Local Flame Displacement Velocity of Hydrogen Added Methane Premixed Turbulent Flames

Masaya NAKAHARA*, Hiroyuki KIDO
Kenshiro NAKASHIMA and Hideaki TAKAMOTO
Department of Mechanical Engineering Science, Kyushu University
Fukuoka, 812-8581 Japan

*E-mail: nakahara@mech.kyushu-u.ac.jp

Introduction

Hydrogen has been regarded as an alternative fuel for the modern combustion devices mainly because of CO_2- and HC-free combustion, and a renewable fuel. Hydrogen used in the combustion devices is not always pure; its purity depends on production methods and costs. Particularly, hydrogen gas reformed from natural gas, coal and biomass includes some hydrocarbons. These are so-called multi-component fuel. Therefore, it is important that the turbulent combustion of multi-component fuel mixtures is comprehended.

In our previous studies [1-2], the turbulent burning velocity for lean and rich hydrogen-added hydrocarbon mixtures, having nearly the same laminar burning velocity, were examined experimentally. As a result, the turbulent burning velocities of lean mixtures increased almost constantly with increasing additional rate of hydrogen, whereas those of rich mixtures showed no such tendency. This trend was also explained qualitatively based on the mean local burning velocity which was estimated by taking account of the preferential diffusion effect for each fuel component. The change in the local burning velocity affects substantially the turbulent burning velocity.

The present study is performed to investigate directly the local flame properties of turbulent propagating flame for lean and rich hydrogen added methane mixtures as two-component fuel mixtures at the weak turbulence condition, in order to clarify the influence of the hydrogen addition to hydrocarbon mixtures on its local burning velocity. Hydrogen added methane mixtures having nearly the same laminar burning velocity with different rates of hydrogen addition are prepared. A two-dimensional sequential laser tomography technique is used to obtain the relationship between the flame shape and the flame displacement. The local flame displacement velocity S_F is quantitatively obtained as the key parameters of the turbulent combustion. The obtained S_F is also discussed quantitatively by the Markstein number which is crucial for describing the influences of flame stretch or curvature on the laminar burning velocity.

Experimental Methods

Apparatus and Procedure

The combustion chamber used in this study is a nearly spherical vessel having a mean inner diameter of approximately 100 mm [3]. 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 [3]. 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 0.03~0.05μm 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. The two fan speeds lead to about 0.35 and 0.49 m/s of the turbulence intensity u', about 1.4 and 2.0 of u'/S_{L0}, and about 40 and 50 of Re_λ, where S_{L0} is the laminar burning velocity and Re_λ the Reynolds number based on the Taylor micro scale λ_g. 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.

Table 1　Properties of mixtures

Mixture	Φ	Molar Fraction				S_{L0}	a_0	ν
		CH_4	H_2*	O_2	N_2	cm/s	mm^2/s	mm^2/s
M08-25NH00	0.8	1.0	0.0	2.50	9.63	25.35	21.05	15.55
M08-25NH02	0.8	0.8	0.2	2.13	8.93	24.79	22.19	15.77
M08-25NH05	0.8	0.5	0.5	1.56	7.42	25.44	24.56	16.25
M08-25NH08	0.8	0.2	0.8	1.00	6.45	25.09	27.85	16.91
M08-25NH10	0.8	0.0	1.0	0.63	6.13	24.71	30.50	17.44
M12-25NH00	1.2	1.0	0.0	1.67	6.67	24.40	21.10	15.60
M12-25NH02	1.2	0.8	0.2	1.42	6.02	24.76	22.72	15.92
M12-25NH05	1.2	0.5	0.5	1.04	5.10	25.09	26.02	16.60
M12-25NH10	1.2	0.0	1.0	0.42	5.02	25.10	32.61	17.91

*δ_H, H_2 additional rate

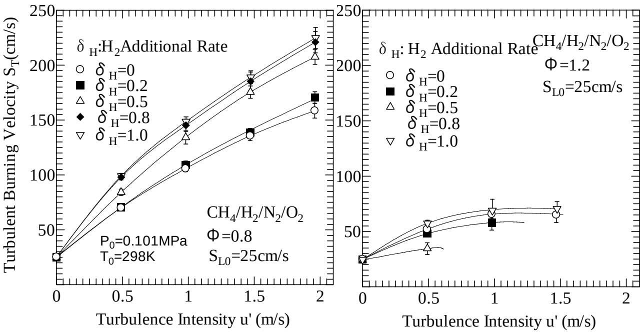


Fig. 1　Turbulent Burning Velocity Characteristics

Properties of Mixtures

The mixtures used in this study are shown in Table 1. They have nearly the same laminar burning velocity (about 25 cm/s) by adding nitrogen to hydrogen added methane-air mixtures, with different additional rates of hydrogen. In Table 1, S_{L0} is the laminar burning velocity measured by the pressure history of combustion [1-3], a_0 the thermal diffusivity, ν the kinematic viscosity and ϕ the total equivalence ratio based on the numbers of carbon and hydrogen atoms of two fuels (= [(x+y/4)(1-δ_H) + δ_H/2] / X_0), where the mixture composition is expressed as $(1-\delta_H)C_xH_y + \delta_H H_2 + X_0 O_2 + X_N N_2$ and δ_H represents the rate of addition as the volume fraction of hydrogen among the total fuel gases.

