AN EXPERIMENTAL STUDY OF THE EFFECT OF HYDROGEN BLENDING ON LAMINAR FLAME SPEED FOR IRAQI LPG

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ABSTRACT

An experimental study on laminar flame speed of the premixed Iraqi liquefied petroleum gas (LPG)-hydrogen /air flames is conducted in a centrally ignited constant volume chamber specially constructed by the authors; at different initial pressures (0.1-0.3MPa) and initial temperature of (308 K). The tests are carried out at a mixture equivalence ratio ranges from 0.8-1.3. The investigated blends of hydrogen are 0-80% by volume .

Experimental results show that the effect of hydrogen addition becomes obvious when the hydrogen blend is larger than 60%. When hydrogen blending 80%, the laminar flame speed of LPG also increases from (2.2-4.75 m/s) for stoichiometric mixture at atmosphere pressure. Increasing initial pressure from (1-3 bar), reduces stretched laminar flame speed of LPG-air mixture from (2.2-1.5 m/s) .

KEYWORD: laminar flame speed, LPG, liquefied petroleum gas, hydrogen, constant volume chamber, LPG-H₂ blending and schlieren.

دراسة تجريبية لتاثير خلط الهيدروجين على السرعة الطباقية للغاز المسال العراقي

هارون عبد الكاظم شهد   احمد شاكر الياسري

الخلاصة :-

تم اجراء دراسة عملية عن سرع الاحتراق الطباقيه لخلائط غازات البترول السائلة مع الهيدروجين والهواء المسبقة الخلط، باستخدام حجرة احتراق ثابته الحجم ذات اشعال مركزي تم تصميمها وبنائها خصيصا من قبل الباحثين وبضغوط ابتدائية مختلفة (0.1-0.3 MPa) ،عند درجه حرارية ابتدائية ثابته (308 K) بالإضافة الى نسب مكافئه مختلفة (0.8 - 1.3). ان نسب خلط الهيدروجين الحجمية التي تم اختبارها كانت0-80%. بيّنت الدراسة أن تأثير نسبة خلط الهيدروجين يصبح اكثر وضوحا عندما تزداد نسبة الخلط عن 60% وعند نسبة خلط 80% من الهيدروجين فان سرعه انتشار اللهب الطباقيه للخليط سوف تزداد من 2.2 m/s الى 4.75 m/s للخليط المتكافئ عند الضغط الجوي. بيّنت النتائج ازدياد الضغط الابتدائي (1-3 bar) فان سرعه ان تشار اللهب الطباقيه للخليط سوف تقل من 2.2 m/s الى 1.5 m/s .

INTRODUCTION

Increasing concern over the fossil fuel shortage and pollution of air, and the requirements for alternative fuels for Internal Combustion Engines (ICEs) have been a major worry for the researchers. The need for sustainable energy systems has led researchers to re-evaluate the combustion process and the prospects of alternative fuels. Several studies have been conducted since the 1930s for hydrogen as an alternative fuel or as a blended fuel to improve the combustion characteristics. In particular, comprehending the combustion performance of hydrogen at varying equivalence ratios, and volumetric percentages with other fuels is essential to optimize engine operations. It is hard to define flames precisely, but the most relevant definition of flames is " visible chemical component undergoing highly exothermic chemical reaction takes place in a small zone with the evolution of heat". It is the measured rate of expansion of the flame front in a combustion reaction **Crispin (1991).** Flames can be produced in two radically different ways depending upon how the reactants are brought together, premixed and non-premixed. Each can be divided into laminar and turbulent depending on the flow regime. Both diffusion and premixed flames are used in combustion utilities for water and space heating, industrial processes, transport and electricity generation. However, while the design of the equipment to use diffusion flames is elementary, such flames produce large amounts of pollution (particularly soot) and are not easily controlled. There has been a move towards the use of premixed flames **Crispin (1991).** There are several methods for measuring the laminar flame speed. These methods are classified according to the type of flame, stationary, and non-stationary flame. This study is concerned with non-stationary flames using constant volume chamber (CVC). CVC is a pressure vessel with a spherical or cylindrical interior. Homogeneous fuel/air mixture is admitted to the vessel and ignited by two opposed thin metal electrodes create a spark at the center of the spherical space; then the flame grows spherically outwards. **Kwon et al. (2002)** stated that the outwardly propagating spherical flame is the phenomenon most relevant to spark-ignited flame propagation and accidental explosions. The first bomb to be used for measuring flame speed was constructed by **Hopkinson (1906)**. The position and temperature of the flame were measured by placing fine platinum wires across the vessel at various radii and measuring their resistance. These wires melted and so had to be replaced after each experiment. The flame speed was calculated from the time taken for the flame to pass from one wire to another, **Stephen (2010)**. **Fiock et al. (1940)** developed the technique by using a glass window with a (10") diameter bomb to film the combustion through a slit onto a rotating drum. The constant volume design can be a spherical interior or cylindrical chamber. The dimensions of the CVC changed from apparatus to another. **Hu et al. (2009)** used a cylindrical combustion chamber with an inner diameter of (180 mm) and a volume of (5.5 L). Two quartz windows with (80 mm) diameter were located at two sides of the vessel. **Mahdi Baloov et al. (2015)** used a cylindrical chamber with a diameter and length of (135 mm). Several researchers, **Gerke et al. (2010)**, **Pareja et al. (2010)**, **Pareja et al. (2011)**, **Dayma et al. (2014)** and **Alekseev et al. (2015)** have studied laminar flame speed of pure hydrogen using different methods and different techniques. They found that the laminar flame speed of stoichiometric hydrogen/air mixture at atmosphere pressure about 12 m.s^{-1} and reach to 16 m.s^{-1} in richer side of stoichiometry. Because of the growing interest in the use of hydrogen as an energy carrier, its environmental properties, and benefit from its properties. The high flame speed of H_2 led researchers to use it as a blended fuel to increase the flame speed consequently improved the combustion process.

