PRACTICAL MEASUREMENTS OF PREMIXED LAMINAR BURNING VELOCITIES AND MARKSTEIN NUMBERS OF IRAQI DIESEL-OXYGENATES-AIR BLENDS

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ABSTRACT

Laminar burning velocities and Markstien length for blends of Iraqi diesel-oxygenates (methanol, ethanol, subflowers biodiesel and yellow grease biodiesel)-air premixed flames are investigated using the spherically expanding flame with central ignition, using constant volume and thermocouples connected to data acquisition system. Unstretched laminar burning velocity, Markstein lengths, Lewis number, Zeldovichnumber and Karlovitz number were obtained at wide range of equivalence ratios (Ø from 0.2 to 1.7).

The Study indicates that although the tested blends are diesel-oxygenates, laminar burning velocities give an obvious difference which demonstrates that thr molecular composition has a great effect on laminar burning velociries of fuels. Maximun laminar burning velocity values occurs around equivalence ratios Ø=1.1. Increasing equivalence ratio influnced Markstein lengths to be decrease for the tested blends-air mixtures. The Zeldovich number maximum values obtained at stoichiometric equivalence ratio (Ø =1.0). The results show that the Markstein lengths were relatively independent of Karlovitz numbers.

Keywords: laminar burning velocity; ethanol; methanol; sunflower oil; yallow greeze, premixed laminar flame, Markstein number; Lewis number; Zeldovich number, Karlovitz number.

قياسات عملية لسرع الأحتراق الطباقية ورقم ماركستين لخلائط ديزل- مؤكسدات عراقية

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الخلاصة :-

تمت دراسة سرع انتشار اللهب وأطوال ماركستين لخلائط ديزل- مؤكسدات عراقية (ميثاول، ايثانول، ديزل حيوي من زيت عباد الشمس وزيوت نباتية مستخدمة) والهواء المسبقة الخلط، باستخدام تمدد لهب كروي مع اشعال مركزي، وباستخدام حجم ثابت ومزدوجات حرارية متصلة بنظام اكتساب المعلومات. وتم الحصول على سرعة انتشار اللهب غير المتمدد

(الملموم)، طول ماركستين، رقم لويس، رقم زولدفيتش ورقم كارلوفيتش، لمدى واسع من النسب المكافئة (Ø من 0.2 لغاية 1.4).

تبين الدراسة أنه بالرغم أن الخلائط المختبرة هي ديزل– مؤكسدات، فان سرعة انتشار اللهب لها تختلف بشكل واضح، بسبب التركيب الجزيئي الذي له تأثير كبير على سرعة انتشار اللهب للوقود.تظهر أعلى قيم سرع انتشار لهب للخلائط المختبرة هي لنسب مكافئة قريبة من (Ø =1.1). يقل طول ماركستين بزيادة النسبة المكافئة لخلائط الهواء–وقود المدروسة، وتم الوصول الى أعلى قيم لرقم زولدفيتش عند النسبة المكافئة المثالية (Ø =1.0). بينت النتائج أن أرقام ماركستين مستقله نسبيا عن أرقام كارلوفيتش.

NOMENCLATURE

Ka	Karlovitz number	
Le	Lewis number	
L_b	Markstein length	
Ma	Markstein number	
Ze	Zeldovich number	
S_n	Stretched laminar burning velocity	(m/sec)
S_l	Unstretched laminar burning velocity	(m/sec)
r_u	Flame radius	(mm)
T_{ad}	The adiabatic flame temperature	(K)
E_a	Activation energy	(J/mole)

Greek symbols

α	Stretch rate	(s^{-1})
δ_l	Laminar flame thickness	(mm)
Ø	Equivalence ratio	
ρ	Mixture density	(kg/m^3)
λ	The thermal conductivity of unburned mixture	(W/m K)
f^o	Mass burnung flux	(g /cm s)

Subscript

n	Properties associated with the stretched flame
l	Properties associated with the unstretched flame

INTRODUCTION

The problems of diminishing fossil fuel reserves and extreme increments in greenhouse gases had led to extensive investigations for alternative fuels to power vehicles, ships and airplanes. Oxygenates materials like methanol, ethanol and vegtable oils can be used in internal combustion engines with only minor adjustments. The Utilization of oxygenates as additaves to diesel result in low hydrocarbon HC, CO and smoke emissions because of the oxygen molecules in its structure (Kapilan, 2008).

Methanol, ethanol and sunflowers oil are frequently indicated as alternative fuels. They can be produced in large quantities from agricultural products such as corn, wheat, sugar-cane, and wood, or from waste products such as sewage and municipal waste (Chaichan, 2010).
Methanol can be produced from NG, where Iraq is considered to be the country of third reserves in the world (Chaichan, 2011 & Abaas, 2010). Also, Ethanol is produced from dates and grapes by fermentation process in Iraq (Chaichan, 2010). While planting sunflowers and its oil manufacturing are available since years in Iraq (Chaichan, 2012).

Laminar burning velocity is an important physiochemical characteristic of the combustible mixture. It influences combustion duration, fuel burning rate and engine performance and emissions. Laminar burning velocity relies on mixture formation, primary pressure and temperature. The burning velocity is acquained as the velocity when unburned gases move in the direction normal to the wave surface through the combustion wave (Gu, 2010).

The laminar burning velocity depends upon the flame stretch rate; hence the former should not be measured without reference to the latter, preferably at the same reference surface (Bradley, 1998). Karlovitz was the first who demonstrated concepts such as flame extinction by introducing the concept of flame stretch, blow-off and stabilization. Stretch is the effective distortion or displacement of a flame surface. This distortion takes place due to hydrodynamic effects such as curvature, unsteadiness and flow non-uniformity. It is a combination of two factors (flame strain rate and curvature effects). It is the cause of deviation of the flame burning speed from that expected for the fuel-air mixture (Karlovitz, 1953).

