Visualization of Multiple Flame Interactions: Appearance Structure and Combustion of LPG-Air Premixed Laminar Flames

U. Makmool, S. Jugjai, and S. Tia

Abstract—Interaction of multiple premixed laminar flames was studied by visualizations of the modified flame structures. Typical line-of-sight flame chemiluminescence image and spatial resolved OH distribution by means of planar laser-induced fluorescence (OH-PLIF) technique were applied for these observations. The premixed flames of liquefied petroleum gas (LPG)/air mixture with three inline nozzles were established to simulate the practical flame characteristics produced by the practical cooking burners. The obtained results are compared as a function of primary equivalence ratio (Φ) and inter-distance (S/D_0) between nozzles. Effect of S/D_0 and Φ on the multiple premixed flame structures is well understood via the clarifying reaction zone distribution, which is in-situ visualized by OH PLIF technique. S/D_0 has a strong effect on interactions between flames, resulting in either flame enhancement or flame inhibition, depending on Φ . CO and NO_x emissions were measured in order to confirm the combustion performance of the multiple flames. It is recommended that the in-situ visualization is the focus for a study of the flame. This will help to avoid misunderstanding of the real combustion as it can be occurred by using the line-of-sight observation technique.

Index Terms—Partially premixed flame, flame structures, reaction zone, OH-PLIF, interaction between flames.

I. INTRODUCTION

A premixed flame is widely used for many combustion systems because it can produce high temperature from flames with low pollutant emissions. Regarding its wide application on domestic utilization in cooking stoves, multiple jets of the laminar premixed flames are produced for the heating processes. Even though the amount of gas used by each stove is small, more than 40 % of the total consumption of LPG (liquefied petroleum gas) in Thailand is used by this type of burner in the residential sector [1]. Thus, the improvement of thermal efficiency and emissions of cooking stoves operating with the premixed flame is a key target for present and future performance regulation. Many previous studies regarding single or multiple premixed flame jets have focused on the

heat transfer process from flames to the target, i.e. flame impingement has been extensively studied. Both heat transfer characteristics (which is implied by heat flux distribution or local/averaged Nusselt number), and pollutant emissions resulting from impinging flame jets were experimentally studied as a function of different key parameters. These include Reynolds number, equivalence ratio, nozzle-to-plate distance, distance between the adjacent burners [2], and inclination angles [3]. These parameters influence flow pattern, which creates distinctly different flame shapes. Remie *et al.* [3] presented a simple relation that predicts the parameters of the burnt gas flow of a flame jet, Bunsen-type flame after expansion over the flame front. They stated that the parameters of the burnt gas flow, i.e. jet velocity and jet width, are important to estimate the heat transfer from flame jets to products. Thermal performance parameters and dynamic properties of the flow field at a flame impingement area, i.e. velocity magnitude, turbulent intensity, vorticity and strain rate, were reported [4]. These confirm the correlation between thermal efficiencies and flow fields which are controlling structures of the producing flame jets.

Extensively, line-of-sight flame visualization techniques, e.g. direct photography of typical visible flame or imaging chemiluminescence emission of the combustion species, i.e. OH, CH and C₂ were performed [5], [6]. However, the emission intensity was integrated along a viewing line. Different parts of the flame, such as the primary and the secondary combustion zones and the inter-zonal region, were observed. Radiation components were not separated. In-situ visualization technique was used to solidly clarify the real combustion situation in flames.

This work investigates the variation of the main reaction zone as a function of the key parameters, i.e. primary equivalence ratio and inter-port spacing. Laminar premixed LPG-air multiple flame structure was observed using both typical line-of-sight observation and OH planar laser-induced fluorescence (OH PLIF) techniques. The OH PLIF was introduced to acquire the in-situ, two-dimensional image of the main reaction zone (i.e., regions containing high concentration of OH species). Precisely revealed reaction zone distribution is expected. This is as a result of the interaction between the adjacent flame jets to further improve burner performance.

