Turbulent Burning Velocities of Two-Component Fuel Mixtures of Methane, Propane and Hydrogen*

Hiroyuki KIDO**, Masaya NAKAHARA**, Jun HASHIMOTO*** and Dilmurat BARAT***

In order to clarify the turbulent burning velocity of multi-component fuel mixtures, both lean and rich two-component fuel mixtures, in which methane, propane and hydrogen were used as fuels, were prepared while maintaining the laminar burning velocity approximately constant. A distinct difference in the measured turbulent burning velocity at the same turbulence intensity is observed for two-component fuel mixtures having different addition rates of fuel, even the laminar burning velocities are approximately the same. The burning velocities of lean mixtures change almost constantly as the rate of addition changes, whereas the burning velocities of the rich mixtures show 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. In addition, a model of turbulent burning velocity proposed for single-component fuel mixtures may be applied to two-component fuel mixtures by considering the estimated mean local burning velocity of each fuel.

Key Words: Internal Combustion Engine, Premixed Combustion, Multi-component Fuel Mixture, Turbulent Burning Velocity, Preferential Diffusion

1. Introduction

Recently, environmental and energy problems have focused attention on the use of various gas fuels, such as natural gas and coal gasification gas. In addition, a prospective combustion technology is expected to produce a synthetic fuel comprised of several components in order to achieve optimal operative conditions for a combustion device. These fuels, as well as conventional fuels such as gasoline, are produced from several components. As the performance of combustion devices is governed largely by burning velocity, knowledge of the burning velocity of multi-component fuel mixtures is important. Consequently, a number of studies have examined laminar burning velocity of these mixtures, which can be predicted to some extent\textsuperscript{17-9}. In contrast, little information on turbulent burning velocity is available\textsuperscript{9}.

In our previous studies\textsuperscript{16,8}, the turbulent burning velocity for single-component fuel mixtures (fuel/oxygen/nitrogen), having nearly the same laminar burning velocity, were examined experimentally. Due to the substantial burning velocity of turbulent flame, the local burning velocity was found to be able to change from the original laminar burning velocity, even under weak turbulence condition, 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 is believed to play an important role in turbulent burning velocity characteristics. In addition, a model for predicting turbulent burning velocity was proposed based on the mean local burning velocity as a reference parameter, rather than on the original laminar burning velocity.

In the present study, in order to clarify the turbulent burning velocity of multi-component fuel mixtures, lean and rich two-component fuel mixtures were prepared while maintaining the laminar burning velocity.
velocity approximately constant, and these turbulent burning velocity characteristics were examined experimentally. Methane, propane and hydrogen were used as fuels, and the rate of addition of fuel in two-component fuel was varied. As a result, a noticeable difference in the measured turbulent burning velocity characteristics is 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. In addition, an attempt is made to apply a model of turbulent burning velocity proposed for single-component fuel mixtures to two-component fuel mixtures. This is done using the mean local burning velocity of a two-component fuel mixture as approximated from each fuel component. The turbulent burning velocity characteristics are explained quantitatively by the model.

2. Experimental Method

2.1 Apparatus and procedure

The combustion chamber used in the present study is a nearly spherical vessel having a mean inner diameter of approximately 120 mm. The combustion chamber has two transparent 80-mm-diameter windows located on opposite sides of the chamber to enable flame observation, and four perforated 100-mm-diameter plates are located on the other four sides. A fan is positioned behind each perforated plate in order to mix the gases and generate approximately isotropic and homogeneous turbulence in the central region of the chamber. Details of the apparatus and procedure are presented elsewhere.

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, at which the initial pressure and temperature were approximately 0.101 MPa and 298 K, respectively. The laminar burning velocity, $S_{0}$, and the turbulent burning velocity, $S_{t}$, were measured via the pressure history of the spherical flame in a closed vessel during the early stage of combustion.

The turbulence intensity, $u'$, was measured for each mixture as a function of the fan speed. The characteristics of the turbulence in the chamber were such that the longitudinal integral length scale $L_{T}$ shows a slight increase and subsequent plateau. In addition, the Taylor's micro scale, $l_{m}$, shows a negligible increase and subsequent decrease with increasing turbulence intensity ($u' \sim 2.0 \text{ m/s}$), approximately $3.3 \pm 0.3 \text{ mm}$ and $1.6 \pm 0.1 \text{ mm}$, respectively.