Miao et al. (2014) used 30% of propane and 70% butane to simulate commercial standard LPG, available in Hong Kong, to investigate laminar flame speed and LBV with

H_2 enrichment of (10-90%) in volume. They found that the accelerating effectiveness is substantial when the percentage of H_2 is larger than 60%. **Ichikawa et al. (2015)** investigated experimentally, and numerically laminar flame speed and LBV of ammonia/H_2/air premixed flames at elevated pressures. The results showed that the flame speed increases with an increase the H_2 blends and decreases with an increase in the initial mixture pressure.

EXPERIMENTAL SETUP

To perform this study, an experimental facility is designed and constructed in the Mechanical Engineering Department Laboratories of Babylon University by **Yasiry, Ahmed Sh. (2016)** . The complete setup of the facility is shown in figs 1 and 2. It consists of a combustion chamber unit that have a cylindrical chamber with (190 mm) inner diameter, (250 mm) height, (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. Pressure and temperature of the combustion are recorded. The second unit (ignition circuit and control unit) is used to produce a powerful spark for supplying the power needed for the electrodes. 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-hydrogen-air mixture, a mixture preparing unit have been designed and constructed for fuels with low partial pressure according to Dalton`s law of partial pressure.
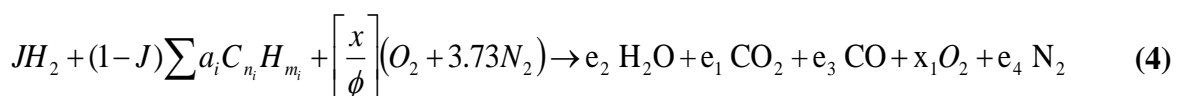
THEORETICAL ANALYSIS

Flame radius is directly measured by the schlieren photography, which shows the gradient of density inside the combustion chamber, hence indicating the location of the flame edge. The luminous front in a shadowgraph image matches the flame radius of the unburned gas. In this study, the unburned gas front radius obtained from the photograph is directly used to calculate the stretched flame speed (S_n). The stretched flame speed (S_n) is calculated using the following approach of **Bradley et al. (1998)**.

$$S_n = \frac{dr}{dt} \tag{1}$$

The stretched flame speed is calculated using a 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). Dalton's law of partial pressures indicates that the ratio of the partial pressures of the fuel and the air will be equal to their molar ratio:

$$P_f = \frac{1}{1+(\frac{4.76x}{\phi})} P_{mix} \tag{2}$$

$$x = \frac{J}{2} + (1-J)*(n+\frac{m}{4}) \tag{3}$$

$$JH_2 + (1-J)\sum a_i C_{n_i} H_{m_i} + \left[\frac{x}{\phi}\right](O_2 + 3.73N_2) \rightarrow e_2\,H_2O + e_1\,CO_2 + e_3\,CO + x_1 O_2 + e_4\,N_2 \tag{4}$$

Where J: Hydrogen fraction, ϕ: Equivalence ratio, n: No. of equivalence carbon atoms and m is no. of equivalence hydrogen atoms

The LPG used in this study is a mixture of multi hydrocarbon fuel which consist of 0.9% C_2H_6, 36.3% C_3H_8, 62.3% C_4H_{10} and 0.5% C_5H_{12}. The LPG/H_2 blends are prepared in the ratios shown in the table (1). The volumetric percentage of fuel in the table (1) are modified to represent the composition after blending with hydrogen.

RESULTS AND DISCUSSION

To give a flavor of the records being analyzed, fig 3 shows a sequence of frames of an expanding spherical flame. The first frame follows ignition with subsequent frames are approximately every (3.75 ms) apart. 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,

$$S_n = \frac{dr}{dt}\bigg|_{(j+1/2)} = \frac{r_{j+1} - r_j}{t_{j+1} - t_j} \tag{5}$$

The radius corresponding to this speed is taken to be the mean radius,

$$r_{(j+1/2)} = \frac{r_{j+1} + r_j}{2} \tag{6}$$

The data necessarily are scattered as a result of this procedure and it is difficult to perceive a clear trend and due to irregularity of flame front shape, averaging four radii versus time for each direction to calculate flame speed, is given by

$$S_n = \frac{dr}{dt} = \frac{\big((r_{j-1} - r_j) + (r_{j+1} - r_j) + (r_{i+1} - r_i) + (r_{i-1} - r_i)\big)\big/4}{t_{j+1} - t_j} \tag{7}$$

Laminar flame speed has been measured experimentally inside the CVC. The effects of hydrogen blending and equivalence ratio at different initial pressures upon the flame speed have been studied. The data used in the analysis are limited within the flame radius ranging from (5-35 mm). It can be seen from figs 4 & 5 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. **Bradley et al. (1998)]** 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). Similar elevating effect is also observed in this study. It can be seen from the figures that S_n drop with increasing flame radius from (5-10 mm) according to equivalence ratio and hydrogen blend. The flame speed calculated before in this region cannot be used 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 increase of S_n indicates that the flame is not fully developed until the radius reaches (15 mm). The radius used in the calculation are from (19-22 mm) in this study.