II. METHODOLOGY

A. Test Burner and Facilities

The test burner was an assembly of a three-vertical-nozzle tube with an in-line arrangement. Each nozzle tube was made

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of a 160 mm stainless steel with a 7 mm inside diameter (D) and an 8 mm outside diameter (D_o), which is sufficient for a fully developed mixture flow before exit. The nozzle tube assembly was placed on a fixture capable of adjusting the inter-distance S between the nozzle centers. Multiple free flame jets with equal mixture flow rate and pressure drop across the rubber host could be produced by adjusting control valves connected to each nozzle tube inlet.

Compressed air was introduced as the primary air to the test burner, whereas the secondary, ambient air was naturally entrained by flames. The liquid-phase LPG (composed of roughly 70% and 30% by volume of propane and butane, respectively) was evaporated by a vaporizer before being supplied to the mixing chamber in order to keep uniformity of gas composition and pressure. Φ (defined by a ratio of the stoichiometric air required for complete combustion to the primary air supplied) was varied by decreasing the primary air flow rate from the stoichiometric air to fuel ratio, i.e. $\Phi = 1.02$, to a fuel rich condition at $\Phi = 1.72$, which corresponds to Reynolds number (based on properties of the primary air) ranging from 500 to 350, respectively. Three inter-distances were set at $S/D_o = 1.0, 1.5$, and 2.0 . The firing rate was kept constant at 0.45 kW (i.e., 0.15 kW for an individual nozzle). The flow rate of air was calibrated by a wet-type gas flow meter with an accuracy of 0.01 liters which was also used to measure the LPG gas flow rate.

B. Imaging of Flame Structure

The flames were captured by two different imaging techniques. The line-of-sight observation technique via the imaging of flame chemiluminescence was introduced. The spatially resolved imaging was carried out by means of the OH-PLIF technique. The imaging procedures to acquire the image types were the following:

C. Line-of-sight Imaging of Flame Chemiluminescence

To acquire flame chemiluminescence intensity, the ICCD camera, a combination of the intensifier (Hamamatsu C9016

series) and the CCD camera (Dantec HiSense MkII) equipped with the UV lens (Niker 60 mm, f 2.8) was used to amplify and collect the chemiluminescence of the flames, respectively. The intensifier unit was needed to increase the signal-to-noise ratio of the chemiluminescence which was very weak for a premixed flame. The light emission which was imaged was a result of the chemical excitation of molecular production at the electronic state. In hydrocarbon oxidation, major emitters are OH^* , CH^* , C_2^* , and CO_2^* [7], [8]. The capturing, i.e. the exposure time, was done continually along the width of 10 ms.

D. Spatially Resolved Imaging of OH-PLIF

The PLIF experimental set-up is shown schematically in Fig. 1. The system components and the mechanism to produce the UV laser sheet to excite the OH species in flame were explained in detail in Makmool (2011) [9]. The UV laser beam of wavelength 282.6 nm and the maximum energy per pulse of 8 mJ was produced. The energy pulse monitor (EPM) was mounted between the laser head and the light sheet formation optic system. Then, it was transformed to a thin sheet with the height fixed at 35 mm. The illuminated plane was cut off at the section along the centerline of the multiple burners that was normal to the camera. Thus, the two-dimensional distribution of fluorescence emission of the excited OH could be observed in the flames.

Fig. 1. Schematic diagram of OH PLIF measurements.

Fig. 2. Schematic diagram of exhaust gases measurements.

The LIF signals of the OH fluorescence emission were detected with an ICCD camera. The optical interference filter of 313 ± 25 nm was coupled with the UV lens (Niker 60 mm, f 2.8), installed in front of the ICCD. This allowed only the selected fluorescence to pass, blocking undesirable ambient light (reflection and stimulated emission). The intensifier

gate width was set at 1,000 ns. In addition, the raw OH-PLIF image was subtracted from the background image to completely suppress any luminosity from flames as well as artificial lighting in the test room. One hundred instantaneous images were averaged and reported in the result as the mean of the OH-PLIF images of all case studies. The radical

absorption was not corrected due to the relatively small field of visualization.

