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Laminar burning velocities, Markstein lengths, and flame thickness of liquefied petroleum gas with hydrogen enrichment

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ABSTRACT

In this paper, experimental data of laminar burning velocity, Markstein length, and flame thickness of LPG flames with various percentages of hydrogen (H₂) enrichments have been presented. The experiments were conducted under the conditions of 0.1 MPa, 300 K in a constant volume chamber. The tested equivalence ratios of air/fuel mixture range from 0.6 to 1.5, and the examined LPG contains 10%–90% of hydrogen in volume. Experimental results show that hydrogen addition significantly increase the laminar burning velocity of LPG, and the accelerating effectiveness is substantial when the percentage of hydrogen is larger than 60%. Effect of hydrogen addition on diffusion thermal instability, as indicated by Markstein length, was analyzed at various equivalence ratios. Hydrogen addition decreases the flame thickness. Equivalence ratio has more dominating effect on flame thickness than hydrogen does. For the fuel with 10% LPG and 90% hydrogen, the flame thickness values are close for all equivalence ratios.

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Introduction

Liquefied petroleum gas (LPG) consists mainly of butane and propane. As one of the main energy sources used for domestic and commercial applications, LPG has the advantages such as stable flame, high heating value, and low processing cost. Although LPG is a relatively clean fuel with low ash and sulfur contents, it still emits a large amount of carbon dioxide (CO₂) and unburned hydrocarbon (HC) during combustion, which are causing serious environmental problems. Besides, the CO₂/HC

emissions, the narrow flammability range of LPG is also an unfavorable factor, and significantly limits application of LPG. Hydrogen, another well known clean fuel, has zero CO₂/CO emission and wide flammability range. However, hydrogen flame can be rather unstable during operation because of its extremely light weight and special combustion characteristics. Also, because of its low density and light molar weight, hydrogen has very low volumetric heating value. It seems that LPG and hydrogen are complementary with each other on emissions, flame stability, and heating value. LPG with hydrogen addition may be helpful in extending flammability

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Nomenclature			
H ₂ %	volumetric percentage of hydrogen in fuel mixture, %	λ	thermal conductivity of unburned gas, cal m ⁻¹ K ⁻¹ s ⁻¹
V _{air}	volume of air, m ³	r _{sch}	schlieren front radius, m
V _{fuel}	volume of fuel, m ³	α	flame stretch rate, s ⁻¹
S _n	stretched laminar flame speed, m/s	S _l	unstretched laminar flame speed, m s ⁻¹
r _u	cold flame front radius, m	L _b	burned gas Markstein length, mm
ρ_b	burned gas density, kg m ⁻³	u _l	unstretched laminar burning velocity, cm s ⁻¹
ρ_u	unburned gas density, kg m ⁻³	δ_l	laminar flame thickness, mm
		C _p	specific heat of unburned gas, cal kg ⁻¹ K ⁻¹
		Ma	Markstein Number

range and reducing CO₂/HC emissions. Furthermore, adding hydrogen in LPG may stabilize the flame and improve volumetric burning velocity of the fuel. Thus, the mixture of LPG and hydrogen may be a potential solution for high energy, low emission, and extended stable flames.

Laminar burning velocity (LBV) is a fundamental property of fuel. It is determined by the kinetics of chemical reaction and the molecular heat and mass transport [1]. LBV is also an important parameter in validating the chemical kinetics [3] and combustion characteristics of a fuel, and hence it is an important parameter in predicting performance and emission of a fuel for any combustion systems [2]. The LPG–H₂ mixture studied in this paper is a unique and complicated fuel mixture containing butane, propane, and hydrogen. Although there are extensive researches on LBVs of hydrogen, propane, and butane individually [3–16], few LBV data are accessible for the mixture of these three fuels.

Markstein length is another important property of fuel, which is related to the diffusional-thermal instability of flame, while flame thickness and density ratio are related to the hydrodynamic instability of flame. By analyzing Markstein length, flame thickness, and density ratio of a LPG-hydrogen flame, the optimal ratio of LPG and hydrogen for a safe and stable flame could be determined [8].

There are several methods to measure the LBV, such as conical flame method, soap bubble method, counterflow burner method, and constant volume combustion bomb

method [2,17]. The constant volume combustion bomb method uses the spherically propagating flame, which has simple flame geometry, low thermal conduction heat loss, and low friction with the vessel wall [1]. There are some other advantages of using the constant volume combustion bomb, it can measure the LBV at high-pressure with less consumption of fuel and easy controllable initial conditions and mixture compositions [3]. In this study, a constant volume combustion bomb was used, and the initial conditions were set as 0.1 MPa and 300 K. The measured data in this study can be used to study the application of LPG–H₂ mixture, and provide useful information for the related studies.

Experimental setup

In this study, experiments were conducted using a constant volume combustion bomb. As shown in Fig. 1, the system consists of a combustion bomb, a gas control system, an ignition system, a lighting system, and data acquisition system. The combustion bomb is of cylindrical shape. Two pressure-resisting quartz windows were installed on the two sides of the combustion bomb to allow the combustion process optically accessible. Electrodes were located in the centerline of the combustion bomb to ignite the mixture. The gas control system includes gas valves, a manometer, and a vacuum pump. The vacuum pump was used to evacuate the

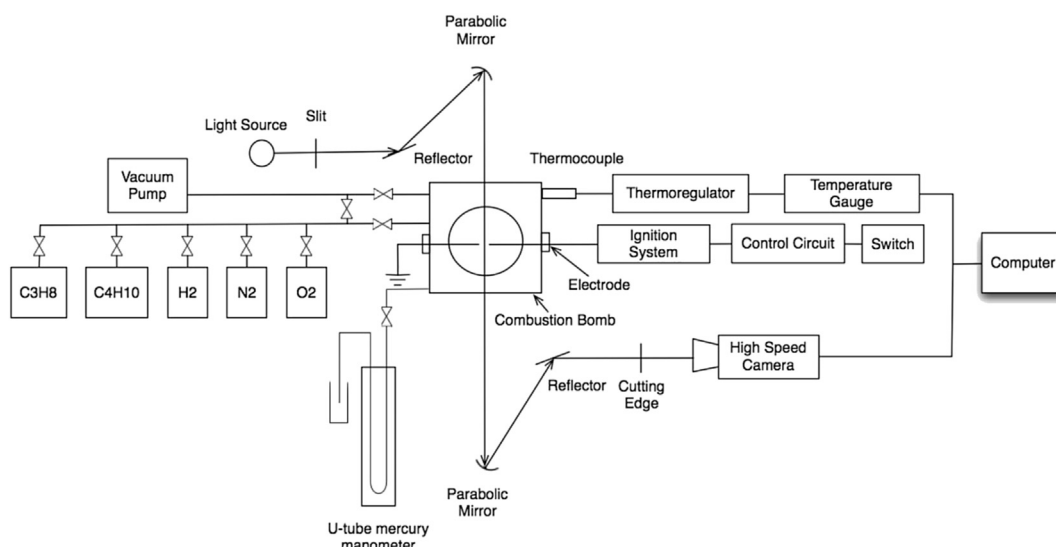


Fig. 1 – Experimental system.

Table 1 – The fuel blends investigated.

