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A Numerical And Experimental Analysis Of Laminar Flame Speed For Pre-Mixed Iraqi Lpg/Air Mixture In A Horizontal Cylindrical Combustion Chamber

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ABSTRACT: In the present work, a numerical and an experiential study is performed to obtain the laminar flame speed for premixed Iraqi LPG-air mixture at different equivalent ratios ranging from 0.6 to 1.4 in a horizontal cylindrical combustion chamber. A horizontal Pyrex cylindrical with dimension (1300 mm) length with (180mm) diameter is used as combustion chamber. The entrance of fuel/air mixture and the ignition source are located at one end of the cylinder while the other end is left open. A high-speed camera is used to record the flame propagation through the cylinder. These videos are then analyzed using Tracker program to obtain the laminar flame propagation speed. Also the Chemkin USC mech 2.0 is used to predict numerically the flame speed. Both experimental and numerical results show that the flame speed increases with equivalence ratio and reaches its maximum value at stoichiometric ratio and decreases as the mixture becomes richer. The study also includes a numerical analysis of the effect of propane/butane ratio on the flame speed. The result shows that high propane ratio enhances flame speed.

KEYWORDS: Laminar flame speed, Flame propagation, Propane/butane, LPG-air mixture combustion, Chemical-kinetics mechanism, Adiabatic flame temperature

INTRODUCTION

In a combustion reaction, the speed of flame is the measured rate of flame front expansion. Although flame velocity is commonly used for fuel, the explosive velocity is a related concept, which for an explosive is calculated in the same relation. Combustion engineers distinguish the speed of laminar flame from the turbulent flam. A study analyzed with the help numerical simulations the experimental work of the centrally ignited expanding flame in constant volume chamber used to study the flame front propagation and assumptions involved during data interpretation [1]. The results concluded that stretch had insignificant effects during the compression stage of the experiment for a wide range of Lewis number. The results also confirmed that the flame radius has large impact on laminar flame speed thus stressing the requirement that the modeling of flame radius needs to be performed accurately by accounting properly for product dissociation, under equilibrium conditions, and thermal radiation from the burned gases. The laminar flame speeds were measured many hydrocarbon fuel flames for 8–30 atm pressures and 400–520 K unburned mixture temperatures. Recent studied the laminar flame velocity of propane (C_3H_8) in O_2/CO_2 atmosphere, both numerically and practically [2]. The laminar flame speed was measured at normal pressure and temperature using a Bunsen flame under specified equivalent ratios and O_2 concentrations. It was found that with increasing the intensity an O_2 concentration the laminar flame speed slowly increased. the equivalent ratio for the highest laminar flame speed is between 1.0 and 1.1. The high concentration of carbon dioxide reduced the propagation of the flame. The study were carried out to explore the effects of carbon dioxide on the laminar flame speed. These effects are attributed to physical chemical characteristics of CO_2. The results showed that the effect of physical characteristics of CO_2 is more significant than the chemical characteristics. They analyzed the flame of a laminar flow in Bunsun burner using optical methods such as OH chemiluminescence or streak photography. It was assumed, in the first method, that the burning velocity is uniform all over the flame surface [3]. The laminar flame speed was then be determined using the mass conservation principle:

$$\rho_u \times S_l \times A = \rho_u \times \dot{Q} \rightarrow S_l = \dot{Q}/A \quad (1)$$

Where

ρ_u: the density of the unburned mixture, $\dot{Q}$: unburned mixture volume flow rat,

S_L: laminar flame speed, A: flame surface area.

The area of the flame was obtained by inspecting the photographs of the flame using different programs as shown in (Figure 2.1).

In the second method, the flame cone angle was calculated and used to obtain the flame velocity (Figure 2.2). This method is suitable for straight sided flames and requires aerodynamically contoured nozzles. It is assumed that the mixture supply speed at the nozzle exit is uniform and the laminar flame speed is then calculated as,

$$\text{COS}\left[\frac{\pi}{2}-\alpha\right]=\frac{S_L}{S_u} \rightarrow S_l=S_U\sin(\alpha) \quad (2)$$

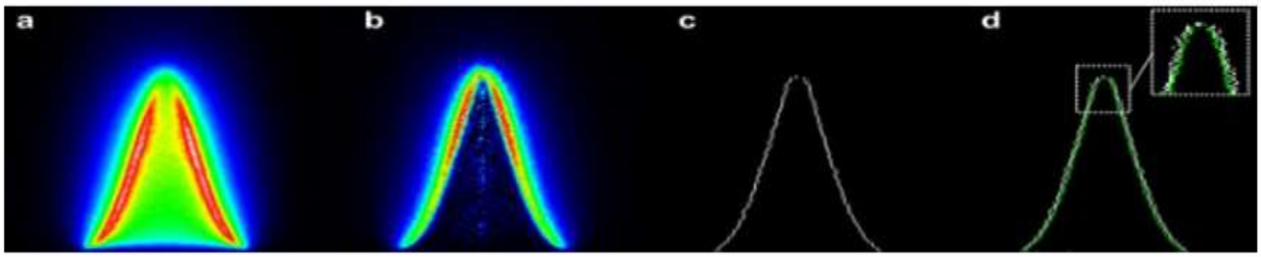
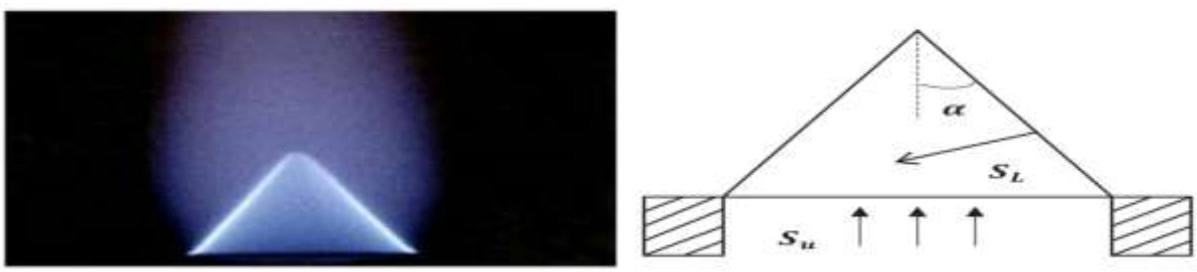


