Effect of Hydrogen Addition on Burning Velocity of LPG-Air Mixtures at Elevated Temperatures

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1 Introduction

Hydrogen is likely to be an important energy carrier in the near future. The main advantage of hydrogen as a fuel is the absence of carbon dioxide emission during combustion. Safety (i.e. hydrogen flammability limits are very broad) and hydrogen storage are causing difficulty in the usage of hydrogen as fuel. One of the possibilities to use hydrogen in current energy environment is adding hydrogen to the hydrocarbon based fuels. The combustion phenomenon for hydrocarbon mixtures are quite clear, and hence design criteria for combustion equipment using hydrocarbon-air mixtures are well known. However, when adding hydrogen to these mixtures, the consequences are unclear. Hence, fundamental knowledge of combustion properties of hydrocarbon-hydrogen mixture is essential to deliver data for a safe transition to hydrogen added hydrocarbon mixtures. Among these, laminar burning velocity, LBV (S_u) is one of the key parameters. The application of hydrocarbon-hydrogen in practical combustion devices like internal combustion engines, industrial and house-hold burners demand the knowledge of LBV. Yu et al. [1] has measured LBV at room temperature for hydrocarbon hydrogen mixtures using the counter-flow method. They have defined new parameter R_H to represent hydrogen addition to hydrocarbon. The effect of the addition of hydrogen to methane has been studied by several authors [1-4]. The hydrogen addition to methane-air mixtures has been investigated using Heat flux method, spherically expanding flames and counter-flow method. Most of these experiments were for room pressure and temperature conditions and various dilutions. Huang and his coworkers [2, 5, 6] studied the effect of hydrogen to methane/natural gas addition at elevated pressures. From the detailed review of the previous studies on the LBV (S_u) measurement of hydrocarbon-hydrogen mixtures, it is identified that most of the works are performed on methane-hydrogen-air mixtures. The LBV data is scares for LPG-H_2-air mixtures at room temperature and elevated temperatures.

Fossil-fuel combustion by-products are proven to be world's most significant threat to children's health and future and are major contributors to environmental injustice. One of the possibilities to reduce emission of hydrocarbon combustion in current energy environment is adding hydrogen to the hydrocarbon based fuels. LPG is the commonly used hydrocarbon in household burners. It is important to understand the combustion properties for the replacement of LPG with LPG-H_2 in existing burners. Hence, the present work is focused on the determination of the laminar burning velocity of LPG- H_2–air mixtures at atmospheric and elevated temperatures using a preheated diverging channel set up. The composition of LPG varies from place to place. For the present study, LPG is prepared as a mixture containing 60% n-butane (C_4H_{10}) and 40% propane (C_3H_8).

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2 Experimental set-up

Diverging channel method is a technique used for measuring the LBV of a combustible mixture at higher temperatures [7-9]. The schematic diagram of the present experimental setup is shown in Figure 1 (Left). Figure 1 (right) shows the direct image of flame front inside the channel. The channel is preheated using a ceramic heater as shown in figure.

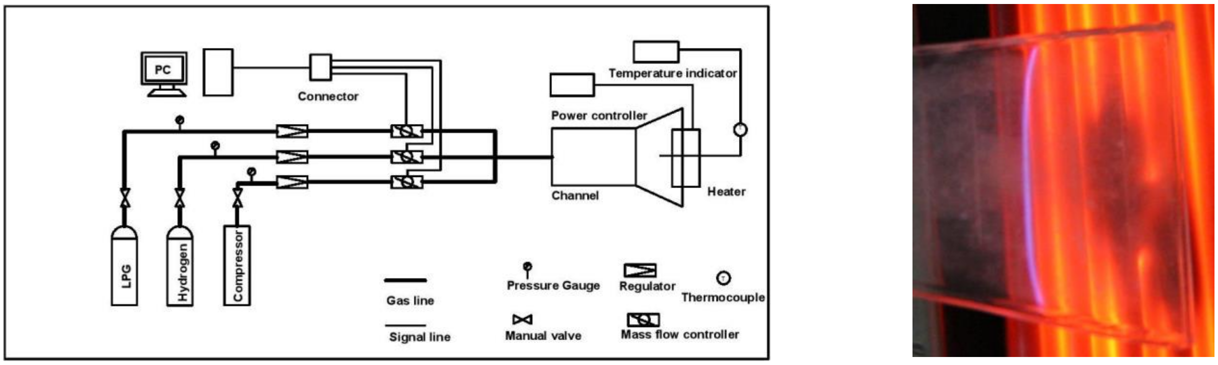

Figure 1. Left: Experimental setup diagram; Right: Direct image of flame-front inside the channel

