

Influence of Flame Stretch on Local Burning Velocity of Turbulent Premixed 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 methane, hydrogen and propane mixtures 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 varied as 1.4 and 2. 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]. 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_2 powder with a diameter of $0.03\sim 0.05\mu\text{m}$ 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 or

1400 rpm, leading to about 0.35 and 0.49 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, η_0 the preheat zone thickness ($=a_0/S_{L0}$), Da_l the Damköhler number ($=L_f/u' \cdot S_{L0}/\eta_0$), Re_l the Reynolds number ($=L_f u'/\nu$), a_0 the thermal diffusivity and ν 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

The mixtures used in this study have nearly the same laminar burning velocity (about 25 cm/s) by adding nitrogen to fuel/air mixtures with two equivalence ratios 0.8 and 1.2. 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, ϕ is the equivalence ratio, D_F/D_O the ratio of diffusion coefficient of fuel to that of oxygen in the mixture, Le the Lewis number ($=a_0/D_d$), and D_d the diffusion coefficient of deficient reactant. The S_{L0} and the turbulent burning velocity S_T 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 [10,11].

Figure 1 shows the measured S_T with respect to u' for mixtures in Table 1. Clear difference in S_T at the same u' can be seen among mixtures with different ϕ and fuel types, even under nearly the same S_{L0} . In the case of methane and hydrogen mixtures, S_T tends to increase as ϕ decreases. In the case of propane mixtures, the tendency of S_T with respect to ϕ is reversed.

2.3 Analytical Procedure

In order to investigate quantitatively the local burning velocity, the local flame displacement velocity S_F 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 V_F at each point can be obtained using two sequential image frames. V_F 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. Finally, the S_F is obtained by the following Eq. (1):

$$S_F = (\rho_b/\rho_u) \cdot V_F \quad (1)$$

where ρ_b and ρ_u are the density of burned gas and unburned mixture, respectively, at 0.101MPa.

The S_F 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 $(R_A/R_C)^3$ being about 0.018, are used, where R_A 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 [12] is determined as the fractional time rate of change of a flame surface element of area A :

$$K = 1/A \cdot dA/dt \quad (2)$$

In this study, the special attention is paid to the change of flame surface area as flame stretch. Accordingly, K_t , 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]:

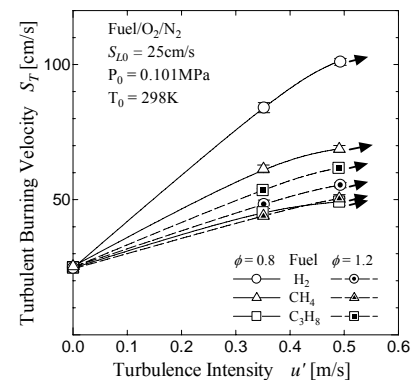


Fig. 1 S_T as functions of fuel types and ϕ

Table 1 Properties of mixtures and test conditions

Mixture	Molar Fraction			ϕ	S_{L0} cm/s	D_F/D_O	Le	Fan Speed 1000 rpm				Fan Speed 1400 rpm			
	Fuel	O ₂	N ₂					u'/S_{L0}	L_f/η_0	Da_1	Re_1	u'/S_{L0}	L_f/η_0	Da_1	Re_1
M08-25N	CH ₄	2.5	9.63	0.8	25.4	1.05	0.89	1.38	33.7	24.3	63.1	1.94	35.9	18.5	94.2
M12-25N	CH ₄	1.67	6.67	1.2	24.4	1.05	0.93	1.44	32.3	22.5	62.9	2.01	34.5	17.1	93.9
H08-25N	H ₂	0.63	6.13	0.8	24.7	2.90	0.42	1.42	22.7	15.9	56.5	1.99	24.2	12.1	84.3
H12-25N	H ₂	0.42	5.02	1.2	25.1	2.84	1.29	1.40	21.5	15.3	55.0	1.97	23.0	11.7	82.2
P08-25N	C ₃ H ₈	6.25	25.63	0.8	24.8	0.57	1.57	1.42	35.5	25.1	66.7	1.98	37.8	19.1	99.7
P12-25N	C ₃ H ₈	4.17	18.54	1.2	25.0	0.58	0.89	1.40	36.8	26.2	68.0	1.96	39.2	20.0	101.6

$$K_l = 2/r_f \cdot (dr_f/dt) \quad (3)$$

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:

$$dA_T = A_2 - A_1 = l_2^2 - l_1^2 \quad (4)$$

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 2 shows variations of the mean values of S_F on positive curvatures $S_{F,mu}$ and those on negative curvatures $S_{F,mb}$ at $u'/S_{L0}=1.4$ with ϕ . It is clearly observed that the values of $S_{F,mu}$ tend to become larger than those of $S_{F,mb}$, and increase with decreasing ϕ for methane and hydrogen mixtures but with increasing ϕ for propane mixtures. Similar relations follow at $u'/S_{L0}=2$.

Figure 3 shows the variation of the mean value of local flame displacement velocity S_F , $S_{F,m}$, against u'/S_{L0} . It is clear from Fig. 3 that $S_{F,m}$ shows some variation in the weak turbulence region, however it has a tendency to approach to a specific value depending on the fuel type and ϕ as u' increases because the effects of curvature and strain on the local burning velocity do not increase infinitely with u' . It should also be noted that the difference in S_T observed in Fig. 1 is attributed to the difference in $S_{F,m}$ for each mixture. Thus, $S_{F,m}$ plays clearly an important role in determining the turbulent burning velocity.

