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Research Article

An Experimental Study for Investigating the Laminar Flame Speed and Burning Velocity for LPG

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Abstract

An experimental study on laminar burning velocity of the premixed Iraqi liquefied petroleum gas (LPG)/ air flames was conducted in a centrally ignited constant volume chamber at different initial pressures (0.1-0.3 MPa) and initial temperature of (308 K). Besides, the tested equivalence ratios of air/fuel mixture range from (0.8 - 1.3). Experimental data of laminar burning velocity, stretch rate and laminar flame speed of LPG flames have been presented. The constant volume chamber has been designed and constructed by authors, as this method considered the most accurate one to measure laminar burning velocity. A mixing chamber, ignition control, data acquisitions and high-speed schlieren photography were used. The adiabatic flame temperature used in predicting the burning velocity was calculated theoretically by a FORTRAN program built to find also the physical properties of reactance and expected product mixtures and compared the results with other software and previously published results. Experimental results showed that the adiabatic flame temperature increases toward stoichiometry and maximum value in slightly rich side, the laminar flame speed of LPG and laminar burning velocity decrease with increasing initial pressure for any stoichiometry. Increasing initial pressure range (1-3 bar), stretched laminar flame speed of LPG-air mixture decreases from (2.2-1.5 m/s) and laminar burning velocity also decreases from (31-20 cm/s). Correlations for initial pressure are derived for fuel–air mixtures.

Keywords: *Premixed, adiabatic flame temperature, laminar burning velocity, laminar flame speed, liquefied petroleum gas, LPG, high-speed camera, schlieren photography, constant volume chamber, stretch rate.*

1. 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.

The fuel used in the study is liquefied petroleum gas (LPG) which consists mainly of butane and propane. Being one of the primary energy sources used for domestic and commercial applications, LPG is prepared by refining petroleum or wet natural gas and is almost entirely derived from fossil fuel sources. Being manufactured during the refining of crude oil, , LPG has many advantages such as higher heating value, virtual absence of Sulphur, leading to cleaner burning with low ash, a complete burning process and less carbon generation and less corrosion and engine wear because LPG burns in the engine in the gaseous phase and stable flame. However, the drawbacks of LPG include that the boiling point is below room temperature, the low vapor pressure of LPG at low temperatures could hinder starting in cold conditions, lower energy density per unit volume, it still emits a significant number of carbon dioxides (CO_2) and unburned hydrocarbon (HC) during combustion, both causing serious environmental problem and narrow flammability range of LPG is also a negative factor and significantly limits the application of LPG.

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

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*Corresponding author: **Ahmed Sh. Yasiry** 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, (Marshall S., 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).

There are some factors affecting on burning velocity and flame speed such as fuel type. Other factor is the enthalpy of combustion of the fuel, since this affects the adiabatic flame temperature where the temperature has the greatest effect on burning velocity (Marshall S, 2010). (Bradley *et al.*, 1991) found that for lean mixtures of the same chemical group, the burning velocity varied approximately linearly with the heat of reaction per kilo mole of the mixture. Two major studies of burning velocity across a broad range of fuels have been made. (Davis and Law, 1998) tested alkanes, alkenes, alkynes, aromatics and oxygenates and also (Farrell *et al.*, 2004) tested a similar range of fuels.

Initial Pressure effects on laminar flame speed and burning velocity is which is fairly weak inverse dependence on flame speed. Several researchers find an empirical equation about the relation between initial pressure and flame speed or burning velocity such as (Turns, 1996) , (Salih, Adil, M, 2006) and (Hu *et al.*, 2009) also provided flame speed/pressure correlation for selected fuels.

2. 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 figures (1) and (2). It consists of a combustion chamber unit that have a cylindrical chamber with (190mm) inner diameter, (250mm) 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. 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 (5ms). 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 designed and constructed. Mixing Processes are based on Dalton`s law of partial pressure. The procedure of preparation is explained by (Yasiry, Ahmed Sh., 2016).