Fuels			Fuel mixture density (g/L)	Stoichiometric air/fuel ratio (vol)	Weight LHV (MJ/kg)
H ₂ %(vol)	C ₃ H ₈ %(vol)	C ₄ H ₁₀ %(vol)			
10	27	63	1.99	26.2	53.32
20	24	56	1.78	23.5	60.73
30	21	49	1.57	20.9	68.14
40	18	42	1.36	18.2	75.55
50	15	35	1.14	15.6	82.96
60	12	28	0.93	13.0	90.37
70	9	21	0.72	10.3	97.77
80	6	14	0.51	7.7	105.18
90	3	7	0.29	5.0	112.59

combustion products and create the vacuum condition in the bomb. Since the initial pressure of the experiment was set as 0.1 MPa, which is close to the atmospheric pressure, a U-tube mercury manometer was used to accurately measure the gas pressure. A schlieren optical system was used to visualize the flame and flame propagation process was recorded by a Phantom V611 high speed CCD camera with 10,000 pictures per second. A thermocouple was installed in the inner side of the combustion bomb to give temperature information. The initial temperature tested in this study is 300 K. For each experimental condition, 3 to 6 times repeated tests were done to ensure data accuracy and repeatability.

Air used in this study is a mixture of 99.9% purity O₂ and 99.9% purity N₂. The ratio between O₂ and N₂ is 21:79. The fuels tested in this study are LPG and hydrogen. To simulate commercial standard LPG available in Hong Kong, and to make the experimental results comparable with our previous research [18], a mixture of propane and butane with volumetric ratio of 3:7 was simulated for the LPG. In this study, LPG with various percentages of hydrogen addition (%H₂) was tested. The volumetric hydrogen fraction (%H₂) was varied from 10% to 90% with an increment of 10%. Some fundamental parameters of fuel mixtures are listed in Table 1.

Before each set of experiment, the combustion bomb was flushed by air for several times to reduce the bomb temperature and ensure no combustion products remained. Since all reactants are gaseous, the reactants mixture was prepared by delivering the reactants one by one into the combustion bomb according to the pre-calculated partial pressures of each reactant until the total pressure inside the bomb reached the initial pressure of 0.1 MPa. The partial pressure depends on both initial pressure and mixture properties, such as equivalence ratio [19]. In this study, an overall equivalence ratio of fuel blend was used in the calculation, and equivalence ratios range from 0.6 to 1.5. Equivalence ratio is calculated by:

$$\phi = \frac{(V_{\text{air}}/V_{\text{fuel}})_{\text{stoichiometric}}}{(V_{\text{air}}/V_{\text{fuel}})_{\text{actual}}} \quad (1)$$

Combustion analyses theory

Laminar burning velocity and Markstein length can be calculated, through a series of calculations, from the schlieren photographs taken during each set of experiments. In this study, all the calculations were based on the assumptions

made by Huzayyin et al. [3], which includes (a) isentropic spherical flame front, (b) thin flame thickness, (c) adiabatic equilibrium, (d) burnt gas characteristics with values equal to calculation based on adiabatic temperature reaction, (e) constant-pressure, (f) gases obeying ideal gas law. Flame radius was obtained from the schlieren photography, which shows the density gradient inside the chamber hence indicating location of flame edge. Since schlieren photography does not show the flame edge directly, the flame radius in the shadowgraph image might be different from the actual one. Bradley et al. [20] gave a correlation between r_{sch} and r_u for iso-octane-air flames, and they also applied the correlation in methane-air flame to calculate the flame speed. However, on the basis of the investigation made by Parsinejad et al. [21], Tahtouh et al. [22] claimed that flame speed was independent on isotherm, and for both thin flames and thick flames, the luminous front in a shadowgraph image corresponds to the flame radius of the unburned gas. In this study, the unburned gas front radius obtained from the shadowgraph was directly used to calculate the flame speed and laminar burning velocity. S_n was calculated using the following approach of Bradley [23].

$$S_n = \frac{dr_u}{dt} \quad (2)$$

The flame stretch rate, which indicates the expanding rate of the flame area [24] for a spherically expanding flame, is defined as

$$\alpha = \frac{2}{r_u} \cdot \frac{dr_u}{dt} = \frac{2}{r_u} S_n \quad (3)$$

There exists a linear relationship between flame speed and flame stretch rate in the early stage of spherical flame propagation as [23]

$$S_l - S_n = L_b \cdot \alpha \quad (4)$$

According to the above relationship, when flame stretch rate is zero, S_l is equal to S_n . L_b of the burned gas can be obtained by calculating the slope by linear fitting between S_n and flame stretch rate.

Since the total volume of burned gases was less than 0.5% of the volume of the combustion bomb, the pressure change in the chamber during flame propagation is negligible [25]. u_l of constant-pressure flame propagation can be deduced from S_l by:

$$u_l = S_l \frac{\rho_u}{\rho_b} \quad (5)$$

Density ratio of the reaction is calculated by density of the unburned mixture and density of the burned mixture. The density ratio was calculated by assuming adiabatic equilibrium.

Laminar flame thickness was then calculated using Equation (6), according to Law et al. [26] and Tang et al. [12]. λ and C_p are the thermal conductivity and the specific heat of unburned mixture, respectively.

$$\delta_l = \frac{\lambda}{C_p \rho_u u_l} \quad (6)$$

Markstein number was then calculated as [8]:

$$Ma = \frac{L_b}{\delta_l} \quad (7)$$

Flame propagation analysis

Fig. 2 presents the schlieren photographs of both LPG and LPG–H₂ flames, under fuel-lean, stoichiometric, and fuel-rich conditions. The curves on flame front (appearing in the burned zone) indicate instability of the flame. Usually a single curve is formed on the flame in the early stage of flame propagation, which is due to spark and electrode, and does not affect the final result. However, as the number of curves increases, the unstable cellular flame is formed. The flame becomes unstable and the radius cannot be used to calculate the LBV according to the methods mentioned in the previous section. It can be seen that for the fuel-lean condition, both LPG and LPG–H₂ flames have relatively smooth flame surface;

