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Experimental Study of Pre-mixed Flames on a Multi-Hole Matrix Burner

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Abstract: This paper deals with an experimental investigation of the flame characteristics of premixed Liquefied Petroleum Gas (LPG) - air mixtures with different equivalence ratios on a multi-hole matrix burner. Lowest possible fuel-lean mixing conditions are envisaged. Results show that the flame pattern changes into four different types which are oscillatory flames in the middle region, flames with oscillations along the centerline, flames with very little oscillations and stable flames from all the holes. Species concentration measurements are performed with the help of gas analyzer and the results show that the concentrations of carbon-monoxide and oxygen decreases, whereas that of carbon-dioxide and nitrous oxide increases with increase in the volumetric flow rate of LPG and air mixture. In addition to this, temperature measurements are carried out using a K-type thermocouple over the burner surface at different heights. Temperature contours for each plane have been presented.

Keywords: Multi-hole matrix burner, Oscillatory flames, K-type thermocouple

1. Introduction

Perforated-plate stabilized flames are typically used in industrial and compact household burners. In these systems there are several conical premixed flames are formed in downstream of the perforated-plate holes. Numerical, analytical and experimental investigations of the steady and dynamic properties of such premixed flame systems have been attempted recently. A couple of relevant works are discussed below.

Yang et al. [1] studied surface flame patterns and stability characteristics in a perforated cordierite burner for fuel reformers. The effects of the equivalence ratio and heating rates are studied to find less emission and more stable surface flame. A specially designed fuel and air mixture is fabricated to produce a stable surface flame.

The results show that the surface flames can be classified into green, red radiant and blue surface flames as the equivalence ratio decreases. Lee et al. [2] performed experiments related to formation of lean premixed flat flame using cylindrical porous metal plate burner. The results show that the flat cylindrical flame mode is changed into green flame, yellow radiation flame, blue flame or lifted-off green flame zones, with decreasing equivalence ratios. Blue flame has wide stability region in stability curve and shows lowest carbon-monoxide CO and nitrous oxide (NOx) emission. CO is decreased as mixture ratio goes leaner but NOx shows almost same emission level. There are several works on ceramic and porous burners, where combustion characteristics and radiation efficiency [3], numerical analysis of heat transfer [4], study of submerged reaction zones [5], burner performance [6], study using liquid fuels [7], emission measurements [8] and lean-fuel applications [9] have been studied.

In this paper, the study of pre-mixed flame characteristics of LPG and air mixture over a multi-hole matrix burner has been done till the lowest possible fuel-lean mixing conditions. The study primarily carried out to develop a low species emission burner which can be operated at ultra-lean mixing conditions. In addition to the flame characteristics at various equivalence ratios (ϕ), the measurement of temperature and species concentrations (CO, NOx, oxygen, O_2 and carbon-dioxide, CO_2) at different locations in and around the flames is also done. The measurements of species concentrations and temperature are carried out by positioning a gas analyzer probe and a thermocouple at different x, y and z axis locations using a traverse arrangement.

2. Experimental Setup and Method

2.1 Experimental apparatus

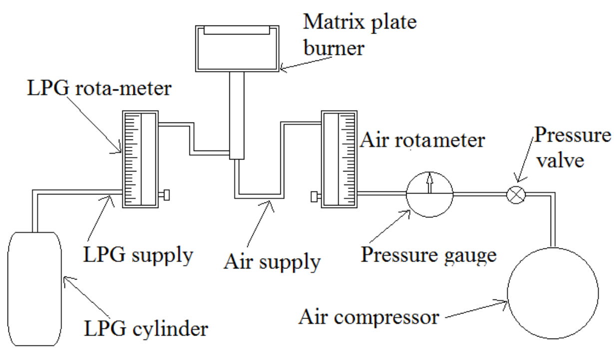

Fig. 1 Schematic of the setup

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The experimental setup mainly consists of a multi-hole matrix plate burner, two rotameters (for LPG and air), fuel cylinder, pressure regulator, pressure valve, traverse arrangement, gas analyzer, weighing machine and air compressor. The schematic of the experimental setup is shown in Fig. 1.

2.2 Mixing chamber

In the multi-hole matrix burner, a metal plate with the dimensions of 85 mm length, 41.5 mm breadth and 7.5 mm thickness is used. This plate consists of 60 identical converging holes of 4.5 mm diameter on one face to 2 mm diameter on the other, arranged in a matrix form. The plate is placed over a slot at the top of the mixing chamber such that the holes with 2 mm face upwards.

