A Study on Influences of Hydrogen addition and Turbulence on Ignition Characteristics of Propane Mixtures

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1 Introduction

In recent years, next-generation engines are required to achieve even higher efficiency, lower harmful emissions, and compatibility with a wide variety of fuels to cope with environmental and energy problems [1]. To achieve such high thermal efficiency, it's important to develop new combustion methods that assure reliable ignition and flame propagation for lean combustion even under high-exhaust gas recirculation and high-intensity turbulent flow conditions [2]. There, however, are a number of difficulties, such as misfire and cycle fluctuations, associated with the lean burn operation. One of the lean combustion instability problems can be resolved through the addition of hydrogen [3,4]. Additionally, elucidation of the mechanisms of ignition and flame kernel development is important to develop safety technologies for predicting and preventing fire or explosion in the hydrogen utilization society. Consequently, several studies have made an intensive effort to clarify some characteristics in detail: flame-kernel development, the relationship of plug diameter and spark gap with minimum ignition energy, combustion characteristics inside a micro channel, and excess enthalpy combustion [5-7]. Recently, there have been theoretical and/or experimental studies in which spherical flame initiation has been examined paying strong attention to the effects of the Lewis number and/or turbulence [8-10]. Note that Shy's group has shown experimentally a global criterion for the minimum ignition energy transition as a function of a Peclet number.

In our previous studies [11,12], the influence of fuel and dilution gas types on fundamental properties of burning velocity was examined for meso-scale outwardly propagating spherical flames with a radius of 5 mm or less in quiescent mixtures. As a result, it is found that the molecular diffusion property of fuel and dilution gas is a significant factor in the relationship between the burning velocity of the flame kernel at the initial stage of ignition and flame radius or flame stretch. However, the influences of hydrogen addition and turbulence on ignition and flame kernel development characteristics in a micro/meso-scale flame region remain unknown.

This study is performed to experimentally investigate the effect of hydrogen addition on properties of ignition and flame-kernel development in both quiescence and isotropic and homogeneous turbulence, in order to examine fundamentally the improvement of ignition and combustion caused by hydrogen addition to lean propane mixtures in high-intensity turbulence field. In this study, first, in quiescence,

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the influence of hydrogen addition on the minimum ignition energy (MIE) as well as the burning velocity characteristics of meso-scale outwardly propagating spherical laminar flames as the flame kernel are examined in a constant volume vessel. The hydrogen added propane mixtures are used, where propane is a typical hydrocarbon and has smaller molecular diffusivity than oxygen. The mixtures with different equivalence ratios (ϕ=0.5~1.4) and hydrogen additional rates (δ_H=0.0~1.0) are used while maintaining the laminar burning velocity (S_{L0}=25 & 15 cm/s). Then, the influence of turbulence on MIE in isotropic and homogeneous turbulence is examined over a wide range of turbulence intensity (u'= ~1.79m/s). Additionally, the effects of hydrogen addition, the equivalence ratio, the Lewis number on MIE and the flame kernel development characteristics are examined in quiescence and turbulence fields. This study also focuses on assessing the presence of MIE transition [9] by using the turbulent Karlovitz number based on the burning velocity of meso-scale flames.

2 Experimental Apparatus and method

The primary hydrogen added propane mixtures [$\delta_H H_2/(1-\delta_H)C_3H_8/O_2/N_2$] used in this study are listed in Table 1. The mixtures with different hydrogen additional rates δ_H and equivalence ratios ϕ are prepared while maintaining the so-called laminar burning velocity S_{L0}, because the ignition and flame kernel can be examined approximately under identical conditions such as preheat zone thickness and thermal expansion. In Table 1, ϕ denotes the total equivalence ratio. δ_H represents the rate of addition of the volume fraction of hydrogen in the total gaseous fuels (δ_H=0, 0.2, 0.5, 0.8 and 1.0). And Le denotes the Lewis number as a_0/D_d, where a_0 is the thermal diffusivity and D_d is the diffusion coefficient of deficient reactant. For lean mixtures, a simple linear effective Le is defined based on Le of each fuel. Besides, S_{L0} is the burning velocity whose flame radius is more than approximately 15 mm. It is calculated by pressure history in the combustion chamber for the unstretched spherical laminar flames [4, 11,12].

