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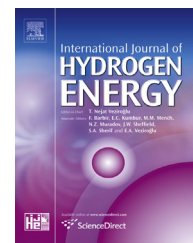
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An experimental study of the effect of hydrogen blending on burning velocity of LPG at elevated pressure

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ABSTRACT

An experimental study on the laminar burning velocity of the premixed liquefied petroleum gas (LPG)/hydrogen/air flames was conducted in a constant volume chamber that centrally ignited at various initial pressures (0.1–0.3 MPa) and initial temperature of (308 K). In addition, the tested equivalence ratios of range from (0.8–1.3), and the investigated blends of hydrogen were (0–80%) by volume. Experimental data of laminar burning velocity, flame thickness, stretch rate, and laminar flame speed and combustion pressure of LPG flames with various blends of H₂ have been presented. The constant volume chamber has been designed and constructed specially for this study, as this method considered the most precise one to measure laminar burning velocity. A mixing chamber, ignition control, data acquisitions and high-speed Schlieren photography were used. Experimental results have been shown that the effect of hydrogen addition becomes noticeable when the hydrogen blend is larger than 60%. When hydrogen blending is 80%, adiabatic flame temperature increases about (40 K), the laminar flame speed of LPG also increases from (2.2–4.75 m/s) and laminar burning velocity from (31–59.5 cm/s). While flame thickness decreases from (0.15–0.07 mm) for stoichiometric mixture at atmospheric pressure. Increasing initial pressure from 1 bar to 3 bar reduces the stretched laminar flame speed of LPG-air mixture from (2.2–1.5 m/s), and laminar burning velocity also decreases from (31–20 cm/s). In contrast, combustion pressure increases from (5–25 bar). Equivalence ratio has a more dominating effect on adiabatic temperature, density ratio and flame thickness than hydrogen does. Correlations between hydrogen blend and initial pressure are derived from LPG–air mixtures.

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Introduction

Increasing concern over the pollution of air and fossil fuel shortage and the requirements for alternative fuels for Internal Combustion Engines (ICEs) and the need for sustainable energy systems have been a major worry for the researchers and led them to re-evaluate the combustion process and the prospects of alternative fuels.

Combustion and its control are vital to survival. A quick glance at environment shows the significance of combustion in daily life as the heat for any residential area mostly comes, directly or indirectly, from combustion. Industrial processes rely primarily on combustion. Physical processes involved in combustion are those involving transport of matter and transport of energy [1].

The laminar burning velocity (LBV) is defined as the velocity at which unburned gases move through the combustion wave

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in the direction normal to wave surface. It is determined by the kinetics of the chemical reaction and the molecular heat and mass transport. LBV is a physiochemical property that describes the movement of reactance towards reaction zone including the mixing and reaction while flame speed is the flow of the flame front, which is a two compound of chemical reaction and the temperature increasing in the same direction.

The production of accurate laminar premixed flames measurements plays a critical role in the process of understanding an extensive range of flames. Though the majority of fuel is probably burnt in turbulent combustion, measurements of LBV are still needed as they serve as input data to many turbulent combustion models.

Laminar burning velocity is also an essential parameter in validating the chemical kinetics and combustion characteristics of the fuel, and hence, it is a significant parameter in predicting performance and emission of fuel for any combustion system [2].

In response to the concern of hydrogen economy to mitigate the global warming problem, there have been meaningful actions in the progress of hydrogen-fueled ICEs. However, due to the high reactivity of hydrogen, and the need for supercharging, hydrogen-fueled engines are prone to knock and pre-ignition, and could potentially emit elevated levels of NO_x . Such an approach is justified further by recognizing that there is no intrinsic reason to achieve zero CO_2 emission; this led researchers to investigate the field of H_2 blending.

Determination of LBV

There are three methods to measure the laminar burning velocity. They are the stagnation plane flame method, the heat flux method, and the combustion bomb method. The stagnation plane flame method can generate different flame patterns, but it is demanding to get a clear flame front and stabilization of the flame under high-pressure conditions. The heat flux method requires to conclude the heat loss as a function of velocity and to extrapolate the results to zero heat loss to get the burning velocity. The combustion bomb method is used for typical propagating spherical flame configuration [3].

According to the flame movement, the methods utilized for the calculations of the LBV classifies into stationary processes; where the reactants are introduced into the reaction zone, for example, Bunsen burner and propagating methods; where the reaction zone is introduced into the reactants, for example, the propagating of flame in the tube. From the propagating methods, the constant volume method is selected in this study because:

- (a) It needs a small amount of fuel.
- (b) It simulates the combustion process in spark ignition engine (SIE).
- (c) It allows for the best control over the initial conditions and mixture composition.
- (d) It is self-consistent and suitable for the conditions of high pressure.
- (e) It can provide local values of the burning velocity at each instantaneous value of pressure.
- (f) Simple flame configuration and well-defined flame stretch rate.

The constant volume method is subjected to some disadvantages that include lengthy and tedious calculations that could be resolved by adopting fast data processing system. The other disadvantage is the initiation of a spherical flame at minimum ignition energy, and suitable matching between the spark gap and the spark energy can solve the non-adiabatic conditions that exist near the end of burning due to heat transfer to the walls of the chamber [4].

