A Study on Burning Velocity Characteristics of Meso-scale Spherical Laminar Flames For Lean-Hydrogen-Propane Mixtures

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1 Introduction

From the viewpoint of the depletion of fossil fuels and the prevention of the progress of global warning in recent years, next generation combustors have goals to achieve very high-thermal efficiency, low emissions and fuel variability [1]. Lean premixed combustion of LPG (liquefied petroleum gas) and NG (natural gas) as well as Gasoline has been studied extensively as one promising technique to reduce the exhaust emissions especially of CO_2 and NOx as well as to improve fuel economy. There are a number of difficulties associated with lean burn operation. One important difficulty is misfire due to not only the increase in minimum ignition energies but also the weak flame kernels. One of the lean combustion instability problems can be resolved through addition of hydrogen [2-4]. The addition of hydrogen might achieve ultra-lean-fueled combustion below a lean flammability limit of hydrocarbon-air mixtures. Generally, since a flame kernel produced by ignition is the beginning of combustion and affects stability in the early combustion stage [5-7], knowledge of the burning velocity characteristics and development of improving combustion methods for micro/meso-scale flames is important, especially for lean and ultra-lean combustion.

On the other hand, improving combustion methods at the micro/meso scale is also one of the most important issues to further develop small scale combustion devices. The reason is that reducing the size of a combustor would increase heat loss and lead to unstable combustion due to the increasing surface-to-volume ratio and the concept of flame quenching distance [8].

However, the effect of hydrogen addition on the burning velocity characteristics of micro-scale spherical laminar flames for lean and ultra-lean hydrocarbon mixtures still remains unknown.

This study investigates experimentally the effects of hydrogen addition and equivalence ratios on burning velocity characteristics of meso-scale outwardly propagating spherical laminar flames in the range of flame radii r_f approximately from 1 to 5 mm, by using lean-fueled hydrogen added propane mixtures including the equivalence ratio below a lean flammability limit of propane-air mixtures, where propane is one of the main

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fuels in LPG. The mixtures having the same laminar burning velocity (S_{L0}=25cm/s) with different equivalence ratios (ϕ=0.5 and 0.8) and hydrogen additional rates (δ_H=0.0~1.0) are prepared.
In order to quantitatively examine the flame radius and the burning velocity of a meso-scale flame, developing flame fronts in a constant volume vessel are recorded by using sequential schlieren photography. The effects of hydrogen addition, the equivalence ratio, the Lewis number and Markstein number on the obtained relationships of flame radius and flame stretch with the burning velocity characteristics are examined.

2 Experimental method

The hydrogen added propane mixtures [$\delta_H H_2$+$(1-\delta_H)C_3H_8$+X_0O_2+$X_N N_2$] used in this study are listed in Table 1. The lean mixtures with different hydrogen additional rates and equivalence ratios are prepared while maintaining the so-called laminar burning velocity S_{L0} at approximately 25 cm/s, by adding nitrogen or oxygen to two-component fuel air mixtures. Due to adopting the mixtures having the same S_{L0} instead of the conventional fuel air mixtures, the burning velocity of outwardly propagating spherical laminar flames can be examined under identical conditions such as preheat zone thickness(or characteristic chemical reaction time), thermal expansion and buoyancy.
In Table 1, ϕ denotes the total equivalence ratio [4] based on the numbers of carbon and hydrogen atoms of two fuels. δ_H represents the rate of addition of the volume fraction of hydrogen in the total gaseous fuels, and δ_H is varied as 0, 0.2, 0.5, 0.8 and 1.0. In this study, the values of ϕ are 0.8 and 0.5, where 0.5 is the equivalence ratio below a lean flammability limit of propane-air mixtures. And *Le* denotes a simple linear effective Lewis number based on the each fuel Lewis number defined as a_0/D_d, where D_d is the diffusion coefficient of deficient reactant [9]. 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].
The combustion chamber, the same chamber that was used in our previous studies [5,6], is a near-spherical vessel with an equivalent inner diameter of about 100 mm, having enough space for meso-scale flames, as shown in Fig.1(a). It is equipped with four transparent windows of 85 mm diameter at four rectangular sides and two perforated plates of 90 mm diameter at the other two sides. Behind each perforated plate, a fan is equipped to mix gases. The experiments are conducted as follows. The gaseous mixture is concocted in the chamber according to the partial pressure of components under atmospheric condition. Once it is well mixed, the prepared mixture is kept at rest and then ignited at the vessel center.
In this study, the meso-scale and macro-scale flames are defined as a flame with a radius less than approximately 5 mm and greater than 7 mm, respectively [5,6].
For the experiment of meso-scale flames with r_f < about 5 mm, an ignition stand is set in the combustion

