BURNING VELOCITIES & FLAME TEMPERATURES OF ETHANOL & BUTANOL-AIR MIXTURES [+]

Esam M. Mohamed [*]

Abstract:

Burning velocities of mixtures of air with Ethanol and Butanol have been obtained from the measured flame speed and flame temperature using a tube method for fuel – air equivalence ratios (ϕ=0.7-1.4) during the pre pressure period of combustion, employing a detailed density correction scheme by using a thermocouple technique.

Maximum values of burning velocity, flame speed, and flame temperature were found to occur at an equivalence ratio (ϕ=1.1) independently of fuel type. Burning velocities of Ethanol & Butanol-air mixtures measured at (301K) and (100kPa.) pressure at a tube of (0.067m) diameter, yielded a maximum velocity of (0.489m/s) for Ethanol – air mixture and (0.46m/s) for Butanol – air mixture. The results for Ethanol-air mixture agree well with the little available published results.

سرعة انتشار اللهب ودرجة حرارة اللهب لخلائط الايثانول والبيوتانول مع الهواء

عصام محي محمد

المستخلص:

تم في هذا البحث قياس سرعة انتشار اللهب الطباقية (Laminar Burning Velocity) لخلائط الايثانول و البيوتانول مع الهواء المسبق الخلط باستخدام طريقة الأنبوب وتقنية المزدوج الحراري ولمدى واسع من النسب المكافئة للخليط (ϕ=0.7-1.4)حيث تم قياس الزمن الذي تستغرقه جبهة اللهب لقطع مسافة محددة. وتم قياس درجة حرارة اللهب عن طريق تاثير الطاقة المنبعثة من جبهة اللهب.

كما تم دراسة تأثير نسبة الخلط على سرعة انتشار اللهب الطباقية. جميع القياسات تمت خلال فترة ثبوت الضغط (Pre-pressure period) وذلك لاستخدام طريقة نسبة الكثافة (Density Ratio Method) في حساب سرعة انتشار اللهب.

سرعة انتشار اللهب الطباقية لخلائط الايثانول – هواء التي تم الحصول عليها في درجة حرارة (301K) و ضغط (100kPa) باستخدام انبوب قطره (0.067 m) مقاربة للنتائج العملية المنشورة مما يؤكد دقة الطريقة والأجهزة المستخدمة في القياس. سرعة انتشار اللهب القصوى لخلائط الايثانول – هواء ولخلائط للبيوتانول–هواء كانت (0.489 m/s) و (0.46m/s) .عند نسبة خلط مكافئة (ϕ=1.1) على التوالي.

[+] **Received on 11/6/2009 , Accepted on 24/8/2010 .**

[*] **Technical Institut / Babylon .**

Introduction:

The laminar burning velocity is one of the most essential parameters for analysis and performance predictions of various combustion engines. It is the velocity, relative to the unburned gas, with which a plane, one-dimensional flame front travels a long the normal to its surface. The majority of turbulent combustion models require knowledge of laminar burning velocity of the fuel-air mixture as a function of the mixture strength. Also reliable experimental data are needed in order to test and calibrate thermokinetic combustion models which have been quite successful for combustion predictions of simple hydrocarbon fuels.

Burning velocities of various hydrocarbon fuels have been measured by several investigators in order to shed some light on the mechanism of flame propagation [1], and to test and validate thermokinetic models and reaction mechanisms of hydrocarbon combustion.

Growing concern about alcohol fuel utilization has also necessitated burning velocity data for studies related to engines fueled with alcohol. Although the majority of alcohol fuel applications at presents are in the form of hydrocarbon – blends, no greater body of data have been reported on the burning rates of Ethanol & Butanol air mixtures in archival literature except that for Ethanol – air mixtures. So, fundamental experimental data on combustion characteristics of alcohol fuels are very limited [2]: in particular only a few studies have been reported for high pressure and temperature conditions [3,4].

The purpose of this paper is to present the results of experimental measurements of burning velocities of the two fuel flames, namely Ethanol & Butanol burning in air using tube method and thermocouple technique. Also reported is the dependence of burning velocity on mixture strength.

