Consumption rate characteristics of a fine-scale unburnt mixture in a turbulent jet premixed flame by high repetition rate PLIF and SPIV

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Abstract
A 10 kHz simultaneous measurement of OH-CH planar laser induced fluorescence (PLIF) and stereoscopic particle image velocimetry (SPIV) is applied to a methane-air turbulent jet premixed flame. The measurement of the flame tip for high Reynolds number conditions shows that isolated fine-scale unburnt mixtures, so-called unburnt mixture islands or reactant pockets, are frequently generated. POD analysis shows that the separation of unburnt mixture from the upstream main reactants is the characteristic flame structure. In our previous study (Johchi et al. 2015), the consumption rates of isolated unburnt mixtures are estimated from changes of area of unburnt region detected in OH and CH PLIF images under the assumptions that the isolated unburnt mixtures are spherical and pillar shapes. The most expected consumption rate conditioned by curvature of flame front is about 0.71 m/s, which is much higher than the laminar burning velocity of the corresponding reactants. The consumption rate increases with the decrease of the radius of the isolated reactants. The reason that the consumption rates of the fine-scale isolated unburnt mixtures are much higher than the laminar burning velocity is discussed based on heat conduction in the isolated unburnt mixture by assuming that the heat release from mass difference between going out and coming in the preheat zone increases the mean temperature of remained reactants to consider enhancement of the effect of heat conduction. From the analysis, characteristic scale of fine-scale unburnt mixture in which heat conduction effect is significant is discussed.

Key words: Fuel consumption rate, Turbulent premixed flame, Reactant pocket, High repetition rate PLIF and PIV

1. Introduction

Consumption rate of reactants in turbulent flows is one of important factors of describing developments for turbulent premixed flames. It is still required to deepen understanding of the consumption rate characteristics and of those mechanism, and then to model them. In the discussion of turbulent burning velocity, flamelet concept has been conventionally considered. Effect of flamelet structures on turbulent burning velocity is reviewed by Driscoll (2008), it is reported that non-flamelet behavior was not significant in the range of the analysis in his study.

Recent progress in computational technologies makes it possible to investigate turbulent flame structures by direct numerical simulation (DNS) with a detailed kinetic mechanism or, at least, reduced one (Baum et al. 1994, Chen et al. 1999, Tanahashi et al. 2000, Tanahashi et al. 2002a, Nada et al. 2004, Sankaran et al. 2007, Aspeden et al. 2011, Hawkes et al. 2012, Shimura et al. 2012). Griffiths et al. (2015) have investigated flame topology by using the recent DNS data of a hydrogen-air premixed flame (Hawkes et al. 2012) and shows the frequency of occurrence of typical flame structures, such as tunnel structures similar to handgrip structure in our previous study (Nada et al. 2004) and reactant pockets as shown in our previous study (Shimura et al. 2012) and so on, whereas flamelet approach was considered to be valid for obtaining topological features in the study by Griffiths et al. (2015). Amato et al. (2015) have investigated flame topology
and burning velocity based on the DNS data of lean hydrogen-air premixed flame (Aspeden et al. 2011), and indicates that the flame with low and negative curvature could show non-flamelet behaviors.

