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Experimental Study of Characteristics of LPG-hydrogen Jet Diffusion Flames

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ABSTRACT

This study presents the experimental investigation of flame length, lift-off velocity and lift-off heights of jet diffusion flames fuelled by a mixture of Liquefied Petroleum Gas (LPG) and hydrogen. LPG is commonly used domestic, automotive and industrial fuel that is around two times heavier than air. When hydrogen is added to LPG, significant flame control and lift-off stability is achieved. Results show that, with the addition of hydrogen, the flame length is decreased and lift-off occurs at higher fuel flow rate; the lift-off height also decreases. Increased heating value, increased diffusivity and increased reactivity are the reasons for increased stability.

Key words: LPG, Hydrogen, jet diffusion flame, flame length, lift-off height, heating value

INTRODUCTION

Industries depend heavily on hydrocarbon fuel based combustion systems. However, issues such as lower flame stability, lower ignitability and emission characteristics of hydrocarbon fuels form the major problems which require attention. Since, the emission regulations and fuel economy standards have become stringent, there is a pressing requirement for alternative fuels and clean combustion systems. Among the clean fossil fuels, LPG has attracted a lot of interest, as it can be liquefied in a low pressure range of 0.7-0.8 MPa, at atmospheric temperature. It also has a higher calorific value when compared to other commercial fuels. However, Lee and Ryu (2005) have reported that the combustion stability of LPG is affected as the equivalence ratio decreases in the fuel-lean region. This instability can be overcome by using a choice of hybrid fuels, where alternative fuels are added in varying compositions. In this respect, hydrogen has emerged as one of the most viable fuels, due to its wide range of flammability limits, lower requirement of ignition energy and higher flame speed. Numerous researchers around the world have preferred hydrogen for this purpose because it can be produced from abundant sources and is environmentally clean. Addition of hydrogen to LPG makes the mixture easier to ignite and also improves the combustion and emission characteristics.

Choudhuri and Gollahalli (2000) studied the characteristics of hydrogen-hydrocarbon mixtures in diffusion flame mode surrounded by a slow co-flowing stream of air. They reported that increasing the hydrocarbon content enhanced the flame length. Later, Choudhuri and Gollahalli (2003) also characterized the hydrogen-hydrocarbon turbulent jet diffusion flames in terms of flame length. They found that the flame length reduces with hydrogen addition in the fuel stream.

Gamany *et al.* (2012) carried out a Computational Fluid Dynamics (CFD) study to predict flame stabilization of a non-premixed turbulent jet using swirling motion. They reported a marked increase in flame stability due to the swirling motion. In this work, the authors have tried to achieve the flame stability by addition of hydrogen along with the fuel. Kumar and Mishra (2008) experimentally investigated the effect of hydrogen addition on visible flame length in a LPG-hydrogen laminar diffusion flame, in addition to other parameters. They reported a marginal reduction in flame length with addition of hydrogen, in a range of flow rates they considered. However, they also reported that the addition of hydrogen up to 20% by volume in the mixture, did not affect the flame length appreciably. When the hydrogen concentration was increased up to 40%, a significant reduction in flame length was reported. This reduction was attributed to the enhanced diffusivity and higher gas temperature. Mishra and Kumar (2008) also carried out a set of experiments to determine the effect of hydrogen addition on flame length when preheated air or preheated air-fuel mixture is used. They reported a reduction in flame length with increasing reactant temperature. Mishra and Kiran (2009) carried out an experimental study to investigate the effect of co-axial air velocity and thickness of a bluff-body on flame stability limits. They observed that the flame gets detached from burner rim at higher velocities and the flame lift-off height increases with increasing fuel flow velocity until the occurrence of flame extinction. Wang *et al.* (2008) carried out a numerical study of hydrogen enhanced LPG and air premixed flames. They studied the variations of adiabatic laminar burning velocity for different equivalent ratios. They reported that the lean flammability limits were extended due to addition of hydrogen. Their results also showed that hydrogen enhanced LPG/air premixed flames were stable for wider range of equivalence ratios. Active research is still being pursued to fully understand the combustion characteristics of LPG-hydrogen mixtures.

