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## **INVESTIGATION OF PREMIXED COMBUSTION PROPERTIES OF GASEOUS FUEL (LPG, PROPANE, AND BUTANE) IN TUBULAR BURNER**

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### **ABSTRACT**

In the present research, the propagation properties of premixed combustion at high stability has been investigated using three types of hydrocarbon fuels (LPG, C<sub>3</sub>H<sub>8</sub>, and C<sub>4</sub>H<sub>10</sub>) in a tubular burner. Experimental work has been carried out for laminar fuel-air mixture.

Bunson burner methods were introduced for designing and manufacturing of integrated combustion system to get a wide range of equivalence ratio introducing all the reactance in combustion process, computed and increase the range efficiency of combustion stability to ( $\zeta_s=9.33\%$ ), reducing losses in dead space zone, reducing emissions products by reducing the emission of (NO<sub>x</sub>,CO).

The laminar burning velocity has been computed using two techniques based on flame frontal surface area and angle of flame front with aid of data image of flame front at atmosphere pressure and Tu=300K for a range of equivalence ratio ( $0.7 < \Phi < 1.5$ ).

Comparison of results with previous literature showed good agreement with the present work.

### **KEY WORDS**

Tubular burner, premixed flame, burning velocity, gases emission.

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## NOMENCLATURE

|                         |                                     |                         |                                |
|-------------------------|-------------------------------------|-------------------------|--------------------------------|
| $A_{\text{blow}}$       | Blow-off area.                      | $\dot{m}_t$             | Mixture mass flow rate.        |
| $A_{\text{flash}}$      | Flash back area.                    | $NO_x$                  | Nitrogen oxides.               |
| $A_o$                   | Flame stability area.               | $ppm$                   | Part per million.              |
| $A_s$                   | Flame surface area                  | $\dot{Q}_{\text{air}}$  | Air Volume flow rate.          |
| $A_t$                   | Cross section area of burner rim.   | $\dot{Q}_{\text{fuel}}$ | Fuel Volume flow rate.         |
| $A/F_{st}$              | Air to fuel ratio stoichiometric.   | $S_L$                   | Laminar flame velocity.        |
| $A/F_{act}$             | Air to fuel ratio actual.           | $T_i$                   | Ignition temperature.          |
| $CO$                    | Carbone monoxide.                   | $T_f$                   | Flame temperature.             |
| $CO_2$                  | Carbone dioxide.                    | $T_o$                   | Unburned gases temperature.    |
| $C_p$                   | Specific heat at constant pressure. | $T_{\text{air}}$        | Air temperature.               |
| $D_t$                   | Diameter of burner.                 | $T_{\text{fuel}}$       | Fuel temperature.              |
| LPG                     | Liquid petroleum gas.               | $T_f$                   | Flame temperature.             |
| MWf                     | Fuel Molecular weight.              | $U_b$                   | Burned gas velocity.           |
| MWa                     | Air Molecular weight.               | $U_u, U$                | Unburned gas velocity.         |
| $\dot{m}_{\text{air}}$  | Air mass flow rate.                 | $UHC$                   | Unburned hydrocarbon.          |
| $\dot{m}_{\text{fuel}}$ | Fuel mass flow rate.                | $u_f$                   | Flame velocity.                |
| <b>Greek symbols</b>    |                                     |                         |                                |
| $\phi$                  | Equivalent ratio.                   | $\rho_u$                | Unburned gas density.          |
| $\phi_{a,f}$            | Constant in equation (18).          | $\rho_b$                | Burned gas density.            |
| $\phi_{f,a}$            | Constant in equation (19).          | $\lambda$               | Thermal conductivity.          |
| $\mu_a$                 | Air Kinematic viscosity.            | $\delta$                | Flame thickness.               |
| $\mu_f$                 | Fuel Kinematic viscosity.           | $\zeta_s$               | Efficiency of Flame stability. |
| $\mu_u$                 | Mixture Kinematic viscosity.        |                         |                                |

## INTRODUCTION

Combustion phenomena arise from the interaction of chemical and physical processes. Combustion can be defined as "rapid oxidation generating heat or both heat and light". This definition emphasizes the intrinsic importance of chemical reactions to combustion. It also emphasizes why combustion is so very important [1].

Combustion transforms energy stored in chemical bonds to heat that can be utilized in a variety of ways. It can be occurring in either a flame or non-flame modes; two classes of flames exist, premixed and non-premixed (or diffusion). In a premixed flame, the fuel and oxidizer are mixed at the molecular level prior to the occurrence of any significant chemical reaction. Gasoline engine combustion is generally considered to have a significant amount of premixed burning. Premixed burning is applied in many industrial devices and processes; examples include gas ranges and ovens, heating applications, and Bunson burners. [2].

## Premixed Flame

A premixed flame is a flame in which the oxidizer has been mixed with the fuel prior to the occurrence of any significant chemical reaction. This creates a thin flame front as all of the reactants are readily available.

It is found that if the flow of the fuel–oxidizer mixture is laminar, the flame speed of premixed flames is dominated by the chemistry. If the flow rate is below the flame speed, the flame will move upstream until the fuel is consumed or until it encounters a flame holder. If the flow rate is equal to the flame speed, it is expected that a stationary flat flame front is normal to the flow direction. If the flow rate is above the flame speed, the flame front will become conical such that the component of the velocity vector normal to the flame front is equal to the flame speed. As a result, the flame fronts of most premixed flames in daily life are roughly conical [3].

In both laminar and turbulent flows, the same physical processes are active, and many turbulent flame theories are based on an underlying laminar flame structure [4].

The temperature profile through a flame is perhaps the most important characteristic. Figure (1) illustrates a typical flame temperature profile, together with other essential flame features. It is convenient to divide premixed flame into two zones: the first preheat zone, where little heat is released and the second reaction zone, where the bulk of the chemical energy is released. At atmospheric pressure, the flame thickness is quite thin, of the order of a millimetre [5].

## Flame Stabilization

Flame stabilization is one of the important subjects in combustion research mainly to the avoidance of flashback and lift-off, and many efforts have been made on this problem.

The methods used for flame stabilization are:

1. By inserting a bluff body at high-speed stream where stagnation region with recirculation of hot burned gas, as illustrated in Figure (2)(A).
2. Opposing jet to stabilize combustion in its stagnation region of low-velocity, as shown in figure (2)(B).
3. A recess wall or a pilot flame is used to avoid the pressure loss in the main stream that happened in the first methods, as illustrated in figure (2)(C) and (D).
4. Tubular flame is thermally stable, because the conductive heat loss behind the flame is negligible due to its symmetrical temperature distribution; in addition, the flame is also aerodynamically stable according to the Rayleigh stability.

## Bunson Cone Flame

In the introduction to this paper, a combustion wave was considered to be propagating in a tube. When the cold premixed gases flow in a direction opposite to the wave propagation and travel at a velocity equal to the propagation velocity (i.e., the laminar flame speed), the wave (flame) becomes stationary with respect to the containing tube. Such a flame would possess only neutral stability and, its actual

position would drift [5]. If the velocity of the unburned mixture is increased, the flame will leave the tube and in most cases, fix itself at the tube exit. If the tube is in vertical position, then a simple burner configuration and flammability limits, as shown in figure (3), are obtained [7].

When the flow velocity is increased to a value greater than the flame speed, the flame becomes conical in shape. The greater the flow velocity, the smaller is the cone angle of the flame. This angle decreases so that the velocity component of the flow normal to the flame is equal to the flame speed. However, near the burner rim, the flow velocity is lower than that in the centre of the tube; at same point in this area, the flame speed and flow velocity equalize, and the flame is anchored by this point [8].

## **EXPERIMENTAL SET-UP**

Most of the factors affecting combustion process are the stability of flame, burning velocity and emission levels. So, in the present work, the experimental rig was designed. This rig is composed of: (1) combustion system by which the premixed flame front is prepared which consists of (a) Valves and regulators to control the flow, (b) Flowmetres (c) Burner and water jacket; (2) Recording and photographing for combustion phenomena. Figure (4) shows a photo of the system and its accessories, figure (5) depicts the flow chart combustion system and figure (6) gives the schematic diagram of the experimental test rig.

