Journal of Engineering and Sustainable Development
Vol. 20, No. 04, July 2016
ISSN 2520-0917
www.jeasd.org

EFFECT OF OXYGEN ENRICHMENT UPON LAMINAR BURNING VELOCITY OF (BUTANE – O_2 – N_2) MIXTURE

Dr. Fouad A. Saleh[1] , *Shaymaa Y. Ibrahim[2]

1) Assist Prof., Mechanical Engineering Department, Al-Mustansiriayah University, Baghdad, Iraq.
2) Ph.D student, Mechanical Engineering Department Department, Al-Mustansiriayah University, Baghdad, Iraq.

Abstract: The effect of oxygen enrichment on the laminar flame speed of (butane – oxygen – nitrogen) premixed mixture. The measurement system is designed to measure the laminar flame speed using a tube – method and optical technique (photodiode).The laminar flame speed results were obtained at atmospheric pressure, initial temperature 301K, three level of oxygen concentration (0.21, 0.23 & 0.25) and equivalence ratio (0.6 – 1.4). All the measurements were carried out at pre-pressure period to use "density ratio method" for the calculation of laminar burning velocity. The adiabatic flame temperature, flame thickness and Zel'dovich number have been calculated theoretically. Validation of experimental work is approved by comparison measured values of laminar burning velocity for (butane – air) mixtures with the available published data. Good agreements are obtained in its comparison with the literature results employed in the present work are successful and precise.

Keywords: *Oxygen enrichment, laminar burning velocity, tube method*

تاثير زيادة الاوكسجين على سرعة انتشار اللهب لخليط
(Butane – O_2 – N_2)

الخلاصة: تم اجراء دراسة عملية لبيان تاثير زيادة الاوكسجين على سرعة جبهة اللهب الطباقية لخليط غاز (البيوتان – اوكسجين – نايتروجين) المسبق الخلط . ولاجراء ذلك تم تصميم منظومة قياس استخدم فيها طريقة الانبوب والتقنية البصرية (الخلايا الضوئية) لقياس سرعة جبهة اللهب . تم ايجاد قيم سرعة جبهة اللهب عند الضغط الجوي ، ودرجة حرارة ابتدائية (٣٠١K) لثلاثة تراكيز من الاوكسجين (٠,٢٣،٠,٢١&٠,٢٥) ونسبة مكافئة (١,٤ – ٠,٦) . جميع القياسات تم اجراؤها في فترة ثبوت الضغط وذلك لاستعمال طريقة نسبة الكثافة لحساب سرعة انتشار اللهب الطباقية . درجة حرارة اللهب ، سمك جبهة اللهب ورقم زيلدوفج تم ايجادها نظريا.تم اختبار صحة النتائج العملية لخليط (البيوتان – هواء) وذلك من خلال المقارنة مع النتائج العملية المنشورة وتبين وجود توافق جيد بينها ، مما يدل على نجاح ودقة التقنية والحسابات المستخدمة في هذا البحث .

1. Introduction

Most combustion processes use air as the oxidant. In many cases, these processes can be enhanced by using an oxidant that contains a higher proportion of oxygen than

---

*Corresponding Author eng.shaimaa1975@yahoo.com

that in air. This is known as oxygen – enhanced combustion. The flame characteristics of oxygen enhanced combustion have big changes from that of air/fuel combustion as: the flame temperature increase significantly, the upper flammability limits increases, the burning velocity increases, the ignition energy reduces, increased flame stability and reduced pollutant emission [1]. Laminar burning velocity is a physical parameter which depends only on the physical and chemical nature of premixed gases [2]. Several studies available on the burning velocity with pure oxygen or oxygen enrichment, but most of these studies use methane as fuel, for examples (Stephanie de Persis et al.)[3] & (Konnov AA, Dyakov IV) [4]. The present study introduce a new measurements of laminar flame speed for fuel(butane)with oxygen enrichment , in addition to study the variation of flame characteristics with increasing oxygen which include adiabatic flame temperature, flame thickness and Zel'dovich number.