From the literature survey presented above, the following summary can be postulated: while various combustion parameters like flame length, flammability limits and emission characteristics have been investigated, the effect of hydrogen addition to LPG, on flame lift-off, has not been adequately investigated. It has also been reported in literature that in general hydrogen has an overall stabilizing effect on the flame structure. This forms the motivation of the current work, where the objectives are to determine the quantitative effects of hydrogen addition to LPG on flame length and lift-off characteristics in jet diffusion flames.

MATERIALS AND METHODS

Figure 1 shows the schematic of the experimental setup. A burner with an exit jet diameter of 0.6 mm is connected to pressurized hydrogen gas cylinder having hydrogen with purity 99.995% and a commercially available LPG cylinder. Commercially available LPG in India has a molecular weight of around 50 to 55. It is around two times heavier than air. It can be assumed to be composed of 60% butane and 40% propane. Pressure regulators are used to control the upstream pressure of these gases. The volumetric flow rate of hydrogen is measured with the help of pre-calibrated hydrogen rotameter. Similarly, LPG flow rate is measured with the help of a pre-calibrated rotameter as shown in Fig. 1. A digital camera, having a capability to capture videos up to a speed on 1000 frames per second, is fixed at a suitable location to capture the digital flame video as well as the shadowgraph images of the resulting flame.

Shadowgraph is obtained by using a light source passed through a slit and a lens. The shadowgraph, which represents the density gradient, is captured by the digital camera. From the shadowgraph image, the thermal plume width, which represents the entrainment zone of a jet through a characteristic visible thermal plume, can be studied.

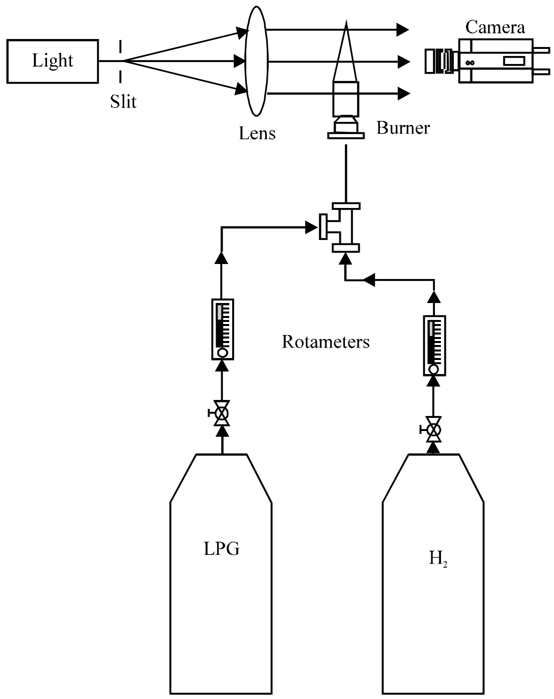

Fig. 1: Schematic of experimental setup

Initially hydrogen gas is cut off from the flow circuit. Flow rate of LPG is gradually varied and for each LPG flow rate, videos of the direct flame and the shadowgraph are recorded at 30 fps for 180 sec. The frames are extracted from each video and the flame characteristics such as visible flame length, plume width and the lift-off heights are extracted by processing the frames using software called image-J. Subsequently, hydrogen is gradually supplied and LPG flow rate is decreased such that the total flow rate is kept constant. Videos are recorded for each case. The total flow rate is also varied. Each experiment has been repeated at least three times to check the consistency. The average flame length, thermal plume width and the flame lift-off heights are then calculated for all cases.

RESULTS AND DISCUSSION

Figure 2 shows the variation of flame height for the cases with different volumetric percentages of hydrogen in LPG-hydrogen mixture. The total flow rate of the mixture is maintained same and two total flow rate cases are shown in Fig. 2. It is clearly seen that as the total fuel flow rate is increased from 3 to 3.5 lph, the flame length increases. Also, the flame height decreases with increasing percentage of hydrogen in the fuel mixture.