Figure 1 shows the schematics of the combustion chamber used in this study. It is a nearly spherical vessel with an inner diameter of about 100 mm, equipped with four observation windows with a diameter of 85 mm at four sides, one of which is integrated with the spark electrodes, and two top and bottom perforated plates of 90 mm diameter. A fan is installed behind each perforated plate. Isotropic and homogeneous turbulence in the combustion chamber could be generated by rotating both fans at the same rotational speed of 1000 and 5000 rpm, that is, the turbulence intensity u' =0.35 and 1.76 m/s. The combustion experiment in the laminar field with u' = 0 m/s is also conducted. In Table 1, L_f the longitudinal integral length scale, η_0 the preheat zone thickness (=a_0/S_{L0}), Da_l the Damköhler number (=$F_l/u' \cdot S_{L0}/\eta_0$), Re_l the Reynolds number (=$L_f \cdot u'/\nu$), and ν the kinematic viscosity.

First, the ignition conditions were determined according to the same manner in our previous studies [11,12]. For the experiment of meso-scale flames with r_f < about 5mm, the diameter of the electrodes (SUS) D is set to 0.1 mm for all mixtures. For the mixtures with S_{L0}=25 cm/s, the spark gap W is 3.0 mm for δ_H=0.0 at ϕ=0.5 & 0.8 and δ_H=1.0 at ϕ=1.4, 0.5 mm for δ_H=1.0, and 1.0 mm for the other mixtures. The ignition energy Ei is adjusted from 4.8 to 101.6 mJ by changing the capacity, after MIE for each mixture has been examined. These ignition conditions were optimized to minimize the effect of Ei and W on the burning velocity characteristic of each meso-scale flame. Here, $Ei_{\min}$ is defined experimentally as the ignition energy at which the successful flame propagation occurs with a 50 percent probability after a flame kernel is formed by spark discharge. The propagation of meso-scale flame in a turbulent field is photographically observed using sequential Schlieren photography. The images are captured with a high-speed digital camera (512×512 pixels, 8 bit, 10000 fps, exposure time 1µs) with an 800 mm focal length lens. The resolution of the images is 0.027 mm/pixel.

3 Results and Discussion

3.1. Flame kernel development characteristics in quiescence

Table 1 Properties of mixtures

Mixture	ϕ	δ_H	Components [mol]				S_{L0}	a_0	Le	1000[rpm]				5000[rpm]			
			H_2	C_3H_8	O_2	N_2	cm/s	mm^2/s		u'/S_{L0}	L_f/η_0	Da_l	Re_l	u'/S_{L0}	L_f/η_0	Da_l	Re_l
P05-25NH00	0.5	0	0	1.0	10.00	24.40	24.6	19.6	1.59	1.42	35.1	24.7	66.4	7.11	44.4	6.24	420
P05-25NH02		0.2	0.2	0.8	8.20	20.09	25.2	20.1	1.35	1.39	35.0	25.2	65.9	6.95	44.3	6.38	417
P05-25NH05		0.5	0.5	0.5	5.50	14.19	25.4	21.4	1.00	1.38	33.2	24.1	64.8	6.89	42.0	6.10	410
P05-25NH08		0.8	0.8	0.2	2.80	8.54	25.2	24.7	0.65	1.39	28.5	20.5	61.5	6.97	36.1	5.18	389
P05-25NH10		1.0	1.0	0	1.00	6.63	24.7	29.5	0.41	1.42	23.5	16.5	57.1	7.11	29.7	4.17	361
P08-25NH00	0.8	0	0	1.0	6.25	25.63	24.8	19.5	1.57	1.42	35.5	25.1	66.7	7.08	44.9	6.34	422
P08-25NH02		0.2	0.2	0.8	5.13	21.04	25.0	20.0	1.34	1.40	34.9	24.9	66.2	7.01	44.1	6.29	419
P08-25NH05		0.5	0.5	0.5	3.44	15.02	24.9	21.4	1.02	1.41	32.5	23.0	64.8	7.05	41.1	5.83	410
P08-25NH08		0.8	0.8	0.2	1.75	8.81	24.9	24.9	0.66	1.41	27.9	19.8	61.5	7.06	35.3	5.01	389
P08-25NH10		1.0	1.0	0	0.63	6.00	24.8	30.7	0.43	1.42	22.6	15.9	56.3	7.11	28.5	4.02	356
P14-25NH00	1.4	0	0	1.0	3.57	12.68	25.3	18.3	0.87	1.40	38.1	27.2	69.6	7.00	48.1	6.88	441
P14-25NH02		0.2	0.2	0.8	2.93	11.22	25.1	19.4	0.90	1.40	36.2	26.0	68.4	6.98	45.8	6.57	433
P14-25NH05		0.5	0.5	0.5	1.96	8.19	25.0	21.8	0.98	1.40	32.1	22.8	65.7	7.02	40.6	5.78	416
P14-25NH08		0.8	0.8	0.2	1.00	5.12	24.9	27.3	1.14	1.41	25.4	18.0	60.2	7.06	32.2	4.55	381
P14-25NH10		1.0	1.0	0	0.36	4.67	24.8	33.5	1.31	1.42	20.7	14.6	54.4	7.10	26.2	3.69	344
P08-15NH00	0.8	0.0	0.0	1.0	6.25	28.38	15.1	19.6	1.58	2.31	21.6	9.3	66.5	11.57	27.3	2.36	421
P08-15NH02		0.2	0.2	0.8	5.13	23.83	15.2	20.1	1.35	2.30	21.1	9.2	66.0	11.52	26.8	2.32	417
P08-15NH05		0.5	0.5	0.5	3.44	16.71	15.2	21.4	1.00	2.31	19.8	8.6	64.7	11.56	25.1	2.17	409
P08-15NH08		0.8	0.8	0.2	1.75	9.98	15.2	24.5	0.65	2.31	17.3	7.5	61.7	11.57	21.9	1.89	390
P08-15NH10		1.0	1.0	0.0	0.63	6.75	14.9	29.7	0.41	2.35	14.0	6.0	57.0	11.77	17.8	1.51	360

