S. Muthu Kumaran and Vasudevan Raghavan*

Experimental Study of Non-Premixed Flames of Liquefied Petroleum Gas and Air in Cross-Flow and the Effects of Fuel Properties on Flame Stability

https://doi.org/10.1515/tjj-2019-0038
Received September 26, 2019; accepted October 06, 2019

Abstract: Stability of flames are affected by fuel properties, geometry of the burner and operating conditions. In this experimental work, first the characteristics of non-premixed flames of Liquefied Petroleum Gas (LPG) and air in cross-flow configuration, where air jet flows perpendicular to the fuel stream, are studied experimentally. Flame transition and stability regimes of non-premixed flames of LPG and air, in a cross-flow burner without and with obstacles, are determined by systematically varying the fuel and air flow rates. Obstacles such as backward facing step and cylindrical bluff bodies are considered. Subsequently, the effects of fuel properties on the stability of flames are analyzed, Flame stability regimes of natural gas (methane) and biogas (methane and carbon-dioxide), measured from a similar burner are available in literature. These have been compared with the stability of LPG flames in terms of power rating of the burner and global equivalence ratio (defined for non-premixed flames).

Keywords: Liquefied petroleum gas, natural gas, biogas, stability maps, power rating, global equivalence ratio

PACS® (2010). 47.54.De, 47.55.Ca, 82.33.Vx, 47.70.Pq, 88.20.jj

Introduction

Flame stability is an important aspect in the design of burners for commercial applications such as stationary gas turbines and turbocharger combustors. Various types of fossil and alternative fuels are used in these burners. Biogas and synthetic gas are examples of alternative fuels. Natural gas (methane) and Liquefied Petroleum Gas (LPG) are commonly used gaseous fossil fuels. LPG is a multi-component fossil fuel, chiefly composed of C_3 (around 25 % to 35 % by volume) and C_4 hydrocarbons (around 65 % to 75 % by volume). Both saturated as well as unsaturated hydrocarbons are present. The properties such as density, mass diffusivity and calorific value are notably different for these fuels. The variations in the fuel properties affect the flame configuration, stability regime and emission performance in a burner.

Several researchers in the past have studied cross-flow diffusion flame in different configurations [1–11]. Hirano and Kanno [2] experimentally measured velocity and temperature fields in a methane-air boundary layer diffusion flame without obstacles. Kundu et al. [3] analyzed the flame stabilization behind bluff bodies using their mathematical model. The predicted results agreed with the experimental values with a small discrepancy, which was attributed to the turbulence model used in the predictions. Ramachandra and Raghunandan [4] studied the effect of flame temperature, fuel and oxidizer concentrations on the stability limits of a diffusion flame. They reported that flame extinction occurred due to thermal quenching for a critical oxidant flux value and at critical oxidant and fuel velocities. Rohmat et al. [5] conducted comprehensive experimental study on methane–air cross-flow flames without and with obstacle such as bluff body and backward facing step. Shijin et al. [10] experimentally studied the stability of laminar cross-flow methane-air flames in the presence of bluff bodies of different shapes, namely, rectangular, semi-circular and triangular. Stability maps for these bluff bodies were plotted as a function of fuel and air velocities. Recently, Harish et al. [11] conducted a detailed experimental study and obtained the flame characteristics and stability maps for biogas-air flames in cross-flow configuration. They established that the change in the fuel type has to be studied systematically. The effects of the presence of backward facing step of varying heights, located at different distances from the leading edge of the fuel plate were studied by systematically varying the fuel and air flow rates. Stability of methane-air flames in the presence of bluff-body in a lean premixed coflow combustor

***Corresponding author: Vasudevan Raghavan,** Mechanical Engineering, Indian Institute of Technology Madras, Chennai, Tamilnadu 600036, India, E-mail: raghavan@iitm.ac.in
S. Muthu Kumaran, Mechanical Engineering, Indian Institute of Technology Madras, Chennai, Tamilnadu 600036, India, E-mail: me15d210@smail.iitm.ac.in

was reported by Mishra et al. [12]. They observed an increase in flame stability and reduced CO emissions for cases with bluff body located at an optimum location. Mishra [13] analysed the stability and emissions from LPG-air flames in a vortex burner. He observed that the flame could be stabilized for global equivalence ratio of 0.05, which is much lower than the lean flammability limit of LPG-air mixture.