Experiments were conducted for measurement of LBV of LPG with 0%, 20% and 40% H_2 addition. For each composition, burning velocities were calculated for equivalence ratios varying from 0.7 to 1.3. The present method helps to calculate the burning velocities over a range of unburnt mixture temperatures, 350-450 K. The LBV at various temperatures were used to develop power law correlation, $S_u = S_{u,o}\left(\frac{T_u}{T_{u,o}}\right)^{\alpha}$. $S_{u,o}$ is the LBV of the mixture at atmospheric conditions. The inlet mass flow rates in MFC's is around 80% of the full scale. This is to reduce the uncertainties in the equivalence ratios. The temperature readings were accurate to ±5K of the actual values. Some of the factors influencing the burning velocity are observed to be compensating each other. The uncertainty in the measured laminar burning velocity due to all these factors is expected to be around ±5% of actual value. The experimental data of burning velocities obtained from the present set up were compared with the numerical predictions using PREMIX code.

3 Temperature effect on laminar burning velocity

During combustion, burners will get heated. This heat will be transferred to the unburnt LPG-air mixture, so that the mixture gets heated. In this case, the temperature of the unburnt mixture reaching the reaction zone will be higher than the ambient temperature. Therefore, it is essential to understand the combustion characteristics at elevated unburnt gas temperatures. Experiments were conducted at various higher temperatures of the unburnt gas for various equivalence ratios. The mixture inlet temperature ($T_u = 300$ K) is taken as the reference temperature. The power-low is fitted to the experimental results as per the equation, $S_u = S_{u0} \times (T/T_u)^{\alpha}$. The burning velocities at various temperatures at stoichiometric condition are shown in Figure 2 (Left), for LPG and LPG with 40% H_2 conditions. The symbols represent the experimental results. The dotted lines are used to represent the numerical predictions for these conditions. Solid lines show the power-law fit for the experimental data. The rise in LBV with unburnt gas temperature can be identified in this graph. The figure also indicates that there is rise in LBV for LPG with 40% H_2 in comparison with that of 0% H_2.

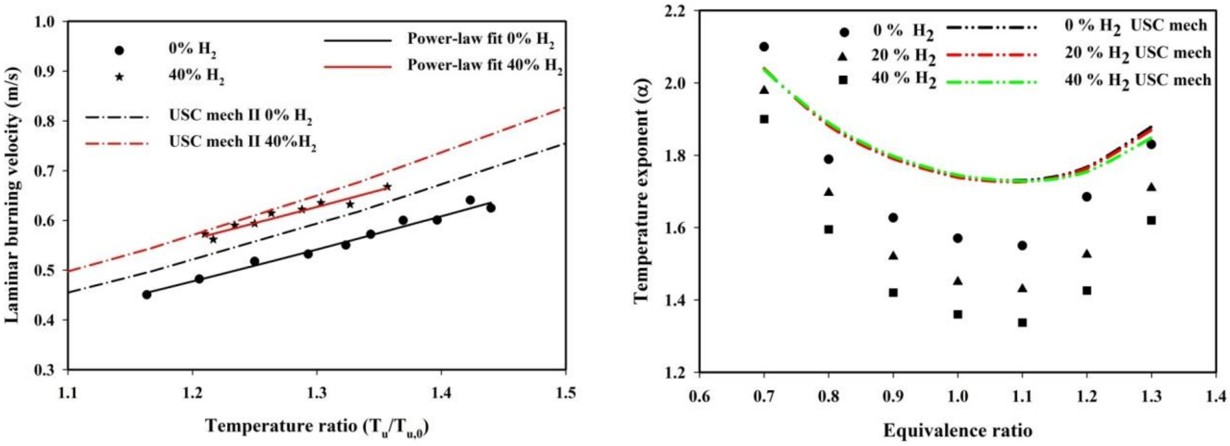

Figure 2. Left: Laminar burning velocities of stoichiometric mixtures at elevated temperatures for 0% and 40% H_2 addition on LPG; Right: The temperature exponent (α) obtained for 0%, 20% and 40% H_2 addition on LPG.