Experimental Apparatus and Procedures:

A horizontal tube with an internal diameter of (0.067m) and length of (1.5m) was used for the measurements of flame speed and flame temperature during the pre- pressure period of combustion. A schematic diagram of the equipment is given in Fig. (1).

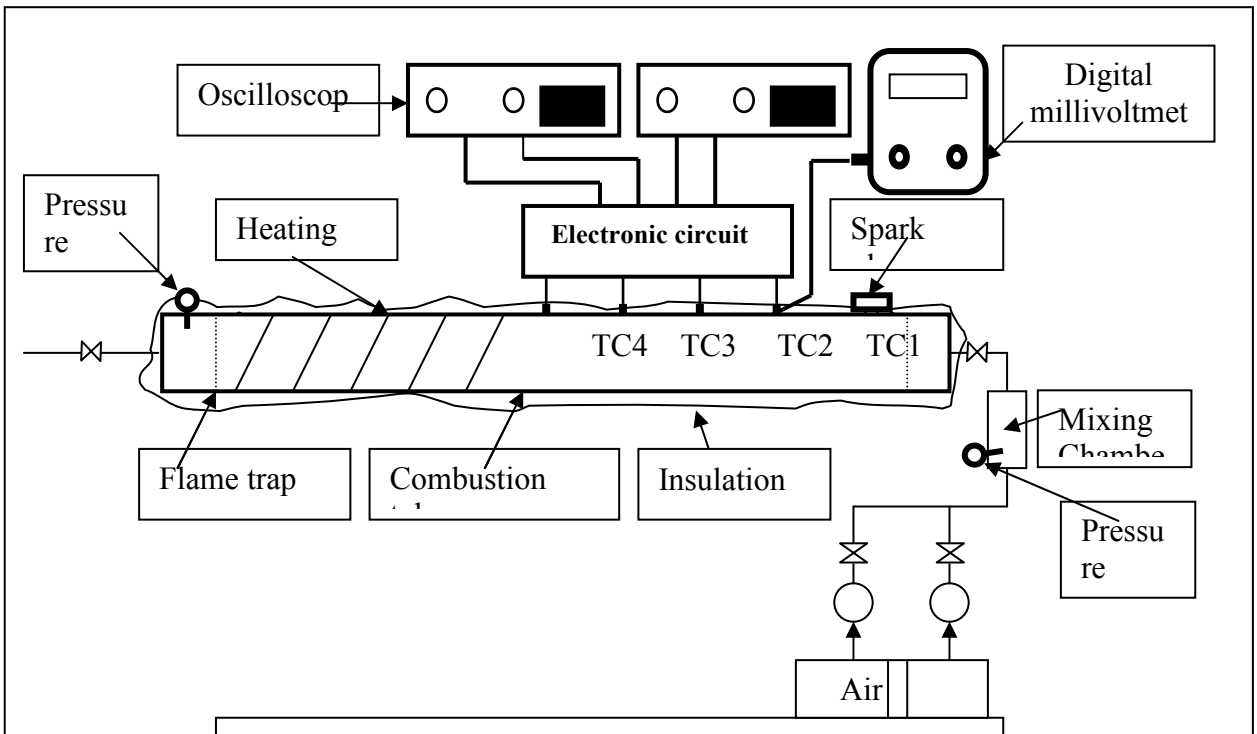


Fig. (1) Schematic diagram of the experimental apparatus.

Connection of other parts to the tube is very easy by welding to have closed system for getting a nearly complete vacuum. The system can be used for different types of gaseous & liquidus fuels under different conditions.

The fuel–air mixture was prepared inside a mixing chamber which had previously been purged and evacuated to (0.00l kPa), depending on the partial pressures of the constituents according to Gibbs-Dalton law. After purging and evacuation operations, a certain amount of fuel was evaporated and introduced into the mixing chamber until reaching the requisite pressure depending on its partial pressure fraction relative to the total pressure of (5 bar) and this was followed by introducing dry air to a final pressure of five bar. Pressure measurements of this step were done by the vaccum pressure gauge of the mixer. The manufacturer made the calibration operation for this pressure gauge, its specifications and applications were found in the special appendix of the device. It is mentioned that the device is very efficient in industrial application. This device was also inspected in Central Organization for Standardization and Quality Control. It is shown that the device is very efficient.

