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Study on the Turbulent Burning Velocity of Hydrogen Mixtures Including Hydrocarbons

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To clarify the turbulent burning velocity of hydrogen in the presence of hydrocarbons, a two-component fuel mixture of hydrogen, methane, and propane was considered. Both hydrocarbon fuel-lean and fuel-rich mixtures were prepared while keeping the laminar burning velocity approximately constant. Even though the laminar burning velocities were approximately the same, a distinct difference in the measured turbulent burning velocity at the same turbulence intensity is observed, depending on the addition of hydrocarbon, the equivalence ratio, and the kind of hydrocarbon. The burning velocities of lean mixtures changed almost monotonically as the rate of addition changed, whereas the burning velocities of the rich mixtures showed no such tendency. This trend can be explained qualitatively based on the mean local burning velocity, which is estimated by taking into account the preferential diffusion effect for each fuel component.

I. Introduction

Hydrogen has been regarded as an alternative fuel for gas turbines, internal combustion engines, and other combustion devices, mainly because of CO_2– and hydrocarbon-free combustion and its status as a renewable fuel. Needless to say, hydrogen is the most useful fuel for rockets, supersonic transports, and microcombustors. Hydrogen used in the combustion devices is not always pure; its purity depends on production methods and costs (particularly, refined hydrogen derived from natural gas, coal, and biomass includes some hydrocarbons). This hydrogen is considered to be a so-called multicomponent fuel. In addition, a prospective combustion technology is expected to produce a synthetic fuel composed of hydrogen and hydrocarbons to achieve optimal conditions for operation of a combustion device.

Because the performance of combustion devices is governed largely by burning velocity, knowledge of the burning velocities of hydrogen mixtures including hydrocarbons as multicomponent fuel mixtures is important. Consequently, a number of studies have examined the properties of laminar combustion, such as the laminar burning velocity and ignition for these mixtures, so that they can be predicted to some extent [1–8]. In contrast, little information on the turbulent burning velocity is available.

According to almost all conventional models of turbulent burning velocity for single-component fuel mixtures [9,10] in the flamelet regime, in which the continuous and thin reaction sheet is predominant, the ratio of the turbulent burning velocity S_T to the local burning velocity is proportional to the ratio of the increased flame surface area caused by turbulence to the laminar flame surface area A_T/A_0. Then A_T/A_0 is well approximated to be proportional to the ratio of the turbulence intensity u' to the local burning velocity, where the local burning velocity is usually taken to be equal to the original laminar burning velocity S_L^0 all over the turbulent flame. On the other hand, recent measurements and theories have suggested that the interactions between the preferential diffusion strongly affect the properties of turbulent premixed flames, such as the local burning velocity in the flamelet regime [11,12]. A similar result was obtained in our previous studies [13,14]. That is, turbulent burning velocity for single-component fuel mixtures (fuel/oxygen/nitrogen) with nearly the same laminar burning velocity were examined experimentally. The local burning velocity, as the substantial burning velocity of turbulent flames, was found to be able to change from the original laminar burning velocity, even under weak turbulence conditions, except for near-stoichiometric mixtures. This change was found to be caused by the preferential diffusion effect due to the molecular diffusivity of reactants and to play an important role in turbulent burning velocity characteristics. In addition, a simple model for predicting turbulent burning velocity was proposed based on the estimated mean local burning velocity S_L as a reference, rather than on the original S_L^0.

In the present study, to clarify the turbulent burning velocity of hydrogen mixtures including hydrocarbons as a multicomponent fuel mixture, lean and rich hydrocarbon-added hydrogen mixtures as two-component fuel mixtures were prepared while keeping the laminar burning velocity approximately constant, in which methane and propane were used as added hydrocarbon and the rate of addition of hydrocarbon was varied. These turbulent burning velocity characteristics were examined experimentally, with special attention to the molecular diffusivity of fuel, by using a constant-volume vessel. As a result, a noticeable difference in the measured turbulent burning velocity characteristics was found between the lean and the rich mixture as the rate of addition varies. This trend can be explained qualitatively by the mean local burning velocity characteristics of each fuel component, as estimated by taking into account the preferential diffusion effect in our previous studies [13,14].

II. Experimental Methods

A. Apparatus and Procedure

The combustion chamber used in the present study is a nearly spherical vessel with a mean inner diameter of approximately 120 mm [13–15]. The cross-sectional view of the combustion chamber observed from the transparent window is shown in Fig. 1. The combustion chamber has two transparent 80-mm-diam windows located on opposite sides of the chamber to enable flame observation, and four perforated 100-mm-diam plates are located on the other four sides. A fan is positioned behind each perforated plate to mix the gases and generate approximately isotropic and homogeneous turbulence in the central region of the chamber.