Homogeneous air/fuel mixture is admitted to the Constant Volume Chamber (CVC) and ignited by two opposed thin metal electrodes that create a spark at the center of the spherical space; then the flame grows spherically outwards. Kwon et al. [5] stated that the propagating outwardly spherical flame is the phenomenon most appropriate to centrally-ignited flame propagation and accidental explosions.

Hopkinson assembled the first bomb to measure the flame speed. The temperature of the flame was measured by fine platinum wires across the chamber at the different radius and measure their resistance. The flame speed was calculated from the time taken for the flame to pass from wire to another [6]. Fiock et al. [7] developed the technique by using a glass window with a (10") diameter bomb to film the combustion.

Burning velocity can be calculated in some ways. One method is to mount a fast response pressure transducer in the outer wall of the bomb. This provides a pressure trace as the flame grows. A computer model is then used to calculate the burning velocity from this pressure record. Secondly, Schlieren photography can be used to visualize the flame. The flame radius can then be measured from these photographs. High-speed cameras have been later replaced by high-speed digital video.

Factors affecting on burning velocity and flame speed

Equivalence ratio

Equivalence ratio (Φ) is the ratio of the actual fuel-air ratio to the stoichiometric fuel-air ratio. Except for very rich mixtures, the variation of burning velocity with equivalence ratio followed that for adiabatic flame temperature, as the primary effect of changing the equivalence ratio is to change the temperature. Hence, it peaked at slightly richer than stoichiometry.

Andrews and Bradley [1], Sharma et al. [8] and other researchers found correlations between flame speed and equivalence ratio for different fuel-air flames.

Alekseev et al. [9] used an updated mechanism to study the effect of temperature on the burning velocity of hydrogen flames for different equivalence ratio and validated the mechanism with many types of research and found that slightly richer than stoichiometric is the region of the maximum LBV.

Initial temperature

Temperature is the largest factor involved in changing burning velocity. The temperature dependencies of laminar burning velocity and flame thickness can be inferred from equations.

Andrews and Bradley [10] estimated the influence of temperature on flame speeds using the empirical correlation for stoichiometric methane-air flames.

Sharma et al. [8] and Metghalchi and Keck [1] suggested a relationship between initial temperature and flame speed.

Tang et al. [11] investigated the burning velocity for propane with different hydrogen fractions at various equivalence ratios. The results showed that the laminar burning velocity increases with the increase in initial temperature.

Initial pressure

Experimental results showed a weak inverse dependence on pressure. Previously, researchers used a bomb with ionization probes to find the pressure dependence of several gases burning stoichiometrically at ambient temperature.

Similar relationships were found by Andrews and Bradley [10], Sharma et al. [8] and Turns [1] for the other fuels, but with different coefficients.

For methane-air flames, Law [12] provided a summary of flame speed data for a range of pressure (up to 5 atm or less) for the following fuels; H_2 , CH_4 , C_2H_2 , C_2H_6 and C_3H_8 . The previously cited work by Metghalchi and Keck [1] also provided flame speed pressure correlation for selected fuels.

Salih, Adil, M [13]. measured the laminar flame speed of (methane, propane, LPG and butane)/air mixtures at different initial pressure and derived an empirical equation to calculate the laminar burning velocity.

Fuel blends

Because of the growing interest in the use of hydrogen as an energy carrier, its environmental properties, and benefit from its features previously mentioned, it seemed worthwhile by many researchers to investigate the laminar burning velocity of hydrogen. The high burning velocity in the H_2 led

researchers to use it as a blended fuel to increase the flame speed consequently improved the combustion process.

Huang et al. [14] measured the laminar burning velocity of H_2 -natural gas/air mixture in a constant volume bomb at standard temperature, pressure, and different equivalence ratios. The results showed that for lean and rich mixture combustion, there exists a linear correlation between flame radius and time. Based on the experiments, a formula for calculating the laminar burning velocity of natural gas/hydrogen/air flames was proposed. Sarli and Benedetto [15] studied laminar burning velocity of H_2/CH_4 /air premixed flames numerically using the CHEMKIN-PREMIX code with the GRI kinetic mechanism. They showed that the values of the laminar burning velocities were always minor than those obtained by averaging LBV of the pure fuels according to their molar proportions. Miao et al. [16] used 30% of propane and 70% butane to simulate standard commercial LPG available in Hong Kong, to investigate laminar burning velocity with hydrogen enrichment of (10%–90%) in volume. They found that the accelerating effectiveness is substantial when the percentage of hydrogen is larger than 60%. Hydrogen addition decreased the flame thickness. For the fuel with 10% LPG, flame thickness values were close to all equivalence ratios.

Tang [21] found that the increasing of H_2 blending will decreased the minimum ignition energy of H_2 /hydrocarbon blends and the ignition behavior of hydrogen/hydrocarbon fuel blends exhibits three distinct behaviors. Furthermore, three behavior regimes for the laminar flame speed of hydrogen/hydrocarbon fuel blends is found.

Experimental setup

An experimental facility is constructed and designed in the Laboratories of Babylon University by Yasiry, Ahmed Sh [17]. The complete schematic diagram of the rig is shown in Fig. 1.