### **Flow Rate Measurement (Flowmetres)**

Flowmetre was used for measuring flow rate of fuel. Controlling process about level of float during the experimental period is very important. Therefore, there must be carefully no float fluctuation by opening alternately the valves, any leak accrues big mistake of measuring of fuel flow rate. The control of hydrocarbon fuel (LPG,  $C_3H_8$ , and  $C_4H_{10}$ ) used supply out of standard gas cylinder by a spherical valve and pressure regulator type of spring loaded.

### **Pressure Measurement (Pressure Gage)**

The used pressure gage type of (Borden gage) by grading (0-16 bar) at line of air supply unit consists of reciprocating compressor of high capacity to ensure no pressure drop rapidly during the experimental period. Gas fuel supplies from gas container. To remain constant pressure during tests, was used a pressure regulator type of spring loaded before pressure gage at same line.

### **Gas Analyser**

The exhaust sample gas was extracted sufficiently downstream in the exhaust pipe, which was connected and sealed to the top of the combustor. Gas analyser type of (TECNO TEST) by probe of stainless steel was used, where the concentrations of  $NO_x$  and  $CO$  were analyzed.

## Equivalence Ratio

It is the ratio between air to fuel ratio stoichiometric to air to fuel ratio actual. For very rich mixtures, the primary effect of equivalence ratio on the flame speed for similar fuels is a result of how this parameter affects flame temperature, thus, the expected maximum flame speed at a slightly rich mixture and fall off on either side. Flame thickness shows the inverse trend, having a minimum near stoichiometric [5].

The model of equivalence ratio is:

$$\phi = \frac{28Q_{fuel}}{Q_{air}} \quad (1)$$

where  $Q_{fuel}$  and  $Q_{air}$  are measured from flowmeters. Therefore, quoted uncertainties of  $Q_{fuel}$  and  $Q_{air}$  are  $\pm 5\%$  and  $\pm 2\%$ , respectively. Assume a normal distribution is used to calculate the quoted uncertainty and let all relevant quantities vary to the fullest practicable extent, we can recover the standard uncertainty of  $Q_{fuel}$  and  $Q_{air}$ . The two partial derivatives are:

$$\frac{\partial \phi}{\partial Q_{fuel}} = \frac{28}{Q_{air}} \quad (2)$$

$$\frac{\partial \phi}{\partial Q_{air}} = \frac{28 Q_{fuel}}{Q_{air}^2} \quad (3)$$

Equivalence ratio ( $\phi$ ) represents:

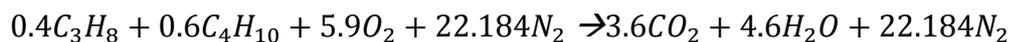
$$\phi = \frac{AF_{stoic}}{AF_{act}} \quad (4)$$

where  $AF_{stoic}$ : is air to fuel ratio at stoichmetric by volume and  $AF_{act}$ : is air to fuel ratio at actual by volume.

We can evaluate  $AF_{stoic}$  by stoichmetric equation of fuel liquid petroleum gas (LPG) and air as follow:



By balance, eq. will become:



$$AF_{Stoich} = Q_{air}/Q_{fuel} \quad (5)$$

$$AF_{Stoich} = \frac{5.9*4.76}{0.4+0.6}$$

$$AF_{Stoich} = 28.084 \text{ m}^3\text{air} / \text{m}^3\text{fuel}.$$

$$\text{But, } AF_{act} = \dot{Q}_{air} / \dot{Q}_{fuel} \text{ by volume, is shown in tables (1) and (2).} \quad (6)$$

## Flammability Limits

Experiments show that the flame will propagate only within a range of mixture strengths, between the so-called lower and upper limits of flammability. The lower limit is the leanest mixture ( $\Phi < 1$ ), that will allow steady flame propagation, while the upper limit represents the richest mixture ( $\Phi > 1$ ). Flammability limits are frequently quoted as percent fuel by volume in the mixture, or as a percentage of the stoichiometric fuel requirement, i.e.,  $\Phi * 100$  percent. Although flammability limits can be defined that are physiochemical properties of the fuel-air mixture, experimental flammability limits are related to heat losses from the system, in addition to the mixture properties and, hence, are generally apparatus dependent [9]. Figure (7) illustrates the effect of mixture composition on the spark energy requirements for ignition of methane-air mixture.

## Reduction Methods of CO and UHC Emission

Conditions favourable to oxidation of CO to CO<sub>2</sub>, and the factors that affect the UHC concentration level are as listed below:

1. Increasing of temperature and pressure in combustor which increases the burning rate via increasing the temperature of the combustion, and increasing the residence time of CO and UHC staying in the combustor via improving a good combustion chamber design.
2. Improving the atomization quality and droplets distribution of liquid fuel to prevent too weak mixtures to support combustion, or over-rich combustion that yields high local concentrations of CO and UHC.
3. When reducing the wall film cooling, this will reduce CO and UHC emissions.

## Reduction Methods of Nitrogen Oxides Emissions

Basically, there are several methods used to reduce NO<sub>x</sub> emissions, these are:

1. Reducing combustion temperature; This can be done by one of the following methods;
  - A. Using fuel rich mixtures to limit the amount of oxygen available in primary zone, such that air staged, over fire air, and burner is out of service methods.
  - B. Using fuel lean mixtures to limit temperature by mitigating energy input in primary zone, such as fuel staged method.
  - C. Injecting cooled oxygen-depleted flue gas into combustion air to mitigate energy.
  - D. Injecting cooled flue gas with added fuel in primary zone, as used in flue gas recirculation, with fuel reburn method.
  - E. Flue gas recirculation, such that cyclone combustor design.
2. Short residence time at peak temperature keeps the vast majority of nitrogen from becoming ionized; this can be achieved by increasing the velocity of reactants supply via reduce the pressure in the exhaust system by using cooling product method.
3. Providing a chemically reducing (reversal of oxidization) substance to remove oxygen from nitrogen oxides, such as used selective catalytic reduction and selective non-catalytic reduction methods.

4. Intentionally raises the valence of the nitrogen ion to allow water to absorb it (i.e., it is based on greater solubility of NO<sub>x</sub> at higher valence). This can be achieved by using ozone, ionized oxygen, and hydrogen peroxide.
5. Removing nitrogen as a reactant either by using Ultra-low nitrogen content fuel or by using oxygen instead of air in the combustion process to form less fuel NO<sub>x</sub>.

### The Laminar Flame Speed and Stability

The flame velocity- also called the burning velocity, normal combustion velocity or laminar flame speed – is more precisely defined as the velocity at which unburned gases move through the combustion wave in the direction normal to the wave surface.

The initial theoretical analyses for the determination of the laminar flame speed fall into three categories: thermal theories, diffusion theories, and comprehensive theories. The historical development followed approximately the same order.

The thermal theories date back to Mallard and Le Chatelier, who proposed that it is propagation of heat back through layers of gas that is the controlling mechanism in flame propagation. As one would expect, a form of the energy equation is the basis for the development of the thermal theory. They postulated (as shown in fig. 8) that a flame consists of two zones separated at the point where the next layer ignites [10].

Conceptually, Mallard and Le Chatelire stated that the heat conducted from zone II in figure (8) is equal to that necessary to raise the unburned gases to the ignition temperature (the boundary between zones I and II). If it is assumed that the slope of the temperature curve is liner, the slope can be approximated by the expression  $[\frac{(T_f - T_i)}{\delta}]$ , where  $T_f$  is the final or flame temperature,  $T_i$  is the ignition temperature, and  $\delta$  is the thickness of the reaction zone. The enthalpy balance then becomes:

$$\dot{m}c_p(T_i - T_o) = \lambda \frac{(T_f - T_i)}{\delta} A \quad (7)$$

where  $\lambda$  is the thermal conductivity,  $\dot{m}$  is the mass rate of the unburned gas mixture into the combustion wave,  $T_o$  is the temperature of the unburned gases, and  $A$  is the cross-sectional area taken as unity. Since the problem as described is fundamentally one-dimensional,

$$\dot{m} = \rho Au = \rho S_L A \quad (8)$$

where  $\rho$  is the density,  $u$  is the velocity of the unburned gases, and  $S_L$  is the symbol for the laminar flame velocity. Because the unburned gases enter normal to the wave, by definition:

$$S_L = u \quad (9)$$

Equation (7) then becomes:

$$\rho S_L c_p (T_i - T_o) = \lambda \frac{(T_f - T_i)}{\delta} \quad (10)$$

$$S_L = \frac{\lambda (T_f - T_i)}{\rho c_p (T_i - T_o) \delta} \quad (11)$$

Equation (11) is the expression for the burning velocity obtained by Mallard and Le Chatelire.