Flame structures and those characteristic flame speeds, such as absolute flame propagation speed and flame displacement speed, for high Reynolds number and more practical conditions have been investigated experimentally. A lot of researches have been conducted to understand turbulent flame structures by multi-species planar laser induced fluorescence (PLIF) (Donbar et al. 2000, Bökcke et al. 2000, Tanahashi et al. 2005, Kiefer et al. 2008, Shimura et al. 2011, Zhou et al. 2015). In the recent work (Zhou et al. 2015), multi-species PLIF including HCO has shown that the broadened reaction zones can be formed in the distributed reaction zones regime. Also direct measurements of the characteristic flame speeds have been conducted by utilizing PLIF and particle image velocimetry (PIV) (Tanahashi et al. 2008a, Kerl et al. 2013, Trunk et al. 2013, Peterson et al. 2015, Johchi et al. 2015). Double-pulse CH PLIF (Tanahashi et al. 2008a) was developed and used for investigation of the absolute flame propagation speed. The double-pulse CH was extended by introducing stereoscopic PIV to measure local turbulent displacement speed directly (Tanahashi et al. 2008b). PIV itself has been utilized for that purpose by defining the location of flame front with local maxima of particle number density (Kerl et al. 2013). Recently, high repetition rate PLIF and PIV are used for investigation of local flame displacement speed in a freely propagating flames (Trunk et al. 2013), a turbulent jet premixed flame (Johchi et al. 2015) and a spark-ignition engine (Peterson et al. 2015). In our previous study (Johchi et al. 2015), 10 kHz measurement of OH-CH PLIF and stereoscopic PIV (SPIV) was applied to the tip of a methane-air turbulent jet premixed flame, and characteristics of consumption rates of fine-scale unburnt mixture islands with respect to flame curvature are investigated. Particularly, for the fine-scale unburnt mixture (reactant pockets), flame displacement speed can be considered as the consumption rate. The results have shown that the turbulent consumption rate increases with the increase of curvature. This fact means that the fine-scale unburnt mixture islands play important role in the increase of global turbulent burning velocity. It should be noted that, basically, these kinds of investigations of flame displacement speeds are based on the identification of an isosurface, typically of the maximum gradient of OH PLIF intensity or particle number density, while it has been suggested that flame structure in fine-scale unburnt mixture cannot be considered as flamelet. Hence it is required to deepen understanding of the characteristics of consumption rate.

In the present study, effects of heat conduction on increase of the consumption rate in the fine-scale unburnt mixture are discussed based on the experimental results obtained in the previous study (Johchi et al. 2015). In the following sections, measurement methods are described in Sec. 2, followed by the characteristics of flame structures and the relation between consumption rate and curvatures in Sec. 3, and the effects of heat conduction on increase of the consumption rate are discussed in Sec. 4. The results are concluded in Sec. 5.

2. Measurement methods

2.1. High repetition rate OH-CH PLIF and stereoscopic PIV

Details of the experimental setup for 10 kHz OH-CH PLIF and SPIV can be found in the literature (Johchi et al. 2015), and are shortly introduced here. For high repetition rate CH PLIF measurement, the \( Q_1(7,5) \) transition of the \( B^2Σ^+ ← X^2Π(0,0) \) band at 390.30 nm is excited and fluorescence from the \( A-X(1,1), (0,0) \) and \( B-X(0,1) \) bands between 420 and 440 nm is detected. For OH PLIF, the \( Q_1(7) \) transition of the \( A^2Σ^+ ← X^2Π(1,0) \) band at 282.93 nm is excited and fluorescence from the \( A-X(1,1), (0,0) \) and \( B-X(0,1) \) bands between 306 and 320 nm is detected. Figure 1 shows a schematic of experimental setup. The laser system of high repetition rate OH-CH PLIF consists of an Nd:YAG laser (Edgewave, a special version of HD-40-III) and two dye lasers (Sirah, Credo). The Nd:YAG laser gives 6 mJ/pulse for 355 nm and 5 mJ/pulse for 532 nm, independently and simultaneously. Each laser beam from the Nd:YAG laser pumps one dye laser with a blend dye of Exalite 389 and Exalite 398 for CH PLIF and Rhodamine 6G for OH PLIF. Laser pulses are emitted with about 0.8 mJ/pulse for 390 nm and 0.2 mJ/pulse for 283 nm at 10 kHz. After two laser beams are lead to the same axis by a dichroic mirror, the beams are expanded by sheet forming optics. The fluorescence of CH radical is collected by 100 mm f/2.0 lens (Carl Zeiss, Makro Planar T*2/100 ZF) with a band pass filter (Semrock, FF01-434/17-25) to block flame radiation and scattering light by particles, and imaged onto an image intensifier (Hamamatsu Photonics, C10880-03F). The amplified images are detected by a high speed camera (Photron, SA-X, 1024 × 888 at 10 kHz). The fluorescence of OH radical is collected by 105 mm f/1.5 UV lens (Nikon, UV-Nikkor) with a band pass filter (Semrock, FF01-320/40-25) and imaged onto an image intensifier (Hamamatsu Photonics, C6534). The amplified images are detected by a high speed camera (Photron, SA-5, 896 × 704 at 10 kHz).

