

Experimental Study on Turbulent Burning Velocities of Two-Component Fuel Mixtures of Methane, Propane and Hydrogen

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ABSTRACT

In order to elucidate the turbulent burning velocity of the two-component fuel mixtures, the lean and rich two-component fuel mixtures, where methane, propane and hydrogen were used as fuels, were prepared keeping the laminar burning velocity nearly the same value. Clear difference in the measured turbulent burning velocity at the same turbulence intensity can be seen among the two-component fuel mixtures with different addition rate of fuel, even under nearly the same laminar burning velocity. The burning velocities of lean mixtures change almost monotonously as changing addition rate, those of rich mixtures, however, do not show such a monotony. These phenomena can be explained qualitatively from the local burning velocities, estimated by considering the preferential diffusion effect for each fuel component. In addition, a prediction expression of turbulent burning velocity proposed for the one-component fuel mixtures can be applied to the two-component fuel mixtures by using the estimated local burning velocity of each fuel mixture.

Keywords : premixed combustion, multi-component fuel mixture, turbulent burning velocity, preferential diffusion.

INTRODUCTION

Recently, from the viewpoint to solve both environmental and energy problems, attention is focused on the usage of various gas fuels such as natural gas and coal gasification gas. These fuels as well as conventional fuels such as gasoline are made up from several components. As the performance of combustion devices can be governed largely by the burning

velocity, it is useful to know the burning velocity of multi-component fuel mixtures. So, a number of studies for the burning velocity of these mixtures have been conducted. But most of those studies have investigated only the laminar burning velocities[1]~[5].

In our previous works[6][7], the turbulent burning velocities for one-component fuel mixtures(fuel/oxygen/nitrogen) of three hydrocarbons and hydrogen, having nearly the

same laminar burning velocity, were examined experimentally. As a result, the molecular diffusivity of fuel in the mixture can be seen to affect its turbulent burning velocity characteristics, leading to the change in the local burning velocity from the original laminar burning velocity. Namely, in turbulent combustion of lighter hydrocarbons with higher diffusivity than oxygen such as methane or hydrogen, the turbulent burning velocity at the same turbulence intensity increases with decreasing equivalence ratio. On the other hand, in the case of heavier hydrocarbons with lower diffusivity than oxygen such as propane, the tendency of the turbulent burning velocity against the equivalence ratio is reversed. These phenomena were found to be explained by the preferential diffusion, and those mean local burning velocity were estimated experimentally.

In the present study, to clarify the turbulent burning velocity of the multi-component fuel mixtures, the lean and the rich two-component fuel mixtures were prepared keeping the laminar burning velocity nearly the same value, and those turbulent burning velocity characteristics were experimentally examined. Where, methane, propane and hydrogen were used as fuels.

As a result, clear difference in the measured turbulent burning velocity at the same turbulence intensity can be seen among the two-component fuel mixtures with different addition rate of fuel, even under nearly the same laminar burning velocity. These phenomena can be explained qualitatively from the local burning velocities, estimated by taking account of the preferential diffusion effect for each fuel component shown in our previous works[6][7]. In addition, an attempt is made to apply a model of turbulent burning velocity

proposed for the one-component fuel mixtures[8] to the two-component fuel mixtures by using the estimated local burning velocity of each fuel mixture.

EXPERIMENTAL APPARATUS AND PROCEDURE

Combustion Chamber and Measurement of Burning Velocity

The combustion chamber used is a nearly spherical vessel with a mean inner diameter of about 120mm. It is fixed with two transparent windows of 80mm diameter at two opposite sides for flame observation, and four perforated plates of 100mm diameter at the other four sides. Behind each perforated plate, a fan is equipped to mix gases and generate approximately isotropic and homogeneous turbulence in the central region of the chamber. Details of the apparatus and procedure are shown elsewhere [6][7].

The experiments were conducted as follows. These mixtures(see Table 1) were concocted in the chamber according to the partial pressure of components and then ignited at the vessel center under desired turbulence intensity and the atmospheric condition where the initial pressure and temperature were about 0.101MPa and 298K, respectively. The laminar burning velocity S_{LO} , and the turbulent burning velocity S_T , were measured by the pressure history of spherical flame in closed vessel in the early stage of combustion[6][7]. Each experiment was repeated more than 10 times to keep the accuracy of measurements.