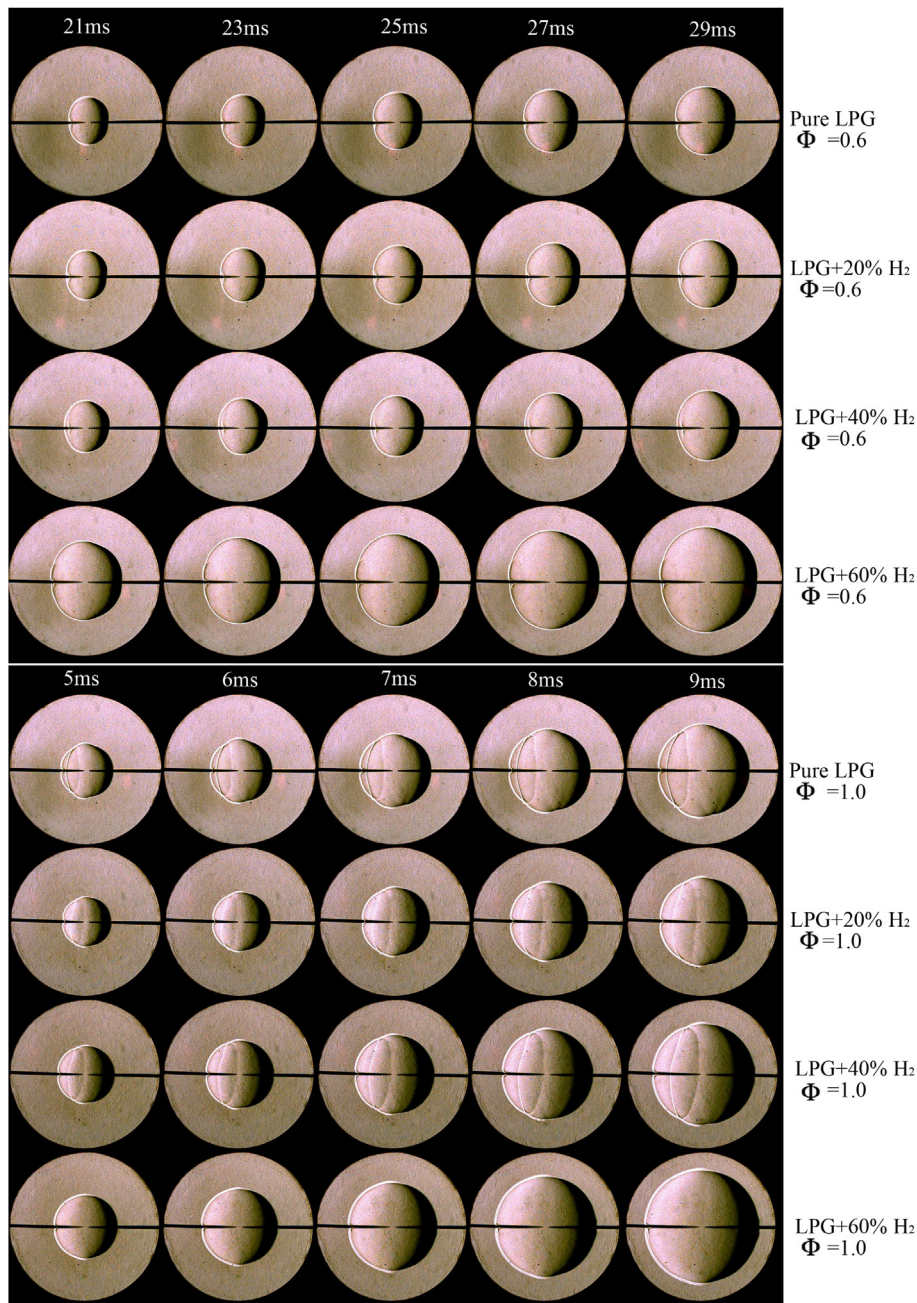


Fig. 2 – Schlieren photographs of LPG and LPG/hydrogen mixture at 0.1 MPa, 300 K.

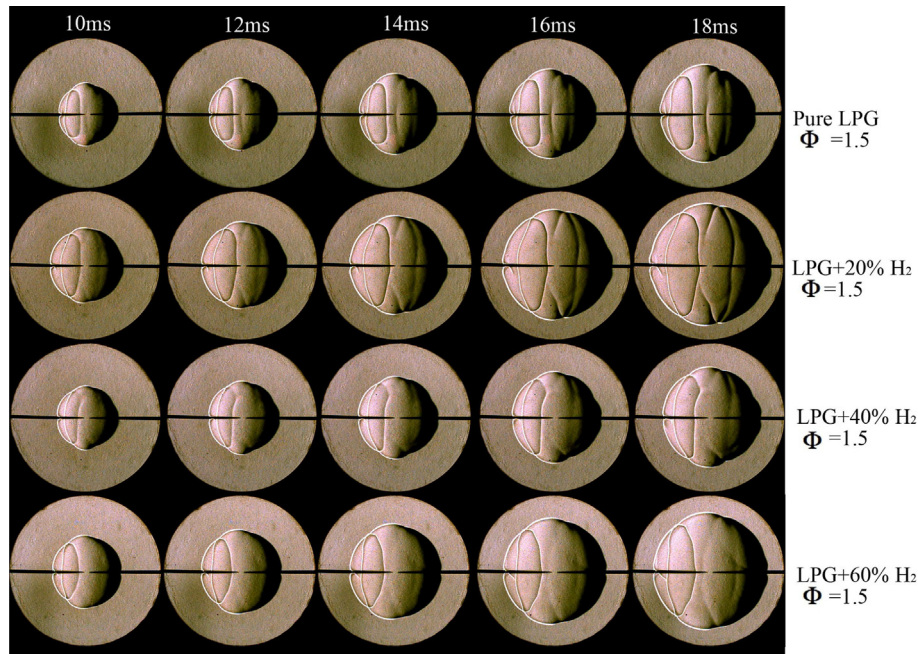


Fig. 2 – (continued).

while for the fuel-rich condition, cellular structure appears in the flame even when the flame radii are still small. These results also agree with results of the Markstein length that for both LPG and LPG–H₂ flame with less than 60%H₂, flame stability decreases with increase of equivalence ratio in the range of 0.6–1.5.

Since all the fuel-lean flames shown in Fig. 2 are smooth without significant discontinuity, it is hard to tell which flame is more stable from the number of curves. However, the irregular flame shape indicates the possibility of curves on the opposite side of the flame. It can be seen from Fig. 2 that the shape of fuel-lean LPG–60%H₂ flame is less symmetrical comparing with the fuel-lean LPG flame, which suggests that H₂ enrichment increases the flame preferential-diffusive instability of fuel-lean LPG flame [11]. For the stoichiometric flame, H₂ additions reduce and blur the flame front curves. For the LPG–60% H₂, the flame front is basically smooth. This shows that H₂ addition can improve stability of the stoichiometric LPG flame. This result also corresponds with the research done by Law and Kwon [8] for the stoichiometric mixture of hydrogen and hydrocarbon fuels. Similar to that of the stoichiometric flame, the stability of fuel-rich LPG–H₂ flame is increased with the increase of H₂ addition.

Fig. 3(a) and (b) show the flame propagation speed of 50% LPG + 50%H₂ against flame front radius (r_u) and flame stretch (α). Since the flame was ignited by electrodes located in the center of the combustion bomb, the ignition energy could affect propagation of flame in the early stage of flame development. Bradley et al. [23] pointed out that the flame speed at a flame radius of less than 5 mm could be elevated by the spark for the iso-octane-air mixtures. Huang et al. mentioned that flame speeds become independent of ignition energy when flame radius exceed 6 mm [27]. Similar elevating effect was also observed in this study, especially for the fuel-rich

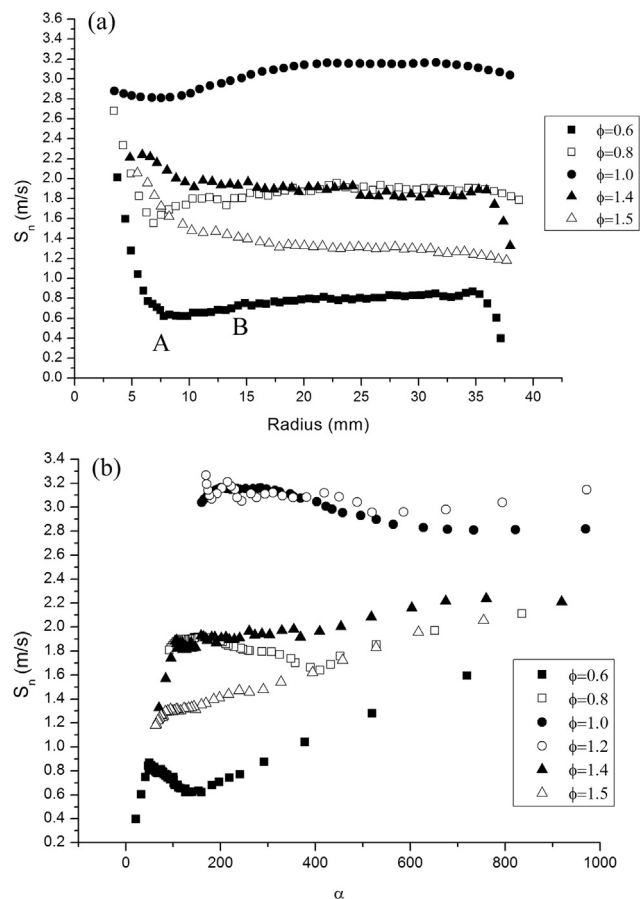


Fig. 3 – (a) Various of S_n with flame radius for 50% LPG + 50%H₂ under various equivalence ratios. (b) Variation of S_n with flame radius for 50%LPG + 50%H₂ under various flame stretch rates.

