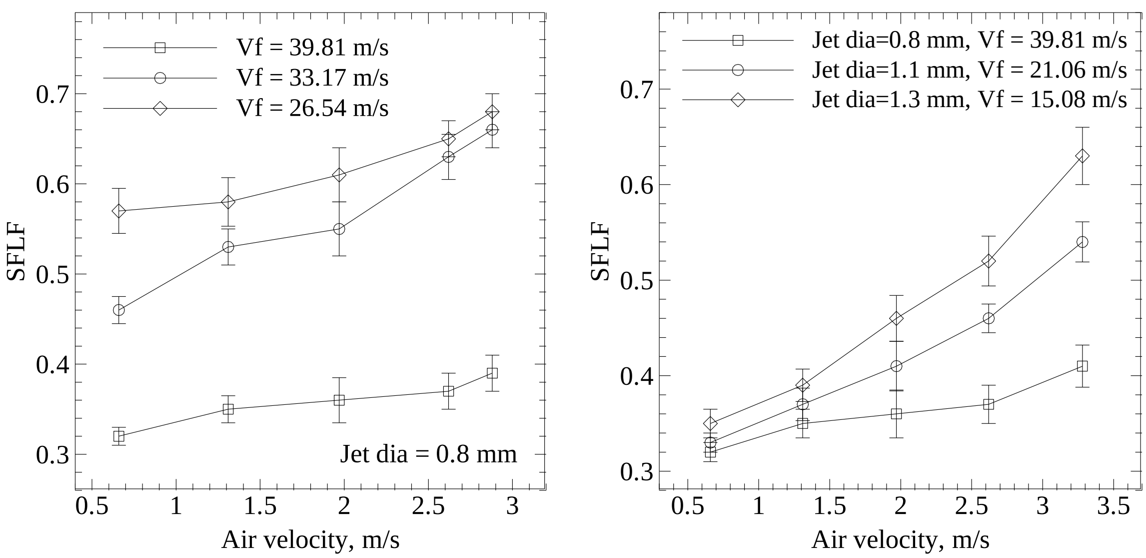


Figure 5. Flame appearance with 15° swirler (a) to (e), with 30° swirler (f) to (i), and with 45° swirler (k) to (o), for V_f = 39.81 m/s.

Soot Free Length Fraction

Formation and destruction of the soot is a typical feature of the diffusion flame. In practical applications of the diffusion flame, soot formation is undesirable. The soot also contributes to radiant heat losses from the diffusion flame. The soot formation can be expressed as the extent of the blue zone of the flame [29]. The blue zone of the diffusion flame is a soot free length of the diffusion flame. In the present work, SFLF is determined to quantify soot formation in the LPG diffusion flame. The SFLF is defined as the ratio of the soot free length (length of the blue zone, H_b) to the total flame length (H_t) of the diffusion flame. The effect of the air velocity from 0.66 m/s to 3.28 m/s on SFLF for three different fuel velocities, V_f = 26.54, 33.17 and 39.81 m/s is shown in Figure 6 (a).

It can be observed that at a constant fuel velocity, SFLF increases with increased air velocity. This is because of the higher strain rate between the fuel and air streams, which results in an elongated blue zone due to improved premixing of the fuel and air. It is also observed that as the fuel velocity decreases, the SFLF increases. Interestingly, it is noted that for the same value of the air velocity, the SFLF is increased as the fuel velocity is decreased. Mahesh and Mishra [42] who reported increasing SFLF with air velocity in the inverse diffusion flame, made similar observations. In a particular fuel velocity, the rate of mixing between air and fuel increases with increasing air velocity. In addition, the mass of the air supply increases, which provides large quantities of oxygen for the combustion of fuel. These improved momentum exchange between the air and fuel streams coupled with oxygen-rich condition improves the fuel combustion and reduces the soot formation. Because of the reduced soot formation, the length of the blue zone increases as the luminous zone length decreases.



(a) (b)

Figure 6. Variation of SFLF with air velocity for (a) fuel jet of diameter 0.8 mm (b) fuel mass flow = 0.000035 kg/s.