Non-uniform diffusion is caused by unequal thermal and mass diffusivities of the deficient reactants.
This effect can be qualitatively represented by Lewis number. Lewis number is the ratio of thermal to mass diffusivity. It is an important parameter in any discussion on flame stretch. Lewis number combined with preferential diffusion (ratio of mass diffusivity of the deficient reactant to excess reactant) is used to represent the non-equidiffusion effects in a flame (Chen, 2009).

Markstein debates the influence of flame stretch on laminar burning velocities and suggested the relation $S_u = S_l + L\alpha$. In this expression S_l represents the unstretched flame speed,

α the flame stretch rate, and L is a proportionality factor that represents the sensitivity of the flame response to stretch rate. This factor bears the dimensions of length. It is commonly mintioned aso as the Markstein length. Markstein lengths represent the contradiction in the local flame speed due to the impact of external stretching, which is crucial in exhibiting the beginning of flame instabilities together with the stretch effect on flame extinction (Aung, 1997).

Markstein number *(Ma)* expresses for the effects of flame stretch that result in changes in laminar burning velocity. It is a function of the ratio of densities of unburned-to-burned gas, and the product of the Zeldovich number (dimensionless activation energy for the burning velocity) and (Lewis number^{-1}) (Bradley, 2008).

Laminar burning velocity can be measured by several experimental approaches utilizing different flame configurations such as spherical expanding flames using closed vessels (Burke, 2009; Halter, 2005), counter-flow or stagnation flames (Vagelopoulos, 1998; Huang, 2004), burner stabilized flat flames using heat flux method (Coppens, 2008; Hermanns, 2010) and Bunsen flames (Lewis, 1987; Ogami, 2006). Among these various techniques, the spherically expanding flame configuration is more identical to flame propagation in the engines and permits attaining the thermodynamic conditions (elevated pressures and temperatures) closed to those encountered in internal combustion (IC) engines (Rozenchan, 2002 & Vries, 2011).

The aim of this study is to distnguish the laminar burning velocities of Iraqi diesel-oxygenates blends. These velocities were studied for a wide range of equivalence ratios at constant initial temperatur and pressures. The study focuses on the effect of adding 20% of methanol, ethanol, yellow grease and sunflowers biodiesel on laminar burning velocity.

EXPERIMENTAL SETUP

The detailed description of the experimental rig used in this study can be found in (Saleh, 2006). Here, main charactristics of the equipment and test procedures used in the measurements are described. The experiments were conducted as **Fig. 1** reveals. The flame while its propagation inside the combustion chamber passing over many thermocouple junctions located or inserted inside the chamber. The thermocouple can be used as a sensor probe. The computer controlled system is used to read the flame velocity inside the cylinder. Six thermocouples were used, fixed inside the cylinder regularly distributed regularly as shown in **Fig. 1**. They are connected to computer in order to collect, process and display the data. An interface circuit is built between the sensors and the computer. The thermocouple signals are red by parallel ports.

To prepare the (fuel-air) mixture, a gas mixer was designed and constructed for mixing fuels and air. The main purpose of pre-mixing of the fuel-air mixture in the mixing unit rather than in the cylinder is to increase the total pressure of the mixture and consequently increase the partial pressure of fuel to increase the accuracy.

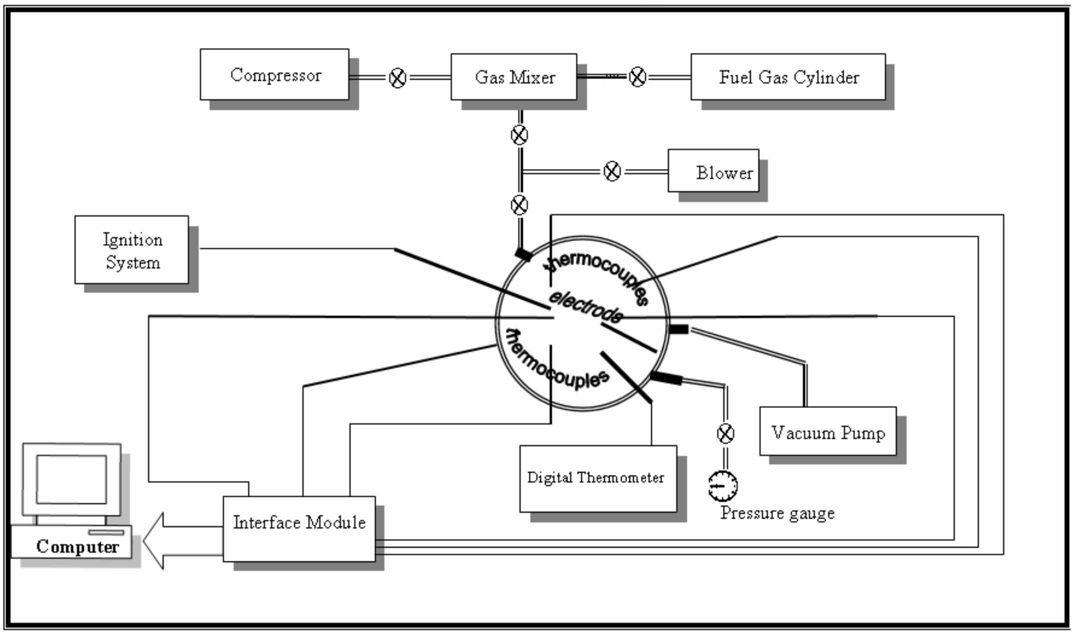

Fig. 1, Block diagram of experimental apparatus

The mixer is made of (iron-steel); it has a cylindrical shape without any skirt to improve the efficiency of mixing operation. Mixer dimensions are (435mm) length, (270mm) diameter and (5 mm) thickness. It withstands a pressure of more than (60 bar) and high temperatures. The mixing unit has five holes of (12.7mm) in diameter. Two holes are used to fix the pressure gauge and vacuum gauge, the third is for admitting the dry air to the mixing unit from the compressor through the filter dryer, the fourth hole is for admitting the fuel from the fuel cylinder through heat exchanger and pressure gauge regulator and the last hole admits the homogeneous mixture to the combustion chamber.