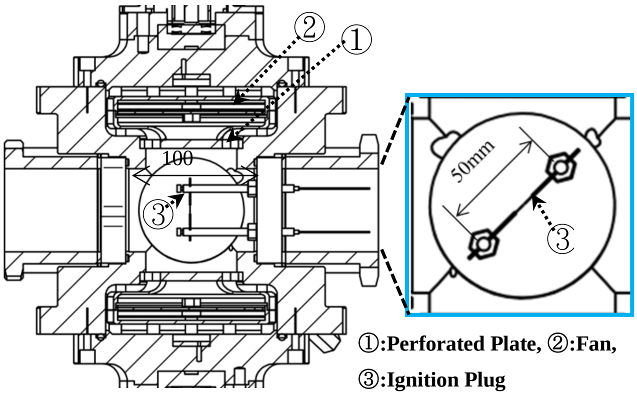


Fig.1 Schematic of combustion chamber for turbulence.

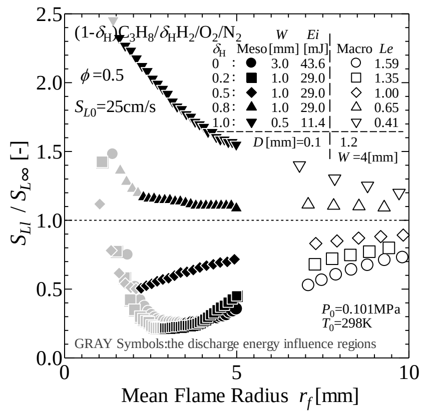


Fig.2 Relationship between r_f and $S_{Ll}/S_{L\infty}$ (ϕ0.5, S_{L0}=25cm/s)

First, as the fundamental combustion characteristics of the mixtures in Table 1, a typical relationship between the burning velocity S_{Ll} of meso-scale flames normalized by $S_{L\infty}$, that is the value of S_{Ll} when the flame stretch is zero (which is almost the same as S_{L0} in this study), and the mean flame radius r_f in a quiescent mixture with S_{L0}=25 cm/s at ϕ=0.5 is shown in Fig. 2. Here, S_{Ll}, $S_{L\infty}$ and r_f are obtained according to the method in our previous studies [4, 11,12]. It is clear from Fig.2 that $S_{Ll}/S_{L\infty}$ at the same r_f increases with δ_H, even if ϕ is 0.5. The burning velocity of meso-scale flames (r_f <5 mm) as the flame kernel is also found to be more sensitive to flame size than that of macro-scale flames (r_f >7 mm).