Table 1: Properties of mixtures.

Mixture	ϕ	δ_H	Components [mol]				S_{L0}	a_0	*Le*	T_p
			Fuel		O_2	Dilution gas	[cm/s]	[mm^2/s]		[K]
P05-25NH00	0.5	0	0 H_2	1.0 C_3H_8	10.00	24.40 N_2	24.6	19.6	1.59	1857
P05-25NH02		0.2	0.2 H_2	0.8 C_3H_8	8.20	20.09 N_2	25.2	20.1	1.35	1857
P05-25NH05		0.5	0.5 H_2	0.5 C_3H_8	5.50	14.19 N_2	25.4	21.4	1.00	1824
P05-25NH08		0.8	0.8 H_2	0.2 C_3H_8	2.80	8.54 N_2	25.2	24.7	0.65	1716
P05-25NH10		1.0	1.0 H_2	0 C_3H_8	1.00	6.63 N_2	24.7	29.5	0.41	1221
P08-25NH00	0.8	0	0 H_2	1.0 C_3H_8	6.25	25.63 N_2	24.8	19.5	1.57	1959
P08-25NH02		0.2	0.2 H_2	0.8 C_3H_8	5.13	21.04 N_2	25.0	20.0	1.34	1962
P08-25NH05		0.5	0.5 H_2	0.5 C_3H_8	3.44	15.02 N_2	24.9	21.4	1.02	1911
P08-25NH08		0.8	0.8 H_2	0.2 C_3H_8	1.75	8.81 N_2	24.9	24.9	0.66	1804
P08-25NH10		1.0	1.0 H_2	0 C_3H_8	0.63	6.00 N_2	24.8	30.7	0.43	1338

chamber as shown in Fig.1(a). Here, the diameter of the electrodes (SUS) D is 0.1mm, the spark gap W is 3.0 mm for the mixture with δ_H =0.0 at ϕ=0.5, 0.5 mm for that with δ_H =1.0, and 1.0 mm for the other mixtures. The ignition energy Ei is adjusted from 4.8 and 101.6 mJ by changing the capacity, after the minimum ignition energy for each mixture has been examined.

To observe meso-scale flames, sequential schlieren images are recorded. Flame images are captured by a high-speed digital camera (512×512 pixels, 8 bit and 10,000 fps) with a 800 mm focal length lens. The captured image data are transferred to a computer, and then a flame radius and burning velocity are calculated. The resolution of the images is 0.027 mm/pixel.

Schlieren photography is also used to observe and compare the burning velocity characteristic of macro-scale flames with meso-scale laminar flames, which propagate outward spherically. The observations are carried out using the combustion chamber, as shown in Fig.1(b), with a replaced ignition plug based on the following conditions [5,6]: D=1.2 mm, W=4 mm, and Ei=1.8 J. The frame speed is 2000~4000 fps and the resolution is 0.11 mm/pixel.

According to our previous study [5,6], a simple definition of the flame radius is adopted to facilitate comparing with the data by other researchers; the mean flame radius r_f of a meso-scale laminar flame at a given time is defined as follows:

$$r_f=[(Z+H)/4] \tag{1}$$

where H is the maximum height and Z is the maximum width of each flame kernel as shown in Fig.2.