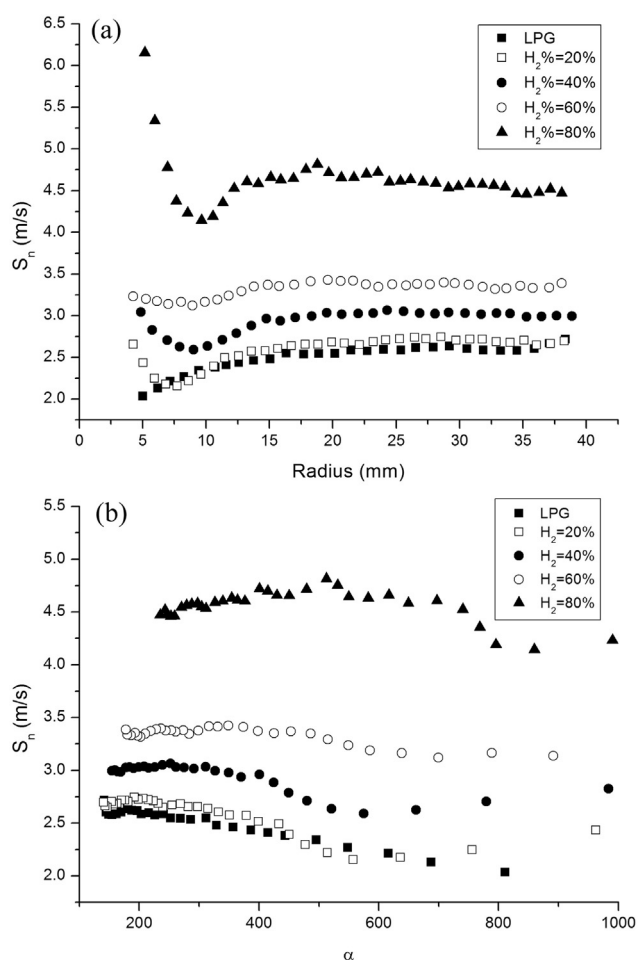


Fig. 4 – (a) Variation of S_n with flame radius for LPG with various hydrogen percentages. (b) Variations of S_n with flame stretch rate for LPG with various hydrogen percentages.

and fuel-lean mixtures, of which the flame speeds are relatively low. As shown in Fig. 3(a) for a fuel-lean flame, such as the one with $\phi = 0.6$, S_n decreases from 2 m s^{-1} to 0.6 m s^{-1} (point A on Fig. 3(a)) when r_u increases from 3 mm to 7 mm. Then S_n gradually increases from 0.6 m s^{-1} to 0.8 m s^{-1} (point B) when r_u increases from 7 mm to 15 mm. The high initial value of S_n is due to the elevating effect of ignition, and the subsequent gradual increase of S_n indicates that the flame is not fully developed before r_u reaches point B [23]. For the stoichiometric mixture, the flame speed for a fully developed flame is relatively high, hence attenuating the spark elevating effect. However, for both fuel-lean and stoichiometric mixtures, the increase of S_n for $r_u = 7\text{--}15$ mm is noteworthy, indicating the certain time for a flame to become fully developed.

Bradley et al. [23] suggested that the data in the increase regime of S_n between Point A and Point B in Fig. 3(a) could not be used to determine the laminar flame speed. To eliminate the interference of underdeveloped flame in the data set, the minimum radius in the calculation are from 15 mm to 17 mm in this study. On the other hand, according to Prathap et al.

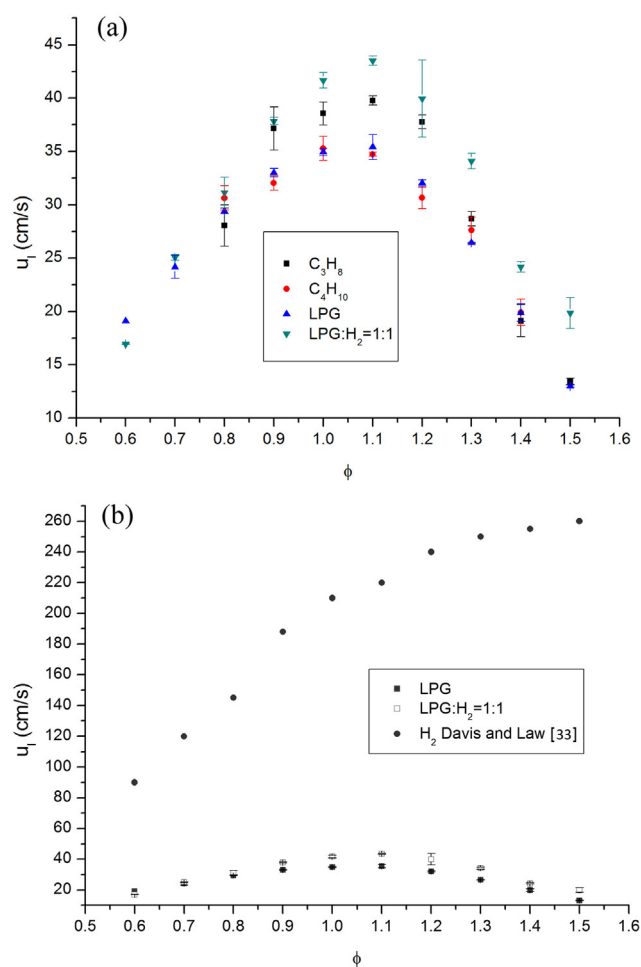


Fig. 5 – Laminar burning velocity of butane, propane, LPG with 50% H_2 , and LPG with various equivalence ratios at 0.1 MPa, 300 K. (a) Present study; (b) data from Ref [33].

[28], only flame radius less than one-third radius of the combustion bomb is reasonable for the calculation. When flame radius exceeds the range, the strain in flow field would notably reduce the burning velocity. This phenomenon is also observed in Fig. 3(a). When r_u is larger than 30 mm (one-third of inner radius of the combustion bomb used in this study), S_n of mixtures starts to fall with r_u .

Fig. 3(a) shows the relationship between S_n and flame stretch. Laminar burning velocity and Markstein length were obtained from the linear fittings of these data. In the early stage of flame propagation, the flame radius is small, the curvature of flame front is large for small spherical surface, resulting in large curvature hence large flame stretch [29]. The sharp decrease of S_n in small stretch rate is due to strain in the flow field as mentioned in previous paragraph, and the sharp increase of S_n in small stretch rate indicates the occurrence of the cellular flame. Considering the influences of spark, cellular flame, and flow field strain, only flame radius from 15 mm to 30 mm were used in the calculations.

