Measurements of Laminar Burning Velocities and Markstein Length for LPG–Hydrogen– Air Mixtures

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Abstract:- An experimental approach to measure the laminar burning velocities and Markstein lengths of LPG/hydrogen/air mixtures was used. Using thermocouples as sensing probs. Measurements of laminar burning velocity as a function of flame stretch was directly deduced using data acquisition system without using any fuel properties. The unstretched laminar burning velocities were obtained through a linear extrapolation to zero stretch. The Markstein lengths were deduced from the linear relationship between the flame speed and flame stretch rate. The estimated values of laminar burning velocities were compared to experimental results of the literature. It was found that the measured laminar burning velocity of LPG increased with increasing hydrogen volume fraction. Markstein lengths demonstrated the increment in flame instability with increasing hydrogen volume fraction. Increasing hydrogen volume fractions widen the equivalence ratio range for both lean and rich sides.

Keywords:- LPG, Hydrogen, laminar burning velocity, Markstein lengths, stretch flame speed, unstretched flame speed.

I.   INTRODUCTION

Improving engine fuel economy and reducing exhaust emissions have become major research topics in combustion and engine development with increasing concern about energy shortage and environmental protection. The main negative effects on the environment by fossil fuel combustion are emissions of NOx, CO, CO_2, and unburned hydrocarbons. The main negative effect of burning fossil fuel on the geopolitical climate is the lack in supply of these fuels and the effect pollution has on politics [1].

Alternative fuels, such as hydrogen, methane, liquefied petroleum gas and dimethyl- ether, are usually regarded to be clean fuels compared to diesel and gasoline, thus the introduction of these alternative fuels is beneficial to the slowing-down of fuel consumption and the reduction of engine exhaust emissions [2].

LPG is one of the best candidates for an alternative fuel because it can be liquefied in a low pressure range of 0.7–0.8 MPa at atmospheric temperature, and it has a sufficient supply infrastructure. LPG fuel also has a higher heating value compared with other fuels [3]. LPG is widely used in IC engines yet its fundamental combustion properties such as laminar burning velocity is still not very well established, which can act as a basic input for engine modeling. One of the most important intrinsic properties of any combustible mixture is its laminar burning velocity. It depends on the mixture composition, temperature and pressure. It is measurable characteristic of the mixture [4]-[5].

Hydrogen holds significant promise as a supplemental fuel to improve the performance and emissions of spark ignited and compression ignited engines. Hydrogen has the ability to burn at extremely lean equivalence rations. Hydrogen will burn at mixtures seven times leaner than gasoline and five times leaner than methane. The flame velocity of hydrogen is much faster than other fuels allowing oxidation with less heat transfer to the surroundings. This improves thermal efficiencies. Efficiencies are also improved because hydrogen has a very small gap quenching distance allowing fuel to burn more completely [6]. In order to properly understand the effect of adding hydrogen to enrich hydrocarbon combustion it is important to understand the basics, Hydrogen increases the laminar burning velocity when it enriched methane or NG [7].

The laminar flame speed is defined as the speed relative to the unburned gas, with which a planar, one-dimensional flame front travels along the normal to its surface [8]. Accurate measurement of unstretched laminar burning velocity, especially for the heavier hydrocarbon fuels typically used in internal combustion engine applications, is necessary for assessing combustion theories and the validation of numerical models [9].

Laminar flame speed embodies the fundamental information on diffusivity, reactivity, and exothermicity of a given mixture and is therefore commonly used to characterize flames. As such, the measurement of laminar flame speed has received considerable attention in the published literature, particularly with regard to the effects of flame stretch on the fundamental (unstretched) laminar flame speed and the attainment of highly accurate, unperturbed measurements [10].