The earliest procedure of calculating burning velocity was to divide the volume flow rate ( $\text{cm}^3\text{s}^{-1}$ ) by the area ( $\text{cm}^2$ ) of flame cone:

$$S_L = \frac{Q}{A} \quad (12)$$

In this research, burning velocity was calculated depending on the flame front dimension and a technique of luminous method according to equation (12). To all types of used paraffin (hydrocarbon fuels); this work is due to possibility of studying the flounce of carbon atoms of burning velocity.

Some investigators have concentrated on the central portion of the cone only, focusing on the volume flow through tube radii corresponding to this portion.

The angle of the cone slant made with the burner axis can also be used to determine  $S_L$ , see figure (9). This angle should be measured only at the central portion of the cone. Thus:

$$S_L = u_u \sin \alpha \quad (13)$$

From the results of conducted experiment for stability, premixed flames were obtained by range of equivalence ratio ( $0.63 < \phi < 1.5$ ), their photo are shown in figure (10). Figure (11) shows the results of burning velocity by using area and angle methods, and figure (12) depicts the comparison of burning velocity range between the present work and previous study [13,14].

To give more accurate description to the effect of flame stability to all types of fuel (number of carbon atoms), we depend on flame stabilization efficiency [15].

$$\zeta_s = \frac{A_o}{A_{blow}} = 1 - \frac{A_{flash}}{A_{blow}} \quad (14)$$

$$A_o = A_{blow} - A_{flash} \quad (15)$$

where ( $A_{blow}$  &  $A_{flash}$ ) the area between flash back and blow-off, respectively with in a wide range of ( $X_f - R_e$ ), while ( $A_o$ ) is the area between those boundaries. To determine Reynold number ( $R_e$ ) and mole fraction for fuel ( $X_f$ ), the following equations wares used [15].

$$R_e = \frac{U \cdot \rho_u \cdot D_t}{\mu_u} \quad (16)$$

The kinematic viscosity for unburned gases can be determined from:

$$\mu_u = \frac{\mu_a}{1 + \frac{X_f}{X_a} \phi_{a,f}} + \frac{\mu_f}{1 + \frac{X_a}{X_f} \phi_{f,a}} \quad (17)$$

From equations (18,19), the constants ( $\phi_{a,f}$  &  $\phi_{f,a}$ ) can be found from:

$$\phi_{a,f} = \frac{\left[ 1 + \left( \frac{\mu_a}{\mu_f} \right)^{0.5} \left( \frac{MW_f}{MW_a} \right)^{0.25} \right]^2}{2\sqrt{2} \left[ 1 + \frac{MW_a}{MW_f} \right]^{0.5}} \quad (18)$$

$$\phi_{f,a} = \frac{\left[ 1 + \left( \frac{\mu_f}{\mu_a} \right)^{0.5} \left( \frac{MW_a}{MW_f} \right)^{0.25} \right]^2}{2\sqrt{2} \left[ 1 + \frac{MW_f}{MW_a} \right]^{0.5}} \quad (19)$$

The value of mole fraction for air and fuel can be obtained from:

$$X_a = \frac{\dot{M}_a}{\dot{M}_t} \quad (20)$$

$$X_f = \frac{\dot{M}_f}{\dot{M}_t} \quad (21)$$

$$\dot{M}_t = \dot{M}_a + \dot{M}_f \quad (22)$$

## RESULTS AND DISCUSSIONS

In this work, the optimum design of burner which increases the stabilization of flame front so as to study the characteristic of flame propagation more precisely than other burners and obtain a uniform flame front with no distortion, figure (10) shows an image to the flame front. The increasing of number of carbon atoms (nc) will increase the burning velocity at any equivalent ratio for gas fuel due to increase in the number of carbon atoms which increases thermal diffusion and thermal conductivity. It has been found that the burning velocity reach its maximum velocity at equivalent ratio ( $\phi=1.01$ ) which is shown in figure (11) where two methods (area method and angle method) have been used to measure the burning velocity.

The experimental data obtained from this work were compared with a previously published data [13, 14], and a good agreement was found between them as shown in figure (12).

Figures (13) and (14) show the calculation of flame stabilization efficiency and its area for (LPG, Propane, and Butane) with air. It has been observed that the area of

stable flame and efficiency decrease as the number of carbon atoms, this is due to different curves in flash back and blow-off due to the increase in the number of carbon atoms.

In Figure (15), it has been shown that the range of values of fuel mole fraction (flash back) is from  $X_f$  (5 – 8%) for Propane ( $nc=3$ ) to  $X_f$  (4 – 5.3%) for Butane ( $nc=4$ ), while the curve of blow-off is changed from  $X_f$  (4.2 – 6.2%) for Propane to  $X_f$  (3.5 – 4.9%) for Butane which results to decrease  $A_{\text{blow}}$  &  $A_{\text{flash}}$ . This will decrease the flame stabilization area (efficiency of combustion stability  $\zeta_s$ ). The range of ( $\zeta_s$ ) increase to ( $\zeta_s=9.33\%$ ) with decrease of number of carbon atoms from ( $nc=3$  to 4), ( $A_{\text{blow}}$  &  $A_{\text{flash}}$ ) which will decrease the flame stabilization area, due to reducing losses in dead space zone of flame front. These properties depend on this chosen suitable burner in industrial application.

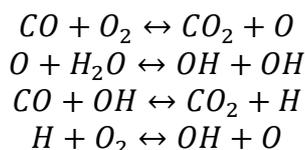
This paper will focus on the  $NO_x$  and  $CO$  emissions in premixed flame combustion in term of equivalence ratio for hydrocarbon fuel (LPG) at stable flame regions. In tests, the emission results depended mainly on one parameter; the equivalence ratio  $\phi$ , which represents the including stable flame region as follow:

**CO result:** Figures (16) shows the characteristics of  $CO$  emissions for the premixed flame combustion as a function of equivalence ratio  $\phi$  for LPG fuel at stable flame regions. Hydrocarbon combustion simplistically can be characterized as a two-step process to form carbon monoxide:

The first step involves the breakdown of the fuel to carbon monoxide; whereas the second step being the final oxidation of carbon monoxide to carbon dioxide.

It well known that  $CO$  is slow to oxidize unless there are some hydrogen containing species present, small quantities of  $H_2O$  or  $H_2$  can have a tremendous effect on the oxidation rate. This is because the  $CO$  oxidation step involving the hydroxyl radical is much faster than the step involving  $O_2$  and  $O$ .

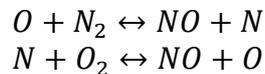
Assuming water is the primary hydrogen containing species, the following four steps describe the oxidation of  $CO$ :



The first reaction is slow and a dose not contributes significantly to the formation of  $CO_2$ , but rather serves as the initiator of the chain sequence. The actual  $CO$  oxidation step, third reaction, is also a chain propagating step, producing  $H$  atoms that react with  $O_2$  to form  $OH$  and  $O$  (fourth reaction). These radicals, in turn, feed back into the oxidation step (third reaction) and first chain branching step (second reaction). The  $CO + OH \leftrightarrow CO_2 + H$  step is key reaction in the overall scheme.

That is, considering that the vorticity and mixing rate of fuel–air decrease with increasing rates of chemical heat release. Thus, the effects of recirculating flow on the flame stability and fuel–air mixing can reduce  $CO$  emission.