The factors which the flame length (L_f) depends on can be given by the following expression (Turns, 2000):

$$L_f = \frac{Q_f}{D_f \ \mathrm{In}\ (1+1/s)} \tag{1}$$

In Eq. 1, Q_f is the total fuel flow rate in $m^3\ sec^{-1}$, D_f is the mass diffusivity of the fuel mixture into air and S is the molar stoichiometric oxidizer fuel ratio. The reason for the drop in the flame

Table 1: Variation of molar stoichiometric oxidizer fuel ratio, mixture molecular weight and fuel heating value with varying hydrogen content in the fuel

Volume of H_2 (%)	H_2 mass fraction	S	Mixture molecular weight (kg/kmol)	Heating value (kJ kg^{-1}) (Turns, 2000)
0	0.046	28	52	50483
15	0.052	24	45	51094
30	0.061	20	37	51952
45	0.075	17	30	53248
60	0.097	13	22	55427

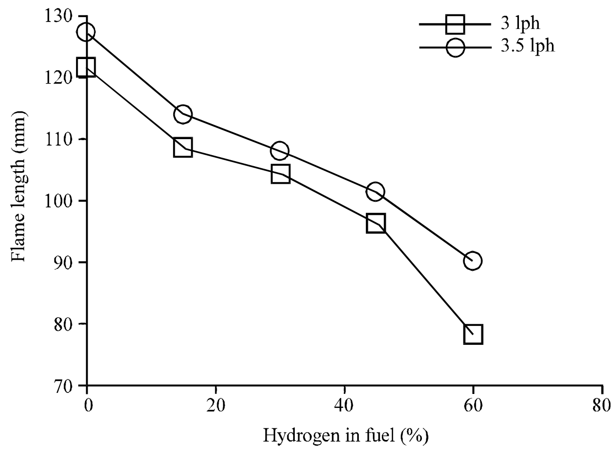

Fig. 2: Variation of flame height with various volumetric percentages of hydrogen in the mixture at total fuel flow rates of 3 and 3.5 lph

height with increased hydrogen content can be explained by noting the fact that when the hydrogen content is increased, the molecular weight of the mixture decreases and due to this the mass diffusivity of the fuel mixture increases; lighter gas has higher diffusivity. Further, the molar stoichiometric oxidizer fuel ratio decreases with increasing hydrogen content. Furthermore, the heating value of the mixture increases which causes an increase in the flame temperature, due to which the diffusivity further increases. These are illustrated in Table 1.

It should be noted that the binary mass diffusivity of hydrogen into air is approximately 0.63 cm^2 sec^{-1} and that of butane into air, is around 0.1 cm^{-2} sec. Therefore, when hydrogen content in the fuel is increased the mass diffusivity of the mixture is significantly enhanced. Due to the increase in the quantities in the denominator of Eq. 1, the flame length decreases as the hydrogen content in the fuel mixture is increased. It can also be noted from Table 1 that the mass fraction of hydrogen is very low. Therefore, a small flow rate of hydrogen causes significant changes in the flame characteristics as a result of increased reactivity and diffusivity of hydrogen. Figure 3 shows the significant decrease in the visible flame height as the hydrogen flow rate is increased. A total fuel flow rate of 3 lph is considered as the flames in this case are attached to the burner rim. The corresponding shadowgraph images are shown in Fig. 4. In the shadowgraph images, the black region at the bottom shows the burner shadow. The maximum intensity (white) lines show the preheat regions in the air (outer white lines) and fuel sides (inner white cone). It is known that when the mixing is enhanced, the preheat line moves away from the flame surface because of the enhanced transport of heat towards the unburned fuel and air sides. Apart from this, a brighter zone is also seen around the inner bright white zones, which represents the

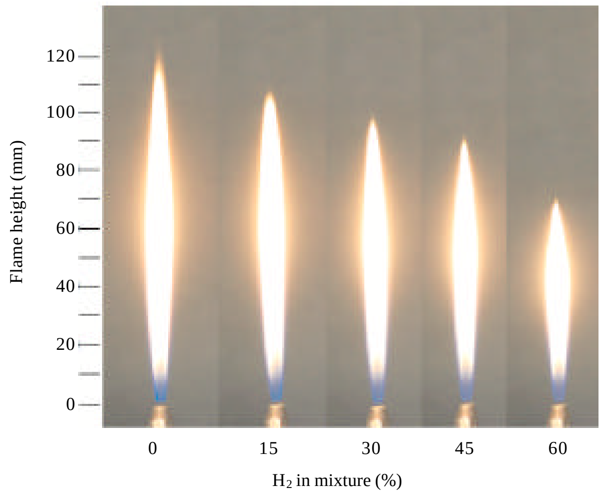

Fig. 3: Flame images at a total fuel flow rate of 3 lph where the flame is anchored to the burner