There are many techniques for measuring experimentally the laminar burning velocity of combustible mixtures, such as counter flow double flames [11], flat flame burner [12]-[13] and spherically expanding flames

[14]-[15]. For a spherically expanding flame in a closed combustion bomb, the stretch imposed on the premixed flame is well defined. The asymptotic theories and experimental measurements have suggested a linear relationship between the flame speeds and flame stretches. Therefore, the fundamental burning velocity of alternative fuel is measured by closed bomb technique. References [14]-[16]-[17]-[18] performed the laminar burning velocity of Spherically expanding flames measurement for syngas, natural gas–hydrogen–air mixtures, methanol and hydrogen enriched natural gas.

The stretch rate is a combination of two effects: the flame curvature and the strain rate. Stretch effects induce modifications on the flame front structure and propagation. The sensitivity of the flame speed to the stretch rate is characterized by the Markstein length. Investigations on the laminar burning velocity [19]-[20] have shown the importance of local stretch for the local burning speed. Based on an asymptotic analysis, several authors [21]-[22] have proposed a linear relation between the stretch rate and the flame speed. This relation is valid when the propagation phenomena are no longer affected by the initial energy deposition needed to initiate exothermic reactions. Moreover, the flame thickness has to remain negligible compared to the flame radius. This linear relation has been extensively applied to outwardly propagating flames [23].

The present paper analyses the laminar burning velocity of enriched hydrogen to LPG-air mixture using the closed bomb method. Various results for laminar burning velocity of LPG-hydrogen-air mixtures were obtained at atmospheric pressure and temperature using thermocouples method and results were compared with the standard available data for propane.

II. EXPERIMENTAL SETUP

In this study the full descriptions of the experimental setup (Fig.1) are located at [24]. Spark-ignited premixed LPG-hydrogen-air flames have been investigated at atmospheric pressure and temperature, over a wide range of equivalence ratios, Ø=0.68-1.53. Experiments were conducted in a constant volume chamber. The chamber is equipped with six thermocouples which were used as a sensor probe (Fig. 2). The equivalence ratio of the mixture is measured and regulated by mixing unit. The mixing unit is made of (iron-steel); it has a cylindrical shape without any skirt to improve the efficiency of mixing operation. Mixer dimensions are (435mm) length, (270mm) diameter and (5 mm) thickness as shown in Fig. 3. It undergoes a pressure of more than (60 bar) and also withstands high temperatures. The mixing unit has five holes of (12.7mm) in diameter. Two holes are used to fix the pressure gauge and vacuum gauge, the third is for admitting the dry air to the mixing unit from the compressor through the filter dryer, the fourth hole is for admitting the fuel from the fuel cylinder through pressure gauge regulator and the last hole admits the homogeneous mixture to the combustion chamber.
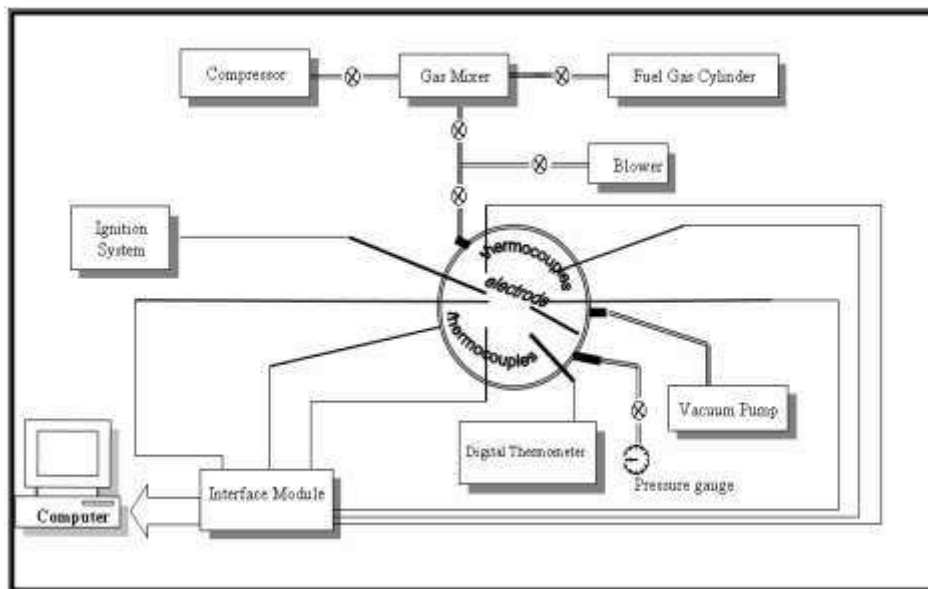