For emphasizing that mixtures were prepared under correct conditions, laboratory analysis was used to find out the mixture contents at different equivalence ratios. This analysis was made in Oil Refineries Administration, Dura Refinery. It is found that the results of analysis are closed to the experimental values for the fuel percentage in the mixtures. The results are as shown in the table below.

Comparison between experimental values and analysis values for fuel percentage in the mixture.

	Φ	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4
Ethanol C_2H_5OH	Exp. Value	4.67	5.30	5.96	6.54	7.15	7.75	8.34	8.92
	Anal. Value	4.61	5.41	5.89	6.72	7.25	7.87	8.38	8.98
Butanol C_4H_7OH	Exp. Value	2.60	2.96	3.32	3.68	4.03	4.38	4.73	5.07
	Anal. Value	2.72	3.23	3.58	3.72	4.13	4.22	4.81	5.17

The combustion tube was also purged and evacuated to (0.001kPa). Pressure measurements of this step were done by a pressure gauge of the same type mentioned above. The mixture was admitted from the mixer to the combustion tube at one atmosphere and heated when necessary in order to obtain the required initial mixture temperature and left for five minutes to become quiescent and homogeneous before ignition at the open end of the tube. The mixture was ignited by electric spark induced to ignite the mixture from an ignition unit giving ignition energy of about 3 Joule. Aflame kernel is produced by ignition, this kernel grows to become flame front that moves through the unburned mixture at a speed which represent the flame speed (S_f).

The combustion tube was equipped with four thermocouples. The types of these thermocouples were calibrated and decided to meet the expected range of flame temperature. The calibration of these devices was accomplished firstly using a standard thermometer in order to check the accuracy of measurement of these probes. Electric heater was put in an isolated water vessel. It contains a heater regulator to vary the water temperature. The standard thermometer and the four-thermocouple junctions were put in the water vessel. The water temperature was recorded before heating operation. After heating to a certain temperature the electric heater was switched off and the water temperature was recorded at the start of the cooling to the initial water temperature that was recorded before heating. Comparison was made between the recorded temperatures, by using standard thermometer and the thermocouples. This process was repeated at higher temperatures to get the calibration curve that are shown in figure (2) for one thermocouple as the others give nearly the same trend. The comparison between standard thermometer and thermocouples show a good agreement, which indicates an accurate measurement result.

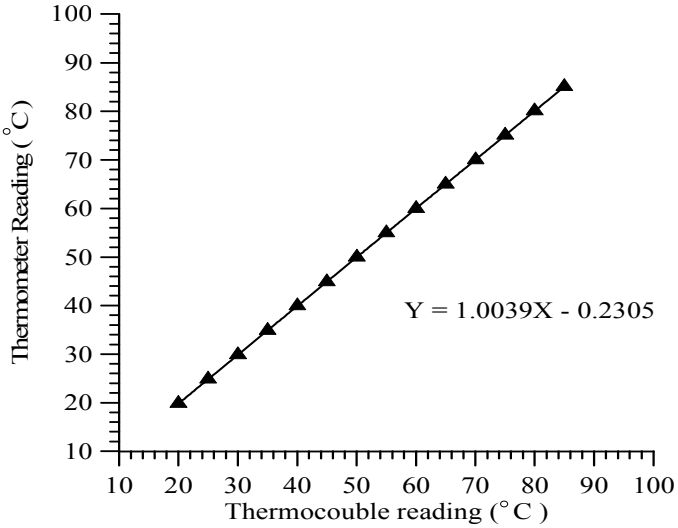


Fig. (2) Calibration curve of the thermocouples.