The characteristics of non-premixed LPG-air flames in a cross-flow burner are not available in literature, while the same for natural gas (methane) flames and biogas flames are available. Thus, in the present study, domestic LPG available in India, is used in a cross-flow burner, in which confined and non-premixed flames sustain. The typical composition of Indian LPG is 0.03 % CH_4, 0.96 % C_2H_6, 13.31 % C_3H_8, 10.22 % C_3H_6, 30.23 % i-C_4H_{10}, 25.32 % n-C_4H_{10}, 3.98 % C_4H_8, 5.03 % i-C_4H_8, 4.99 % *trans*-2-C_4H_8, 3.64 % *cis*-2-C_4H_8, 1.96 % i-C_5H_{12} and 0.33 % n-C_5H_{12}. In these burners, the operating range is extended by installing obstacles such as backward facing step and cylindrical bluff bodies at appropriate locations before the fuel stream. The resulting flame regimes and stability boundaries have been compared with respective data for methane (natural gas) and biogas from literature. The operating range of the burner is kept to 1.4 kW and the maximum cross-flow air velocity is 3 m/s.

Experimental setup and procedure

The cross-flow burner used in the present study is the same as the one used by Harish et al. [11], where all the required details are available. Figure 1 shows a simplified schematic of the cross-flow setup. The burner consists of an air supply system, fuel supply system and a test section. The air supply system consists of pressure regulator, filter, moisture removal and calibrated rotameters. The maximum uncertainty in the air flow rate is ± 10 liters per minute (lpm), which corresponds to an uncertainty of ± 0.05 m/s in air velocity. The metered air passes through a settling chamber of 200 mm diameter. The settling chamber has two sections of length 150 mm and 300 mm. A honeycomb structure is placed at the exit of this section to ensure that uniform flow enters the test section.

The fuel supply system consists of a commercial LPG cylinder fitted with a domestic regulator. Since LPG is a mixture of several hydrocarbons, measurement of its volumetric flow rate is non-trivial. Thus, a 5 kg LPG cylinder is kept over a load cell (maximum capacity 6 kg, with accuracy of 0.1 grams). It is allowed to flow through a standard glass rotameter with a control valve. At a given rotameter setting, the change in the mass of LPG for a duration of 30 minutes has been measured. This corresponds to the mass flow rate (kg/s) of LPG at that rotameter setting. The rotameter has been calibrated using this procedure. The accuracy of the load cell is 0.1 grams and the uncertainty in measuring the fuel flow rate is estimated as $\pm 0.166 \times 10^{-6}$ kg/s.

Baseline case without obstacles and cases with backward facing step of heights 5 mm, 10 mm and 15 mm, located at 10 mm upstream of the leading edge of the fuel plate have been considered. Further, bluff bodies of rectangular, triangular and semi-circular shapes have also been used as obstacles. Detailed experimental

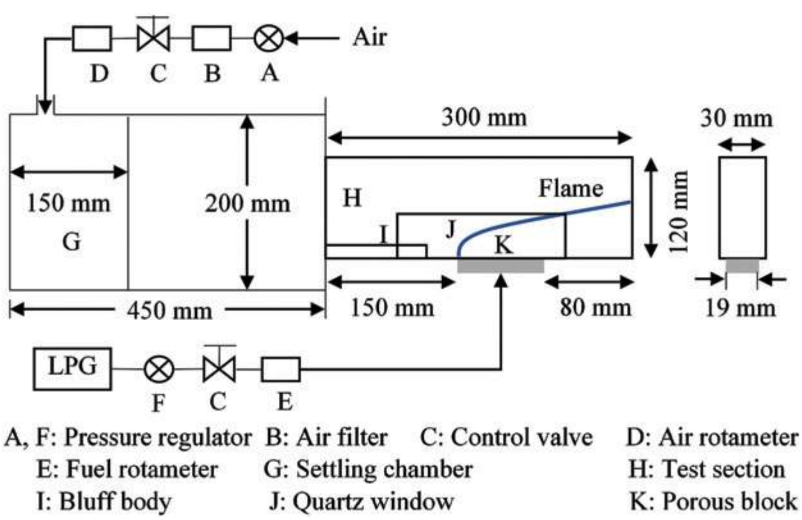

Figure 1: Schematic of experimental setup; bluff body (part I) is either a backward facing step or a cylindrical object.

procedure has been reported in Harish et al. [11]. Since LPG flames are sooty, soot particle deposition over the porous fuel injector plate is unavoidable. Thus, care is taken to blow air through the porous plate after the completion of an experimental trial to inject out the soot particles. All the experimental cases are repeated at least thrice to ensure consistency and repeatability. Only stable flame regimes are presented. Flames separated from obstacles and flame blow-off are not studied here. LPG flame stability maps are plotted for all the cases and have been compared with stability maps for methane and biogas published in literature.