A cover is added on one side of the mixer in order to connect the fan to a power source of (12 volt) DC. Through a glass sealed electrical connections, which are sealed completely to prevent any leakage of fuel vapors to improve the mixing operation and obtain a homogenous mixture. All welding in the cylinder is done using Argon welding, and tested by increasing the internal pressure of the cylinder to avoid any leakage.

The mixture preparation process has a significant role in measuring the burning velocity. The process is based on partial pressure of mixture components according to Gibbs-Dalton Law to obtain an accurate equivalence ratio, because the ratio has effect on flame speed. The preparation of the mixture is done inside a mixing box, which was designed for this purpose.

The mixture is prepared by making the secondary mixing box is sufficiently purged of air or any previous mixture used in previous experiments, so that it reaches approximately (0.001 bar) pressure. The flashing process is done by admitting dry air to the box till it reaches a pressure of (1 atm). This process is repeated three times to be certain that the mixing box is completely flushed. After the third flushing process, the box will be vacuumed. The diesel-oxygenates blends will be admitted to the mixing box then vacuumed. This process is repeated for one or two times such that all the components in the mixing box will be filled with gas fuel only.

After the vacuum process of the mixing box is performed as shown in the first two steps a predetermined amount of fuel will be admitted to the mixing box according to the partial pressure (read from vacuum gauge) that is fixed on the box relative to one atmosphere such that the pressure valve stays closed during the process time to ensure that it is not damaged.

Dry air will be admitted to the box till it reaches mixture pressure of (1 atm). The vacuum pressure valve will be closed and the pressure valve will be opened, to compress the dry air using a compressor to a total pressure of (5bar) absolute for a certain equivalence ratio (lean, stoichiometric or rich). An electrical heater was supplied to the mixing box to preserve the mixture temperature at the desired degree (453 K in this study).

To obtain a homogenous mixture a mixing fan was operated for (3-5 minutes), the homogeneous mixture will be admitted to the cylinder from the mixer at the required pressure and sustained for (5 min) to mitigate before ignition to obtain a laminar flame and to obtain a mixture free of turbulence and eddies, then the mixture will be ready for ignition. Meanwhile, the computer and ignition system will be prepared. The fan is stopped for a while in order to prepare the combustion chamber for a new experiment. Fuel tank was cleaned after each blend used and dryed and filled with the other blend. The blends then were passed through electrical heat exchanger to be heated and vaporized.

Laminar burning velocity and Markstein numbers

Subsequent to mixture preparation as described above, a central spark ignition was ignited and flames were initiated. The procedures for obtaining the flame burning velocity were similar to those employed for gaseous mixtures (Bradley, 1998; Bradley, 1996). The amount of air m_a is expressed as:

$$m_a = \frac{p_u V}{R_g T_u} \qquad (1)$$

where R_g is the gas constant of air, while p_u is the initial pressure and T_u is the initial temperature of air in the combustion vessel. By measuring air mass flow rate (m_{air}), then the actual fuel/air ratio is defined as:

$$\text{Actual fuel/air ratio} = m_{fuel}/\ m_{air} = (m_{diesel}+m_{oxygenate})/\ m_{air} \qquad (2)$$

The stoichiometric fuel/ air ratio was calculated, and then equivalence ratio can be defined as (Abdul Haleem, 2007):

$$\emptyset = \frac{\frac{[D]}{[air]-\frac{[Oxy]}{([Oxy]/[air])_{st}}}}{\left(\frac{[D]}{[air]}\right)_{st}} \qquad (3)$$

Where [D] indicates the molar concentration of diesel fuel, [air] represents molar concentration of air and [Oxy] demonstrates the molar concentration of oxygenate in the blend.

For a spherically expanding flame, the stretched flame velocity (S_n) manifests the flame propagation velocity. It is derived from dividing the flame radius versus time data as

$$S_n = \frac{dr_u}{dt} \qquad (4)$$

Where (r_u) is the radius of the flame and (t) is the time. S_n can be directly obtained from the flame measurements by data acquisition system. Flame stretch rate (α) dipcts the dilating rate of flame front area, in a quiescent mixture is acquainted as:

$$\alpha = \frac{\Delta(\ln A)}{\Delta t} = \frac{1}{A}\frac{dA}{dt} \qquad (5)$$

Where (A) is the area of flame. For a flame front that outwardly and spherically expanding, the flame stretch rate can be simplified as:

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

Flame stretch may impact the laminar burning velocity, and it may controls the laminar burning velocities in the limits of small stretches, through a linear relationship between the flame speeds and the flame stretch rates; that is:

$$S_n = S_l - L_b\alpha \qquad (7)$$

Where (S_l) is the unscratched flame speed, and (L_b) is the Markstein length of burned gases. From equations (4) to (6), the stretched flame speed (S_n) and flame stretch rate (α) can be calculated. The unscratched flame speed (S_l) can be obtained as the intercept value at α = 0, in the plot of (S_n) against (α), and the burned gas Markstein number (L_b) is the negative value of the slope of S_n–α curve.

Markstein length reflects the flame stability. Positive values of L_b, which correspond to Lewis numbers larger than unity, and the flame speeds, will diminish with the increase in flame stretch rate. If any kind of protuberance comes out at flame front (stretch increasing), the flame speed at flame protruding position will be squelch, as a result the flame becomes stable. In compareson with negative values of L_b harmonize to Lewis number smaller than unity, which indicates that flame velocity is increased with the increasing of flame stretch rate. In this case, if any kind of protuberance appears at flame front, the flame speed at flame protruding position will be increased, and this decreases flame front stability (Qin, 2005 & Liao, 2004). A dimensionless Markstein number, Ma, can be obtained as:

$$Ma = \frac{L_b}{\delta_l} \qquad (8)$$

Here δ_l is laminar flame thickness given by $\delta_l = \nu / S_l$, where ν is the kinematic viscosity of unburned mixture and S_l is the unstretched laminar burning velocity of the flame (Bradley et al., 1998).