The calibration of these devices was accomplished again using the combustion tube and a standard photodiode to validate the measurements by these thermocouples at higher temperatures. The standard photodiode and the thermocouples were fixed in the tube wall and subjected to heat that generates during the flame propagation at a certain equivalence ratio. Afterwards two dual channel oscilloscopes (calibrated by the manufacturer and inspected in Central Organization for Standardization and Quality Control) detected the values of generated voltage from the standard photodiode and any three thermocouples at the time when the flame propagates inside the combustion tube. This step was repeated several times at higher equivalence ratio (up to ϕ=1.1, as the maximum flame temperature attained), in order to vary the radiation intensity that falls on the standard photodiode and the thermocouples. One value of the voltage signals was measured by a direct connection of a digital millivoltmeter with the fourth thermocouple junction, to be compared with the oscilloscopes reading to get more accurate readings.

The resulting voltage values were recorded and plotted to get the calibration curve between the standard photodiode and the used thermocouples. Figure (3), shows this calibration curve for one thermocouple as the others show the same trend.

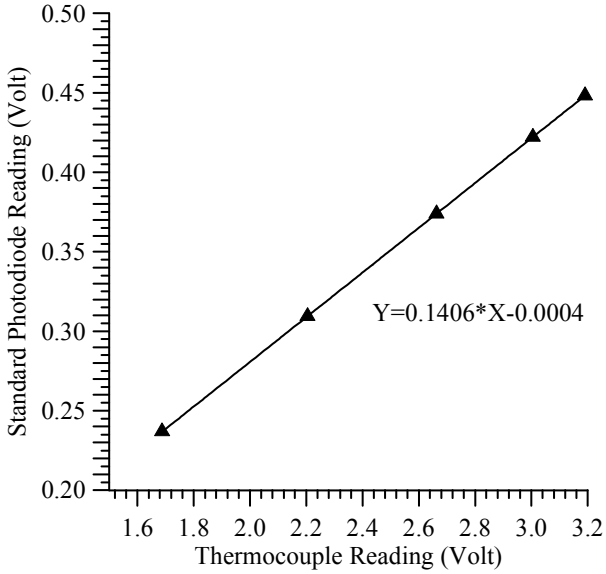


Fig. (3) Calibration curve of the thermocouples.

The thermocouples are (0.25m apart), which is suitable to tube length. The first thermocouple is (0.2m apart) from the spark ignition plug, this distance is very important to ensure that measurements occur at fully developed flame front [1]. The length of the test section of the combustion tube becomes (0.95m), and the remaining part is (0.55m) in length to allow pressure rising at the end of the tube to carry measurements at pre-pressure period of combustion.

For all experiments, as the flame traveled along the tube, it passes the four thermocouples upon which it imposed a transient temperature rise. The resultant four voltage signals were detected by the two dual channel oscilloscopes, two for each oscilloscope, so the magnitude and the time of any two successive signals was obtained and used to calculate the flame temperature and flame speed respectively.

The standard photodiode generates voltage of (1 Volt) when the radiation intensity is directed at (9.614) Watt. The photodiode diameter is (2 mm). The values of the generated voltage of the used thermocouples are plotted on the calibration curve after each test to find out the opposite voltage for the standard photodiode and consequently the falling radiation intensity on the used thermocouple. Then the emission power was obtained and used to obtain the flame temperature by using Stefan-Boltzman law [$E=\sigma*T_b^4$], [5]. The results were also compared with that obtained by direct measurement of flame temperature using a digital thermometer connected directly with any thermocouple. A reasonable agreement was found which validate the used method of measurements at high temperatures.

The electronic circuit was equipped with four amplification units for the four channels of measurements and calibrated to get the same voltage for the same intensity of radiation that falls upon the thermocouples to ensure a fully developed flame front occurrence.

Experimental Results and Discussion:

1- The flame speed and temperature:

The flame speed (S_f) and flame temperature (T_b) was measured via thermocouples as mentioned previously. The results were obtained for a wide range of Ethanol & Butanol – air mixture. Figures (4&5) respectively show the flame speed and flame temperature for the both types of fuels. It can be observed that for a given fuel - air mixture, the flame speed and flame temperature increase as the mixture strength went from the lean limit towards the stoichiometric. On the rich side, when the amount of fuel increases in the mixture the amount of heat lost as a result of incomplete combustion becomes greater. Then, the heat liberated was decrease and decreases the flame temperature and flame speed as a result of that reduction.