Prathap et al. (2008) suggested that the range of the flame radius is less than the one-third radius of the combustion bomb to be reasonable for the calculation. One-third of the inner radius of the combustion bomb used in this study is (63 mm). In this study, using a flame radius r_u of (20 mm) to compare with the other parameter because the flame speed for a fully developed flame is relatively high and approximately stable, together with the consideration of isobaric combustion. The third 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 and only from (5-35 mm) region to be study.

EFFECT OF INITIAL PRESSURE

To identify the cause for flame speed decreasing as the pressure increases. The flame temperature is insensitive to changes in pressure, then initial and final temperature will change hence the branching reactions. The effects of initial pressure on the laminar flame speed of LPG-air mixture blends with H_2 for different equivalence ratios are demonstrated in fig 4 and 5. Fig 6 presents the flame speed at (20 mm) flame radius for difference hydrogen blends and initial pressure. The effect of hydrogen on flame speed becomes more obvious at blending ratio higher than (60%). The results also show that the flame speed decreases with increasing pressure for any stoichiometry; which is in qualitative agreement with the previously reported behavior for all types of fuel as presented by **Tang et al. (2008)**.

EFFECT OF STOICHIOMETRY AT ATMOSPHERIC PRESSURE

The experimental flame speed versus stoichiometry limits is illustrated in fig 7 for LPG with many hydrogen blending ratios at atmosphere pressure. The figure 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. The figure shows that the stoichiometric mixture for any blend of hydrogen has the higher flame speed than lean or rich mixtures. For the lean and stoichiometric mixture, there is enough oxygen to burn the fuel completely and hence, all the heat is released. At stoichiometric mixture flame is just enough oxygen to burn the fuel and no excess air, and then the flame temperature should be theoretically maximum and hence flame speed. However, due to the mixing processes, the maximum temperature is attended at equivalence ratio between (1.10-1.15) hence the flame speed. On the rich side, the flame temperature drops due to incomplete combustion and dissociation and hence flame speed. It is also noticed from the fig7 that the flame speed at (ϕ=1.3) is higher than that at (ϕ=0.8) for blending ratio less than (60%). For blending ratio higher than (60%), the flame speed at (ϕ=0.8) is greater than that at (ϕ=1.3) because of the effect of adiabatic flame temperature .

EFFECT OF HYDROGEN BLEND AT ATMOSPHERIC PRESSURE

The experimental flame speed versus radius data is plotted for various hydrogen blends in fig 9.a. 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. The flame speed decreases, as the flame grows larger until the radius becomes (10 mm) then it almost remains constant. This drop is more clear at H_2 blending higher than (60%). It develops significant since H_2 becomes the main fuel that has a minimum ignition energy of (0.017 MJ) while propane and butane have a minimum ignition energy of (0.26 MJ) for each. The excess energy released would cause this behavior. It is worth noting that under the stoichiometric condition either at atmosphere pressure fig 9.a or elevated pressure figs 4.b and 5.b, the ignition energy results in an initial flame speed significantly higher than that of the steady flame speed for the LPG-H_2 flames with increasing H_2 blends. The variation of S_n with hydrogen blends for various initial pressure is plotted in fig 9.b. It shows that the flame speed increases with the increase of the blends of hydrogen for all the initial pressure.

CONCLUSIONS

1- A new experimental apparatus has been built for the measurement of the laminar flame speed of the LPG-H_2-air mixture during the pre-pressure period of combustion over a range of equivalence ratios and at different initial pressures.

2- Experiments are conducted to study the laminar flame speed of LPG at various hydrogen blends under varying initial pressure of 0.1-0.3 MPa and an initial temperature of 308 K.

3-The early stage propagation features of LPG and LPG-H_2 flames were compared. Hydrogen addition accelerates the laminar flame speed of LPG flames for all equivalence ratios.

4-The effect is more evident when hydrogen blending ratio is larger than 60%. A small amount of LPG results in a strong decelerating effect on hydrogen fuel. 20% LPG decreases the laminar flame speed to 64% of the flame speed for pure hydrogen.

5-The maximum value of laminar flame speed is at the lowest initial pressure and with increasing the initial pressure, the laminar flame speed decreases.

Table 1: Tested Fuel Blends.

Fuel % (vol.)					Stoichiometric air/fuel ratio (vol.)
H_2 %	C_2H_6 %	C_3H_8 %	C_4H_{10} %	C_5H_{12} %	
0	0.9	36.3	62.3	0.5	28.25
20	0.72	29.04	49.84	0.4	23.08
40	0.54	21.78	37.38	0.3	17.91
60	0.36	14.52	24.92	0.2	12.73
80	0.18	7.26	12.46	0.1	7.56