To examine the effect of fuel jet diameter on SFLF, three fuel jets are considered. Figure 6 (b) compares the measured SFLF for the jet diameter 0.8 mm, 1.1 mm and 1.3 mm with a constant fuel flow of 0.000035 kg/s. For a different diameter of the fuel jet, the curve confirms the general pattern of the rise in the SFLF with the rise in the air velocity as shown in Figure 6 (b). The SFLF increases with increasing fuel jet diameter. In case of a fuel jet of larger diameter, the fuel velocity decreases. This results in an increased residence time, which increases the blue zone of the diffusion flame and reduces the length of the luminous zone.

Flame Stability

The stable flame remains anchored at the burner outlet and resists liftoff and blowoff over a wide operating range. Liftoff prevention is an important design criterion for the gas burner. The flame stability information is useful to determine the operating limits of the burner. The present study investigates the flame stability of the LPG diffusion flame at different fuel velocities. Increasing the air velocity beyond the liftoff values leads to an increase in the liftoff distance until the flame abruptly blows off. In order to examine the influence of swirler on flame stability, the fuel jet of a diameter of 0.8 mm is selected. Various combinations of air and fuel velocities are investigated to study flame stability until the flame blowoff occurs. The critical value of the air velocities is observed for the swirler with 15°, 30°, and 45° vane angles when the flame blowoff occurs. Table 1 shows the critical values of the air velocity when the flame blowoff occurs for various cases (with and without swirler).

Table 1. Blowoff velocity for fuel velocity of 13.27–39.81 m/s (Jet diameter = 0.8 mm).

Fuel velocity, m/s	Air velocity, m/s (without swirler)	Air velocity, m/s (15° swirler)	Air velocity, m/s (30° swirler)	Air velocity, m/s (45° swirler)
13.27	1.71	2.11	2.36	2.49
19.91	2.49	2.75	2.88	3.15
26.54	2.88	3.28	3.41	3.67
33.17	3.15	3.67	3.93	4.19
39.81	3.28	3.93	4.32	4.59

Table 2. Blowoff velocity for the fuel mass flow of 0.000035 to 0.000012 kg/s.

Fuel mass flow kg/s	Air velocity, m/s (Jet diameter= 0.8mm)	Air velocity, m/s (Jet diameter=1.1mm)	Air velocity, m/s (Jet diameter=1.3mm)
0.000035	3.28	3.93	4.32
0.000029	3.15	3.54	3.93
0.000023	2.88	3.28	3.67
0.000018	2.49	2.75	2.88
0.000012	1.70	2.10	2.23