Effect of H_2 addition on S_n and flame stretch is shown in Fig. 4((a) and (b)). As shown in Fig. 4(a), S_n increases significantly with the increase of hydrogen fraction, especially for

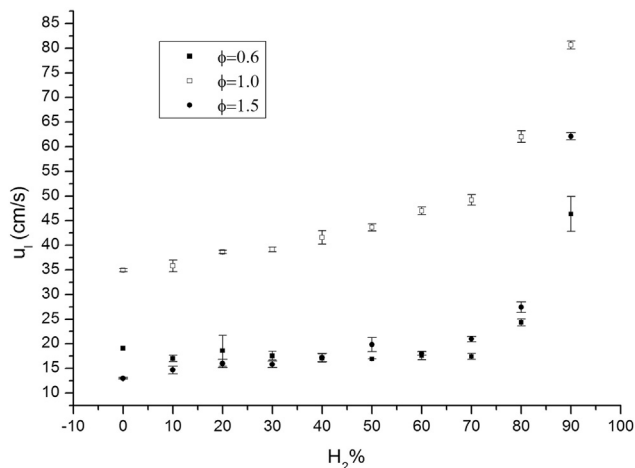


Fig. 6 – Laminar burning velocity of LPG with various hydrogen percentages at 0.1 MPa, 300 K.

the 20%LPG + 80%H₂ flame. The ignition energy greatly rises S_n of 20%LPG + 80%H₂ in the early stage of the flame. For both LPG-air and 80%LPG + 20%H₂ flames, although they have very close S_n , their reactions to ignition energy are quite different. For the LPG-air flame, the ignition energy does not lead to an initial S_n , which is higher than the corresponding stable S_n ; while for the 80%LPG + 20%H₂ flame, the ignition energy results in a relatively higher initial S_n .

It is worth noting that under the stoichiometric condition, the ignition energy results in an initial flame speed significantly higher than that of the stable flame speed for the LPG–H₂ flames, but for the pure LPG, the initial flame speed is lower than the stable flame speed. This phenomenon suggests that in the early stage of combustion, hydrogen may burn ahead of LPG resulting in higher S_n under the stoichiometric condition.

Laminar burning velocity

Previous literature showed that hydrogen addition significantly increased the LBV of hydrocarbons including butane and propane [8,12,17,30–32]. Fig. 5(a) compares the laminar burning velocities of butane, propane, LPG, and 50%LPG + 50% H₂. The LBV of 50%LPG + 50%H₂ is higher than those of butane, propane, and LPG, especially under the stoichiometric and fuel-rich conditions, indicating that H₂ addition also increases the LBV of LPG (butane and propane) mixture. Although H₂ addition increases the LBV of LPG, the trends of LBV against equivalence ratio are similar between LPG and 50%LPG + 50% H₂. Fig. 5(b) compares the LBV of H₂ and LBV of 50%LPG + 50% H₂. It is noteworthy that pure hydrogen has very high LBV in the range of equivalence ratios being investigated, and the highest LBV appears at around $\phi = 2$ for H₂, and appear at around $\phi = 1.1$ for both LPG and 50%LPG + 50%H₂. These results clearly suggest that for the 50%LPG + 50%H₂, LPG dominates the LBV under various equivalence ratios.

It is observed in Fig. 6 that the LBV of LPG increases with the increase of H₂ addition, especially for the stoichiometric

mixtures. Moreover, the rate of increase in LBV also increases with the increase of hydrogen fraction. It is noteworthy that the LBV of 10%LPG + 90%H₂ under the stoichiometric condition is 80.66 cm/s, which is remarkably lower than that of pure H₂, 220 cm/s [11]. For the fuel mixture containing 90%H₂, H₂ is the dominating gas. However, the 10% LPG in the fuel mixture reduces the LBV of H₂ to less than half of that of pure hydrogen. This behavior indicates that even a small amount of LPG has a strong decelerating influence on the LBV of H₂ added mixture, and this also explains the dominating influence of LPG on the LBV of 50%LPG + 50%H₂. Similar decelerating effect of other hydrocarbons on hydrogen was also reported by Law et al. and Tang et al. [8,12].

To better understand the effect of hydrogen addition on the properties of a fuel, the flame equilibrium temperature and thermal diffusivities of reactant mixtures were calculated and plotted against hydrogen fraction in LPG as shown in Figs. 7 and 8. It is found that the effect of H₂ addition on the equilibrium temperature is insignificant, and it reveals that equivalence ratio has higher influence on flame temperature than hydrogen fraction does. Different from equilibrium temperature, variation of thermal diffusivities of reactant mixtures to hydrogen fraction gives the similar trend to that of LBV to hydrogen fraction. The increasing effectiveness of H₂ addition on thermal diffusivity becomes significant when hydrogen fraction is larger than 50%. The enhanced thermal diffusivity due to H₂ addition accelerates flame propagation of LPG.

Markstein length

Burned gas Markstein length (L_b) is one important global parameter of a laminar flame, and is related to flame front diffusional-thermal instability [8]. Fig. 9 gives Markstein length (L_b) and Markstein number (Ma) of LPG flames at various hydrogen fractions and equivalence ratios.

For the fuel-rich mixtures, L_b increases with the increase of hydrogen fraction, indicating the increase of flame front stability. H₂ flame has higher stability under fuel-rich condition

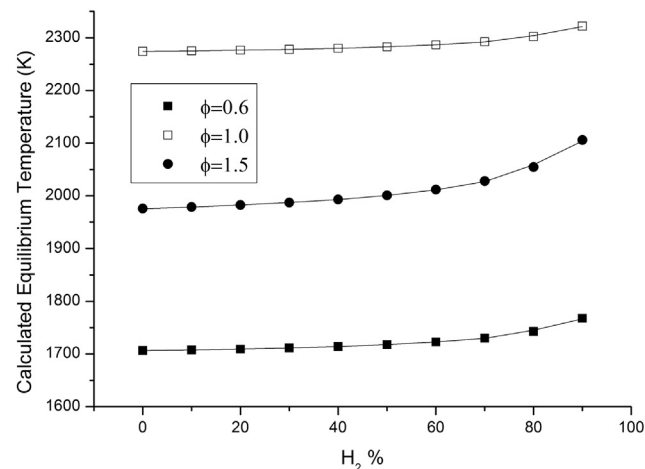


Fig. 7 – Calculated adiabatic equilibrium temperature of reactant mixtures under 300 K, 0.1 MPa.