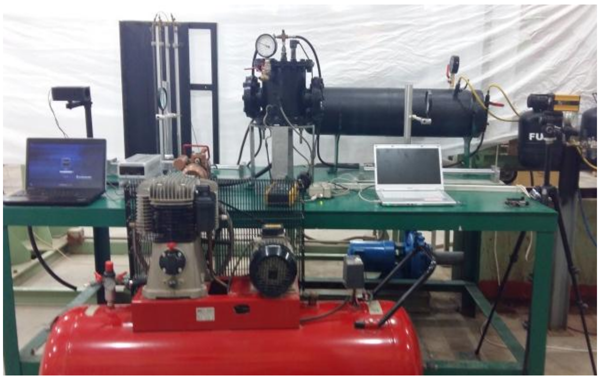
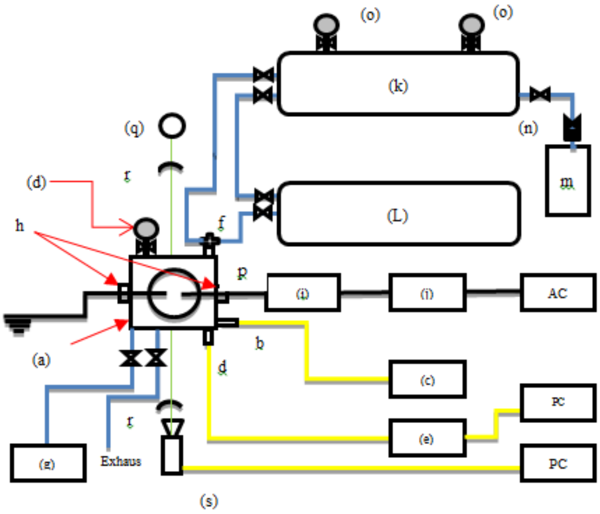


Fig.1 Photograph of the experimental apparatus used in the study



i. Combustion chamber unit:- (a) Combustion chamber, (b)Thermocouple, (c) Temperature recorder, (d) Pressure gauge, (e) Data logger, (f) Safety valve (g) vacuum Pump ii. Ignition unit:- (h) Electrodes, (i) Ignition system (j) Control system and switch. iii. Mixture preparing unit:- (k) Mixer, (L) Air compressor, (m) Fuel storage tank, (n) Pressure Regulator, (o) Initial and total pressure gauges (p) Flame trap. iv. Capturing unit :- (q) Light source, (r) Lenses (s) High-speed camera

Fig. 2 Schematic Layout for Experimental Setup

3. Theoretical Analysis

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:

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

$$\sum a_i C_{n_i} H_{m_i} + \left[\frac{x}{\phi}\right](O_2 + 3.73N_2) \rightarrow e_2\ H_2O + e_1\ CO_2 + e_3\ CO + x_1 O_2 + e_4\ N_2 \tag{2}$$

The LPG 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} (Yasiry, Ahmed Sh. ,2016). 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 researchers.

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). 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,

$$S_n = \frac{dr}{dt} = \frac{r_{j+1} - r_j}{t_{j+1} - t_j} \tag{3}$$

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

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

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). A general definition of a stretch at any point on the flame surface is the Lagrangian time derivative of the logarithm of area (A) of any infinitesimal element of the surface.

$$\alpha = \frac{d(\ln A)}{dt} = \frac{1}{A}\frac{dA}{dt} \tag{5}$$

For the outwardly propagating spherical flame, the flame stretch rate can be deduced in the following form,

$$\alpha = \frac{1}{A}\frac{dA}{dt} = \frac{2}{r_u}\frac{dr_u}{dt} = \frac{2}{r_u}S_n \tag{6}$$

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

$$S_l - S_n = L_b\alpha \tag{7}$$

The unstretched propagation speed, S_l, can be obtained as the intercept value at α =0, in the plot of S_n against α. The burned gas Markstein length, L_b, is the negative slope of S_n-α a fitting curve (Hu *et al.*, 2009). Markstein length can then be defined as the decrease in burning velocity per unit stretch. The unstretched laminar burning velocity, u_1, is related to S_1 through the mass conservation across the flame front.