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Properties of mixtures</th>
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<tr>
<td>Mixture</td>
<td>$\phi$</td>
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<tr>
<td>M08H8O20-25</td>
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<tr>
<td>M08H8O25-25</td>
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<tr>
<td>M08H10O25-25</td>
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<tr>
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<tr>
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<tr>
<td>M12P17O25-25</td>
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2.2 Composition of mixture

The two-component fuel mixtures used in the present study are listed in Table 1. Two fuels were chosen among methane, propane and hydrogen. The two-component fuel mixtures were prepared while maintaining the laminar burning velocity at approximately 25 cm/s. In Table 1, $\phi$ denotes the total equivalence ratio based on the numbers of carbon and hydrogen atoms of two fuels as follows,

$$\phi = \left( \frac{x + y}{4} \right) (1 - \delta) + (z + \beta / 4) / x_0$$

where the mixture composition is expressed as $(1 - \delta)C_xH_y + \delta C_zH_z + x_3O_3 + x_4N_z$. Here, $\delta$ represents the rate of addition as the volume fraction of the added fuel among the total fuel gases. Hydrogen for methane-hydrogen and propane-hydrogen mixtures and propane for methane-propane mixtures are selected as the added fuels.

In this experiment, the values of $\phi$ are fixed at 0.8 and 1.2, and $\delta$ is varied as 0, 0.2, 0.5, 0.8 and 1.0. Methane-hydrogen mixtures having $\phi = 1.2$ and $\delta = 0.8$ (M12H8O-25) could not be prepared by means of the 2.5 J of ignition energy used in the present study. In Table 1, $a_0$ and $\nu$ are the thermal diffusivity and kinematic viscosity, respectively.

Figure 1 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 for methane, propane and hydrogen mixtures, respec-
In Figs. 1(a) and (b), the plotted solid circle represents the laminar burning velocity of the CH₄/N₂/air and C₆H₆/N₂/air mixtures having the same equivalence ratio and N₂/O₂ ratio of the methane-propane mixture described in Table 1. In Fig. 1(c), the solid circle represents the laminar burning velocity of the H₂/N₂/air mixture having the same equivalence ratio and N₂/O₂ ratio of methane-hydrogen and propane-hydrogen mixtures having $\phi=0.8$.

**3. Results and Discussion**

**3.1 Turbulent burning velocity**

Figures 2(a) and (b) show the variation of the measured turbulent burning velocity $S_T$ with respect to the turbulence intensity $u'$ for methane-hydrogen, propane-hydrogen and methane-propane mixtures having $\phi=0.8$ and 1.2, respectively.

From Fig. 2, a distinct difference in the turbulent burning velocity at the same turbulence intensity is seen among the two-component fuel mixtures having different rates of addition of fuel, $\delta$, even under nearly identical 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 methane-hydrogen and propane-hydrogen mixtures at the same $u'$ increase almost constantly as the rate of addition of hydrogen increases; whereas those
of methane–propane mixtures decrease almost constantly as the rate of addition of propane increases.

In the case of the rich mixtures, however, the changes in the turbulent burning velocity do not show such a constant trend. In rich methane–hydrogen mixtures, the value of $S_t$ first decreases as the rate of addition of hydrogen, $\delta$, increases. Then, as $\delta$ reaches 0.8, the combustion can no longer be sustained, as mentioned above. However, for $\delta=1.0$, the combustion can be sustained and $S_t$ is approximately equal to that for $\delta=0$.

In rich propane–hydrogen mixtures, the value of $S_t$ increases slightly as the rate of addition of hydrogen increases up to 0.5. However, as $\delta$ increases further, the value of $S_t$ begins to steeply decrease.

In methane–propane mixtures, the value of $S_t$ first increases as the rate of addition of propane $\delta$ increases. When $\delta$ becomes larger than approximately 0.5, the increase in $S_t$ with increasing $\delta$ is negligibly small.

As in a previous study\(^{(11)}\), these results indicate that the addition of hydrogen to lean hydrocarbon mixtures improves turbulent burning velocity characteristics. For rich hydrocarbon mixtures, however, such an improvement cannot be obtained.