The time-resolved stereoscopic PIV consists of two Nd:YAG lasers (Lee Laser, LDP-100MQG), optical system and two high speed cameras (Photron, SA-5, 736×448 pixels at 20 kHz). The maximum power of these lasers is 50 W at 10 kHz.
kHz. Laser beams from two lasers become double-pulsed beams through the laser beam combining optics of a polarizer and a half-wave plate, and the double-pulsed beams are expanded by the laser sheet optics same with that for PLIF. The cameras are located with about ±20.0° to capture stereoscopic particle images, and Scheimpflug condition (Prasad 1995) is applied. SiO$_2$ of 1.0 μm mean diameter are used for tracer particles. A high spatial resolution PIV algorithm used in this study can be found in our literatures (Tanahashi et al. 2002b, Tanahashi et al. 2008c).

2.2. Turbulent jet premixed burner and experimental conditions

The investigation of consumption rate was conducted through the high repetition rate PLIF and stereoscopic PIV in turbulent jet premixed flames. The details of the jet burner can be found in the previous literatures (Ueda et al. 2009, Johchi et al. 2015). Figure 2 shows a schematic of the turbulent jet premixed burner. This burner has a main jet nozzle of 10 mm inner diameter (D) and a surrounding nozzle of 60 mm for flame holding. In the previous study (Johchi et al. 2015), the high repetition rate measurement was conducted for three different jet velocity: $U_0 = 10, 15$ and 20 m/s ($Re_D = 6667, 10001$ and $13333$). $Re_D$ is Reynolds number based on the nozzle diameter (D) and mean axial velocity at the jet exit. Equivalence ratio is fixed to 1.0 for the main flame and 0.86 for the surrounding flame. Measurements are conducted at axial distance of $x/D = 5, 7, 8$ and 10. Here, x is distance from the jet exit. There is no preheating for reactants through the experiments. Table 1 shows the turbulence characteristics measured by a hot-wire constant
temperature anemometer with X-probe (Kanomax Japan, Model0250R, tungsten Φ=5 μm) preliminarily for inert flow. In table 1, \( l \) is the integral length scale, \( Re_l \) is the Reynolds number based on \( l \) and \( u'_{rms} \), \( Re_\lambda \) is the Reynolds number based on Taylor micro scale \( \lambda \) and \( u'_{rms} \), \( \eta \) is Kolmogorov length scale and \( S_L \) is the laminar burning velocity. These conditions are classified into the corrugated flamelets in the turbulent combustion diagram. Details of laser thickness and configuration used in the measurement can be found in the literature (Johchi et al. 2015). The laser thicknesses of CH and OH PLIF are about 400 μm. In the present study, the results for the case of \( U_0 = 20 \text{ m/s} \) and \( x/D = 10 \) are mainly analyzed.

3. Characteristics of flame structures

Figure 3 shows an example of successive images of flame and flow structures for the case of \( U_0 = 15 \text{ m/s} \) and \( x/D = 7 \) obtained by the laser diagnostics. Due to the entrainment of burnt gas in the unburnt region, flame front sometimes appears to be disconnected. In these region, strong flow motion can be observed, which is caused by the large scale vortical motion generated by Kelvin-Helmholtz instability. Fine-scale unburnt mixtures are frequently generated in the more downstream region and for higher Reynolds number cases. Figure 4 shows an example of successive images of OH and CH PLIF for the case of \( U_0 = 20 \text{ m/s} \) and \( x/D = 10 \). The convected large scale unburnt mixture islands are split into small ones in this region.