Fig 1   Photograph of The Experimental Apparatus Used in The Study
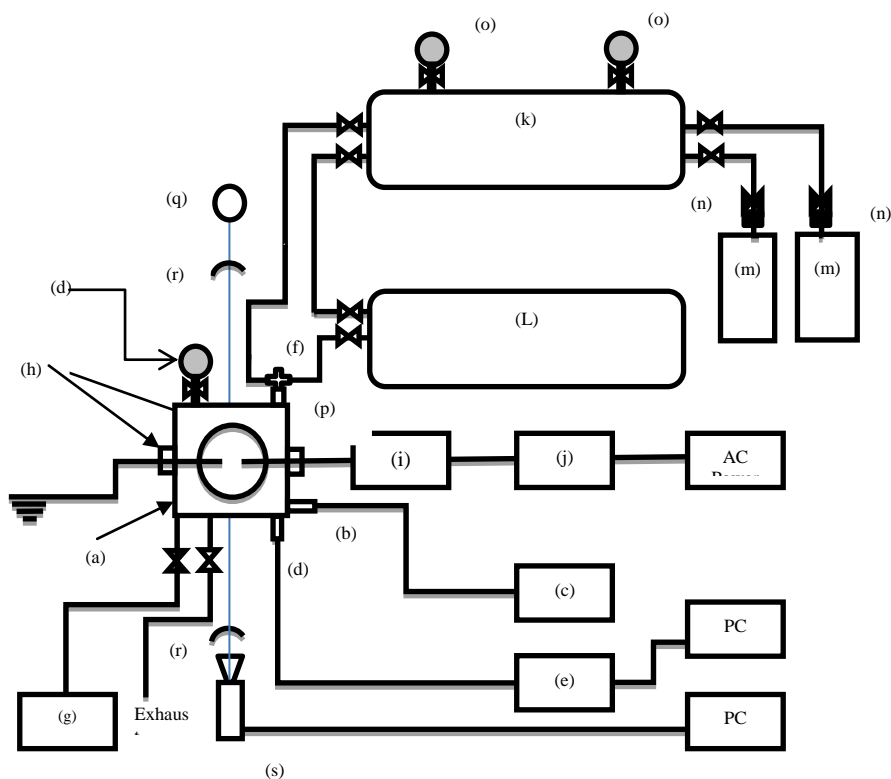
Fig 2 : Schematic Layout for Experimental Setup

 i. **Combustion Chamber Unit:- (a)** Combustion Chamber, **(b)**Thermocouple,

 ii. **(c)** Temperature Recorder, **(d)** Pressure Gauge, **(e)** Data Logger,

 iii. **(f)** Safety Valve and **(g)** Vacuum Pump.

 iv. **Ignition Unit:- (h)** Electrodes**,**

 v. **(i)** Ignition System and

 vi. **(j)** Control System and Switch.

 vii. **Mixture Preparing Unit:**- **(k)** Mixer, **(L)** Air Compressor,

 viii. **(m)** H2 and Fuel Storage Tank, **(n)** Pressure Regulator,

 ix. **(o)** Initial and Total Pressure Gauges and **(p)** Flame Trap**.**

 x. **Capturing Unit:- (q)** Light Source, **(r)** Lenses and **(s)** High-Speed Camera.

(a)

40%
H_2

60%
H_2

80%
H_2

(b)