Fig. 1: Block diagram of experimental apparatus

A cover is added on one side of the mixer in order to connect the fan to a power source of (12volt) DC. Through a glass sealed electrical connections, which are sealed completely to prevent any leakage of gas to improve the mixing operation and obtain a homogenous mixture. All welding in the cylinder is done using Argon welding, and tested by increasing the internal pressure of the cylinder to avoid any leakage.
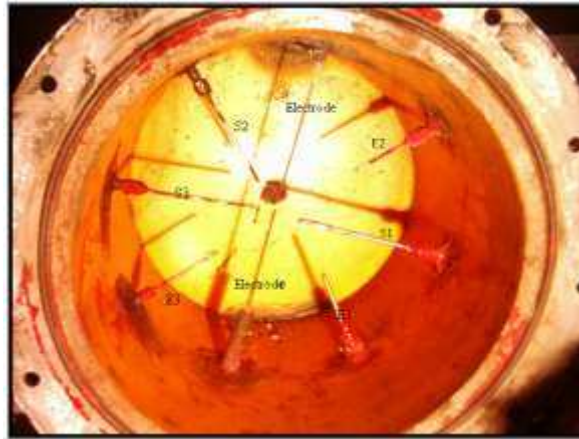
Fig. 2: The internal structure of combustion chamber

The mixture is then ignited by centrally located electrodes energized by standard capacitive ignition system. Minimum spark energy is supplied to ensure free propagation from initial phase of combustion.

The partial pressures were determined by initial pressure, hydrogen fraction (HVF) (the volume fraction of the hydrogen in the fuel of hydrogen-enriched natural gas), equivalence ratio Ø (the ratio of the actual fuel/air ratio to the stoichiometric ratio). In this study, hydrogen, with purity of 99.95% was used. The LPG constitution is listed in Table 1.
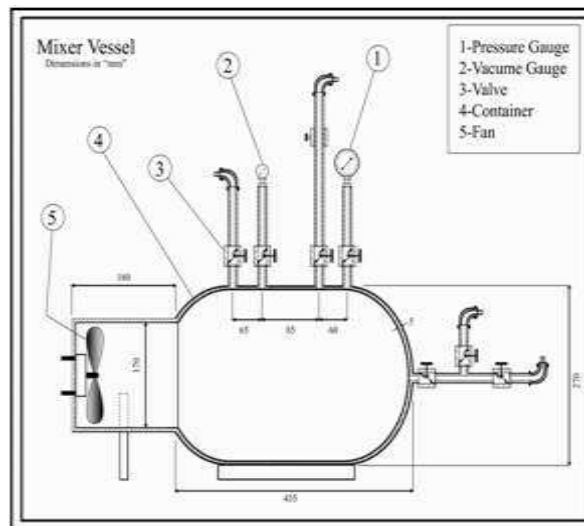

Fig. 3: Mixture preparing unit diagram

Flame temperatures were recorded in the experiment by means of thermocouples, where the initial pressure and temperature kept the same value for mixtures with different hydrogen fractions. The initial conditions were strictly controlled in the experiments to realize the same initial pressure and temperature. For avoiding the influence of wall temperature on mixture temperature, an enough interval between two experiments is set, providing enough time for wall to cool down and keeping the same initial temperature.