The mean burning velocity of outwardly propagating spherical laminar flames is calculated by the following equation [5,6,10]:

$$S_{Ll}=[(\rho_b/\rho_u)\cdot(dr_f/dt)] \tag{2}$$

where ρ_b and ρ_u are the density of burned gas and unburned mixture respectively, and dt is the acquisition rate of images.

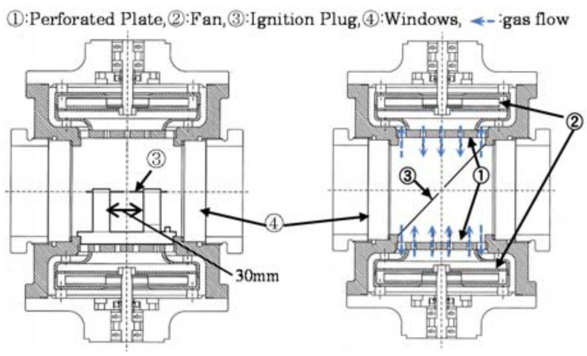
It is known that for outwardly propagating spherical laminar flames, flame stretch affects its burning velocity. To examine flame stretch, the Karlovitz number is defined as follows [5,6,10]:

$$Ka=(2/r_f\cdot dr_f/dt)\cdot(\eta_{0l}/S_{Ll}) \tag{3}$$

where η_{0l} is the preheat zone thickness based on S_{Ll} (=a_0/S_{Ll}).

3 Results and Discussion

Figure 3 shows the relationship between the obtained burning velocity S_{Ll} normalized by $S_{L\infty}$ and the flame



(a) Meso-scale flame (b) Macro-scale flame

Figure 1. Schematic of combustion chamber

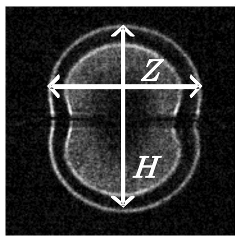
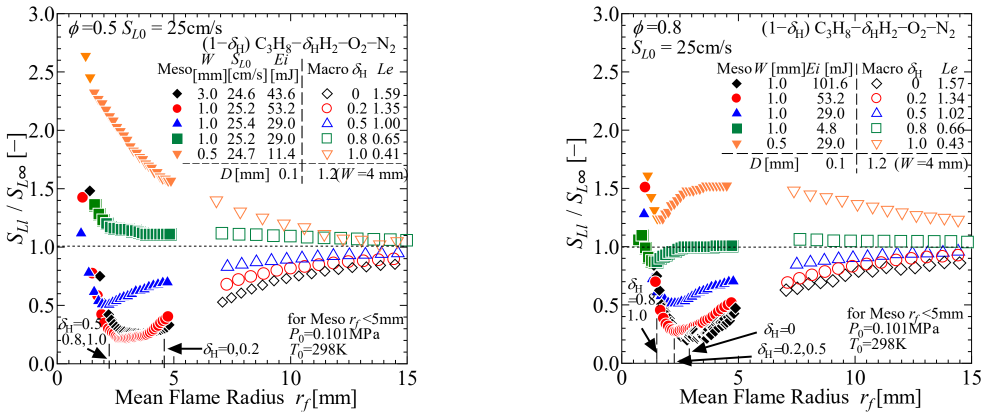


Figure 2. Schlieren photograph and definition of flame radius

radius r_f, for H_2 added C_3H_8 mixtures with S_{L0}=25 cm/s at ϕ=0.5 and 0.8. In Fig. 3, open symbols denote experimental results of macro-scale flames (r_f>7mm). It is recognized that there are sudden drops of $S_{Ll}/S_{L\infty}$ just after ignition, as shown in Fig. 3. As mentioned in our previous study [5,6], the drop regions to the left of vertical-thick-dashed lines in Fig. 3 are excluded from following discussion in order to neglect the spark effects.