Figure 1. OH glow recording process: (a) Initial transcript; (b) inverted able picture; (c) Full enhanced after contour reversal from Abel (d) Superimposed picture outlines with/ without Abel inversion ().[3]



(a) (b)

Figure 2. Bunsen flame (a) photography of ER=1 for methane flame at (10 bar); (b) graphic diagram of the conical flame Bunsen. [3]

A study the laminar flame speed of methane/ammonia mixtures under oxygen enriched conditions with variable mixture composition; methane/ammonia ratios (0.1- 0.2), oxygen mole fractions (35% - 40%), and carbon dioxide mole fractions (45% - 65%) in a counter flow flame configuration at atmospheric pressure and initial temperature of 300 K [4]. The experimental results showed that the laminar flame speeds inversely proportional with carbon dioxide concentration and directly proportional with oxygen concentrations. The results also showed that ammonia effect depended on the mixture equivalence ratio. They compared their experimental results with the numerical results obtained by three chemical kinetics mechanisms: the Okafor, Mendiara and HUST (Huazhong University of Science and Technology) mechanisms. The comparisons showed that the HUST Mechanism results were in good agreement with the experimental results. Others performed an experimental analysis of the effect flame speed on the cooling distance in a rectangular section combustion chamber. Three types of fuel-air mixtures were examined namely, the CH_4-air, C_3H_8-air, andC_2H_4-air [5]. The tests were carried out in a constant volume combustion chamber composed of two chambers separated by the quenching section at pressure close to atmospheric, with an initial temperature of the chamber walls and unburnt mixture of 293 K. Flame quenching was obtained from pressure measurements, while the apparent flame speed was estimated from fast schlieren imaging. Similar trends were obtained for the studied mixtures. The quenching distance of the turbulent flames is about twice larger than that of the laminar flames. A studied the flame propagation in in spherical chamber using two optical techniques simultaneously, high speed tomography and Schlieren photography [6]. Other important flame characteristics are also studied, such as the un-stretched flame propagation speed and Markstein length in combustion products. Two high-pressure, high-temperature, constant-volume vessels were used in the study. Flame speed measurements of CH_4 / air mixtures with mixture Lewis numbers moderately away from unity were used. Unburnt mixture equivalence ratio were varied from lean to rich at temperatures of 298–373 K, and pressures of 1 atm and 5 bar. Thorough evaluation of the data with several extrapolation techniques was undertaken. A systematic extrapolation approach was presented to give more confidence into results generated experimentally.

A recent study stated that one of the most significant intrinsic property of a combustible mixture is the laminar flame speed [7]. Due to its importance, different methods for measuring the speed of the laminar flame have been developed. The pace at which an adiabatic, extended, pre-mixed planar flame advances relative to the un-burned mixture is described. The laminar flame propagation contains the physical and chemical information on the diffusivity and exothermicity of the mixture. In practical combustion systems, it influences or even decides the blazing rate of fuel/air mixtures. Previous study has developed an elaborated chemical-kinetics model for comprehensive NH_4/CH_4 mixture combustion [8]. Characteristics of ignition delay, un-stretched laminar flame speed and combustion gaseous emissions in the exhaust were obtained over a wide range of equivalence ratios and NH_4 fractions. High NO concentration was obtained while CO and CO_2 concentrations tend to drop when adding NH_4. For more understanding of the effect of NH_4 addition to CH_4, analyses of laminar premixed flame structure was made. The impact of ammonia substitution was illustrated by analyzing relevant specific radicals under elevated pressure and initial temperature. It was indicated that pressure has significant effect than initial temperature. A studied experimentally the laminar flame speed of comb pre-mixed LPG / H2 / air mixture in a centrally ignited constant volume combustion chamber at initial conditions 308 K, and various initial pressures from 0.1 to 0.3 MPa [9]. Different mixture equivalence ratios, from 0.8 to 1.3, in addition to different mixing ratios of hydrogen ranging, from 0-80% according to the mass, were tested. Physiochemical properties such as laminar flame speed and C.C LPG pressure flame were introduced with different combinations of hydrogen. High-speed Schlieren imaging technology was used. Experimental results showed that the effect of hydrogen blending became obvious when the hydrogen ratio is larger than 60%. At a blending ratio of 80%, the adiabatic flame temperature, the laminar flame speed and laminar burning velocity were all improved while the flame thickness decreased stoichiometric mixture at atmosphere pressure. It was noticed that increasing the initial pressure reduced the stretched laminar flame speed and laminar burning velocity of LPG-air mixture. Fig et al. (2016) performed an experimental and numerical analysis of CH_4 combustion and flame advancing in horizontal cylindrical combustion chamber [10]. They studied the effect of stoichiometry and cylinder diameter in addition to ignition location. At one end the cylinder was allowed to vent to the atmosphere, while at the other end a solid wall. Tubes with diameters ranging from 5 to 71 cm were used. They noticed a direct relationship between the maximum laminar flame propagation velocity and tube diameter. A 2D numerical simulation were carried out with ANSYS Fluent. A hot-wall was used as an ignition source, with burning velocity trends consistent with experimental data. A functional relationship between stoichiometric uniform burning velocity and tube diameter was presented. Based on a experimentally and numerically, the fundamental flame properties of mixtures of air with hydrogen, carbon monoxide, and C_1–C_4 saturated hydrocarbons [11]. The study comprises the use of the counter-flow configuration to determine flame speeds as well as premixed flames extinguishing and ignition limits. The experiments were simulated using the kinetic model of the USC Mech II. It was found that when hydrocarbons were added as additives to the hydrogen flames, flame ignition, spread, and extinction were impacted .in a counterintuitive way. It was also found that replacing CH_4 with C_3H_8 or n-C_4H_{10} in hydrogen flames reduces the reactivity of the mixture under both preignition and vigorous fiery conditions.