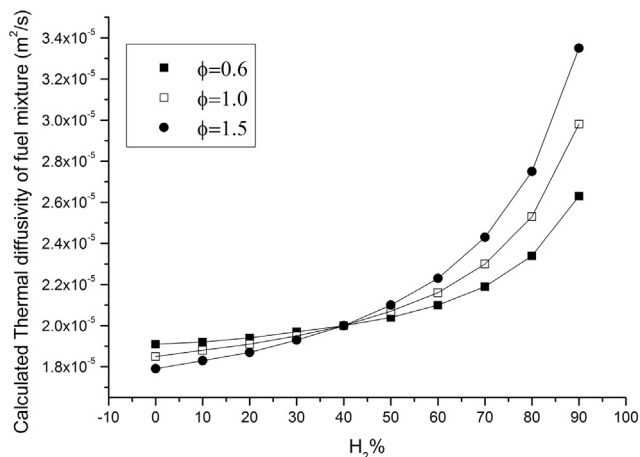


Fig. 8 – Thermal diffusivities of reactant mixtures.

than under fuel-lean or stoichiometric conditions according to published experimental and analytical studies [34,35], while propane and butane flames are stable under fuel-lean condition as shown in Fig. 10. Also experimental results of Bechtold

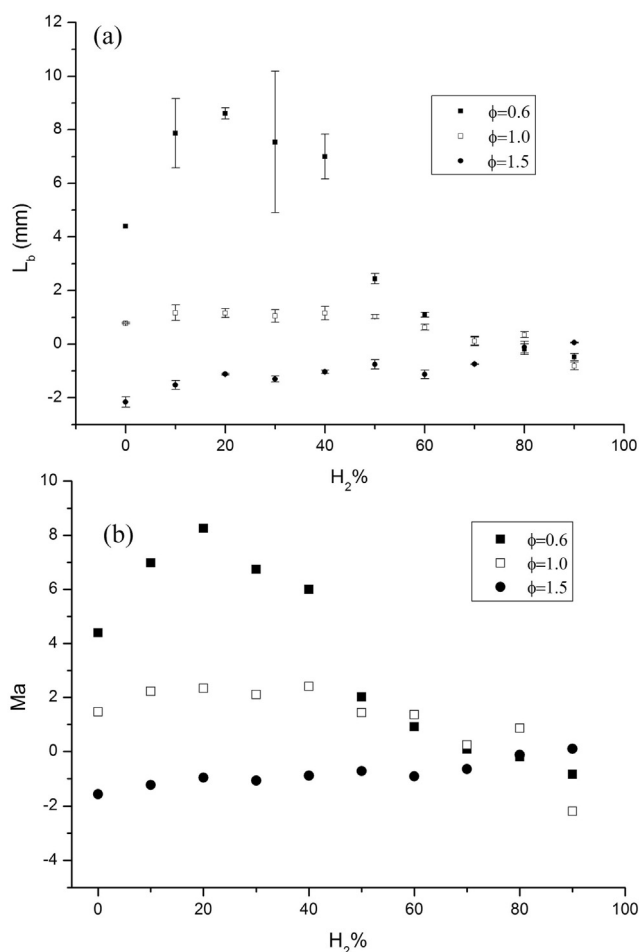


Fig. 9 – Markstein length and Markstein number of LPG with various H₂ percentages at 0.1 MPa, 300 K. (a) Markstein length; (b) Markstein number.

and Matalon [35] showed that under the fuel-rich condition, Markstein number of hydrogen is larger than some hydrocarbons, including propane. Therefore, fuel-rich LPG–H₂ mixtures ($\phi = 1.5$) would be more stable with the increase of H₂ fraction. These results are consistent to those observed from the Schlieren photographs in Fig. 2. The photos show fewer discontinuities on the 40%LPG + 60%H₂ flame with $\phi = 1.5$ compared to those of pure LPG flame.

For fuel-lean mixtures, Markstein length L_b tends to decrease with the increase of hydrogen addition, and the reduction is more significant when hydrogen fraction is larger than 30%. Same trend was also observed by Tang et al. [12] in the stoichiometric mixtures, influence of hydrogen fraction is not so remarkable, but Markstein length L_b also starts to decrease when hydrogen fraction is higher than 50%. It is noteworthy that at small hydrogen fraction, there seems an improvement in the stability of both fuel-lean and stoichiometric LPG–H₂ flames, being more significant for the lean flames.

The effect of equivalence ratio on Markstein lengths of LPG and LPG–H₂ flames is given in Fig. 10. Hydrocarbons with more than three carbon atoms are inherently diffusively stable under fuel-lean condition [8]. For LPG, Markstein length decreases with the increase of equivalence ratio. For H₂, however, Markstein length increases with the increase of equivalence ratio in the range of $\phi = 0.6$ –1.5. For 50% LPG + 50%H₂, Markstein length decreases with the increase of equivalence ratio. Although addition of H₂ up to 50% does not significantly change the trend of Markstein length against equivalence ratio, it reduces the decreasing rate of Markstein length.

Flame thickness and density ratio

Hydrodynamic instability is also a key parameter, which affects flame front stability. Flame thickness has an inhibiting effect on hydrodynamic instability, while density ratio has a promoting effect [8].

Data in Fig. 11(b) indicate that for the three equivalence ratios, hydrogen addition reduces the density ratio of unburned gas and burned gas. The effectiveness is more substantial when hydrogen fraction is higher than 60%. Hydrogen addition also reduces flame thickness of the LPG flame, as shown in Fig. 11(a), especially for the stoichiometric and fuel-rich flames. It can be seen that H₂ addition has notable influence on flame thicknesses of fuel-lean and fuel-rich mixtures than that on the stoichiometric mixtures at very high hydrogen fraction. The reduction in density ratio and flame thickness has opposite effects on the hydrodynamic instability of the flame.

For the fuel-lean mixtures, from pure LPG to 50%LPG + 50% H₂, flame thickness drops by 40%, and density ratio (the density jump across the flame) reduces only by about 4%. The corresponding reductions for fuel-rich and stoichiometric mixtures are 59% and 36% for thickness, and 7% and 1.8% for density ratio. This may suggest that H₂ addition could enhance the hydrodynamic instability of LPG flame. Data with similar trend were also reported by Law et al. [8] for propane–H₂ flames.

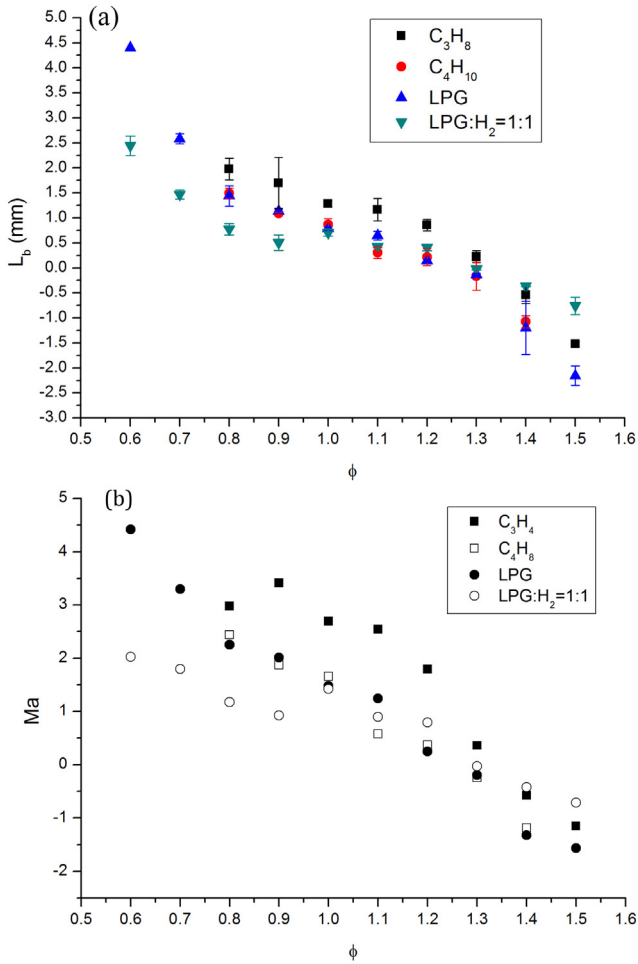


Fig. 10 – (a) Markstein length of propane, butane, LPG, LPG with 50% H₂, and LPG with various equivalence ratios under 0.1 MPa, 300 K. (b) Markstein number of propane, butane, LPG, LPG with 50% H₂, and LPG with various equivalence ratios under 0.1 MPa, 300 K.