E. CO and NO_x Measurements

The pollutants emission test was guided by the European testing standards for gas heated catering equipment [10], [11]. A standard hood was used to collect exhaust gases to the analyzer with the minimizing of dilution effects (Fig. 2). The pan was filled with water and covered by a hood for collecting the exhaust gases separately from the generated steam, which was vented through the vertical channels integrated into the hood. The exhaust gases were then sampled by a probe which connected to an emission analyzer at the hood exit. Emission analysis was carried out by using the Messtechnik Eheim model Visit01L, which is a portable emission analyzer designed specifically for quasi-continuous measurement. The measuring ranges of the analyzer were 0-10,000 ppm for CO and 0 - 4,000 ppm for NO with the measuring accuracy of ± 5 , ± 4 ppm (from the measured value), respectively, and resolution of 1 ppm. Repeated measurement showed an uncertainty of about 10% for the species concentrations. Combustion was checked within 15 minutes after ignition, and the concentrations of CO, NO and CO₂ were measured. To achieve adequate accuracy, dilution by ambient air was arranged so that the CO₂ content in the sample of the products of combustion was at least 2%. This was done by adjusting an opening area of the restrictor installed at the hood exit.

III. RESULTS AND DISCUSSION

A. Flame Appearances

Fig. 3a and Fig. 3b show the corresponding flame chemiluminescence images and the OH PLIF images of a single flame, respectively. The equivalence ratio of 1.02, 1.20, 1.28, and 1.71, from the left to the right, was increased by decreasing primary air flow rate. These single flames images were recorded and presented in order to be used as the reference flame structures, which do not factor in the interaction between the nearby flames.

B. Line-of-sight Chemiluminescence Images of the Single Flame

Fig. 3a shows the corresponding line-of-sight images of chemiluminescent flame. The color contour represents the chemiluminescence intensity; the highest to the zero one are color from red to dark blue, respectively.

Fig. 3. Structure of the single premixed flames.

As shown in these images, for the fully premixed flame at $\Phi = 1.02$, the inner cone is slender in shape but is diluted in flame chemiluminescence intensity. Increasing Φ , the inner premixed cone length decreases while flame chemiluminescence intensity increases. The maximum intensity was reached at $\Phi = 1.28$ (Fig. 4), corresponding to when the minimum premixed cone (Fig. 5) was achieved. This may infer that the maximum burning rate is achieved at this equivalence ratio. Increasing equivalence ratio to $\Phi = 1.71$, the premixed cone length increases and its chemiluminescence signal decreases (see Fig. 4 and Fig. 5).

As shown the chemical reactions are taking place closer to the burner rim (see Fig. 3a) rather than around the premixed cone, due to an insufficient amount of premixed air. Near the burner rim, secondary air entrainment occurs most effectively. This is owing to a high velocity of the emerging jet induces the stationary surrounding air.

C. OH PLIF Images of the Single Flame

Fig. 3b shows the corresponding images of OH PLIF. The OH PLIF contours are used as a tool to indicate the oxidation zone. In contrast to the line-of-sight images, the OH PLIF signal was not detected inside the premixed cone. This is due to the fact that combustion does not take place there. The OH region distribution extends from the outer side of the premixed cone to the diffusion layer. At the stoichiometric flame, i.e. $\Phi = 1.02$, the OH region relies uniformly beyond the premixed cone. The highest intensive zone appears around the tip of the premixed cone, due to a highly preheating effect obtained by diffusion of the high temperature intermediate species from both sides of the apex. Thus, the fuel oxidation process within this location is enhanced. As Φ increases (i.e., $\Phi = 1.20$ and $\Phi = 1.28$), the OH region moves away from the inner cone to the secondary combustion zone and a double flame structure (i.e., premixed flame plus diffusion flame) is established. In a fuel-rich mixture ($\Phi = 1.71$), the OH PLIF structure is nonpremixed-like flame structure, i.e., the premixed cone does not exist.