EXPERIMENTAAL SETUP

The test rig is constructed in the Department of Mechanical Engineering Laboratories of Babylon University in Iraq. It involves a heat-resistant, up to (1000 ^{o}C), Pyrex cylinder used as a combustion chamber with the dimensions of (175 mm) inner diameter, (180 mm) outer diameter, (5 mm) wall thickness, and (1300 mm) length, fuel injection and control unit, ignition circuit and gas control, mixture preparing unit and flame photography unit. The setup is designed for dual fuel supply, liquid, or gas. However, it is used in this research for a single fuel, which is Iraqi LPG in this work. The combustion chamber is closed at one end with a Teflon flange and vented to the atmosphere at the other end. The flange accommodates the fuel/air mixture supply ports, the nitrogen supply ports, and the igniter. The mixture is supplied through six ports arranged in a ring formation at 60 mm from the cylinder axis. Nitrogen is used as a shield to protect the cylinder walls from high temperatures when needed. The cylinder is installed horizontally and support by two wooden pieces on metal table. Fig 1&2 show the complete details of rig setup. The mixture preparation and supply unit consists of an LPG cylinder, an air compressor, and a vacuum pump. The fuel/air mixture is prepared in a mixing tank according to the required fuel air ratio depending on Dalton's law of partial pressures. The mixing tank has a capacity of 37.5 L. The mixture is prepared at a pressure of 4 bar. The LPG and air flow rates to the mixer are controlled by regulator valves and gauge pressure as shown in Figure 2. The flow rate to the combustion chamber of the unburned mixture is measured by a controlled by a solenoid valve and a digital flow meter as shown in Figure (3A & 3B) respectively. The ignition source is installed on the Teflon flange at the cylinder axis. For safety precautions, a flame arrestor and a flame trap are used to prevent flame flashback to arrive at the mixer. The photography unit consists of high-speed camera and computer a PC. The camera is type AOS - Q-PRI portable camera of high-speed with ultra-high resolution image (3 Mega Pixels), (1.3×10^9 B) domestic memory and (16,000 FPS) as illustrated in fig (3 C). It is set 500×576 pixels for 4000 FPS and total recording time of 1.1 sec. Ten percent of the time is set before triggering to ensure that all the process is recorded when the triggers, the ignition unit, and the camera are switched on.

The Iraqi LPG is used as the fuel in this study. It consists of many hydrocarbon components (Ethane, Propane, butane, and Pentane) as shown in table 1. The volume analysis is supplied by the Al-Hillah gas factory where the fuel is supplied.

Table 1. Chemical Composition of Iraqi LPG

Items	C_2H_6	C_3H_8	C_4H_{10}	C_5H_{10}
Volumetric Fractions (%) by Volume	0.7	55.8	41.5	2

From this analysis, the average chemical formula (C_nH_m) of the fuel is obtained using the following equations.

$$C_n = \sum X_i C_i \quad (3)$$

Where: -

i: Component number

X_i : Mole fraction for component (i)

C_i: Number of carbon atoms for component (i)

C_n: Average number of carbon atoms in LPG

$$H_m = \sum X_i H_i \quad (4)$$

Where: -

H_m: Average number of hydrogen atoms in LPG

H_i: Number of hydrogen atoms for component (i)

C_nH_m: The average chemical formula of LPG

The average chemical formula of Iraqi LPG is found to be $C_{3.358}H_{8.68}$ with an average molecular weight of 48.976.

