Effect of Oxygen Enrichment on Laminar Burning Velocity of Methanol and Ethanol – Oxygen – Nitrogen Mixtures

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ABSTRACT
The effect of oxygen enrichment on the laminar flames speed for (methanol and ethanol – oxygen – nitrogen) premixed mixtures have been detected practically. Measurement system is designed to measure the laminar flame speed using a tube – method and optical technique (photodiode). Where the flame front position had been located by photodiode. The laminar flame speed measured at atmospheric pressure, 301K initial temperature, three level of oxygen concentration (0.21, 0.23 & 0.25), and equivalence ratios from 0.7 to 1.2. All experimental work was carried out at constant pressure in order to use density ratio method for the calculation of laminar burning velocity. Also the dependencies of flame thickness and Zel’dovich number on oxygen enrichment and equivalence ratio were explored. Using Oxygen enrichment techniques increases the laminar burning velocity and decreasing the flame thickness and Zel’dovich number. The maximum value of burning velocity occurs at equivalence ratio (1.1) at all Oxygen level. While the maximum increasing percentage in laminar burning velocity occurs at equivalence ratio (0.7) by (60.5% and 87.7%) for methanol and ethanol respectively.

Oxygen enrichment, mixture strength and type of alcohols dependence of burning velocity is represented by empirical relation.

Validation of the present work results is approved by comparison with the available published data for (methanol and ethanol – air) mixtures, and show good agreement between them, which indicates that the measurements and the calculations employed in the present work are successful and precise.

Keywords: Oxygen enrichment, Methanol, Ethanol, laminar burning velocity, tube method, flame thickness, Zel’dovich number

INTRODUCTION
Oxygen enhanced combustion is a technology use pure oxygen or oxygen enriched air to burn fuel. It is a good technique to improve the combustion process because of the benefits obtained due to the reduction of nitrogen which acts as a diluent in the mixture and dilutes the reactive oxygen and the absorbed energy due to its high heat capacity, reducing the combustion efficiency. This technology use in many industrial applications such as metal heating and melting, waste incineration, glass melting and brick firing. 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].
Alcohol burns with lower flame temperature and luminosity lead to the decrease of the peak temperature inside the combustion chamber; therefore the heat loss and NOx emissions are lowered. The oxygen content in there structure reduces the heating value more than gasoline does. Also, alcohols can be used with low cost in internal combustion engines with minor adjustment [2]. For example using ethanol as fuel for spark ignition engine have some advantages over gasoline, where it has better antiknock characterization and improves the engine’s thermal efficiency with the increase in compression ratio [3]. The application of methanol and ethanol in engines is not new. During the oil crises of the 1970s and 1980s, many studies and large scale fleet trails with methanol – fuelled vehicles were conducted in California and Canada [4].

Laminar burning velocity is a physical parameter which depends only on the physical and chemical nature of premixed mixtures [5]. The present study introduce new measurements of laminar flame speed for Methanol and Ethanol with oxygen enrichment and using density ratio method to find the one of important flame parameters (laminar burning velocity), in addition to study the variation of flame temperature, flame thickness and Zel’dovich number with increasing oxygen.

**Nomenclature**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>$C_p$</td>
<td>Specific heat at constant pressure (kJ/kg K)</td>
</tr>
<tr>
<td>$E/R_u$</td>
<td>Activation temperature (K)</td>
</tr>
<tr>
<td>$I$</td>
<td>Flame thickness factor</td>
</tr>
<tr>
<td>$N$</td>
<td>Mole ratio : the ratio of number of moles of reactants to that of products</td>
</tr>
<tr>
<td>$N_p, N_r$</td>
<td>Number of moles for product &amp; reactant respectively</td>
</tr>
<tr>
<td>$n_c, n_H, n_O$</td>
<td>Number of atoms(carbon,hydrogen and oxygen)respectively</td>
</tr>
<tr>
<td>$P_u$</td>
<td>Initial pressure of mixture (atm.)</td>
</tr>
<tr>
<td>$r_b$</td>
<td>Flame radius (mm)</td>
</tr>
<tr>
<td>$R_u$</td>
<td>Universal gas constant (kJ/kmol.K)</td>
</tr>
<tr>
<td>$S_F$</td>
<td>Laminar flame speed (cm/sec)</td>
</tr>
<tr>
<td>$S_L$</td>
<td>Laminar burning velocity (cm/sec)</td>
</tr>
<tr>
<td>$S_{Lo}$</td>
<td>Laminar burning velocity at the laboratory conditions</td>
</tr>
<tr>
<td>$T_m$</td>
<td>Mean temperature (K)</td>
</tr>
<tr>
<td>$T_u$</td>
<td>Unburned gas temperature (K)</td>
</tr>
<tr>
<td>$Ze$</td>
<td>Zel’dovich number</td>
</tr>
<tr>
<td>$\delta$</td>
<td>Flame thickness (mm)</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>Thermal conductivity (J/m.s.K)</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>Exponent of the number of carbon atoms</td>
</tr>
<tr>
<td>$\rho_b$</td>
<td>Burned gas density (kg/m$^3$)</td>
</tr>
<tr>
<td>$\rho_u$</td>
<td>Unburned gas density (kg/m$^3$)</td>
</tr>
<tr>
<td>$\Phi, \bar{\phi}$</td>
<td>Equivalence ratio</td>
</tr>
<tr>
<td>$O_2$</td>
<td>Volume fraction of oxygen</td>
</tr>
<tr>
<td>$\Delta L$</td>
<td>Distance between two photodiodes (cm)</td>
</tr>
<tr>
<td>$\Delta t$</td>
<td>Measured time between two photodiodes (sec)</td>
</tr>
<tr>
<td>$T_b$</td>
<td>Burned (or adiabatic) gas temperature (K)</td>
</tr>
</tbody>
</table>