The stretch rate (α) can be nondimensionalized by characteristic flow time to obtain the Karlovitz number, *Ka*, as follows:

$$Ka = \alpha / (S_l / \delta_l) \qquad (9)$$

The Karlovitz number (*Ka*) is defined as the nondimensional stretch factor, using the thickness of the unstretched flame (δ_l) and the normal unstretched laminar flame velocity (S_l) to form a reference time (Kuo, 2005):

$$Ka = \frac{\delta_l}{S_l} k = \frac{Residence\ time\ for\ crossing\ an\ unstretched\ flame}{Characteristc\ time\ for\ flame\ stretching} \qquad (10)$$

Where, $k = \frac{\partial V_t}{\partial s}$, and ($V_t$) denotes the tangential component of the fluid velocity (*V*) ahead of the flame front and (*s*) a location on the flame front, then the stretch is a function of the tangential velocity along the flamefront. The flame experiences positive (negative) stretch, when (-*Vt*/-*s*) is positive (negative) (De Goey, 1999). For convenience, the Karlovitz number can be written as a sum of two parts due to the contribution from strain and curvature as follows:

$$Ka = Ka_s + Ka_c \qquad (11)$$

From eqs 6, 7, and 8, the following relationship is derived,

$$\frac{S_n}{S_l} = 1 - MaKa \qquad (12)$$

It is found that the decrease in the burning velocity of stretched flame becomes relatively smaller with decreasing *Ma* at the same Karlovitz number.

The Lewis number is appraised out of the ratio of the mixture thermal diffusivity to the mass diffusivity of the more deficient reactant. Lewis number combined with preferential diffusion (ratio of mass diffusivity of the deficient reactant to excess reactant) is used to represent the non-equidiffusion effects in a flame. For a conceptual understanding, planar flames will be chosen for this discussion on these effects. Consider mixtures with Le>1, the heat floss from the flame is greater than the mass diffusion into the flame, resulting in the flame having a lower flame temperature and vice versa. Mixtures for which the deficient reactant is more diffusive (Le<1), the flame region becomes more stoichiometric therefore, increasing flame temperature (Singh, 2010). The Lewis number can be defined as

$$Le = \frac{\lambda}{\rho_u C_p D_{AB}} \qquad (13)$$

Where λ is the thermal conductivity of unburned mixture, (ρ_u) is the density of unburned mixture, C_p is the specific heat of the unburned mixture, and D_{AB} is the binary mass diffusion coefficient of the deficient reactant (D_{AB} values were taken from (Welty, 2008)). It was pointed out since transport properties are fairly strongly dependent on temperature and mixture compositions, which vary significantly across the flame, *Le* should be deduced from the flame response (flame response: the instabilities that might increase the total burning by a flame do so by stretching and curving the flame. Because these strains themselves can significantly change a flame's local burning rate, the onset and growth rate of flame instabilities are directly affected by curvature (Dursi, 2003)).

In practice, it is suitable to derive the activation temperature, E_a/R, from the linear plot of 2 ln (f^0) against $1/T_{ad}$, as the following function was recommended (Sun, 1999):

$$\frac{E_a}{R} = -2\frac{d\ \ln\,(f^0)}{d(\frac{1}{T_{ad}})} \qquad (14)$$

where E_a is the activation energy (activation energy: the minimum energy required to srart a chemical reaction), R is the universal gas constant, and T_{ad} is the adiabatic flame temperature, f^0 is the mass burning flux, which can be obtained from the following equation:

$$f^0 = \rho_u S_l \qquad (15)$$

where ρ_u is the unburned gas density and S_1 is the laminar burning velocity.

Zeldovich number (*Ze*) demonstrates the mass burning flux dependance on the activation temperature. It is a dimensionless form of the overall activation energy (Bradley, 1998),

$$Ze = \frac{E_a}{R}\frac{T_{ad} - T_u}{T_{ad}^2} \qquad (16)$$

Materials

The commercial Iraqi diesel fuel was used in this study. This fuel charatrized with its meduim cetane number (CN=48.5 in this study) and high sulfer content (10000 ppm in this study). Ethanol (99.7% purity) was used in this work. It was distlated from Iraqi drink named (Araq) for several times to purfiy it from any residuals. Ethanol–diesel blended fuel was prepared by mixing solublizer and cetane number improver (1.5% by volume) together the ethanol (18.5% by volume), and then the mixture was blended with diesel fuel (80% by volume). This blend was named E20.

Methanol is charactrized by its low solubility in diesel fuel. A solvent consisting of oleic and iso-butanol was added (2% by volume). A cetane number improver was used (2% by volume) to increase methanol cetane number. Methanol (16% by volume) was mixed first with these substances, and then it was blended with diesel (80% by volume). This blend was named M20.

To prepare a biodiesel fuel from sunflower oil a transesterification process was used. This process consists of taking 200 ml of methanol and 3.5 g of sodium hydroxide (lye) in a beaker and mixed well for 5 min. One litre of Iraqi sunflowers oil (produced by General Company of Vegetable oils-Bagdad- Iraq) was added and stirred for 15 min at 65°C. The stirring was stopped and then the glycerin was allowed to settle down in the beaker. Later, the biodiesel (ester) was separated by washing and then boiled to remove the moisture. The resulted biodiesel was used in this work (20% biodiesel + 80% diesel fuel) without any additives. This blend was named B20.