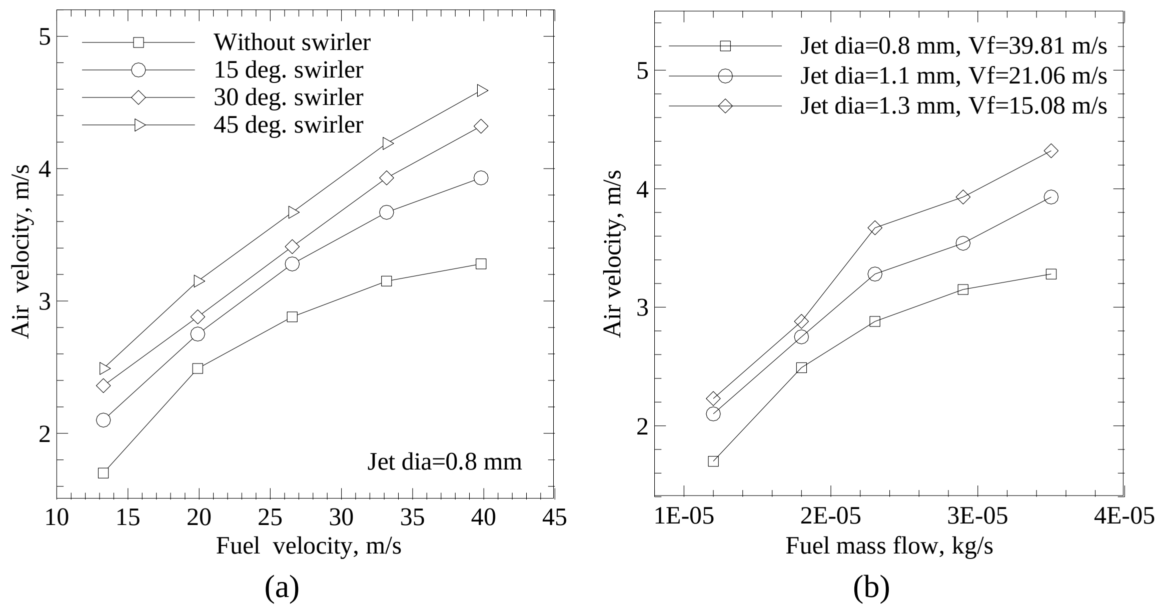


Figure 7. Stability limits (a) with and without swirler for fuel jet of diameter 0.8 mm (b) at various fuel mass flow rate.

Figure 7(a) shows the stability limits of the diffusion flame with and without swirler for the fuel jet with a diameter of 0.8 mm. In the case of without swirler, it can be seen that the stability of the flame increases with increasing fuel velocity. Similar observations are made during the blowoff of swirl stabilised diffusion flame with swirler of 15°, 30°, and 45°. It is noted that the flame stability increases with the use of the swirler. Moreover, the stability limits increase as the swirler vane angle increases. Swirler vanes impart the tangential motion to the air and fuel mixture as the mixture passes through the swirler. This tangential motion results in radial expansion of the air-fuel mixture, which forms a low-pressure region at the swirler outlet. Therefore, a recirculation zone occurs in the flame regime [37, 38], which increases the air-fuel mixing process and increases the residence time, resulting in increased stability limits.

The effect of the variation of the fuel jet diameter on the stability limits without swirler is examined by direct observation. Table 2 shows the critical values of air velocity when a blowoff occurs for different fuel jet diameters. The results are plotted in Figure 7 (b) for a different fuel mass flow of 0.000035 to 0.000012 kg/s. It is observed that the stability limits for the diffusion flame increase with the increase of the fuel jet diameter. With a higher fuel jet diameter, the fuel velocity decreases. This increases the residence time of the fuel, thereby increasing the fuel combustion rate, which improves flame stability.

CO emission

CO emission characteristics are investigated at different equivalence ratios of the diffusion flame in the tube type burner. The CO emission level is measured with the flue gas analyser for the fuel jet diameter of 0.8 mm. Table 3 shows the measurement of CO emission at different Φ for a constant mass flow rate of fuel M_f = 0.000035, 0.000029 and 0.000023 kg/s.

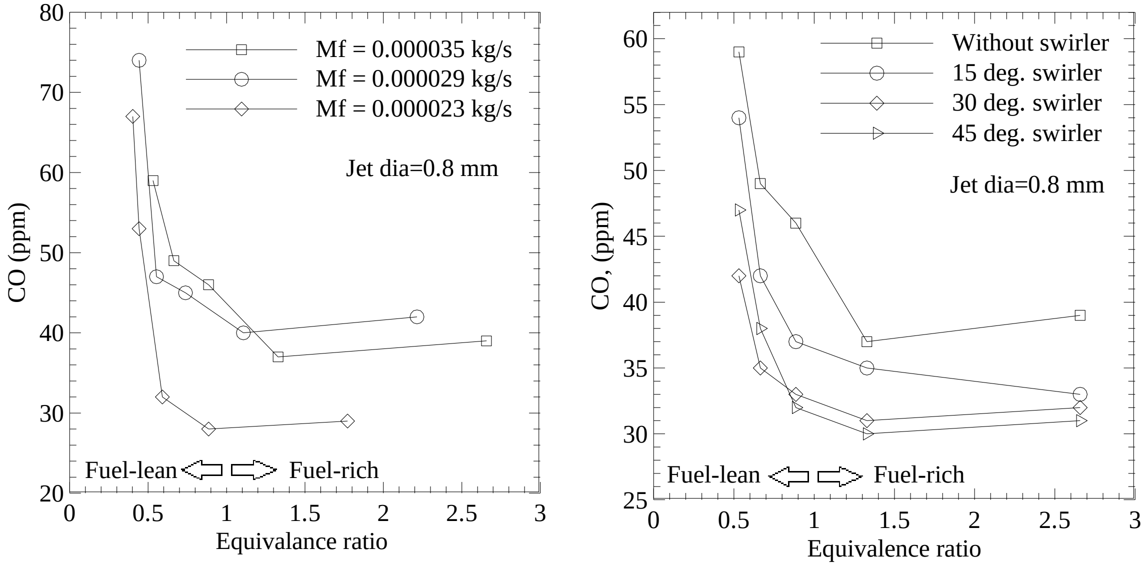
Table 3. CO emission at various mass flow of air (fuel jet diameter = 0.8 mm).