Table 1: Compositions of LPG

Items	CH_4	C_2H_6	C_3H_8	C_4H_{10}	Iso-C_4H_{10}
Volumetric fractions	1.2	0.08	47.8	32.45	18.47

Laminar burning velocity and Markstein numbers

To calculate the affecting variables [25] calculation method was used, applying the reading from the experimental rig. For a spherically expending flame, the stretched flame velocity, S_n, reflecting the flame propagation speed, is derived from the flame radius versus time data as

$$S_n = \frac{dr_u}{dt} \qquad (1)$$

Where r_u is the radius of the flame and t is the time. S_n can be directly obtained from the flame measurements.

Flame stretch rate, α, representing the expanding rate of flame front area, in a quiescent mixture is defined as

$$\alpha = \frac{d(\ln A)}{dt} = \frac{1}{A}\frac{dA}{dt} \qquad (2)$$

Where A is the area of flame. For a spherically outwardly expanding flame front, the flame stretch rate can be simplified as

$$\alpha = \frac{1}{A}\frac{dA}{dt} = \frac{2}{r_u}\frac{dr_u}{dt} = \frac{2}{r_u}S_n \qquad (3)$$

In respect to the early stage of flame expansion, there exists a linear relationship between the flame speeds and the flame stretch rates; that is,

$$S_l - S_n = L_b\alpha, \qquad (4)$$

Where S_l is the unstretched flame speed, and L_b is the Markstein number (Markstein length) of burned gases. From eqs. (1) and (3), the stretched flame speed, S_n, and flame stretch rate, α, can be calculated.

The unstretched flame speed, S_l, can be obtained as the intercept value at α = 0, in the plot of S_n against α, and the burned gas Markstein number L_b is the slope of S_n–α curve. Markstein number can reflect the stability of flame. Positive values of L_b indicate that the flame speed decreases with the increase of flame stretch rate. In this case, if any kinds of protuberances appear at the flame front (stretch increasing), the flame speed in the flame protruding position will be suppressed, and this makes the flame stability. In contrast to this, a negative value of L_b means that the flame speed increases with the increase of flame stretch rate. In this case, if any kinds of protuberances appear at the flame front, the flame speed in the flame protruding position will be increased, and this increases the instability of the flame. When the observation is limited to the initial part of the flame expansion, where the pressure does not vary significantly yet, then a simple relationship links the spatial flame velocity S_l to unstretched laminar burning velocity u_l, given as

$$u_l = \rho_b S_l/\rho_u \qquad (5)$$

where ρ_b and ρ_u are the densities for burned gases and unburned gases. The equation

$$u_n = S\left[S_n \frac{\rho_b}{\rho_u}\right] \qquad (6)$$

is used to determine the stretched laminar burning velocity u_n, and the stretched mass burning velocity u_{nl}, proposed by [26], is calculated from

$$u_{n1} = \frac{\rho_b}{\rho_b - \rho_u}(u_n - S_n) \qquad (7)$$

in which S is a rectified function and it depends upon the flame radius and the density ratio, and accounts for the effect of the flame thickness on the mean density of the burned gases. The expression for S in the present study used the formula given by [26],

$$S = 1 + 1.2\left[\frac{\delta_l}{r_u}\left(\frac{\rho_u}{\rho_b}\right)^{2.2}\right] - 0.15\left[\frac{\delta_l}{r_u}\left(\frac{\rho_u}{\rho_b}\right)^{2.2}\right]^2 \qquad (8)$$

Here δ_l is laminar flame thickness, given by $\delta_l = \nu/u_l$, in which ν is the kinetic viscosity of the unburned mixture.

