Experimental Study of LPG Flames in Different Configurations

S. Muthu Kumaran, Omkar Sanjay Karve, Yashodhan Bharat Kadam and Vasudevan Raghavan*
Department of mechanical engineering, Indian Institute of Technology Madras, Chennai – 600036, India.
*Corresponding author: Email: raghavan@iitm.ac.in, Phone: +91-44-22574712

Abstract

The main objective of this paper is to experimentally study Liquefied Petroleum Gas (LPG) flames in different configurations using shadowgraph and direct images, and to measure plume temperature using thermocouples. Thermal plumes are created by buoyancy effects and they indicate the movement of entraining ambient air towards the flame zone. The entrainment rate and plume structure depend on the initial jet momentum, temperature field and the local air velocity adjacent to the flame. All the experiments have been done in a lab-scale co-flow burner. From shadowgraph images, the plume extents have been studied. The temperature field in the plume is measured using a K-type thermocouple, which provides quantitative data for any model validation. Further, visible flame extents have been measured from direct photographs of flames. Variations of plume width in different burning configurations have been presented and discussed.

Keywords: Liquefied petroleum gas; partially premixed; flame height; shadowgraph; thermal plume

1. Introduction

Liquefied petroleum gas (LPG) is widely used around the globe as cooking and transportation fuels. It is a mixture of several hydrocarbons, chiefly, that of propane and butane. Numerous experimental studies have been reported earlier on LPG flames. Kumar and Mishra [1, 2] measured the visible flame characteristics such as flame length, lift-off height, blow-off velocity and pollutant emissions from pure LPG jet diffusion flames and LPG-H2 flames. Later they also investigated the effect of preheated LPG-H2 mixtures on visible flame characteristics [3]. Shahad and Yassar [4] reported the soot formation and temperature distribution in LPG partially premixed flames. The temperature field in the flame was probed using an R-type thermocouple. However, the level of premixing is extremely low and the flame characteristics resembled those of a diffusion flame. Koli et al. [5] experimentally studied the effects of co-flow and partial premixing of air on LPG flames. They analysed the variation of flame length, soot inception point, flame speed and pollutant emissions with systematic increase in primary and secondary air. Although several visible flame characteristics have been reported earlier, the entrainment region near the burner exit has not been adequately investigated. Further, the temperature data for LPG flames in different configurations are scarce in literature. These form the motivation of this study. The present work focuses on analyzing the entrainment region near the burner exit using shadowgraph technique and temperature field in the thermal plume.

Shadowgraph is a simple technique used to analyse flows with strong density gradients. Since flames exhibit strong density gradients, which arise from temperature and species gradients, shadowgraph technique is extensively used to visualize the flow around a flame. Experimentally determined density gradients (shadowgraph images) can be compared with numerical predicted data. Khan et al. [6] used a numerical model to investigate the structure of CO-H2 diffusion flames. The numerical model was validated by comparing the second gradient of density field from simulations with the shadowgraphs obtained from experiments. Fujisawa et al. [7] studied the role of large-scale structures in flickering co-flow flames. They visualized the high temperature region and soot formation zone from the shadowgraphs of these flames. Yojiro et al. [8] analysed the mixing of fuel-air mixture in a pulse combustion system using shadowgraph
images. They observed that the turbulent eddies generated by the pulsation process enhanced the mixing of fresh mixture and hot gases inside the chamber. Pizzuti et al. [9] investigated the laminar burning velocity and flame propagation of methane-air premixed flames inside a combustion chamber. The burning velocity was determined from shadowgraph images recorded using high speed camera. Yasir et al. [10] studied the instabilities in turbulent non-premixed flames. The shadowgraph images revealed the presence of two modes of instabilities, one from fuel jet and another from the recirculation zones present in the vicinity of bluff body. Xie et al. [11] analysed the variation of burning velocity in laminar flames entrained with coal particles. The burning velocity was determined from cone angle measurements obtained from shadowgraph images.