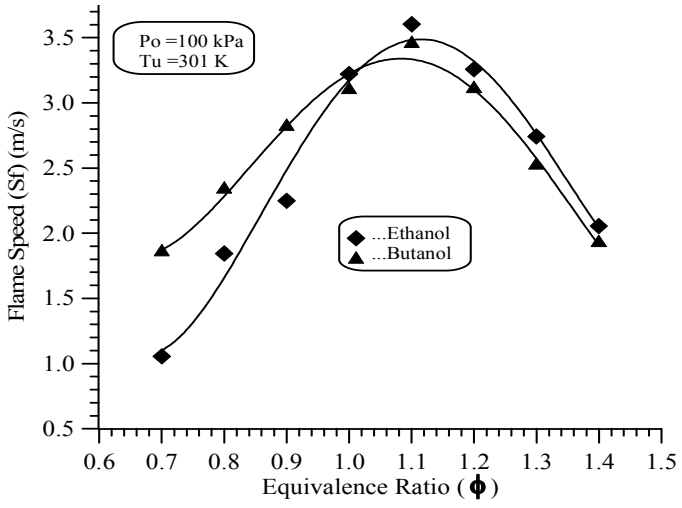
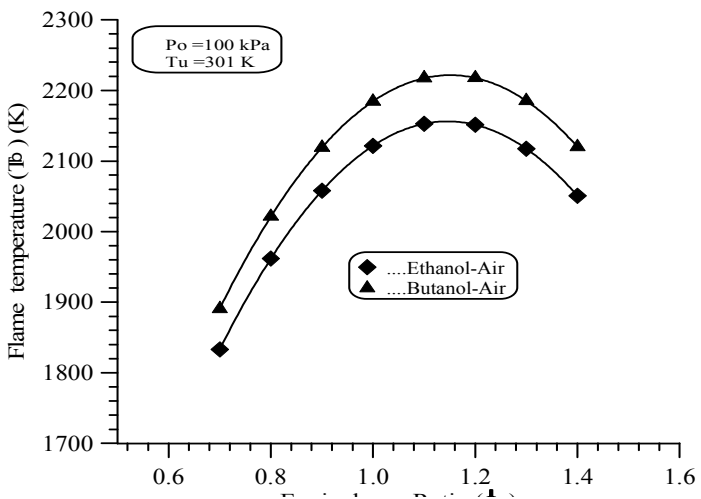


Fig. (4) Flame speed of Ethanol and Butanol - Air mixtures.



The results indicate a significant dependence of flame speed and temperature upon the type of fuel (i.e the number of carbon atoms). In figure (4), it can be observed that with increasing the number of carbon atoms the flame speed decreases (especially at high values of equivalence ratio), while the flame temperature increases as shown in figure (5). This behaviour is mainly due to change in thermal diffusivity of fuel, which is a function of fuel molecular weight [6].

2- Burning velocity:

The burning velocity (S_u) can be obtained from the measured flame speed (S_f) by using the following equation [1].

$$S_u = \frac{\overline{\rho_b}}{\rho_u} . S_f \qquad \text{……..(1)}$$

Which is valid for the pre-pressure period of combustion, where (ρ_u) is the density of unburned mixture. The main difficulty in using this equation is the evaluation of the mean density of the burned gas ($\overline{\rho_b}$) as it is a function of the local temperature in the flame region.

If the variation of temperature through the flame region radius (r_b) is known, the following equation can be used to obtain the mean burned gas density [1].

$$\overline{\rho_b} = \frac{3}{r_b^3} \int_0^{r_b} \rho_b(r) \cdot r^2 \cdot dr \qquad \text{……..(2)}$$

Where ($\rho_b(r)$) is a function of local temperature which varies in radial direction.