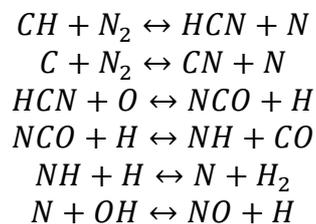
**NO<sub>x</sub> result:** Figure (17) shows the characteristics of NO<sub>x</sub> emissions for the premixed combustion as a function of  $\phi$ . However, the NO<sub>x</sub> emissions gradually increase with increasing equivalence ratio. The increase in NO<sub>x</sub> emission with heat input rate can be explained by the fact that the thermal NO formation increases, Thermal NO contains two chains reaction:



which can be extended by adding the reaction



But the prompt NO formation remains constant with increasing heat input rate. Prompt NO includes six chains reaction [1]:



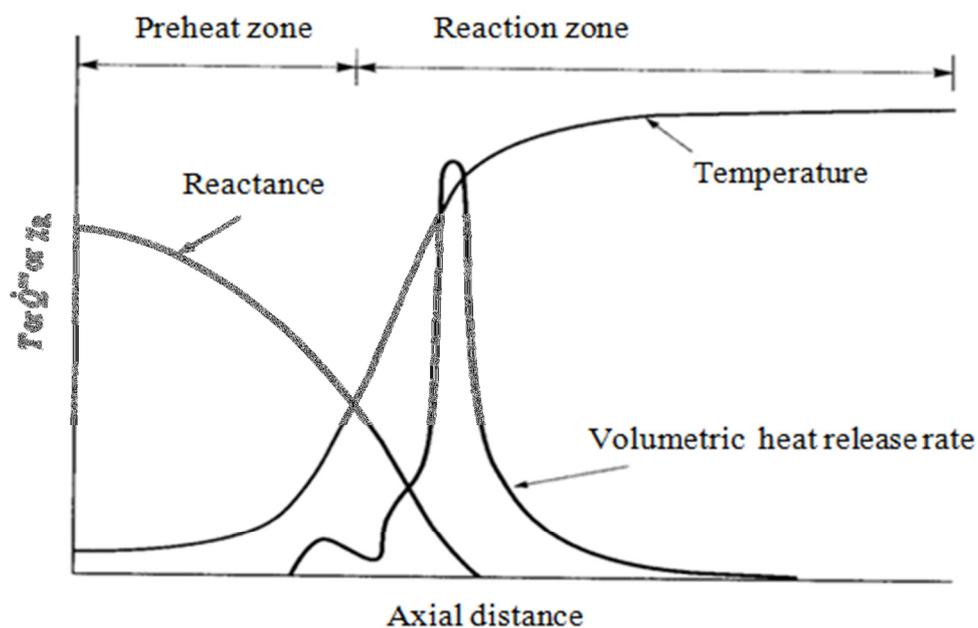
From these experiments and previous studies, it can be estimated that the NO<sub>x</sub> reduction with increasing heat input rate is attributed to the decrease in thermal NO due to an increase in turbulent intensity and fuel–air mixing through swirling premixed. However, this estimation is not clear, because there is insufficient data relating flow and flame structures in this study.

## CONCLUSIONS

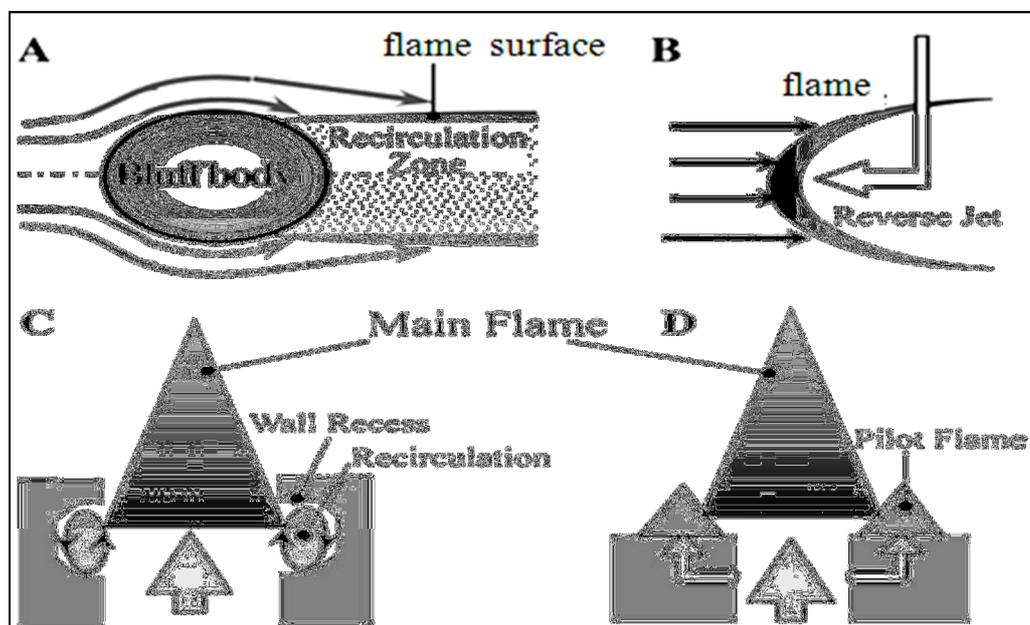
1. The highest burning velocity occurred when the equivalence ratio is approximately equal to ( $\phi=1.01$ ), where the fuel and air mixture is equal to stoichiometric conditions.
2. Efficiency of combustion stability increases to ( $\zeta_s=9.33\%$ ) with a decrease of number of carbon atoms from ( $n_c=3$  to 4), ( $A_{\text{blow}}$  &  $A_{\text{flash}}$ ) which will decrease the flame stabilization area and depend on this chosen suitable burner in industrial application.
3. The NO<sub>x</sub> emissions for hydrocarbon fuel decrease with the decrease of equivalence ratio.
4. The CO emissions decrease with the decrease of  $\phi$ , and minimum CO emissions are observed at ( $\phi=1$ ) because of high flame temperature.
5. Burning velocity magnitude by using angle method is higher than area method at stoichiometric ratio, because of losses of unburned mixture.
6. For all hydrocarbon fuels the fuel mole fraction ( $X_f$ ) increase with increase Reynolds number ( $Re$ ) of mixture, for two properties flash back and blow-off of flame front.

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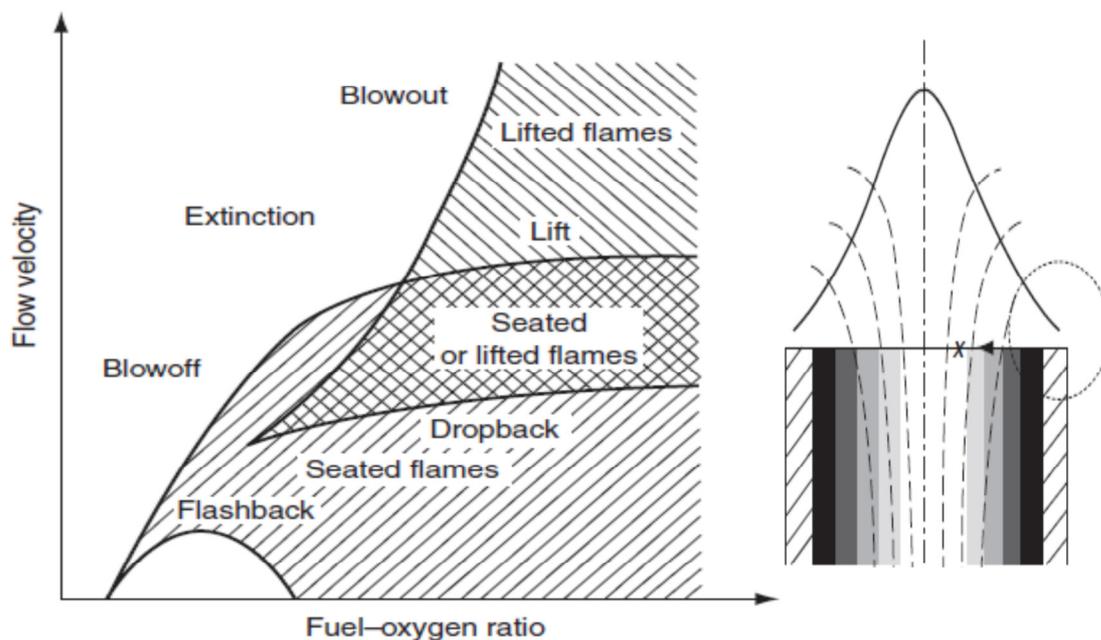
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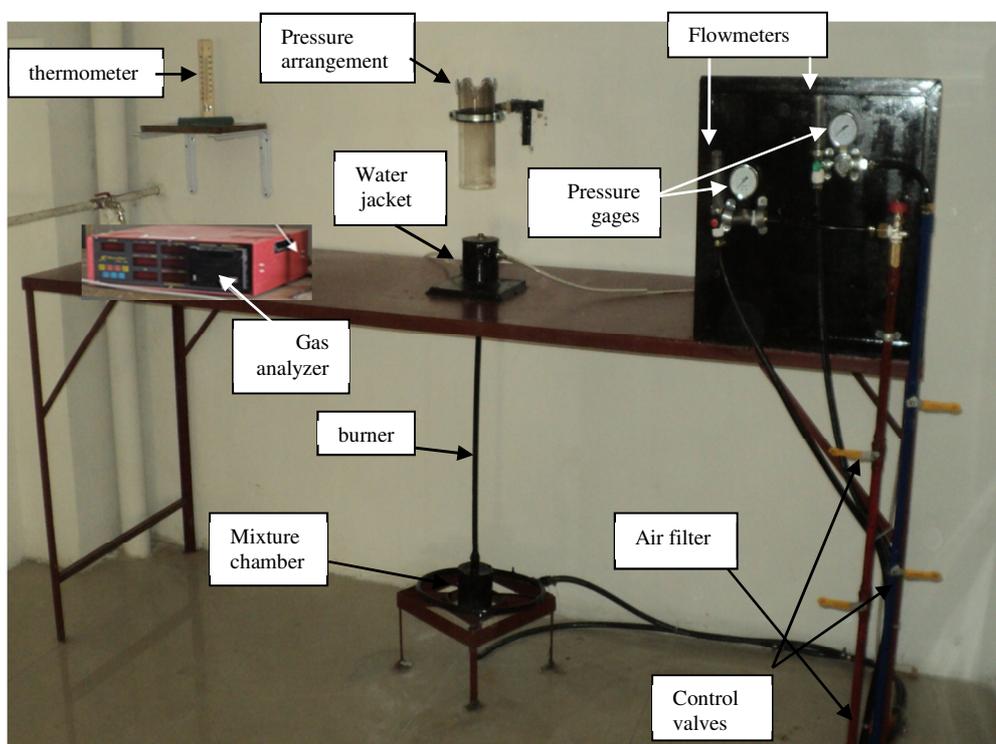
**Fig.1.** Flame structure, temperature and heat-release rate profiles [5].