It is clear from the above studies that the shadowgraph technique is a useful technique to investigate the flow structures and features around the flame zone. No earlier studies have reported shadowgraph images of LPG flames in different configurations and thus, such a study is taken up in this work. This data can be used for validating a numerical model to study LPG flames.

2. Experimental Setup and Methodology

2.1 Rotameter calibration

Since LPG is a multi-component fuel, a straightforward measurement of its flowrate is non-trivial. A basic rotameter, with an uncertainty of ±2%, has been calibrated to indicate the mass flow rate of LPG. A 5 kg LPG cylinder is placed on a precision load cell that can reveal the mass of the cylinder with an accuracy 0.1 grams. For a given setting in the rotameter, the amount of LPG transported through the rotameter in a time duration of 30 minutes has been measured using the load cell. This is repeated thrice and the average mass loss rate is estimated. A calibration chart is obtained for mass loss rate versus rotameter readings. The maximum uncertainty in measuring the LPG flow rate is estimated as ±0.274 g/h. Figure 1 shows the calibration chart.

![Calibration chart for LPG rotameter](https://example.com/calibration_chart.png)

2.2 Details of the setup

The experiments are conducted on a lab-scale co-flow burner. The co-flow burner has a fuel tube of 10 mm diameter surrounded by a co-flow tube of 42 mm in diameter. Both the fuel and co-flow tube are provided with steel mesh to enhance mixing as well as to avoid flashback. LPG is supplied from a domestic LPG cylinder. Air from a compressor storage tank has been used for meeting the primary and secondary air supply. Filters and water separation units have been used to remove dust and moisture from the air. The flow rate of secondary air is measured by calibrated rotameter. The uncertainty in the rotameter is ±2% over the full range, which corresponds to a maximum uncertainty of ±22.15 g/h. The primary air flow rate is controlled by mass flow controller (MFC) with an uncertainty of ±0.1%. The maximum uncertainty in the equivalence ratio of the mixture is estimated as ±0.03. The fuel and primary air mixture is supplied to the burner through a mixing chamber. Figure 2 gives a schematic of the experimental setup used in the present study. Table 1 provides the list of experiments conducted in the present study.

| Table 1: Flow rates considered in experiments | y = -0.0325x² + 1.0237x
R² = 0.9986 |
<table>
<thead>
<tr>
<th>Type</th>
<th>Fuel (g/h)</th>
<th>Primary air (%)</th>
<th>Co-flow air (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jet diffusion flames</td>
<td>10, 12.9, 15.5, 17.9</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Jet diffusion flames in co-flow</td>
<td>10</td>
<td>-</td>
<td>Stoichiometric, 200, 300, 400</td>
</tr>
<tr>
<td>Partially premixed flames</td>
<td>10</td>
<td>10, 20, 30, 40, 50</td>
<td>-</td>
</tr>
<tr>
<td>Partially premixed flames in co-flow</td>
<td>10</td>
<td>10, 20, 30, 40, 50</td>
<td>100</td>
</tr>
</tbody>
</table>

Figure 2: Schematic of the experimental setup

2.3 Temperature measurement

Temperature measurements have been carried out in the stable plume region, without probing into the primary flame zone. Here, the temperature is comparatively lower than that in the flame zone and thus, a K-type thermocouple has been used. The thermocouple has a wire diameter of 0.25 mm and a bead diameter of 1 mm. The thermocouple bead is present inside a stainless-steel sheath. The error in the measured temperature is ±20 K. The thermocouple is connected to a data logger (Agilent, 34972A) and the readings are recorded. Readings are taken at an interval of 500 milliseconds for one minute and have been averaged. The thermocouple is attached to a three-dimensional traverse system (Fig. 2) for accurate spatial measurement. Both axial and radial temperature profiles are measured for different flame configurations. All the experiments are repeated three times.

