EXPERIMENTAL INVESTIGATION ON LIFT-OFF, BLOWOUT, AND DROP-BACK IN PARTIALLY PREMIXED LPG OPEN FLAMES IN TUBULAR BURNER

by

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The higher pollutant level in non-premixed combustion and safety issues pertaining to premixed combustion can be counteracted by partially-premixed mode of combustion. The partially premixed flames exhibit the benefits of both premixed and non-premixed flames. Partially premixed flames enhances complete combustion leading to reduced soot formation and hence lower emission. However, the equivalence ratio plays an important role in the stability of such flames. This paper reports the experimental investigation on the flame characteristics and stability of partially premixed LPG-air flames in tubular burner. The stability curve obtained for the base case without any secondary flow shows that the velocity at lift-off, drop-back, and blowout increases with increasing equivalence ratio. In the presence of secondary co-flow air, the lift-off and blow off velocity decreases compared to base case indicating poor stability due to extensive flame stretch leading to aerodynamic quenching. The experimental results show that the velocity of flow at lift-off, blowout, and drop-back are higher in the presence of secondary swirl air than the base case. Co-swirl air increases the stability due to better mixing at the flame base with increased residence time. Flame stability deteriorates with co-flow air as co-flow strains the flame boundary due to flame stretch.

Key words: *partially premixed flames, equivalence ratio, lift-off, blowout, drop-back*

Introduction

The burners used in many applications employ flames which operate in premixed and non-premixed mode of combustion. There are many practical situations where the mode of combustion is partially premixed combustion. Partial premixed combustion is encountered in many applications including Bunsen burners, staged combustors, gas turbine combustors, and Diesel engines. Partially premixed flames (PPF) are used where non-sooting, stable and safe combustion is essential. Non-sooting and low pollution technologies that are safe are important to address the current energy crisis and stringent emission norms [1-4]. The burners used for domestic and industrial applications employ premixed, non-premixed combustion or combination of both. In premixed mode of combustion, the flames are non-luminous, non-sooty, and short. However, occurrence of flash back prevails due to the mismatch between the port velocity and the burning velocity causing safety issues. Contrarily, in non-premixed or diffusion mode, though safety issues due to flash back does not exist, the flames are highly luminous and

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sooty resulting in huge heat loss due to radiation and produces more pollutant due to incomplete combustion. Partially premixed type of combustion is a combination of both and is used in applications such as Bunsen burners, staged combustors, gas turbine combustors, and Diesel engines. In partially premixed combustion, a stream of fuel mixed with a sub-stoichiometric amount of oxidizer (primary air) that exhibits the combined advantage of both premixed and diffusion flames. The sub-stoichiometric amount of air used for premixing (primary aeration) depends on the type of fuel and the application. However, the stability of PPF can be ascertained only for a range of equivalence ratio and beyond that the flame becomes unstable getting detached from the burner and eventually blows out [5, 6] causing incomplete combustion and poor burner efficiency. Depending upon the design and operating conditions, it may sometimes result in causing destruction of the burner system and human injuries due to the accumulated vapour cloud that are flammable [7]. To overcome this issue and to achieve complete and stable combustion of jet flames, co-flow or co-swirl air enveloping the central jet is conventionally used [8]. However, the stability with the secondary flow can also be ascertained for certain applications and for certain operating conditions.

Flame characteristics and stability

Flame instabilities blow-off, flash-back, lift-off, blowout, and drop-back situation encountered in open tubular burner flames have been extensively published in [9-11]. The phenomenon of flame flash back occurs when the gas-flow velocity (port velocity U_P) is less than laminar burning velocity U_L. For $U_P > U_L$, the flame lifts off from the burner rim and may eventually blows off. The balance in the local flame burning velocity and flow velocity at the flame base causes the flame jet to burn stably. However, when this balance is disturbed, with increasing flow velocity, the flame lifts off and eventually blows out and blow off. The spectroscopic studies proposed that at the base of the jet flame, air and fuel are premixed by the process of inter-diffusion, so that the downward velocity of the premixed flame formed at the base counteracts with the upward flow velocity, thus preventing flame lift-off [12]. It has been explained that in a lifted jet- flame, the flow at the flame base becomes turbulent due to the mixing of air entrainment into the flame base, and that the flame element at the base burns at a speed corresponding to turbulent burning velocity [13].