Air flow, M_a (kg/s)	M_f = 0.000035 kg/s		M_f = 0.000029 kg/s		M_f = 0.000023 kg/s	
	Φ	CO (ppm)	Φ	CO (ppm)	Φ	CO (ppm)
0.000204	2.66	39	2.21	42	1.77	29
0.000408	1.33	37	1.11	40	0.89	28
0.000613	0.89	46	0.74	45	0.59	32
0.000817	0.66	49	0.55	47	0.44	53
0.001021	0.53	59	0.44	74	0.40	67

Table 4. CO emission with the swirler at various mass flow of air, M_f = 0.000035 kg/s.

Air flow, M_a, (kg/s)	Equivalence ratio Φ	CO (ppm) Without swirler	CO (ppm) 15° swirler	CO (ppm) 30° swirler	CO (ppm) 45° swirler
0.000204	2.66	39	33	32	31
0.000408	1.33	37	35	31	30
0.000613	0.89	46	37	33	32
0.000817	0.66	49	42	35	38
0.001021	0.53	59	54	42	47

A variation of the CO emission is plotted with respect to equivalence ratio, Φ in Figure 8 (a). It is observed that at a mass flow rate of the fuel M_f = 0.000035 kg/s, CO first decreases from 39 ppm at Φ = 2.66 and reaches a minimum value of 37 ppm at Φ = 1.33. It then steadily rises to a peak of 59 ppm at Φ = 0.53. This trend is almost similar to another mass flow rate of the fuel. The minimum value of CO is observed near the stoichiometric condition as complete combustion takes place due to adequate mixture strength of the air and fuel. The higher value of CO observed at the fuel-lean regime. This can be attributed to an increase in the air velocity from the burner outlet, which leads to the reduction of the residence time of the combustion products in the diffusion flame. Therefore, inhibiting the conversion of CO into CO_2 and hence results in a higher concentration of CO [29].



(a) (b)

Figure 8. (a) Variation of CO with Φ for a constant mass flow rate of fuel and (b) variation of CO with Φ ratio with swirler.

The effect of swirling flow on CO emission is also investigated using swirlers with vane angle 15°, 30°, and 45°. Table 4 shows the observations of CO emission at different Φ with a fuel jet diameter of 0.8 mm. The Observed CO emission is plotted with respect to the equivalence ratio for a constant mass flow rate of fuel M_f = 0.000035 kg/s in Figure 8 (b). It is observed that the CO emission level reduces with the swirler. Interestingly, it is also observed that the CO emission is decreased as the swirler vane angle is increased. The 45° swirler achieved the lowest CO emission of 30 ppm at Φ = 1.3. CO is found higher in the diffusion flames with and without swirl at $\Phi \geq 0.7$, indicating incomplete combustion. An improved mixing between the fuel and air streams and the prolonged residence time in the flame regime due to swirling ensures complete combustion [37, 38]. These results in the reduction of the emission of CO compared to the burner without swirler. The study indicates that the swirling flow achieves a low emission of CO.