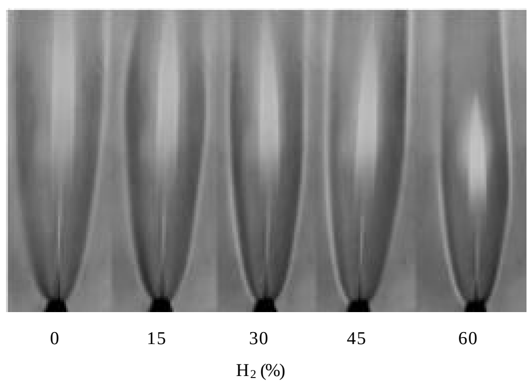

Fig. 4: Shadowgraph images at a total fuel flow rate of 3 lph for different H_2 concentration

luminous flame zone in the direct flame images. As observed in the digital images, the shadowgraphs also show the decrease in the flame height through the luminous zones.

The thermal plume width is the distance between the outer white zones at any distance from the burner exit. This is calculated by processing the shadowgraph frames in image-J software and MATLAB. The thermal plume width in pixel is converted to millimeter using a conversion factor. The conversion factor is found by measuring the number of pixel in a given dimension of a known object. For example, the number of pixels of the outer diameter of the nozzle is calculated as 23. Since the outer diameter of the nozzle is 4 mm, one pixel corresponds to (4/23) mm. The thermal plume is measured within an accuracy of around 0.2 mm.

The thermal plume width is plotted as a function of burner height in Fig. 5, up to a height of 50 mm from the burner exit. Except the 30% hydrogen case, the thermal plume width are almost same for the other cases, especially up to a height of around 20 mm. After this, the 15 and 60% hydrogen cases produces notably higher plume width than the pure LPG case, indicating that the preheat zone for air has moved out due to enhanced mixing. The 45% hydrogen case has almost

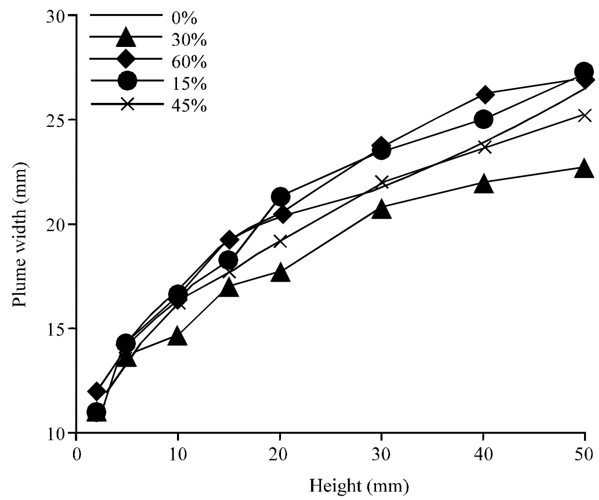

Fig. 5: Variation of thermal plume width along the burner axis for 3 lph for different H_2 concentration

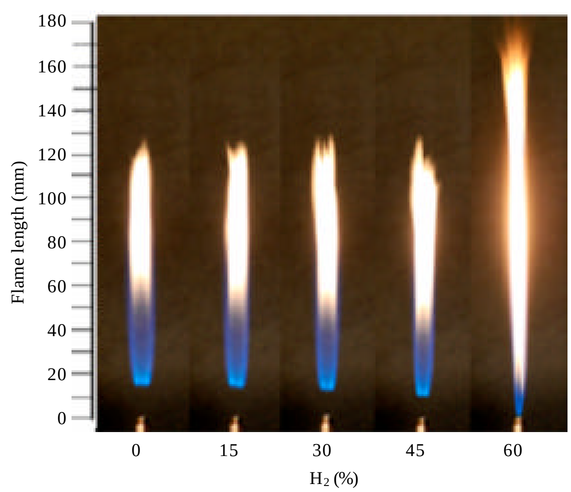

Fig. 6: Flame images at a total flow rate of 7 lph for different percentage of hydrogen in the fuel mixture

same plume width as that of the pure LPG case (0%). It is interesting to note that the 30% case has the least plume width. The variations in the mass diffusivities and the reactivity of the fuel mixture are the combined causes for these trends.