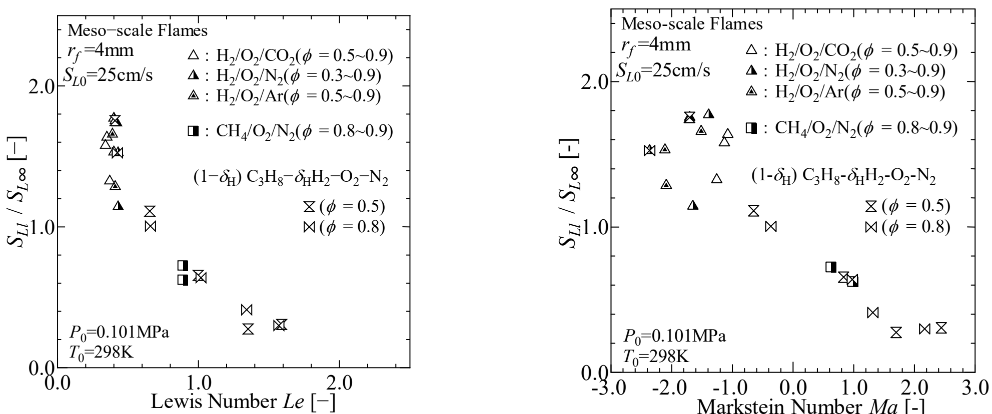
It is clear from Fig. 3 that $S_{Ll}/S_{L\infty}$ at the same r_f increases with increasing the H_2 additional rate δ_H, even if ϕ is 0.5, which is below a lean flammability limit of propane-air mixtures. The burning velocity of meso-scale flames (r_f<5mm) is also found to be more sensitive to flame size than that of macro-scale flames. Additionally, $S_{Ll}/S_{L\infty}$ is approximately unity when δ_H gets to 0.8. The interesting tendency can be also observed for the mixtures with δ_H=0.8 and 1.0 at ϕ=0.8: when r_f becomes smaller than about 5mm, S_{Ll} turns from an increase to a decrease as r_f deceases. This suggests that these mixtures individually have an optimal value of flame size with respect to the burning velocity.

Some theoretical studies have pointed out the importance of the Lewis number *Le* in the burning velocity of laminar flames with curvature [11]. Other measurements and theories have also suggested that the Markstein number *Ma* is a crucial parameter that should describe the sensitivity of stretch or curvature on the burning velocity of laminar flames [10,12]. Accordingly, an attempt is made to examine the relation among the burning velocity of meso-scale flames, *Le* and *Ma*. Figure 4 shows variations of the $S_{Ll}/S_{L\infty}$



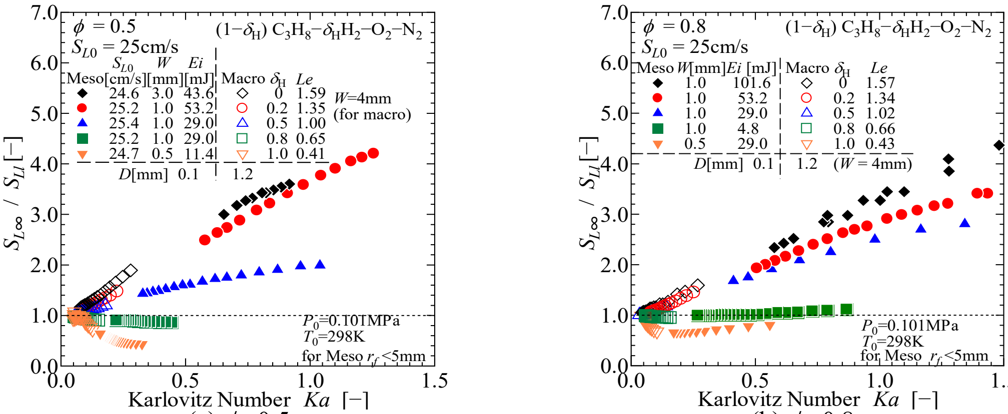
(a) ϕ=0.5 (b) ϕ=0.8

Figure 3. Variation of S_{Ll} with r_f as functions of δ_H



(a) $S_{Ll}/S_{L\infty}$-Le (b) $S_{Ll}/S_{L\infty}$-Ma.