Fig. 4. Effect of Φ on the maximum chemiluminescence intensity.

Fig. 5. Effect of Φ on the premixed cone length.

Due to the fact that primary air concentration is too low for fuel oxidation, burning velocity is relatively low, long flame length is established. High OH PLIF intensity occurs in the outer region, where fuel and air are reached each other. Thus, the oxidation reaction is controlled by diffusion of the fuel-rich mixture into the surrounding air.

D. Multiple Flame Interactions

To investigate the effect of multiple flame interaction on flame structure, a modification of flame shape was determined by means of a change in the premixed cone length. In Fig. 6, premixed cone length of the central flame of the three in-line multiple flames (L_m) was measured and compared with that of a single flame (L_s), with no nearby flames. It was presented in term L_m/L_s . In this comparison, it shows an enhanced burn rate of the multiple flames because the premixed cone length was reduced compared with that of the single flame (i.e., $L_m/L_s < 1$). The richer flame results in a stronger flame interaction, i.e. the larger reduction in flame length occurred, especially at $S/D_o = 1.0$. The reduction in flame length may be due to the strong self-preheating effect which occurred when the flames were placed close to each other. The burn rate was enhanced, and the central premixed cone length was reduced.

Fig. 7a and Fig. 7b, respectively, show the corresponding chemiluminescence and OH PLIF images of the multiple flames of different inter-distances, i.e., $S/D_o = 1.0, 1.5$, and 2.0 at the same equivalence ratio of $\Phi = 1.28$. In Fig. 7a, a significant difference in intensities of the chemiluminescence signals of the flames was not observed. However, at $S/D_o = 1.0$, the central flame yielded a slightly higher chemiluminescence intensity and smaller premixed cone as compared with those of the nearby ones.

Fig. 6. Effect of S/D_o on reduction of the premixed cone length.

Fig. 7. Multiple flames appearance at $\Phi = 1.28$.

At this spacing, the combustion may be significantly improved because of the intense exchange of heat and reactive species between the nearby flames resulting in a greater reduction of premixed cone length (as observed in Fig.

6). Flames at the other greater inter-distances yield no significant difference in either the chemiluminescence intensity or the premixed cone length.

In contrast to the line-of-sight chemiluminescence images, the OH-PLIF images (Fig. 7b) show vast differences in the structures of the three flame spacing. At $S/D_o = 1.0$, the flame produces a non-uniform distribution and less intense OH PLIF structure. Due to a relative decrease in OH PLIF intensity, it seems as if the oxidation via OH distribution is inhibited especially at the central area of the multiple flames.. It is indicated that a poor or incomplete combustion occurs inside the central region of the multiple flames. This phenomenon is in the opposite trend to the observation of flame chemiluminescence image, as previously explained.

At spacing of $S/D_o = 2$, three independent, cool, inner cones covered with their own outer cones of the OH species are obtained. The interaction between the nearby flames was not observed, i.e. the OH PLIF structure was not significantly changed compared with that of the single flame at the same equivalence ratio (see Fig. 3).

An interesting phenomenon is revealed with multiple flames at an intermediate inter-distance of $S/D_o = 1.5$. At the outer region of each individual flame, the OH species merge into a single, large, global outer cone of the OH PLIF. Higher intensities with more uniform distribution of OH-PLIF structure were produced as compared with that of the other S/D_o .

These results show that the interpretation of flames based on the chemiluminescence images alone can lead to misunderstanding of the related combustion phenomena.

E. CO and NOx Emissions

Fig. 8. Effect of S/D_o and heating height on emission at $\Phi = 1.28$.