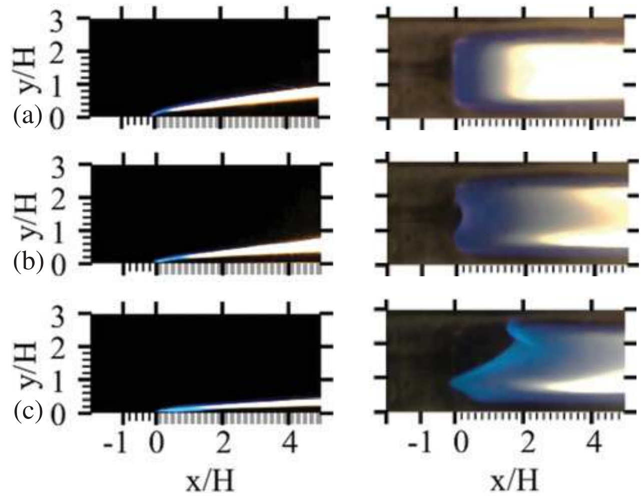

Figure 2: Direct photographs of front (left) and top (right) views of LPG-air cross-flow flames without any obstacle, for a fuel velocity of 0.0055 m/s, showing (a) plate stabilized, (b) symmetrically and (c) asymmetrically separated flame regimes. Start of the fuel injector plate is at x/H = 0.

Results and discussion

High definition images are extracted from videos of flames and are processed to improve their appearance. This also ensures proper visibility of the leading edge of the flame, which is otherwise masked by the non-uniform luminosity from the flame, contributed by the bright yellow color due to soot radiation (luminous) and the dull blue color (non-luminous) near the flame anchoring region. Image processing is carried out using an in-house program developed in MATLAB. The regimes of LPG flames are much similar to those of methane (Rohmat et al. [5], Shijin et al. [10]) and biogas (Harish et al. [11]) flames. In the baseline case, plate stabilized, symmetrically stabilized and asymmetrically stabilized flame regimes are obtained by varying the air velocity. In the cases with obstacles, regimes such as plate stabilized, lifted and flames stabilized in the rear side of the obstacle are obtained. Discussions for formation of these flame regimes are reported in Rohmat et al. [5] and Harish et al. [11].

Baseline cases

Figure 2 presents the direct photographs of front and top views of flames without any obstacles (baseline cases) for a fuel velocity of 0.0055 m/s. Different stability regimes such as plate stabilized, symmetric and asymmetric flames are observed with gradual increase in air velocity [11]. Plate stabilized flames are observed to be steady and two-dimensional in nature. They resemble a boundary layer flame. The region around the leading edge of the flame is blue in color, caused by the mixing of fuel with fresh incoming air at those locations. The downstream portion of the flame appears yellow in color showing the characteristics of a non-premixed flame as well as soot radiation.

Flame anchors towards the side walls in a symmetric manner. As the air velocity is further increased, the V-shape intensifies and the flame begins to oscillate around its leading edge. With further increase in air velocity, the oscillations in the flame propagate rapidly in the longitudinal direction. Flame anchoring point detaches from one side and moves downstream as observed from the top view. This asymmetrically separated flame (Harish et al. [11]) edge is unsteady and oscillates continuously trying to reattach and separate from the side wall. From this regime, a further increase in the air velocity results in the flame moving away from the leading edge of the fuel injector plate. After this, the flame sustains for a narrow range of air velocity before being blown off completely (blow-off velocity not reported here).

Cases with backward facing step

The effect of step height on flames stabilized behind backward facing step is discussed here. In Figure 3, the plate stabilized (left column) lifted (middle column) and step stabilized (right column) flame regimes are compared for the cases with backward facing steps of heights 5 mm (Figure 3(a)), (b) 10 mm (Figure 3(b)) and (c) 15 mm (Figure 3(c)). The rear face of the step is located at a