$$A\rho_b S_l = A\rho_u u_l \tag{8}$$

Where A is the flame front area, ρ_u and ρ_b are the unburned and burned gas densities, respectively. The unstretched laminar burning velocity, can be obtained from equation (8) (Miao *et al.*, 2014).

$$u_l = S_l \frac{\rho_b}{\rho_u} \tag{9}$$

2. Results and Discussion

To better understand the effect of equivalence ratio on the properties of a fuel, the adiabatic flame temperature and density ratio are calculated and plotted against equivalence ratio as shown in the fig. (3). The maximum value of flame temperature is on the rich side of the mixture and not at the correct mixture as the results of neglecting dissociation effect. The density ratio is inversely proportional to the temperature, so when the combustion process occurs, the density of mixture decreases with increasing the temperature. The minimum density ratio occurs in slightly rich limits due to the effect of temperature of final products.

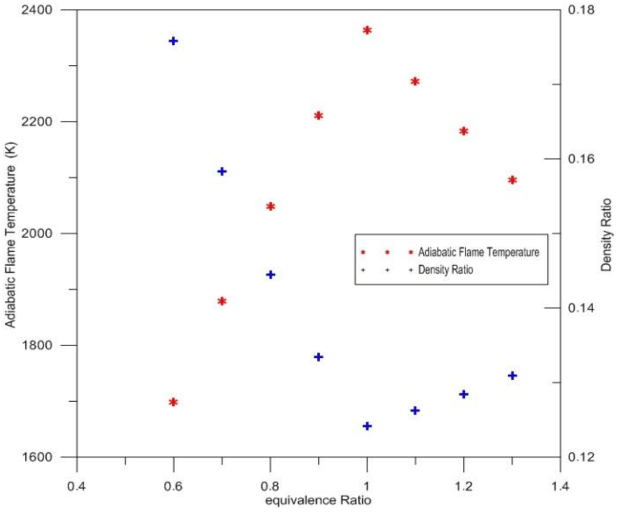
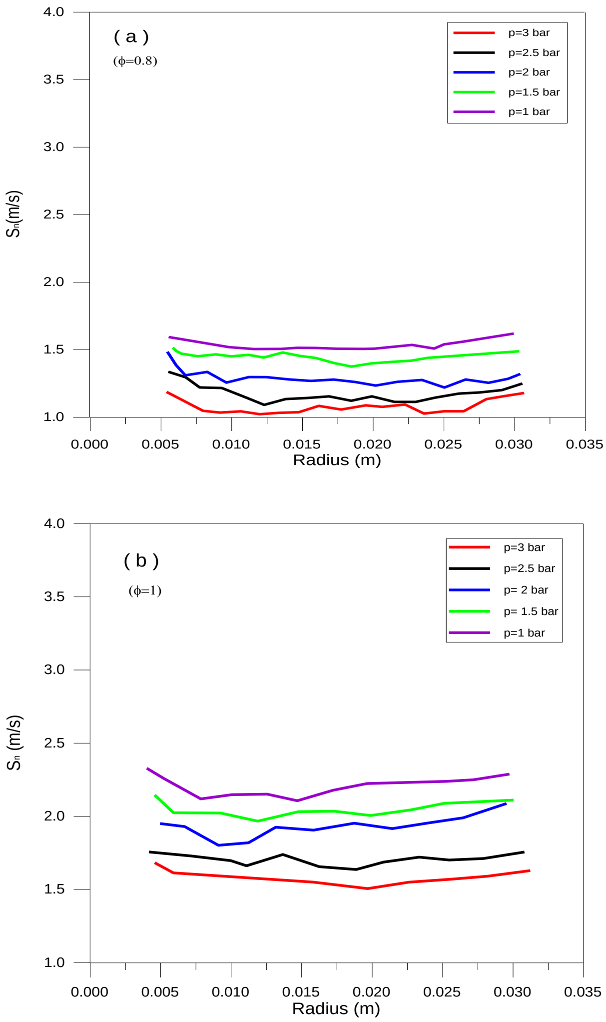


Fig.3 Calculated adiabatic flame temperature and density ratio for LPG at T_0 = 308K and p_0 = 1 bar

It can be seen from Fig. (4) 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. 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 effect of ignition energy, and the subsequent gradual increase of S_n indicates that the flame is not fully developed until the radius reaches (15 mm). The third region when flame radius exceeds (35mm), when the strain in flow field would notably reduce flame speed and the effect of combustion pressure. The first and third region are not considered in the calculation.