It is a difficult task to determine the temperature profile through the flame region for different mixture strengths. In the present work, the method of evaluation of ($\overline{\rho_b}$) is the same as originated by [7]. A precise temperature distribution is not required, and the assumption of linear temperature variation through a flame front of thickness (δ) is sufficiently accurate. This transforms the problem to one of flame thickness measurement.

The flame thickness (δ) is difficult to define; strictly, it is the distance between the position where the first temperature rise occurs, due to heat conduction from the reaction zone, and the

position where the maximum burnt gas temperature is first attained. It was calculated according to the following equation given by [8].

$$\delta = \frac{2\bar{\lambda}}{s_u \cdot c_p \cdot \rho_u} \qquad \text{.....(3)}$$

In equation (3), ($\bar{\lambda}$) & (c_p) are the mean values of the thermal conductivity and specific heat through the flame region, which are constant values at specific temperature. Figure (6) show the variation of flame thickness with the mixture strength for both types of fuel.

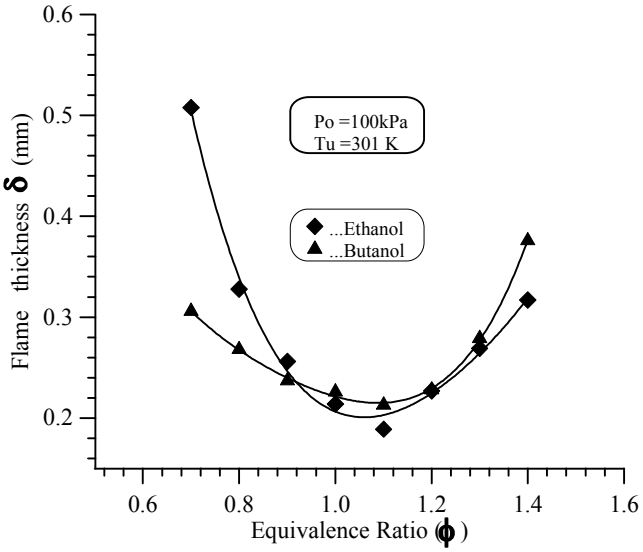


Fig. (6) Flame thickness of Ethanol and Butanol - air mixtures.

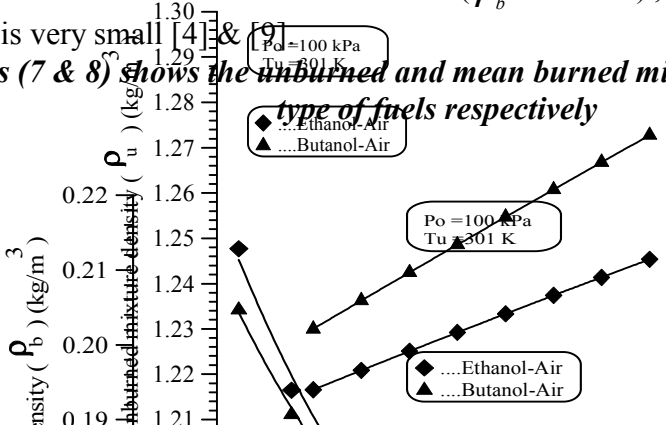
This parameter increases rapidly as the flammability limits are approached. Minimum value of flame thickness is reached near optimum air-fuel ratio and this leads to more accurate numerical values of burning velocity.

Using equation (3) and the following linear temperature profile for $(r_b\text{-}r) \leq \delta$ given by [8] in equation (2), gives an estimate of the actual mean density of the burned mixture.

$$T = \frac{r_b(T_b - T_u) + \delta \cdot T_u}{\delta} - \frac{(T_b - T_u)}{\delta} \cdot r \qquad \text{.....(4)}$$

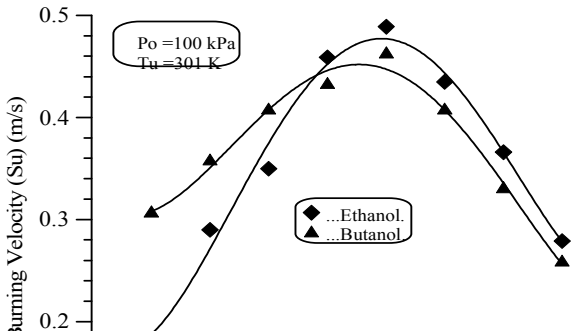
The present results based on a flame radius ($r_b = 0.025m$), as the corresponding cut-off pressure rise is very small [4] & [9].

