Full Length Research Paper

The effect of initial pressure and temperature upon the laminar burning velocity and flame stability for propane-air mixtures

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Laminar burning velocity is very important for both combustion modeling and kinetic scheme validation and improvement. Accurate experimental data are needed. To achieve this, a spherical flame with constant pressure method was chosen, since it allows high-pressure and high-temperature initial conditions. Considerations were established to link between stretched and unstretched velocities, where the stretch factor controls the burning velocity. Because of the lack of data for burning velocity of propane-air mixtures at elevated pressures and temperatures, and the importance of such data for the applications in engines and turbines as described previously, it is necessary to obtain data for these conditions. Results for higher initial pressures and temperatures have been obtained for a wide range of equivalence ratios. The laminar burning velocity of propane–air mixtures was measured using thermocouples technique. The experiments were carried out for a wide range of equivalence ratios from $\emptyset$= 0.5 to $\emptyset$= 1.5, mixture initial temperatures of 300 to 350 K, and mixture initial pressure from 0.5 to 1.5 bar. The detailed uncertainty analysis shows the accuracy of the present measurement within ±5%. The present measurements are successfully validated against existing experimental and computational results. The peak burning velocity was observed for slightly rich mixtures even at higher mixture temperatures. The burning velocity was observed to decrease with increasing initial pressure. Markstein Number increases with increasing with equivalence ratio increases from lean to rich mixtures. But it decreases with increasing initial temperature.

Keywords: Initial pressure, Temperature, Laminar burning velocity, Flame stability for propane-air mixtures

INTRODUCTION

Ever since prehistoric times, combustion has always been the major energy production process. The high level of development reached over the last century is mostly due to impressive technological improvements that result from massive utilization, transformation and control of the main energy resource: fossil oil. However, fossil energy combustion leads to high levels of pollutant emissions, such as carbon monoxide, greenhouse gases and particles (Varea, 2013). Propane as a gaseous fossil fuel is used in many residential, commercial, and industrial systems and processes. By burning the propane in combination with air, the mixture produces a flame that can be applied to heating appliances, ovens, or in the manufacturing of glass products (Blanchard, 2012). In

many studies, propane was chosen as test fuel.2, 4-8, 10-12, 14 Indeed, propane is the smallest hydrocarbon which participates to reactions typical for larger hydrocarbons, and therefore its study affords a better understanding of the combustion mechanisms of larger hydrocarbon fuels (RAZUS, 2012 & Basco, 2012).

Laminar flame speed is an important fundamental physicochemical property of a fuel–air mixture, which can be used to validate the chemical reaction mechanisms and to gain a better understanding of the combustion process, such as the turbulence combustion in SI engines and power generation systems (Wu, 2011 & Tang, 2010). Many researches have been conducted to predict the accurate measurements of the laminar burning velocity of propane–air mixtures. Researchers have used several techniques, including the combustion bomb method (Tang, 2009 & Huzayyin, 2008) counter jet or stagnation plane method (Yu, 1986 & Zhao, 2004) and heat flux method (Bosschaart, 2004). (Kim, 2011) used an annular diverging tube to predict the laminar burning velocity of fuel– air mixtures at ambient conditions. Large part of these researches has not considered the effect of heat loss and thermal regeneration between flame and walls in such small channels. Most of the available experiments provide the burning velocity data at ambient temperature and pressure only. Therefore, accurate burning velocity data for propane–air mixtures at high temperatures and pressures will be helpful in the design of various practical devices (Chaichan, 2013).

Laminar burning velocity is a strongly dependent parameter of mixture features, e.g. initial temperature, pressure and mixture equivalence ratio. And generally, this fundamental parameter is determined at standard condition, for example, atmospheric pressure and initial temperature of 298 K, or relatively low temperature and pressure, primarily owing to some difficulties in experimental setups and measurements. However, in most practical applications, initial pressure and temperature of the mixture are often higher than the standard values. Therefore, it is very important to quantify the effects of pressure and temperature on these fundamental parameters (Liao, 2012 & Chaichan, 2013).

In this study, we focus on the description of the spherical expanding flame technique at constant pressure using thermocouples technique. This configuration makes it possible to reach thermodynamic conditions before ignition, at elevated pressures and temperatures. It is very difficult to reach these conditions using steady state methods (flat flame burner, rim-stabilized conical flame, counterflow), where the operational ranges is limited due to flame stability problems. In addition, the technique used in the present study can integrate the stretch effect because it can be extracted from the direct topology of the spherical flame.