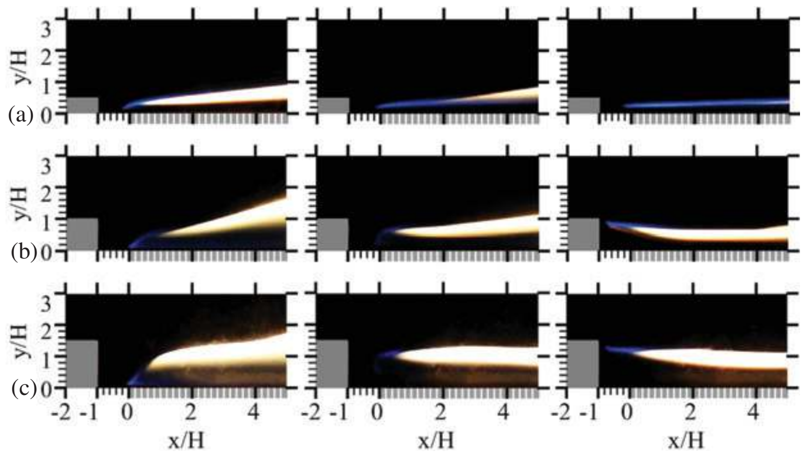

Figure 3: Direct photographs of front views of flames behind backward facing step of height (a) 5 mm, (b)10 mm and (c) 15 mm, located 10 mm upstream of the leading edge of the fuel injector, for a fuel velocity of 0.002 m/s, showing plate stabilized (left column), lifted (middle column) and step stabilized (right column) flame regimes.

distance of 10 mm upstream of the fuel injector plate. For these cases, the fuel velocity is maintained as 0.002 m/s and air velocity is varied to obtain different flame regimes. The curvature of the plate stabilized flame near its leading edge increases with an increase in step height as shown in Figure 3(a), (b) and (c) (left column). The flame thickness is also seen to increase with step height. Larger recirculation zone is expected to prevail at higher step heights and this enhances mixing of fuel with air as well as with product gases to a greater extent. The flame shape is affected as a result of these. At higher air velocities, lifted flames for different step heights are shown in the middle column of Figure 3. Clear changes in the flame curvature are observed for the lifted flames as compared to the plate stabilized flames. However, this distinction is predominant at lower step heights. It is observed that for the smallest step height (5 mm), the blue flame region has extended up to x/H of around 2 and the flame is not seen as lifted as in the other two cases.

Step stabilized flames are presented in Figure 3(a) to (c) (right column). For 5 mm step height, the flame appears completely blue in color and has become almost flat. The leading edge of the flame is not seen closer to the rear surface of the step as in the other step heights. For higher step heights, the flame leading edge clearly anchors near the rear surface of the step. These flames display a small curvature near their leading edge and become almost flat at downstream locations. The recirculation zone formed behind the step transports the fuel close to the step and makes the flame to anchor near that location. The flame is stabilized a few millimeters away from the step and this distance decreases with increasing step height. For a step height of 5 mm, the flame has not moved notably from the leading edge. The main difference between a lifted flame and a step stabilized flame for a step height of 5 mm is the curvature at the leading edge. This decreases clearly for step height of 10 mm and 15 mm. It should be noted that in the case of biogas, step stabilized flame regime is not observed for 5 mm step height case (Harish et al. [11],).

Cases with cylindrical bluff bodies

The flame behind a rectangular bluff body of height 10 mm, located 10 mm from the leading edge of the fuel plate is shown in Figure 4(a). For a fuel velocity of

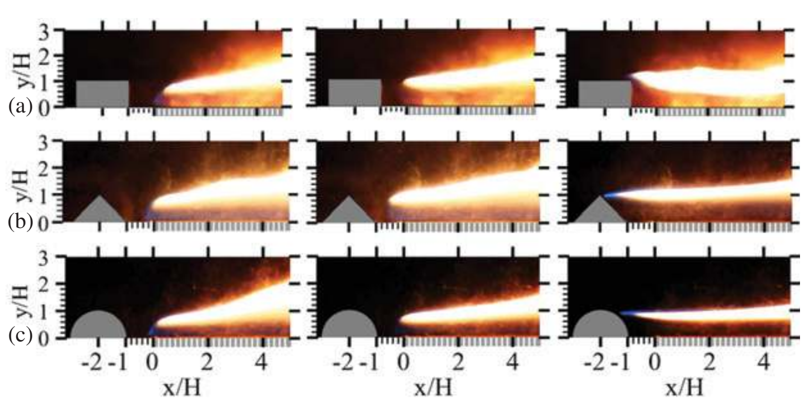

Figure 4: Direct photographs of front views of the flames behind (a) rectangular bluff body, (b) triangular bluff body and (c) semi-circular bluff body, located 10 mm upstream of the leading edge of the fuel injector, for a fuel velocity of 0.0034 m/s, showing plate stabilized (left), lifted (middle) and bluff-body (right) stabilized flame regimes.