In Figure 2 (b), the temperature exponent, α obtained for 0%, 20% and 40% H_2 addition on LPG is shown for equivalence ratio varying from 0.7 to 1.3. The experimental results are compared with the numerical predictions obtained from PREMIX code using USC Mech II reaction mechanism. The results show that there is significant variation between the temperature exponent values obtained from experiment and computation. This variation shows that updating is required in the existing reaction mechanism for the prediction for temperature exponent.

4 Laminar burning velocity at atmospheric condition

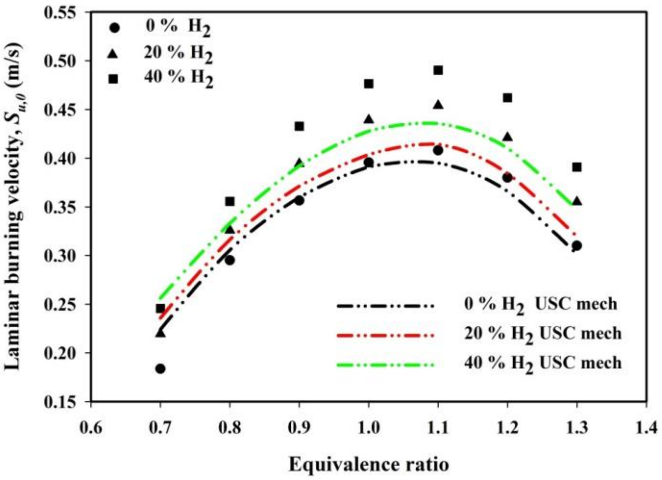

Figure 3. Laminar burning velocity at atmospheric condition ($S_{u,0}$), of LPG-H_2 mixtures for 0%, 20% H_2 and 40% H_2 compositions at various equivalence ratios (ϕ).

In the present study, the LBV at atmospheric condition ($S_{u,o}$) of LPG-air mixtures, at 0%, 20% and 40% hydrogen addition has been calculated for equivalence ratios from 0.7 to 1.3 as shown in Figure 3. The LBV at atmospheric condition is calculated using correlation of the measured data. It is observed from the experimental results that the LBV of the mixture increases when the percentage of hydrogen in the mixture is increased.

5 Effect of Hydrogen addition on laminar burning velocity

The laminar burning velocity (S_u) of LPG calculated at 420 K, for 0%, 20% and 40% hydrogen addition, at various equivalence ratio is shown in Figure 4. Peak value of LBV is obtained at equivalence ratio 1.1. A significant increase in laminar burning velocity can be observed when hydrogen percentage in the mixture increased from 0% to 40%.

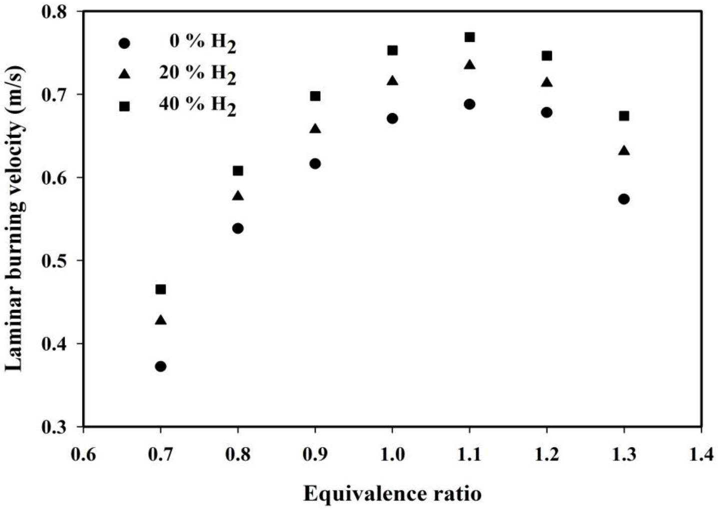

Figure 4. Laminar burning velocity at 420 K for 0%, 20% and 40% H_2 addition on LPG.