The turbulence intensity u' were measured for each mixture against the fan speed. The characteristics of turbulence in the chamber are that the longitudinal integral length scale L_f shows a slight increase and following flat-

tening out and the Taylor's micro scale λ_g shows a negligible increase and following decrease with increasing the turbulence intensity ($u' \sim 3.67\text{m/s}$), being about $3.3 \pm 0.3\text{mm}$ and $1.49 \pm 0.1\text{mm}$, respectively.

Mixture Composition

The two-component fuel mixtures used in this study are shown in Table.1. Methane and hydrogen were chosen as the light fuel, and propane as the heavy fuel. The lean ($\Phi=0.8$) and the rich ($\Phi=1.2$) two-component fuel mixtures were prepared keeping the laminar burning velocity nearly the same value

Table 1 Properties of mixtures

Mixture	Φ	Molar Fraction					S_{l0} cm/s	a_0 mm ² /s	ν mm ² /s
		CH ₄	C ₃ H ₈	H ₂	O ₂	N ₂			
M08H00-25	0.8	1.00	-	0.00	2.50	9.63	25.30	21.05	15.55
M08H02-25	0.8	0.80	-	0.20	2.13	9.56	25.01	22.12	15.75
M08H05-25	0.8	0.50	-	0.50	1.56	7.66	24.95	24.47	16.23
M08H08-25	0.8	0.20	-	0.80	1.00	6.50	25.40	27.81	16.90
M08H10-25	0.8	0.00	-	1.00	0.63	6.25	25.25	30.35	17.40
M12H00-25	1.2	1.00	-	0.00	1.67	6.83	24.90	21.09	15.60
M12H02-25	1.2	0.80	-	0.20	1.42	6.23	24.70	22.68	15.91
M12H05-25	1.2	0.50	-	0.50	1.04	5.31	24.18	25.87	16.56
M12H10-25	1.2	0.00	-	1.00	0.42	5.08	24.50	32.49	17.89
P08H00-25	0.8	-	1.00	0.00	6.25	25.00	25.40	19.47	14.66
P08H02-25	0.8	-	0.80	0.20	5.13	21.78	25.25	20.04	14.80
P08H05-25	0.8	-	0.50	0.50	3.44	15.13	25.47	21.41	15.13
P08H08-25	0.8	-	0.20	0.80	1.75	9.28	24.74	24.73	15.94
P08H10-25	0.8	-	0.00	1.00	0.63	6.25	25.25	30.35	17.40
P12H00-25	1.2	-	1.00	0.00	4.17	18.96	24.60	19.01	14.41
P12H02-25	1.2	-	0.80	0.20	3.42	15.72	24.78	19.72	14.57
P12H05-25	1.2	-	0.50	0.50	2.29	11.23	24.56	21.57	15.02
P12H08-25	1.2	-	0.20	0.80	1.17	6.77	25.16	26.04	16.12
P12H10-25	1.2	-	0.00	1.00	0.42	5.08	24.50	32.49	17.89
M08P00-25	0.8	1.00	0.00	-	2.50	9.63	25.30	21.05	15.55
M08P02-25	0.8	0.80	0.20	-	3.25	12.84	25.39	20.44	15.20
M08P05-25	0.8	0.50	0.50	-	4.38	17.72	25.34	19.93	14.92
M08P08-25	0.8	0.20	0.80	-	5.50	22.00	25.57	19.61	14.74
M08-P10-25	0.8	0.00	1.00	-	6.25	25.00	25.40	19.47	14.66
M12P00-25	1.2	1.00	0.00	-	1.67	6.83	24.90	21.09	15.60
M12P02-25	1.2	0.80	0.20	-	2.17	9.21	25.11	20.26	15.11
M12P05-25	1.2	0.50	0.50	-	2.92	12.83	25.15	19.57	14.72
M12P08-25	1.2	0.20	0.80	-	3.67	16.50	25.11	19.19	14.50
M12P10-25	1.2	0.00	1.00	-	4.17	18.96	24.60	19.01	14.41

25cm/s. Φ denotes the total equivalence ratio[9] based on the numbers of carbon and hydrogen atoms of two fuels as follows,

$$\Phi = [(x+y/4)(1-\delta) + (\alpha+\beta/4)\delta]/X_0 \quad (1)$$

where, the mixture composition can be expressed $(1-\delta)C_xH_y + \delta C_\alpha H_\beta + X_0O_2 + X_NN_2$. δ represents the addition rate as the volume fraction of the added fuel in the whole fuel gases, and hydrogen for methane-hydrogen and propane-hydrogen mixtures and propane for methane-propane mixtures are called the added fuel.