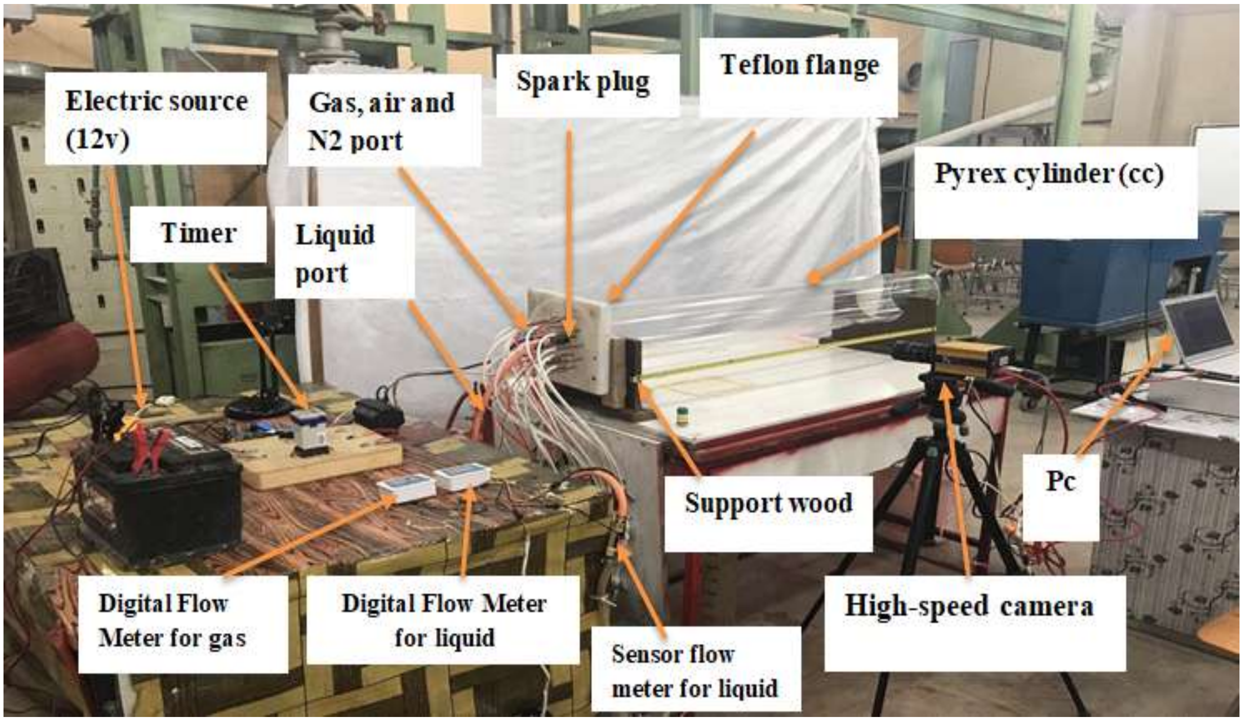


Figure 3. the Experimental Rig

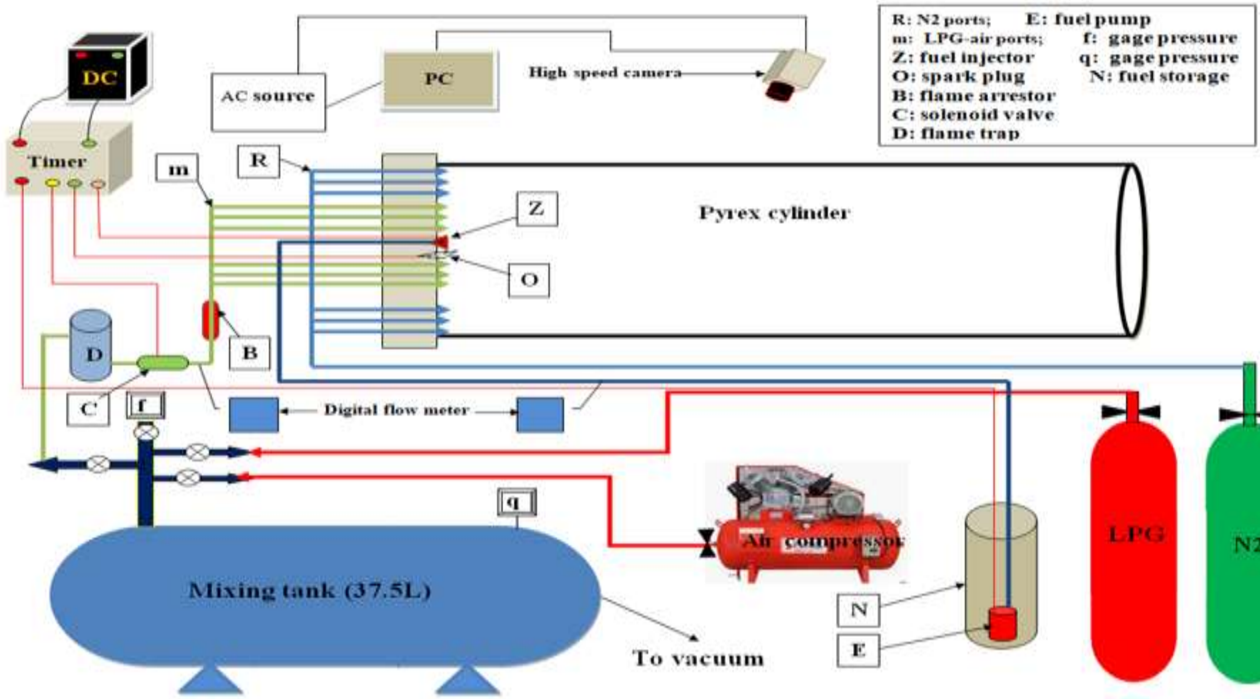


Figure 4. Schematic diagram of The Experimental Setup

Figure 5. Different Measuring Instrumentations

NUMERICAL PREDICTION OF LAMINAR FLAME SPEED (CFD MODEL)

Chemkin-pro is one of the most common S.P (software package) used for the simulation reactions of chemical and analysis chemical kinetics. It was developed originally by Sandia National Laboratory, after which Reaction Design Inc. retained and improved it, and recently became part of the ANSYS program.

To study the combustion of a premixed of LPG-air flames, the 1-dimensional model of laminar flame was used to simulate LPG-air characteristics of the flames. A study identified the intensity of laminar flame as one the crucial component affecting spread of premixed combustion flames [12].

In this work, the CHEMKIN-PRO software is used to simulate the speed of flame propagation in a horizontal cylindrical (C.C) of a premixed LPG/air mixture. The effect of equivalence ratio and chemical composition of LPG on the velocity of the laminar flame is studied. The mixture is introduced to combustion chamber at 1 bar and 300 K. The equivalence ratio ranged from 0.6 to 1.4.

The general fuel/air mixture chemical reaction equation is shown below.

$$\sum a_i C_{n_i} H_{m_i} + (x/\phi)(O_2 + 3.76N_2) \rightarrow e_1 CO_2 + e_2 H_2O + e_3 CO + e_4 N_4 + X_1 O_2 \quad (5)$$

$$\sum a_i C_{n_i} H_{m_i} = a_1 CH_4 + a_2 C_2H_6 + a_3 C_3H_8 + a_4 C_4H_{10} + a_5 C_5H_{12} + \ldots \quad (6)$$

Where:

ϕ = Equivalence ratio.

e_1= Number CO_2 moles in produce.

e_2= Number H_2O moles in produce.

e_3= Number CO moles in produce.

e_4= Number N_2 moles in produce

X_1= Number O_2 moles in produce

X= Number O_2 mole in reactance.

However, the reaction mechanism used in the Chemkin software involves 111 species and 784 reactions [13-14]. Some of these reactions are shown below as examples.

$n\text{-}C_3H_7 \rightarrow C_2H_4 + CH_3$ (R1)

$C_2H_4 + H + M \rightarrow C_2H_5 + M$ (R2)

$C_2H_5 + H \rightarrow CH_3 + CH_3$ (R3)

$p\text{-}C_4H_9 \rightarrow C_2H_4 + C_2H_5$ (R4)

$i\text{-}C_3H_7 + O \rightarrow CH_3CHO + CH_3$ (R5)

$CH_3CHO + X \rightarrow CH_3CO + XH$ (R6)

$CH_3CO \rightarrow CH_3 + CO$ (R7)

Where X stands for H, O, or OH_ CH_3

Overall equivalence ratio for the dual fuel calculated using the equation [15]:

$$\varphi = \frac{\left(\frac{F}{A}\right)_{act}}{\left(\frac{F}{A}\right)_{stioc}} \quad (7)$$

The reactants inlet velocity to the combustion chamber is calculated such as below.

$$\dot{Q} = A.V \quad (8)$$

$$V = \frac{\dot{Q}}{A}$$

$$A = \frac{\pi}{4} * d^2 * n$$

Where:

$\dot{Q}$: Volume flow rate mixture ($\frac{m^3}{s}$)

V: inlet velocity ($\frac{m}{s}$)

A: total mixture inlet ports area (m^2)

n: number of inlet ports.