Figures (7 & 8) shows the unburned and mean burned mixtures density for the both type of fuels respectively



To validate the method and the apparatus used in this work, a set of measurements were carried out with stoichiometric methane-air mixtures at (300K) and (100kPa), to be compared to reported burning velocity data, as the majority of experimental studies dealing with the determination of laminar burning velocity have been devoted to methane-air mixtures [1 & 7], and as a results, there exists a considerable amount of data on burning characteristics of methane-air-mixtures. The present results yielded a velocity of (0.42m/s ±0.02) for stoichiometic methane- air mixture, which is in very good agreement with the published data by either hot wire or double-ignition methods, and this confirms the validity of the method and apparatus used.

The variation of the laminar burning velocities of Ethanol & Butanol with mixture strength at (301K) unburned mixture temperature and (100 kPa) pressure is shown in figure (9). The data points at each equivalence ratio (ϕ), represent the mean values of more than ten repetitive experiments.



All the two fuels show maximum burning velocities at the same equivalence ratio (ϕ=1.1). The occurrence of maximum value of burning velocity at the rich side of the mixture and not at the correct chemical mixture is one of the results of dissociation at high temperature. When the released energy is completely used to heat the combustion products, the resulting temperature may attain the highest level. At such a temperature, however the combustion products dissociate into fractions of molecule, e.g., atoms & free radicals [10].
The dissociation leads to the formation of ionized oxygen atoms (O), these atoms are in equilibrium with the burned gases in case of stoichiometric mixture. But for slightly rich mixture, due to the formation of (CO), an exothermic reaction takes place between (CO) & (O), which leads to the formation of (CO_2) and release additional amount of energy that acts to raise the flame temperature, flame speed and as a result the burning velocity.
When the amount of fuel in the mixture increases substantially on the rich side, the amount of heat lost as a result of the incomplete combustion becomes greater than that liberated as a result of the reaction between the ionized oxygen atoms and the carbon monoxide molecules. So, the maximum flame temperature occurs at slightly rich mixture and then decrease with increasing of mixture strength on the rich side and decreases the flame speed and burning velocity.

Ethanol exhibits higher burning rates than those of Butanol for stoichiometric and rich mixtures do and lower rates for lean mixtures.

The results of experiments with Ethanol – air mixtures compared to the available experimental data are shown in figure (10). The maximum burning velocity of ethanol-air mixtures appears to be (0.48m/s) approximately according to the published data for an initial mixture temperature of (300K). Present study yielded a velocity of (0.489m/s) for Ethanol and (0.46m/s) for Butanol-air mixtures at (301 K) initial mixture temperature. Measured velocities at other equivalence ratios of Ethanol-air mixtures are in agreement with the published data and this confirms the validity of the method used.

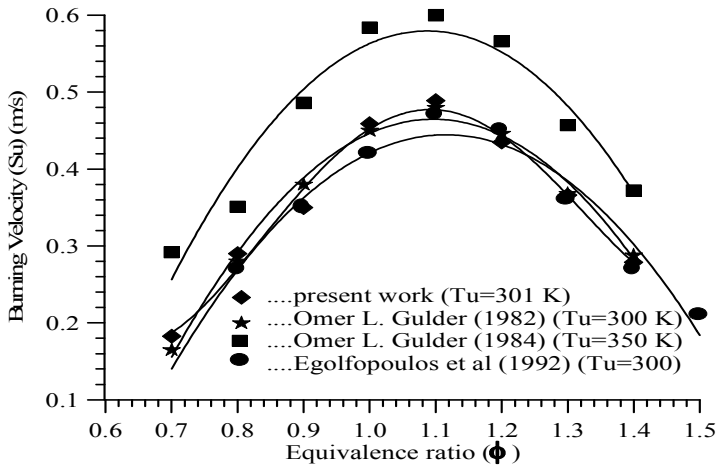


Fig. (10) Comparison of Burning velocity of Ethanol - Air mixtures.