There are circumstances where the flame blows off without lifting off and this depends on mixture strength and port velocity. A comprehensive study on flame stretch theory explained the blow-off phenomenon which states that flame extinction occurs due to the extensive stretching of the flame boundary due to the steep boundary velocity gradient at the burner rim [14]. This process of flame extinction is known as aerodynamic quenching which causes the flame front to lose heat to the unburned mixture, and it gets extinguished due to severity of aerodynamic quenching. The study indicated that rich flame is capable of withstanding higher port velocity at incipient lift compared to lean flame. The secondary combustion effect at the stabilization zone releases additional energy at the flame base. The entrainment of oxygen from the ambience at the flame base offsets the heat loss caused by aerodynamic quenching [8].

It has been observed that the flame blowout occurs due to local extinction of the flame-lets caused by sufficiently large strain rates in the flow [15]. Few researchers have presented premixed model of turbulent burning velocity to describe lifted jet-flames and emphasized the fact that the flame propagation occurs around the periphery of the large eddies and that in the intermittent region, these are often too fuel-rich in their core to be flammable and that flame jet stability is affected by the large eddy structure of the jet at the region of flame stabilization [16].

Flame stability in a cross-flow conditions for burners operating in vertical and horizontal configurations was studied in a quiescent ambience [17]. They highlighted that for fuel rich conditions, cross-flow and buoyancy effects of hot gases enhance flame stability in a horizontal configuration. The stability study on the characteristics of rim-attached open premixed flames in swirling air streams showed that the blow-off velocities are higher in the presence of swirl air in the secondary stream. An experimental study at atmospheric and sub atmospheric pressures reported that the blowout limit curve shrinks with decreasing ambient pressure [18]. A imaging study of methane nitrogen flames at blowout condition have been studied and the flame images obtained from experiments with diluted-methane flames indicate that the diffusion flame shortens and disappears as the flame proceeds towards blowout [19].

A study with air dilution carried out observed for a given jet velocity, air-dilution increases the lift-off height because of an increase in the stoichiometric mixture fraction value, which usually resides in regions with higher velocity [20]. It has also been observed that the difference in the flame leading edge and the main combustion zone is found to be larger in the highly diluted cases. A similar study using a CFD tool on the lift-off and blowout behavior of non-premixed syngas flames focussing on flame characteristics has been published [21]. A detailed study on the flame characteristics on partially-premixed methane-air jet flame were performed for different fuel flow rates and equivalence ratio. The results showed that the average height, flame length and flame base area decreased while the lift-off distance increased with the amount of air injected [22].

Motivation and objectives

Flame stability and its characteristics have been studied extensively using various burner configurations, operating conditions and fuel. The factors affecting flame stability has been thoroughly studied by many researchers. The stability has been found to depend predominantly on the inlet conditions such as flow rate and mixture strength. Though many investigations were carried out on partial premixed combustion, not many have reported the effect of secondary or coaxial flow stream on flame stability and energy release. This paper aims at carrying out an experimental study on PPF with secondary flow to collect stability data of partially premixed LPG air flames.

The general objective of the present work is to study the stability of LPG air jet flame in a co-axial tubular burner. The specific objectives of this experimental study are:
– to study the stability of flame for a range of equivalence ratio,
– to study the effect of equivalence ratio on flame characteristics such as flame color and length, and
– to study the effect of secondary flow on flame stability.

Experimental work

The experiments on the PPF are carried out in an axisymmetric tubular co-flow burner as shown in fig. 1. Figure 1(a) shows the experimental burner used. The mixing tube at the centre of the burner is 9.5 mm inner diameter and 2.5 mm thick.