Figure 3 shows variations of the $S_{Ll}/S_{L\infty}$ rearranged at r_f=4mm from Fig.2. In Fig.3, the other mixtures with S_{L0}=25cm/s are also plotted. It is clear from Fig.3 that for lean mixtures at ϕ=0.8 as well as 0.5, $S_{Ll}/S_{L\infty}$ tends to increase monotonically with increasing δ_H. On the other hand, for the rich mixture at ϕ=1.4, the opposite trend can be observed. Namely, $S_{Ll}/S_{L\infty}$ decreases with increasing δ_H.

Some theoretical studies have pointed out the importance of the Lewis number Le in the burning velocity of micro/meso-scale laminar flames [7]. Accordingly, an attempt is made to examine the relationship between the burning velocity of meso-scale flames and Le. Figure 4 shows variations of the $S_{Ll}/S_{L\infty}$ rearranged at r_f=4 mm with Le. In Fig. 4, the mixtures with S_{L0}=15 cm/s at ϕ=0.8 are also plotted. It is

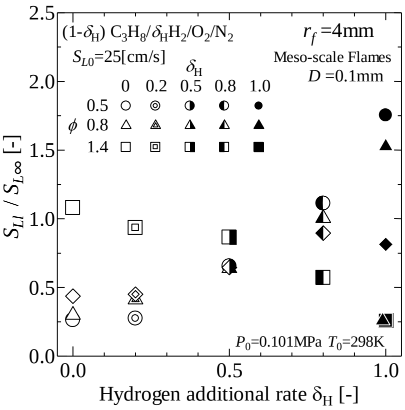


Fig.3 Influences of ϕ and δ_H on $S_{Ll}/S_{L\infty}$ at r_f=4mm for mixtures with S_{L0}=25cm/s

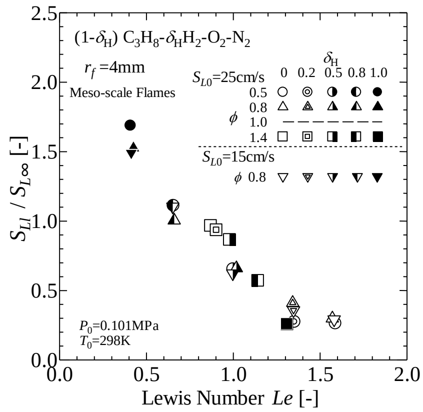


Fig.4 Relationships between $S_{Ll}/S_{L\infty}$ at r_f=4mm and Le for mixtures with S_{L0}=25&15cm/s

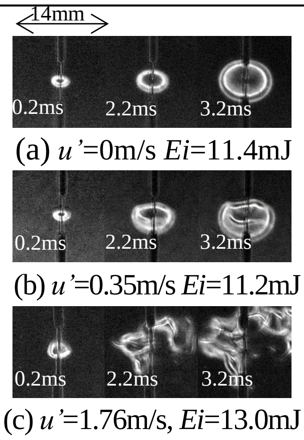


Fig.5 Schlieren images in turbulence (ϕ=0.8, δ_H=0.5, S_{L0}=25cm/s)

obvious from Fig. 4 that $S_{Ll}/S_{L\infty}$ at r_f =4 mm tends to decrease with increasing Le, irrespective of ϕ, δ_H and S_{L0} under this study's condition. This indicates that Le could be comprehensive parameters for the establishment of a model with respect to the burning velocity of meso-scale flames as the flame kernel in quiescence.