**EXPERIMENTAL SETUP AND DATA PROCESSING**

In this study, the flame speed was measured experimentally by using a tube method with optical technique. Figure (1) shows the general layout of the test rig built in “Mechanical Engineering Dept., Al-Mustansiriya University” for the purpose of this study. The test rig consists from four units (1) combustion tube unit : it made from copper (inside diameter 67mm, 2000mm length,3mm thickness), mounted with electrical heater and insulation to heat the initial mixture and maintain the adiabatic process during the test.(2) Mixing chamber unit : it made of iron steel used to prepare the mixture where the partial pressure method used to prepare the mixture. (3) Ignition unit consists from spark plug and electronic circuit. (4)Measuring flame
speed unit : consists from (a) four photodiodes were fixed on a tube with a distance ( 25 cm) between them to measure the time required for moving flame front from one photodiode to other using two digital storage oscilloscopes and (b) the 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 where all measurements occur at pre-pressure period, pressure meter: to measure the quantity of fuel, oxygen and nitrogen during the preparation of mixture. High purity gases (99.99 \%) of oxygen, nitrogen, and high purity of methanol and ethanol were used. For accuracy, the flame speed measurements were repeated seven times at each condition.

The density ratio method introduced by Andrews and Bradley [6] was used to calculate the laminar burning velocity from measured flame speed as the following equations.

\[ S_L = \frac{\rho_b}{\rho_u} S_F \quad \text{----- (1)} \]
\[ \frac{\rho_b}{\rho_u} = \frac{T_u}{T_b} N.l \quad \text{----- (2)} \]

\[ S_F = \frac{\Delta L}{\Delta t} \quad \text{----- (3)} \]

The magnitudes of mole ratio and flame thickness factor have been calculated according to the relations of the researches Andrews and Bradley [7], where:

\[ N = \frac{\Sigma N_r}{\Sigma N_p} \quad \text{----- (4)} \]
\[ I = \frac{1.04}{r_b^3} \left((r_b - \delta)^3 + \frac{3}{T_b T_u^2} \delta \ln \left[ \frac{T_b}{T_u} \right] \right) \quad \text{----- (5)} \]

Where (Nr and Np) calculated from the balance of combustion equation as in the below:

\[ C_{n_c} H_{n_H} O_{n_O} + \frac{a_{sto}}{\phi} \left[ O_2 + \left( \frac{1 - \frac{\Omega_{oxg}}{\Omega_{oxg}}}{} \right) \right] N_2 \rightarrow \Sigma Products \quad \text{----- (6)} \]

The adiabatic flame temperature and equilibrium composition with oxygen enrichment was calculated by using a computer program of “Olikara & Borman” [8] after suitable modifications. The modification includes the change in mole ratio of nitrogen to oxygen. This program considers the dissociation for 11 species (O, N, H₂, O₂, N₂, OH, CO, NO, H₂O and CO₂) in the products of combustion. **Flame thickness**, could be defined that distance in which the first temperature rise occur until reach the maximum value (Tb). Blint’s correlation [9] was used for calculation flame thickness.

\[ \delta = \frac{2 \lambda}{\rho_u c_p \cdot S_L} \left( \frac{T_b}{T_u} \right)^{0.7} \quad \text{----- (7)} \]
Thermo-physical properties are constant values at specific temperature and evaluated at mean temperature 
“Tm = (Tu + Tb)/2”.

Zel’dovich Number, it is important parameter for planer laminar flames to describe the sensitivity of chemical reactions to the variation of the adiabatic flame temperature and activation temperature. Zel’dovich number given in the following equation [10]:

\[ Ze = \frac{E}{2 R_u \cdot T_0^2} (T_b - T_u) \] ----- (8)

RESULTS AND DISCUSSIONS

Figure (2) shows the variation of adiabatic flame temperatures of (methanol (CH3OH) and ethanol (C2H5OH) – oxygen – nitrogen) flames with equivalence ratios at three 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=1.05). 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].

The measured flame speed at different equivalence ratio and oxygen enrichment of (methanol and ethanol – oxygen – nitrogen) mixtures was shown in figure (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.