RESULTS AND DISCUSSIONS

The results are split into two parts, the numerical results and the results of the experiment. For the LPG/air mixture, the stretched laminar flame speed S_L for different equivalence ratios from 0.6 to 1.4 is calculated numerically neglecting the effect of ethane and pentane because their mole fractions are very low in the fuel analysis and account for propane and butane only. Fig 6 displays the effect of equivalence ratio on stretched laminar flame speed for different blends of propane and butane. It is obvious that the maximum flame speed is obtained for the stoichiometric mixture for all blends and decreases on both sides for lean and rich mixtures. This is caused by the fact stoichiometric mixture has the highest flame temperature as shown later and the known fact that the flame speed is heavily dependent on temperature. Since the pure propane has the highest adiabatic flame temperature and hence the highest flame speed it is noticed that as the propane mole fraction increases the flame speed increases. Fig 7 shows the effect of the equivalence ratio for different on flame speed for LPG, pure propane and pure butane. The fig shows that the flame speed reaches its maximum value at ER equals unity and decreases on both sides and that the pure propane has the highest flame speed followed by LPG for all ER.

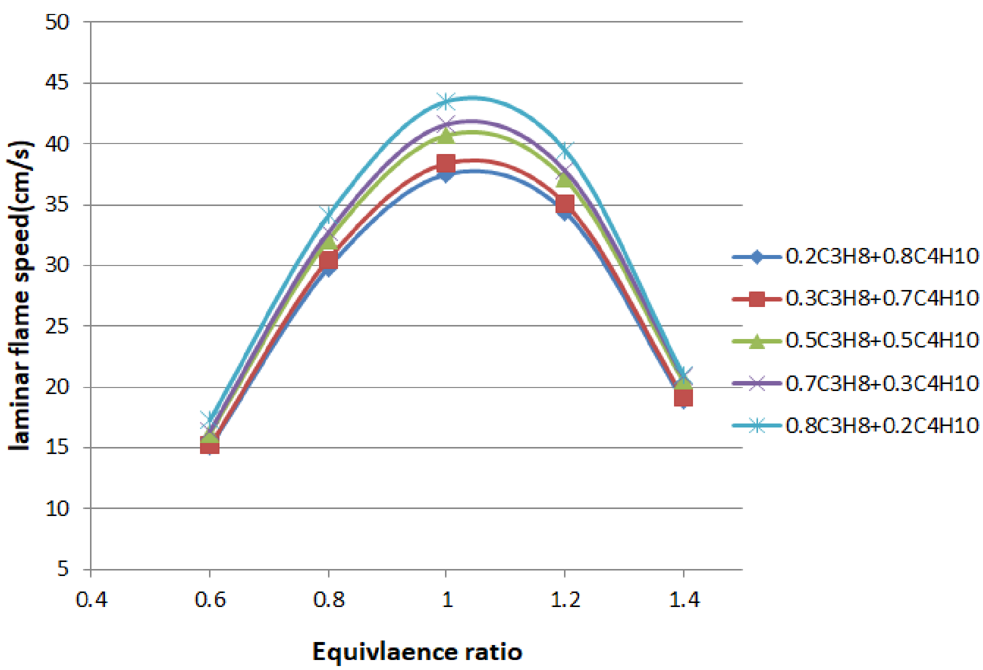


Figure 6. Predicted Laminar Flame Speed against ER for Different propane butane blends

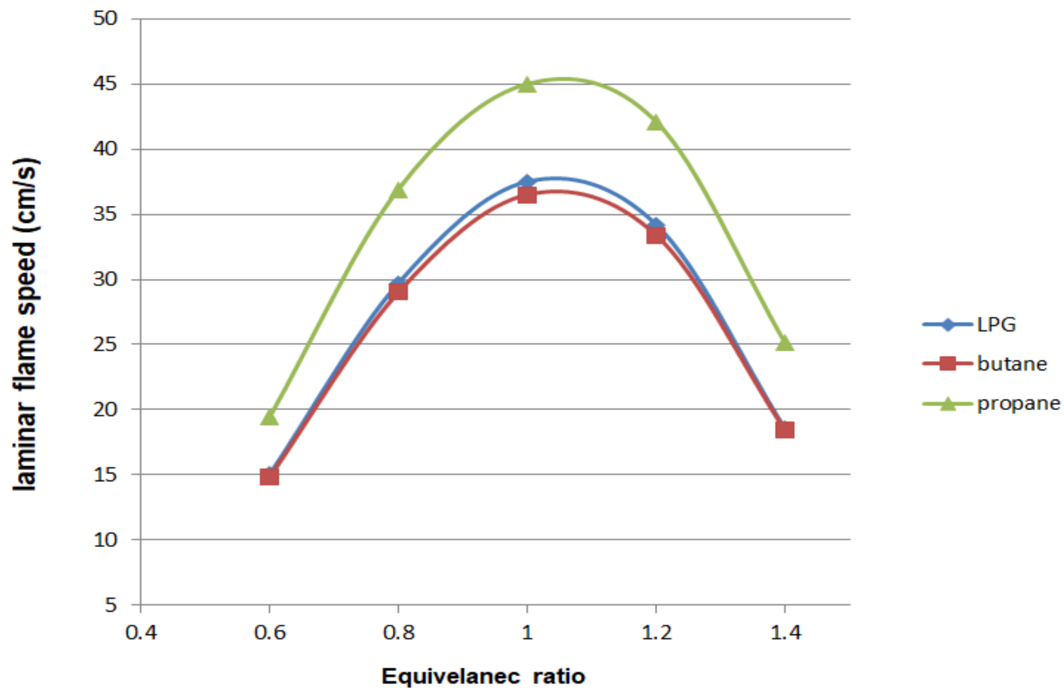


Figure 7. Predicted Laminar Flame Speed against ER for LPG, Pure Propane and Pure Butane

Figure 8 shows the variation of adiabatic flame temperature for LPG, pure propane, and pure butane with an ER. It is clear that the propane has the maximum adiabatic temperature followed by LPG and then the butane. The stoichiometric mixture has the maximum temperature for the three fuels. This is due to the highest LCV propane compared to other fuels.