The effect of secondary flow on flame stability and flame characteristics has been studied by adding a secondary stream through the annular gap between the central mixing tube and the outer tube. A nozzle fitted at the mouth of the outer tube provides a 10 mm annular gap between the concentric pipes. The flow passage of the outer tube is adequately long to ensure streamlined flow. The fuel gets premixed with the primary air in the central tube and enters the flame zone. The secondary flow used in this study is only air. The LPG is used as fuel and dilut-

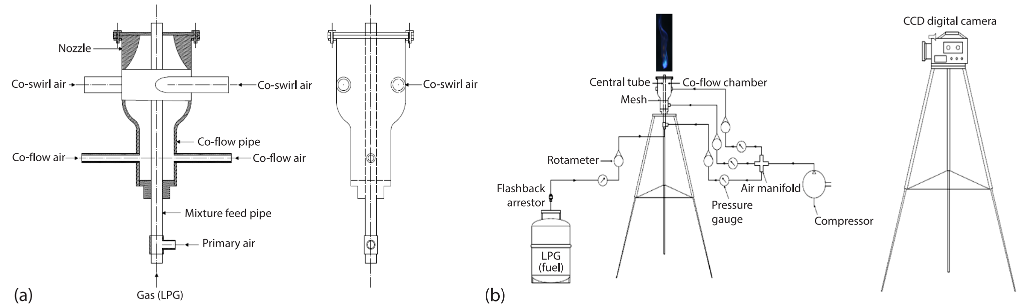

Figure 1. (a) Schematic of co-flow tubular burner and (b) schematic of experimental test rig

ed over a range of equivalence ratios. The fuel and air-flow rates are metered separately using rotameters and the burner feed pressure is regulated using pressure regulators. Air is supplied at a uniform rate from a compressor. The schematic of the experimental rig is shown in fig. 1(b).

The present investigation focuses on the flame characteristics and stability of partially premixed LPG air flames in an open tubular burner with and without secondary air. Three cases of experiments were carried out:
– with only primary flow without secondary air (base case),
– with secondary co-stream of air (co-flow case), and
– with secondary swirl stream of air (co-swirl case).

All the cases were carried out with varying primary aeration and hence the equivalence ratio. The flame characteristics and stability are obtained from the high quality images captured using digital camera.

Experimental run

The stability limits in operating the experimental tubular burner in partial premixed mode has been carried out with liquefied petroleum gas. At first a certain amount of fuel, Q_{fuel}, is passed through the main tube and is burnt as a pure non-premixed flame. A metered quantity of primary air (sub stoichiometric) is passed through the main tube and mixed with the fuel. The flow rate of primary air, Q_{air}, is increased up to a point where the flame starts to flutter off the burner mouth which is considered as lift-off (incipient). The instability is due to the dynamic imbalance created because of the mismatch between the flame burning velocity and flow velocity (port velocity). The flame lift-off velocity in this study is the velocity at the condition when the flame base just begins to flutter but not detached from the burner mouth completely. The flow rate of air is further increased until a point where the flame blowout is observed. When the flame blows out, the flow rate of air is decreased so that the flame drops back and a seated flame is again observed which is termed as the flame drop-back. The velocity corresponding to lift-off, blowout and drop-back are observed at varying mixture strength and port velocity. The secondary air stream is introduced through the outer tube to study the effect of secondary air on the stability of the flame at the lift-off, blowout and drop-back conditions. The study on the effect of secondary stream has been done with co-flow air (co-flow case) and co-swirl air (co-swirl case). The swirl component in the secondary stream has been induced by letting the flow in the tangentially opposite direction in the coflow tube. The stability tests are carried out at different fuel and air-flow rates. Each experimental observation is repeated three times and the data obtained are found to be reproducible within ±4% variation.

The port velocity U_P and equivalence ratio, ϕ, for a port area A_P are calculated:

$$U_P = \frac{Q_{air} + Q_{fuel}}{A_P} \tag{1}$$

$$\phi = \frac{\left(\dfrac{Q_{fuel}}{Q_{air}}\right)_{actual}}{\left(\dfrac{Q_{fuel}}{Q_{air}}\right)_{stoichiometeric}} \tag{2}$$

The experimental parameters are given in tab. 1.