To investigate the dominant structure of the turbulent jet premixed flame, a snapshot proper orthogonal decomposition (POD) analysis (Sirovich 1987) is applied to a series of 10,000 OH PLIF images for the case of \( U_0 = 20 \text{ m/s} \) and \( x/D = 10 \). Figure 5 show the obtained POD modes. Since a mean OH image is preliminary subtracted, a positive value means burnt gas in the unburnt region and a negative value represents unburnt mixture in the burnt region on average. The first mode, which has 43% of the energy, is uniform distribution and represents burnt region without any unburnt mixture. The POD eigenmodes well represent characteristic flame structures shown in Fig. 4. Around flame tip (\( x/D = 10 \)) in high Reynolds number condition (\( U_0 = 20 \text{ m/s} \)), the second, third and sixth modes show the convection of large scale unburnt mixture islands. The less energetic modes, after seventh mode, represent the formation and rapid consumption of the fine-scale unburnt mixture. These characteristic structures which appear in high energetic modes are not observed in the upstream or in lower Reynolds number cases, and are expected to be consumed rapidly and it may enhance turbulent burning velocity. The formation of fine-scale unburnt mixture and its rapid consumption are statistically meaningful around the tip of the high Reynolds number jet premixed flame.

| \( u_0 \) [m/s] | \( x/D \) | \( Re_0 \) | \( Re_\lambda \) | \( u'_{rms} \) [m/s] | \( l \) [mm] | \( \lambda \) [mm] | \( \eta \) [mm] | \( u'_{rms}/S_L \) | \( l/\delta_T \) |
|----------------|---------|----------|------------|--------------|--------|--------|--------|-------------|--------|
| 10             | 5       | 666.7    | 93.4       | 1.15         | 6.21   | 0.998  | 0.0580 | 2.88        | 150.8  |
| 15             | 7       | 1000.1   | 173.1      | 2.12         | 11.65  | 1.006  | 0.0429 | 5.31        | 282.8  |
| 20             | 8       | 1333.3   | 228.5      | 2.81         | 15.22  | 0.999  | 0.0372 | 7.04        | 369.5  |
| 20             | 10      | 1333.3   | 256.8      | 2.87         | 18.83  | 1.100  | 0.0386 | 7.19        | 457.1  |
Fig. 4 Successive images (from the left) of OH (upper) and CH (lower) of the turbulent jet premixed flame for the case of $U_0 = 20$ m/s and $x/D = 10$.

Fig. 5 The first ten POD eigenmodes of flame structure for $U_0 = 20$ m/s and $x/D = 10$ (The values next to the number of each mode show the energy of the mode).

Fig. 6 Joint probability density functions of circularity and radius of fine-scale unburnt mixture.
4. Characteristics of consumption rate of fine-scale unburnt mixture

The consumption rate of the isolated unburnt mixture was evaluated from changes of area of unburnt region identified by OH or CH PLIF images under the assumption that the isolated reactants have spherical and pillar shapes. The method for identification of the unburnt mixture is as follows: (1) OH PLIF image is binarized with a threshold and fine-scale unburnt mixtures are detected, (2) the perimeter of the detected unburnt region (L) is calculated, (3) the radius of the unburnt mixture (r) is estimated by that of an equivalent circle in perimeter. Figure 6 shows the probability density functions of radius and circularity of detected fine-scale unburnt mixtures. Colored lines show isolines of probability, and the scatter plot is presented only in regions of probability below 0.012. The most expected radius and circularity are about 0.7 mm and 1.2, respectively. In addition, the isolated unburnt mixtures with smaller radius are more likely to be circle shape.