Table 5. CO emission with different fuel jet diameter for constant M_f = 0.000035 kg/s.

Equivalence ratio Φ	CO (ppm) Jet diameter=0.8 mm	CO (ppm) Jet diameter=1.1 mm	CO (ppm) Jet diameter=1.3 mm
2.66	39	27	25
1.33	37	25	24
0.89	46	28	32
0.66	49	40	45
0.53	59	64	69

Three fuel jets of diameter 0.8, 1.1 and 1.3 mm are examined for a constant mass flow rate of fuel M_f =0.000035 kg/s to determine the effect of the fuel jet diameter on the CO emission. Table 5 shows the observations of CO emission at various equivalence ratio. Figure 9 shows the CO emission for different fuel jet diameters with variation in equivalence ratio. It is observed that in all cases, the curves confirm the general pattern of those shown in Figure 8 (a) and (b).

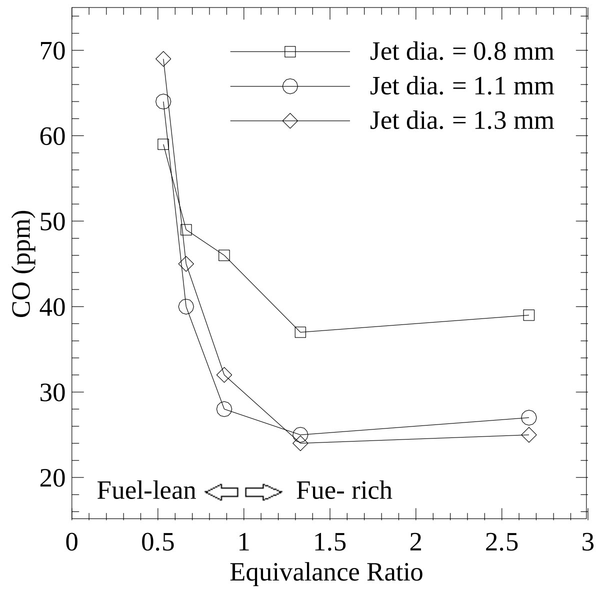


Figure 9. Variation of CO for different fuel jet diameter for M_f = 0.000035 kg/s.

As observed in Figure 9, the emission of CO is significantly affected by the variation in the diameter of fuel jet. The emission of CO decreases with the increase of the fuel jet diameter for the constant mass flow rate of the fuel. The curves for fuel jet diameter of 1.1 and 1.3 mm are comparable. The CO emission gradually decreases from the fuel-rich regime to the fuel-lean regime and then suddenly increases. As the diameter of the fuel jet increases, the velocity of the fuel decreases. This increases the residence time of the combustion products in the flame regime, which ensures complete combustion of the fuel. Therefore, a reduced CO emission level is observed in a fuel-rich regime with a larger diameter of fuel jet.

CONCLUSIONS

The present research aims to investigate the combustion characteristics of LPG diffusion flame in a tube type burner. The important findings of present research work can be summarized as follows;

- The fuel and air velocities have a strong influence on the appearance of the LPG diffusion flame. For a constant fuel velocity, blue zone increases with increased air velocity and luminous zone decreases. Diffusion flame with swirl is wider, shorter and more stable.
- The SFLF increases with increasing air velocity at a constant fuel velocity, which indicates the reduction of soot formation in the diffusion flame. This is because of the higher strain rate between the fuel and air streams, which results in an elongated blue zone due to enhanced premixing between air and fuel. SFLF increases with reduction in fuel velocity.
- The blowoff velocity of the diffusion flame increases with increasing fuel velocity. The swirl increases the stability limits of the diffusion flame in a tube type burner.
- The CO emission level reduces when the swirler is used. CO emission decreases as the angle of the swirler vane increases. Swirler with 45° vanes achieved the lowest CO emission of 30 ppm at $\Phi = 1.3$. CO is found higher in the diffusion flames with and without swirl at $\Phi \leq 0.7$, indicating incomplete combustion. The minimum value of the CO emission occurs near the stoichiometric condition.

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