2. Experimental Setup

Figure (1) shows the general layout of the test rig built in "Mechanical Engineering Dept., Al-Mustansiriyah University" for the purpose of this study. The test rig consists from four units (1) Combustion unit , made from copper tube (inside diameter 67mm, 2000mm length,3mm thickness), provided with electrical heater and insulation to heat the initial mixture and maintain the adiabatic process during the test,(2) Mixing chamber unit , made from iron steel used to prepare the mixture using the partial pressure method, (3) Ignition unit, consists from spark plug and electronic circuit , (4) Measuring flame speed unit : consists from (a) Four photodiodes which fixed on the tube with a distance (25 cm) between them to measure the time required for moving flame front from one photodiode to other by using two digital storage oscilloscopes and (b) An electronic circuit to amplify the signal of photodiode,(5) Instruments: which include " thermocouple: to measure initial temperature of mixture, pressure transmitter: to measure the pressure of combustion, pressure meter: to measure the quantity of fuel , oxygen and nitrogen during the preparation of mixture. High purity gases (99.99 %) of oxygen and nitrogen used. All measurements occur at pre-pressure period. For accuracy, the flame speed measurements were repeated seven times at each condition.

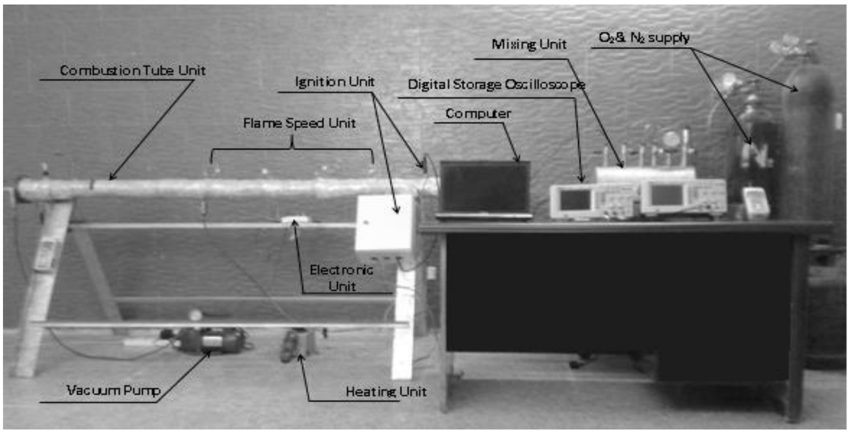

Fig. 1: Experimental Set Up

3. Experimental Procedure

1- Before preparing the mixture, the mixing vessel was sufficiently purged from any previous mixture by using the vacuum pump.

2- Preparing the mixture which consists from (butane, O_2 and N_2) inside the mixer according to its partial pressure fraction relative to the total pressure of (3 bar). The quantities of (butane, N_2 and O_2) were regulated by pressure regulator.

3- A waiting time of (5 minutes) was then allowed to permit the (butane, N_2 and O_2) to mix completely and to obtain a good mixing and homogenous mixture.

4- After that, the combustion tube was evacuated by the vacuum pump to a pressure of (0.001 bar), and then refilled with homogenous mixture “supply from mixer” to atmospheric pressure.

4. Experimental Calculation

To calculate the laminar burning velocity from measured flame speed, the density ratio method introduced by Andrews and Bradley [5] was used as the following equations.

$$S_L = (\rho_b/\rho_u).\ S_F \quad (1)$$

$$\rho_b/\rho_u = (T_u/T_b).\ N.I \quad (2)$$

The flame speed (S_F) is calculated from experimental measurements as the following:

$$S_F = \Delta L/\Delta t \quad (3)$$

The magnitudes of mole ratio and flame thickness factor have been calculated according to the relations given by Andrews and Bradley [6], where:

$$N = \sum N_r/\sum N_p \quad (4)$$

$$I = 1.04/r_b^3[\ (r_b - \delta)3 + (\ 3\ T_b\ r_b^3\ )/(\ T_b - T_u\ )\ \ln\ (\ T_b/T_u)] \quad (5)$$

Where (N_r & N_p) can be calculated from the balance of combustion equation as in the following equation:

$$C_4H_{10} + (6.5/\Phi)\ [O_2 + ((1- \Omega_{oxg})/\ \Omega_{oxg})\ N_2] = \text{Products} \quad (6)$$

The adiabatic flame tem perature with oxygen enrichment was calculated by using a computer program of “Olikara & Borman” [7] after we done suitable modifications for this program. The modification includes the change in mole ratio of nitrogen to oxygen in the range (3.762 “air” to 0.001 " approximately pure oxygen"). This program considers the dissociation for 11 species (H, O, N, H_2, O_2, N_2, OH, CO, NO, H_2O and CO_2) in the products of combustion.