To prepare the last blend 200 ml of alcohol and 3.5 g of sodium hydroxide (lye) were taken in a beaker and mixed well for 5 min. To this 1 liter of used vegetable oil (disposal from several frying restaurants in Baghdad) was added and stirred for 15 min at 65°C and contiue the process as described in the former paragraph. The resulted biodiesel was used in this work (20% biodiesel+80% diesel fuel). This blend was named W20.

Fuel properties of diesel fuel and the other four fuels are given in **Table 1**. All chemical tests were conducted at Chemical Engineering Department-University of Technology. These properties were compared with others from litratures and they were found comparable.

Uncertainity Analysis

In this study, the experiments were conducted at least three times for each condition, and the averaged values are used in the analysis. This procedure was used to ensure the repeatability of the results within the experimental uncertainty (95% confidence level). The accuracy of the thermocouple is 1 K, and the variation in initial temperature is 453 ± 2 K. Thus, the relative error in initial temperature is 0.566%. Mixtures are prepard according to the partial pressure of the consitituents. Uncertainties in the pressure measurements of the fuel vapor and air are less than 0.1%. Additionally, the 2.5% accuracy in measuring radius and accounting for random errors, results in an uncertainty of less than 5% in measurement of flame speed. For each condition, three tests were conducted to minimize random errors in the experimentally determined flame speeds and Markstein lengths. The avarage value was reported along with 95% confidence intervals from these experiments for each condition.

RESULTS and DISCUSSION

Spherical or cylindrical vessels are known to be most adequate for laminar flame speed measurements, because the flame front experiences uniform stretch effects and propagate isotropically through the mixture. Spherical flames can exist for mixtures close to the flammability limits due to stretch effects, extending the range of equivalence ratios that can be measured. Therefore, this configuration has become popular in the recent past for laminar flame speed measurements to provide accurate and reliable experimental data (de Vries, 2011).

1. System valdiation

Due to the lack of available literature data on the laminar burning velocities of Iraqi diesel-oxygenates blends, the first tests were conducted to measure the laminar burning velocities of methanol-air mixtures, and the results were compared with available data in previous literatures to validate the present measurement system. **Fig. 2** demonstrates the present measurments of the laminar burning velocities of methanol-air flames, compared with other experimental results from (Metghalchi, 1982, Liao, 2007, Saeed, 2004 and Wu, 2011). The comparison shows good accession, verifinf the high accuracy in measuring the laminar burning velocity.

2. Strech Flame Propagation Speed

Fig. 3 represents the stretched flame propagation speed versus the flame radius. The stretched flame propegation spead increases with the increase of flame raduis. This phenomenon reveals the relationship between flame speed and flame stretch. The stretched flame propagation speed increases with the increase of equivalence ratio M20 and E20 preceede diesel fuel while B20 and W20 staid behind it. As (Abaas, 2010 & Chaichan, 2010) litratures revealed, methanol and ethanol have higher burning velocities compared with the other oxygenates and diesel, which affect the resulted stretched flame propegation spead.

Fig. 4 illustrates that the stretched flame propagation speed shows a linear relationship with the stretch rate. The stretched flame propagation speed decreases with the increase of the stretch rate (decreasing flame radius). Thus, the slope of the (S_n–α) curve is negative and the Markstein length is positive. In this instance, the flame is stable to the diffusional thermal instability as stated by (Hassan, 1998). The slope of the S_n–α curve increases with increasing equivalence ratio as the figure shows.

The unstretched flame propagation speed versus the equivalence ratio for the tested blends is shown in **Fig. 5**. The relation between the equivalence ratio and S_l tends to take the bell shape. The burning velocity starts with low values near lower flammability limit in the lean mixture side and then increases as equivalence ratio increases until it reaches a maximum value at nearly the stoichiometric mixture. On the rich side, it begins to decrease again. The maximum burning velocity occurs at equivalence ratio of 1.1, which is similar to the conventional hydrocarbon fuels.

The lower values of the laminar burning velocity in the lean side could be explained due to the excess air, which dilute the reactant mixture ahead of the flame front. On the other hand, laminar-burning velocity decreases in the rich side due to incomplete combustion, which leads to decrease the flame temperature that tends to slow down the reaction rate.

Comparison of data with those of diesel fuel shows that the laminar burning velocity of M20 is always greater than any of the other blended fuels. This appears to be due to methanol addition effect. E20 has relatively closer values to M20, while W20 has the lowest values. Diesel fuel in the range of Ø=1 to 1.3 exceeded E20. This is due to its aromatic content which gives it a high pyrolysis and cracking rate as (Bradley, 1996) has reported.

3. Markstein Length

Markstein length rather than Markstein number is used to characterize the flame response to stretch in this study, because the flame thickness varies significantly when different definitions are used. The Markstein length is dependent upon the equivalence ratio and experimental conditions. As **Fig. 6** reveals, Markstein lengths give positive values in all cases over the experimental range, indicating that the flame is stable one.

Markstein length depends only on the Lewis number of the deficient reactant according to the asymptotic theory as (Bechtold, 2001; Law, 2000) demonstrated. In lean mixtures, the Markstein length depends on the Lewis number of the fuel, whereas in rich mixtures, the Markstein length depends on the Lewis number of oxidizer. The values of Markstein length that are calculated can be very different for lean and rich mixtures, especially for the heavy hydrocarbon air mixtures for which the fuel Lewis number can be quite large (Pradley, 1996).

This indicates that flame propagation accelerate with decreasing stretch rate as the flame propagates, here the (diesel/oxygenates blends-air) flames in this study are all stable to the diffusional-thermal instability. The maximum values of Markstein lengths were evaluated at equivalence ratio between (Ø=0.4-0.5), which is the range of diesel engines operation equivalence ratios.