### 3.2 The Preferential Diffusion Effect

According to conventional models of turbulent burning velocity, 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. Here, 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\(^{(12)}\), the turbulent flame surface area of single-component fuel mixtures at the same weak turbulence condition was found to be approximately dependent on only the turbulence intensity. This result corresponds with the premise of the conventional models. Therefore, the turbulent flame surface area of two-component fuel mixtures having nearly the same laminar burning velocity may be approximately equal at the same turbulence intensity.

Therefore, the difference in turbulent burning velocity depending on the rate of addition of fuel and the total equivalence ratio, as shown in Fig. 2, cannot be explained by the turbulent flame surface area alone. Consequently, this difference must be attributed to the change in the local burning velocity from the original laminar burning velocity.

In the following section, in order to examine the trends shown in Fig. 2, the local burning velocity characteristics of single-component fuel mixtures will be shown quantitatively using an experimental method.

#### 3.2.1 Local burning velocity of single-component fuel mixtures

The turbulent burning velocity characteristics of single-component fuel mixtures having the same laminar burning velocity examined in our previous studies\(^{(12,16)}\) showed trends similar to those observed in Fig. 2. That is, a clear difference in turbulent burning velocity with respect to equivalence ratio and fuel type was observed. This mechanism was found to be explained by the preferential diffusion effect, by which the molecular diffusivity can change the local equivalence ratio at the convex part of the flame toward unburned mixture, which could govern the characteristics of the entire combustion field, leading to a change in the mean value of the local burning velocity due to the substantial burning velocity of the turbulent flame as compared to the laminar burning velocity. In addition, we propose a method of estimating experimentally the mean local burning velocity, $S_t$, and the value of local equivalence ratio increase, $\delta \phi$, as the characteristic values of preferential diffusion effect.

Figure 3 shows the estimated $S_t$ and $\delta \phi$ for single-component fuel mixtures of methane, propane and hydrogen having $S_{le}=15$ and 25 or 10 cm/s. In the case of methane and hydrogen mixtures, the values of $\delta \phi$ and $S_t/S_{le}$ 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 methane and hydrogen due to the preferential diffusion effect. On the other hand, such an improvement can be obtained for rich propane 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 $S_t$ and $\delta \phi$ as $S_{le}$ varies is larger for hydrogen mixtures than for hydrocarbon mixtures.

#### 3.2.2 Local burning velocity of each fuel

As mentioned above, the change in local burning velocity plays an important role in the trends observed in Fig. 2. Here, we discuss these trends based on the mean local burning velocity characteristics of each fuel contained in the two-component fuel of Fig. 3.

In the lean methane–hydrogen and propane–hydrogen mixtures of Fig. 2(a), the mean local burning velocities increase with increasing rate of addition of hydrogen $\delta$, because hydrogen has higher $S_t$ for a
lean mixture, as shown in Fig. 3. Therefore, $S_T$ increases with increasing $\delta$, as shown in Fig. 2(a). In lean methane–propane mixtures, the mean local burning velocity of these mixtures decreases with increasing rate of addition of propane $\delta$, because propane has a lower $S_l$ for a lean mixture. Thus, $S_T$ decreases with increasing $\delta$.

On the other hand, for the case of rich methane–hydrogen mixtures, neither methane nor hydrogen are expected to show improved turbulent combustion due to preferential diffusion, as shown in Fig. 3. As a result, the changes in the $S_l$ with increasing rate of addition may become complicated.

In rich propane–hydrogen mixtures, propane has some effect by which to improve the turbulent combustion. Hydrogen, however, has no such effect, as shown in Fig. 3, indicating that $S_T$ decreases with increasing rate of addition of hydrogen.

In addition, in rich methane–propane mixtures, as is the case in propane–hydrogen mixtures, $S_T$ increases with increasing rate of addition of propane.

Thus, the turbulent burning velocity characteristics of two-component fuel mixtures can be explained qualitatively by the local burning velocity $S_l$ of each fuel comprising the two-component fuel. In addition, these characteristics are determined by the balance of both mean local burning velocities.