III.   RESULTS and DISCUSSION

The flames of premixed LPG–hydrogen–air mixtures speeds were measured and the flame radiuses were obtained. Figures 4, 5& 6 show the measured flame radius versus time after ignition for LPG with hydrogen volume fractions (HVF) of 25, 50 and 75% vol at various equivalence ratios (representing lean (Ø=0.6), stoichiometric (Ø=1.0) and rich (Ø=1.3) fuels respectively).
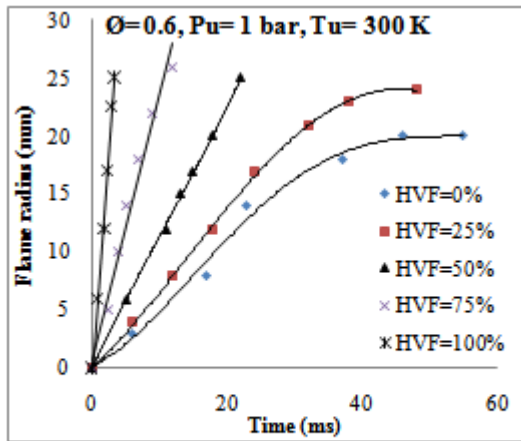
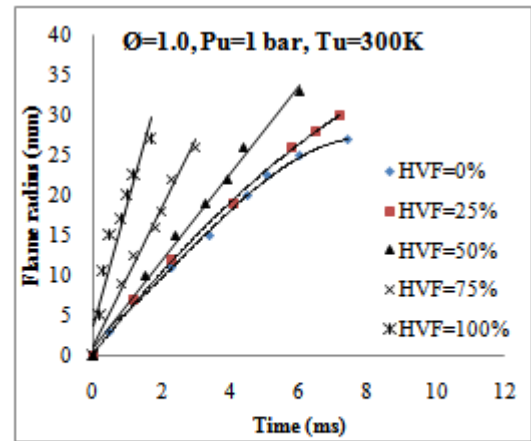Fig. 4: Flame radius versus time for variable hydrogen volume fractions

Fig. 5: Flame radius versus time for variable hydrogen volume fractions

After ignition, the flame expands spherically, whose radius increases at different speeds depending on hydrogen fraction (i.e. fuel constitution), equivalence ratio (mixture lean or rich). With the increase of hydrogen fraction from 0% vol to 100% vol, the flame expands much more rapidly at all tested conditions (as shown by the pre-mentioned figures). Equivalence ratio has greater effect on flame propagation speed of the fuel with low hydrogen fraction than that of the fuel with high hydrogen fraction.

The gradient of r_u–t curves reflected different behavior of flame radius with time at different equivalence ratios. In the case of lean mixture combustion (Ø= 0.6) at fig. 4, the flame radius increases with time but the increasing rate (gradient of curve) decreases with flame expansion for LPG and for mixtures with low hydrogen fractions, while there exists a linear correlation between flame radius and time for mixtures with high hydrogen fractions.

In the case of rich mixture combustion (Ø= 1.3), as fig. 6 shows, the flame radius shows a slowly increasing rate at early stages of flame propagation and a quickly increasing rate at late stages of flame propagation for LPG and for mixtures with low hydrogen fractions, and there also exists a linear correlation between flame radius and time for mixtures with high hydrogen fractions. In contrast to these, combustion at stoichiometric mixture demonstrates a linear relationship between flame radius and time for LPG–air flame, hydrogen–air flame, and natural gas– hydrogen–air flame, as fig. 5 represents.

As shown in Fig. 7. It was also found that the hydrogen-enriched LPG with high hydrogen fraction (HVF=75%) can sustain relatively wider equivalence ratios than the fuel with low hydrogen fraction (HVF=25%) does. It was observed that the fuel with high hydrogen fraction has stronger capability to maintain its flame propagation speed under ultra lean conditions than the fuel with low hydrogen fraction.
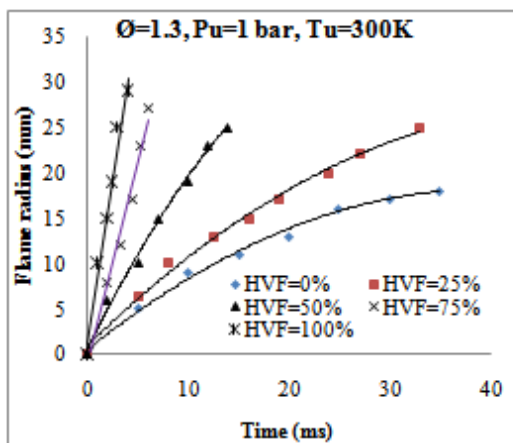