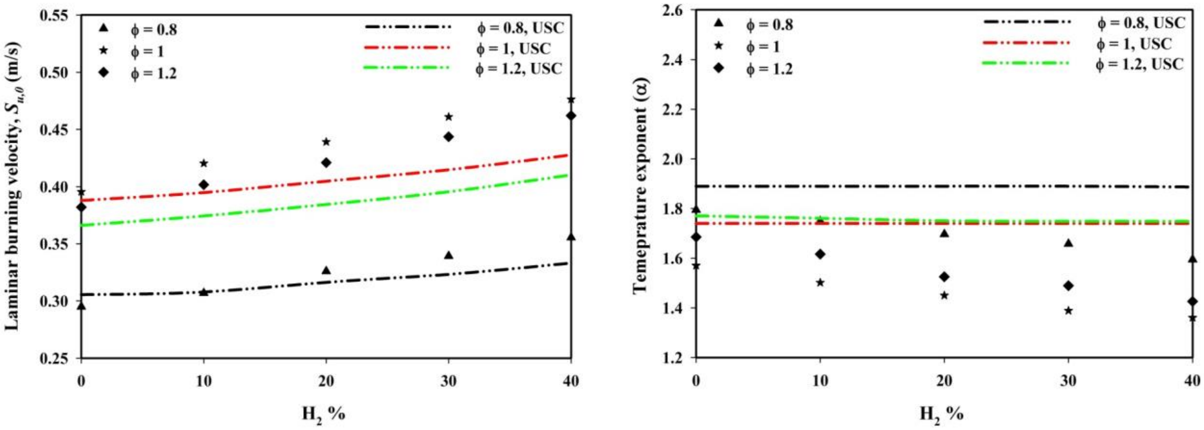

Figure 5. Left: Laminar burning velocity at atmospheric condition ($S_{u,o}$); Right: Temperature exponent, of LPG-H_2 mixtures at 0%, 20% and 40% H_2.

The laminar burning velocity at atmospheric condition ($S_{u,o}$) and temperature exponents (α), of LPG-H_2 mixtures at 0%, 20% and 40% H_2 for various equivalence ratios are shown in Figure 5 (Left) and (Right) respectively. The figures show that LBV increases with increase in H_2 content, whereas the temperature exponent decreases with increase in H_2 content in the mixture. From the figures it can be observed that the variation in burning velocity and temperature exponent with the percentage of hydrogen addition is close to linear.

4. Conclusions

The present experimental study investigated the effect of hydrogen addition in the LBV of LPG-air mixture at elevated temperatures using a preheated diverging channel setup. Experiments were conducted for 0%, 20% and 40% H_2 compositions in the mixture, at various equivalence ratios ranging from 0.7 to 1.3. The LBV results obtained for these mixture compositions indicate that the LBV increases with increase in hydrogen addition. The experimental results show that the LBV of the mixture has a significant increase with increase in unburnt gas temperature.

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References

[1] Bougrine S, Richard S, Nicolle A, Veynante D. (2011). Numerical study of laminar flame properties of diluted methane-hydrogen-air flames at high pressure and temperature using detailed chemistry. international journal of hydrogen energy. 36:12035.
[2] Hu E, Huang Z, Zheng J, Li Q, He J. (2009). Numerical study on laminar burning velocity and NO formation of premixed methane–hydrogen–air flames. International journal of hydrogen energy. 34:6545.
[3] Law CK, Kwon OC. (2004). Effects of hydrocarbon substitution on atmospheric hydrogen–air flame propagation. International Journal of Hydrogen Energy. 29:867.
[4] Morrone B, Unich A. (2009). Numerical investigation on the effects of natural gas and hydrogen blends on engine combustion. International journal of hydrogen energy. 34:4626.
[5] Hu E, Huang Z, He J, Zheng J, Miao H. (2009). Measurements of laminar burning velocities and onset of cellular instabilities of methane–hydrogen–air flames at elevated pressures and temperatures. international journal of hydrogen energy. 34:5574.
[6] Huang Z, Zhang Y, Zeng K, Liu B, Wang Q, Jiang D. (2006). Measurements of laminar burning velocities for natural gas–hydrogen–air mixtures. Combustion and Flame. 46:302.
[7] Akram M, Kumar S. (2011). Experimental studies on dynamics of methane-air premixed flame in meso-scale diverging channels. Combustion and Flame. 158:915.
[8] Akram M, Kumar S, Saxena P. (2013). Experimental and computational determination of laminar burning velocity of liquefied petroleum gas-air mixtures at elevated temperatures. Journal of Engineering for Gas Turbines and Power. 135.
[9] Akram M, Saxena P, Kumar S. (2013). Laminar Burning velocity of methane–air mixtures at elevated temperatures. Energy & Fuels. 27:3460.