An Experimental Study on Influence of Markstein Number on Local Burning Velocity of Two-component Fuel Premixed Turbulent Flames

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1 Introduction

As combustion in most practical systems occurs in the flamelet regime [1] and the performance of combustion devices is governed largely by burning velocity, knowledge of the burning velocity of premixed turbulent flames in the flamelet regime is important. Recent measurements and theories have suggested that the interactions between the preferential diffusion and flame stretch of laminar premixed flames affect strongly the properties of turbulent premixed flames such as the burning velocity in the flamelet regime [2,3]. Therefore, the Markstein number $Ma$, which is a crucial parameter that should describe the sensitivity of flame stretch or curvature on the burning velocity of laminar premixed flames, has been studied widely to aim to elucidate and model the properties of laminar and turbulent premixed flames [4-8].

In this study, the influence of positive stretch on the local flame properties of turbulent propagating flames in the flamelet regime was investigated experimentally for two-component fuel mixtures, whose fuels are hydrogen, methane and propane, having nearly the same laminar burning velocity ($S_{L0}=25\text{cm/s}$) and different equivalence ratios ($\phi=0.8$ and $1.2$). The ratio of the turbulence intensity $u'$ to $S_{L0}$ was set to 1.4. A 2D laser tomography technique was used to obtain the temporal local flame configuration and movement in a constant-volume vessel, and then the local flame displacement velocity $S_F$, curvature $1/r$ and stretch $K$ of turbulent flames were quantitatively measured as the key parameters on turbulent combustion. Additionally, the Markstein number $Ma$ was obtained from outwardly propagating spherical laminar flames, in order to examine the effect of positive stretch on burning velocity.

2 Experimental Methods

2.1 Apparatus and Procedure

The combustion chamber used in this study is a nearly spherical vessel having a mean inner...
diameter of approximately 100 mm [8,9] as shown in Fig. 1. The combustion chamber has four transparent 85-mm-diameter windows located on four rectangular sides of the chamber to enable flame observation, and two perforated 90-mm-diameter plates are located on the other two sides. A fan is positioned behind each perforated plate in order to mix the gases and generate nearly isotropic and homogeneous turbulence in the central region of the chamber.

The optical system for laser tomography is used to obtain the two dimensional sequential tomograms of propagating flame [8,9]. For the laser sheet light source, a continuous-wave Nd:YAG laser (5W at 532nm) is adopted. Using three cylindrical lenses, the laser beam is focused into a sheet at the measurement location. TiO\textsubscript{2} powder with a diameter of 0.03–0.05\textmu m is used as the seeding particles. The scattered light is imaged using a high-speed camera (an acquisition rate of 2000 frames/s). The spatial resolution in the flame images obtained is 0.12 mm. The experiments are conducted as follows. The mixtures are concocted in the chamber according to the partial pressure of components and then ignited at the vessel center under desired turbulence intensity and atmospheric condition where the initial pressure and temperature are about 0.101 MPa and 298 K, respectively. The turbulent combustion experiments are done under the turbulence condition with the fan speed being 1000 rpm, leading to about 0.35 m/s of the turbulence intensity \( u' \). The characteristics of turbulence are shown in Table 1. In Table 1, \( S_{L0} \) is the laminar burning velocity, \( L_f \) the longitudinal integral length scale, \( \eta_0 \) the preheat zone thickness (=\( a_0/S_{L0} \)), \( D_d \) the Damköhler number (=\( L_f/u'S_{L0}/\eta_0 \)), \( Re_t \) the Reynolds number (=\( L_f/u'\nu \)), \( a_0 \) the thermal diffusivity and \( \nu \) the kinematic viscosity.

The sequential tomography for each mixture in Table 1 is repeated 5 times for the laminar combustion and 10 times for the turbulent combustion at the same condition, respectively. In this study, only the upper part of images from the center of chamber is analyzed.

### 2.2 Properties of Mixtures

Methane or propane added hydrogen mixtures having nearly the same laminar burning velocity (\( S_{L0} \approx \) about 25 cm/s) with different addition rates of methane or propane (\( \delta = 0, 0.2, 0.5, 0.8 \) and 1.0) and equivalence ratios as lean and rich (\( \Phi = 0.8 \) and 1.2) are prepared for experiments. Here, three fuels are also adopted, where methane and hydrogen are lighter fuels with higher diffusivity than oxygen and propane is a heavier fuel with lower diffusivity than that. In Table 1, \( \Phi \) denotes the total equivalence ratio [10] based on the numbers of carbon and hydrogen atoms of two fuels as follows; \( \Phi = [(x+y/4)\delta+(1/2)(1-\delta)]/X_0 \), where the mixture composition is expressed as \( \delta C_x H_y + (1-\delta)H_2 + X_0 O_2 + X_0 N_2 \). \( \delta \) represents the rate of addition as the volume fraction of hydrocarbon among the total fuel gases, and \( Le \) is the Lewis number(=\( a_0/D_d \)), where \( D_d \) is the diffusion coefficient of deficient reactant, however the Lewis numbers of lean two-component fuel mixtures (putted in parentheses in Table 1)
are estimated from a linear interpolation of single-component values; $Le = Le_1 \cdot \delta + Le_2 \cdot (1-\delta)$, where $Le_1$ and $Le_2$ are Lewis numbers of methane or propane and hydrogen, respectively\[11\]. The $SL_0$ and the turbulent burning velocity $ST$ are measured by the pressure history of combustion in the chamber in the early stages of combustion where the pressure rise was 0.01 to 0.02 MPa \[12,13\].