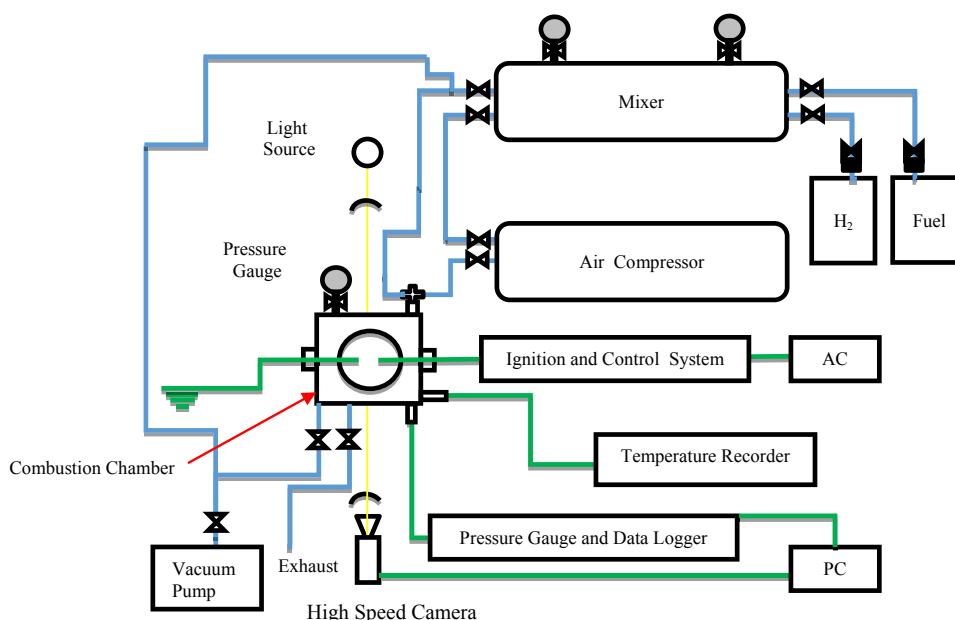


Fig. 1 – Schematic diagram of the experimental apparatus.

It consists of a combustion chamber unit that has a cylindrical chamber with (250 mm) height, (190 mm) inner diameter, (10 mm) wall thickness and a volume of (7.2 L). Two pressure-resisting quartz windows with (108 mm) diameter are installed on the two sides of the combustion chamber by two flanges. Temperature and pressure of the combustion are measured. An ignition circuit and control unit are used to produce a powerful spark by supplying the power needed for the electrodes with a duration of (5 ms). An optical system is used to visualize the flame and flame propagation process with a high-speed camera (16,000 frames per second). A light source and collimating lenses are used. Finally, to prepare the LPG-air mixture, a mixture-preparing unit has been built. Mixing Processes are based on Dalton's law of partial pressure. Yasiry, Ahmed Sh. [18] explains the procedure of preparation.

Theoretical analysis

Dalton's law of partial pressures shows that the ratio of the partial pressures of the air and the fuel will be equal to their molar ratio. LPG fuel used in this study is a mixture of multi hydrocarbons. It consist of 0.9% C_2H_6 , 36.3% C_3H_8 , 62.3% C_4H_{10} and 0.5% C_5H_{12} . LPG-air mixture burns adiabatically at constant pressure, then the absolute enthalpy of the reactance at the initial state equals the absolute enthalpy of the product at the final state, and adiabatic flame temperature can be calculated theoretically by a Fortran program written by the researcher.

In this study, the unburned gas front radius obtained from the photograph is directly used to derive the stretched flame speed (S_n). The stretched flame speed (S_n) is calculated using Eq. (1). The data are obtained from the experimental radius versus time values by using Tracker software to trace the flame front for subsequent frames. The instantaneous flame speed is taken to be the slope of the line segment connecting two neighboring radii versus time points. The stretched flame speed is calculated using software (Tracker version 4.87) for both Cartesian coordinates by tracking the flame front for each subsequent frame from the movie recorded by the high-speed camera and the output data would be (S_n , r , and t). A general definition of a stretch at any point on the flame surface is the Lagrangian time derivative of the logarithm of area of any infinitesimal element of the surface. For the outwardly propagating spherical flame, the flame stretch rate can be deduced in the following form,

$$S_n = \frac{dr}{dt} = \frac{r_{j+1} - r_j}{t_{j+1} - t_j} \quad (1)$$

During the pre-pressure period, there exists a linear relationship between the flame propagation speed and the stretch rate (α); that is

$$S_i - S_n = L_b \alpha \quad (2)$$

The unstretched propagation speed, (S_i) can be obtained as the intercept value at $\alpha = 0$, in the plot of S_n against α . The burned gas Markstein length, L_b , is the negative slope of S_n - α fitting curve [2]. Markstein length can then be defined as the decrease in burning velocity per unit stretch. The unstretched

laminar burning velocity, u_l , is related to S_i through the mass conservation across the flame front.

$$u_l = S_i \frac{\rho_b}{\rho_u} \quad (3)$$

Where A is the flame front area, ρ_u and ρ_b are the unburned and burned gas densities, respectively.