$\Phi=0.8$ $\Phi=1$ $\Phi=1.3$
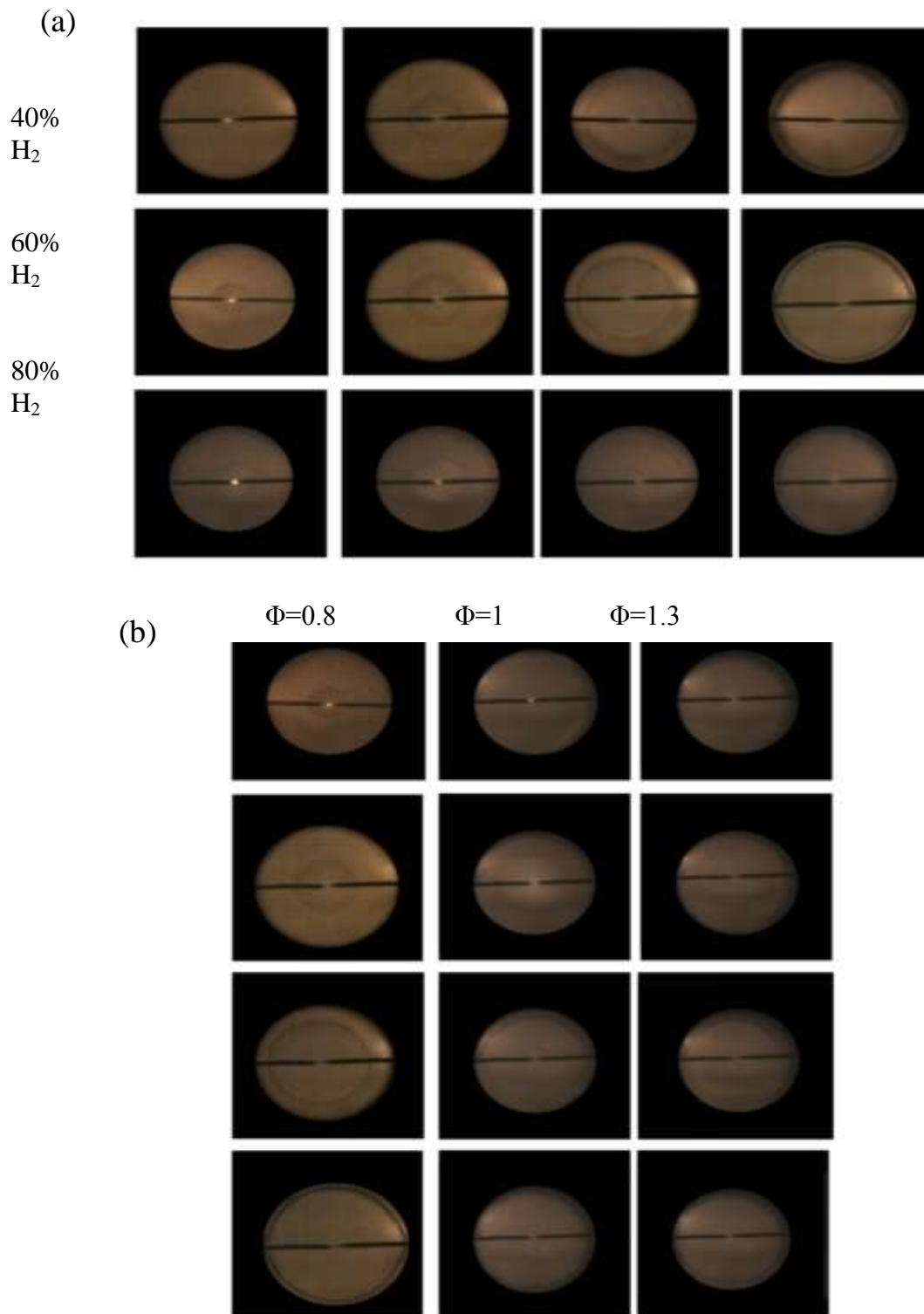
Fig 3: Photographs of Flame Propagation for Initial Pressure 3 bar
with time intervals of 3.75 ms for,
   a- Different Hydrogen Blend at Equivalence Ratio 0.8.
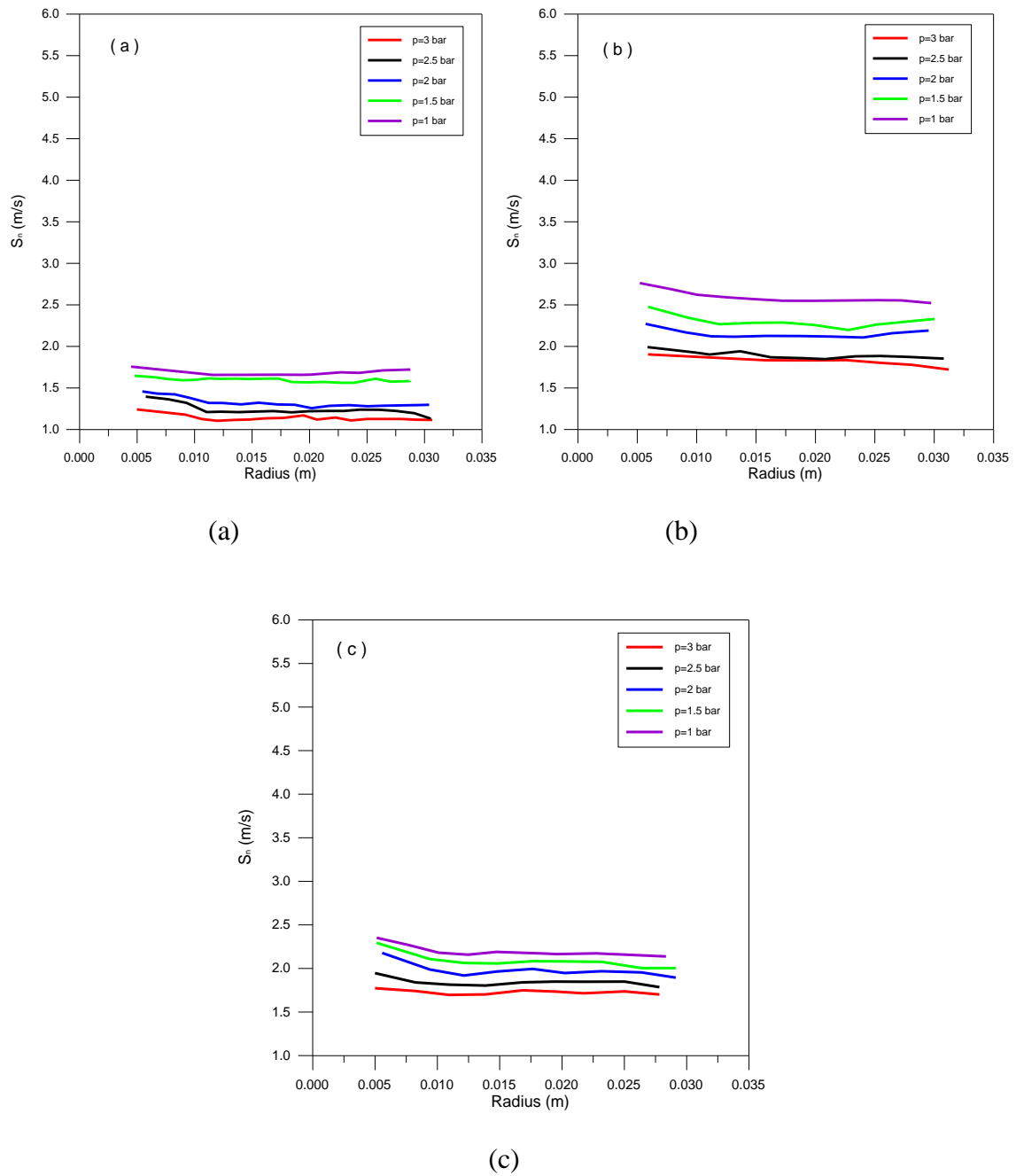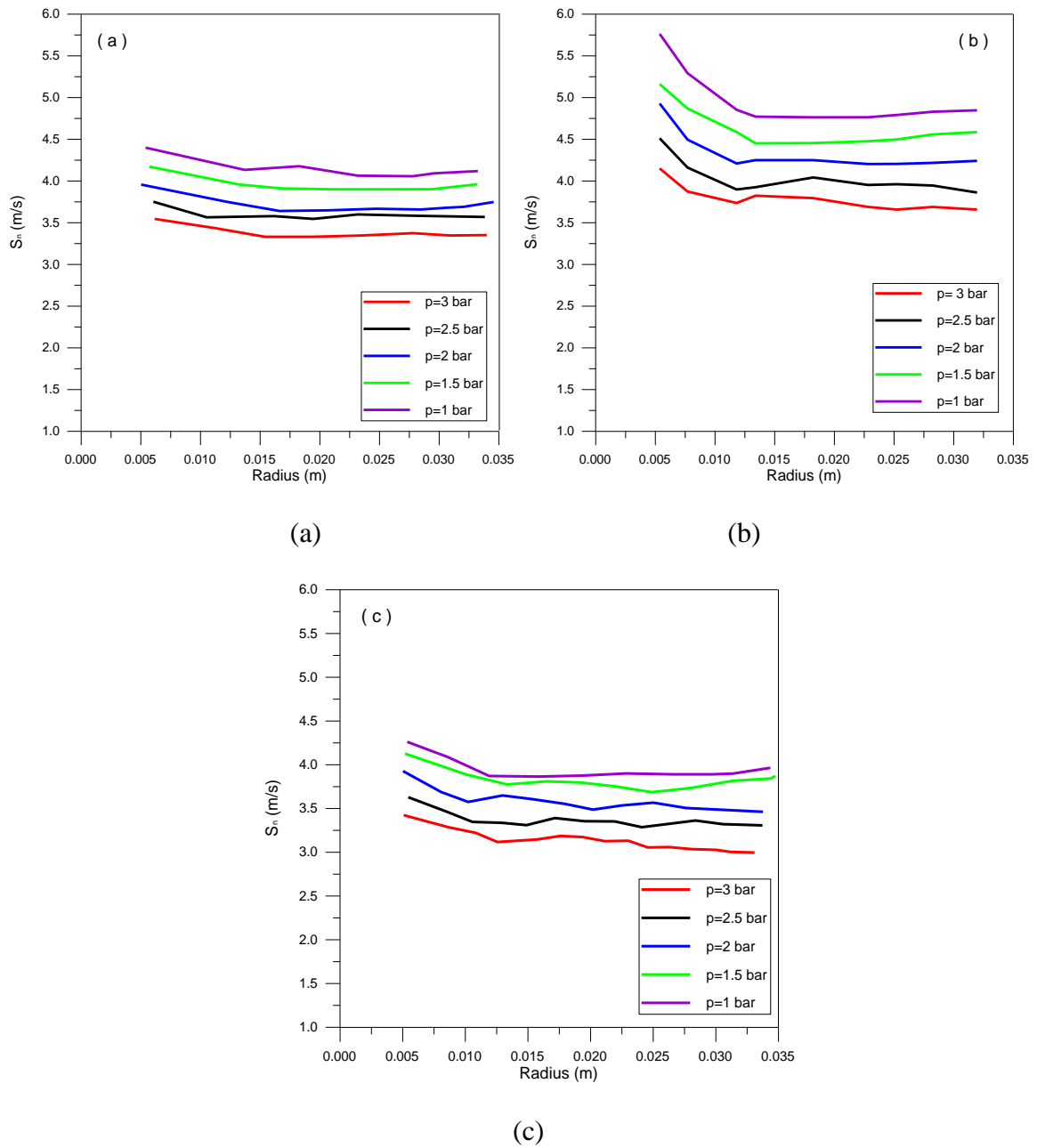   **b-** Different Equivalence Ratio for 60% H_2.