**Fig. 2.** Methods of flame stabilization, (A) bluff body, (B) opposing jet, (C) recess wall, and (D) pilot flame [6].



**Fig. 3.** seated and lifted flame regimes for Bunsen-type burners [8].



**Fig.4.** The test rig of experimental work.

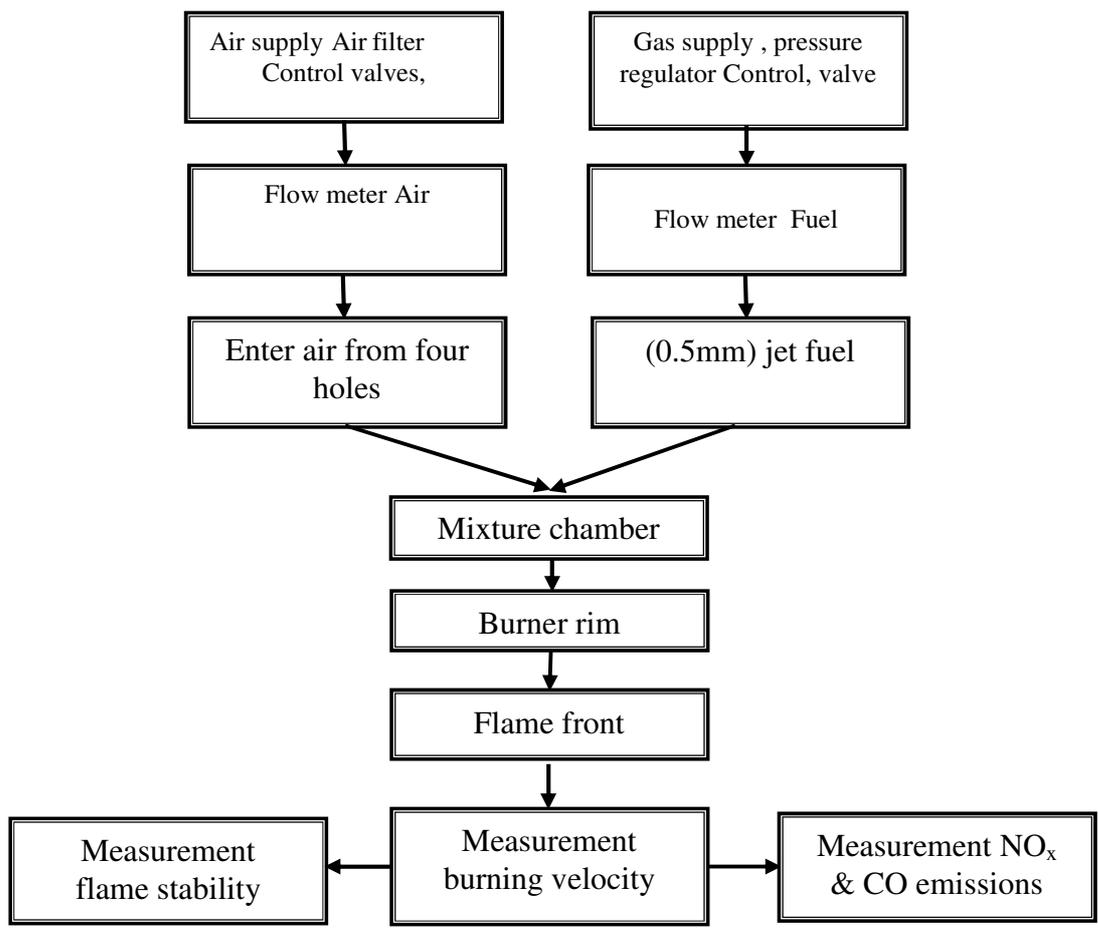


Fig.5. Flow chart combustion system.

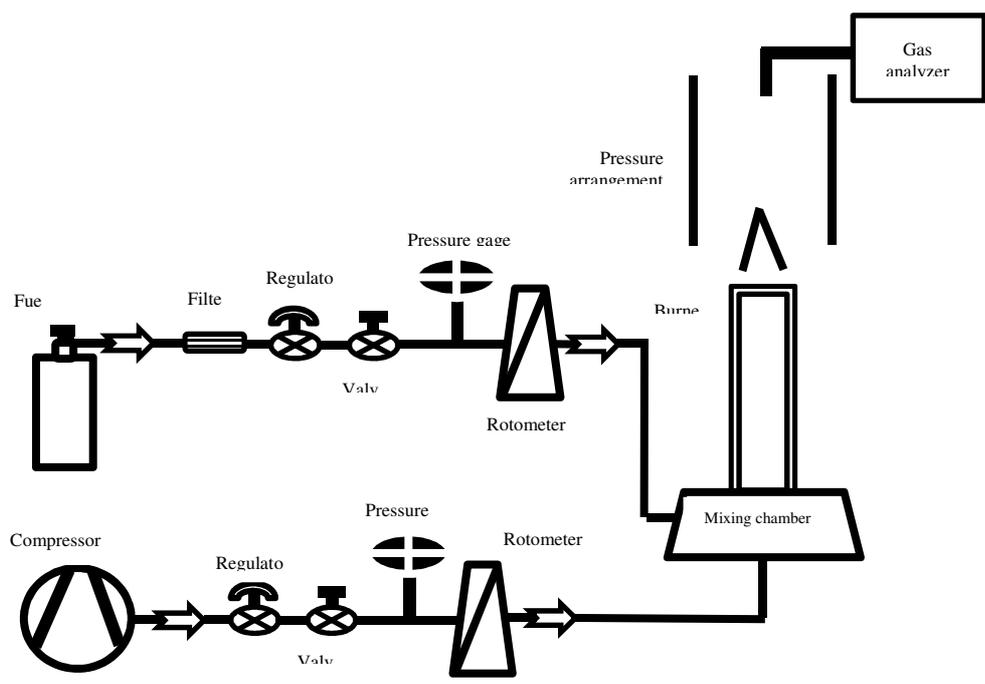
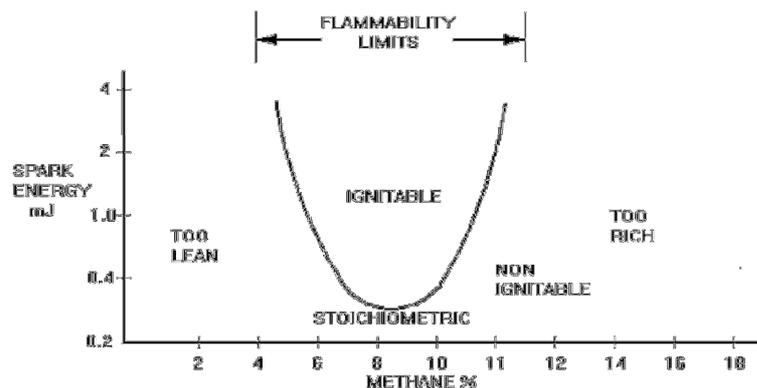
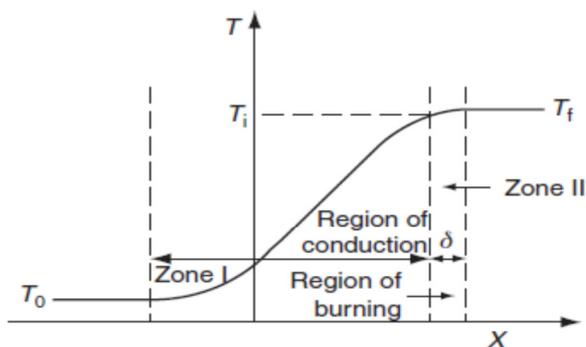