Results and discussion

Laminar flame speed

Laminar flame speed has been captured experimentally through the window of CVC. The effects of hydrogen blending, equivalence ratio at different initial pressures upon the flame speed have been studied. The results of the expanding spherical flame experiments are presented. To give an example of the records being analyzed, Fig. 2 shows a sequence of frames of an expanding spherical flame with a different equivalence ratio. The first frame immediately follows ignition while subsequent frames are approximately every (3.75 ms). Using software (Tracker) to trace the flame front for subsequent frames from the data are obtained from the experimental radius versus time values. The instantaneous flame speed is taken to be the slope of the line segment connecting two neighboring radii versus time points.

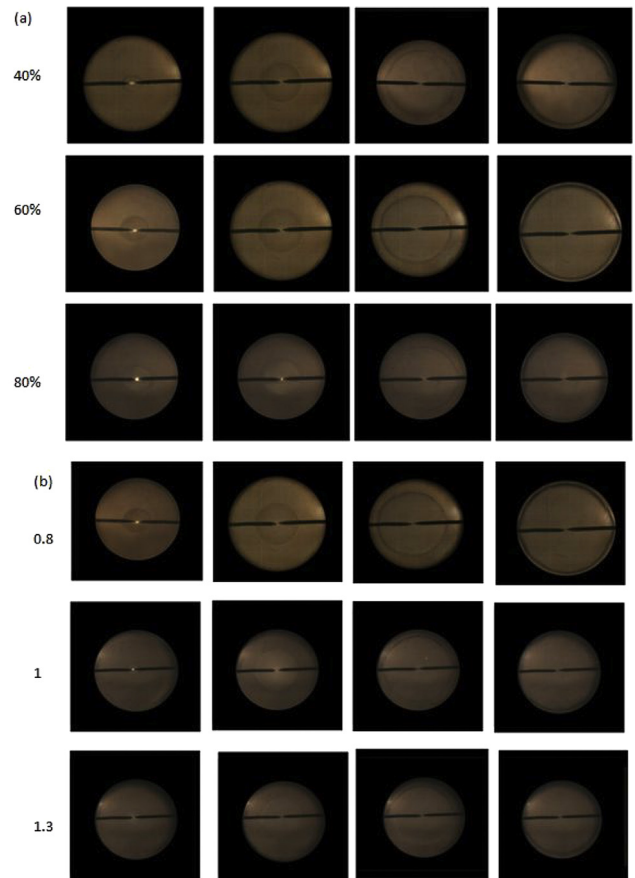


Fig. 2 – Photographs of flame propagation for initial pressure 3 bar with: a-Different hydrogen blend at equivalence ratio 0.8. b-Different equivalence ratio for 60% H_2 .

The data used in the analysis are limited within the flame radius ranging from (5–35 mm). It can be seen from the Fig. 3 that the flame speed behavior can be divided into three regions. The first region; initiation region, (when the flame radius is less than (7 mm)) the ignition energy could affect the propagation of flame that is centrally ignited, in the early stage of flame development. As mentioned previously, Bradley et al. [19] pointed out that the ignition energy would elevate the flame speed for the iso-octane-air mixtures at a flame radius of less than (5 mm). The flame speed calculated before in this region cannot be used to determine the laminar flame speed because of the interference of underdeveloped flame. The second region is the fully developed region, where S_n would be almost constant. The high initial value of S_n is due to the elevating effect of ignition, and the subsequent gradual decrease of S_n indicates that the flame is not fully developed until the radius reaches (15 mm). Prathap et al. [20] suggested that the range of the flame radius is less than the one-third radius of the combustion bomb used in this study is (31 mm). One-third of the inner radius of the combustion bomb used in this study is (31 mm). The third region, end region, when flame radius exceeds (35 mm), the strain in flow field would notably reduce flame speed also the effect of combustion pressure presented. The first and third region are to be out of the calculation.

1) Effect of Initial Pressure.

The effects of initial pressure on the laminar flame speed of LPG-air mixtures blended with H_2 for different equivalence

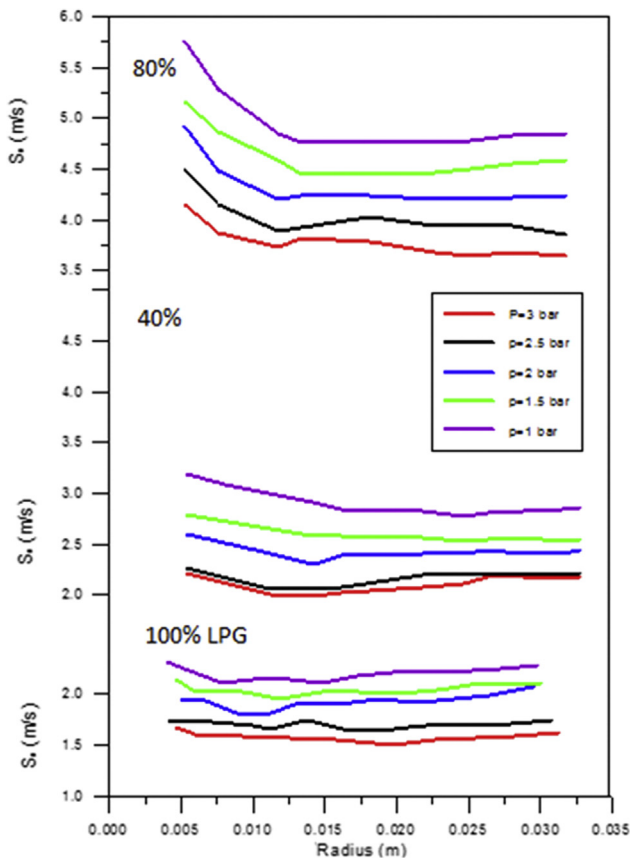


Fig. 3 – Variation of stretched flame speed (S_n) with flame radius for various hydrogen blend at stoichiometric mixture.