### 3.3 Quantitative discussion of turbulent burning velocity considering local burning velocity for two-component fuel mixtures

The discussion of turbulent burning velocity characteristics of two-component fuel mixtures in section 3.2 is based on the estimated $S_l$ of single-component fuel mixtures, taking into account preferential diffusion, which is absent from the discussion of the mechanism of chemical reaction, which may be more complex than that of a single-component fuel mixture. The discussion above, however, appears to be qualitatively valid. Thus, the preferential diffusion effect may be important with respect to the turbulent burning velocity for the two-component fuel mixtures, as well as single-component fuel mixtures.

In our previous study\(^\text{[6]}\), we proposed a simple model for predicting turbulent burning velocity for single-component fuel mixtures which adopted $S_l$ taking into account the preferential diffusion effect as a reference, rather than the original laminar burning velocity. As shown in Fig. 4, the validity of this model was confirmed for the single-component fuel mixtures and the type of fuel, the equivalence ratio and the laminar burning velocity were varied extensively. This model applies to the range in which the relationship between the turbulent burning velocity and turbulence intensity is almost proportional, and can be written as follows.

\[
0 < Ka_l \leq 0.5
\]

\[
S_T = \left( S_l + \frac{\gamma_{u'}}{2} \right) (1 - Ka_l^\gamma)
\]  \hspace{1cm} (2)

where $S_l$ is the mean local burning velocity, $\alpha$ is a flame configuration factor \([-((L_r + \eta) (L_r)^2)]$, $Ka_l$ is the Karlovitz number \(= u'/\alpha_{l} (S_l)\), $\eta$ is the preheat zone thickness \(= a_{l}/S_l\) and $a_{l}$ is the thermal
diffusivity based on the local equivalence ratio.

In the following section, an attempt is made to apply Eq. (2) to the two-component fuel mixture and evaluate the validity of the equation, in order to examine quantitatively the turbulent burning velocity characteristics of two-component fuel mixtures.

3.3.1 Estimation of local burning velocity
First, the mean local burning velocity must be estimated for the two-component fuel mixture, because this is the most important factor in the proposed expression. In the previous study\(^1\), the laminar burning velocity of hydrocarbon-hydrogen air mixtures was measured in detail in order to examine the effects of rate of addition and equivalence ratio. As a result, the laminar burning velocity of the two-component fuel mixture was found to be approximated by the laminar burning velocity of each single-component fuel mixture at the same equivalence ratio and N\(_2\)/O\(_2\) ratio as its composition, as weighted by the oxygen consumption ratio of each fuel. In the present study, the mean local burning velocity \(S_l(V, \Phi)\) of two-component fuel mixtures is approximated based on the previously described results via the following equation:

\[
S_l(V, \Phi) = (1 - V) \cdot S_l(1 - \delta, \phi) + V \cdot S_l(\delta, \phi)
\]

(3)

where \(V = \delta \cdot (a + \beta/4) / [(1 - \delta) \cdot (x + y/4) + \delta \cdot (a + \beta/4)]\) is the mole fraction of oxygen consumed by the added fuel. \(S_l(1 - \delta, \phi)\) and \(S_l(\delta, \phi)\) are the mean local burning velocities of each fuel mixture based on each composition at equivalence ratio, \(\Phi\).

The values of \(S_l(1 - \delta, \phi)\) and \(S_l(\delta, \phi)\) are approximated using Figs. 1 and 3, via the following assumption and simple procedure.

a. Methane-propane mixtures: The \(S_l(1 - \delta, \phi)\) of methane having \(\Phi = 0.8\) and the \(S_l(\delta, \phi)\) of propane mixture having \(\Phi = 1.2\) can be calculated using the values of \(S_l/S_{10}\) and \(S_{10}\) obtained from Fig. 3(a) and the contour lines of the laminar burning velocity based on its composition (e.g., N\(_2\)/O\(_2\)) [solid symbols plotted in Fig. 1(a) and (b)], respectively. The values of \(S_l/S_{10}\) for methane and propane mixtures were assumed to be 1.25 and 1.05, respectively, because changes in \(S_{10}\) (plotted solid symbols in Fig. 1) with respect to N\(_2\)/O\(_2\) were comparatively small.