Expermintal Setup

The experimental system used in this study is illustrated as shown in Fig. 1; a detailed description of the experimental setup is in (Saleh, 2006). The flame is propagated inside the flame chamber passing over many thermocouple junctions located or inserted inside the chamber (Figs. 2 & 3). The thermocouple can be used as a sensor probe. The computer control system is used to read the flame speed inside the cylinder. Six thermocouples were fixed and used inside the cylinder, and it were distributed regularly as shown in Fig 1. They are connected to computer in order to collect, process and display the data. These collected data are getting at a very short time period. An interface circuit is built between the sensors and the computer. The thermocouple signals are reading through the parallel port. A computer program (control system software) is used to activate the port and process the data controlled. Below is a determination for the hardware and software of the control system used to connect the thermocouples to a computer as shown in Fig. 4. The control system was designed with the cooperation of Computer Engineering and Information Technology Dept., University of Technology.

To prepare the mixture (fuel-air), a gas mixer has been designed and constructed for gaseous fuels compounds that have a low partial pressure like (methane, propane, LPG & butane). The main purpose of preparing 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.

The mixer (Fig. 4) 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 undergoes a pressure of more than (60 bar) and also withstands 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 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 gas 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 an important role

in measuring the burning velocity. The process performed is based on partial pressure of mixture components and 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 partial pressure for propane is low so this method is used to obtain an increasing partial pressure for the used propane-air mixture.

The combustible mixture was prepared by adding propane and air according to their calculated partial pressures. Propane was admitted first, followed by air. The partial pressures were determined by initial pressure, equivalence ratio Ø (the ratio of the actual fuel/air ratio to the stoichiometric ratio).

The adiabatic temperatures were calculated by using the following equations, where the initial pressure and temperature kept the same value for mixtures. The initial conditions were strictly controlled in the experiments to realize the same initial pressure and temperature. For avoiding the influence of wall temperature on mixture temperature, an enough interval between two experiments is set, providing enough time for wall to cool down and keeping the same initial temperature.

Laminar burning velocity and Markstein numbers

To calculate the affecting variables (Haung, 2006) calculation method was used, applying the reading from the experimental rig. For a spherically expending flame, the stretched flame velocity, S_n, reflecting the flame propagation speed, is derived from the flame radius versus time data as

$$S_n = \frac{dr_u}{dt} \qquad (1)$$

Where r_u is the radius of the flame and t is the time. S_n can be directly obtained from the flame measurements. Flame stretch rate, α, representing the expanding rate of flame front area, in a quiescent mixture is defined as

$$\alpha = \frac{d(\ln A)}{dt} = \frac{1}{A}\frac{dA}{dt} \qquad (2)$$

where A is the area of flame. For a spherically outwardly expanding flame front, the flame stretch rate can be simplified as

$$\alpha = \frac{1}{A}\frac{dA}{dt} = \frac{2}{r_u}\frac{dr_u}{dt} = \frac{2}{r_u}S_n \qquad (3)$$

In respect to the early stage of flame expansion, there exists a linear relationship between the flame speeds and the flame stretch rates; that is,

$$S_l - S_n = L_b\alpha, \qquad (4)$$

Where S_l is the unstretched flame speed, and L_b is the Markstein number (Markstein length) of burned gases. From eqs. (1) and (3), the stretched flame speed, S_n, and flame stretch rate, α, can be calculated. Markstein debates the influence of flame stretch on laminar burning velocities. 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.

The unstretched 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 slope of S_n–α curve. Markstein number can reflect the stability of flame. Positive values of L_b indicate that the flame speed decreases with the increase of flame stretch rate. In this case, if any kinds of protuberances appear at the flame front (stretch increasing), the flame speed in the flame protruding position will be suppressed, and this makes the flame stability. In contrast to this, a negative value of L_b means that the flame speed increases with the increase of flame stretch rate. In this case, if any kinds of protuberances appear at the flame front, the flame speed in the flame protruding position will be increased, and this increases the instability of the flame. When the observation is limited to the initial part of the flame expansion, where the pressure does not vary significantly yet, then a simple relationship links the spatial flame velocity S_l to unstretched laminar burning velocity u_l, given as