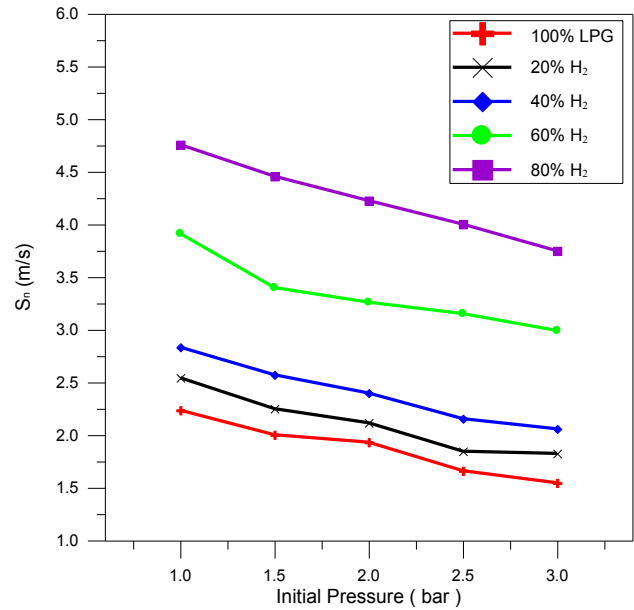


Fig. 4 – Variation of S_n with initial pressures for LPG with various H_2 percentages at $\phi = 1$ at flame radius of 20 mm.

ratios are demonstrated in Fig. 3. Fig. 4 presents the flame speed at (2 cm) flame radius for difference hydrogen blends with initial pressure. The effect of hydrogen on flame speed becomes clearer at mixing ratio higher than (60%). The results also show that the flame speed decreases with increasing pressure for any stoichiometry.

When the initial pressure increases, the amount of mixture of the same volume will be increased hence, the density of mixture would be increase and thermal diffusivity decreases with increase the density. The resistance of unburnt mixture to diffusive the flame so that the flame speed will drop.

2) Effect of Equivalence Ratio at Atmospheric Pressure

The experimental flame speed versus stoichiometry limits is illustrated in Fig. 5 for LPG with different hydrogen blending at atmosphere pressure. It shows that the flame speed increases as the mixtures go from the lean limits towards the stoichiometric mixture, and then decreases as approaches for rich mixtures.

3) Effect of Hydrogen Blends at Atmospheric Pressure

The experimental flame speed versus various hydrogen blends in Fig. 6. Two important points are worth noting about the results. First, the propagation of the flame increases with the increase of hydrogen blends, and the increment of the flame propagation speed becomes larger with the increase of hydrogen blends especially when hydrogen blend is more than (60%) since the flame temperature of hydrogen is higher than LPG, hence flame speed.

It is worth noting that under the stoichiometric condition either at different pressure Fig. 6 or elevated pressure Fig. 3, the ignition energy results in an initial flame speed

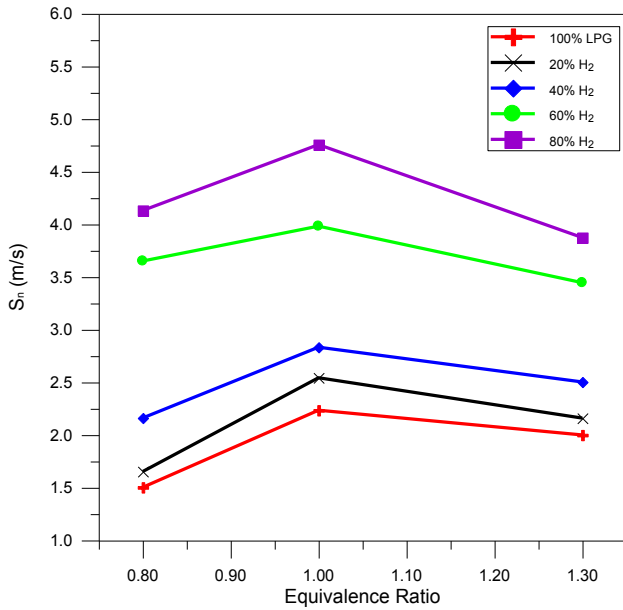


Fig. 5 – Variation of S_n with equivalence ratios for LPG with various H₂ percentages at (20 mm) radius and atmosphere pressure.