Fig. 12(a) shows that the effects of equivalence ratio on flame thickness are quite similar for both LPG and 50% LPG + 50%H₂ flames. Thickest flame thickness was found for fuel-lean mixture. The stoichiometric mixture has the thinnest flame thickness. There is a parabolic relationship between flame thickness and equivalence ratio. Besides having the similar trends, the values of flame thickness of LPG and LPG-50%H₂ are also very close.

Comparing Fig. 12(a) with Fig. 12(b), it is found that the trend of density ratio goes opposite with that of flame thickness, and it is hard to identify the effect of equivalence ratio on the hydrodynamic instability of LPG or LPG–H₂ flame.

Conclusion

Experiments were conducted to study the laminar burning velocities and flame stability of LPG with various hydrogen fractions under initial condition of 0.1 MPa and 300 K. The early stage propagation features of LPG and LPG–H₂ flames

were compared. Laminar flame speeds and laminar burning velocities of LPG–H₂ fuels were measured. Flame instability including both diffusional-thermal instability and hydrodynamic instability were discussed in the view of Markstein length, flame thickness, and density ratio. The following results were obtained:

Hydrogen addition accelerates laminar burning velocity of LPG flames for all equivalence ratios. The accelerating effectiveness is substantial when hydrogen fraction is larger than 60%. When hydrogen fraction increases from 80% to 90%, LBV increases for about 50%. But the accelerating effectiveness is unobvious when hydrogen fraction is less than 50%. Small amount of LPG results in a strong decelerating effect on hydrogen fuel. And 10% LPG decreases the LBV of hydrogen-LPG to the half of hydrogen. The relationship between thermal diffusivity of the reactant mixture and hydrogen fraction is similar with that between LBV and hydrogen fraction, indicating that the enhanced thermal diffusivity accelerates the burning velocity of LPG–H₂ mixtures.

For fuel-rich mixture, hydrogen addition reduces the diffusional-thermal instability of LPG (increases Markstein

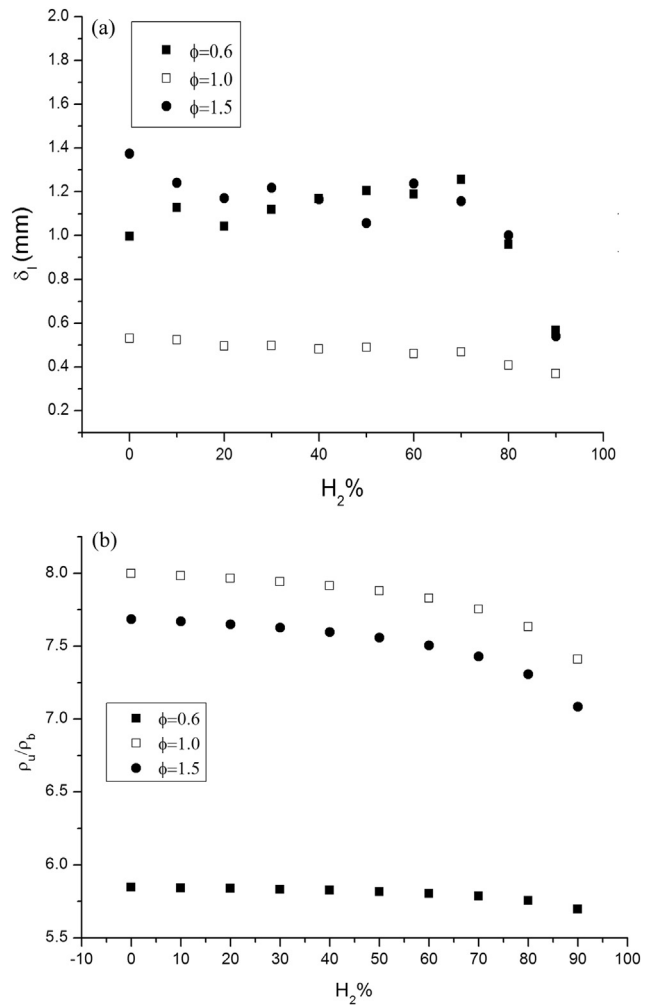


Fig. 11 – (a) Flame thickness of LPG–H₂ flames with various H₂ percentages. (b) Calculated density ratio of LPG–H₂ flames with various H₂ percentages.

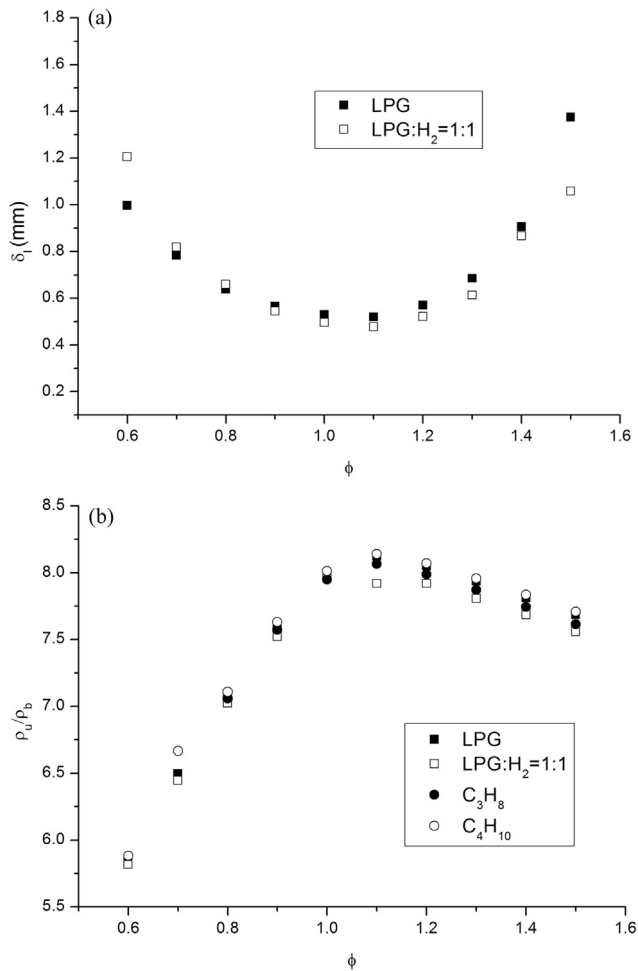


Fig. 12 – (a) Flame thickness of butane, propane, LPG, LPG with 50% H₂ enrichment, and LPG with various equivalence ratios. (b) Calculated density ratio of butane, propane, LPG, LPG with 50% H₂ enrichment, and LPG with various equivalence ratios.

length), while for fuel-lean and stoichiometric mixtures, hydrogen addition decreases Markstein length hence exaggerates the thermal instability. Although hydrogen addition reduces both flame thickness and density ratio of reaction mixtures, flame thickness drops with H₂ addition more significantly than to the density ratio. Hydrogen addition enhances the hydrodynamic instability of LPG.

Equivalence ratio has notable influence on LBV of LPG compared with hydrogen. Equivalence ratio has opposite effects on density ratio and flame thickness.