At the bottom surface of the mixing chamber, there is a 15 mm diameter hole at the center from which fuel and air mixture is supplied. A small distributor wooden plate, metal wool and metal meshes are used to uniformly distribute the mixture in the mixing chamber. A 10 cm long metal pipe is connected to supply the air and fuel mixture with OD 15 mm and ID 13 mm at the bottom surface of the mixing chamber. The schematic of the burner is shown in Fig. 2.

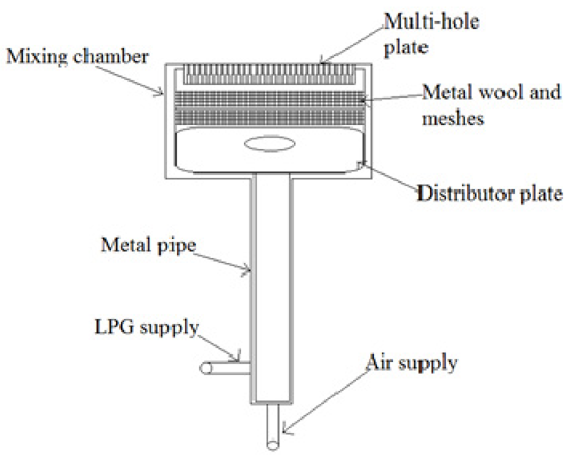


Fig. 2 Schematic of the burner

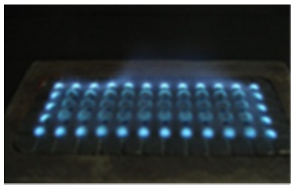
2.3 Fuel and air mixture

In the present experimental study, LPG (60% butane and 40% propane) is used as a fuel. The equivalence ratio value is changed by varying the volumetric flow rates of the fuel and air with the help of corresponding rotameters. To change the value of equivalence ratio the volumetric flow rate of LPG is kept constant and the volumetric flow rate of air is varied and different pre-mixed flame patterns are analyzed. The air rotameter used has a range of (0 - 16 lpm) and least count of 0.5 lpm whereas the LPG rota-meter has a range of (0 - 18 lph) and a least count of 0.3 lph.

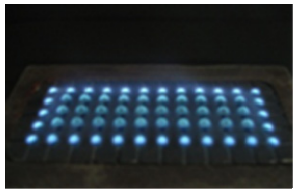
3. RESULTS AND DISCUSSIONS

3.1 Flame characteristics in matrix burner

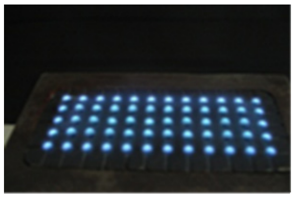
The experimental study of premixed flame characteristics is carried out for three LPG volumetric flow rates; 3 lph, 6 lph and 9 lph. In order to calculate the mass flow rate of LPG, a weighing machine with a least count of 1 g is used. For every volumetric flow rate of LPG, the mass loss is measured at least for three times and the corresponding mass flow rate is measured. The mass flow rates are calculated as 15 g/h, 21 g/h and 24 g/h for the corresponding volumetric flow rates of 3 lph, 6 lph and 9 lph, respectively. For each flow rate of LPG, four different cases are analyzed with the help of a digital camera and the observations are presented subsequently.



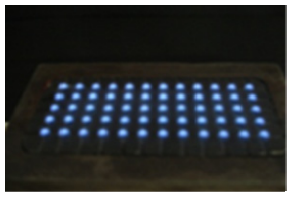
(a) Case 1



(b) Case 2



(c) Case 3



(d) Case 4

Fig. 3 Flames from various cases

As observed from Figure 3, for case 1, stable flames are seen at boundary holes but the middle region flames oscillate. For case 2, there are increased numbers of stable flames at middle region but the flames along the centerline are seen to oscillate more. For case 3, quite stable flames observed everywhere with very little oscillations of flames along the centerline and for case 4, perfectly stable flames are observed through the all holes. For every case, the oscillation index (OI) defined as the ratio of the number of flames oscillating to the total number of flames and the oscillation frequency (f) have been calculated with the help of a high speed video. In order to measure the oscillation frequency, a high-definition video for every case is recorded and then image post-processing (using image-J software) is done to measure the oscillation frequency.