Figure 2 shows the measured $ST$ at $u' = 0.49$ m/s with respect to $\delta$ for mixtures in Table 1. Clear differences in $ST$ at the same $u'$ can be seen among mixtures with different $\Phi$, $\delta$ and fuel types, even under nearly the same $SL_0$. In the case of lean mixtures, the $ST$ at the same $u'$ decreases almost monotonically as $\delta$ increases. In the case of rich mixtures, however, the changes in the $ST$ do not show such a monotonic trend. In our previous studies \[10\], the phenomenon in Fig. 2 has been discussed on the basis of the preferential diffusion effect on the local burning velocity.

### 2.3 Analytical Procedure

In order to investigate quantitatively the local burning velocity, the local flame displacement velocity $SF$ is determined according to the same method as our previous studies \[8,9\]. An outline of the procedure is as follows. In the first place, each flame front position can be detected as discrete points (pixels), using appropriate threshold. Then, the curvature $1/r$ at each point can be calculated by vector product and geometrical procedures. The curvature of the convex part toward the unburned mixture is defined as positive. In the next place, the local flame propagation speed $VF$ at each point can be obtained using two sequential image frames. $VF$ can be calculated based on the flame travel period and the flame movement distance. It was assumed that the direction of flame front movement was right-angled to the tangential line on the point of flame front because the flame travel period from flame1 to flame2 was short enough. Finally, the $SF$ is obtained by the following Eq. (1):

$$SF = \left(\frac{\rho_b}{\rho_u}\right) \cdot VF$$

where $\rho_b$ and $\rho_u$ are the density of burned gas and unburned mixture, respectively, at 0.101MPa.

The $SF$ might be affected by the progress rate of flame propagation, because the pressure in the combustion chamber increases slightly with the flame propagation. A means to remove this influence, which is the same as previous studies \[8,9\], is adopted. For the discussion of the analyzed results, the flame images, which are taken at the same condition as the progress rate ($R_d/R_c)^3$ being about 0.018, are used, where $R_d$ and $R_c$ denote the equivalent radius based on the burned area of 2D flame image and that based on the chamber volume, respectively.

Meanwhile, the general expression of the flame stretch $K$ \[14\] is determined as the fractional time
rate of change of a flame surface element of area $A$:

$$K = 1/A \cdot dA/dt$$  \hspace{1cm} (2)

In this study, the special attention is paid to the change of flame surface area as flame stretch. Accordingly, $K_l$, which denotes Eq.(2) for outwardly propagating spherical laminar flames, can be simplified by just using a time history of the flame radius $r_f$ as follows [5]:

$$K_l = 2/r_f \cdot (dr_f/dt)$$  \hspace{1cm} (3)

On the other hand, the definition of $K_T$, which denotes Eq.(2) for turbulent flames, seems to be not so simple as that for laminar flames. In this study, the area of turbulent-flame element ($A_T$) in $K_T$ is determined as $K_T = 1/A_T \cdot dA_T/dt$, where $dA_T$ at each detected point can be approximately calculated based on the length of chord between neighboring points on flame1, $l_1$, and that between the points where the normal vectors on the points on flame1 cross the flame2, $l_2$, as follows:

$$dA_T = A_2 - A_1 = l_2^2 - l_1^2$$  \hspace{1cm} (4)

where flame1 denotes an image concerned for analysis and flame2 denotes the successive image of the flame. It was assumed that the direction of flame movement was at a right angle to the tangential line on the point of flame1 because the flame travel period from flame1 to flame2 was short enough, and the surface area of each flame element was a square of the chord of two neighboring points because the distance between the analyzed points was also short enough.

3 Results and Discussion

3.1 Local Flame Displacement Velocity

Figure 3 shows the variation of the mean value of local flame displacement velocity $S_{F,m}$ at $u'/S_{L0} = 1.4$, against $\delta$. From Fig. 3, $S_{F,m}/S_{L0}$ for lean mixtures tends to decrease with increasing $\delta$ of methane or propane. For rich mixtures, there are a few available data for methane-added hydrogen mixtures, however $S_{F,m}/S_{L0}$ of mixture with $\delta=0.0$ shows to be almost the same value as that with $\delta=1.0$, and $S_{F,m}/S_{L0}$ of mixture with $\delta=0.8$ is smaller than that with $\delta=1.0$. The $S_{F,m}/S_{L0}$ of rich propane-added hydrogen also shows a peak around $\delta=0.5$. It should also be noted that the difference in $S_T$ observed in Fig. 1 is attributed to the difference in $S_{F,m}$, regardless of $\Phi$, $\delta$ and fuel types. Thus, $S_{F,m}$ plays clearly an important role in determining the turbulent burning velocity.