Experiments were conducted as follows. The mixture (see Table 1) was created in the chamber by setting the partial pressures of components and then producing ignition at the center of the vessel under the desired turbulence intensity and atmospheric condition, for

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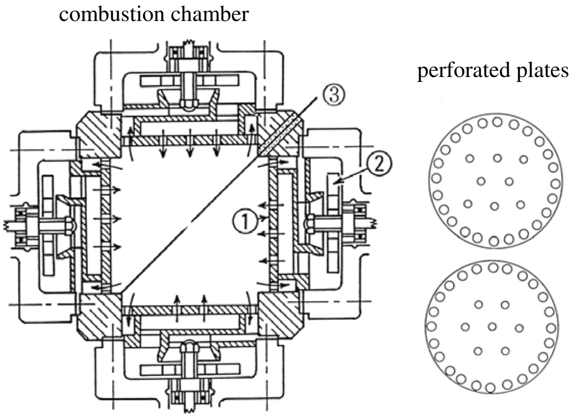


① perforated plate, ② fan, ③ ignition plug

Fig. 1 Cross-sectional view of combustion chamber.

which the initial pressure and temperature were approximately 0.101 MPa and 298 K, respectively.

The turbulence intensity u' was measured as a function of the fan speed. The characteristics of turbulence in the chamber were obtained by the two-point correlation method using hot-wire anemometry, as shown in Fig. 2 [15]. In Fig. 2, L_f is the longitudinal integral length scale, λ_g is Taylor's microscale, and η_k is the Kolmogorov scale. L_f shows a slight increase and subsequent plateau and λ_g shows a negligible increase and subsequent decrease with increasing turbulence intensity, approximately 3.3 ± 0.3 and 1.6 ± 0.1 mm, respectively.

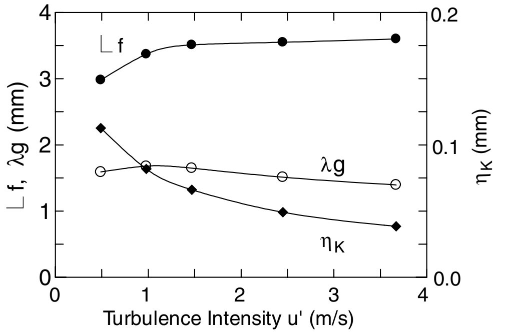


Fig. 2 Turbulent characteristics in the combustion chamber.

B. Measurement of Burning Velocity

In this study, Lewis's formulation given in [16] is adopted to calculated the laminar burning velocity S_L^0. That is, S_L^0 is measured by the pressure history of combustion in the chamber [13,14] in the early stages of combustion, in which the pressure rise is 0.01 to 0.02 MPa to satisfy the assumption of the flame being spherical, as follows:

$$S_L^0 = \frac{r_0}{3(P_e - P_0)} \left(\frac{P_0}{P}\right)^{\frac{1}{\gamma}} \left(1 - \left(\frac{P_0}{P}\right)^{\frac{1}{\gamma}} \frac{P_e - P}{P_e - P_0}\right)^{-\frac{2}{3}} \frac{\mathrm{d}p}{\mathrm{d}t} \qquad (1)$$

where $\mathrm{d}p/\mathrm{d}t$ is the rate pressure rise, r_0 is the radius of the equivalent sphere of the combustion chamber, γ is the ratio of the specific heat at constant pressure to that at constant volume, P_0 is the initial pressure (0.101 MPa), P_e is the final pressure of constant-volume adiabatic combustion, and P is the transient pressure when the burning velocity was measured. Here, P_e is difficult to obtain experimentally, and so we use the theoretical value.