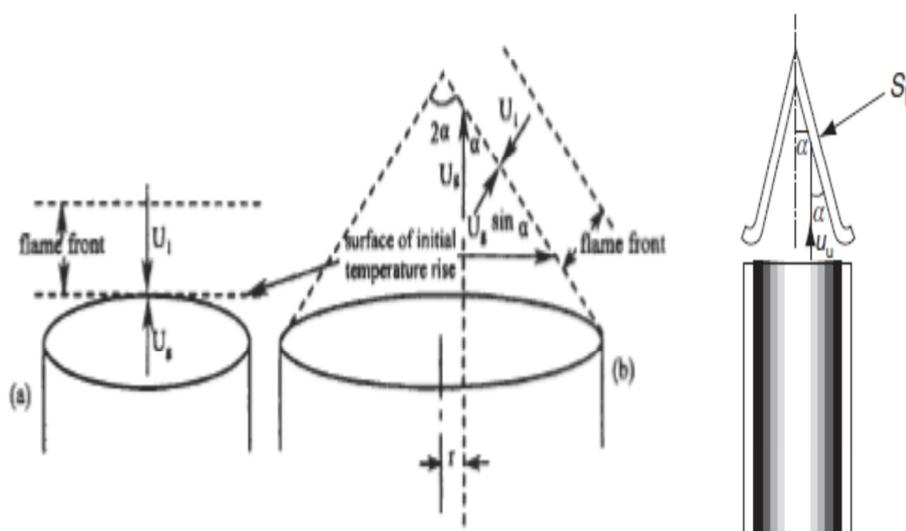
Fig. 6. Schematic diagram of the experimental test rig.



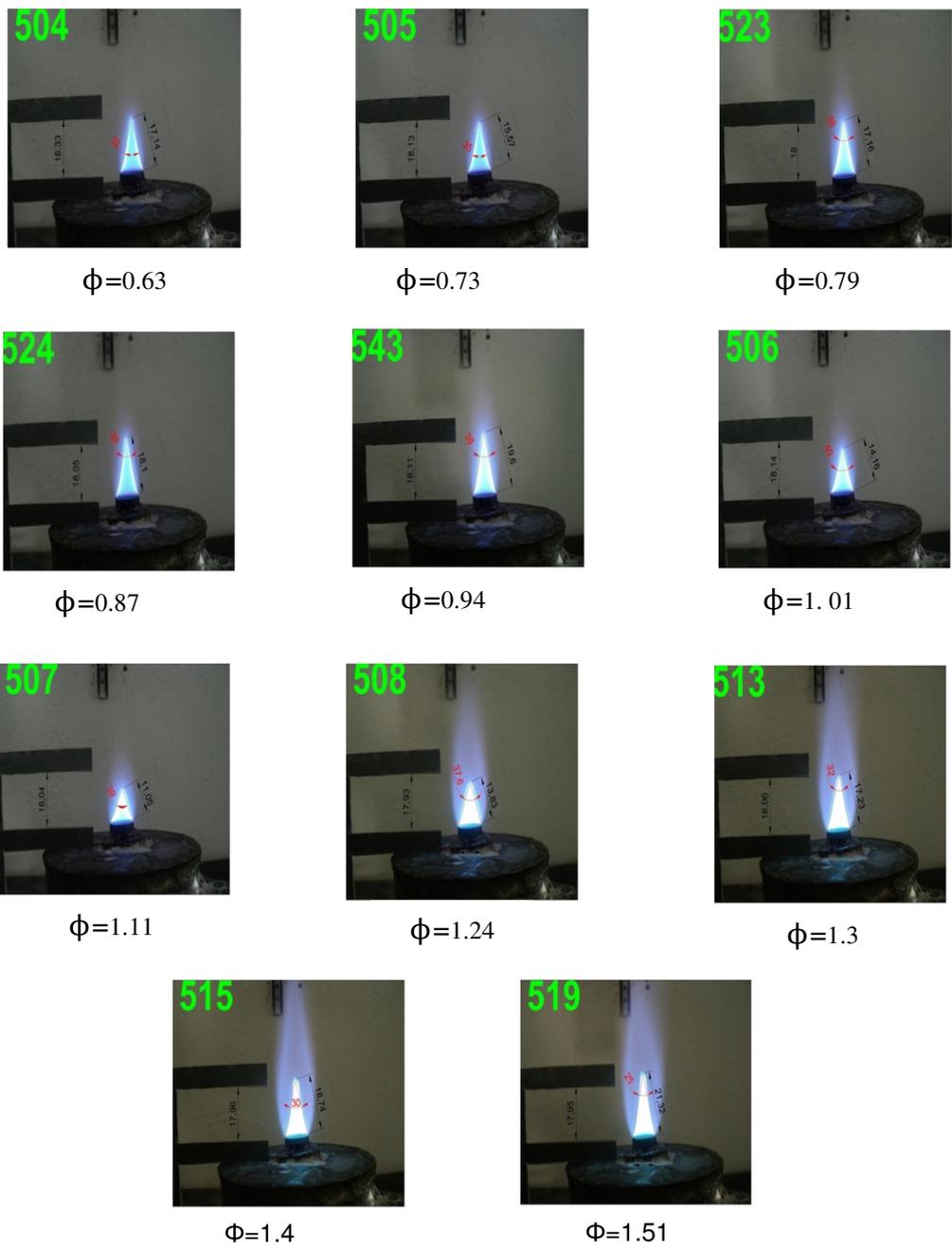
**Fig.7.** Ignition curve and flammability limits for methane-air mixtures at atmospheric pressure and 26 °C [11].



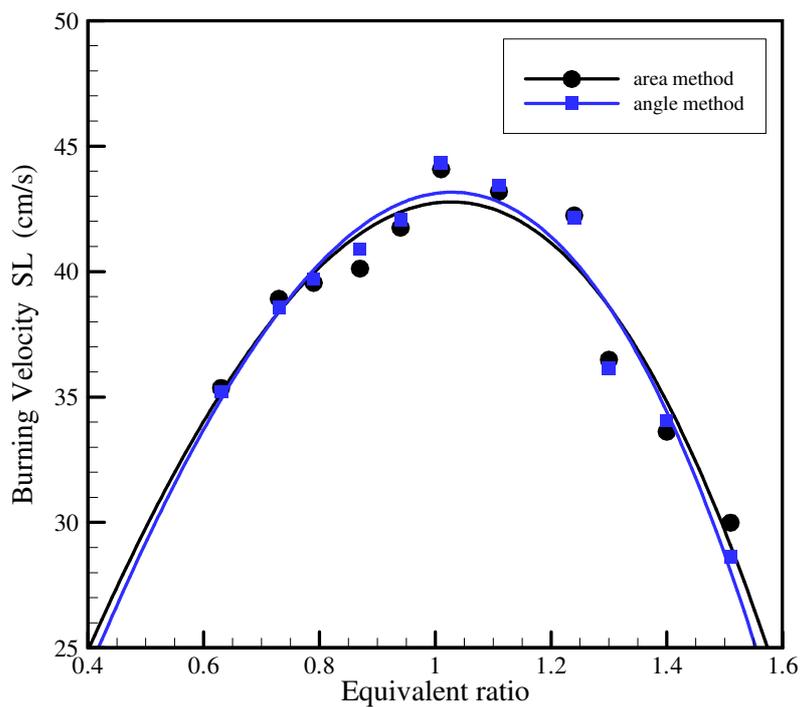
**Fig.8.** Mallard-Le Chatelire description of the temperature in a laminar flame wave. [10]