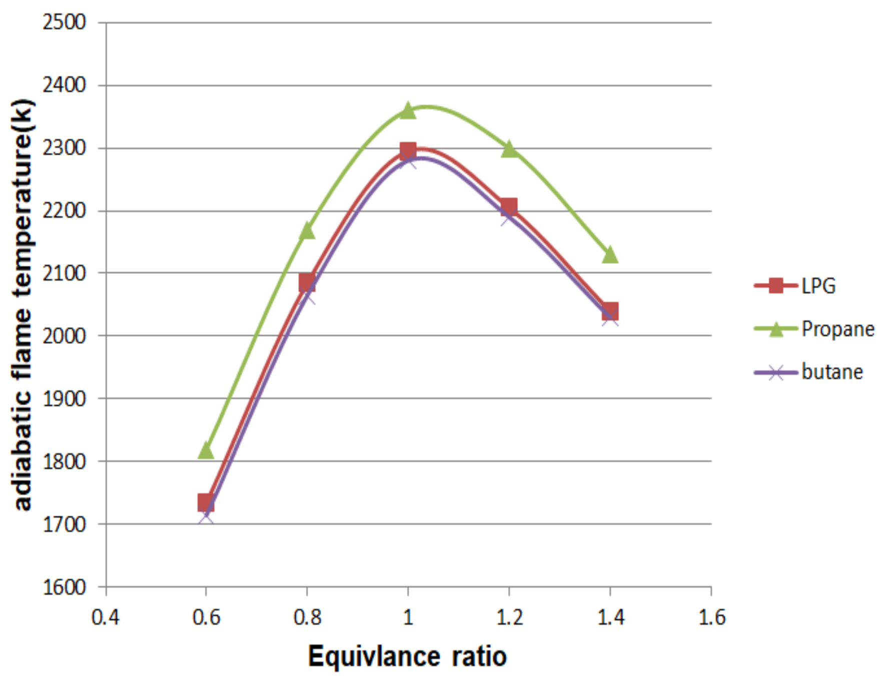


Figure 8. Effect of ER on Adiabatic Flame Temperature for LPG, Pure Propane and Pure Butane

Figure 9. Shows the influence of propane mole fraction on the adiabatic flame temperature for three ERs (ER=0.6, 1.0, 1.4). It is found that the temperature of the adiabatic flame increases almost linearly as the mole fraction of propane increases due to the rise of the LCV mixture as the mole fraction of the propane increases.

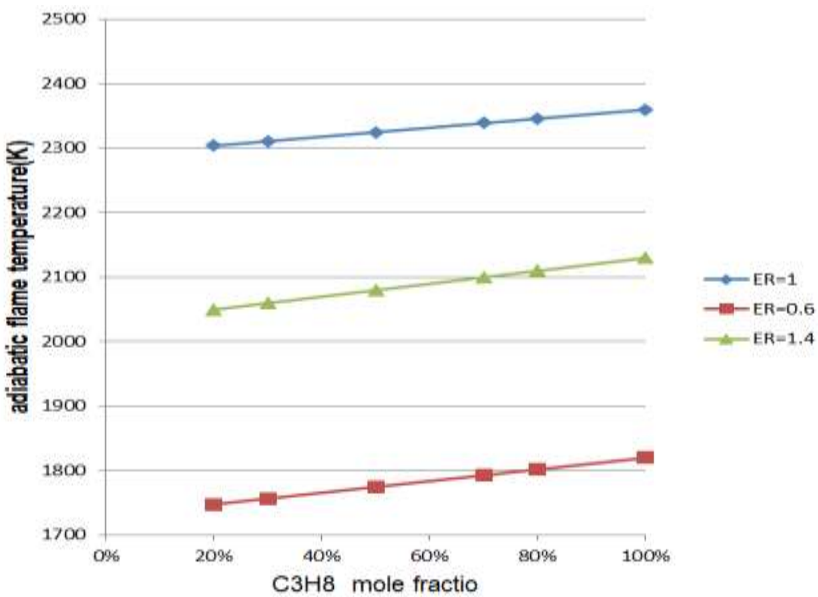


Figure 9. Adiabatic Flame Temperature against Propane Mole Fraction for Different ER

Figure 10 shows the dependency of laminar flame speed on propane mole fraction for different ER. It seems that the flame speed varies almost linearly with propane mole fraction for all ER.

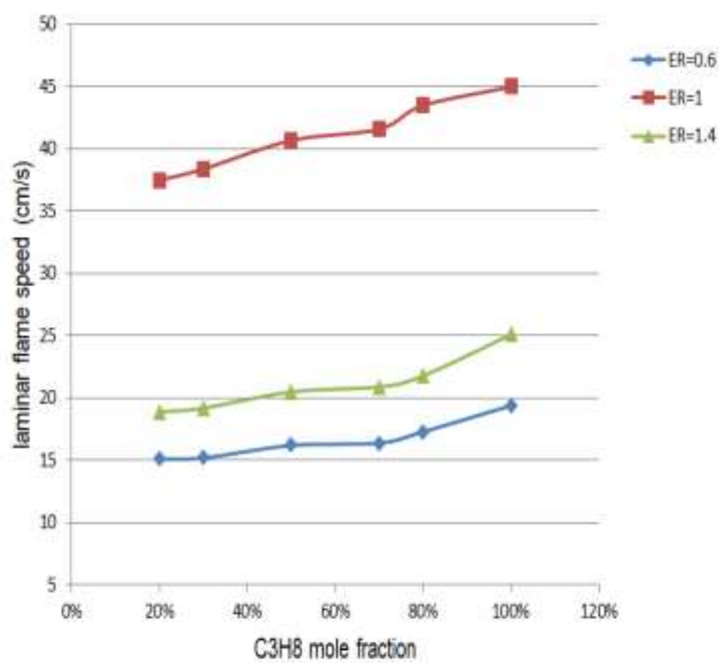


Figure 10. Laminar Flame Speed against Propane Mole Fraction for Different ER

The measured flame speed is derived from the Schlieren photography recording analysis. The flame front Radius obtained from the recordings at any time is used in this analysis directly to determine the stretched laminar flame velocity S_n. The stretched flame velocity S_n is determined using the following equation **(Bradley et al. 1998)[16].**