2.4 Temperature correction

Thermocouples are subjected to heat loss due to conduction, convection and radiation. Hence the actual gas temperature is higher than the temperature recorded by the thermocouple. Martins et al. [12] suggested that conductive losses may be neglected in thermocouples with length 160 times the wire diameter. The length of the thermocouple is more than 70 mm and the wire diameter is 0.25 mm. Following this, the conductive losses are neglected in the present study. However, losses due to convection and radiation are significant and corrections are made for these.

Bradley and Mathews [13] suggested that the losses due to convection and radiation can be corrected using following correlation.

\[
T_g = T_t + \frac{\varepsilon_t \sigma T_t^4}{h_t},
\]

where \(T_g\) represents the gas temperature (K), \(T_t\) is the temperature measured by the thermocouple (K), \(\varepsilon_t\) is the emissivity of the thermocouple, \(h_t\) is the heat transfer coefficient (W/m²K) and \(\sigma\) is the Stefan-Boltzmann constant (5.67×10⁻⁸ W/m²K⁴). The emissivity of the thermocouple is taken as constant equal to 0.22 as suggested by Kaskan [14].

The correlation for the convective heat transfer coefficient is given as [13],

\[
h_t = \frac{1}{\frac{1}{h_{t,ref}} + \frac{1}{h_{t,conv}}},
\]

with \(h_{t,ref}\) and \(h_{t,conv}\) being the reference and convective heat transfer coefficients, respectively.

\[
\frac{1}{h_{t,ref}} = \frac{1}{h_{t,conv}} \frac{1}{h_{t,ref}} + \frac{1}{h_{t,conv}} = \frac{1}{h_{t,conv}},
\]

where \(h_{t,conv}\) is the convective heat transfer coefficient, \(h_{t,ref}\) is the reference heat transfer coefficient, and \(h_{t,ref} = \frac{1}{\frac{1}{h_{t,conv}} + \frac{1}{h_{t,ref}}}\).

The correlation for the convective heat transfer coefficient is given as [13],

\[
h_{t,conv} = \frac{\frac{1}{h_{t,ref}} + \frac{1}{h_{t,conv}}}{\frac{1}{h_{t,ref}} + \frac{1}{h_{t,conv}}},
\]

where \(h_{t,conv}\) is the convective heat transfer coefficient, \(h_{t,ref}\) is the reference heat transfer coefficient, and \(h_{t,ref} = \frac{1}{\frac{1}{h_{t,conv}} + \frac{1}{h_{t,ref}}}\).

The correlation for the convective heat transfer coefficient is given as [13],

\[
h_{t,conv} = \frac{\frac{1}{h_{t,ref}} + \frac{1}{h_{t,conv}}}{\frac{1}{h_{t,ref}} + \frac{1}{h_{t,conv}}},
\]

where \(h_{t,conv}\) is the convective heat transfer coefficient, \(h_{t,ref}\) is the reference heat transfer coefficient, and \(h_{t,ref} = \frac{1}{\frac{1}{h_{t,conv}} + \frac{1}{h_{t,ref}}}\).
\[ Nu = \frac{h_D}{k_g} = 0.42 \text{Pr}^{0.2} + 0.57 \text{Pr}^{0.33} \text{Re}^{0.5} \]  

Equation (2), is valid for Reynolds number in the range 0.01<Re<10^4. \( D \) is the bead diameter (m), \( k_g \) is the thermal conductivity of the gas (W/mK). The thermal conductivity is calculated as,

\[ k_g = 3.75 \times 10^{-5} T_c + 0.04 \]  

Prandtl number (Pr) of the fluid is calculated as,

\[ Pr = \frac{\nu}{\alpha} \]  

where \( \nu \) is the kinematic viscosity of the fluid (m^2/s) and \( \alpha \) is the thermal diffusivity of the fluid (m^2/s) and are calculated as a function of temperature using kinetic theory of gases [15]. The Reynolds number of the flow is calculated as,

\[ Re = \frac{uD}{\nu} \]  

where \( u \) is the velocity of the product gases relative to the bead (m/s). Since velocity measurement just outside the flame zone is tedious as well as expensive, a simplified numerical model has been used to estimate the range of velocities in the plume region, where temperature measurement has been carried out. In these simulations, single step global reactions for propane and butane oxidation are considered. Simulations are done using a commercial software ANSYS-FLUENT version 16.1. These simulations cannot reveal the flame structure, since a short chemical kinetics mechanism is required for accurately determining the flame zones. However, these simulations can give an estimation of the range of velocities in the plume region.