For the LPG mass flow rate of 15 g/h, case 1 is observed at an equivalence ratio of 0.82 with an air volumetric flow rate of 4 lpm. The oscillation index (OI) is calculated as 0.5 i.e., 30 flames are oscillating out of total 60 flames. The oscillation frequency (f) is calculated as 6.80 Hz. Case 2 is observed at the equivalence ratio of 0.73 with an air volumetric flow rate of 4.5 lpm. For this case, OI = 0.22 and f = 8.50 Hz. Case 3 is observed at the equivalence ratio of 0.65 with an air volumetric flow rate of 5 lpm. For this, OI = 0.13 and f=11.33 Hz. Finally for case 4, the equivalence ratio is

0.59, volumetric air flow rate is 5.5 lpm, OI = 0, i.e. no oscillations in the flames. Similar pre-mixed flame patterns are observed for the other two LPG mass flow rates of 21 g/h and 24 g/h. The results are presented in Table 1.

Table 1 Effect of LPG flow rate on flame characteristics

Case	LPG Flow Rate (g/h)	Air Flow Rate (lpm)	ϕ	OI	f (Hz)
1	15	4	0.82	0.50	6.80
2	15	4.5	0.73	0.22	8.50
3	15	5	0.65	0.13	11.33
4	15	5.5	0.59	0.00	-
1	21	7	0.65	0.46	4.25
2	21	7.5	0.61	0.20	4.86
3	21	8	0.57	0.11	5.67
4	21	8.5	0.54	0.00	-
1	24	9.5	0.55	0.45	2.83
2	24	10	0.52	0.18	3.09
3	24	10.5	0.50	0.10	3.40
4	24	11	0.48	0.00	-

From Table 1, it is observed that the stable flame front is obtained at the equivalence ratio values of 0.59, 0.54 and 0.48, for the LPG mass flow rates of 15 g/h, 21 g/h and 24 g/h, respectively. Thus it can be concluded that the stable flame observed in decreasing equivalence ratio values for increasing fuel flow rates. It can also be concluded that, for every LPG mass flow rate, oscillation index decreases with increase in the air volumetric flow rate as expected and the oscillation frequency increases.

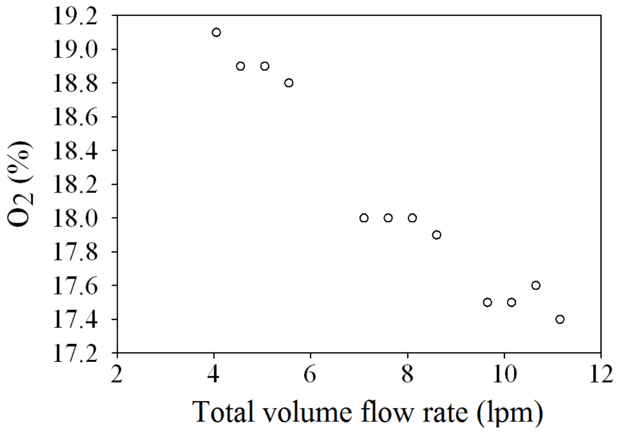
3.2 Species measurement

The species measurement is done by using a gas analyzer. To measure the species concentrations, an inverted funnel arrangement connected to the gas analyzer probe is placed over the burner at a height of 1 cm from the top surface. The concentrations of species such as O_2, CO, CO_2, and NOx are shown in Fig. 4(a-d) as a function of mixture (total) volume flow rate. From Fig. 4 it can be observed that, in case of O_2 and CO measurement the species concentrations decreases with increase in the volumetric flow rate of LPG and air mixture whereas species concentrations increase in case of CO_2 and NO_X. Within each LPG flow rate the variations are also different for different species.

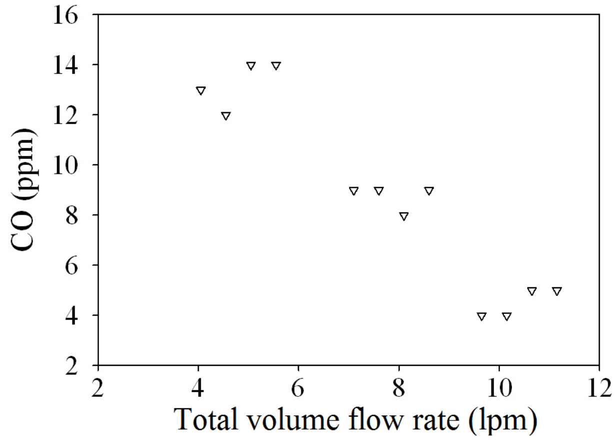
3.3 Temperature measurement

The temperature measurement is done by using a K-Type thermocouple for two equivalence ratio values of 0.59 and 0.82 for the LPG mass flow rate of 15 g/h. To measure the temperature at different x, y and z positions a traverse arrangement is used.