$$S_n=dx/dt \tag{9}$$

The recordings are analyzed using the Tracker program version 4.87 for (Cartesian coordinates) with the following setting, as mentioned in table (2)

Table 2. Setting of Tracker Software that Measuring Flame Speed.

Setting of Clip	
Frame of start	Variable
Size of step	5 (frame)
Frame of end	Variable
Time of start	Variable
Frame rate of frame	4000 f/s
dt of frame	2.50E-4 s

Figure 11 shows the measured stretched laminar flame speed against equivalence ratios for the LPG-air mixture. For each cases of mixture studied of the combustion, laminar flame speed of fuel-poor increases of the mixtures with the ER up and reaches a maximum value for stoichiometric mixture and then under fuel-rich regimes decrease. This behavior is similar to that obtained numerically in Figure 6

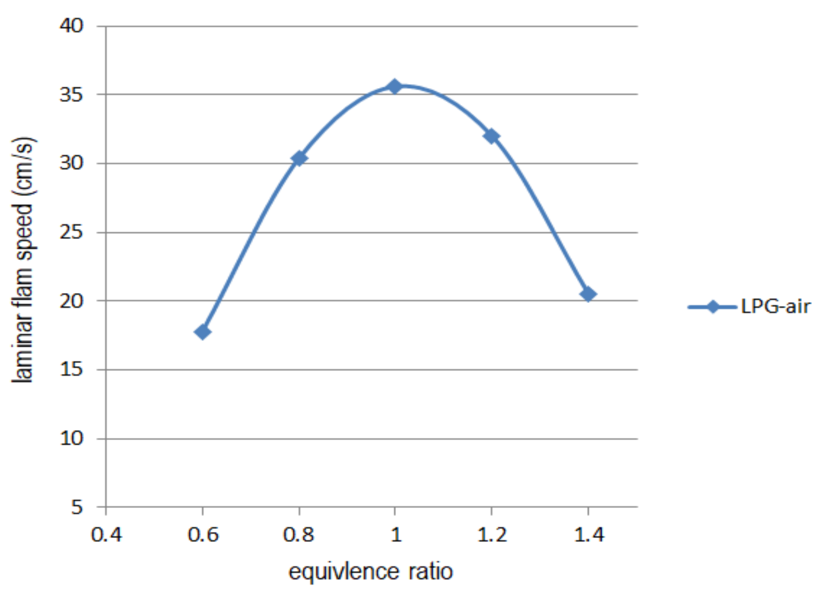


Figure 11. Experimental Laminar Flame Speed

In Figure 12,the temperature of the adiabatic flame was plotted against the equivalence ratio for LPG in which case, the temperature of the adiabatic flame increases with fuel-lean increases to stoichiometric combustion at ER=1, reaching the maximum temperature at these In Figure13, the flame speed of a laminar increases with adiabatic flame temperature increases.

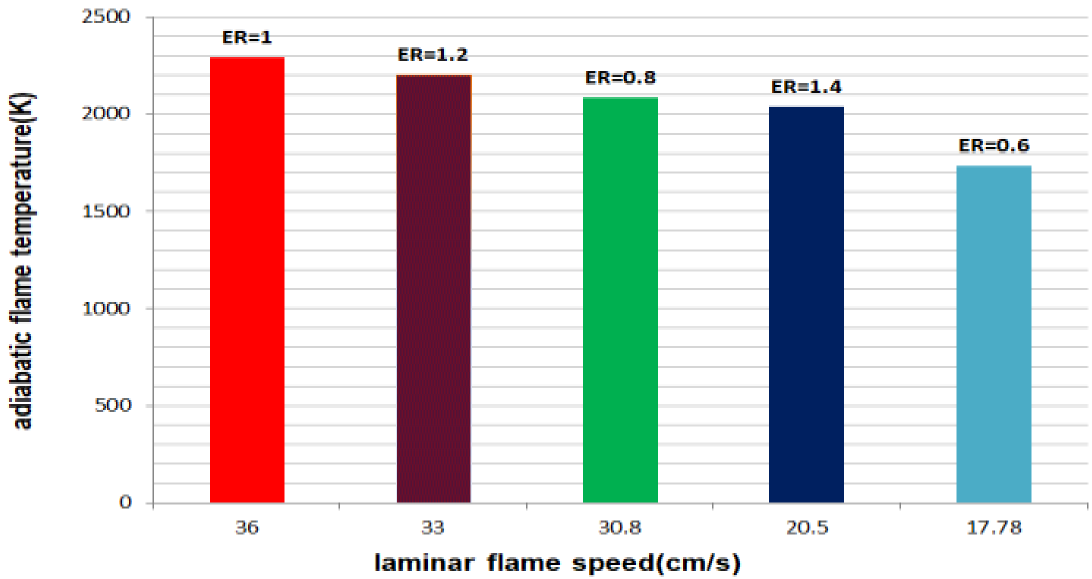


Figure 12. Laminar Flame Speed against Adiabatic Flame Temperature

In Figure 13, a comparison between the practical calculations and the theoretical calculations of the flame velocity shows us, where we notice that the results are close to some extent. We notice that the laboratory calculations of the flame velocity are less and this is logical, but there are inaccuracies and some laboratory errors.