2.5 Shadowgraph setup

Figure 3 gives a schematic of the shadowgraph setup. Light emitted from a source is concentrated using a condensing lens. This concentrated light is made to fall on an aperture. The aperture acts as a point source with adjustable vertical slit. A parabolic mirror of 150 mm diameter is placed at a distance equal to its focal length from the aperture. The parallel rays originating from the mirror passes through the test section (flame) and forms an image on the screen. An A4 sheet (100 GSM) fixed to a flat board is used as a screen. The strength of the source and the aperture is adjusted to get a clear image of the shadow. This image is then recorded using a high definition camera.

![Shadowgraph setup diagram](image)

A – Light source       B – Condensing lens       C – Aperture
D – Parabolic mirror   E – Test section       F – Screen       G – Camera

Figure 3: Schematic of shadowgraph imaging system

3. Results and Discussion

3.1 Image processing

High definition shadowgraph images are captured using Nikon HD camera with 8-bit grayscale resolution (256 gray levels). The images are processed using an image processing software ImageJ. The plume width is determined from the grayscale intensity plots of the shadowgraphs. The intensity plots are also obtained from shadowgraphs using ImageJ. The intensity is plotted along the radial direction at three different axial locations, \( z = 0.5d \), \( z = d \) and \( z = 1.5d \), where \( d \) represents the diameter of the fuel tube. The intensity value 255 corresponds to complete white color, while 0 corresponds to complete black. Depending on the light intensity in the shadow the grayscale value varies in the range from 0 to 255.
Figure 4(a) shows an intensity plot for the case of a simple jet diffusion flame. It is observed that the grayscale intensity peaks at two radial locations on either side of the axis (located at 0 mm). These peaks correspond to two relatively white lines in the shadowgraph. The length between the peaks is a measure of the thermal plume width in the flame. A similar intensity plot is generated for a partially premixed flame as shown in Fig. 4(b). Here, three distinct peaks are visible with one more around the center of the burner. The two peaks on either side represents the entrainment region as discussed for Fig. 4(a). The third peak around the axis of the burner represents the premixed inner core of the flame. It should be noted that the peak intensity represents the preheat zone in the flame. For a jet diffusion flame this zone is formed on the air side. In case of a partially premixed flame, this zone is formed on both fuel and air sides of the flame. This is due to the presence of double flame as a result partially premixing of fuel and air.

![Grayscale intensity plots](image)

Figure 4: Grayscale intensity plots in a (a) pure jet diffusion flame and (b) partially premixed flame with 20% primary air

### 3.2 LPG jet diffusion flames

In this set of experiments, LPG jet diffusion flames are analysed. The fuel flow rate is increased progressively from 10 g/h to 17.9 g/h. Figure 5 presents the shadowgraph images of jet diffusion flames. The dark region at the bottom represents the burner shadow. Two distinct regions are observed in the shadowgraphs, the inner zone and the outer plume. The inner zone indicates the flow developed by the fuel jet emanating from the burner. It can also be noted that the tip of the inner zone is darker when compared to its bottom. This is due to the presence of soot near the flame tip in diffusion flames. The outer plume (relatively whiter lines) represents the preheat zone in the flame. The outer plume indicates the extent of mixing of ambient air with the fuel. It is visible that the height of inner cone increases with an increase in the fuel flow rate. Also, the intensity of the inner cone increases with an increase in the fuel flow rate as a result of an increase in the soot formation. The intensity of the inner cone decreases in the radial direction due to mixing of fuel and ambient air. For higher flow rate, 17.9 g/h, the flame length exceeds the diameter of the mirror. Hence, the shadow is not visible completely along the axis. Further, it is also noted that the plume is stable for all the flow rates used.
Figure 5: Shadowgraph of LPG jet diffusion flames for different fuel flow rate (a) 10 g/h (b) 12.9 g/h (c) 15.5 g/h and (d) 17.9 g/h