Conclusions:

Laminar burning velocity, flame speeds and flame temperatures for ethanol & butanol-air mixtures were measured over a wide range of equivalence ratio. The experimental results obtained suggest that the density ratio method and the tube method with the thermocouple technique, by which the measurements were confined to the pre-pressure combustion period, yield reliable burning velocity data.

For ethanol and butanol-air flames, the burning velocity (Su) increases with increasing (ϕ) for the fuel-lean region, while (Su) decreases with increasing (ϕ) for the fuel rich region.

Ethanol exhibits higher burning velocities than those of butanol for stoichiometric and rich mixtures, and lower rates for lean mixtures.

The laminar burning velocities for Ethanol-air flames were compared with the little available data from other researchers. There is good agreement between our data and data by Egolfopulous et al. and Gulder for all the equivalence ratios.

The maximum burning velocity of ethanol appears to be (0.48m/s) approximately according to the published data for an initial mixture temperature of (300K). Present study yielded a velocity of (0.489m/s) for ethanol – air mixture and (0.46m/s) for butanol – air mixture.

Nomenclature:

Su	Laminar burning velocity (m/s.).
S_f	Laminar flame speed (m/s.).
T_u	Unburned gas temperature (K).
T_b	Burned gas temperature (K).
E	Emissive power per unit area (Watt/m^2).
σ	$5.669*10^{-8}$ W/m^2.K^4, Stefan-Boltzman constant.
ρ_u	Unburned gas density (kg/m^3).
$\overline{\rho_b}$	Mean burned gas density (kg/m^3).
ϕ	Equivalence ratio.
TC	Thermocouple.
δ	Flame thickness (mm).
$\overline{\lambda}$	Mean thermal conductivity of flame region (W/m.K).
Cp	Mean specific heat of flame region (J/mol.K).

References:

1. Andrews, G. E. and Bradley, D. "Determination of burning velocities: A critical review" *Combustion and Flame*, Vol.18, pp. 133-153, 1972.
2. Gulder, O.L. "Burning velocities of Ethanol-Isooctane blends", *Combustion and Flame*, Vol. 56, pp.261-268, 1984.
3. Metghalchi, M. and Keck, J.C. "Burning velocities of mixtures of Air with Methanol, Isooctane, and Indolene at high pressure and temperature", *Combustion and Flame*, Vol. 48, pp.191-210, 1982.
4. Gulder, O.L. "Laminar burning velocities of Methanol, Ethanol and Isooctane-air mixtures", *Nineteenth Symposium (international) on combustion / The combustion institute*, pp.275-281, 1982.
5. Holman, J.P. "*Heat Transfer*", McGRAW-HILL Kogakusha, Ltd., 1976.
6. Putman, A. A. , Ball, D. A. and Levy, A. "Effect of fuel composition on relation of burning velocity to product of quenching distance and flashback velocity gradient", *Combustion and Flame*, Vol.37, pp. 193-196, 1980.
7. Andrews, G. E. and Bradley, D. "The burning velocity of Methane-Air mixtures", *Combustion and Flame*, Vol.19, pp. 275-288, 1972.
8. Spalding, D.B. "*Combustion & Mass Transfer*", Pergamon, Oxford, 1979.
9. Andrews, G. E. and Bradley, D. "Determination of burning velocity by double ignition in a closed vessel", *Combustion and Flame*, Vol.20, pp.77-89, 1973.
10. Chang, S. L. and Rhee, K.T. "Adiabatic flame temperature estimates of lean fuel –air mixtures", *Combustion science and technology,* Vol. 35, pp.203-206, 1983.
11. Egolfopoulos, F. N., Du, D. X. and Law, C. K. "A study on Ethanol oxidation kinetics in laminar premixed flames, flow reactors and shock tubes", Proc. Combust. Inst. 24, pp. 833-841, 1992.