3.2 Influence of positive stretch due to Markstein number on the local burning velocity of turbulent flames

The Markstein number $Ma$ for outwardly propagating spherical laminar flames can be obtained from the following expression proposed by Faeth et al. [5]:

$$S_{L,u}/S_{L} = 1 + Ma \cdot Ka_l$$  \hspace{1cm} (5)

where $S_{L,u}$ is the burning velocity of the spherical laminar flame relative to the unburned mixture (i.e., stretched laminar burning velocity), and $S_{L,u}$ the value of $S_u$ when the flame stretch is 0 (which is almost the same as $S_{L0}$ in this study), and $Ka_l$ the Karlovitz number based on Eq.(3).

Due to the similarity on the flame configuration between the outwardly propagating spherical laminar flames and the convex part of turbulent flames toward the unburned mixture, both flames have basically positive stretch and curvature. Accordingly, the relationship between the estimated $Ma$ and the $S_{F,m}/S_{L0}$ obtained at
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$u'/S_{L0}=1.4$ is examined as shown in Fig. 4, where $S_{F,ma}$ is the mean values of $S_F$ on convex parts toward the unburned mixture of turbulent flames. It is clear from Fig. 4 that $S_{F,ma}/S_{L0}$ tends to increase with decreasing $Ma$, irrespective of $\delta$, $\Phi$ and fuel types. This tendency accords with Eq.(5) as $S_{L}/S_{L,0}$ tends to increase with decreasing $Ma$ at the same $Ka_l$. This suggests that there exists a qualitative relationship between the $Ma$ estimated based on laminar flames and the $S_F$ obtained from turbulent flames.

Figure 5 shows the variation of $S_{F,ma}/S_{L0}$ at $u'/S_{L0}=1.4$ with the Lewis number Le in Table 1 for comparison with $Ma$. From Fig. 5, there exists an obvious relationship between the $S_{F,ma}/S_{L0}$ and $Le$, as similar to that between $S_{F,ma}/S_{L0}$ and $Ma$ in Fig. 4.

Finally, an attempt is made to examine quantitatively the effect of positive stretch caused by $Ma$ on the local burning velocity of turbulent flames. Equation 5 can be rewritten for the convex part of turbulent flames toward the unburned mixture with positive stretch as follows:

$$S_{L,0} / S_{L} = 1 + Ma \cdot Ka_l$$

where, $S_L$ is the burning velocity of turbulent flames at $1/r>0$ and $KT>0$ using the $Ma$ obtained by Eq.(5) and $Ka_l$, the Karlovitz number based on Eq.(4) as follows:

$$Ka_l = 1 / n \cdot \left( \sum_{i} K_{n_i} \cdot u'/S_{L,0} \right), \text{ at } 1/r > 0 \& KT > 0$$

Figures 4 and 5 show that $S_{L}/S_{L,0}$ as well as $S_{F,ma}/S_{L0}$ tend to increase with decreasing $Ma$ and $Le$ irrespective of $\delta$, $\Phi$ and fuel types. However, it is also clear that the trends of $S_{L,0}/S_{L,0}$ correspond with those of $S_{F,ma}/S_{L0}$ only qualitatively. That is, for mixtures with larger $Le$ or larger $Ma$, differences between $S_{L,0}/S_{L,0}$ and $S_{F,ma}/S_{L0}$ are smaller, however for $Le < 1$ or $Ma < 0$ the differences are considerably larger and tends to increase with decreasing $Le$ or $Ma$. Therefore, this suggests that for turbulent flames with larger $Le$ and $Ma$, especially $Le > 1$ or $Ma > 0$, the effect of $Ma$ becomes predominant on the change in the local burning velocity at the convex part of turbulent flames toward the unburned mixture with positive stretch. On the other hand, for turbulent flames with $Le < 1$ and $Ma < 0$, the other predominant effects can be expected to exist. A notable effect of these is the preferential diffusion, because for $Le < 1$ the molecular transport is dominant.

Further consideration with respect to practical influences of the gas flow near flame front [15] and the three-dimensional configuration [16] may be necessary. However, it is clear at least for the mixtures with $Le<1$ or $Ma<0$ that the change in the local burning velocity of turbulent flames with $\delta$, $\Phi$ and fuel types cannot be explained quantitatively by the Markstein number represented the effect of flame stretch based on laminar flames.

Figure 4. Relationship among the Markstein number $Ma$, the $S_{F,ma}/S_{L0}$, and the $S_{L,0}/S_{L,0}$ estimated by the $Ma$

Figure 5. Relationship among the Lewis number $Le$, the $S_{F,ma}/S_{L0}$, and the $S_{L,0}/S_{L,0}$ estimated by the $Ma$
References