0.0034 m/s, a plate stabilized flame forms at an air velocity below 0.62 m/s, as shown in Figure 4(a) (left column). The flame is quite steady and two-dimensional in nature, and anchors in the region between the plate and the rear surface of the bluff body. The flame has a noticeable curvature around its leading edge. With a gradual increase in air velocity, the flame lifts-off from the plate, slightly moves towards the rear surface of the bluff body and sustains as a lifted flame (Figure 4(b), middle column). This flame is also quite steady and has a small curvature near the leading edge. When the air velocity is increased further, the lifted flame attaches to the rear surface of the bluff body and establishes as a bluff body stabilized flame. The flame stabilizes few millimeters ahead and above the top right corner of the bluff body as observed in Figure 4 (c) (right column). In the case of a bluff body, there are recirculation zones in the front and back surfaces of the bluff body (Shijin et al. [10],). This creates a shear layer at the front corner of the bluff body, resulting in a complicated flow field. Hence, the flame anchors very close to the rear end of the bluff body. Both the lifted and bluff body stabilized flames are observed from their top views to be three-dimensional in nature.

Figure 4(b) shows the instantaneous direct photographs of the flames stabilized behind a triangular cylindrical bluff body of height 10 mm, located 10 mm upstream of the fuel injector plate. Similar to a rectangular bluff body, a plate stabilized flame anchors in the region between the plate and the rear side of the triangular bluff body (Figure 4(b), left column). This flame is steady and two-dimensional in nature. The curvature near the leading edge is smaller when compared to plate stabilized flame seen in the case of a rectangular bluff body Figure 4(a) (left column). With gradual increase in the air velocity, the flame first transitions to a lifted flame and then to a bluff body stabilized flame as observed in Figure 4(a). In the case of a triangular bluff body, for the bluff-body stabilized flame, the fuel is dragged up to the unique top edge of the bluff body and the flame anchors near that location. Flow separation takes place at the top edge and the flow dynamics are expected to be quite different in this case when compared to the rectangular bluff body due to the presence of inclined faces of the triangle. Subsequently, the mixing of fuel and air occurs slightly downstream as compared to a rectangular bluff body (Shijin et al. [10],). Figure 4(c) shows the flames stabilized behind a semi-circular cylindrical bluff body for the same fuel velocity of 0.0034 m/s. At low air velocity, a plate stabilized flame is established between the plate and bluff body, which is quite similar to the other cases. In this regime, the effect of the shape of the bluff body is not significant enough. The flame undergoes a transition to lifted flame and bluff body stabilized flame regimes, with a gradual increase in air velocity. For a semi-circular bluff body, the bluff body stabilized flame has no unique anchoring point because of its shape, as seen in the cases of other two bluff bodies.

Stability maps

A stability map is important to fix the operation zone for a given burner configuration. A fuel flow rate (velocity) is set and the air velocity is gradually increased. At each air velocity, sufficient time is given to observe the occurrence of transition from one regime to the other. For each fuel velocity, the air velocity is varied in the range 0.2 m/s to 3 m/s. The uncertainty in obtaining the boundary of a regime is ± 10 lpm (liter per minute), which corresponds to an uncertainty in the air velocity of ± 0.05 m/s.

Figure 5 presents the stability maps in terms of air and fuel velocities for cross-flow LPG-air flames. Filled symbols represent the boundary of plate stabilized flames for all cases and unfilled symbols represent the transition to asymmetrically separated flames for the cases without obstacles. Also, unfilled symbols represent the transition to the step stabilized flame for the cases with a backward facing step or a cylindrical bluff body. It is evident from Figure 5 that the transitioning boundary values of LPG flames are quite different from those of methane [5, 10] and biogas [11] flames, as dictated from the change in the fuel properties. Properties of methane, biogas and LPG are listed in Table 1.

In order to compare the stability maps of different fuels, the map is plotted in the coordinates of power rating (PR) of the burner and global equivalence ratio (GER). Global equivalence ratio for the non-premixed flame is defined as stoichiometric air-fuel ratio divided by the ratio of mass flow rate of air to the mass flow rate of the fuel in the burner. Power rating is obtained by multiplying the mass flow rate of the fuel to its calorific value. It should be noted that the fuel velocity is low when the calorific value of the fuel is higher for a given power rating. Similarly, the air velocity is low for higher GER.

Stability maps of LPG are compared with the corresponding experimental data reported using biogas [11] and methane [5]. Figure 6 shows the comparison of stability regimes for LPG (circles, solid lines), biogas (triangles, dashed lines) and methane (rectangles, dash-dot lines) flames without obstacles. It is clear that