In Table 1, a_0 and ν are the thermal diffusivity and kinematic viscosity, respectively. The methane-hydrogen mixture (M12H08-25) with $\Phi = 1.2$ and $\delta = 0.8$ could not be arranged under the ignition energy of 2.5J used in this study.

RESULTS AND DISCUSSION

Turbulent Burning Velocity of Two-component Fuel Mixture

Figure 1 shows the variation of the measured turbulent burning velocity S_T with the turbulence intensity u' for different addition rate of fuel δ .

From Fig.1, clear difference in the turbulent burning velocity at the same turbulence intensity can be seen among the two-component fuel mixtures with different addition rate of fuel, even under nearly the same laminar burning velocity. In addition, there exists an obvious difference between the changes in the turbulent burning velocities as increasing the addition rate in lean mixtures and those in rich mixtures.

In the case of the lean mixtures, the values of S_T of methane-hydrogen and propane-hydrogen mixtures at the same u' show to increase almost monotonously as addition rate

of hydrogen increases. And those of methane-propane mixtures decrease almost monotonously as addition rate of propane increases.

In the case of the rich mixtures, the changes in the turbulent burning velocities, however, do not show such a monotony as follows.

In rich methane-hydrogen mixtures, the values of S_T show at first to decrease as addition rate of hydrogen δ increases. And suddenly the mixture with δ being 0.8 cannot be arranged as mentioned above. When δ achieves 1.0, the mixture, however, can be arranged and its S_T shows to be nearly equal to that with $\delta = 0$.

In rich propane-hydrogen mixtures, the values of S_T slightly increase as addition rate of hydrogen δ increases until about 0.5. Those, however, suddenly decrease as δ increases over 0.5.

In methane-propane mixtures, the values of S_T increase at first as addition rate of propane δ increases. When δ becomes larger than about 0.5, those increases are negligibly small as increasing δ .

Discussion Considering Preferential Diffusion Effect

It is well known that the predominant factors on the turbulent burning velocity are the flame surface area and the local burning velocity under the weak turbulent condition. In our previous work[10], the surface area of turbulent flame of one-component fuel mixtures at the same weak turbulence condition was found to be almost dependent only on u' . Meanwhile, from the examination of turbulent burning velocities for these one-component fuel mixtures in our previous works[6][7], clear difference in S_T of mixtures with having the same S_{L0} , similar to Fig.1, was observed as mentioned in the introduction.

These results indicated that the turbulent burning velocity was mainly affected by the local burning velocity and the local burning velocity changed from the original laminar burning velocity caused by the preferential diffusion effect.

In the same way, the local burning velocity of two-component fuel mixture can possibly change from the original value. An attempt to elucidate the mechanism of phenomena in Fig.1 is made, focusing on the local burning velocity as follows.

Discussion Based on the Local Burning Velocity of One-Component Fuel Mixture.

In our previous works[6][7], we proposed an experimental method, which could estimate quantitatively the mean local burning velocity S_L for one-component fuel mixtures, taking the preferential diffusion into consideration.

Figure 2 shows the ratio of the estimated S_L to S_{L0} against equivalence ratio ϕ for one-component fuel mixtures with $S_{L0} = 25\text{cm/s}$. From Fig.2, in the case of methane and hydrogen mixtures, the values of S_L/S_{L0} in the lean side show to get larger than those in the rich side. Namely, improving the combustion performance caused by preferential diffusion effect can be clearly enhanced in the lean mixture for methane and hydrogen mixtures. Whereas in the case of propane mixtures, such improving effect can be obtained in the rich mixture. Furthermore, S_L/S_{L0} of lean hydrogen mixture is larger than that of hydrocarbon mixture since hydrogen has the higher molecular diffusivity.