4. Effective Lewis number

Fig. 7 illustrates the effective Lewis number of the diesel-oxygenates blends-air- laminar premixed flames versus equivalence ratio. The effective Lewis number decreases with the increase of equivalence ratio, and the effect of equivalence ratio is becoming larger when the mixture becomes leaner than (Ø =0.8). The enrichment of air with blends will result in the reduction of thermal diffusive coefficient leading to the reduction of effective Lewis number as (Bechtold, 2001) clarified. The study suggests that the flame front trends to be more stable at lean mixtures.

5. Zoldovich number

Since the development of the diffusive-thermal instability involves the change of the flame structure, the Zeldovich number should affect the cell development as demonstrated by (Jun, 2010). **Fig. 8** shows Zeldovich number of tested blends-air laminar premixed flames versus equivalence ratio. It can be seen that Zeldovich number increases with the increase of equivalence ratio till stoichometric condition, due to increments in the adiabatic flame temperature. However, the Zeldovich number shows a decreasing trend with mixture enrichment, which point out the dominant effect of adiabatic flame temperature on Zeldovich number.

Zeldovich number gets its maximum values under stoichometric condition, which is in agreement with the results of (Liao, 2004). Meanwhile, the Zeldovich number of M20 blends gets its maximum value preceded other blends.

6. Karlovitz number

Fig. 9 reveals experimental results of S_n/S_l as a function of Karlovitz number (*Ka*), for some specific equivalence ratios for the tested blends. The behaviour of S_n/S_l is found to rely on the equivalence ratio (Ø) and here is a linear relationship between *Ka* and S_n/S_l. That is, S_n/S_l decreases with decreasing Ø (increasing *Le*) at the same *Ka*. It should be noted that the slope of these lines coincide with Markstein number (*Ma*) for each blend.

The linear behavior of the burning velocity with Karlovitz number supports that the Markstein number is independent of the Karlovitz number as it was verified by (Aung, 1997). Also the generally low Karlovitz numbers obtained for all blends and equivalence ratios indicates small influence of stretch rate on diesel-oxygenates-air flames. As it was pointed out by (Bradley, 1996 and Aung, 1997), the Markstein length is a fundamental property of premixed laminar flames and it is necessary to measure it precisely.

CONCLUSIONS

The goals of the present paper have been to assess the combustion properties of Iraqi diesel oxygenates fuels and to outline and develop experimental database necessary for practical usage of these blends in Iraq. Centrally ignited, spherically expanding flames have been measured using thermocouples technology and data acquisition to determine the effect of equivalence ratio on the laminar burning velocities of blends (M20, E20, B20 & W20)–air mixtures. The stretch imposed at the flame front has been explored experimentally and the Markstein lengths are estimated to characterize its effect. The main points of the present paper are:

1- The measuring technique used in the present work was proved to be suitable for laminar burning velocity measurements. The comparisons of laminar burning velocity of methanol-air mixture with the results reported previously show a good agreement, which validates the present study.

2- An uncertainty analysis was presented. Uncertainties in equivalence ratios are a strong function of the accuracy of the pressure and temperature measurments used. Obtained uncertainties were less than 5% which was considered accebtable for pressent work.

3- The maximum value for the laminar burning velocity occurs at equivalence ratios near Ø=1.1. Richer or leaner mixtures result in a lower laminar burning velocity. At this equivalence ratio the initial temperature approaches its maximum values, affecting the unstretched flame propagation speed and the laminar burning velocity.

4- Markstein lengths decrease with the increasing equivalence ratio of tested blends–air mixtures, indicating that a leaner equivalence ratio decreases the diffusional-thermal instability of the flame front. Maximum Markstien length occurred at diesel engine eqivalence ratio range (Ø=0.4 to 0.5).

5- Lewis number decreases with the increase of equivalence ratio. The study suggested that the flame front tends to be more stable at lean mixtures.

6- Zeldovich numbers have been obtained. The Zeldovich number is increased with the increase of equivalence ratio till the stoichiometric (Ø=1) then it reduced.

7- The results show that Markstein numbers were relatively independent of Karlovitz numbers.

Table 1, Properties of Iraqi diesel, methanol, bioethanol, Sunflower biodiesel and yellow grease biodiesel

Property	Diesel	Methanol	Ethanol	Sunflower Biodiesel	Yellow Grease
Chemical formula	C_8 to C_{25}	CH_3OH	C_2H_5OH	C_{12} to C_{22}	C_{12} yo C_{22}
Oxygen content by mass	0	50	34.8	11	9
Density at NTP (kg/l)	0.81	0.79	0.79	0.911	0.92
Lower heating value (MJ/kg)	44.22	20.09	26.95	38.8	35.8
Stoichiometric air fuel ratio	14.7	6.5	9	13.8	13.8
Ctane number	45-60	0-8	10-20	39.2	37.6
Boiling point at 1 bar (°C)	244-380	65	79	230	315
Heat of vaporization (kJ/kg)	233	1100	838	-	-
Flammability limits in air (Ø)	0.166-1	0.23-1.81	0.28-1.91	-	-
Adiabatic flame temperature (°C)	2100	1870	1920		
Flame point (^oC)	59	11	14	243	209
Cloud point (^oC)	-13.8			-4.37	-2.7
Pour point (^oC)	-29			-13.54	-10.4