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REFERENCES

- [1] Zeldovich YB, Barenblatt GI, Librovich VB, Makhviladze GM. *Mathematical theory of combustion and explosions*. Consultants Bureau; 1985.
- [2] Stone R, Clarke A, Beckwith P. Correlations for the laminar-burning velocity of methane/diluent/air mixtures obtained in free-fall experiments. *Combust Flame* 1998;114:546–55.
- [3] Huzayyin AS, Moneib HA, Shehatta MS, Attia AMA. Laminar burning velocity and explosion index of LPG–air and propane–air mixtures. *Fuel* 2008;87:39–57.
- [4] Qin X, Kobayashi H, Niioaka T. Laminar burning velocity of hydrogen–air premixed flames at elevated pressure. *Exp Therm Fluid Sci* 2000;21:58–63.
- [5] Bosschaart KJ, de Goey LPH. The laminar burning velocity of flames propagating in mixtures of hydrocarbons and air measured with the heat flux method. *Combust Flame* 2004;136:261–9.
- [6] Kobayashi H, Kawazoe H. Flame instability effects on the smallest wrinkling scale and burning velocity of high-pressure turbulent premixed flames. *Proc Combust Inst* 2000;28:375–82.
- [7] Muppala SPR, Nakahara M, Aluri NK, Kido H, Wen JX, Papalexandris MV. Experimental and analytical investigation of the turbulent burning velocity of two-component fuel mixtures of hydrogen, methane and propane. *Int J Hydrogen Energy* 2009;34:9258–65.
- [8] Law CK, Kwon OC. Effects of hydrocarbon substitution on atmospheric hydrogen–air flame propagation. *Int J Hydrogen Energy* 2004;29:876–9.
- [9] Marshall SP, Stone R, Heghes C, Davies TJ, Cracknell RF. High pressure laminar burning velocity measurements and modelling of methane and n-butane. *Combust Theor Model* 2010;14:519–40.
- [10] Verhelst S, Woolley R, Lawes M, Sierens R. Laminar and unstable burning velocities and Markstein lengths of hydrogen–air mixtures at engine-like conditions. *Proc Combust Inst* 2005;30:209–16.
- [11] Kwon OC, Faeth GM. Flame/stretch interactions of premixed hydrogen-fueled flames: measurements and predictions. *Combust Flame* 2001;124:590–610.
- [12] Tang C, Huang Z, Jin C, He J, Wang J, Wang X, et al. Laminar burning velocities and combustion characteristics of propane–hydrogen–air premixed flames. *Int J Hydrogen Energy* 2008;33:4906–14.
- [13] Bradley D, Lawes M, Liu K, Verhelst S, Woolley R. Laminar burning velocities of lean hydrogen–air mixtures at pressures up to 1.0 MPa. *Combust Flame* 2007;149:162–72.
- [14] Liao SY, Jiang DM, Gao J, Huang ZH, Cheng Q. Measurements of Markstein numbers and laminar burning velocities for liquefied petroleum gas–air mixtures. *Fuel* 2004;83:1281–8.
- [15] Tang CL, Huang ZH, Law CK. Determination, correlation, and mechanistic interpretation of effects of hydrogen addition on laminar flame speeds of hydrocarbon–air mixtures. *Proc Combust Inst* 2011;33:921–8.
- [16] Tseng LK, Ismail MA, Faeth GM. Laminar burning velocities and Markstein numbers of hydrocarbon air flames. *Combust Flame* 1993;95:410–26.
- [17] Boushaki T, Dhué Y, Selle L, Ferret B, Poinot T. Effects of hydrogen and steam addition on laminar burning velocity of methane–air premixed flame: experimental and numerical analysis. *Int J Hydrogen Energy* 2012;37:9412–22.
- [18] Miao J, Leung CW, Cheung CS. Effect of hydrogen percentage and air jet Reynolds number on fuel lean flame stability of LPG-fired inverse diffusion flame with hydrogen enrichment. *Int J Hydrogen Energy* 2014;39:602–9.

- [19] Miao H, Ji M, Jiao Q, Huang Q, Huang Z. Laminar burning velocity and Markstein length of nitrogen diluted natural gas/hydrogen/air mixtures at normal, reduced and elevated pressures. *Int J Hydrogen Energy* 2009;34:3145–55.
- [20] Bradley D, Gaskell PH, Gu XJ. Burning velocities, Markstein lengths, and flame quenching for spherical methane-air flames: a computational study. *Combust Flame* 1996;104:176–98.
- [21] Parsinejad F, Keck JC, Metghalchi H. On the location of flame edge in shadowgraph pictures of spherical flames: a theoretical and experimental study. *Exp Fluids* 2007;43:887–94.
- [22] Tahtouh T, Halter F, Mounaïm-Rousselle C. Measurement of laminar burning speeds and Markstein lengths using a novel methodology. *Combust Flame* 2009;156:1735–43.
- [23] Bradley D, Hicks RA, Lawes M, Sheppard CGW, Woolley R. The measurement of laminar burning velocities and Markstein numbers for iso-octane–air and iso-octane–n-heptane–air mixtures at elevated temperatures and pressures in an explosion bomb. *Combust Flame* 1998;115:126–44.
- [24] Tang C, He J, Huang Z, Jin C, Wang J, Wang X, et al. Measurements of laminar burning velocities and Markstein lengths of propane–hydrogen–air mixtures at elevated pressures and temperatures. *Int J Hydrogen Energy* 2008;33:7274–85.
- [25] Broustail G, Seers P, Halter F, Moréac G, Mounaïm-Rousselle C. Experimental determination of laminar burning velocity for butanol and ethanol iso-octane blends. *Fuel* 2011;90:1–6.
- [26] Law CK, Jomaas G, Bechtold JK. Cellular instabilities of expanding hydrogen/propane spherical flames at elevated pressures: theory and experiment. *Proc Combust Inst* 2005;30:159–67.
- [27] Huang Z, Zhang Y, Zeng K, Liu B, Wang Q, Jiang D. Measurements of laminar burning velocities for natural gas–hydrogen–air mixtures. *Combust Flame* 2006;146:302–11.
- [28] Prathap C, Ray A, Ravi MR. Investigation of nitrogen dilution effects on the laminar burning velocity and flame stability of syngas fuel at atmospheric condition. *Combust Flame* 2008;155:145–60.
- [29] Saeed K, Stone CR. Measurements of the laminar burning velocity for mixtures of methanol and air from a constant-volume vessel using a multizone model. *Combust Flame* 2004;139:152–66.
- [30] Zhang Y, Wu J, Ishizuka S. Hydrogen addition effect on laminar burning velocity, flame temperature and flame stability of a planar and a curved CH_4 – H_2 –air premixed flame. *Int J Hydrogen Energy* 2008;34:519–27.
- [31] Miao H, Jiao Q, Huang Z, Jiang D. Measurement of laminar burning velocities and Markstein lengths of diluted hydrogen-enriched natural gas. *Int J Hydrogen Energy* 2009;34:507–18.
- [32] Hu E, Huang Z, He J, Jin C, Zheng J. Experimental and numerical study on laminar burning characteristics of premixed methane–hydrogen–air flames. *Int J Hydrogen Energy* 2009;34:4876–88.
- [33] Davis SG, Law CK. Determination of and fuel structure effects on laminar flame speeds of C1 to C8 hydrocarbons. *Combust Sci Technol* 1998;140:427–49.
- [34] Aung KT, Hassan MI, Faeth GM. Flame stretch interactions of laminar premixed hydrogen/air flames at normal temperature and pressure. *Combust Flame* 1997;109:1–24.
- [35] Bechtold JK, Matalon M. The dependence of the Markstein length on stoichiometry. *Combust Flame* 2001;127:1906–13.