Table 1. Experimental parameters

Burner	Co-axial tubular burner
Operating pressure	Atmospheric pressure
Fuel	LPG
Fuel flow rate	0.21 m^3 per hour
Co-flow rate, V_{c1}	1.84 m^3 per hour
Co-flow rate, V_{c2}	5.29 m^3 per hour
Co-swirl rate, V_{s1}	3.33 m^3 per hour
Co-swirl rate, V_{s2}	5.29 m^3 per hour

Results and discussions

Experimental results on the stability tests are discussed in this section. Figures 2-5 shows the photographic images of partially premixed LPG air flames at incipient lift-off, blowout and drop-back for base case and with co-flow or swirl-air cases. Figures 2(a) and 2(b) show the attached and lifted flame and fig. 2(c) shows the flame at drop-back condition while burning in the quiescent atmosphere for a fuel flow rate of Q_{fuel} = 0.21 m^3 per hour.

The blue portion above the flame base is seen to be shorter in the case of drop-back flame compared to the stable flame before lift-off. The dense blue color of the lifted-flame base is due to the nature of premixed turbulent combustion [14].

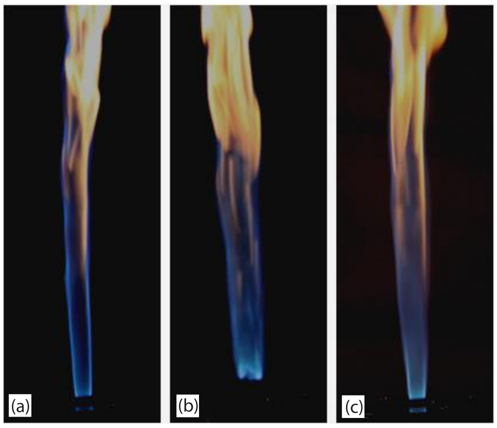

Figure 2. Attached, lifted, and drop-back flames in quiescent atmosphere, Q_{fuel} = 0.21 m^3 per hour

Figures 3(a) and 3(b) show the seated and lifted flames in the presence of co-flow with flow rate, V_{c1} = 1.84 m^3 per hour. Figure 3(c) shows the lifted stretched flame that blow off with a slightest increase in port velocity. In this case, drop-back could not be observed because of the extensive aerodynamic stretch imposed by the co-flow stream. The flame boundary gets over strained leading to quenching. Therefore, beyond fig. 3(c), the stretched, detached flame rises and immediately blows off.

Figure 4 shows the stable flame operating at Q_{fuel} = 0.21 m^3 per hour with swirl flow rate, V_{s1} = 3.33 m^3per hour and fig. 5 for swirl flow case with swirl flow rate, V_{s2} = 5.29 m^3 per

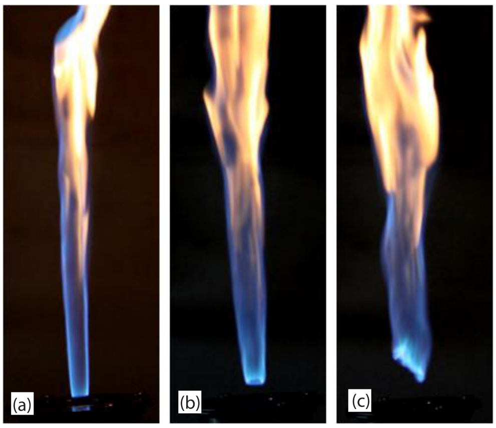

Figure 3. Attached and lifted flames in the presence of co-flow, V_{c1} = 1.84 m^3 per hour

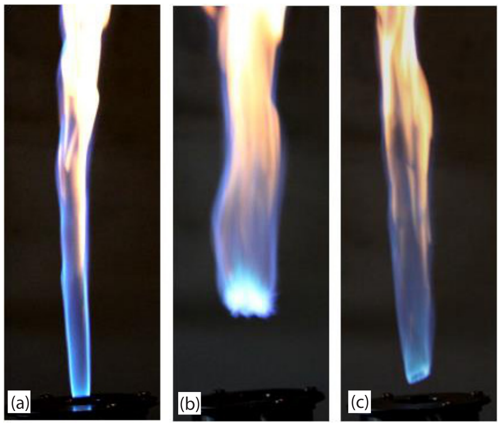

Figure 4. Attached, lifted and drop-back flames in the presence of swirl Q_{fuel} = 0.21 m^3 per hour for V_{s1} = 3.33 m^3 per hour

hour, respectively. Beyond capturing fig. 4(b), flame drop-back has been observed as shown in fig. 4(c).