Fig. (4) also shows the stretched flame speed with flame radius at different initial pressures and equivalence ratios. As expected, the figure shows that the stretched flame speed decreases with increase initial pressure. The figure also shows that the stretched flame speed peaks at stoichiometric mixture.

stretch is inversely proportional to the radius as shown in equation (6), so its effect decreases as the flame grows. This would be expected on very general grounds as the radius increases, the flame becomes less curved and more like a planar, one-dimensional and, therefore, unstretched flame. The stretch rate has very high values during the initial stages of combustion due to 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.



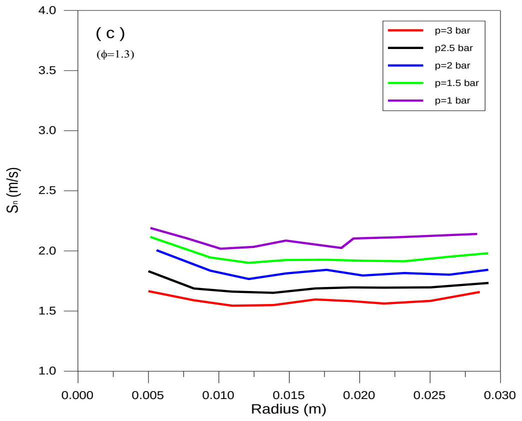
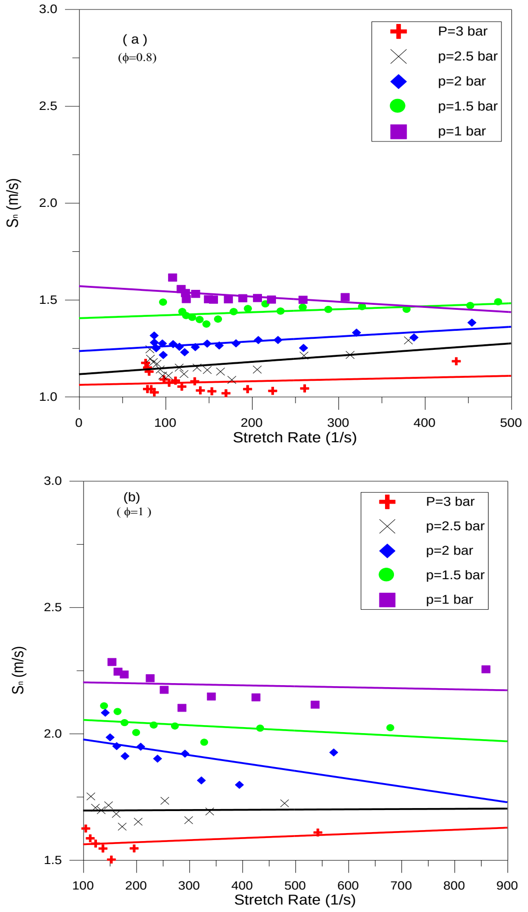


Fig. 4 Variation of stretched flame speed (s_n) with flame radius for LPG for various equivalence ratios

The unstretched flame propagation speed, S_l, is obtained as the intercept value of S_n at α=0 in the plot of S_n versus α. Importantly, this gives the value of laminar burning velocity u_l from equation (7). The sharp decrease of S_n in small stretch rate is due to the strain in the flow field, and the sharp increase of S_n in small stretch rate indicates the occurrence of the cellular flame. Considering the influences of spark, cellular flame, and flow field strain, only flame radius from (8-30 mm) are used in the calculations. It can be seen from Fig. (5) that the maximum stretch occurs at minimum initial pressure and the maximum value of flame speed occurs at the stoichiometric mixture. The slope of S_n with a stretch rate almost negative.