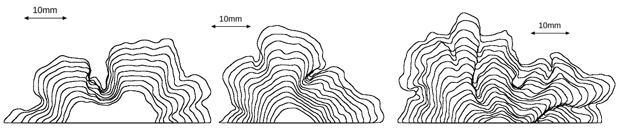
Figure 1 shows the variation of the measured turbulent burning velocity S_T with u' for mixtures in Table 1. Clear difference in S_T at the same u' can be seen among mixtures with different δ_H and ϕ, even under nearly the same S_{L0}. S_T for lean mixtures shows to increase almost constantly as δ_H increases. S_T for rich mixtures, however, does not show such a trend.

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 [3,4]. 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 (see Fig. 2). 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):

$$S_F = (\rho_b/\rho_u)V_F \qquad (1)$$

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



(a)M08-25NH00(b)M08-25NH05(c) M08-25NH10

Fig. 2 Temporal Evolution of Flame Front Contours (u'/S_{L0}≈1.4)

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 [3,4], 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.

Results and Discussion

Observation of Turbulent Flame

Figure 2 shows the temporal evolution of the upper part flame-front contours of the sequential tomograms of turbulent flames for some lean mixtures at u'/S_{L0} = 1.4. The flames are observed to be wrinkled having a continuous flame front, despite of δ_H. The scales of the flame wrinkles show to become smaller with increasing δ_H. The trends can be also observed for rich mixtures.

Local Flame Displacement Velocity

Figure 3 shows variations of the mean values of S_F on positive curvatures $S_{F,mu}$ and those on negative curvatures $S_{F,mb}$ normalized by S_{L0} at u'/S_{L0} =1.4 with δ_H . It can be clearly obtained that for lean mixtures $S_{F,mu}$ tends to be larger than $S_{F,mb}$, whereas for rich mixtures the difference between $S_{F,mu}$ and $S_{F,mb}$ seems to be not clear.

Figure 4 shows variations of the mean value of S_F, $S_{F,m}$, normalized by S_{L0} with u'/S_{L0}. From Fig. 4, $S_{F,m}$ is affected by u'/S_{L0} to some extent, especially for larger δ_H mixtures. And $S_{F,m}$ can be expected not to increase or decrease to infinity with increasing u'/S_{L0}. It suggests that the effects of curvature and strain due to turbulence on the local burning velocity do not increase infinitely with increasing u'. Additionally, the $S_{F,m}$ tendency in Fig. 4 corresponds well with the result in Fig.1. That is, the difference in the turbulent burning velocity in Fig. 1 is attributed to the difference in the mean local burning velocity.

The changes in the local burning velocity of turbulent flames as seen in the obtained S_F seem to be explained based on the preferential diffusion, Lewis number and Markstein

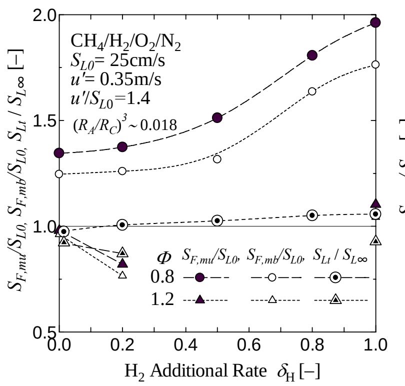


Fig. 3 $S_{F,mu}$, $S_{F,mb}$ and S_{Lt} (u'/S_{L0}≈1.4)

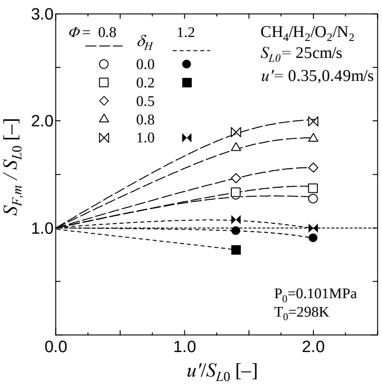


Fig. 4 $S_{F,m}$ as a function of u'/S_{L0}

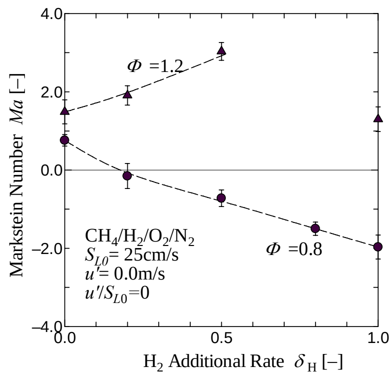


Fig. 5 Variation of Ma with δ_H

number, as the same way as our previous studies that was examined for hydrogen or hydrocarbon fueled mixtures [1-3]. This study attempts to discuss quantitatively the local burning velocity on the convex part of turbulent flames toward the unburned mixture at $u'/S_{L0} \approx 1.4$ by the Markstein number.