Table 1 Properties of mixtures

	Molar fraction							
Φ	H_2	CH_4	C_3H_8	O_2	N_2	S_L^0, cm/s	a_0, mm^2/s	ν, mm^2/s
0.8	1.0	0.0	——	0.63	6.25	25.25	30.35	17.40
0.8	0.8	0.2	——	1.00	6.50	25.40	27.81	16.90
0.8	0.5	0.5	——	1.56	7.66	24.95	24.47	16.23
0.8	0.2	0.8	——	2.13	9.56	25.01	22.12	15.75
0.8	0.0	1.0	——	2.50	9.63	25.30	21.05	15.55
1.2	1.0	0.0	——	0.42	5.08	24.50	32.49	17.89
1.2	0.5	0.5	——	1.04	5.31	24.18	25.87	16.56
1.2	0.2	0.8	——	1.42	6.23	24.70	22.68	15.91
1.2	0.0	1.0	——	1.67	6.83	24.90	21.09	15.60
0.8	1.0	——	0.0	0.63	6.25	25.25	30.35	17.40
0.8	0.8	——	0.2	1.75	9.28	24.74	24.73	15.94
0.8	0.5	——	0.5	3.44	15.13	25.47	21.41	15.13
0.8	0.2	——	0.8	5.13	21.78	25.25	20.04	14.80
0.8	0.0	——	1.0	6.25	25.00	25.40	19.47	14.66
1.2	1.0	——	0.0	0.42	5.08	24.50	32.49	17.89
1.2	0.8	——	0.2	1.17	6.77	25.16	26.04	16.12
1.2	0.5	——	0.5	2.29	11.23	24.56	21.57	15.02
1.2	0.2	——	0.8	3.42	15.72	24.78	19.72	14.57
1.2	0.0	——	1.0	4.17	18.96	24.60	19.01	14.41
0.8	1.0	0.0	——	0.63	7.31	14.89	29.15	17.14
0.8	0.8	0.2	——	1.00	7.70	14.91	26.91	16.69
0.8	0.5	0.5	——	1.56	8.92	15.26	24.06	16.13
0.8	0.2	0.8	——	2.13	10.41	15.15	22.04	15.73
0.8	0.0	1.0	——	2.50	11.03	15.26	21.03	15.54
0.8	1.0	——	0.0	0.63	7.31	14.89	29.15	17.14
0.8	0.8	——	0.2	1.75	10.76	14.96	24.30	15.88
0.8	0.5	——	0.5	3.44	18.06	15.23	21.34	15.16
0.8	0.2	——	0.8	5.13	25.39	15.16	20.13	14.87
0.8	0.0	——	1.0	6.25	30.00	15.39	19.65	14.75
1.2	0.8	——	0.2	1.17	7.56	14.93	25.61	16.06
1.2	0.5	——	0.5	2.29	14.85	14.76	21.43	15.09
1.2	0.2	——	0.8	3.42	18.45	15.14	19.85	14.66
1.2	0.0	——	1.0	4.17	22.71	14.85	19.25	14.53

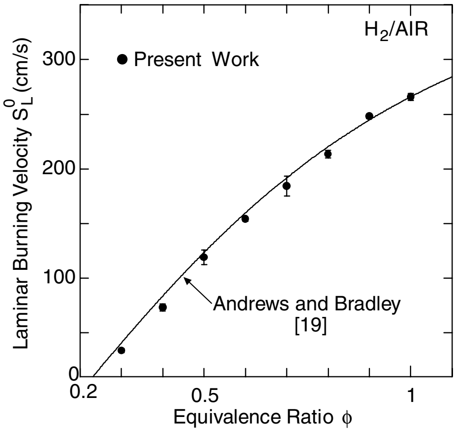


Fig. 3 Comparison of measured S_L^0 by Eq. (1) with Andrews and Bradley [19].

The turbulent burning velocity S_T is approximated by the relation [17]

$$\frac{S_T}{S_L^0} \approx \left(\frac{\mathrm{d}p}{\mathrm{d}t}\right)_T \bigg/ \left(\frac{\mathrm{d}p}{\mathrm{d}t}\right)_L^0$$

where $\mathrm{d}p/\mathrm{d}t$ is the pressure increase rate, and subscripts T and ${}_L^0$ designate turbulent and laminar combustion, respectively. Each experiment is repeated more than 10 times to keep the accuracy of measurements, with the initial pressure and temperature being 0.101 MPa and 298 K, respectively.

The validity of the burning velocity by the method used in this study has been confirmed in our previous studies [13,14,18]. For example, the present S_L^0 based on Eq. (1) for H_2–air mixtures is shown in Fig. 3 for comparison with the measurement of Andrews and Bradley [19]. It is clear from Fig. 3 that they are in good agreement, both quantitatively and qualitatively.

C. Composition of Mixture

The hydrogen (H_2) mixtures including hydrocarbon as the two-component fuel mixtures used in the present study are listed in Table 1. Methane (CH_4) and propane (C_3H_8) are adopted as hydrocarbon fuels. The former is a lighter hydrocarbon with higher diffusivity than oxygen, and the latter is a heavier hydrocarbon with lower diffusivity than oxygen. In this study, an evaluation of the turbulent burning velocity characteristics is performed, keeping the ratio of characteristic chemical-reaction time to characteristic turbulent-mixing time approximately constant, because it is well known that the characteristic ratio affects the turbulent-combustion phenomenon. For this purpose, special mixtures with the same S_L^0 with different equivalence ratios and amounts of hydrocarbon addition are made up experimentally by adding nitrogen to two-component fuel air mixtures, as shown in Table 1. In this experiment, the values of the S_L^0 are fixed at approximately 15 and 25 cm/s.