Here, consumption rate obtained in the previous study (Johchi et al. 2015) based on the pillar assumption is introduced. Figure 7 shows the most expected consumption rate ($S_{T,l}$) with respect to mean curvature ($k = 1/r$). The curvature of flame elements convex toward the burnt side is shown to be negative. The consumption rate tends to be increase with the decrease of r (or k). At the maximum, the consumption rate reaches 1.25 m/s when $k \approx 1.6 \times 10^3$ m$^{-1}$ ($r \approx 0.63$ mm) The most expected consumption rate is approximately 0.71 m/s at $k \approx 0.3 \times 10^3$ m$^{-1}$ ($r \approx 3.3$ mm). This value is much higher than its adiabatic laminar burning velocity (0.39 m/s). It should be noted that heat conduction is one of factors which have great effects on the fine-scale structures, and effect of flame stretch on the increase of the consumption rate is not necessarily significant in the present condition because Lewis number is close to unity due to equivalence ratio of 1.0 for methane-air premixed flame. Also absorption of flame radiation does not have large effects on heating up of reactants for the present condition since the absorbing species is mainly methane. Hence it can be considered that what has a large effect on the enhancement of $S_{T,l}$ is heating up of the unburnt mixtures through heat conduction. The effect of heat conduction is discussed in the followings.

4.1. Impact of heat conduction on the increase of the consumption rate

Temperature increase of unburnt mixture increases its laminar burning velocity. Figure 8 shows laminar burning velocities with respect to temperature of unburnt reactants, which is calculated by CHEMKIN PREMIX (Kee et al. 1989) with GRI-Mech 3.0 (Smith et al. 1989). By using the data shown in Fig. 8, mean temperature of unburnt mixture is estimated under the assumption that the most expected consumption rate shown in Fig. 7 is solely caused by temperature increase of the reactants. The estimated mean temperature ($T_m$) is shown in Fig. 9. $T_m$ reaches up to about 590 K for the isolated unburnt mixture of the maximum consumption rate. On the other hand, the consumption rate and consequently $T_m$ decrease for the radius of 0.5 mm. This is because some small unburnt mixture with radius of about 0.5 mm is significantly consumed to the extent that it cannot be identified properly in the next image and such a sample with high speed consumption is not counted in the results. To overcome this limitation in the future, much higher repetition rate
measurement such as double-pulse setup is required.

To understand how heat conduction is significant in the fine-scale unburnt mixtures, temperature evolution of isolated unburnt mixture is considered by assuming that the heat release from mass difference between going out and coming in the preheat zone increase the mean temperature of remained reactants. Figure 10 shows a schematic of inwardly propagating premixed curved flame. Here, $\delta_T$ is preheat zone thickness, $A_u$ and $A_b$ are areas of upstream edge of preheat zone and flame surface, $\dot{m}_u$ and $\dot{m}_b$ are mass flow rates of burnt gas going out through the thin reaction zone and unburnt mixture flowing into the preheat zone, $\dot{R}$ is flame displacement speed and can be considered to be consumption rate. Under the assumption of quasi-steadiness in flame coordinate ($\eta = R - r$), the mass conservation equation is written as follows (Sun et al. 1999):

$$\frac{\partial \dot{m}}{\partial \eta} - \rho \dot{R} \frac{\partial A}{\partial \eta} = 0. \quad (1)$$

By integrating Eq. 1 in the preheat zone, the variance between $\dot{m}_u$ and $\dot{m}_b$ can be described as

$$\dot{m}_u - \dot{m}_b = -\rho_u \dot{R} A_b \left( 1 - \frac{A_u}{A_b} \right). \quad (2)$$
Fig. 10 Schematic diagram of the flame structure of fine-scale unburnt mixtures.

Fig. 11 Temperature at which the laminar burning velocity corresponds to the most expected consumption rates with respect to the radius, and estimated temperature developments of isolated unburnt mixture with the initial radius of \( r_0 \) and initial temperature of 297 K under the pillar assumption.

Here, considering stream tube of flame, the ratio of \( A_u \) to \( A_b \) is,

\[
\frac{A_u}{A_b} = \frac{R - \delta_T}{R}.
\]

Assuming that the temperature of isolated unburnt mixture homogeneously is increased by the reaction heat of \( \dot{m}_b - \dot{m}_u \), the temperature increase rate is,

\[
\frac{\Delta T}{\Delta t} = \frac{q_c (\dot{m}_b - \dot{m}_u)}{\rho_u V c_p},
\]

where \( q_c \) is heat of combustion reaction, \( V \) represents a volume of isolated unburnt mixture and \( c_p \) does specific heat at constant pressure.

