Numerical and Experimental Investigation on the Combustion of Premixed Propane – Air Mixtures

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Abstract. The behaviour of a premixed propane flame in three dimensions was studied numerically and experimentally in a jet flow combustor at different equivalence ratio, Reynolds numbers and turbulent intensity. The detailed attract here has come up with data of propane-air mixtures flame propagation over a range of equivalence ratios (\(e\)) between 0.6 lean flame to 1.3 rich flame on environmental conditions of temperature and atmospheric pressure. The instantaneous flame was visualized using a high-speed camera on the domain of the burner of 100 mm diameter. From 174 to 472 images were recorded for each experimental test. Flame surface density was obtained from the instantaneous image of the flame. The influence of the flame area density in the evaluation of the flame propagation will be discussed. The study shows that the increase in turbulent intensity leads to increase the turbulent flame propagation speed subsequently increase in flame area density at a constant an equivalence ratio value. Also, it was shown that the wrinkling flame shape is the dominant characteristic leading to the increased turbulence intensity. The research results are expected to be used for developing jet flow combustor burners.

Keywords: turbulent combustion, premixed flame propagation, equivalence ratio.

1. Introduction
Currently, renewable energies are receiving increasing attention every day. These energies are used to reduce gasoline and fuel consumption due to their burning every day. So the goal is to identify fuel mixtures with fewer effect for climate without losing its main properties to their purpose. It is necessary to investigate the optimization of the burning, which make progress a project and design the burners which need the information of the main flame characteristics, such as mixture flame propagation speed, laminar flame speed and flame surface density. An essential parameter in the laminar flame study is the determination of laminar flame speed (\(S_L\)), which have been calculated using diverse methods, such as the use of a flat flame burner with a Bunsen burner [1-4], spherical flames [5] or just a Bunsen burner. Sadeghi et al. [6] studied experimentally the influence of equivalence ratio on methane premixed flame drive in the combustor. Their results showed that the flame location in the combustor is moved toward the reactor outlet by increasing the equivalence ratio toward the fuel rich side.
Richardson et al. [7] studied the influence of equivalence ratio differences on flame propagation and structure of methane-air laminar counterflow flames. They showed that the propagation velocity counts on the equivalence ratio rise through a flame.

The investigation on the flame area density equation and its numerical explanation are listed in Prasad et al. [8] and Mohammed Kh. Abbas [9]. The crossed-planar tomography techniques are using by Bingham et al. [10] to determine the flame surface density from data of tomographic images. Moreover, the experimental study of flame area density is related to low turbulence intensities such as Deschamps et al. [11]. The influence of turbulence on the flame location was studied by a few of researchers. Hartung et al. [12] used circular duct combustor to recognize flame location from intensity of the hydroxide ion value. Moreover, the flame position was studied by utilizing laser tomography technique [13].

Lean premixed flame in a gas turbine combustor was investigated by Yilmaz et al. [14]. They utilized methane - air flames at different equivalence ratios values. Their results showed that flame length and thickness were decreases at increasing equivalence ratio. Thus concerning to the significance of the influence of flame moving on the function of the jet flow combustor, the main goal of this study is concentrate on the investigation of the significant factors on the function of premixed propane–air flames in the jet flow combustor. Therefore, in this paper, the influence of mixing ratio between propane and air (as equivalence ratio), turbulent intensity and flame area density on flame moving (as flame location) are investigation.

2. mathematical model

The equivalence ratio is the mass of fuel-to-oxidizer ratio to the stoichiometric mass fuel-to-oxidizer ratio and it is determined as follows.

\[
\phi = \frac{\dot{m}_{C3H8}}{\dot{m}_{air}} = \frac{\dot{m}_{C3H8}/\dot{m}_{air}}{\left(\dot{m}_{C3H8}/\dot{m}_{air}\right)_{st}}
\]  

(1)

Where, the \(\dot{m}_{C3H8}\) and \(\dot{m}_{air}\) are a mass fraction of propane and air respectively, and subscript st denoted to stoichiometric condition.

The combustion rate plays a vital role in the premixed turbulent flames. When the scale of turbulence is greater than the thickness of the flame, the turbulent flow wrinkles the laminar flame front and increases both the reaction rate and the flame surface area. The total combustion rate of the flame is evaluated by integration the local combustion rate over the flame surface. The flame surface density, \(\Sigma\) is known as the mean flame-surface area per unit volume of the wrinkling flame caused by turbulence. The combustion rate of the reactants per unit volume (\(\dot{\omega}\)), can be described as[15,16].

\[
\dot{\omega} = \rho_u S G \Sigma (x)
\]  

(2)

where \(\rho_u\) is represent the density of the unburned gases, G is the flame stretch factor and \(\Sigma (x)\) is the local flame surface density. The formula of the flame surface density based on the progress variable of the flame can be described as [15,17,18,19],

\[
\Sigma (x) = \langle |\nabla c| \delta (c - c_f) \rangle
\]  

(3)

where \(\nabla c\) is the flame front gradient, \(\delta (c - c_f)\) is the instantaneous flame front location.