It is difficult to determine S_L for two-component fuel mixtures by experimental method. Because its diffusion characteristics are more complicated. Here, we discuss the phenomena of two-component fuel mixtures in Fig.1

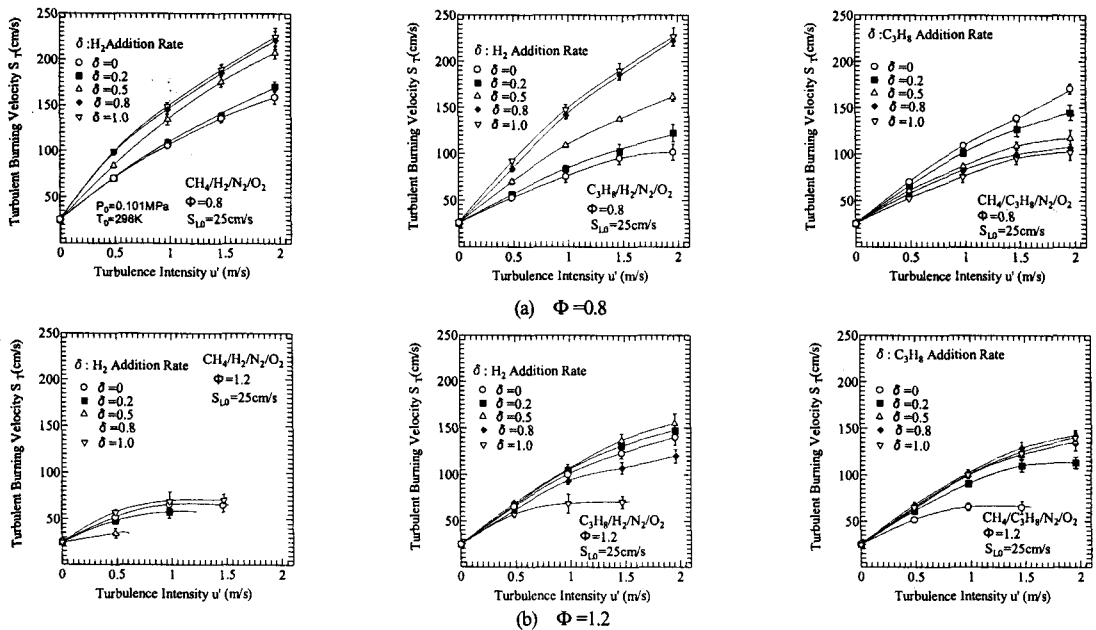


Fig. 1 Turbulent Burning Velocities of Two-Component Fuel Mixtures

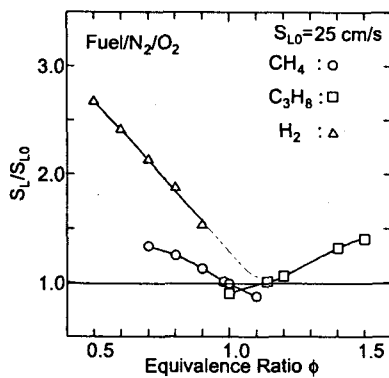


Fig. 2 Variation of S_L/S_{L0} with ϕ

based on the results in Fig.2 as follows.

In the case of the hydrogen added lean mixtures, the local burning velocities of these mixtures increase with increasing δ of hydrogen, because hydrogen has the higher S_L in the lean side as shown in Fig.2. So, S_T increases with increasing δ as shown in Fig.1. In the case of the propane added lean mixtures, the local burning velocities of these mixtures decrease with increasing δ of propane, because the

propane has lower S_L in the lean side. So, S_T decreases with increasing δ as shown in Fig.1.

On the other hand, in rich methane-hydrogen mixtures, both methane and hydrogen in the rich side cannot be expected to have the effect of improving the turbulent combustion due to the preferential diffusion as shown in Fig.2. So, it is conceivable that the changes in the S_T as increasing δ may become complicated. In rich propane-hydrogen mixtures, propane has some effect of improving the turbulent combustion, but hydrogen has not such effect as shown in Fig.2. This indicates that S_T decreases as increasing δ of hydrogen in the region of large addition rate. Finally, in rich methane-propane mixtures, S_T increases as increasing δ of propane, from the similar discussion above.