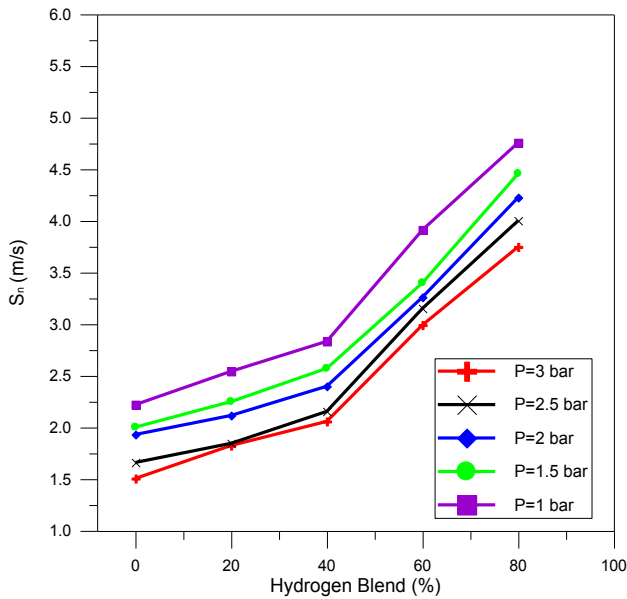


Fig. 6 – Variation of S_n with H₂ percentages at stoichiometric mixture at (20 mm) radius and different initial pressure.

significantly higher than that of the stable flame speed for the LPG-H₂ flames with increasing H₂ blends.

Stretched rate and unstretched flame speed

When the propagation of flame is small, the stretch rate of the flame front surface is significant. Removing the data affected by the ignition energy and electrodes during the early stage of flame development (less than 10 mm) and removing data of

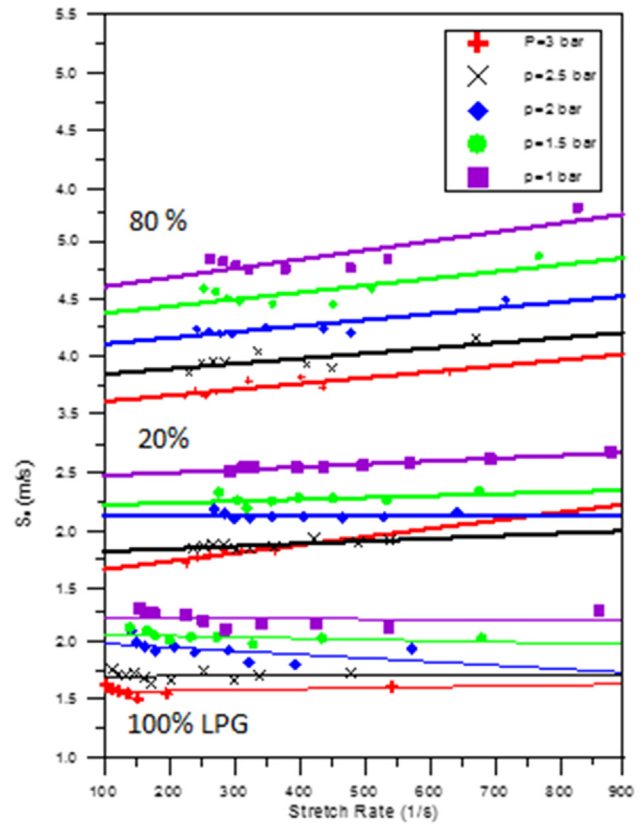


Fig. 7 – Various of stretched flame speed (S_n) with stretch rate for different H₂ blend for $\phi = 1$.

large radius where the pressure is increased (beyond 32 mm), a linear correlation between the stretched flame propagation speed and the flame stretch rate is demonstrated.

The stretch is inversely proportional to the radius, so as the flame grows its effect decreases. This would be predictable as the radius increases; the flame becomes less curved and one-dimensional more like a planar, and, therefore, flame become unstretched.

The stretch rate has very high values during the initial stages of combustion due to a small amount of radius and the significant curvature associated with a small, spherical surface. As the flame grows, so does the radius of curvature and consequently the stretch tends to zero asymptotically. Burning velocity is affected by flame stretch, and hence, can only be truly determined when the stretch is negligible (see Fig. 7).

Laminar burning velocity

LBV is a significant restriction of a combustible mixture because it contains the necessary information regarding its exothermicity, reactivity, and diffusivity.

The radiation, convection, and conduction are the source of heat transfer that affected the propagation of flame from the flame front by, to the unburned gases. Also, the unburned gas velocity depends on the flame temperature, as it increases by its increment. The variation of thermal diffusivities of reactant mixture with hydrogen blend has a similar to that of flame temperature with

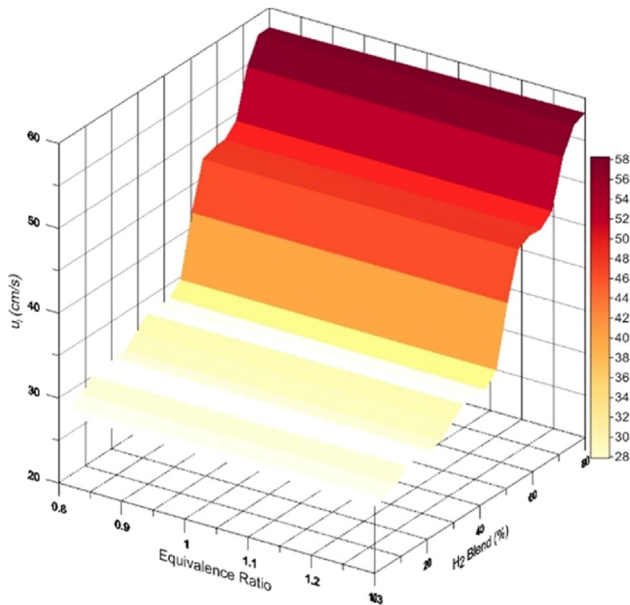


Fig. 8 – Surface of laminar burning velocity versus equivalence ratio and H₂ blend at atmosphere pressure.