Markstein number

A linear relationship between the laminar burning velocity and flame stretch has been suggested [5,6]. Faeth et al. [7] have proposed the following relationship for outwardly propagating spherical laminar flames.

$$S_{L\infty}/S_{Ll} = 1+MaKa \qquad (2)$$

where S_{Ll} is the burning velocity of laminar combustion, $S_{L\infty}$ the value of S_{Ll} when the flame stretch =0, Ma the Markstein number, Ka the Karlovitz number [$=K\cdot(a_0/S_{Ll}{}^2)$], K the flame stretch [$1/A\cdot\delta A/\delta t = (2/r_f\cdot dr_f/dt)$], A the flame surface element and r_f the flame radius. From Eq. (2), the burning velocity of stretched flames tends to increase with decreasing Ma.

Figure 5 shows Ma obtained from spherical laminar flames, based on the procedure proposed by Faeth et al. [3,7]. From Fig. 5, in the case of lean mixtures, Ma decreases constantly with increasing δ_H. In the case of rich mixtures, however, the change in Ma does not show such a constant trend. According to Eq. (2), the trend of Ma can explain qualitatively that of $S_{F,mu}$ in Fig. 3.

An attempt is made to acquire the quantitative influence of Ma obtained from laminar flames on the burning velocity of turbulent flames. The mean burning velocity at the positive curvature of turbulent flames estimated based on Ma, S_{Lt}, normalized by $S_{L\infty}$ at $u'/S_{L0} \approx 1.4$ is plotted in Fig. 3. $S_{Lt}/S_{L\infty}$ is calculated from Eq. (2), where A in K of turbulent flames is approximately estimated based on the distance between adjoining two points on normal vectors for turbulent flame fronts with $1/r > 0$ and $K > 0$.

From Fig. 3, the trends of $S_{Lt}/S_{L\infty}$ seem to correspond with those of $S_{F,mu}/S_{L0}$. In the case of rich mixtures, the difference between $S_{Lt}/S_{L\infty}$ and $S_{F,mu}/S_{L0}$ is a little, whereas in the case of lean mixtures the difference is much larger. Therefore, this suggests that the effect of Ma for rich hydrogen added methane mixtures affects predominately the local burning velocity at convex part of turbulent flames toward the unburned mixture. In the case of lean those mixtures, however, the predominant other effects can be expected to exist.

Conclusions

In this study, in order to investigate the local burning velocity characteristics of the turbulent flame of hydrogen added methane mixtures, the local flame displacement velocity S_F has been measured directly with using two-dimensional sequential tomograms. It is found that the obtained S_F plays an important roll in the turbulent burning velocity. The mean local burning velocity at convex part of turbulent flames toward the unburned mixture caused by the Markstein number S_{Lt} attempts to be estimated. A quantitative relationship between S_F and S_{Lt} can be observed only for rich hydrogen added methane mixtures.

References

[1] Kido, H., Huang, S., Tanoue, K., and Nitta, T., "Improving the Combustion Performance of Lean Hydrocarbon Mixtures by Hydrogen Addition", *JSAE Review*, Vol.15, No.2, (1994), pp.165-170.

[2] Kido, H., Nakahara, M., Hashimoto, J., and Barat, D., "Turbulent Burning Velocities of Two-Component Fuel Mixtures of Methane, Propane and Hydrogen", *JSME International Jour.*, Vol.45,No.2, Ser.B, (2002), pp.355-362.

[3] Kido, H., Nakashima, K., Nakahara, M., and Hashimoto, J., D., "Influence of Local Flame Displacement Velocity on Turbulent Burning Velocity", *Pro. Combustion Institute*, Vol. 29, (2002), pp. 1855-1861.

[4] Hashimoto, J., Ph. D. thesis, Kyushu University, Fukuoka, Japan, (2001).

[5] Williams, F.A., "Combustion Theory 2nd," The Benjamin/Cummings, 1985, p.349.

[6] Peters, N., "Turbulent Combustion," Cambridge University Press, 2000, p.95.

[7] Know, S., Tseng, L.-K., and Faeth, G. M., "Laminar Burning Velocities and Transition to Unstable Flames in $H_2/O_2/N_2$ and $C_3H_8/O_2/N_2$ Mixtures," *Combust. Flame,* 90(1992), pp.230-246.