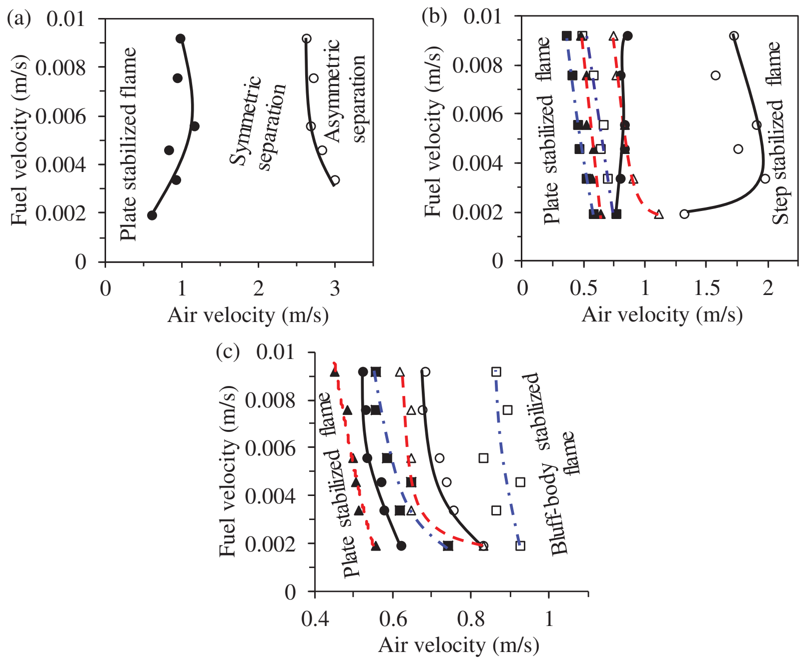

Figure 5: Stability maps of LPG flames for cases (a) without obstacles, (b) with backward facing steps of height 5 mm (circles), 10 mm (triangles) and 15 mm (rectangles) and (c) with bluff body of rectangular (rectangles), triangular (triangles) and semi-circular (circles) shapes.

Table 1: Thermophysical properties of fuels used in the study.

Fuel	Calorific value (kJ/kg)	Density (kg/m^3)	Molecular weight (kg/kmol)	Diffusivity × 10^{-5} (m^2/s)
Methane	50,016	0.65	16	2.214
Biogas [11]	15,390	1.162	28.6	1.814
LPG	45,893	2.20	54.18	1.056

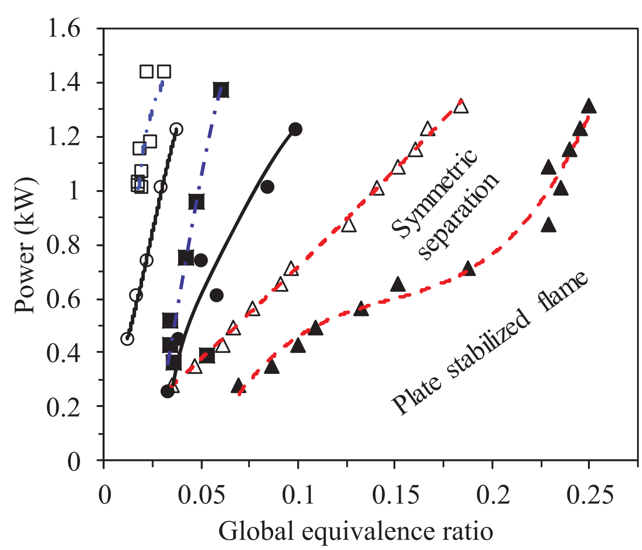

Figure 6: Stability map in power rating vs. GER plot for flames without obstacles fuelled by LPG (solid lines and circles), biogas (dash lines and triangles) and methane (dash-dot lines and rectangles). Filled symbols show transition from plate stabilized to symmetrically separated regime and unfilled symbols show transition from symmetrically separated to asymmetrically separated regime.

methane forms plate stabilized flames (filled rectangles) at much smaller GER, followed by the LPG flames (filled circles). The higher diffusivity of methane is the reason for sustaining a plate stabilized flame at a lower GER as compared to LPG or biogas.

Biogas is able to sustain a plate stabilized flames (filled triangles) only at notably higher GER (at low air velocities) values. Although biogas has a higher diffusivity compared to LPG, it is not able to sustain plate stabilized flames at higher air velocities. This is due to its inherent CO_2 content, which significantly reduces the calorific value as well as reduces the flame temperature. LPG and methane are able to form asymmetrically separated flames at much lower GER (less than around 0.03). For lower power rating, methane flames are in the oscillatory flame regime as reported by Rohmat et al. [5] and hence not reported here. The asymmetrically separated flame boundary is quite away, towards higher GER, for biogas flames. At low power rating, LPG and methane have similar transition boundaries, and there is a clear distinction for biogas flames even at lower power ratings.