Fig. 8 shows corresponding combustion performances in terms of CO and NO_x emissions of the impinging multiple flames at differing heating height. In this case, the distance of impingement surface (i.e., the water-filled pan) from the burner exit was varied and normalized by the nozzle diameter (H/D). This effect was also investigated as it will be applied to the household cooking burner. The result shows that the closest multiple flames ($S/D_o = 1.0$) yield the highest CO emissions and the lowest NO_x emission. Seemingly, the poorest combustion was achieved compared with other flame spacings. By this combustion measurement, the result not agrees with observation by the typical line-of-sight flame image. On the other hand, it was well correlated with the in-situ OH PLIF image in which the poor OH distribution

was observed for the multiple flames at $S/D_o = 1.0$ (Fig. 7b). Increasing S/D_o decreased CO emission but increased NO_x emission because the larger amount of secondary air is entrained through the free space between each adjacent burner.

Regarding the effect of heating height, at $H/D = 1.0$, the flame jets were emerging from the burners with relatively high velocities and interrupted by the presence of impingement surface downstream. Hence, the residence time of combustion is shortened and the flames are strongly quenched. Therefore, significantly high CO emission and low NO_x was measured for all considered S/D_o .

At $H/D > 1$, the difference in combustion performances of both CO and NO_x emission, by the influent of S/D_o , was revealed due to the fact that combustion efficiency becomes dominant. As H/D increased, CO emission decreased and NO_x emission increased. This is explained by the fact that an increase in H/D will reduce the amount of cold mixtures which will impinge to the surface and increase the combustion residence time. It also increases the amount of the secondary air entrainment. In contrast to the CO emissions, the highest NO_x emission is achieved at $S/D_o = 1.5$ and at any given H/D . It can be inferred that the highest flame temperature might be achieved; hence, high thermal- NO_x was produced. Compared to the flame at $S/D_o = 2.0$, where the individual flame in the group is freely combustible as the lowest concentration of CO gases was detected, it seem as moving the flames closer to each other at $S/D_o = 1.5$, combustion enhancement was occurred. Even as CO emissions slightly increase, the higher flame temperature may be achieved owing to higher measurable NO_x emission. At this flame spacing, interaction between the adjacent flames produces combustion recirculation and preheats surrounding air. Thus, it shows improved combustion efficiency. Furthermore, the oxidation reaction is distributed intensively inside the interaction regions of the nearby flames (Fig. 7b). On the other hand, combustion can be considered to be inhibited for the grouped flames with no gap, i.e. $S/D_o = 1.0$. Not only is the secondary air entrainment blocked, but the flames may also be quenched by the interference from nearby flames. Combustion efficiency decreases, yielding highest CO emission and lowest NO_x .

At $H/D = 5$, all groups emit less CO. At the highest impingement, both CO and NO_x emissions become identical. The flames are less inhibited and are more naturally burned. Combustion residence time and the amount of surrounding air increase high enough to complete the combustion.

IV. CONCLUSION

OH PLIF technique was implemented with line-of-sight chemiluminescence imaging technique in order to capture flame appearances to study the affect of the interaction of multiple premixed liquefied petroleum gas (LPG)-air flames. The combustion was checked via measuring CO and NO_x emission at differing inter-spacing between the flames. The following conclusions can be drawn from the studied results:

1) The flame at equivalence ratio of 1.28 emits maximum chemiluminescent intensity and corresponds to the smallest premixed cone length.

- 2) The interaction of the multiple flames significantly modified natural combustion of the individual flame. S/D_o has a strong affect on interactions between flames, resulting in either flame enhancement or flame inhibition, depending on Φ .
- 3) The OH-PLIF measurement was the most reliable technique to uncover the combustion situation existing in the flames. A clarifying reaction zones distribution was revealed and can be used for a better explanation of the effect of flame structure on emissions. Flame enhancement and inhibition were clearly observed, which were accessed with difficulty by means of the conventional line-of-sight imaging techniques.
- 4) Interpretation using only the appearance chemiluminescence structure is ambiguous and can lead to misunderstanding in the real combustion taking place in the flame. This can be explained by the fact that emission signals are line-of-sight integrated.
- 5) This study results in an understanding of the insight into the structure of the multiple premixed impinging flames. This may be useful in the future design a practical cooking burner.

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