Figure 6 shows the measured plume width in LPG jet diffusion flames. The maximum uncertainty from the three trials is ±1 mm. It is observed that as the fuel flow rate is increased, the initial momentum of the fuel jet increases. This results in higher relative velocity between the fuel and the ambient air, which causes an increased entrainment near the bottom of the flame. The plume width increases due to the increase in the entrainment rate. For a given fuel flow rate, the plume width shows a notable increasing trend with an increase in the axial location from 5 mm to 10 mm. After this, with a further increase in the axial location, the variation in the plume width becomes negligible, indicating very small amount of air entrainment at those locations. Further, it becomes almost a constant or shows a slight decreasing trend.

The plume temperature is measured for a jet diffusion flame for a flow rate 10 g/h and the temperature corrections are applied. Figure 7(a) presents the radial temperature profile at two axial locations of z = 70 mm and z = 90 mm. It is observed that the maximum temperature occurs at the axis in the plume region as expected. The plume temperature decreases along the radial direction (around 700 K decrease happens within a radial distance of 10 mm). It further gradually reaches to the ambient temperature. The temperature data has been measured within an uncertainty of ±20 K. Figure 7(b) presents the axial temperature profile in the plume measured from an axial location of 7 cm to 27 cm above the burner exit.

It is observed that unlike in the radial profiles, the temperature decreases more gradually in the axial direction. That is, the axial temperature gradients are lower than the radial temperature gradients.
The high velocity gradients in the radial direction, created by the relative velocity between the burnt gases and ambient air, form the reason for rapid drop in temperature in radial direction.

The visible flame heights have been measured from direct photographs of the flames. The maximum uncertainty in the flame height is ±1 mm for all the cases reported in this paper. Figure 8 presents the direct photographs of jet diffusion flames for four fuel flow rates. Since the laminar flame length is directly proportional to the volumetric flow rate of the fuel, the flame height increases with an increase in fuel flow rate for pure jet diffusion flames as expected. This can be approximately estimated from the correlations proposed by Roper [16]. The correlations are obtained for pure fuels and using it for a multicomponent fuel like LPG underpredicts the flame length. This is due to differences in the mass diffusivities of various components present in the fuel. Further, the correlations are derived for non-sooty flames like methane and thus poorly predicts the flame length of highly sooty flames [16]. However, the correlation predicts the increasing trend in flame length quite accurately.

The width of the flame is observed to decrease slightly because of higher air entrainment due to increased fuel flow. The bottom of the flame appears blue in colour due to mixing of fuel with ambient air. The entrainment is strong at these locations. The remaining part of the flame appears bright yellow in
colour due to soot radiation. At lower flow rates, the flame appears to be closed indicating the completion of soot oxidation within the flame. At higher flow rates, as shown in Figs. 8(c) and 8(d), soot wings appear at the flame tip. The soot incepted and agglomerated has not been able to oxidize completely within the flame zone in these cases. Table 2 presents the variation of flame height of jet diffusion flames as a function of fuel flow rate.

<table>
<thead>
<tr>
<th>Fuel flow rate (g/h)</th>
<th>Flame height (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>49.5</td>
</tr>
<tr>
<td>12.9</td>
<td>75</td>
</tr>
<tr>
<td>15.5</td>
<td>101</td>
</tr>
<tr>
<td>17.9</td>
<td>162</td>
</tr>
</tbody>
</table>