In Table 1, Φ denotes the total equivalence ratio [18] based on the numbers of carbon and hydrogen atoms of two fuels, as follows:

$$\Phi = [(1/2)(1-\delta) + (\alpha + \beta/4)\delta]/X_0 \tag{2}$$

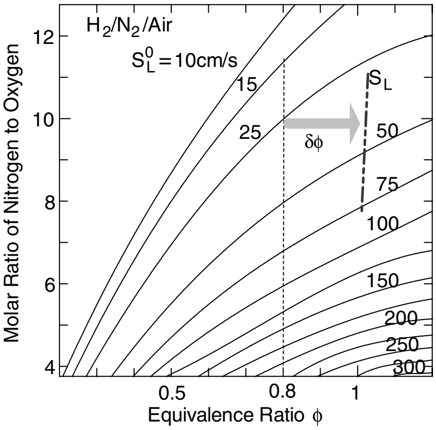
where the mixture composition is expressed as

$$(1-\delta)H_2 + \delta C_\alpha H_\beta + X_0O_2 + X_NN_2$$

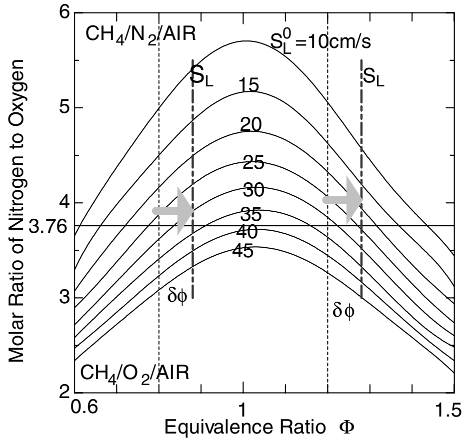
where δ represents the rate of addition as the volume fraction of the added hydrocarbon (methane or propane) among the total fuel gases.

In this experiment, the values of Φ are fixed at 0.8 and 1.2, and δ is varied as 0, 0.2, 0.5, 0.8, and 1.0. Hydrogen–methane mixtures with $\Phi = 1.2$, $\delta = 0.2$, and $S_L^0 = 25$ cm/s and with $\Phi = 1.2$ and $S_L^0 = 15$ cm/s and one hydrogen–propane mixture with $\Phi = 1.2$, $\delta = 0.0$, and $S_L^0 = 15$ cm/s could not be ignited by means of the 2.5 J of ignition energy used in the present study. In Table 1, a_0 and ν are the thermal diffusivity and kinematic viscosity, respectively.

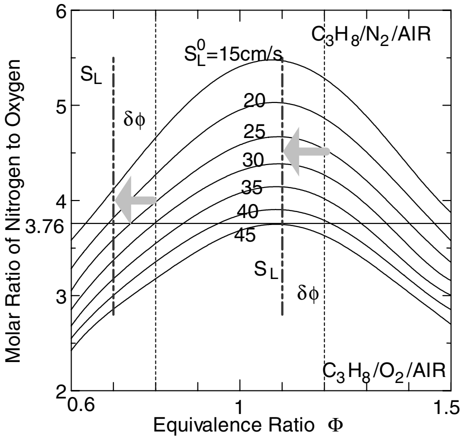
Figure 4 shows the contour lines of the laminar burning velocity as a function of the molar ratio of nitrogen to oxygen (N_2/O_2) and the equivalence ratio of single-component fuel mixtures ϕ for hydrogen, methane, and propane mixtures, respectively. The solid lines in Fig. 4 are plotted as the isopleths for S_L^0 fitted by using experimental data. In Fig. 4, $\delta\phi$ and S_L denote the mean value of local equivalence ratio increase and the mean local burning velocity of turbulent flames, respectively, which are determined by a method described later. The thick arrows also illustrate the directions and the values of the change



a) H_2



b) CH_4



c) C_3H_8

Fig. 4 Contour lines of laminar burning velocity S_L^0 with N_2/O_2 and equivalence ratio ϕ.

in the equivalence ratio due to the preferential diffusion for each single-fuel mixture.

III. Results and Discussion

A. Turbulent Burning Velocity

Figure 5 shows the variation of the measured turbulent burning velocity S_T with respect to the turbulence intensity u' for hydrogen–methane and hydrogen–propane mixtures with $S_L^0 = 25$ cm/s and $\Phi = 0.8$ and 1.2; Fig. 6 shows the same for $S_L^0 = 15$ cm/s.

From Figs. 5 and 6, a distinct difference in the turbulent burning velocity at the same turbulence intensity is seen among the hydrogen mixtures with different rates of addition of hydrocarbon δ, even under nearly the same laminar burning velocities. In addition, a noticeable difference exists between the changes in the turbulent burning velocities of lean mixtures and those of rich mixtures as the rate of addition increases.

In the case of the lean mixtures, the values of S_T of hydrogen–methane and hydrogen–propane mixtures at the same u' decrease almost monotonically as the rate of addition of hydrocarbon increases, regardless of the type of hydrocarbon and S_L^0. The decrease in S_T with adding propane also appears to be larger than that with adding methane.