3. Experimental details

Figure 1 is depicted a jet flow combustor with 100 mm inner diameter and 550 mm length was used as an experimental reactor. Turbulence was generated by an active grid and include a sets of rotating wings by ten rods connected to ten motors. Test rig includ a set of piping and valves to transmitted and controlled fuel and air mixture. The mixture is mixed at various equivalence ratios, then injected inside the combustion chamber to produce a premixed flame. The flame can be stabilized by flame holder. Also, include high speed camera to capture images of premixed flame at environment conditions. The image has (576 x 720) pixels visualized to representing study on the characteristic of the flame location and topology. Each image is examined to debrief the flame area density. For each flame factor (equivalence ratio and Reynolds number), 174 - 472 instantaneous flame images are recorded. The
mean of the instantaneous flame images is processed to get the flame contour which represented flame location inside the combustor domain to estimate flame surface density. Table 1 presents the inlet flow conditions at different equivalence ratios used in this study.

![Figure 1. Schematic diagram of the experimental facility setup.](image)

Table 1. Inlet flow conditions at different equivalence ratios

| Equivalence ratio, \( \phi \) | Mass fraction of fuel | Mass fraction of Oxygen | Mass fraction of Nitrogen | Inlet mean velocity (m/s) |
|-------------------------------|-----------------------|-------------------------|---------------------------|---------------------------|
| 0.6                           | 0.0389                | 0.2353                  | 0.7258                    | 0.1720                    |
| 0.7                           | 0.0451                | 0.2338                  | 0.7211                    | 0.1484                    |
| 0.8                           | 0.0512                | 0.2323                  | 0.7165                    | 0.1307                    |
| 1                             | 0.0632                | 0.2293                  | 0.7075                    | 0.1059                    |
| 1.1                           | 0.0691                | 0.2279                  | 0.7030                    | 0.0969                    |
| 1.3                           | 0.0806                | 0.2251                  | 0.6943                    | 0.0830                    |

4. Results and discussion
The contour of the numerical results of flame surface density \( \Sigma(x) \), at different equivalence ratios from lean \( \Phi=0.6 \) to rich \( \Phi=1.3 \) values is shown in Figure 2. The \( \Sigma(x) \) profile is maxima at the center of the burner and has a Mushroom shape. The flame location is confined in the combustion chamber domain in the area between the flame holder region and the end of jet burner pipe. The \( \Sigma(x) \) profiles have similar concave shapes symmetry about the central burner axis and do not change whatever equivalence ratio values; because of \( \Sigma(x) \) values are almost equipollent. This action was already revealed by F. Halter et al. [16]. This is related to turbulent length scale condition that remains fixed at variation of the equivalence ratio.
The flame surface density $\Sigma(x)$ profile as a function of the progress variable at different equivalence ratios is shown in Figure 3. The $\Sigma(x)$ is increased until approximately the half of reactants is transformed to products then decreased for both $\Phi=0.555$ and $0.625$. These results in good agreement trend with results obtained from Gulder and Samllwood [15].

The experimental results of this study are implemented in Figure 4, [3, 20]. The first row represented the instantaneous snapshots of flame front propagations in images, 1-5 and the main of 174 images in image 6 at $\Phi=0.555$ and Reynolds number equal to 4660. The flame location is confined in the area between the flame holder region and the end of jet pipe flow. Flame holder stabilizes the flame. The ten motors to rotate the active grid to generate turbulence are seen in these images. The second row represented the instantaneous snapshots in images, 1-5 and the main of 341 images in image 6 at $\Phi=0.588$ and $Re=4410$. In these images, we focus on the flame region only. In the third row images which represented flame front propagations in images, 1-5 and the main of 472 images in image 6 at $\Phi=0.606$ and $Re=2571$. In the last row which represented flame front propagations in images, 1-5 and the main of 316 images in image 6 at $\Phi=0.625$ and $Re=2496$. Hence the flame is still confined between the flame holder region and the end of jet pipe flow region. Unfortunately, all tests were implemented in lean flame range. All experimental images are showing the same tendency of flame locations whatever equivalence ratio values. This scenario is a well-known phenomenon observed in combustion experiments of Halter et al. [16].

The influence of turbulent intensity on flame front propagation is display in Figure 5, which show the experimental results of the main of 341 locations at $\Phi=0.588$ and $Re=4410$ at different turbulent intensity from weak to strong values. The flame front propagations are clear different by increasing
turbulence. The flame location is moved toward burner jet pipe flow by increasing turbulence subsequently, the flame surface density is increased. Strong turbulence influential usually results in flames that burn propagates faster and release higher heat.

Figure 3. flame surface density profile as a function of progress variable at different equivalence fuel-air ratios.
Figure 4. Instantaneous snapshots (1-5), and the average (6) of the experimental flame propagation images at different equivalence ratios and Reynolds numbers.
5. Conclusion

In this work, flame surface densities for premixed propane-air flames were studied numerically and experimentally at different equivalence ratios, Reynolds number and turbulent intensity. At different equivalence ratio range of up to 1.3, the flame surface density contour as a function of the progress variable was found to be insensitive to equivalence ratio variation. Moreover, the asymmetric stable flame may be formed inside the combustor domain. Our results denote that the increase in flame surface density by diverse equivalence ratio may not be the controlling for flame speed propagation growing in turbulent combustion region especially when $\Phi$ is increasing from 0.555 to 0.625 and decreasing Reynolds number from 4660 to 2496. Furthermore, Flame surface density and the flame location was showed more sensitive by increasing turbulent intensity and moved the flame location toward the combustor jet pipe flow. Hence, this study is thought to be beneficial for those who work in turbulent combustion.

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Figure 5. Mean of 341 instantaneous of experimental flame location at $\Phi$=0.588, Re=4410 and (1) weak, (2) moderate and (3) strong turbulent intensity.
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