Figure 5. exhibits the same case with a higher swirl rate, V_{s2}, where it operates at a higher port velocity of around 12 m/s. The lift and blowout velocity are found to be higher than base case, demonstrating better stability. However, drop-back was not possible at higher swirl.

Figures 2(a), 3(a), and 4(a) are stable (seated) flames just before flame incipient lift. The lifted flame, though detached from the burner rim, stabilizes itself at a point downstream and this stabilization is found to be better at higher equivalence ratio for all the three cases and is attributed to better mixing of air and fuel.

The stability curve for the base cases (without secondary flow) and with co-flow and co-swirl is shown in figs. 6-8. The stability diagram is a plot that relates port velocity and equivalence ratio. Figure 6 shows the conventional stability diagram of PPF issuing from the central pipe into a quiescent atmosphere (base case). The observations and trends observed in this study on flame blowout with coflow is similar to the trends available in the existing literature [23-25] for base and swirl cases.

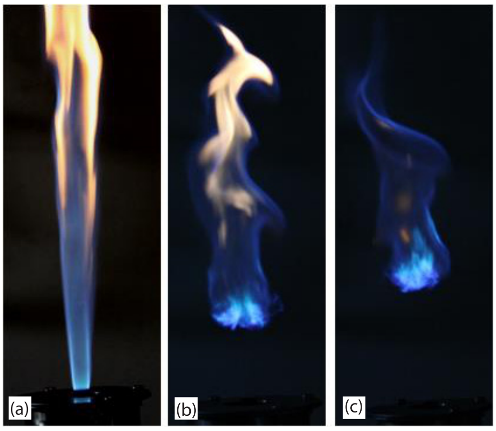

Figure 5. Attached, lifted and blowing out flames in quiescent atmosphere, Q_{fuel} = 0.21 m^3 per hour for V_{s2} = 5.29 m^3 per hour

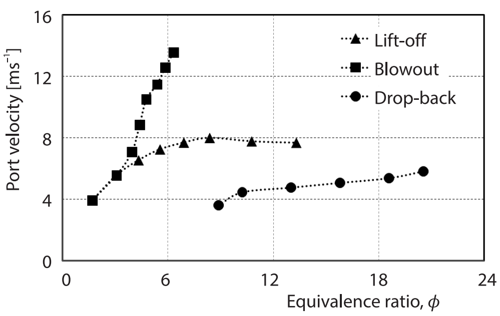

Figure 6. Stability diagram for base case (without secondary flow)

Figure 6 shows the stability diagram of PPF in the presence of co-flow air with flow rate V_{c1} = 1.84 m^3 per hour and V_{c2} = 5.29 m^3 per hour. With, co-flow, it is not possible to observe drop-back of flame on the port. Figure 8 presents the stability diagrams of flame with external swirl-air with flow rate V_{s1} = 3.33 m^3 per hour and V_{s2} = 5.29 m^3 per hour. These diagrams demonstrate that the lift-off and blowout velocities with co-swirl are higher due to increased residence time. The drop-back velocity of flames with co-swirl, V_{s1}, is found to be higher than flame without co-swirl situation. At higher swirl intensity, it was difficult to observe drop-back condition, as lifted flames immediately blew-off (referred to as lift-blow-off) and flames became unstable at higher fuel flow rates. Another clear observation is that the mean flame lengths decreased with the premixing level and the lift-off distance increased with equivalence ratio. Also, the standoff distance (distance between the burner port and the detached stable flame) of the flame increases with equivalence ratio and the results complement the results obtained in the existing literature [26, 27].