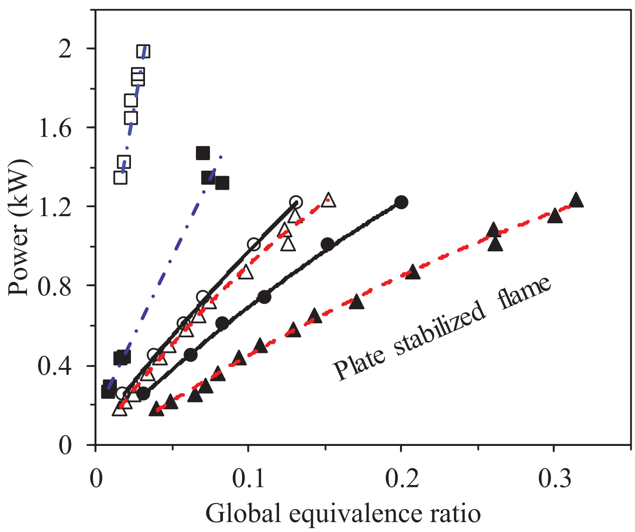

Figure 7: Comparison of stability maps for LPG (solid lines and circles), biogas (dash lines and triangles) and methane (dash-dot lines and rectangles) flames behind a backward facing step. Filled symbols show the boundary of plate stabilized and lifted flames and unfilled symbols show the boundary of lifted and step stabilized flames.

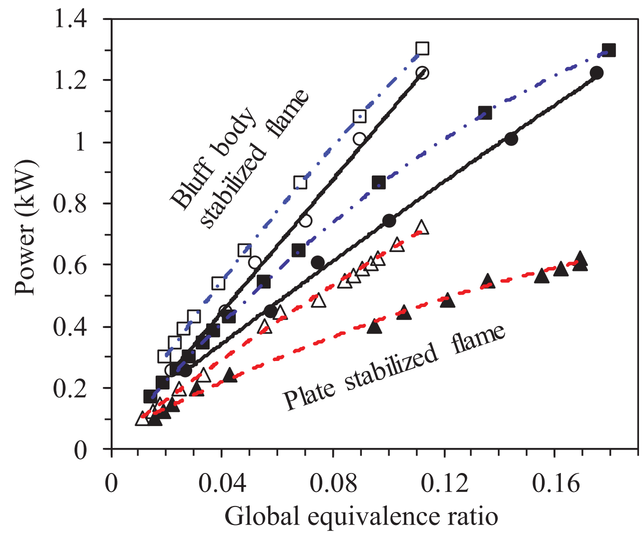

Figure 8: Comparison of stability maps for different fuels, LPG (circles), biogas (triangles) and methane (rectangles) for a rectangular bluff body. Filled symbols represent transition from plate stabilized to lifted flame and unfilled symbols represent transition from lifted to bluff body stabilized flame regime.

This is due to higher fuel flow rates required for biogas for attaining a given power rating.

Figure 7 shows the comparison of stability regimes for LPG (circles, solid lines), biogas (triangles, dashed lines) and methane (rectangles, dash-dot lines) flames formed behind a backward facing step of height 10 mm located at 10 mm upstream of fuel injector plate. It is clear that methane forms plate stabilized flames (filled rectangles) at much smaller GER. There is a clear difference in the transition boundaries of methane as compared to other two fuels, especially at higher power ratings. At lower power ratings these boundaries seem to merge. Rohmat et al. [5] have not reported data for transition to step stabilized flames for methane at lower power ratings. As opposed to no obstacle cases, the stability of biogas and LPG flames is seen to be improved much behind a backward facing step. Biogas, due to its low calorific value, shows a distinct transition boundary at higher power rating.

It is clear that the boundaries of lifted and step stabilized flame regimes are almost the same for LPG and biogas at low power ratings. However, at higher power rating the boundaries widen significantly and the transition occurs faster for biogas flames. This is due to high velocity of biogas as compared to LPG. This boundary is at higher GER when compared to that of methane. It is clear that as the fuel mixture becomes heavier (higher molecular weight), step stabilized flames are formed at lower air velocities (higher GER).

Figure 8 shows the comparison of stability regimes for LPG (circles, solid lines), biogas (triangles, dashed lines) and methane (rectangles, dash-dot lines) flames formed behind a rectangular cylindrical bluff body of height 10 mm located at 10 mm upstream of fuel injector plate. The transition boundaries of methane flames are now comparable to those of LPG flames behind the bluff body.

It is clear that all the fuels display similar performance at low power ratings, below 0.2 kW and produce plate stabilized flames for GER value higher than around 0.01. Similarly, at higher power rating more than 1 kW, LPG and methane flames have comparable transition boundaries. Biogas flames have distinct transition boundaries at intermediate power ratings. Data for higher power ratings are not available for biogas flames behind a rectangular bluff body.