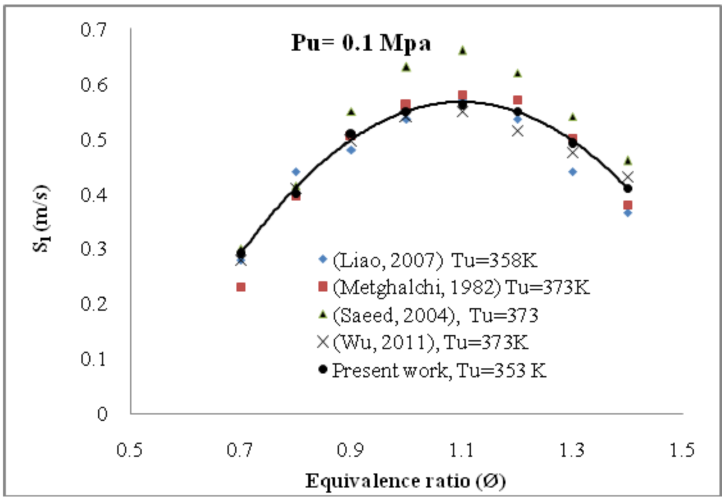

Fig. 2, laminar burning velocity for methanol-air mixtures versus equivalence

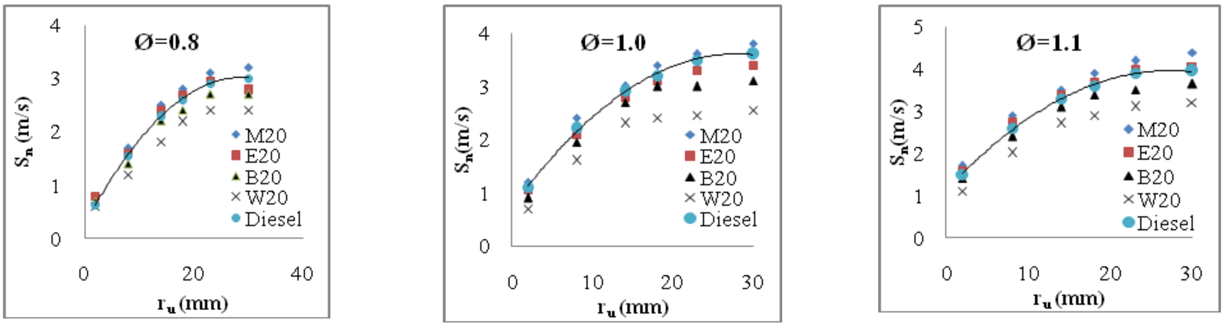

Fig. 3, Variations of Stretched flame speeds with flame raduis for specific equivalence ratios (Ø)

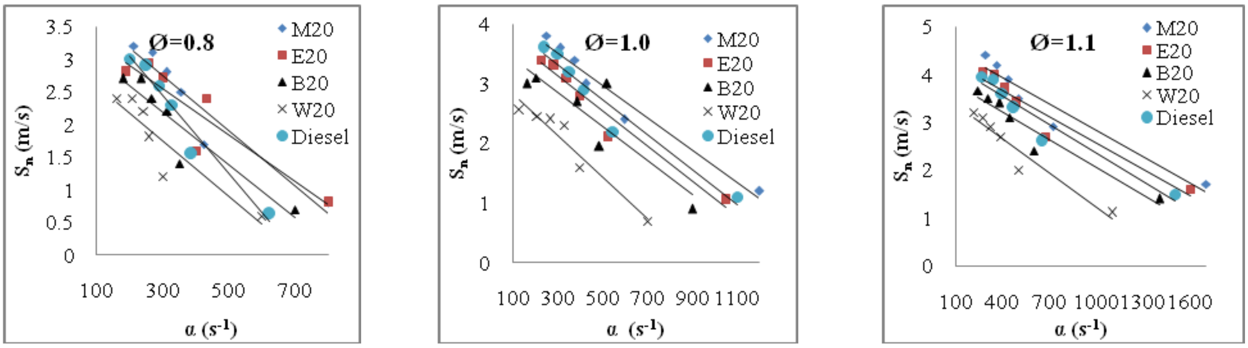

Fig. 4, Variations of flame speeds with different stretch rates and equivalence ratios

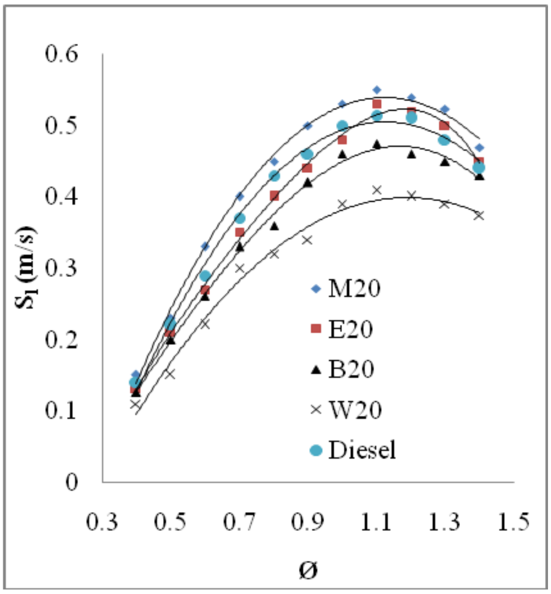

Fig.5, unstretched laminar burning velocity versus equivalence ratios of the tested blends.

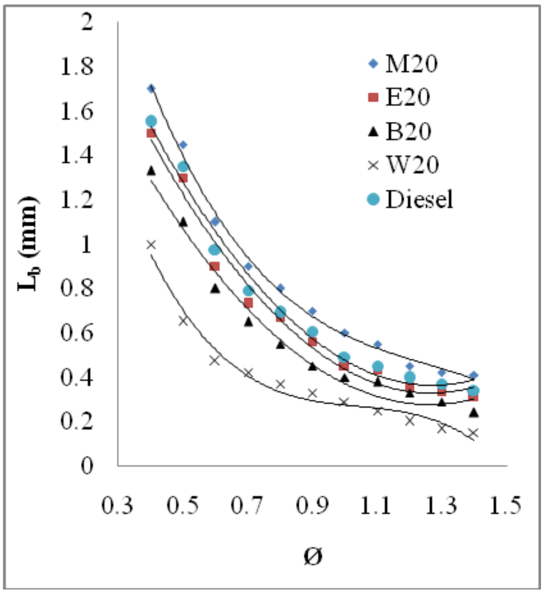

Fig. 6, burned gas Markstein length versus equivalence ratios of the tested blends.