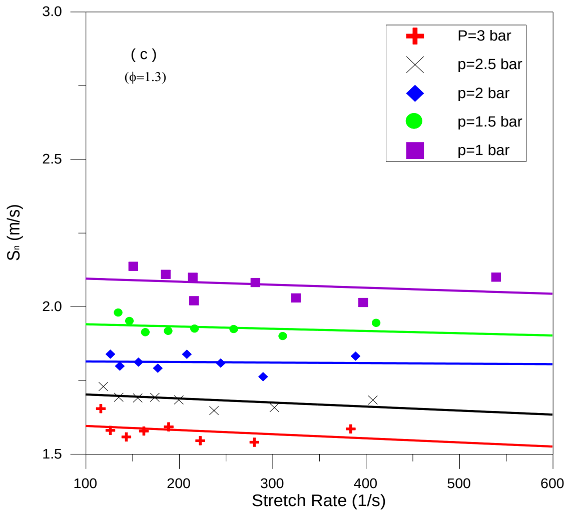


Fig. 5 Various of stretched flame speed (s_n) with stretch rate for LPG for various equivalence ratios

Fig. (6) indicates that the results of unstretched laminar flame speed show that for a specific equivalence ratio and different initial pressure, the value of S_l decreases with increasing initial pressure. The unstretched flame speed increases highly towards stoichiometry because of the flame temperature increases hence flame speed.

Laminar burning velocity is an important parameter of a combustible mixture because it contains the basic information regarding its diffusivity, exothermicity and reactivity. The laminar burning velocity depends on the fuel type, temperature and pressure of the initial mixture and the equivalence ratio. The propagation of flame is due to heat transfer from the flame front by radiation, convection and conduction, to the unburned gases.

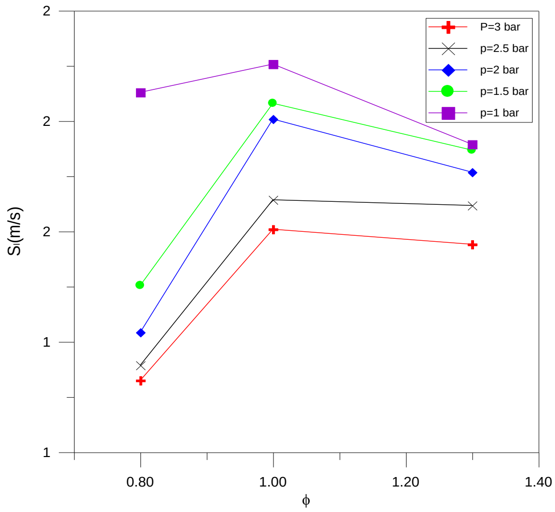


Fig. 6 Unstretched flame speed (Sl) with equivalence ratio for 100% LPG for various initial pressure

Fig. (7) show the variation of burning velocity with equavilance ratio at different initial pressures. It is observed that the trend of variation in burning velocity with equivalence ratio is similar to the results of flame speeds with the same condition. It appears that burning velocities of LPG-air mixture decrease with initial pressure increase. It has concluded that maximum laminar burning velocity occurs at stoichometric mixture because of the effect of flame temperature.

The present results is represented by the following emperical exponential equation which is valid for stoichomertic mixture in the initial pressure range for 1-3 bar with a regression analysis (R-squared) for equations of fitting curve is 0.947844.

$$u_l(p) = \exp(-0.202804 \times P) \times 36.9441 \qquad (10)$$

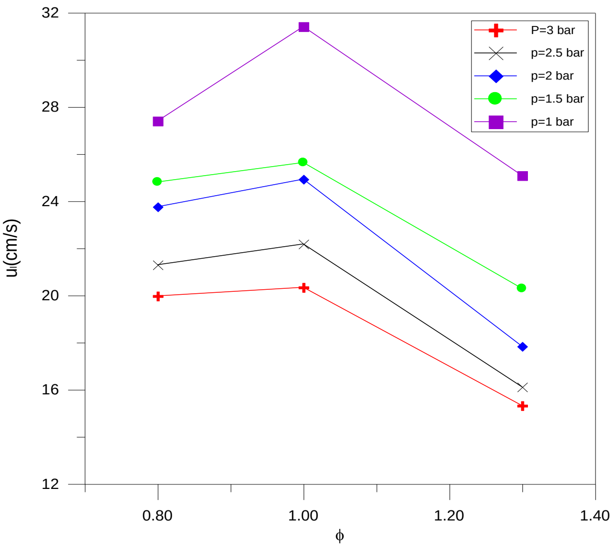


Fig.7: Laminar Burning Velocity (ul) with Equivalence Ratio for 100% LPG for Various Initial Pressure