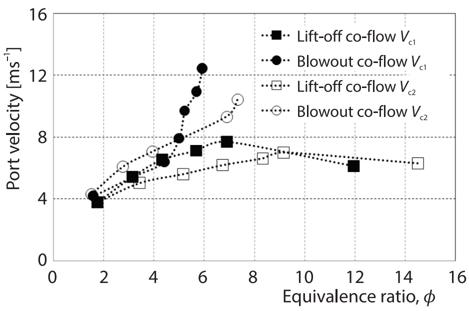

Figure 7. Stability curve for partially premixed flame with co-flow stream (V_{c1}=1.84 m^3 per hour and V_{c1} = 5.29 m^3 per hour)

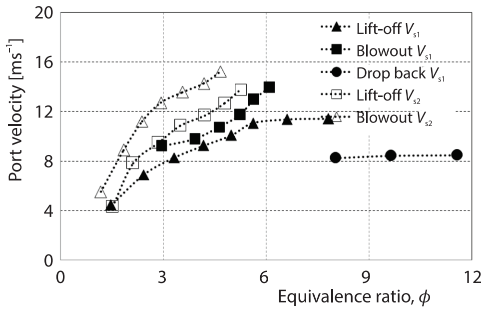

Figure 8. Stability curve for partially premixed flame with co-swirl stream (V_{s1} = 3.33 m^3 per hour and V_{s2}= 5.29 m^3 per hour)

Figures 9 and 10 compares the stability data on lift-off and blowout observed for all the cases, respectively. These results clearly show that stability is rendered poorer with co-flow, while co-swirl increases flame stability.

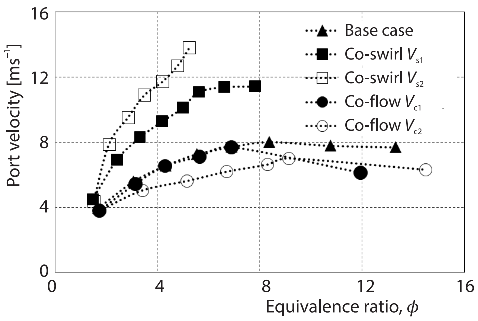

Figure 9. Comparison of flame lift-off velocity without and with secondary stream

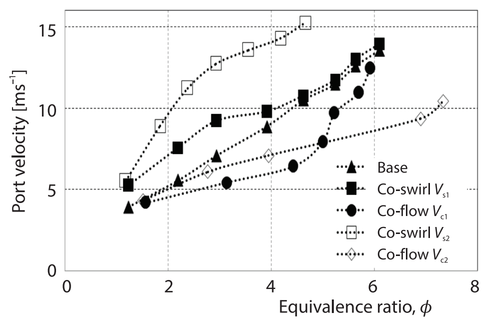

Figure 10. Comparison of blow out velocity without and with secondary stream

The observed trends can be explained it is valid that swirling air increases residence time for the reacting mixture comprising of hot fuel- rich product gases and swirl-air around the flame base. With higher residence time the severity of aerodynamic quenching at the flame base is reduced, hence flame stability is improved. In contrast, the deteriorated stability with co-flow air is attributed to the increased aerodynamic flame stretch due to co-flow stream. The stability curve shows that the stable operating range of the burner is higher with co-swirl air than co-flow air. The results obtained from the present study are in agreement with the results obtained from the computational study for the same burner configuration and operating conditions [4].

Conclusion

Experiments on partially premixed LPG air tubular flames have been carried for a range of equivalence ratios. Three sets of experiments have been carried out without secondary stream, with co-flow stream and with co-swirl stream of air. With the amount of partial premixing, the mean flame lengths decreases; while the lift-off distance increases with equivalence ratio as observed from the flame images. The phenomena of lift-off, blowout and drop-back has been experimentally observed. The stability curve plotted shows the following results. The stability of the flames in the presence of co-flow air is found to be poorer than flame with no co-flow air and is attributed to flame quenching due to flame stretch. The excessive stretching due to the streamlined co-flow can lead to local quenching of flame front causing drop-back not possible. In contrast, the stability is found to be better in the presence of co-swirl air. This is due to better mixing of air and fuel at the flame base with increased residence time. The results show that the lift, drop-back and blowout velocities are found to be higher for the flames operating with higher swirl and least for high co-flow rate. Stability data obtained are found to be in line with the data available in literature. The data obtained from the present study on flame characteristics and stability will have implications in the design of atmospheric aerated LPG burners. The merged stability diagrams for all cases shows that the stable operating range of the burner is higher with co-swirl air than co-flow air.

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