Quantitative Discussion of the Turbulent Burning Velocity

In the section above, discussion of the turbu-

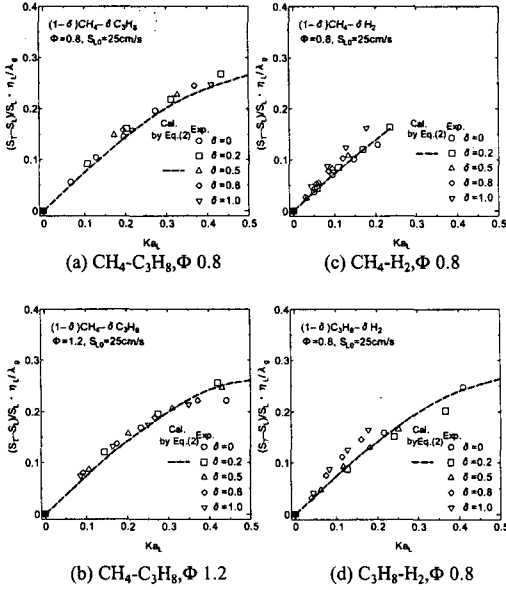


Fig. 3 Comparison of Predictions with Measurements

lent burning velocity characteristics of two-component fuel mixtures in Fig.1 is made based on the estimated S_L of one-component fuel mixture taking account of preferential diffusion. Where, the examination from the viewpoint of the mechanism of chemical reaction is absent, while the chemical reaction of two-component mixtures may be more complex than that of one-component fuel mixture. The discussion above, however, seems to be qualitatively valid. Thus, the local burning velocity considering the preferential diffusion may play an important role in the turbulent burning velocity for the two-component fuel mixtures as well as one-component fuel mixtures.

Then, an application of the prediction expression of turbulent burning velocity[8], which is proposed for the one-component fuel mixtures, is made for the two-component fuel mixtures. The mean local burning velocity, which is the important factor in the proposed expression, must be estimated at first for two-

component fuel mixture. In this study, the mean local burning velocity $S_L(V, \Phi)$ of each mixture is approximated based on results in the previous work[9] by the following equation;

$$S_L(V, \Phi) = (1-V) \cdot S_L(1-\delta, \Phi) + V \cdot S_L(\delta, \Phi) \quad (2)$$

where, $V = (\delta \cdot (\alpha + \beta/4) / [(1-\delta) \cdot (x+y/4) + \delta \cdot (\alpha + \beta/4)])$ 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 velocity of each fuel mixture, respectively, which are estimated from our previous results[6][7] based on each composition at equivalence ratio being Φ .

Figure 3 shows the rearranged data from Fig.1 using the estimated $S_L(V, \Phi)$ as a basic parameter. $(S_T - S_L)/S_L \cdot \eta_L/\lambda_g$ is plotted against Ka_L for methane-propane and hydrogen added lean mixtures. In Fig.3, the broken lines plotted are calculated by the proposed expression[8] for the mixtures with $\delta = 0.2$. Where, η_L is the preheat zone thickness ($= a_l/S_L$), λ_g the Taylor's microscale and Ka_L the Karlovitz number ($= u' / \lambda_g \cdot \eta_L / S_L$). Here, the values of $S_L(V, \Phi)$ cannot be estimated for the hydrogen added rich mixtures, due to the lack of S_L data in the rich side of hydrogen.

The differences between the measured values and calculated ones for the hydrogen added lean mixtures seem to be a little larger than those for methane-propane mixtures. However, it is obvious that the measured turbulent burning velocities can be well approximated by using the proposed expression based on $S_L(V, \Phi)$. Thus, a simple expression proposed for the one-component fuel mixtures can be well applied to the two-component fuel mixtures. This fact shows that the preferential diffusion plays an important role in the turbulent combustion of two-component fuel

mixtures as well as one-component fuel mixtures.

CONCLUSIONS

(1) Clear difference in the measured turbulent burning velocity at the same turbulence intensity can be seen among the two-component fuel mixtures with different addition rate of fuel, even under nearly the same laminar burning velocity. The burning velocities of lean mixtures change almost monotonously as addition rate changes, those of rich mixtures, however, do not show such a monotony.

(2) The mean local burning velocity, taking account of preferential diffusion, plays an important role in the turbulent combustion of two-component fuel mixtures as well as one-component fuel mixtures.

Acknowledgements

This work was supported by Grant-in-Aid for "Research for the Future" Program, Production and Utilization- Technology of Hydrogen Aiming at the Hydrogen Energy Society-TASK 4, and also by Grant-in-Aid for Scientific Research (B) No.11450087, from the Japan Society for the Promotion of Science, and was greatly appreciated.

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