On the other hand, the \(S_l(1 - \delta, \phi)\) of methane having \(\Phi = 1.2\) and the \(S_l(\delta, \phi)\) of propane having \(\Phi = 0.8\) can be calculated as follows. First, the values of \(S_{10}\) and \(\delta\phi\) are obtained from the contour lines of laminar burning velocity based on its composition [solid symbols plotted in Fig. 1(a) and (b)] and Fig. 3(b), respectively. Next, the value of \(S_{10}\), which can be found at the equivalence ratio increased by \(\delta\phi\) while maintaining N\(_2\)/O\(_2\) constant [see open symbols in Fig. 1(a) and (b)], is simply \(S_l(1 - \delta, \phi)\) or \(S_l(\delta, \phi)\). Here, the values of \(\delta\phi\) with respect to methane and propane mixtures were assumed to be 0.08 and -0.10, respectively, because the change in \(S_{10}\) with respect to N\(_2\)/O\(_2\) was also found to be comparatively small.

b. Methane-hydrogen and propane-hydrogen mixtures: The \(S_l(\delta, \phi)\) of hydrogen having \(\Phi = 0.8\) can be calculated using the values of \(S_l/S_{10}\) and \(S_{10}\) obtained from Fig. 3(a) and the contour lines of laminar burning velocity based on its composition (e.g., N\(_2\)/O\(_2\)) [solid symbols plotted in Fig. 1(c)], respectively. In these hydrogen mixtures, the change in \(S_{10}\) with respect to N\(_2\)/O\(_2\) at the same \(\phi\) appears to affect greatly the characteristic value of the preferential diffusion effect, such as \(S_l/S_{10}\), because the change in \(S_{10}\) with respect to N\(_2\)/O\(_2\) for these hydrogen mixtures is larger than that for these hydrocarbon mixture as shown in Fig. 1. In order to take this effect into account, a simple method was used. The relationship between \(S_l/S_{10}\) and \(S_{10}\) was approximated to be a function whereby \(S_l/S_{10}\) asymptotically reaches unity when \(S_{10}\) becomes sufficiently large. Therefore, the value of \(S_l/S_{10}\) can be calculated for each \(S_{10}\) plotted as a solid symbol in Fig. 1(c). On the other hand, the values of \(S_l(1 - \delta, \phi)\) of methane and propane having \(\Phi = 0.8\) was calculated by the method described above.

The hydrogen-added rich mixtures were not examined in the present study. Since the \(S_l(\delta, \phi)\) of hydrogen having \(\Phi = 1.2\) could not be calculated due to the lack of experimental data concerning the characteristic values of the preferential diffusion and the contour lines of the laminar burning velocity or rich mixtures.

![Fig. 5 Approximated local burning velocity of two-component fuel mixtures](image-url)
than for methane–propane mixtures. Accordingly, the turbulent burning velocity characteristics of two-component fuel mixtures, as well as those of one-component fuel mixtures, can be reproduced via Eq. (2).

This procedure can not yet be applied to rich hydrocarbon mixtures under hydrogen addition. However, the turbulent burning velocity characteristics of two-component fuel mixtures can be reproduced, despite the use of a simple procedure by which the mean local burning velocity is approximated using Eq. (3) based on the mean local burning velocity of each fuel. This indicates that the preferential diffusion effect plays an important role in the turbulent combustion of two-component fuel mixtures, as well as in that of single-component fuel mixtures.

4. Conclusions

The turbulent burning velocity of the two-component fuel mixtures, which have methane, propane or hydrogen as fuels and have the same laminar burning velocity, was examined. The following conclusions were attained:

(1) A distinct difference in the turbulent burning velocity characteristics with respect to the rate of addition of fuel exists between lean and rich mixtures. The turbulent burning velocity of lean mixtures changes almost constantly as the rate of addition changes. The turbulent burning velocity of rich mixtures, however, do not show such a trend.

(2) Improvement of turbulent combustion due to the addition of hydrogen to the hydrocarbon mixture can be obtained for lean mixtures. In contrast, such improvement is not always possible for rich mixtures.

(3) The mean local burning velocity which takes into account the preferential diffusion effect plays an important role in the determination of turbulent burning velocity for two-component fuel mixtures, as well as for single-component fuel mixtures.

(4) When the mean local burning velocity can be estimated using Eq. (3), the simple expression of turbulent burning velocity proposed for single-component fuel mixtures is confirmed to be applicable to the two-component fuel mixtures.

References


(3) Milton, B.E. and Keck, J., Laminar Burning