### 3.3 LPG co-flow diffusion flames

Figure 9 presents the shadowgraph images of LPG diffusion flames in co-flow. In these experiments, the fuel flow rate is fixed at 10 g/h and the co-flow air is gradually increased from 0% (without co-flow) to 400% of the stoichiometric value (theoretical air flow rate required for the given fuel flow rate). The presence of co-flow increases the air entrainment rate as expected. This is visible from the increase in plume width near the burner exit. In general, the amount of air required for complete combustion is little higher than the stoichiometric value. Hence, increasing the co-flow air enhances mixing and heat transfer to the preheat zone. Further, the flames in the co-flow environment are more stable than jet diffusion flames. This is because the co-flow curtails any cross currents in the ambient, and onset of instability due to natural entrainment, which may disturb the flame eventually. However, with further increase in co-flow air, above 200%, no significant change in the flame and plume extents are observed, and the plume width and height of the inner cone in the shadowgraphs also remain constant.

![Figure 9: LPG diffusion flames in co-flow for fuel flow rate 10 g/h and co-flow air (a) 0% (b) 100% (c) 200% and (d) 400% of stoichiometric value](image)

Figure 10 presents the temperature profiles measured in a co-flow flame with 100% co-flowing air. Similar trends as observed in Fig. 7 have been observed for this case. Apart from this, flame heights of co-flow diffusion flames are measured and it has been noted that the visible flame height remains almost a constant for all the cases considered (not reported here).
3.4 LPG partially premixed flames

In these experiments, the characteristics of partially premixed flames are investigated. The fuel flow rate is maintained at 10 g/h and primary air is increased gradually up to 50% of the stoichiometric value. Figure 11 presents the shadowgraph images of partially premixed LPG flames. Figure 11(a) presents shadowgraph of jet diffusion flame (without partial premixing) for comparison. It is observed from Fig. 11(b) that for the case with 10% partial premixing, the intensity of the inner zone (dark zone) is reduced. This is because the mixture density reduces and becomes almost equal to the density of air. Since there is a negligible density variation between the mixture and ambient air, the intensity of the inner zone decreases. With further increase in primary air to 20% (Fig. 11b), the inner zone almost disappears. Since a part of air required for combustion in present in the mixture, the flame length decreases rapidly with partial premixing. Increasing the primary air further to 30%, it is observed that the inner zone loses its identity completely and only two bright lines (white lines) are visible as a result of high temperature in the preheat zone on core flow side.

Figure 12 shows the variation of thermal plume width with respect to burner height in partially premixed flames. The maximum uncertainty in measuring the plume width is ±1 mm. It is observed that as the primary air is increased the plume width increases due to increased rate of mixing. Above 30% primary aeration, the plume width increases significantly. This is because of the increase in the preheat zone thickness with an increase in primary air.
Figure 12: Variation of plume width with burner height in LPG partially premixed flames for fuel flow rate 10 g/h and primary air (p.a) of 0%, 10%, 20%, 30% and 50% of stoichiometric value.

Figure 13 presents the radial temperature profiles in a partially premixed flame with 20% primary air. Even though similar trends are observed as in Figs. 7 and 10, the slope variation is quite different in this case as a result of changes in flame extent in axial and radial directions due to partial premixing.

Figure 13: Temperature profile in partially premixed flame with 20% primary air (a) radial temperature profile at 70 mm and 90 mm from burner exit and (b) axial temperature profile.

A significant difference between a jet diffusion flame and a partially premixed flame is the presence of soot. Jet diffusion flames are sooty (indicated by bright yellow colour and soot wing at its tip). With an increase in primary air, the extent of the yellow region reduces and the soot radiation also decreases. Figure 14 shows the direct photographs of partially premixed flames. The flame length decreases significantly with an addition of primary air. In the presence of primary air, lesser amount of oxygen is required from the ambient for completing the combustion process. Moreover, the reaction rate increases with increase in primary air, which subsequently reduces the flame length.