Figure 11 shows estimated temperature developments of isolated unburnt mixture based on Eq. 4. It is assumed that the unburnt mixture is separated into burnt region as a fine-scale unburnt mixture with the initial radius of \( r_0 = 0.6 \text{ mm} \sim 3.0 \text{ mm} \) and the initial temperature of 297 K, and that the unburnt mixture keeps the pillar shape. With the decrease of radius of unburnt mixture due to the progress of reaction, temperature of remained unburnt mixture increases. Because of the volume-surface ratio, the increase rate of temperature is more significant for the smaller radius. The red plot in Fig. 11 shows the estimated mean temperature \( (T_m) \) shown in Fig. 9. \( T_m \) in \( r < 0.8 \text{ mm} \) agrees with the estimated temperature developments of unburnt mixture with initial radius of about \( 1.5 \text{ mm} \sim 3.0 \text{ mm} \). \( T_m \) in the range of \( r > 1.2 \text{ mm} \) are larger than the estimated temperature development and the temperature of isolated reactants of such a large radius does not largely change, which means that increase of their consumption rate might be caused by strain rate or by the high
circularity. On the other hand, the small unburnt mixture of $r < 0.8$ mm does not significantly affected by strain rate, because Taylor micro length scale of the present condition is about 1 mm, and consequently heat conduction can be considered as the main factor of the increase of consumption rate. In other words, the temperature increase in fine-scale unburnt mixtures might be considered as flame-flame interaction, and as interactions between preheat zones of inwardly propagating flames. In our previous study based on DNS of a hydrogen-air turbulent planar jet premixed flame (Shimura et al. 2012), the increase of HO$_2$ concentration is observed in the isolated fine-scale unburnt mixtures. In hydrogen-air flames, the temperature rise in reactants enhances the rate of chemical reaction of (H + HO$_2$ (+ M) ⇔ HO$_2$ (+ M) and HO$_2$ concentration (Tanahashi et al. 2002a, Nada et al. 2004). Similarly, flame-flame interaction might occur in the fine-scale unburnt mixture. These points are indispensable to understand the consumption rate characteristics of reactants including fine-scale mixtures. To clarify these flame-flame interaction in hydrocarbon flame, simultaneous measurements of formaldehyde (CH$_2$O) and OH will be conducted since production rate of a species, HCO, which largely contributes to heat release can be estimated via CH$_2$O and OH PLIF by considering a reaction, CH$_2$O + OH ⇒ H$_2$O + HCO (Paul and Najm 1998), and also 1-dimensional DNS of the flame-flame interaction in the simple flame geometry for the future work.

5. Conclusions

A simultaneous measurement of OH-CH PLIF and SPIV at 10 kHz is applied to a methane-air turbulent jet premixed flame to investigate consumption rates of turbulent flames. From the measurement of the flame tip for high Reynolds number conditions, it has been clarified that isolated fine-scale unburnt mixtures which are frequently generated, POD analysis shows that the separation of unburnt mixture from the upstream main reactants is the characteristic flame structure. The consumption rate has been analyzed from the change of area of unburnt region during the successive PLIF images based on the pillar- and spherical-shape assumption (Johchi et al. 2015). The most expected consumption rates obtained is much higher than the laminar burning velocity. It reaches about 1.8 times of $S_L$.

A factor of the increase of consumption rate has been investigated in terms of heating up of isolated unburnt mixture through heat conduction. It is assumed that the heat release from mass difference between going out and coming in the preheat zone increases the mean temperature of remained reactants to consider enhancement of the effect of heat conduction. The analysis has shown that the increase of consumption rate of fine-scale mixtures of $r < 0.8$ mm is significantly affected by heat conduction, and that large scale isolated mixture is considered to be affected by fluid motion. Consumption rate and flame-flame interaction will be investigated by OH-CH$_2$O PLIF and 1-dimensional DNS of fine-scale inwardly propagating flames in the future work.

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