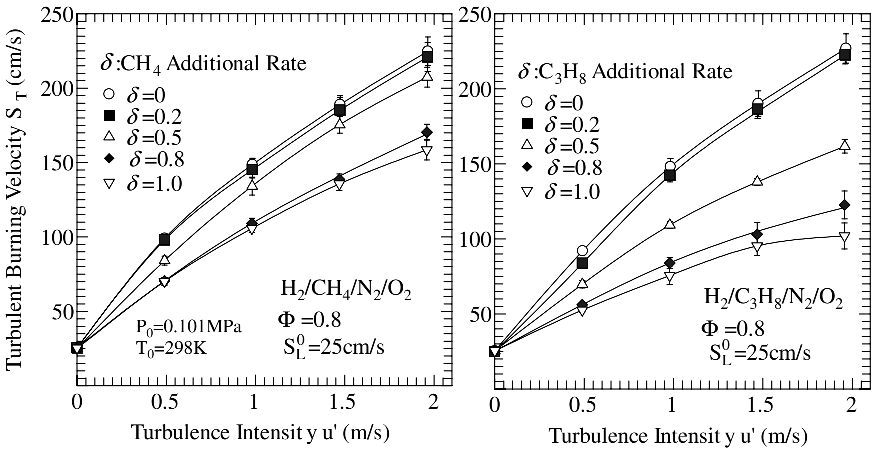
In the case of the rich mixtures, however, the changes in the turbulent burning velocity do not show such a monotonic trend. In rich hydrogen–methane mixtures with $S_L^0 = 25$ cm/s, the combustion for the rate of addition of methane $\delta = 0$ can be sustained, and the value of S_T is approximately equal to that for $\delta = 1$. However, as δ reaches 0.2, the combustion can no longer be sustained, as shown in Table 1. Then as δ increases further, the combustion can be sustained again and its S_T increases with δ.

In rich hydrogen–propane mixtures, the value of S_T increases as the rate of addition of propane δ increases up to 0.5. However, as δ increases further, the value of S_T begins to slightly decrease.

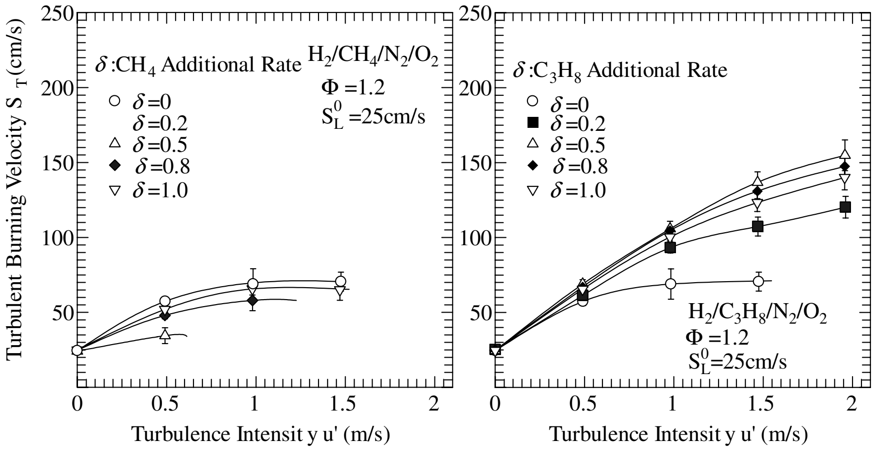
As in a previous study [18], these results indicate that the addition of hydrocarbon to the lean hydrogen mixture has a negative effect on its turbulent burning velocity. In other words, the addition of hydrogen to lean hydrocarbon mixtures improves turbulent burning velocity characteristics. On the other hand, the turbulent burning velocity of rich hydrogen mixtures is not always adversely affected by adding hydrocarbon.

B. Preferential Diffusion Effect

According to conventional models of turbulent burning velocity [9,10], the predominant factors contributing to turbulent burning velocity are the flame surface area and the local burning velocity under the weak turbulent condition, at which the turbulent burning velocity increases proportionally with increasing turbulence intensity. The surface area is well approximated to be proportional to the turbulence intensity, and the local burning velocity must be equal to the original laminar burning velocity defined in the one-dimensional adiabatic condition. Based on the analysis of turbulent flame tomography in our previous study [20], the turbulent flame surface area of single-component fuel mixtures at the same weak turbulence condition was found to be approximately dependent only on the turbulence intensity. This result corresponds with the premise of the conventional models [9,10]. Accordingly, the turbulent flame surface areas of hydrocarbon-added hydrogen mixtures with nearly