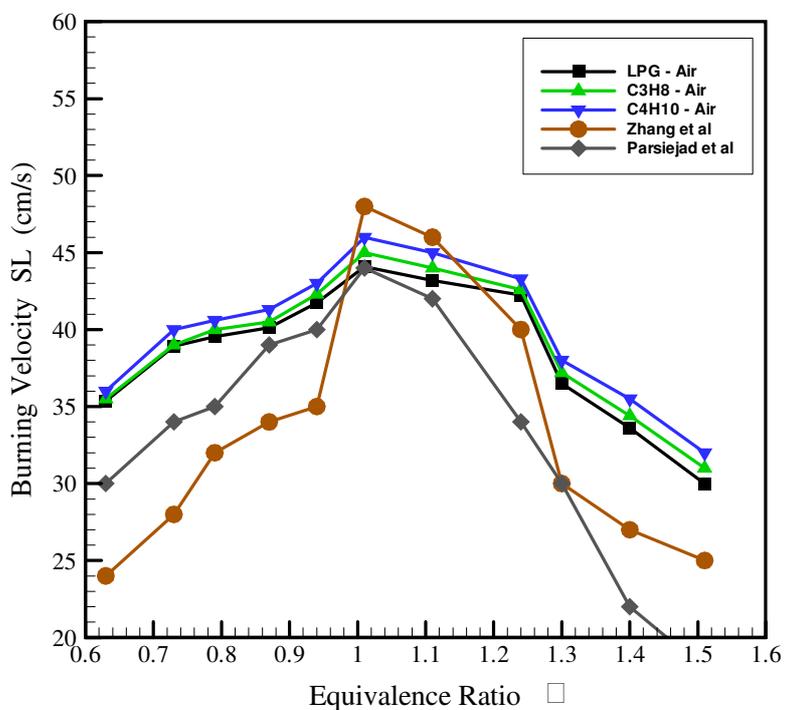
**Fig.9.** Velocity vectors in a Bunsen core flame [12].



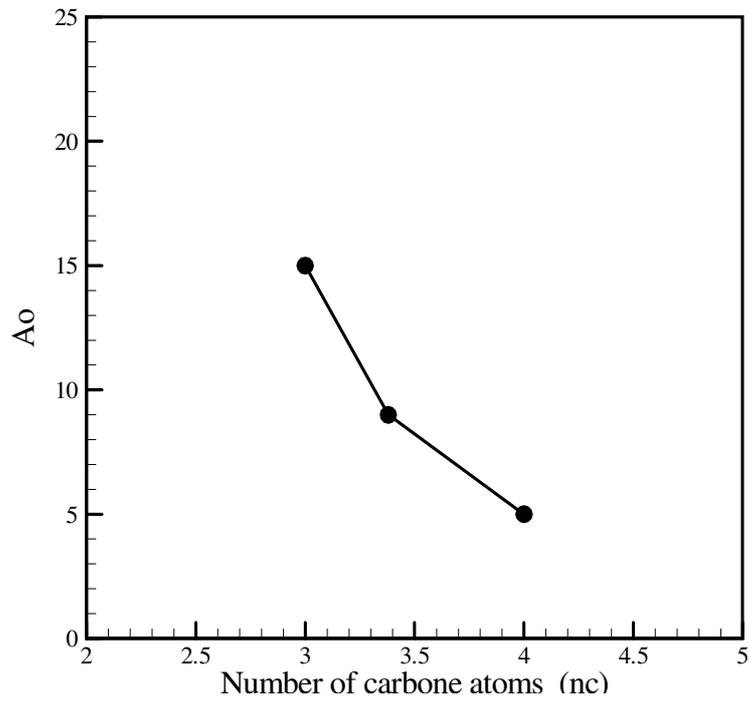
**Fig.10.** Shows Bunsen cone flame for LPG fuel at range ( $0.63 < \phi < 1.51$ ).



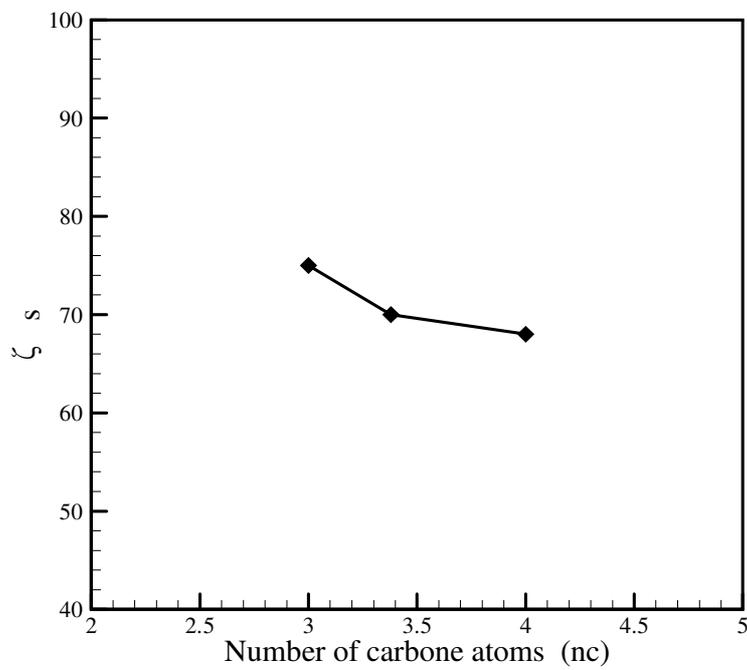
**Fig.11.** burning velocity by using area and angle methods for LPG fuel.



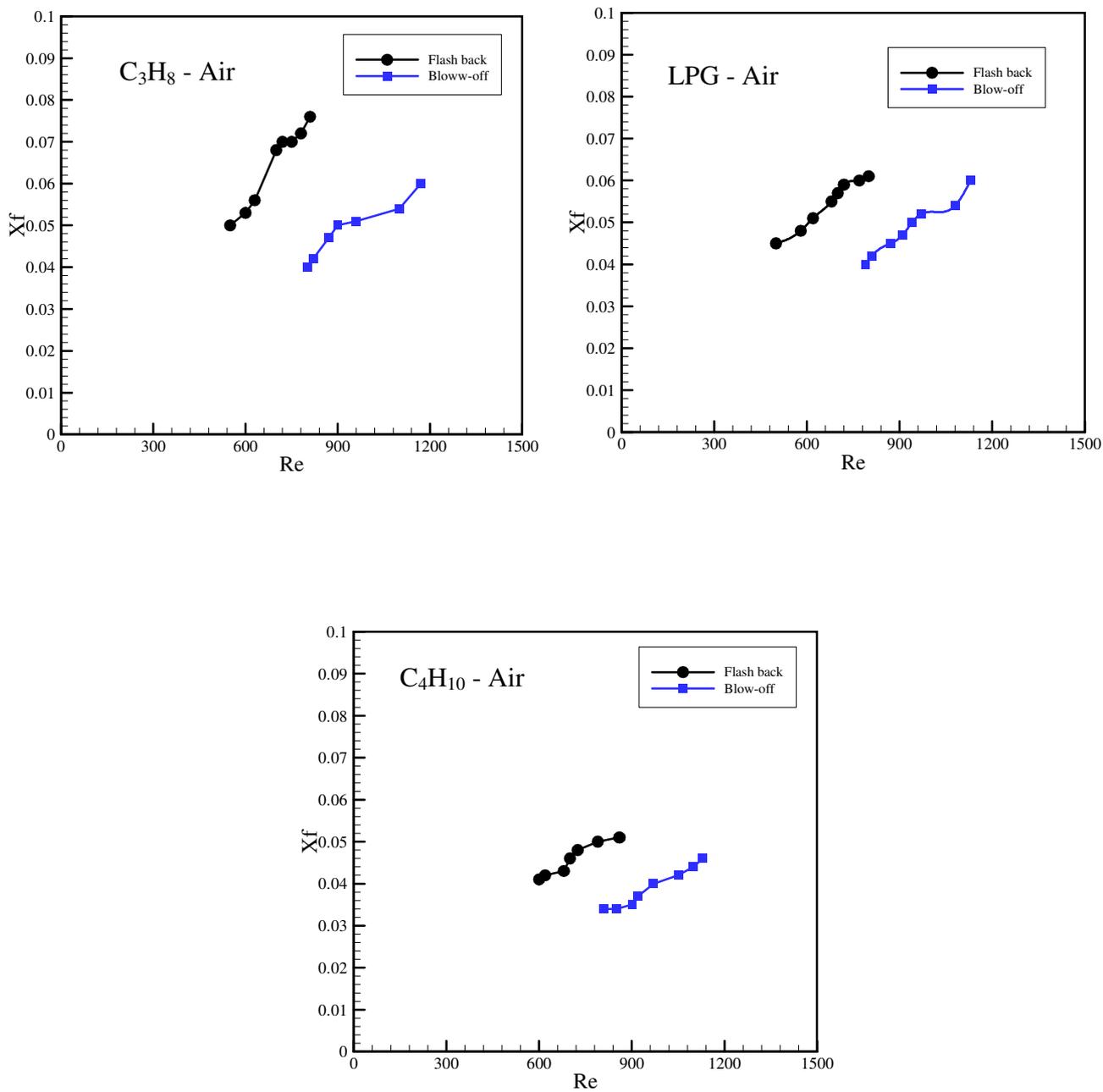
**Fig.12.** Compare burning velocity range between present work and previous study.