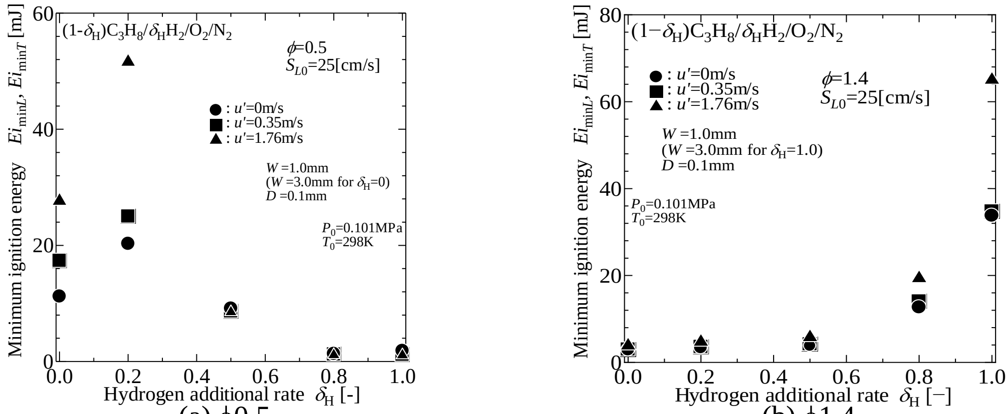
3.2. Ignition in isotropic and homogeneous turbulence

Figure 5 shows typical sequential schlieren images of the mixtures with S_{L0}=25 cm/s at ϕ=0.8 and δ_H=0.5 at u'=0, 0.35 and 1.76 m/s. As shown in Fig. 5, the flame kernel propagates spherically and symmetrically from the electrode in the laminar field at u'=0.0 m/s. The flame kernel at u'=0.35 m/s is not affected by turbulent gas flow immediately after ignition, but cannot hold its shape when it becomes large after about 3.2 ms. In contrast, at u'=1.76 m/s, the flame kernel begins to lose its shape and corrugate under the influence of turbulent flow from the time when the flame kernel is formed immediately after ignition, and then the flame front becomes more complicated as the flame grows.

Figure 6 shows the relationship between the obtained MIE and δ_H for mixtures with S_{L0}=25 cm/s at ϕ=0.5 and 1.4. Ei_{minL} and Ei_{minT} are Ei_{min} at u'=0 m/s and that at u' =0.35 and 1.76 m/s, respectively. It can be seen from Fig. 6 (a) that Ei_{minL} and Ei_{minT} for lean mixtures at ϕ=0.5 tend to decrease with increasing δ_H, except for δ_H=0 (W=3.0 mm), which means ignition becomes easier as δ_H increases. Besides, for δ_H=0 and 0.2, Ei_{minT} tends to increase as u' increases, whereas, for δ_H >0.5, Ei_{minT} is almost constant regardless of u'. In contrast, for rich mixtures at ϕ=1.4, Ei_{minL} and Ei_{minT} tend to increase with δ_H regardless of u'. Also, Ei_{minT} is almost constant for δ_H up to about 0.5, above which Ei_{minT} tends to increase with u'.

Next, we also discuss the effects of Le like Fig. 4. Figure 7 shows the relationship between Ei_{minT}/Ei_{minL} and Le for the mixtures in Table 1. From Fig. 7, for the mixtures with S_{L0}=25cm/s, Ei_{minT}/Ei_{minL} tends to decrease approximately as Le decreases regardless of ϕ, δ_H and u', and has a good correlation with Le. Furthermore, for Le > about 0.8, Ei_{minT}/Ei_{minL} at u'=1.76 m/s is larger than that at u'=0.35 m/s, at the same Le, and the difference tends to increase as Le increases. However, for Le < about 0.8, Ei_{minT}/Ei_{minL} tends to be smaller than unity. The difference of u' also has almost no influence on Ei_{minT}/Ei_{minL} at the same Le, and conversely, Ei_{minT}/Ei_{minL} at u'=1.76 m/s is slightly smaller than that at u'=0.35 m/s. It is also seen from Fig. 7 that MIE in turbulence can not be comprehensively explained only by Le, because a few values of Ei_{minT}/Ei_{minL} in Fig. 7 are much larger than the others.