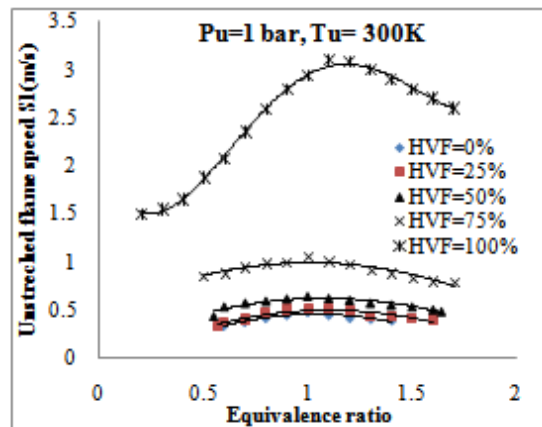Fig. 6: Flame radius versus time for variable hydrogen volume fractions

Fig. 7: Unstretched flame speed versus equivalence ratio for variable HVF.

The stretched flame speed is the derivative of flame radius with time, which reflects the flame moving speed relative to the combustion wall. Fig. 8 illustrates the stretched flame speeds of stoichiometric mixtures versus flame radius. It is clearly shown that the more the hydrogen gas is added, the faster the flame propagates. For the fuel with (HVF=25%), the stretched flame speed increases with the increase of flame radius in most cases. However, in the case of the fuel with 75% vol. hydrogen the speed decreases slightly with the increase of flame radius.

Fig. 9 gives the stretched flame speed versus the flame stretch rate at stoichiometric equivalence ratios and variable hydrogen fractions. A linear correlation between the stretched flame speed and the flame stretch rate is found. The unstretched flame speed, S_l, is obtained by extrapolating the line to $\alpha = 0$, while the gradient of the Sn–α curve gives the value of the Markstein number.
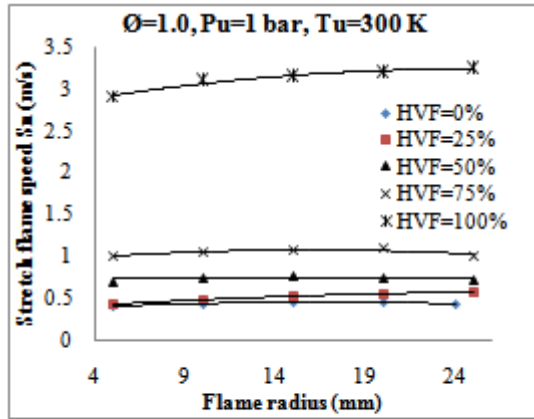

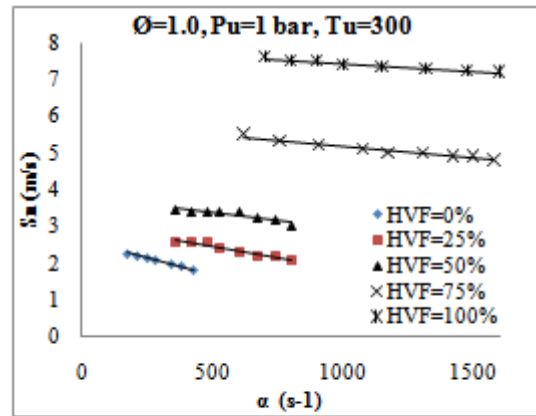Fig. 8: Stretched flame speed versus flame radius for variable HVF

Fig. 9: Stretched flame speed versus flame stretch rate at Ø=1

In the case of a LPG–air flame, the stretched flame speed decreases with the increase of flame stretch rate. In the case of a mixture with HVF=25%, negative gradients of Sn–α curves are derived, and these correspond to positive values of Markstein number, indicating the stability of flames of mixture combustion. In the case of high hydrogen fraction (a mixture with 75% hydrogen), negative values of Markstein number are presented, and this indicates a stable flame for rich mixture combustion and an unstable flame for lean mixture combustion in the case of high hydrogen fraction.