Some comparison for experimental rig and written program are made before by (Yasiry, Ahmed, Sh., 2016) to make sure the physical and procedure of experimental are valid to use. Fig. (8) shows comparison between experimental results and previous researches for methane.

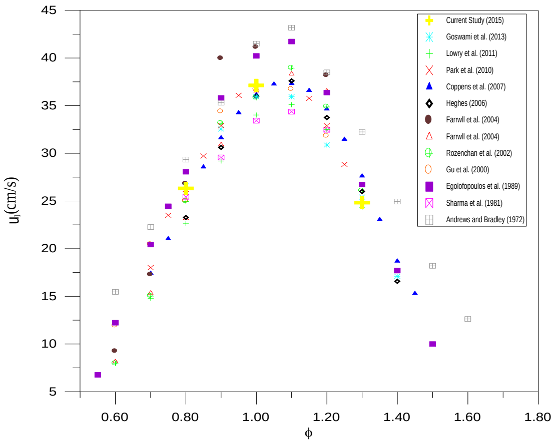


Fig. 8 Comparison of Experimental Data for The Burning Velocity of Methane at T_0 = 298 K and p_0 = 1 bar with The Data Obtained from **[33 & 83]**

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

Researcher, technique	C_2H_6	C_3H_8	C_4H_{10}	C_5H_{12}	C_nH_m	
					n	m
Miao *et al.*, CVC	0	1	0	0	3	8
Chakraborty *et al.*, FBT	1.4	30.1	67.7	0	3.639	9.262
Salih, CVT	3.33	57.08	38.35	1.24	3.375	8.75
Huzayyin *et al.*, CVC	0.04	26.41	73.54	0	3.734	9.468
Miao *et al.*, CVC	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	0	0	1	0	4	10

Figure (9) compares the laminar burning velocities of butane, propane, fuel at difference composition according to the table (1). The LBV of butane is higher than those of propane, and LPG, especially under the stoichiometric and fuel-rich conditions.

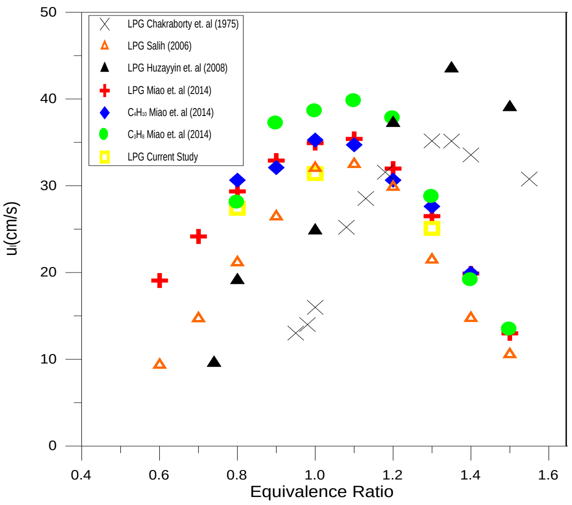


Fig. 9 Laminar Burning Velocity Versus Equivalence Ratio for Different Fuel Mixtures at Atmosphere pressure

Conclusions

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

2-Experiments are conducted to study the laminar burning velocity of LPG under varying initial pressure of 0.1-0.3 MPa and different equivalence ratios at temperature of 308 K.

3-Correlations between variables are derived for LPG-air mixtures.

4-The maximum value of laminar burning velocity is at the lowest initial pressure and with increasing the initial pressure, the laminar burning velocity decreases.

5-Equivalence ratio has a notable influence on laminar burning velocity of LPG and it became maximum at stoichiometric mixture.

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