Flame thickness, could be defined as the distance in which the first temperature rise occur until reach the maximum value (T_b). Blint's correlation [8] was used in the present work for calculating flame thickness.

$$\delta = (2\,\lambda/ \rho_u.C_p.S_L)(T_b/T_u)^{0.7} \tag{7}$$

Thermo-physical properties are assumed to be constant values at specific temperature and evaluated at mean temperature "$T_m = (T_u + T_b) /2$ " . [9] Used to calculate these properties.

Zel'dovich Number, It is important parameter for laminar flames to describe the sensitivity of chemical reactions to the variation of the adiabatic flame temperature. Zel'dovich number is given by the following equation [10]:

$$Ze = (E/ 2\, R_u\, .\, T_b^2)(T_b-T_u) \tag{8}$$

The activation temperature (E/R_u) can be derive from the linear plot of experimental results ($2\ln(\rho_u S_L)$ against ($1/Tb$) directly.

5. Results and Discussions

Fig. (2) Shows the variation of adiabatic flame temperatures of (butane – O_2 – N_2) flames with equivalence ratios and different oxygen enrichment levels. It can be observed that the flame temperature increases with the increment of the equivalence ratio on the weak side of the mixture till it reaches the maximum value at (Φ=1.1). Afterwards it starts to decrease on the rich side of the mixture with increment of equivalence ratio. This is due to the relation between the heat of combustion and the heat capacity of the products, where both of these decline when the equivalence ratio exceeds unity, but the heat capacity decreases slightly faster than heat of combustion between Φ=1 and the peak rich mixture . Moreover the increasing of oxygen in the mixture produces an increment in the flame temperature by increasing the heat capacity of the mixture[11].

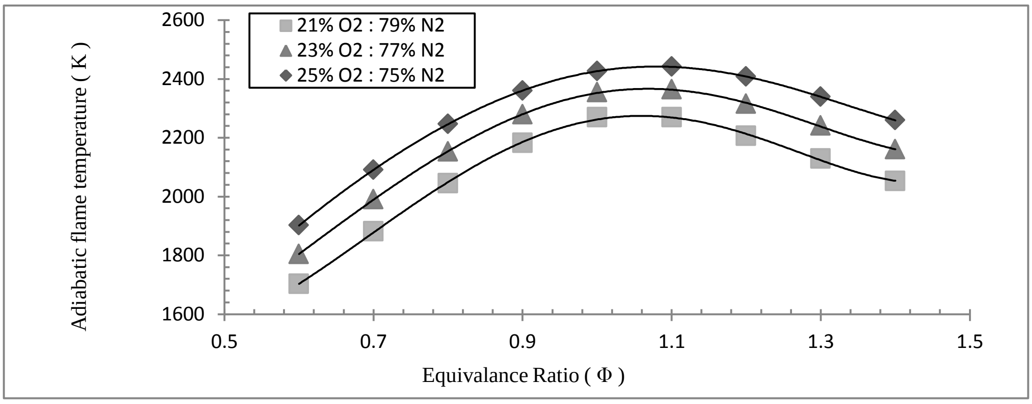

Fig. (2): Adiabatic flame temperature vs. equivalence ratio at different oxygen enrichment levels

The measured flame speed at different equivalence ratio and oxygen enrichment of (butane – O_2 – N_2) mixture was shown in Fig. (3). The variation of flame speed had the same trend of adiabatic flame temperature with equivalence ratios and oxygen enrichment levels. Increment the oxygen as the oxidizer will lead to increase the flame temperature and consequently the reaction rate, thus increasing the flame speed.