The figure shows the Sn–α curve for mixtures with different hydrogen fractions at the stoichiometric equivalence ratio. The results show that the Markstein number decreases with the increase of hydrogen fraction, and this indicates that the flame stability will decrease with the increase of hydrogen fraction.

The Markstein length also depends on the hydrogen fraction of the fuel as fig. 10 indicates. For the fuel with low hydrogen fraction (25% vol. in this study), the Markstein length tends to increase from negative value to positive one, indicating that the flame tends to become more stable. On the other hand, for the fuel with high hydrogen fraction (75% vol. in this study), the Markstein length tends to be slightly decreased with the increase of equivalence ratio.

Measurements showed that the addition of hydrogen can decrease the Markstein number of the laminar premixed hydrogen-LPG flames as the flame tends to be unstable due to the effect of fast diffusing component (hydrogen).

The relationship between laminar burning velocities and stretch rate is plotted in Fig. 11. As shown in the figure, the difference between the stretched laminar burning velocity u_n and the stretched mass burning velocity u_{nl} can be clearly observed. The stretched laminar burning velocity u_n, which denotes the rate of mixture entrainment, always increases as the stretch rate increases. In contrast, the mass burning velocity u_{nl}, which is the burning velocity related to the production of unburned gas, is usually decreased as the stretch rate increases. Speed difference ($u_n - u_{nl}$) increases with the increase of stretch rate, and this would be due to the influence of flame thickness on burning velocities. A large value of ($u_n - u_{nl}$) is seen at small radii (corresponding to high stretch rate), where the flame thickness is of the same order as the flame radius. As the definition indicated, a high value of stretch rate corresponds to a small flame radius; thus the influence by flame thickness becomes great. When stretch rate reaches zero, the flame radius becomes infinity; thus the effect of flame thickness can be neglected, and u_n and u_{nl} will get the same value, u_l, the unstretched laminar burning velocity.
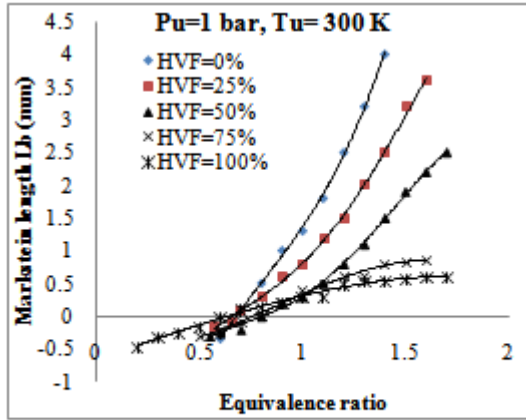
Fig. 10: Markstein length for wide range of equivalence ratios at variable HVF
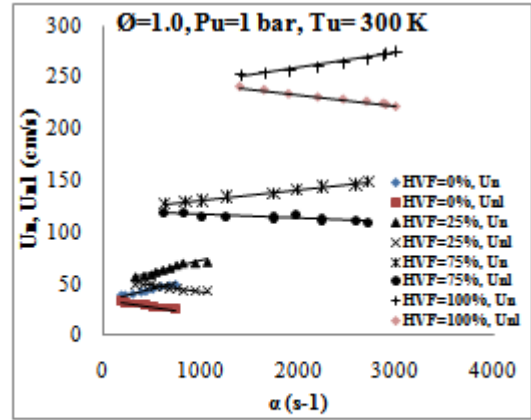

Fig. 11: the stretched flame speed versus the flame stretch rate

A comparison of unstretched laminar burning velocities versus equivalence ratios for LPG–air flames (Fig. 12), while the comparison of unstretched laminar burning velocities of hydrogen–air flames is illustrated in Fig. 12. The results show that the present work gives data consistent with those of others both for various LPG and pure hydrogen flames. For LPG–air flames, (as Fig 12 shows) except for the data from [4], which give values higher than those of others and the maximum values occurred in the rich side, the present work gives values consistent with other experimental results.