Figure (4) illustrates the variations in mole ratio (N) 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. The behavior of flame thickness factor is represented in figure (5). In the lean mixture, as the equivalence ratio increases, the flame thickness factor decreases and reaches its minimum value at (ϕ ≈1.1). This point represents the inflection point of the curves. Afterwards, the flame thickness factor increases by the increment of equivalence ratio on the rich
side of mixtures. This behavior of flame thickness factor is mainly due to the variation of flame temperature with equivalence ratio, which we have previously mentioned.
The results of laminar burning velocity estimated according to equation (1) are shown in figure (6). 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 (60.5% and 87.7%) for methanol and ethanol respectively at equivalence ratio (0.7). Figures (7) shows the laminar burning velocity as a function of the fuel type “number of carbon atoms”. Increasing the number of carbon atoms decreases the burning velocity due to the increment in the flame temperature. While Figures (8) shows the variation of laminar burning velocity with oxygen enrichment, as it appears clearly Oxygen will increase burning velocity at all equivalence ratios.

Figure (9) shows the comparison of the results of present work for case (methanol and ethanol - 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.

The oxygen enrichment, mixture strength and number of carbon atoms of burning velocity can be represented by the following relation:

\[ \text{Laminar Burning Velocity} \]

\[ \text{Equivalence Ratio (} \Phi \text{)} \]

\[ \begin{array}{c}
21\% \text{ O2 : 79\% N2} \\
23\% \text{ O2 : 77\% N2} \\
25\% \text{ O2 : 75\% N2}
\end{array} \]

Fig. (6) : Variation of laminar burning velocity with equivalence ratio (\( \Phi \)) at three oxygen enrichment levels

\[ \begin{array}{c}
\Phi = 0.8 \\
\Phi = 1.0 \\
\Phi = 1.2
\end{array} \]

Fig. (7) : Variation of laminar burning velocity with number of carbon atoms at different mixture strength for (Methanol and Ethanol – air) mixtures
Laminar burning velocity (cm/s)

\[ \text{O}_2 \text{ (vol. %)} = 0.8 \]
\[ \text{O}_2 \text{ (vol. %)} = 1.0 \]
\[ \text{O}_2 \text{ (vol. %)} = 1.2 \]

\[ \text{C}_2\text{H}_5\text{OH} - \text{O}_2 - \text{N}_2 \]

\[ \text{CH}_3\text{OH} - \text{O}_2 - \text{N}_2 \]

Fig. (8): Variation of laminar burning velocity with oxygen enrichment level

Fig. (9): Comparison of laminar burning velocity with the published data at \( T_u = 301 \text{ K} \) & \( P_u = 1 \text{ atm} \).
\[
S_l(\Phi, \Omega_{O_2}, n_c) = S_{lo}(\Phi, \Omega_{O_2}) \times (n_c)\gamma \quad (9)
\]

Where

\[
S_{lo} = A_1 + B_1 \Phi + C_1 \Phi^2 + D_1 \Phi^3 \quad (10)
\]

And

\[
\gamma = A_2 + B_2 \Phi + C_2 \Phi^2 \quad (11)
\]

Where

\[
\begin{align*}
A_1 &= 5848.8 - 481.02 \Omega_{O_2} + 10.179 \Omega_{O_2}^2 \\
B_1 &= -18403 + 1487.2 \Omega_{O_2} - 31.19 \Omega_{O_2}^2 \\
C_1 &= 18672 - 1483.1 \Omega_{O_2} + 31.041 \Omega_{O_2}^2 \\
D_1 &= -6188.7 + 484.42 \Omega_{O_2} - 10.128 \Omega_{O_2}^2 \\
A_2 &= 13.855 - 1.5581 \Omega_{O_2} + 0.0393 \Omega_{O_2}^2 \\
B_2 &= -29.087 + 3.2053 \Omega_{O_2} - 0.0801 \Omega_{O_2}^2 \\
C_2 &= 16.397 - 1.7499 \Omega_{O_2} + 0.043 \Omega_{O_2}^2
\end{align*}
\]

Where, can be used this empirical equation with an percentage error about (± 2 %), for the conditions (Tu=301 K, Pu=1 atm., 0.21 ≤ \( \Omega_{O_2} \) ≤ 0.25 and 0.7 ≤ \( \Phi \) ≤ 1.2).

Figure (10) 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 (\( \Phi = 1.1 \)). Afterwards, the flame thickness increases with increases the equivalence ratio on the rich side of the mixture. This is due to the relation among (\( \delta \)), thermo-physical properties and laminar burning velocity (SL) 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 [11].

Zel’dovich number has the same trend of flame thickness as shown in figure (11). 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.

Figure (10) : Flame thickness (\( \delta \)) vs. equivalence ratio at different oxygen enrichment.
CONCLUSIONS

1- The laminar flame speed and the burning velocity increase with the amount of oxygen increasing in the combustion mixture.

2- Zel’dovich number and flame thickness decrease with oxygen enrichment.

3- The comparison of the present results of laminar burning velocity with other published results give a good agreement for case of air.

REFERENCES

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