3.2 Effect 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]:

$$S_{L\infty}/S_{Ll} = 1 + Ma \cdot Ka_l \quad (5)$$

where S_{Ll} is the burning velocity of the spherical laminar flame relative to the unburned mixture (i.e., stretched laminar burning velocity), and $S_{L\infty}$ the value of S_{Ll} 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. Therefore, an attempt is made to examine quantitatively the effect of positive stretch caused by Ma based on Eq.(5) obtained from spherical laminar flames 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:

$$S_{L\infty}/S_{Ll} = 1 + Ma \cdot Ka_t \quad (6)$$

where, S_{Ll} is the burning velocity of turbulent flames at $1/r > 0$ and $K_T > 0$ using the Ma obtained by Eq.(5) and Ka_t , the Karlovitz number based on Eq.(4) as follows:

$$Ka_t = 1/n \cdot \left(\sum_i^n K_{\pi_i} \cdot a_{o_i} / S_{Fi}^2 \right), \text{ at } 1/r > 0 \ \& \ K_T > 0 \quad (7)$$

Figure 4 shows the variation of the estimated $S_{Ll}/S_{L\infty}$ with Le at $u'/S_{L0} = 1.4$. Also, the $S_{F,mu}$ is plotted for comparison. The trends of $S_{Ll}/S_{L\infty}$ seem to correspond with those of $S_{F,mu}/S_{L0}$ only qualitatively. For mixtures with Le being larger than about 1 ($Le > 1$), differences between $S_{Ll}/S_{L\infty}$ and $S_{F,mu}/S_{L0}$ are a little, while for $Le < 1$ the differences are considerably larger. Therefore, this suggests that for larger Le turbulent flames, especially $Le > 1$, the effect of Ma becomes predominant on the local burning velocity at the convex part of turbulent flames toward the unburned mixture with positive stretch. However, for turbulent flames with $Le < 1$, the other predominant effects can be expected to exist. One of notable effects is the preferential diffusion, because for $Le < 1$ the diffusivity of the reactant is greater than the thermal diffusivity. From the viewpoint, in the case of methane and hydrogen mixtures, the diffusion coefficient of fuel is larger than that of oxygen as shown in Table

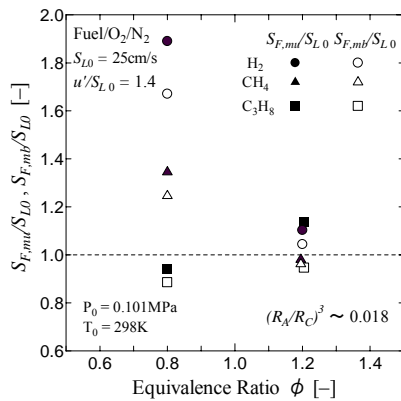


Fig. 2 Variation of $S_{F,mu}$, $S_{F,mb}$ with ϕ ($u'/S_{L0}=1.4$).

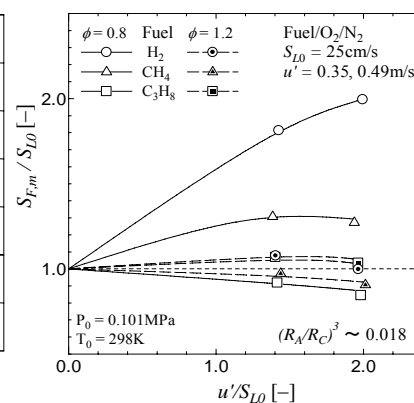


Fig. 3 Variation of $S_{F,m}/S_{L0}$ with u'/S_{L0} , fuel types and ϕ .

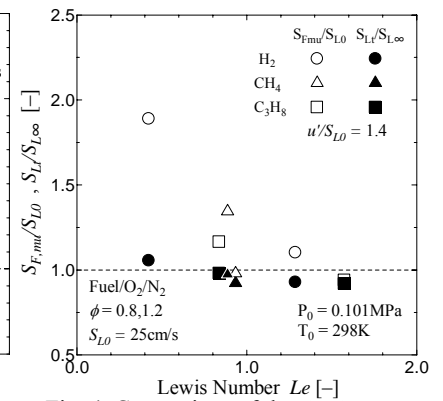


Fig. 4 Comparison of the $S_{L'}/S_{L\infty}$ estimated by the Ma based on laminar flames $S_{F,mu}/S_{L0}$ of turbulent flames ($u'/S_{L0}=1.4$).

1, so fuel can diffuse more to the convex flame toward the unburned mixture caused by the preferential diffusion. This shows that the local burning velocity for the leaner mixture ($Le < 1$) increases due to fuel being the deficient reactant. On the other hand, the diffusion coefficient of propane is smaller than that of oxygen. Therefore, for richer propane mixtures ($Le < 1$) the local burning velocity increases in that convex part.

Further consideration with respect to practical influences of the gas flow near flame front [13] and the three-dimensional configuration [14] may be necessary. However, it is clear at least for the mixtures with $Le < 1$ that the change in the local burning velocity of turbulent flames with fuel types, ϕ and u'/S_{L0} can not be explained quantitatively by the Markstein number represented the effect of flame stretch based on laminar flames.

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