(a)

(b)

(c)

Fig 4 : Variation of Stretched Flame Speed (S_n) with Flame Radius for 20% Hydrogen
blend for Various Equivalence Ratios (a) for ϕ=0.8, (b) for ϕ=1 and (c) for ϕ=1.3
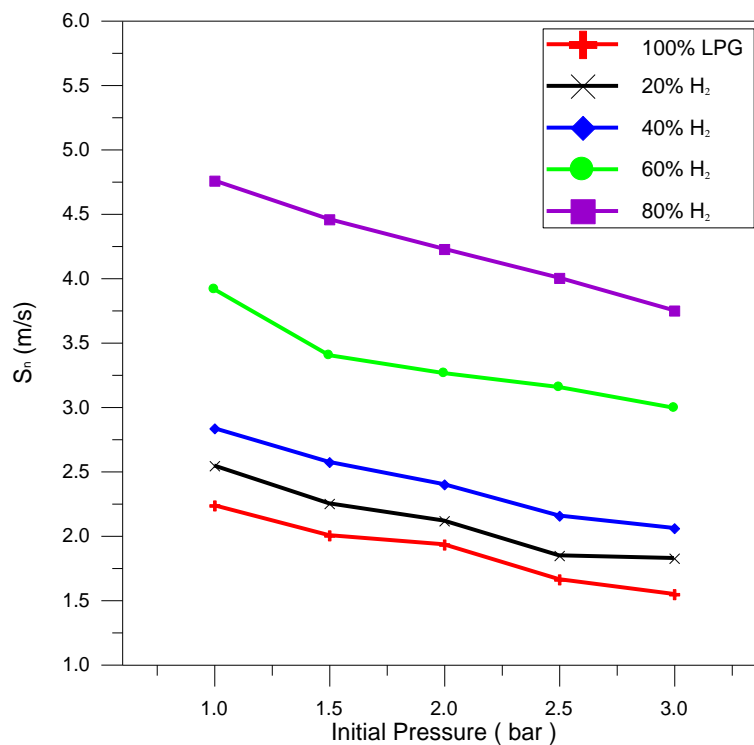
(a)

(b)

(c)