Recently, Shy's group [9] reported that there exists a global criterion for the MIE transition as a function of a Peclet number. In our previous study [13] for the turbulent burning velocity S_T, a simple model for predicting S_T had been proposed based on local burning velocity as the substantial burning velocity of turbulent flames instead of S_{L0}. Finally, we attempt to ascertain whether the existence of the transition



(a) ϕ0.5 (b) ϕ1.4

Fig. 6 Relationships between MIE(Ei_{minL} & Ei_{minT}) and δ_H in turbulece (S_{L0}=25cm/s)

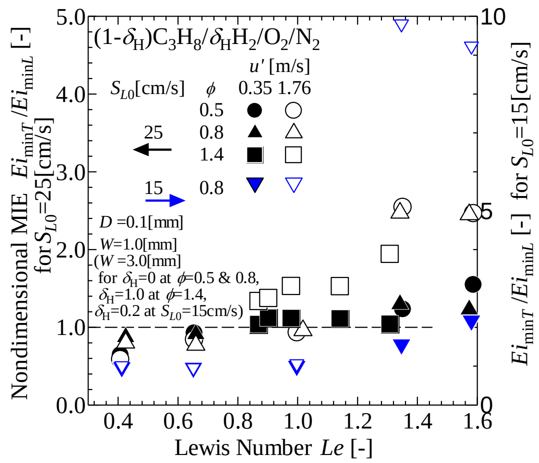


Fig. 7 Relationships between Ei_{minT}/Ei_{minL} and Le for mixtures with S_{L0}=25&15cm/s

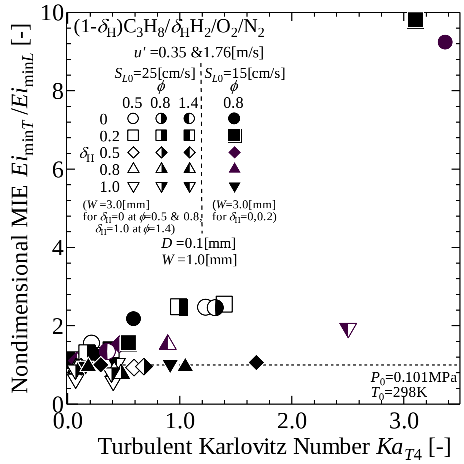


Fig. 8 Relationship between Ka_{T4} and Ei_{minT}/Ei_{minL} as functions of ϕ, δ_H and u'/S_{L0}

region of MIE can be comprehensively summarized using a non-dimensional number representing the flame stretch based on the substantial burning velocity of a flame kernel. Therefore, the turbulent Karlovitz number as a non-dimensional flame stretch defined by the following equation is used.

$$Ka_T = u'/\lambda_g \cdot \eta_{0l} / S_{Ll} \quad (1)$$

where λ_g is the Taylor-micro scale and η_{0l} is the preheat zone thickness based on S_{Ll} [$=a_0/S_{Ll}$]. In this study, Ka_T is estimated as Ka_{T4} whose S_{Ll} is the burning velocity of a meso-scale flame at r_f=4mm as shown in Fig.4. Figure 8 shows the relationship between Ei_{minT}/Ei_{minL} and the estimated Ka_{T4}.

From Fig. 8, Ei_{minT}/Ei_{minL} first shows a small increase with increasing Ka_{T4} regardless of ϕ, δ_H and u'/S_{L0}, followed by a significant rise with Ka_{T4} beyond about 3. Although data is insufficient at present, it is indicated that Ka_T based on S_{Ll} could be an important factor to determine the transition region of Ei_{minT}/Ei_{minL} from successful ignition to misfire.

4 Conclusions

The main conclusions are as follows:

(1) The improvement of the burning velocity characteristics of a meso-scale flame in quiescence for $\delta_H H_2/(1-\delta_H)C_3H_8/O_2/N_2$ mixtures with S_{L0}=25 cm/s is brought about by increasing δ_H for the lean mixtures at ϕ=0.5 and 0.8 while by decreasing δ_H for the rich mixture at ϕ=1.4.

(2) As a result of Ei_{minT} in an isotropic turbulence field, it is found that the ignition characteristics in turbulent flow fields at *u'* up to about 1.76 m/s are improved by increasing δ_H for mixtures at ϕ=0.5 and 0.8, while by decreasing δ_H for mixtures at ϕ=1.4.
(3) For *Le* > about 0.8, Ei_{minT}/Ei_{minL} is larger than unity and increases with *u'*, but for *Le* < about 0.8, Ei_{minT}/Ei_{minL} tends to be smaller than unity.
(4) The transition region of the minimum ignition energy could be summarized regardless of ϕ, δ_H and u'/S_{L0} by using the turbulent Karlovitz number Ka_{T4} whose S_{Ll} is the burning velocity at r_f=4mm in quiescence.

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