When the total flow rate is gradually increased from 3 lph, at a total flow rate of around 3.8 lph, the flame lifts-off for pure LPG case. This corresponds to a jet exit velocity of around 6.9 m sec^{-1} for 0.6 mm exit diameter. This is termed as lift-off velocity. This flame lift-off is very sudden phenomenon and occurs rapidly. Care is taken in the present study to gradually increase the fuel flow rate so as to capture this initial lift-off velocity. As the hydrogen content is increased in the fuel, it is apparent that the initial lift-off is delayed. Furthermore, it can be observed that when the fuel contains 60% hydrogen by volume, the flame never lifts-off even at the highest flow rate considered in this study.

Figure 6 presents the flame photographs for the case of total fuel flow rate equal to 7 lph. At this high fuel flow rate, as the percentage of hydrogen is increased, the flame lift-off height

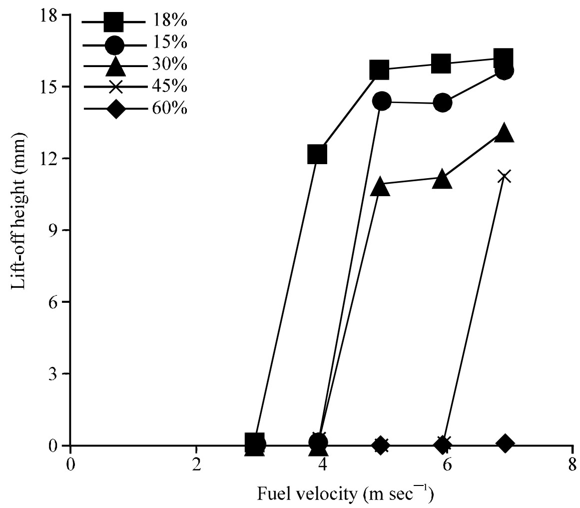

Fig. 7: Variation of flame lift-off height with jet exit velocity for different volumetric percentages of hydrogen

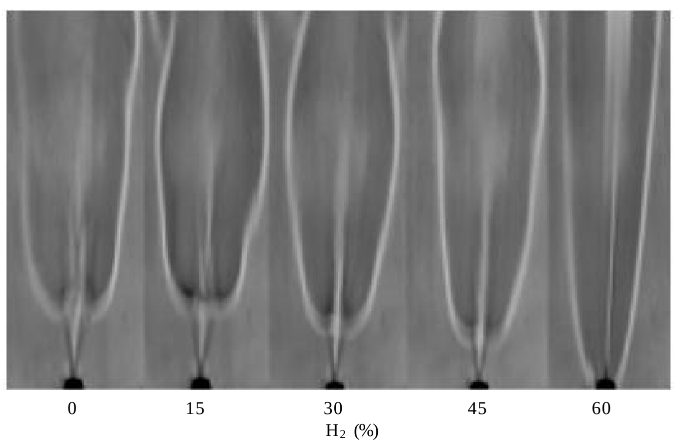

Fig. 8: Shadowgraph images at a total fuel flow rate of 7 lph for different volumetric percentages of hydrogen

decreases gradually. This continues till the percentage of hydrogen in the fuel mixture is around 45%. When the hydrogen content is increased to 60%, the flame stabilizes at the burner rim. It can also be noted from Fig. 6 that, irrespective of the hydrogen content and the lift-off height, the flame height is almost same, around 130 mm, for the all the cases till hydrogen is 45% by volume. This is because of the fact that the lifted flame behaves as partially premixed flame with its bottom zone behaving as a premixed flame with bright blue colored flame zone. Due to fuel richness in the mixture, the later part of the flame is seen to be luminous; the luminosity is much lesser when compared to the pure diffusion flames shown in Fig. 3. It is also noted that the overall blue region in the flame also decreases with the addition of hydrogen.

It can be noted from Table 1 that the heating value increases with hydrogen addition. This results in an increase in the flame temperature due to which the reactivity increases. This higher reactivity and higher diffusivity when more hydrogen is present in the mixture, produces short and stable flames.