$$u_l = \rho_b S_l / \rho_u \qquad (5)$$

where ρ_b and ρ_u are the densities for burned gases and unburned gases. The equation

$$u_n = S\left[S_n \frac{\rho_b}{\rho_u}\right] \qquad (6)$$

is used to determine the stretched laminar burning velocity u_n, and the stretched mass burning velocity u_{nl}, proposed by (Bradley et al., 1998), is calculated from

$$u_{n1} = \frac{\rho_b}{\rho_b - \rho_u}(u_n - S_n) \qquad (7)$$

in which S is a rectified function and it depends upon the flame radius and the density ratio, and accounts for the effect of the flame thickness on the mean density of the burned gases. The expression for S in the present study used the formula given by (Bradley et al., 1998),

$$S = 1 + 1.2\left[\frac{\delta_1}{r_u}\left(\frac{\rho_u}{\rho_b}\right)^{2.2}\right] - 0.15\left[\frac{\delta_1}{r_u}\left(\frac{\rho_u}{\rho_b}\right)^{2.2}\right]^2 \qquad (8)$$

Here δ_l is laminar flame thickness, given by $\delta_l = v/u_l$, in which v is the kinetic viscosity of the unburned mixture.
In practice, it is suitable to derive the activation temperature, E_a/R, from the linear plot of 2 ln (f) against
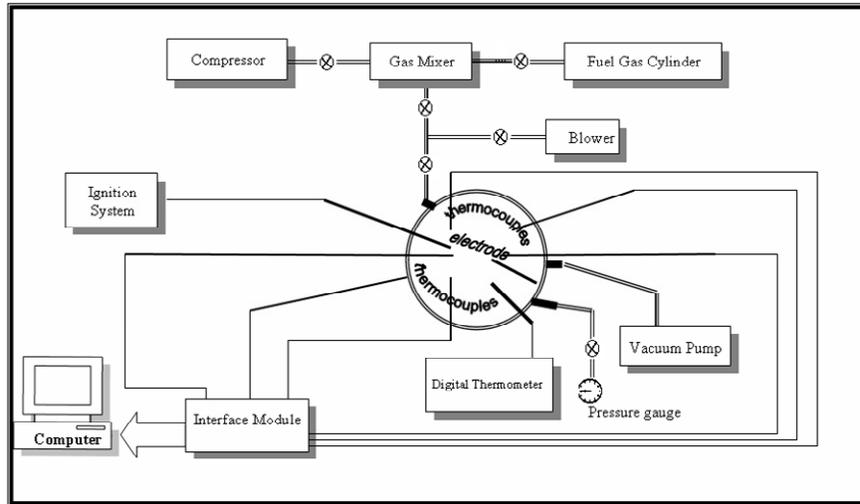
Figure. 1, Block diagram of experimental apparatus
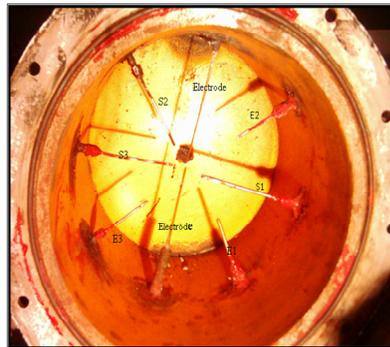

Figure 2. the internal structure of combustion chamber

Figure 3. the outer structure of combustion chamber

$1/T_{ad}$, as the following function was recommended (Sun, 1999):

$$\frac{E_a}{R} = -2 \frac{d \ln (f^0)}{d(\frac{1}{T_{ad}})} \qquad (9)$$

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:

$$f^0 = \rho_u S_l \qquad (10)$$

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

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

$$Ze = \frac{E_a}{R} \frac{T_{ad} - T_u}{T_{ad}^2} \qquad (11)$$

Uncertainty 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 300 ± 2 K. Thus, the relative error in initial temperature is 0.04%. Mixtures are prepared according to the partial pressure of the constituents. Uncertainties in the pressure measurements of the propane and air are less than 0.1%. Additionally, the
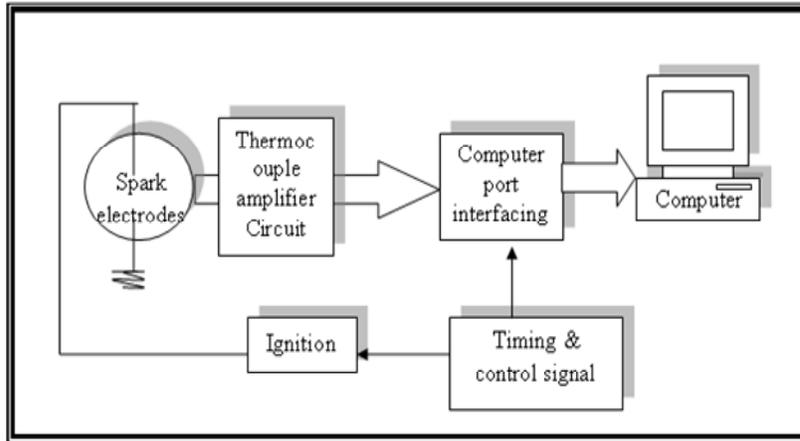
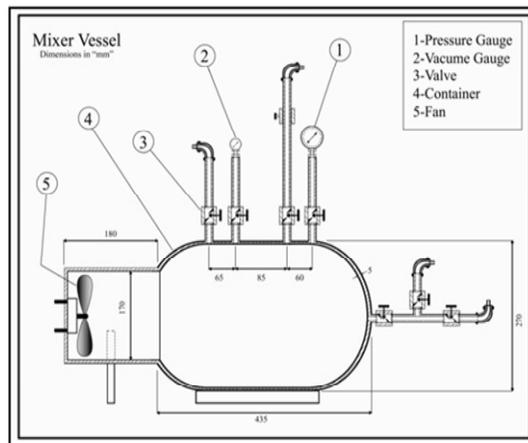**Figure 4.** Block Diagram of Interfacing Circuit

Figure 5. Mixture preparing unit diagram

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 average 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).

System valdiation

Due to the usage of new technique in measuring laminar burning velocity, and to validate the resulting measures the results were compared with available data in previous literatures to validate the present measurement system. Fig. 6 demonstrates the present measurements of the laminar burning velocities of propane-air flames, compared with other experimental results from (Hamid, 1986, Yu, 1986, Hani, 1998, Arkan, 2000 and Al-Salman, 2002). The comparison shows good accession, verifying

the high accuracy in measuring the laminar burning velocity.

Elevated temperature effect

Fig. 7 shows the variation of the burning velocities as a function of unburned gas temperature with fixed pressure (P_u= 1 bar) for wide range of equivalence ratios from Ø=0.5 to 1.5. It can be seen from the figure that at a fixed pressure the burning velocities for propane-air mixtures increase with temperature. The maximum laminar burning velocity laid at Ø=1.1 for the three cases. These results give good agreements with (Saeed, 2007, Gerstein, 1951 and Davis, 1998). Increasing initial temperature from 300 to 325 K caused an increment of 21.6%, while at 350K the increment was 43.7%.

Fig. 8 shows the variation of burning velocity as a function of equivalence ratio and temperature at fixed pressure at 0.5 bar. It can be seen from the figure that the burning velocity increases with the increase in initial temperature (300, 325 and 350 K). The maximum burning velocity achieved in the present work was at Ø=1.1 and T_u=350 K. The reduction in initial pressure from 1 to 0.5 bar caused an increment in burning velocities with a rate of 22.5%for 300K, 13.88% for 325%K and 17.47% for 350K.

Fig. 9 represents the effect of equivalence ratio on laminar burning velocity of propane-air mixture at fixed pressure of 1.5 bar. It can be seen from the figure that the burning velocity increases with the increase in initial temperature (300, 325 and 350 K). The maximum burning velocity achieved in the present work was at Ø=1.1 and T_u=350 K as the preceding figures. The increasing of initial pressure from 1 to 1.5 bars caused a reduction rate of 23% for 300K, 24% for 325K and 11.44% for 350K.

Elevated pressure effect

Fig. 10 represents the effect of elevated pressure on laminar burning velocity of lean propane-air mixture (Ø=0.8) with variable temperatures. It is clear that increasing pressure reduces laminar burning velocity of the mixture especially at low temperatures. Laminar burning velocities at high pressure and low temperature are low as the figure indicated. At p=1.5 bar and 300 K the measured laminar burning velocity was 18 cm/sec.

Fig. 11 illustrates the effect of elevated pressure on laminar burning velocity of stoichiometric propane-air mixture (Ø=1.0) with variable temperatures. The same effect for pressure is indicated here, but at high temperatures (350 K) this effect is relatively limited. The opposite effects of pressure and temperature cause the resultant laminar burning velocity.