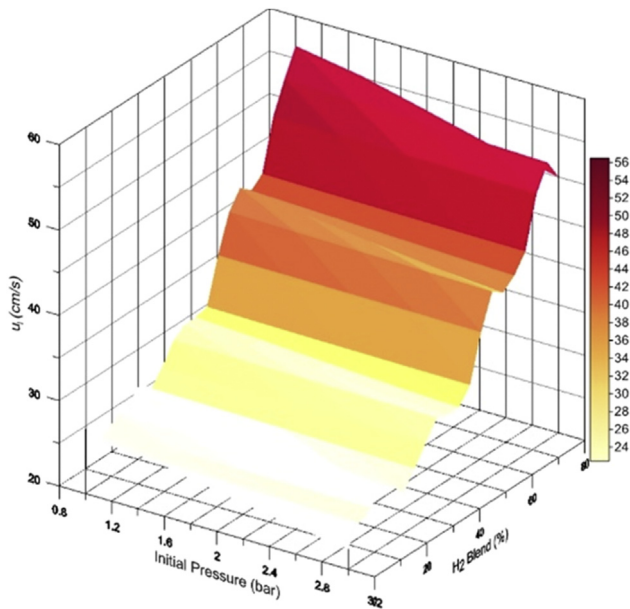


Fig. 9 – Surface of laminar burning velocity versus equivalence ratio and H₂ blend at stoichiometric mixture.

hydrogen blend. The effect of H₂ addition on thermal diffusivity becomes significant when hydrogen blend is larger than (50%). The enhanced thermal diffusivity due to H₂ addition accelerates LBV of the mixture. Figs 8 and 9 shows that LBV increases when initial pressure decreases and increase H₂ blending.

1) Correlation of Laminar Burning Velocity

LBV increase exponentially with the increase of hydrogen blends and they decrease exponentially with the increase of

initial pressure. The equations of fitting curve about hydrogen blends and pressure are

$$\text{for } (\phi = 1, P = 1 \text{ bar}, 0 \leq J_{H_2} \leq 0.9) \quad (4)$$

$$u_l(H_2) = \exp(J_{H_2} \times 0.00821509) \times 29.4031$$

$$\text{and for } (\phi = 1, 100\% \text{ LPG}, 1 \text{ bar} \leq P \leq 3 \text{ bar}) \quad (5)$$

$$u_l(p) = \exp(-0.202804 \times P) \times 36.9441$$

The effects of hydrogen blend and pressure on laminar burning velocity can be correlated with the following empirical expression,

$$\text{for } (\phi = 1, 0 \leq J_{H_2} \leq 0.9, 1 \text{ bar} \leq P \leq 3 \text{ bar}) \quad (6)$$

$$u_l = u_{l,0} - 5.22 \times \left(\frac{P}{P_0}\right) + 36 \times J_{H_2}$$

Where subscript 0 represents is reference condition, that is, $P_0 = 1$ bar. Laminar burning velocity for 100% LPG at reference condition, $u_{l,0}$, at the stoichiometric mixture, is 31.72 cm/s.

Many types of research showed that hydrogen addition significantly increased the LBV of hydrocarbons including butane and propane. Fig. 10 compares the laminar burning velocities of butane, propane, fuel at difference composition and 60% H₂ blend according to the Table 1. The LBV of 60%H₂ blends 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.

The addition of H₂ reduces the carbon atoms number in the mixture which increases the laminar burning velocity. The thermal diffusivity is the most important parameter that change the burning velocity of fuels containing different numbers of carbon atoms.

Flame thickness

Hydrodynamic instability is a critical parameter, which affects flame front stability. Flame thickness has an inhibiting effect

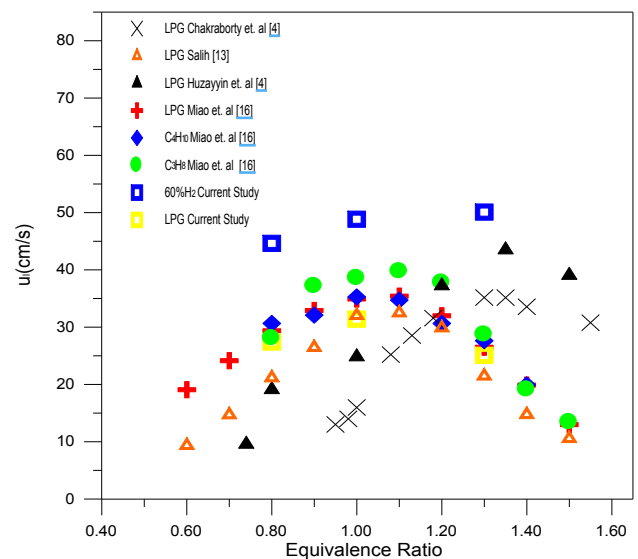


Fig. 10 – Laminar burning velocity versus equivalence ratio for different fuel mixtures at atmosphere pressure.