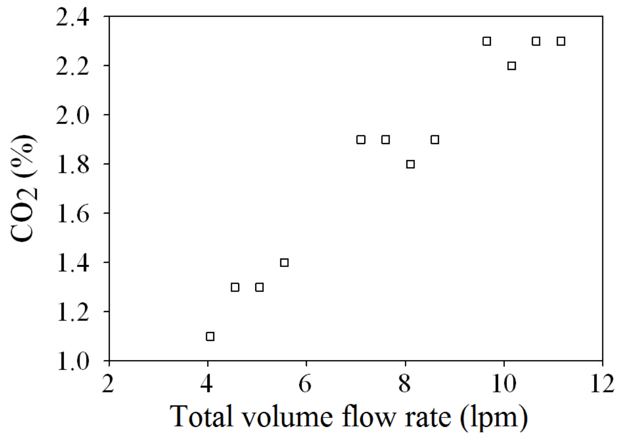
The thermocouple has a diameter of 1.5 mm is kept at an angle of 45° over the burner surface so that the temperature can be measured at a particular position with minimum heat being transferred to the wire from flame. The temperature measurement is done at five planes above the burner surface at the heights of 1 cm, 1.5 cm, 2 cm, 2.5 cm and 3 cm. In each plane the temperature measurement is done at 24 positions (6 x 4 matrix form) with the help of traverse arrangement. Therefore for both ϕ values, the temperature measurement is done at 120 positions. The raw temperature values are then corrected for convection and radiation temperature losses. Temperature contours are shown in Figs. 5 and 6 for ϕ =0.59 and 0.82.



(a)



(b)



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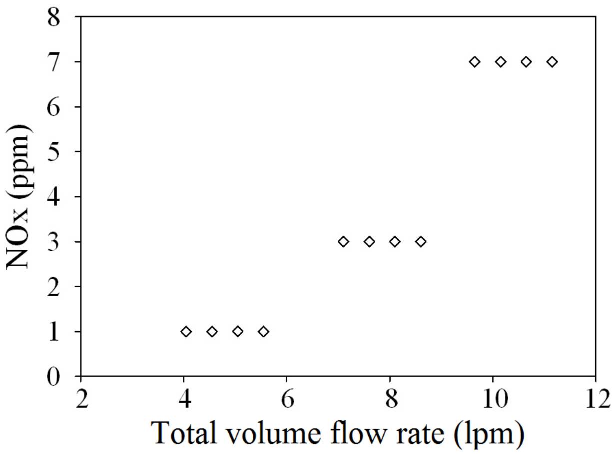


(d)

Fig. 4 Variations of concentrations of species such as (a) O_2, (b) CO, (c) CO_2, and (d) NOx

From the temperature contours, it is observed that the temperature values are symmetrical about the middle line for each plane and decrease with increasing height from the surface of the burner. Also when the equivalence ratio is decreased, the temperature values also decrease.

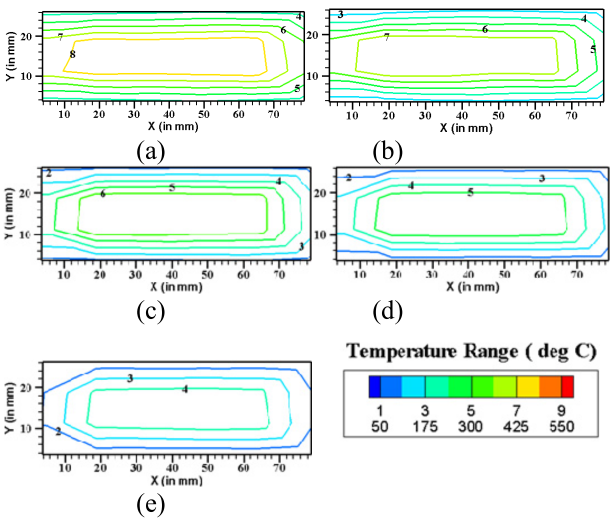
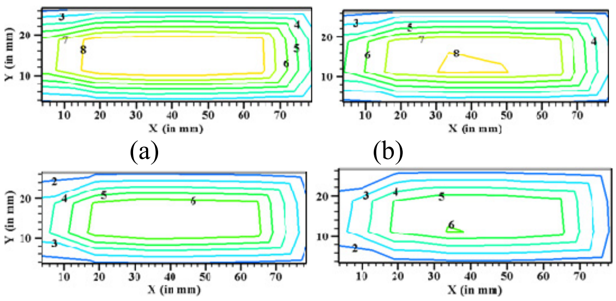
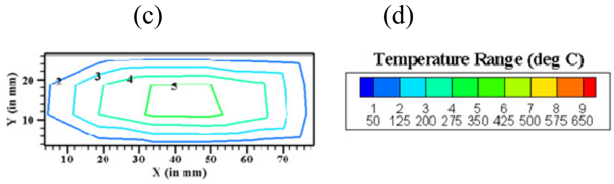