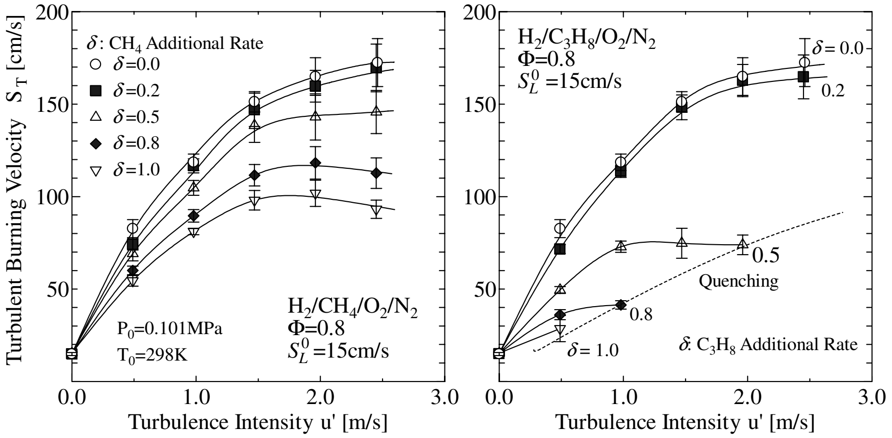


a) Φ=0.8

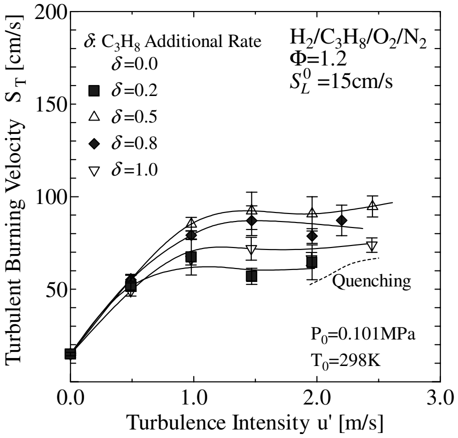


b) Φ=1.2

Fig. 5 Turbulent burning velocities of $(1-\delta)H_2$-δCH_4 and $(1-\delta)H_2$-δC_3H_8 mixtures ($S_L^0 = 25$ cm/s).



a) Φ = 0.8



b) Φ = 1.2

Fig. 6 Turbulent burning velocities of $(1-\delta)H_2$-δCH_4 and $(1-\delta)H_2$-δC_3H_8 mixtures ($S_L^0 = 15$ cm/s).

the same laminar burning velocity used in this study may be approximately equal at the same turbulence intensity.

This indicates that the difference in turbulent burning velocity, depending on the rate of addition of hydrocarbon and the total equivalence ratio, as shown in Figs. 5 and 6, cannot be explained by the turbulent flame surface area alone. Consequently, this difference must be attributed to the change in the local burning velocity of turbulent flames from the original laminar burning velocity.

In the following section, to examine the trends shown in Figs. 5 and 6, the local burning velocity characteristics of single-component fuel mixtures will be shown quantitatively by using an experimental method.

1. *Local Burning Velocity of Single-Component Fuel Mixtures*

The turbulent burning velocity characteristics of single-component fuel mixtures with the same laminar burning velocity examined in our previous studies [13,14] showed a trend similar to those observed in Figs. 5 and 6. That is, a clear difference in turbulent burning velocity with respect to the equivalence ratio and the fuel type was observed. This mechanism was found to be explained by the preferential diffusion effect [21], by which the difference in molecular diffusivity among reactants can change the local equivalence ratio at the convex part of the turbulent flame toward the unburned mixture, which could govern the characteristics of the entire combustion field. Consequently, this leads to a change in the mean value of the local burning velocity, which is equal to the substantial burning velocity of the turbulent flame front, as follows.

In the case of hydrogen and methane mixtures, the diffusion coefficient of fuel is larger than that of oxygen, and so fuel can diffuse more to the convex flame toward the unburned mixture as the dominant part caused by the preferential diffusion. The local equivalence ratio at this dominant part increases from the original equivalence ratio (see the arrow in Figs. 4a and 4b), leading to an imaginary increase in the equivalence ratio in the whole combustion field, in which the molar ratio of nitrogen to oxygen is invariable because of nearly the same diffusive coefficient. This increase in the equivalence ratio can bring forth the increase of the mean local burning velocity for the lean mixtures because fuel is the deficient reactant in the lean mixtures. On the other hand, the diffusion coefficient of propane is smaller than that of oxygen. Therefore, in propane mixtures, the mean local burning velocity tends to increase with richer mixtures (see the arrow in Fig. 4c).

In addition, we propose a method of estimating the mean local burning velocity S_L experimentally and the mean value of local equivalence ratio increase $\delta\phi$ as the characteristic values of preferential diffusion effect [13,14]. An outline of the procedure is as follows.

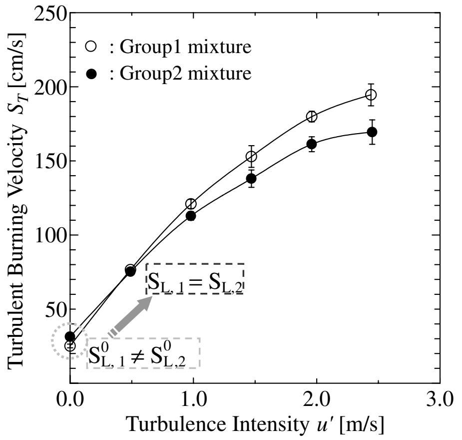
The two values are estimated under the following assumptions in the weak turbulence condition ($u' \sim 0.75$ m/s) in which the flame surface area increases almost linearly with u':

1) The surface area of turbulent flame solely depends on the turbulence intensity.