Figure 14: Direct photographs of LPG partially premixed flames with fuel flow rate of 10 g/h and primary air varied as (a) 10%, (b) 20%, (c) 30% and (d) 40% of stoichiometric value.
Further, the soot formation is reduced with an increase in primary air. This is because the soot oxidation is enhanced due to the availability of more oxygen. It is clear that the yellow region slowly disappears as the primary air is increased gradually. A bright bluish green flame cone is visible in Fig. 14(d), which is one of the characteristics of a premixed flame. With 40% primary air, the mixture is within the flammability limits of LPG. Hence a premixed inner flame surrounded by a diffusion flame (double flame configuration) is observed.

3.5 LPG partially premixed flames in co-flow

Figure 15 presents the shadowgraph images of LPG partially premixed flames with co-flow air. In these flames, the fuel flow rate is fixed at 10 g/h, co-flow air is maintained at the stoichiometric value (100%) and primary air is varied from 0% to 50% of the stoichiometric value.

It is observed from Fig. 15 that the height of the inner cone reduces with an increase in primary air. Further, the presence of primary air increases the heat released in the reaction zone, which increases the heat transfer to the preheat zone on both core and co-flow sides. Hence the thermal plume width increases with increase in primary air.

Figure 16 shows the variation of plume width in partially premixed flames with co-flow. It is seen that the plume width decreases initially when primary air is increased from 0% to 10%. When primary air is increased beyond 10%, the plume width increases. It is also noted that for the same amount of premixing, the plume width is higher when co-flow air is included. This is because the presence of co-flow enhances mixing and widens the preheat zone on the air side. Further, it also improves the oxidation of CO and OH radicals formed during combustion. The variation trend of plume width is quite different from that presented in Fig. 13, for partial premixed flames without co-flow air. The maximum uncertainty in these measurements is about ±0.5 mm.
Figure 16: Variation of plume width with burner height for partially premixed flames in stoichiometric (100%) co-flow with primary air (p.a) 0%, 10%, 20%, 30% and 50% of stoichiometric value.

Figure 17 presents the temperature profiles in partially premixed flames with co-flow. The slope variation is quite different in this case as a result of co-flow that that observed in partial premixed flames without co-flow (Fig. 13). Here, small increase in the peak temperature (of about 25°C) due to marginal increase in flame height (about 2 mm) is observed.

Figure 17: Temperature profile in partially premixed flame with stoichiometric co-flow and 20% primary air, (a) radial temperature profile at 70 mm and 90 mm from burner exit, and (b) axial temperature profile.

Figure 18 presents the direct photographs of partially premixed flames with co-flow. These are similar to those presented in Fig. 14. The co-flow does not affect the zones and extents of yellow and blue regions in the visible flames. However, there are small variations in the axial length of the flames as tabulated in Table 3.

Figure 18: Direct photographs of LPG partially premixed flames with stoichiometric co-flow, primary air is varied as (a) 10%, (b) 20%, (c) 30% and (d) 40% of stoichiometric value.

Table 3: Flame height (in mm) of partially premixed flames

<table>
<thead>
<tr>
<th>Primary air (%)</th>
<th>Partially premixed flames</th>
<th>Partially premixed flames in co-flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>37</td>
<td>38</td>
</tr>
<tr>
<td>20</td>
<td>34</td>
<td>32</td>
</tr>
<tr>
<td>30</td>
<td>31</td>
<td>31</td>
</tr>
<tr>
<td>40</td>
<td>26</td>
<td>27</td>
</tr>
<tr>
<td>50</td>
<td>23</td>
<td>26</td>
</tr>
</tbody>
</table>

5. Conclusions

LPG flames from a lab scale burner are analysed in different configurations using shadowgraph visualization technique. Thermal plume width is measured to study the extent of entrainment zone in flames. Results indicate that the plume width increases with increase in fuel flow rate. For a partially premixed flame the plume width increases for primary air greater than 30% of the stoichiometric value,
where a double flame structure is visible. The temperature field in the plume region indicates that the peak temperature for partially premixed flames is lower than that of jet diffusion flames. This is due to reduction in the flame height as a result of premixing with air. Further, flame height is measured from direct photographs and reported for all LPG flames studied. These quantitative data can be used for validation of numerical or mathematical models used for simulating LPG flames.

6. References