Table 1 – Fuel concentration. (CVC Constant Volume Chamber Technique, CVT Constant Volume Thermocouple Technique, FBT Flat Flame Burner Technique).

Constituents	C ₂ H ₆		C ₃ H ₈		C ₄ H ₁₀		C ₅ H ₁₂		C _n H _m	
	n	m	n	m	n	m	n	m	n	m
Researcher, technique, [ref.]										
Miao et al., CVC [16],	0	1	0	0	3	8				
Chakraborty et al., FBT [4],	1.4	30.1	67.7	0	3.639	9.262				
Salih, Adil, M., CVT [13],	3.33	57.08	38.35	1.24	3.375	8.75				
Huzayyin et al., CVC [4],	0.04	26.41	73.54	0	3.734	9.468				
Miao et al., CVC [16],	0	30	70	0	3.7	9.4				
Current Study, CVC	0.9	36.3	62.3	0.5	3.624	9.248				
Miao et al., CVC [16],	0	0	1	0	4	10				

on hydrodynamic instability while density ratio has a promoting effect.

Fig. 11 shows the variation in flame thickness with equivalence ratio for initial atmospheric pressure. The flame thickness decreases with increasing hydrogen blend. For hydrogen blend higher than 50%, the drop of decreasing in flame thickness is more evident. The minimum value of flame thickness is slightly near stoichiometric. Hydrogen addition increases the adiabatic flame temperature due to increasing chemical reaction rate, hence increases the burning velocity. The flame thickness is inversely proportional to the laminar burning velocity. Flame thickness decreases with the increasing hydrogen blends and decreases towards stoichiometry.

Combustion pressure

Fig. 12 shows that the maximum combustion pressure increases with the increase of the initial pressure and increases

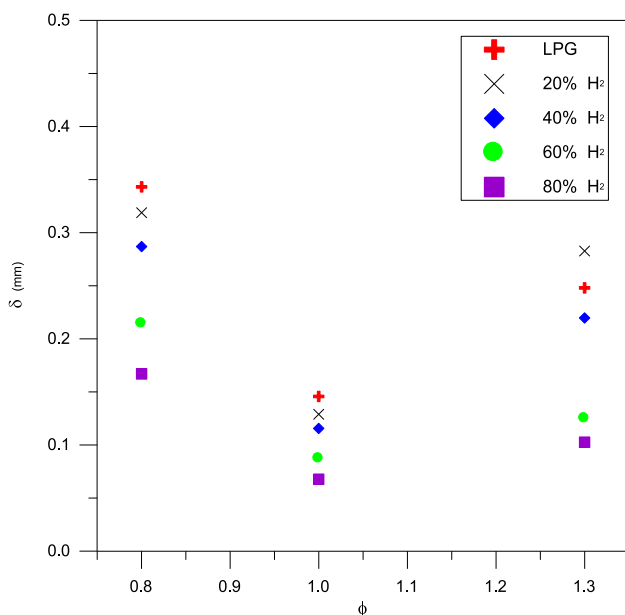


Fig. 11 – Flame thickness versus equivalence ratio for different hydrogen blend at initial pressure of 1 bar.

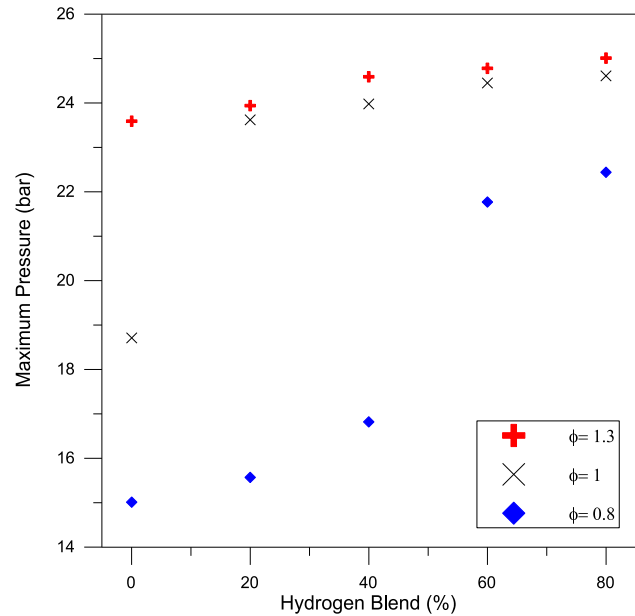


Fig. 12 – Maximum combustion pressure versus hydrogen blend for different equivalence ratios at initial pressure of 3 bar.

with increase hydrogen blends because H₂ addition increases the flame temperature, hence increases the combustion pressure for any stoichiometry and the maximum value is the rich mixture.

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