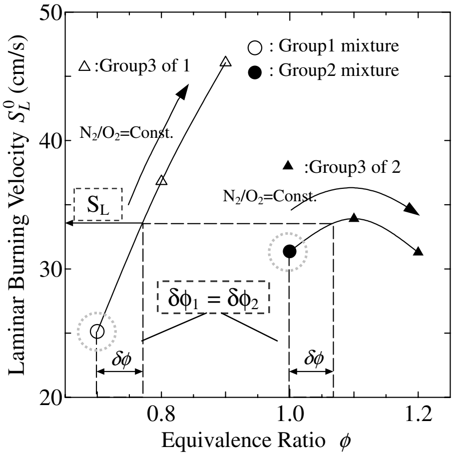
2) The increase rate of local equivalence ratio depends only on the property of fuel in the mixture, irrespective of the original equivalence ratio.

3) The ratio of molar fraction of oxygen to that of nitrogen is constant everywhere in the unburned zone.

In the first step, an attempt is made to find a pair of mixtures experimentally, for which the local burning velocities of turbulent flame are nearly the same ($S_{L,1} = S_{L,2}$), but laminar burning velocity and composition are different ($S_{L,1}^0 \neq S_{L,2}^0$), as illustrated in Fig. 7a. When two mixtures with the same fuel show nearly the same value of S_T at a certain moderate u', the local burning velocities of the two

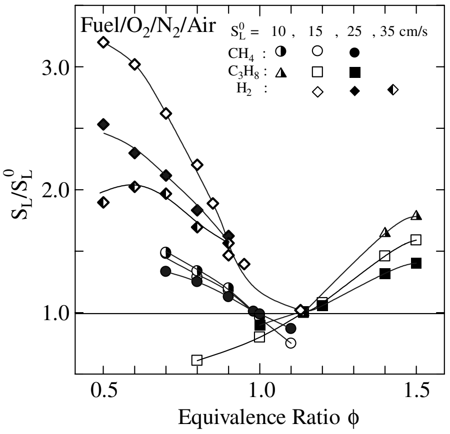


a) Step 1 : turbulent combustion

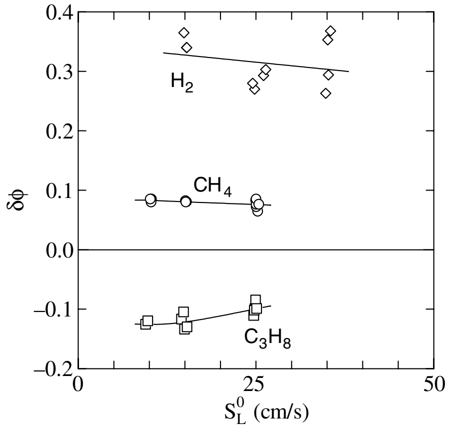


b) Step 2 : laminar combustion

Fig. 7 Illustration of the procedure estimating the mean local burning velocity S_L for single-component fuel mixtures.



a) Variation of S_L/S^0_L with ϕ and S^0_L



b) Variation of δϕ with S^0_L

Fig. 8 S_L and $\delta\phi$ for single-component fuel mixtures.

mixtures must be nearly equal, because the flame-front area is mainly influenced by the turbulence intensity based on assumption 1. As shown in Fig. 7a, one mixture is labeled as group 1 in Table 1, and the other mixture is labeled as group 2.

In the second step, the mean local burning velocity of turbulent flame S_L and the value of the local equivalence ratio increase $\delta\phi$ are estimated quantitatively. Figure 7b shows the measured laminar burning velocities of each pair, in which the equivalence ratio is varied, keeping the molar ratio of nitrogen to oxygen constant. These mixtures are of group 3, as illustrated in Fig. 7b. From assumptions 2 and 3, the preferential diffusion similarly affects each mixture of a pair, leading to the same change in the local equivalence ratio. This indicates that the value of the local equivalence ratio increases and that the local burning velocities of the pair of mixtures must be nearly equal. Thus, the change of local equivalence ratio and the local burning velocity of each pair, which show equal values at the same time on the pair curves of measured laminar burning velocity, are found, as shown in Fig. 7b. They are denoted as $\delta\phi$ and S_L, respectively.

Figure 8 shows the estimated S_L and $\delta\phi$ for single-component fuel mixtures of methane, propane, and hydrogen with $S^0_L = 10$, 15, 25, and 35 cm/s. In the case of hydrogen and methane mixtures, the values of $\delta\phi$ and S_L/S^0_L for the lean mixtures are positive and become larger than those for the rich mixtures. In other words, combustion performance is enhanced for lean mixtures of hydrogen and methane due to the preferential diffusion effect, whereas in the case of propane, such an improvement can be obtained for rich mixtures.