Conclusions

Cross-flow non-premixed LPG-air flames have been systematically studied using lab-scale experimental setup. Flame regimes and stability maps have been presented for cases without and with obstacles such as backward facing step and cylindrical bluff body. Stability maps in the coordinates of power rating and global equivalence ratio have been plotted to compare the characteristics of fuels such as methane, biogas and LPG. Clearly, the properties such as calorific value and mass diffusivity dictate the transition from one stability regime to another. Biogas has lower calorific value and an intermediate mass diffusivity when compared to LPG and methane. Thus, its stability characteristics are quite distinct. Higher fuel flow rate for a given power rating and suppression of flame temperature due to the inherent presence of carbon-dioxide form reasons for such behaviour. LPG and methane have comparable calorific values. However, LPG is quite heavier than methane. Thus, the formation of plate stabilized flame occurs at higher GER for LPG. Obstacles improve the stabilization regimes for biogas.

In the presence of backward facing steps, the transition from plate stabilized flame occurs at lower air velocity due to the presence of the step. However, more stable step stabilized flame is formed behind the step when compared to asymmetrically separated flames, which form in the cases with no obstacles at higher air velocities. The case with smallest step height of 5 mm is seen to produce wider range of plate stabilized and lifted flames. Cases with step heights of 10 mm and 15 mm produce step stabilized flames at much lower air velocities (less than approximately 1.2 m/s). When methane is used, plate stabilized flames form at much smaller GER when compared to LPG and biogas due to higher diffusivity of methane.

Transition from plate stabilized flame to lifted, and from lifted flame to bluff body stabilized flame occurs at higher air velocity for rectangular bluff body, followed by semi-circular and then triangular bluff bodies. Flame behind triangular bluff body display wider regime of bluff body stabilized flame. When methane is used, the flames behind a rectangular cylindrical bluff body are comparable to those of LPG flames behind the same bluff body. LPG, methane and biogas flames display similar characteristics at low power ratings, below 0.2 kW, and produce plate stabilized flames for GER value higher than around 0.01. At power rating more than 1 kW, LPG and methane flames behind the rectangular bluff body have comparable transition boundaries. Biogas flames behind the same bluff body have distinct transition boundaries at intermediate power ratings due to its lower calorific value and intermediate mass diffusivity.

It can be mentioned that backward facing step is able to provide wider stability than a rectangular bluff body.

References

1. Nicholson HM, Field JP. Some experimental techniques for the investigation of the mechanism of flame stabilization in the wakes of bluff bodies. Symp Combust Flame Explosion Phenom. 1948;3:44–68.
2. Hirano T, Kanno Y. Aerodynamic and thermal structures of the laminar Boundary layer over a flat plate with a Diffusion flame. Symp (Int) Combust. 1973;14:391–8.
3. Kundu KM, Banerjee D, Bhaduri D. Mathematical modelling of flows in bluff-body flame stabilizers. Appl Math Model. 1977;1:276–80.
4. Ramachandra A, Raghunandan BN. Investigations on the stability and extinction of a laminar diffusion flame over a porous flat plate. Combust Sci Technol. 1984;36:109–21.
5. Rohmat TA, Katoh H, Obara T, Yoshihashi T, Ohyagi S. Diffusion flame stabilized on a porous plate in a parallel airstream. Aiaa J. 1998;36:1945–52.
6. Huang RF, Chang JM. The stability and visualized flame and flow structures of a combusting jet in cross flow. Combust Flame. 1994;98:267–72.
7. Torero JL, Bonneau L, Most JM, Joulain P. On the geometry of laminar diffusion flame established over a flat plate burner. Adv Space Res. 1995;16:149–52.
8. Lavid M, Berlad AL. Gravitational effects on chemically reacting laminar boundary layer flows over a horizontal flat plate. Symp (Int) Combust. 1997;16:1557–68.
9. Chen CY, Chang CC, Pan KL, Yang JT. Flame lift-off and stabilization mechanisms of nonpremixed jet flames on a bluff-body burner. Combust Flame. 1998;115:51–65.
10. Shijin PK, Babu A, Raghavan V. Experimental study of bluff body stabilized laminar reactive boundary layers. Int J Heat Mass Transfer. 2016;102:219–55.
11. Harish A, Rakesh Ranga HR, Babu A, Raghavan V. Experimental study of flame characteristics and stability regimes of biogas – Air cross flow non-premixed flames. Fuel. 2018;223:334–43.
12. Mishra DP, Kannan R. An experimental study of lean premixed combustor. Int J Turbo Jet Engines. 2003;20:245–53.
13. Mishra DP. Experimental studies of low emission vortex burner. Int J Turbo Jet Engines. 2008;25:27–35.