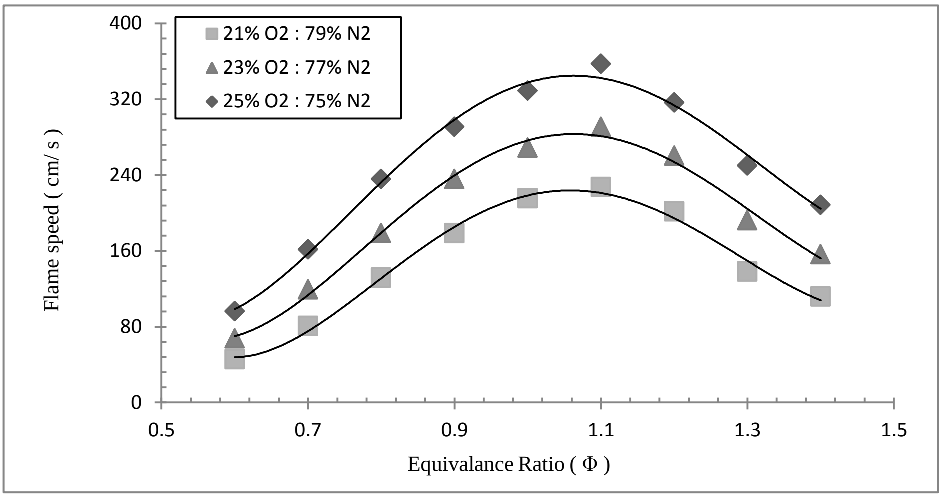

Fig. (3): Flame speed (S_F) vs. equivalence ratio at different oxygen enrichment levels

The results of laminar burning velocity estimated according to equation (1) are shown in Fig. (4). The laminar burning velocity increases with increment oxygen levels as a result in reaction rate which is due to increase adiabatic flame temperature. The experimental results show that the maximum value for laminar burning velocity occur at equivalence ratio = 1.1, and the maximum increase percentage was (23.45%).

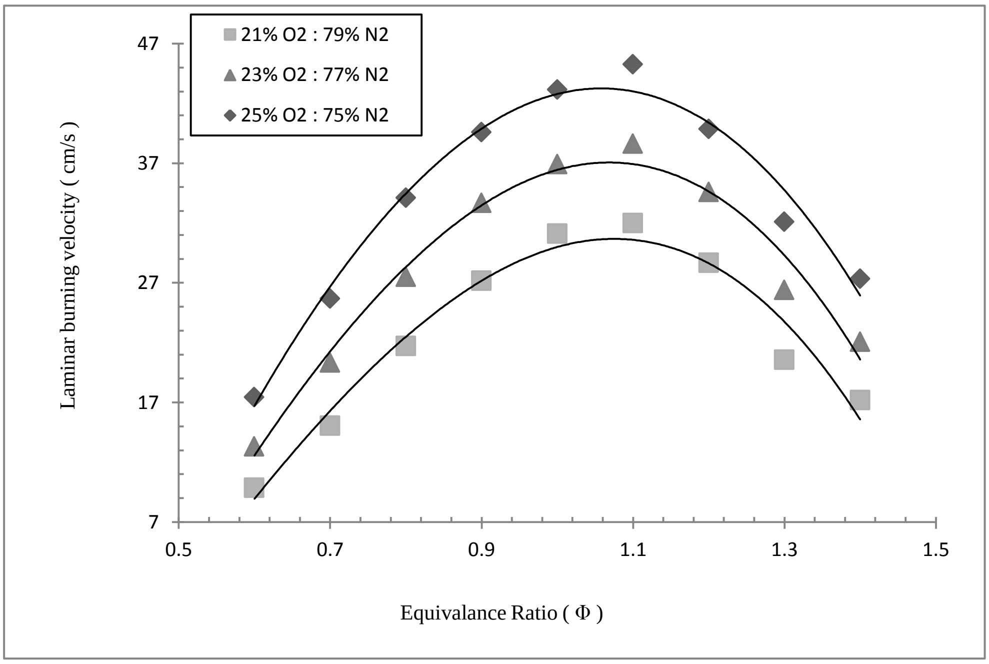

Fig. (4): Laminar burning velocity (S_L) with equivalence ratio at different oxygen enrichment levels

Fig. (5) Illustrates the variations in mole ratio at different equivalence ratios (Φ) and at different oxygen enrichment levels. It can be observed from this figure that the mole ratio decreases with increase the equivalence ratio. The trend of variation in (N) with (Φ) is similar to the three oxygen enrichment levels. Increase oxygen enrichment level and equivalence ratio will decrease the number of moles of reactants and increase the number of moles of products; therefore mole ratio decreases.