Figure 4. Relationships between $S_{Ll}/S_{L\infty}$ rearranged at r_f=4mm and Lewis number, and Markstein number



(a) ϕ=0.5 (b) ϕ=0.8

Figure 5. Relationship between Karlovitz number Ka and $S_{L\infty}/S_{Ll}$

rearranged at r_f=4mm from Fig. 3 with Le and Ma. In Fig. 4, H_2–O_2–dilution gas mixtures, where Ar and CO_2 as well as N_2 are adopted as dilution gas, and CH_4 mixtures with S_{L0}=25 cm/s in our previous studies [5,6] are also plotted, in order to examine the influences of dilution gas and fuel types.

It is obvious from Fig. 4 that $S_{Ll}/S_{L\infty}$ at r_f = 4 mm tends to decrease with increasing both Le and Ma, irrespective of H_2 additional rates as well as dilution gas types and, fuel types and ϕ. This indicates that a mixture with smaller Le and Ma due to the larger additional amount of H_2 to lean mixtures is more adequate for ultra-lean combustors from the point of view of improving combustion. Besides, Le has a discontinuous value when ϕ is unity. If taking it into consideration, the Ma could possibly be a comprehensive parameter for the establishment of a model with respect to burning velocity of meso-scale flames. Furthermore, the burning velocity characteristics will need to be discussed by using so-called effective Lewis numbers instead.

Figure 5 shows the relationship between Ka and $S_{L\infty}/S_{Ll}$. As far as this experimental range, it is also clear from Fig. 5 that S_{Ll} at the same Ka increases with δ_H, even under the condition of ultra-lean mixtures below the lean flammability limit of propane-air mixtures. In the case of the lean mixtures with δ_H under about 0.5, S_{Ll} tends to decrease linearly with increasing Ka, while for the mixtures with δ_H over about 0.8, such trends cannot be observed. Especially, for the mixtures with δ_H=0.8 and 1.0 at ϕ=0.8, S_{Ll} first increases and then decreases with increasing Ka. Namely, this indicates that some mixtures individually have an optimal value of flame stretch with respect to burning velocity. In other words, there exist some mixtures whose burning velocity characteristics of meso-scale flames could not be defined on extrapolation of those of macro-scale flames.

4 Conclusions

The fundamental characteristics of burning velocity S_{Ll} of meso-scale flames with a radius r_f <5mm for $\delta_H H_2$–$(1-\delta_H)C_3H_8$ mixtures with different equivalence ratios (ϕ=0.5 and 0.8) and hydrogen additional rates (δ_H=0.0~1.0) having nearly the same laminar burning velocity(S_{L0}=25cm/s) are investigated experimentally by using schlieren photography. The main conclusions are as follows:

1. In the small r_f region(r_f<5mm), the burning velocity at the same r_f and Ka tends to increase with increasing the H_2 addition, even if ϕ is 0.5, which is below a lean flammability limit of propane-air mixtures.
2. S_{Ll} at r_f=4mm also tends to decrease with increasing the Lewis number and the Markstein number, irrespective of H_2 additional rates, fuel types and ϕ.

5 Acknowledgment

The authors acknowledge the assistance of Mr. K. Takagi, Mr. Y. Onishi, Mr. T. Nishihara, Mr. S. Tokunaga, Mr. W. Ikegami and Mr. I. Yanagihara for performing experiments. This work was also partially supported by JSPS KAKENHI Grant Number JP 16K06124.

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