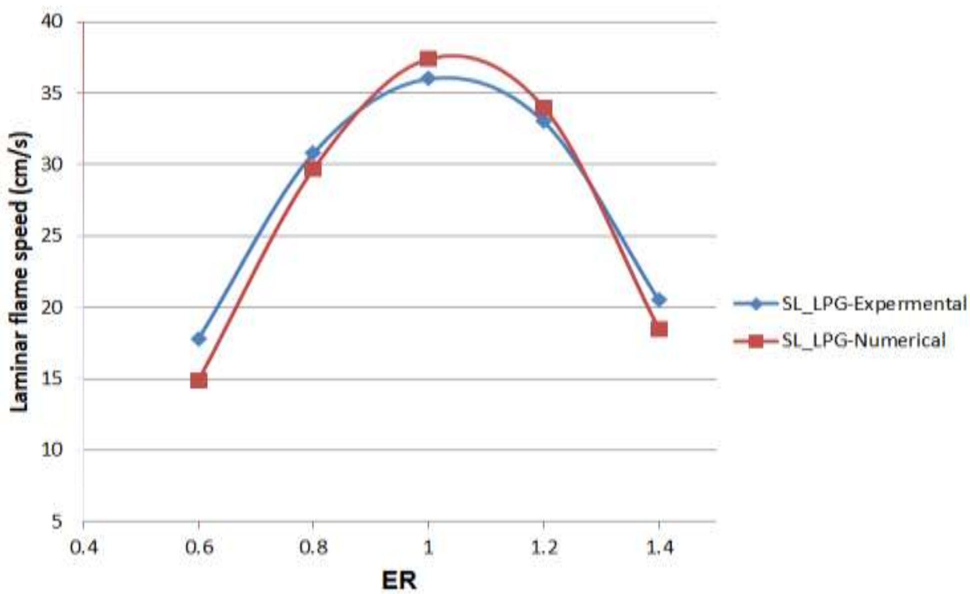


Figure 13. comparison between a practical and theoretical

In the current work, there are some pictures showing us the propagation of the flame, which were taken by a high-speed camera, shown in Figure 14 below.

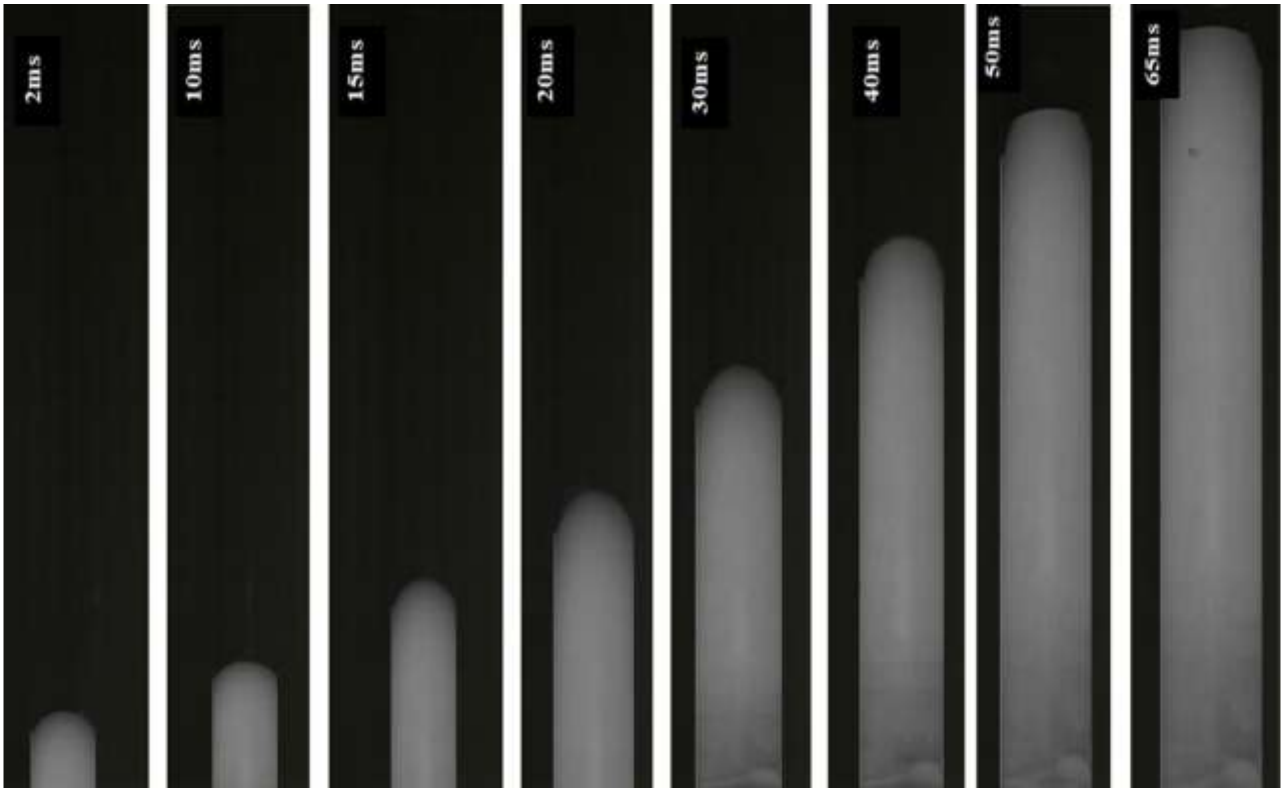


Figure 14. High-speed camera images in the present study for flame propagation

CONCLUSIONS

From this dissertation can be drawn the following conclusions :

1-Experimental and empirical tests indicate that the laminar flame speed has a maximum value for the stoichiometric mixture and decreases for all measured fuels on both sides ;

2- For all measured fuels, the laminar flame speed increases with adiabatic flame temperature.

3-Propane has a higher laminar flame velocity and adiabatic flame temperature than butane and LPG.

4-For propane and butane mixtures it is observed that the velocity of the laminar flame increases with increasing propane mole fraction.

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