Fig 5 : Variation of Stretched Flame Speed (S_n) with Flame Radius for 80% Hydrogen blend for Various Equivalence Ratios (a) for ϕ=0.8, (b) for ϕ=1 and (c) for ϕ=1.3

Fig 6 Variation of S_n with Initial Pressures for LPG with Various Hydrogen
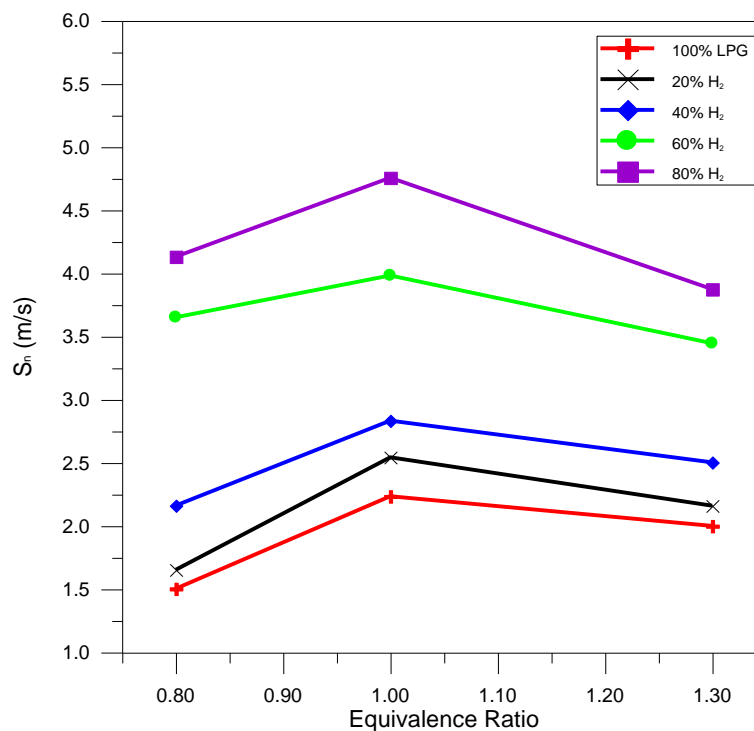Percentages at Equivalence Ratio (ϕ =1) at Flame Radius of 20 mm.

Fig 7 Variation of S_n with Equivalence Ratios for LPG with Various Hydrogen
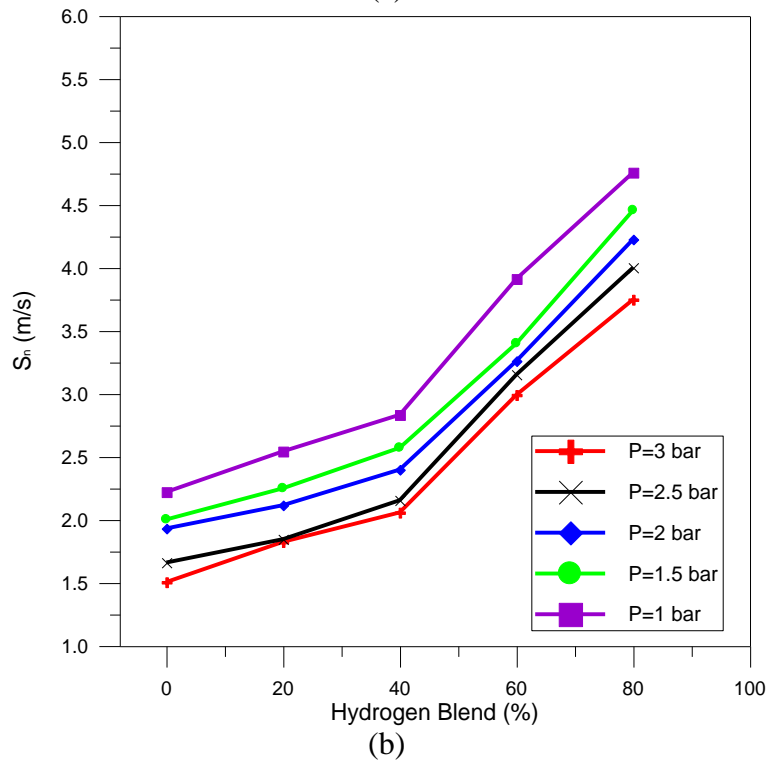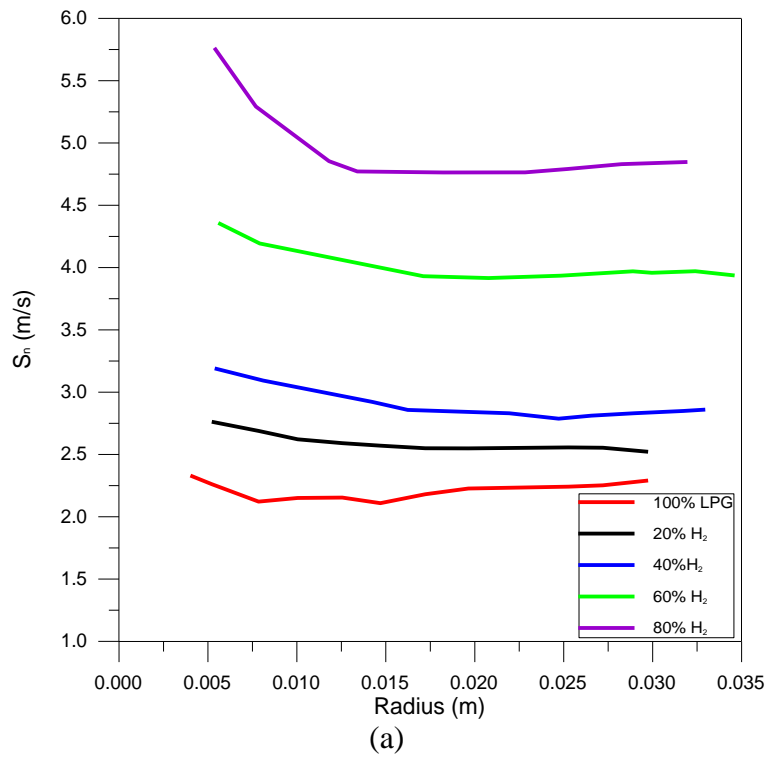Percentages at (20 mm) Radius and Atmosphere Pressure.