For hydrogen–air flames (as Fig.13 represents), except for the data from [27], which give lower values compared to those of others, the present work gives values consistent with other experimental results. This proves the data correctness obtained from this study, as well as it provides data for wider range of equivalence ratio, compared with other works. Unfortunately there were no available data for hydrogen enriched LPG to compare with, that means the need for more work in this field to explore the variable behaviors of hydrogen enriched LPG-air mixtures.
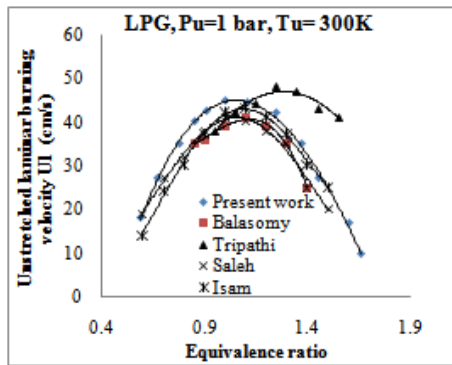

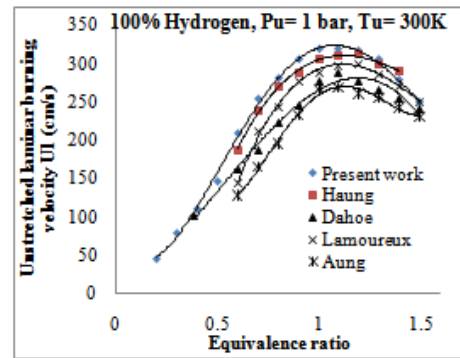Fig. 12: Unstretched burning velocity for wide range of equivalence ratio of LPG fuel

Fig. 13: Unstretched burning velocity for wide range of equivalence ratio of hydrogen fuel

IV.   CONCLUSIONS

Laminar flame characteristics of LPG–hydrogen–air flames were studied in a constant volume bomb at normal temperature and pressure, using thermocouples method. Laminar burning velocities and Markstein lengths were obtained at various ratios of hydrogen to LPG (volume fraction from 0 to 100%) and equivalence ratios (Ø from 0.6 to 1.6). The influence of stretch rate on flame was also analyzed. The results are summarized as follows:

(1) For lean mixture combustion, flame radius increases with time, but the rate of increase decreases with flame expansion for LPG and for mixtures with low hydrogen fractions, while at high hydrogen fractions, there exists a linear correlation between flame radius and time.

For rich mixture combustion, there is also exists a linear correlation between flame radius and time for mixtures with high hydrogen fractions. Combustion at stoichiometric mixture demonstrates the linear relationship between flame radius and time for LPG–air, hydrogen–air, and LPG–hydrogen–air flames.

(2) Hydrogen–air flame gives a very high value of the stretched flame speed compared to those of natural gas–air flame and natural gas–hydrogen– air flames, even for high hydrogen fraction.

(3) Enrichment of 25 & 50% hydrogen to LPG-air has very little effect on burning velocities for lean and rich mixtures and remarkable effect on stoichiometric mixtures.

(4) Enrichment the mixture with hydrogen expands the equivalence ratio range and makes it wider.

(5) Unstretched laminar burning velocities are increased with the increase of hydrogen fraction. Markstein lengths are decreased with the increase of hydrogen fraction, indicating that the flame instabilities are increased with the increase of hydrogen fraction.

(6) For a fixed hydrogen fraction, the Markstein length and flame stability increase with the increase of equivalence ratios.

(7) Very good agreement is obtained between values of laminar burning speed and Markstein length values determined with the present methodology and values found in the literature.

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