Fig. 5 Temperature measurement for ϕ =0.59; (a) plane 1 at 1 cm height; (b) plane 2 at 1.5 cm height; (c) plane 3 at 2 cm height; (d) plane-4 at 2.5 cm height and (e) plane 5 at 3 cm height.





(e)

Fig. 6 Temperature measurement for ϕ =0.59; (a) plane 1 at 1 cm height; (b) plane 2 at 1.5 cm height; (c) plane 3 at 2 cm height; (d) plane-4 at 2.5 cm height and (e) plane 5 at 3 cm height.

3.4 Cooling characteristics

The effects of burner cooling on the characteristics of stable flames got from case 4 are studied. By circulating cooling water around the mixing chamber, the water temperature and the burner wall temperature are maintained as constant. The stable flames were simulated for a fixed LPG flow rate of 15 g/h. Temperature of water in the cooling pan is increased gradually and the equivalence ratio for which a stable flame (case 4) is obtained is plotted on the graph shown in Fig. 7.

It is observed from the graph that higher equivalence ratio is required to produce a stable flame when the burner is sufficiently cooled, that is when the water bath is at a low temperature. As the water bath temperature increases, the equivalence ratio producing stable flames from each hole decreases. However, after a certain bath temperature, the equivalence ratio value remains constant irrespective of the water bath temperature.

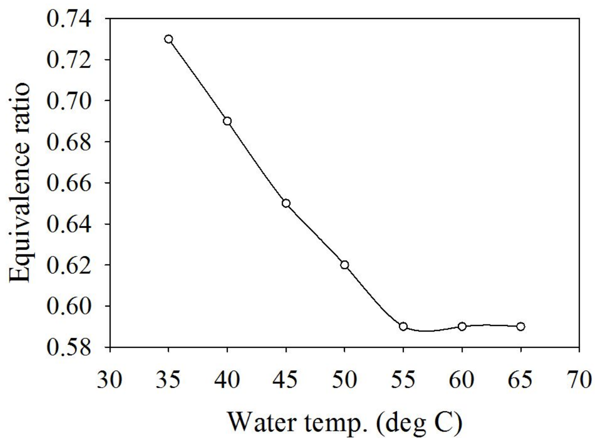


Fig. 7 Bath temperature and equivalence ratio at which stable flames are observed

4. Conclusions

The experimental study of pre-mixed flame characteristics for LPG and air mixture has been carried out to evaluate the lowest possible fuel-lean conditions and the results are summarized below.

1) The flame patterns at different equivalence ratios are analyzed and it can be concluded that the stability of the pre-mixed flame increased with decrease in the equivalence ratio.
2) The flame pattern changed into four different types with decrease in the ϕ values, which are oscillatory flames in the middle region, flames with oscillations along the centerline, flames with very little oscillations and stable flames from all the holes.
3) The stable flame front is obtained at the equivalence ratio values of 0.59, 0.54 and 0.48 for the LPG mass flow rates of 15 g/h, 21 g/h and 24 g/h, respectively.
4) CO and O_2 species concentrations decreased whereas the CO_2 and NOx species concentrations increased with increase in the volumetric flow rate of LPG and air mixture.
5) The temperature measurement is done and the results show that the temperature values are symmetrical about the centre line in each plane and decreased with increase in the height of a plane from the top surface of the burner.
6) The multi-hole matrix plate burner is found to be more efficient with less species emissions in comparison with an ordinary large size single-hole burner. The operability of the burner at ultra-lean mixing conditions is also achieved experimentally.

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