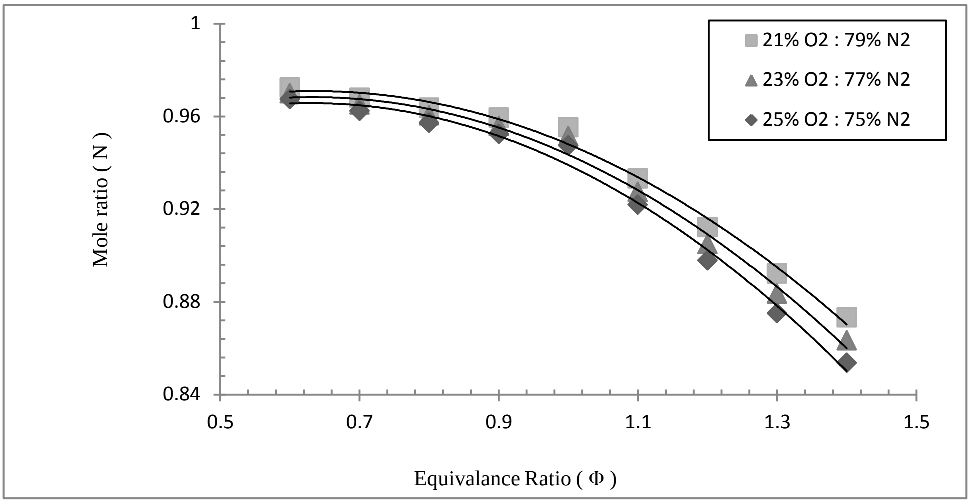

Fig. (5): Mole ratio (N) vs. equivalence ratio at different oxygen enrichment levels

Fig. (6) Shows the effect of equivalence ratio and oxygen enrichment on the flame thickness. Hence, the flame thickness have a U-shape dependence on equivalence ratio, where it decreases with increasing the equivalence ratio on the lean side of the mixture till reaching the minimum value at (Φ = 1.1). Afterwards, the flame thickness increases with increases the equivalence ratio on the rich side of the mixture. This is due to the relation among (δ), thermo-physical properties and laminar burning velocity (S_L) which depends on the chemical reaction rate. When the chemical reaction rate increases, the flame temperature increases also, resulting in increment of burning velocity that leads to decrease the flame thickness and vice-versa. That is the flame thickness is inversely proportional to the chemical reaction rate, which represents the rate of liberating the combustion energy [12].

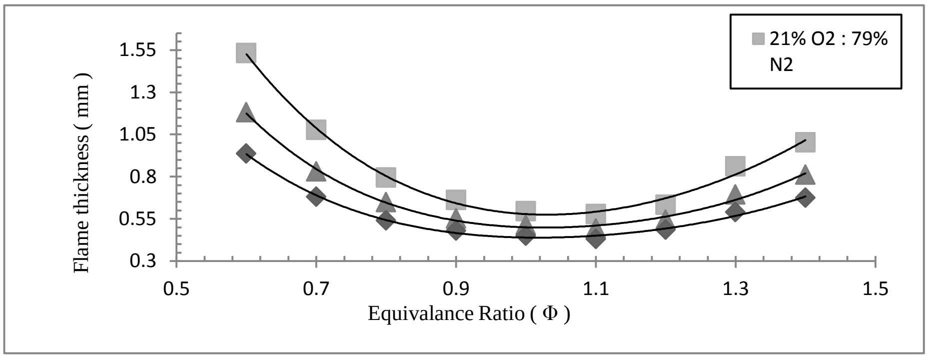

Fig.(6) : Flame thickness (δ) vs. equivalence ratio at different oxygen enrichment levels

Zel'dovich Number has the same trend of flame thickness as shown in figure (7).This is due to the inverse relationship between (Ze) and adiabatic flame temperature, where increasing oxygen concentration increasing adiabatic flame temperature which decreasing Zel'dovich number.