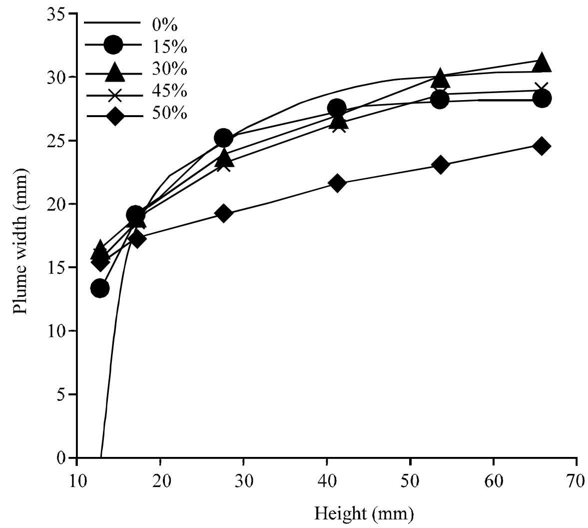

Fig. 9: Variation of thermal plume width along the burner axis for 7 lph for different volumetric percentages of hydrogen

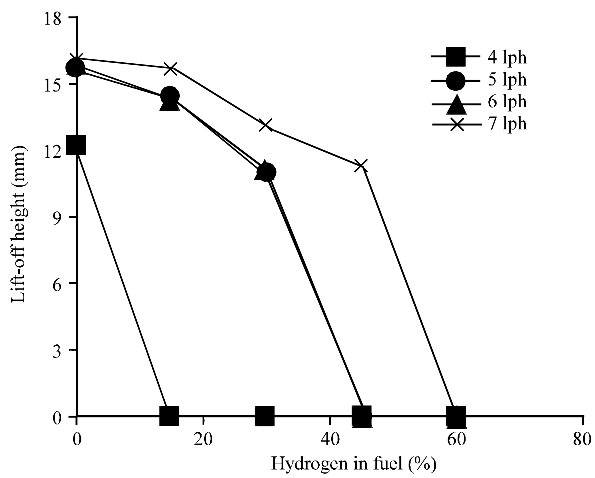

Fig. 10: Variation of flame lift-off height with hydrogen addition for different total fuel flow rates

When the flame anchors to the burner rim due to further hydrogen addition (60% by volume), the flame length increases to around 180 mm. The anchored flame exhibits the behavior of a jet diffusion flame, where the flame length is one of the important characteristics.

The lift-off heights are plotted as functions of the fuel-mixture jet velocity and %hydrogen in the fuel mixture in Fig. 7. The increase in the fuel jet velocity and the decrease in the lift-off heights with increasing percentages of hydrogen in the fuel mixture is apparent from Fig. 7. This indicates increased stability with hydrogen addition.

Figure 8 shows the corresponding shadowgraph images for 7 lph case shown in Fig. 6. The image clearly shows that the thermal plume width and the lift-off height get reduced with increasing hydrogen concentration in the fuel. Figure 9 shows the variation of thermal plume width with respect to height from the nozzle exit. It is seen that the thermal plume is narrower for the 60% hydrogen case, which indicates that the plume width of burner-attached flames are smaller than the lifted flames. This is because the lifted flames are partially premixed in nature and have increased rate of mixing. The effect of total flow rate on lift-off characteristics is shown in Fig. 10. It is clear that as the total flow rate is increased, higher amount of hydrogen is required to produce stable flames.

CONCLUSIONS

This study presents the experimental investigation of flame length, lift-off velocity and lift-off heights of jet diffusion flames fuelled by a mixture of LPG and hydrogen. Jet diffusion flame experiments have been carried out using a burner having 0.6 mm exit diameter. The flow rates of LPG and hydrogen are controlled to have varying percentages of hydrogen in the fuel mixture. Digital flame videos are captured for each case and processed to calculate the visible flame length and lift-off height. When hydrogen is added to LPG, significant flame control and lift-off stability is achieved. Results show that, with the addition of hydrogen, the flame length is decreased and lift-off occurs at higher fuel flow rate; the lift-off height also decreases. The increased heating value, increased mass diffusivity and increased reactivity of hydrogen are the reasons for producing increased stability.

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