Furthermore, characteristic values for the preferential diffusion effect of hydrogen mixture are larger than those of methane and propane mixtures because hydrogen has higher molecular diffusivity. In addition, the changes in S_L and $\delta\phi$ as S^0_L varies are larger for hydrogen mixtures than for hydrocarbon mixtures.

2. *Qualitative Discussion of Turbulent Burning Velocity for Hydrocarbon-Added* H_2 *Mixture*

As already mentioned, the change in the mean local burning velocity of turbulent flames plays an important role in the trends observed in Figs. 5 and 6. Unfortunately, the method of S_L, as shown in Fig. 7, cannot apply to the two- component fuel mixtures, because the reactants of the mixtures need to be classified into two groups, which are the higher and the lower diffusive reactants (e.g., one group is fuel and the other is N_2 and O_2) when the proposed method is employed. Two-component fuel mixtures, however, must be classified into three groups such as hydrogen, methane (or propane), and N_2–O_2 groups, due to their molecular diffusivity. In this section, we discuss these trends based on the mean local burning velocity of each fuel (H_2, CH_4, or C_3H_8) of Fig. 8 contained in the two-component fuel.

In the lean hydrogen–methane and hydrogen–propane mixtures of Figs. 5a and 6a, the mean local burning velocities decrease with increasing rate of addition of methane or propane δ, because hydrogen has higher S_L for lean mixtures at the same S^0_L than hydrocarbons, as shown in Fig. 8a. Therefore, S_T decreases with increasing δ, as shown in Figs. 5a and 6a. Additionally, because the values of S_L of lean propane mixtures were shown to be smaller than not only those of methane, but also of its original laminar burning velocities, propane can be expected to have a large effect on the turbulent burning velocity of lean hydrogen mixtures, compared with methane, as observed in Figs. 5a and 6a.

On the other hand, for the case of rich hydrogen–methane mixtures, neither methane nor hydrogen in rich mixtures is expected to show improved turbulent combustion, due to preferential diffusion, as shown in Fig. 8a. As a result, the changes in the S_T with an increasing rate of the addition of methane may become complicated. Furthermore, combustible mixtures for rich hydrogen–methane with $S_L^0 = 15\ \mathrm{cm/s}$ cannot be made, even under the laminar condition.

In rich hydrogen–propane mixtures, propane has some effect by which to improve the turbulent combustion. Hydrogen, however, has no such effect, as shown in Fig. 8a. This suggests that S_T increases with an increasing rate of the addition of propane.

This indicates that the turbulent burning velocity characteristics of hydrocarbon-added hydrogen (two-component fuel) mixtures can be explained qualitatively by the mean local burning velocity S_L of each fuel comprising two-component fuel mixtures. In addition, these characteristics seem to be determined by the balance of both mean local burning velocities.

The present study is discussed based on the S_L estimated by only taking into account preferential diffusion of single-component fuel mixtures. Further considerations with respect to a wider range of mixtures (such as equivalence ratios) and a direct measurement of the mean local burning velocity of two-component-fuel premixed turbulent flames by a visualization method are necessary and may also be required from the view of chemical kinetics [22], because the trend of S_T of rich mixtures appears to be a little complicated. The preceding discussion, however, appears to be qualitatively valid. Thus, the preferential diffusion effect may be important with respect to the turbulent burning velocity for the hydrocarbon-added hydrogen mixtures (two-component fuel mixtures), as well as for single-component fuel mixtures.

IV. Conclusions

The turbulent burning velocities of lean and rich hydrogen including hydrocarbon (methane or propane) mixtures, which have the same laminar burning velocities, was examined, with special attention to the local burning velocity characteristics of turbulent flames. The major conclusions are as follows:

1) A distinct difference in the turbulent burning velocity characteristics with respect to the rate of addition of hydrocarbon exists between lean and rich mixtures. In the case of lean mixtures, the turbulent burning velocity decreased almost monotonically as the rate of addition of methane or propane increased. This indicates that the addition of hydrocarbon to the lean hydrogen mixture has a negative effect on its turbulent burning velocity. In the case of rich mixtures, however, the changes in the turbulent burning velocity did not show such a monotonic trend, but seemed to be dependent on the type of hydrocarbon.

2) In the lean hydrogen mixtures used in this study, the negative effect of the addition of propane on the turbulent burning velocity tends to be larger than that of methane, because propane has lower diffusivity than oxygen, compared with methane.

3) It is indicated that the mean local burning velocity that takes into account the preferential diffusion effect can possibly play an important role in the determination of turbulent burning velocity for hydrocarbon-added hydrogen mixtures, as well as for single-component fuel mixtures.

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