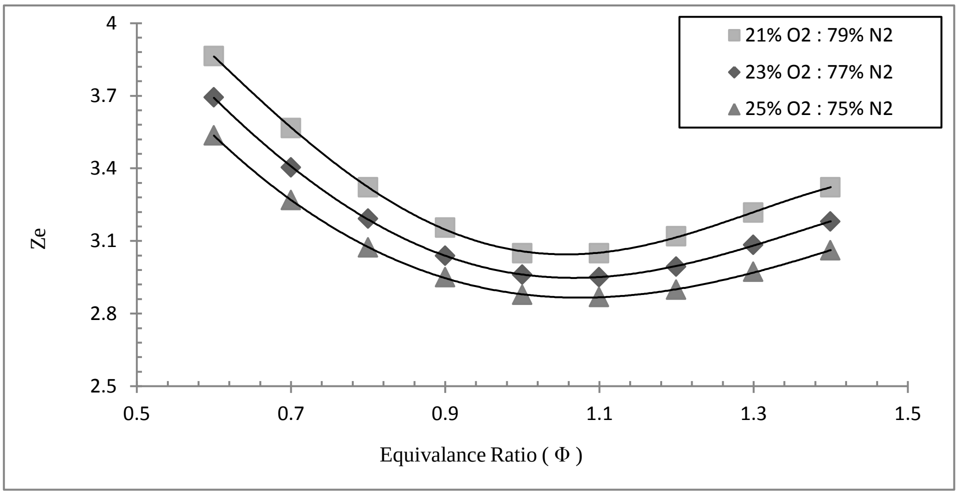

Fig.(7) : Zel'dovich number (Ze) vs. equivalence ratio at different oxygen enrichment levels

Fig. (8) Shows the comparison of the results of present work for case (butane - air) mixture with the published results which gives a good agreement between them. The slight differences in the values of burning velocity associated with the different techniques.

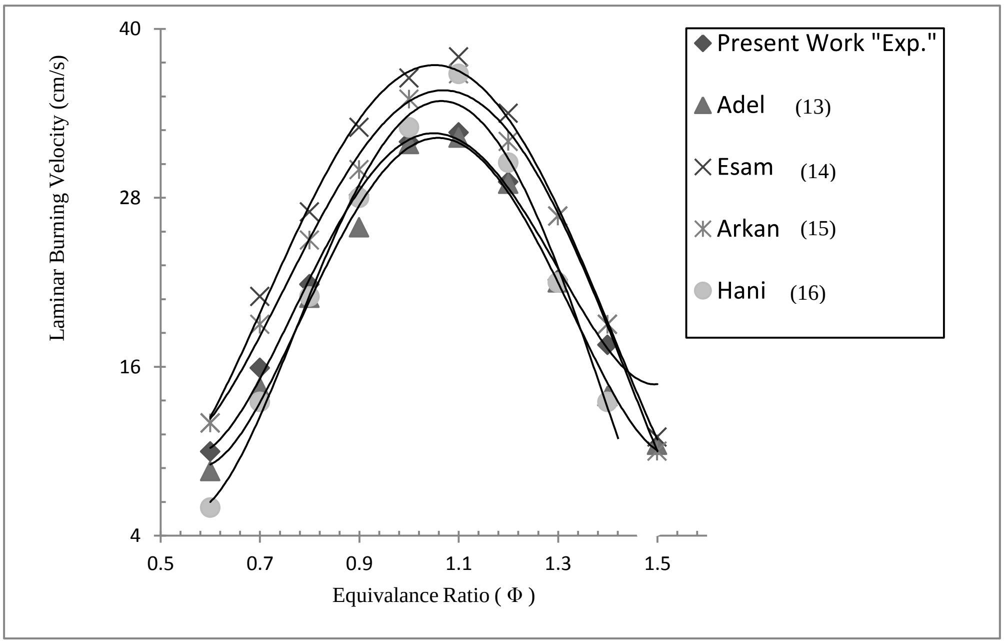

Fig. (8): Comparison of present results with the published results

6. Conclusions

1 - The laminar flame speed and the burning velocity increase with increasing oxygen enrichment level.