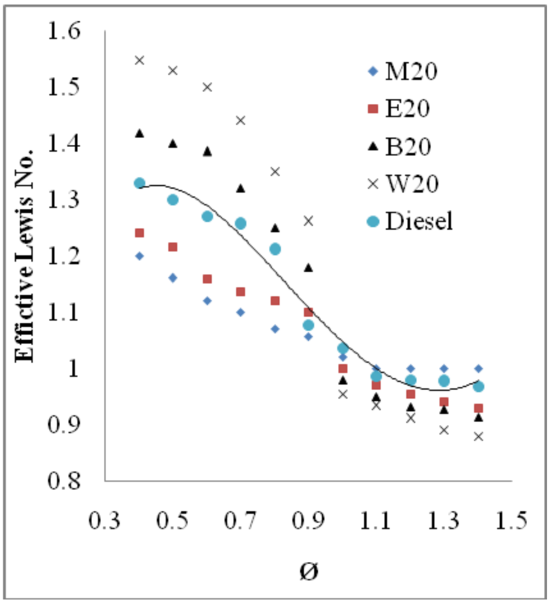

Fig. 7, effictive Lewis number versus equivalence ratios of the tested blends.

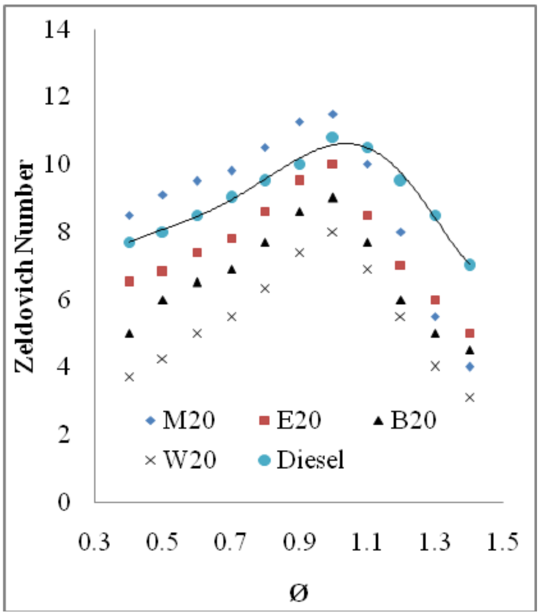

Fig. 8, Zeldovich number versus equivalence ratios of the tested blends.

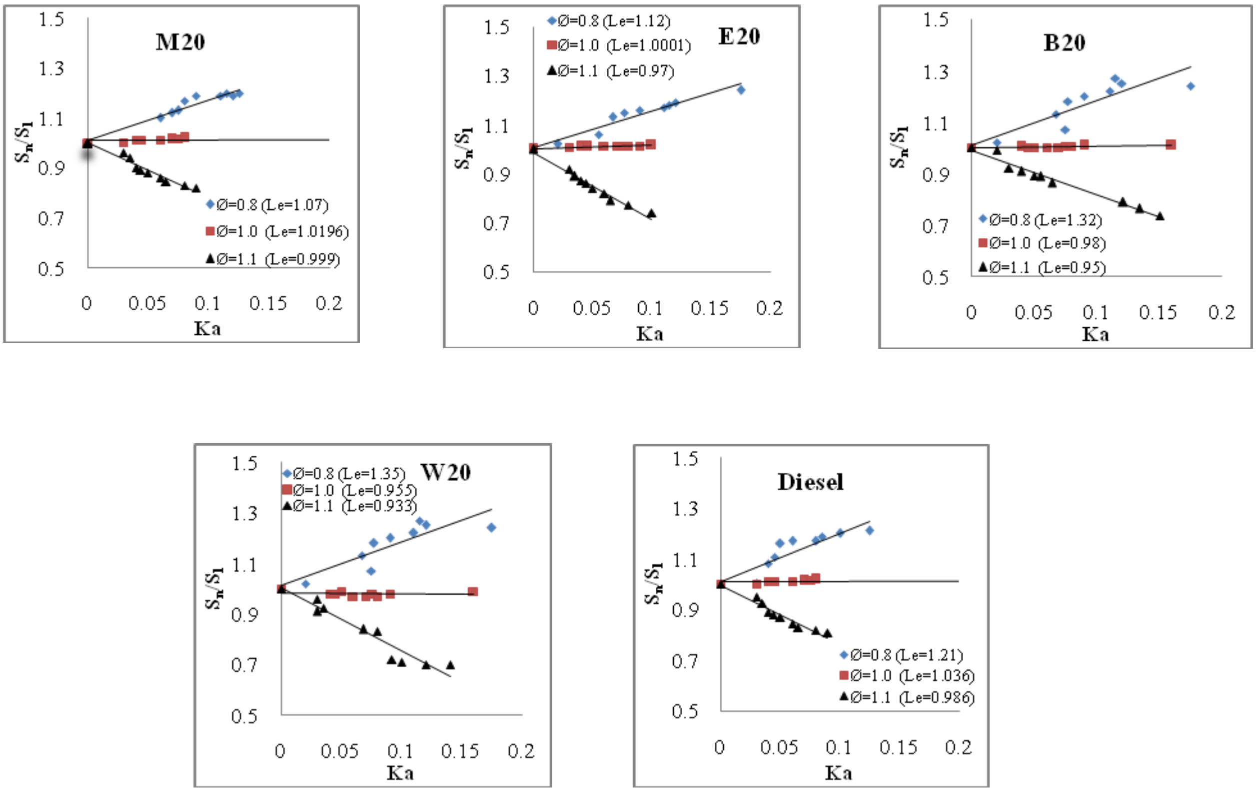

Fig. 9, Variations of S_n/S_l with Karlovitz number for specific equivalence ratios

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