Fig 8 : Variation of S_n with **a)** Flame Radius for LPG with Various Hydrogen Blends for Stoichiometric Mixture (ϕ=1) at Atmosphere Pressure **b)** Hydrogen Percentages at Equivalence Ratio=1 at (20 mm) Radius and different initial Pressure

REFERENCES

Taylor, Simon Crispin, Burning velocity and the influence of flame stretch, unpublished Ph.D. thesis, Department of Fuel and Energy University of Leeds, UK, 1991.

Yasiry, Ahmed, Sh. , "Experimental Study of the Effect of Hydrogen Blending on Burning Velocity of Different Fuels", unpublished MSc thesis, Department of Mechanical Engineering, College of Engineering, University of Babylon, Babylon , Iraq, 2015.

Kwon, O. C., Rozenchan, G., and Law, C. K., "Cellular instabilities and self-acceleration of outwardly propagating spherical flames", In Proceedings of the Combustion Institute, Vol. 29, Pp. 1775-1783, 2002.

Marshall, Stephen P., "Measuring Laminar Burning Velocities", unpublished Ph.D thesis, University of Oxford, Uk, 2010.

Fiock, E. F., Marvin, Jr, C. F., Caldwell, F. R., and Roeder, C. H., "Flame speeds and energy considerations for explosions in a spherical bomb" National Advisory Committee on Aeronautics Report NACA-TR-682, 1940.3

Erjiang Hu, Zuohua Huang, Jiajia He and Haiyan Miao, "Experimental and numerical study on laminar burning velocities and flame instabilities of hydrogen-air mixtures at elevated pressures and temperatures", International Journal of Hydrogen Energy, Vol. 34, Pp. 8741-8755, 2009.

Mahdi Baloo, Bijan Mollaei Dariani, Mehdi Akhlaghi and Iman Chitsaz, "Effect of iso-octane/methane blend on laminar burning velocity and flame instability", Fuel, Vol. 144, Pp. 264-273, 2015.

U. Gerke, K. Steurs, P. Rebecchi and K. Boulouchos, "Derivation of burning velocities of premixed hydrogen/air flames at engine-relevant conditions using a single-cylinder compression machine with optical access ", International Journal of Hydrogen Energy, Vol. 35, Pp. 2566-2577, 2010.

Jhon Pareja, Hugo J. Burbano and Yasuhiro Ogami, "Measurements of the laminar burning velocity of hydrogen-air premixed flames", International Journal of Hydrogen Energy, Vol. 35, Pp. 1812-1818, 2010.

Jhon Pareja, Hugo J. Burbano, Andre´s Amell and Julia´n Carvajal, "Laminar burning velocities and flame stability analysis of hydrogen/air premixed flames at low pressure", International Journal of Hydrogen Energy, Vol. 36, Pp. 6317-6324, 2011.

Guillaume Dayma, Fabien Halter and PhiliPp.e Dagaut, "New insights into the peculiar behavior of laminar burning velocities of hydrogen-air flames according to pressure and equivalence ratio", Combustion and Flame, Vol. 161, Pp. 2235-2241, 2014.

Vladimir A. Alekseev, Moah Christensen and Alexander A. Konnov, "The effect of temperature on the adiabatic burning velocities of diluted hydrogen flames: A kinetic study using an updated mechanism", Combustion and Flame Vol. 162, Pp. 1884-1898, 2015.

J. Miao, C.W. Leung, Zuohua Huang, C.S. Cheung, Huibin Yu and Yongliang Xie, "Laminar burning velocities, Markstein lengths, and flame thickness of liquefied petroleum gas with hydrogen enrichment", International Journal of Hydrogen Energy, Vol. 39, Pp.1302-13030, 2014.

Akinori Ichikawa, Akihiro Hayakawa, Yuichi Kitagawa, K.D. Kunkuma Amila Somarathne, Taku Kudo and Hideaki Kobayashi, "Laminar burning velocity and Markstein length of ammonia/hydrogen/air premixed flames at elevated pressures", International Journal of Hydrogen Energy, Vol. 40, Pp. 9570-9578, 2015.

Bradley, D., Hicks, R. A., Lawes, M., Shepp.ard, G. W., and 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", Combustion and Flame, Vol. 115, Pp. 126-144, 1998.

Prathap C, Ray A and Ravi MR., "Investigation of nitrogen dilution effects on the laminar burning velocity and flame stability of syngas fuel at atmospheric condition", Combustion and Flame,.Vol. 155, Pp. 145-160, 2008.

Chenglong Tang, Jiajia He, Zuohua Huang, Chun Jin, Jinhua Wang, Xibin Wang and Haiyan Miao, "Measurements of laminar burning velocities and Markstein lengths of propane-hydrogen-air mixtures at elevated pressures and temperatures", International Journal of Hydrogen Energy, Vol. 33, Pp.7274-7285, 2008.