2 - The experimental results in conditions of (butane – air) mixtures, give a good agreement with the available published results.

3- Zel'dovich numbers and flame thickness are decrease with oxygen enrichment.

Abbreviations

C_p	*Specific heat at constant pressure (kJ / kg.K)*
E/R_u	Activation temperature (K)
I	Flame thickness factor
ILPG	Iraqi liquefied petroleum gas
N	Mole ratio : the ratio of number of moles of reactants to that of products
N_p , N_r	Number of moles for product & reactant respectively
P_u	Initial pressure of mixture (atm.)
r_b	Flame radius (mm)
R_u	Universal gas constant (kJ / kmol.K)
S_F	Laminar flame speed (cm / sec)
S_L	Laminar burning velocity (cm / sec)
T_b	Burned (or adiabatic) gas temperature (K)
T_m	Mean temperature (K)
T_u	Unburned gas temperature (K)
Ze	Zel'dovich number
δ	Flame thickness (mm)
λ	Thermal conductivity (J/m.s.K)
ρ_b	Burned gas density (kg / m^3)
ρ_u	Unburned gas density (kg / m^3)
Φ, $\emptyset$	Equivalence ratio
Ω_{oxg}	Volume fraction of oxygen
ΔL	Distance between two photodiodes (cm)
Δt	Measured time between two photodiodes (sec)

8. References

1. Baukal C.E., (1998), "Oxygen – Enhanced Combustion", by CRC Press LLC.
2. Gao,Y. & Chow,W.K. ,(2005), "A Brief Review on Combustion Modeling" , International Journal on Architectural Science, vol.6, No.2, pp.: 38 – 69 .
3. Stephanie de Persis et al, (2013),"Effects of O_2 enrichment and CO_2 dilution on laminar methane flames", Energy 55, pp.: 1055 – 1066 .

4. KonnovA.A,Dyakov IV, (2005), " Measurement of propagation speeds in adiabatic cellular premixed flames of CH_4+O_2+CO_2",Experimental Thermal and Fluid Science 29(8),901 – 7,.
5. Andrews G.E. & Bradley D., (1972-a)," Determination of burning velocity, a critical review", Combustion and Flame, 18, pp.:133 – 153.
6. Andrews G.E. & Bradley D., (1972-b)," The burning velocity of methane – air mixtures", Combustion and Flame, 19, pp.:275 – 288,.
7. Olikara C. & G.L.Borman, (1975), "A Computer Program for Calculating Properties of Equilibrium Products with Some Application to IC Engines", SAE Paper No.750468,
8. Blint,R.J., (1986), "The relationship of the laminar flame width to flame speed", Combustion Science and Technology 49(1),pp.: 79-92,.
9. Perry, S., (1984),"Chemical Engineering Hand Book", New York, McGraw – Hill, 6th ed.
10. Sun CJ,Sung CJ,Law CK," Dynamics of weakly stretched flames: Quantitative description and extraction of global flame parameters", Combustion and flame , vol.118,No.1-2,pp.:108-128, (1999).
11. KUO, K.K., (1986),"Principle of Combustion", New York, John Wiley and Sons .
12. Toong, T.Y., (1983),"The Dynamics of Chemically Reacting Fluids" , New York McGraw-Hill,
13. Adel M.S., (2006), "Effect of Initial Pressure upon Laminar Burning Velocity of Paraffin’s Gaseous Fuel in Closed Vessel", Ph.D. thesis, University of Technology, Baghdad, Iraq, .
14. Esam, M. M. Al-Salman, (2002), "The Effect of Tube Diameter on the Laminar Flame Propagation of the Gaseous Hydrocarbons-Air Mixtures", Ph.D. Thesis, University of Technology, Baghdad, Iraq
15. Arkan, F.S., (2000), "Effect of Initial Temperature on Flame Propagation through Tube for (Methane, Propane, LPG and Butane)-Air Mixtures", M.Sc. Thesis, University of Technology, Baghdad, Iraq, .
16. Hani M.A., (1998)." A Study on Laminar Flame Propagation of propane, LPG, Butane and Hydrogen – air Mixtures through Tube", M.Sc. Thesis, University of Technology, Baghdad, Iraq, .