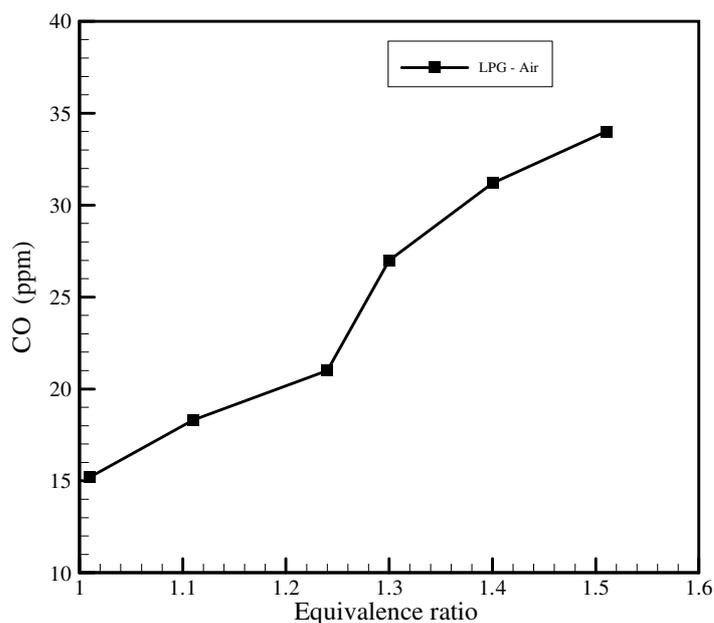
**Fig.13.** effect number of carbon atoms in area of stability.



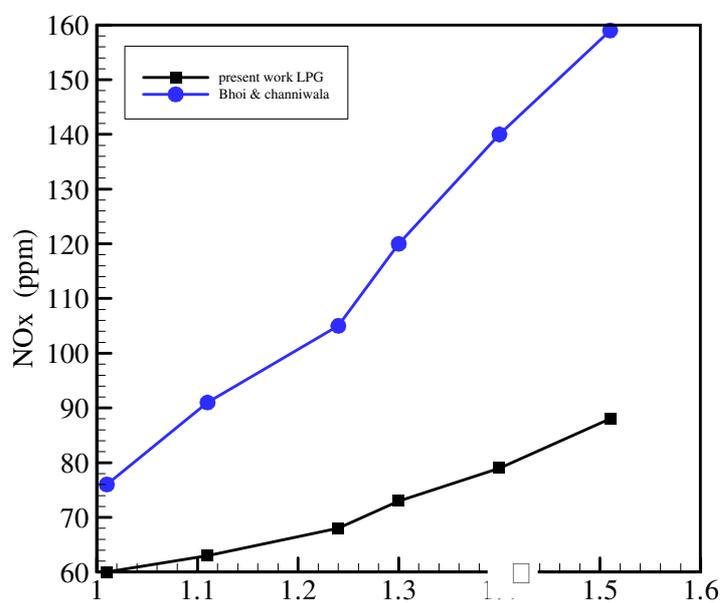
**Fig.14.** effect number of carbon atoms in efficiency of stability.



**Fig.15.** variable mole fraction of fuel with Reynolds number.



**Fig.16.** characteristics of CO emissions as a function of equivalence ratio.



**Fig.17.** characteristics of NO<sub>x</sub> emissions as a function of equivalence ratio with previous study

**Table (1). Determine burning velocity by using (Area method)**

| Number of picture | flow rate of gas (L / min) | flow rate of air (L / min) | (A/F)a | Equivalence ratio $\Phi$ | Burner diameter | Surface area cm <sup>2</sup> | Burning velocity cm/sec |
|-------------------|----------------------------|----------------------------|--------|--------------------------|-----------------|------------------------------|-------------------------|
| 504               | 0.4                        | 15                         | 37.5   | 0.63                     | 1.6             | 7.259                        | 35.36                   |
| 505               | 0.46                       | 15                         | 32.61  | 0.73                     | 1.6             | 6.62                         | 38.92                   |
| 523               | 0.5                        | 15                         | 30     | 0.79                     | 1.6             | 6.533                        | 39.55                   |
| 524               | 0.55                       | 15                         | 27.27  | 0.87                     | 1.6             | 6.46                         | 40.12                   |
| 543               | 0.59                       | 15                         | 25.42  | 0.94                     | 1.6             | 6.224                        | 41.75                   |
| 506               | 0.63                       | 15                         | 23.81  | 1.01                     | 1.6             | 5.91                         | 44.08                   |
| 507               | 0.7                        | 15                         | 21.43  | 1.11                     | 1.6             | 6.059                        | 43.19                   |
| 508               | 0.78                       | 15                         | 19.23  | 1.24                     | 1.6             | 6.226                        | 42.24                   |
| 513               | 0.82                       | 15                         | 18.29  | 1.3                      | 1.6             | 7.225                        | 36.49                   |
| 515               | 0.88                       | 15                         | 17.05  | 1.4                      | 1.6             | 7.873                        | 33.62                   |
| 519               | 0.95                       | 15                         | 15.79  | 1.51                     | 1.6             | 8.864                        | 29.99                   |

**Table (2). Determine burning velocity by using (Angle method)**

| Number of picture | flow rate of gas (L / min) | flow rate of air (L / min) | (A/F)a | Equivalence ratio $\Phi$ | Burner diameter | Angle ( $\alpha$ ) degree | Mixture velocity | Burning velocity cm/sec |
|-------------------|----------------------------|----------------------------|--------|--------------------------|-----------------|---------------------------|------------------|-------------------------|
| 504               | 0.4                        | 15                         | 37.5   | 0.63                     | 1.6             | 16                        | 127.72           | 35.198                  |
| 505               | 0.46                       | 15                         | 32.61  | 0.73                     | 1.6             | 17.5                      | 128.22           | 38.549                  |
| 523               | 0.5                        | 15                         | 30     | 0.79                     | 1.6             | 18                        | 128.55           | 39.717                  |
| 524               | 0.55                       | 15                         | 27.27  | 0.87                     | 1.6             | 18.5                      | 128.96           | 40.914                  |
| 543               | 0.59                       | 15                         | 25.42  | 0.94                     | 1.6             | 19                        | 129.3            | 42.087                  |
| 506               | 0.63                       | 15                         | 23.81  | 1.01                     | 1.6             | 20                        | 129.63           | 44.327                  |
| 507               | 0.7                        | 15                         | 21.43  | 1.11                     | 1.6             | 19.5                      | 130.21           | 43.457                  |
| 508               | 0.78                       | 15                         | 19.23  | 1.24                     | 1.6             | 18.8                      | 130.87           | 42.168                  |
| 513               | 0.82                       | 15                         | 18.29  | 1.3                      | 1.6             | 16                        | 131.2            | 36.158                  |
| 515               | 0.88                       | 15                         | 17.05  | 1.4                      | 1.6             | 15                        | 131.7            | 34.08                   |
| 519               | 0.95                       | 15                         | 15.79  | 1.51                     | 1.6             | 12.5                      | 132.28           | 28.626                  |