Fig. 12 declares the effect of elevated pressure on laminar burning velocity of rich propane-air mixture (Ø=1.3) with variable temperatures. Pressure effect here is clearer than the former figures where the reduction in laminar burning velocities is large for 300 and 325 K mixtures. For mixtures at 350 K pressure effect was limited. Laminar burning velocity at rich mixtures more than Ø=1.2 affected highly with increasing pressure. The measured reduction for Ø=1.3 and 300 K initial temperature was 41% at P=1.5 bar compared with laminar burning velocity for the same equivalence ratio at the same initial temperature but P=1 bar.

Markstein Length

Zeldovich Number

Markstein length *(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). Fig. 13 represents the effect for wide range of equivalence ratios at specific initial pressure (P=1 bar). Increasing temperatures reduced Markstein length which indicates flame stability reduction. Markstein length increased with increasing equivalence ratios. While increasing pressure for fixed temperature (300 K) as in Fig. 14 increases Markstein length indicating better flame stability. Cellular structures appear at rich mixture flame front of propane–air mixture at high initial temperature due to the combined effect of diffusional-thermal and hydrodynamic instabilities.

The development of the diffusive-thermal instability involves changes in the flame structure. (Zeldovich, 1981) and others observed that flames, especially in rich mixtures are ready to develop a cellular flame structure. This flame instability is attributed to both hydrodynamic and thermo-diffusive effects, and affects the smooth, stable propagating flame forcing it to become unstable (Bradley, 1976). The Zeldovich number should affect the cell development as demonstrated by (Jun, 2010). Fig. 15 shows Zeldovich number of tested propane-air laminar premixed flames versus equivalence ratio. It can be seen that Zeldovich number increases with the increase of equivalence ratio till Ø= 1.1 condition, due to increments in the adiabatic flame temperature. However, the Zeldovich number shows a decreasing trend with mixture enrichment above this equivalence ratio, which point out the dominant effect of adiabatic flame temperature on Zeldovich number. Zeldovich number gets its maximum values at Ø= 1.1. Zeldovich numbers decreases with increasing temperature at fixed pressure. Fig. 15 declares that Zeldovich number increases with the

increase of pressure demonstrating better flame thermal stability.

CONCLUSSIONS

Propane is highly flammable fuel source when in the presence of oxygen. Experimental measurements for spherically expanding laminar flames of propane-air mixtures were conducted under initial temperatures of 3508 K to 450K, pressure of 0.5 to 1.5 bar and equivalence ratio of 0.5 to 1.5, in a constant volume combustion bomb. The main conclusions are summarized as follows:

1. Laminar flame speed of propane–air premixed mixtures peaks near an equivalence ratio of 1.1. It increases with increasing initial temperature and decreasing the initial pressure.

2. Adiabatic flame temperature peaks near the equivalence ratio of 1.1 due to the product dissociation and reduced amount of heat release. The adiabatic flame temperature increases with the increase of initial temperature and is insensitive to initial pressure at rich mixture side.

3. Markstein length increases with the increase of equivalence ratio and initial pressure, while it decreases with the increase of initial temperature. Cellular structures appear at rich mixture flame front of propane–air mixture at high initial temperature due to the combined effect of diffusional-thermal and hydrodynamic instabilities.

4. Laminar burning flux peaks near an equivalence ratio of 1.1 and increases with the increase of initial temperature and pressure.

5. Zeldovich numbers have been deduced for the pressure, temperature and equivalence ratio dependencies. Zeldovich numbers increase with the increase of pressure and decreases with the increase of initial temperature.

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NOMENCLATURE

Lb	Markstein length	
Ma	Markstein number	
Ze	Zeldovich number	
Sn	Stretched laminar burning velocity	(m/sec)
Sl	Unstretched laminar burning velocity	(m/sec)
ru	Flame radius	(mm)
Tad	The adiabatic flame temperature	(K)
Ea	Activation energy	(J/mole)

Greek symbols

a	Stretch rate	(s-1)
dl	Laminar flame thickness	(mm)
Ø	Equivalence ratio	
?	Mixture density	(kg/m3)
?	The thermal conductivity of unburned mixture	(W/m K)
fo	Mass burning flux	(g /cm s)

Subscript

n	Properties associated with the stretched flame
l	Properties associated with the unstretched flame
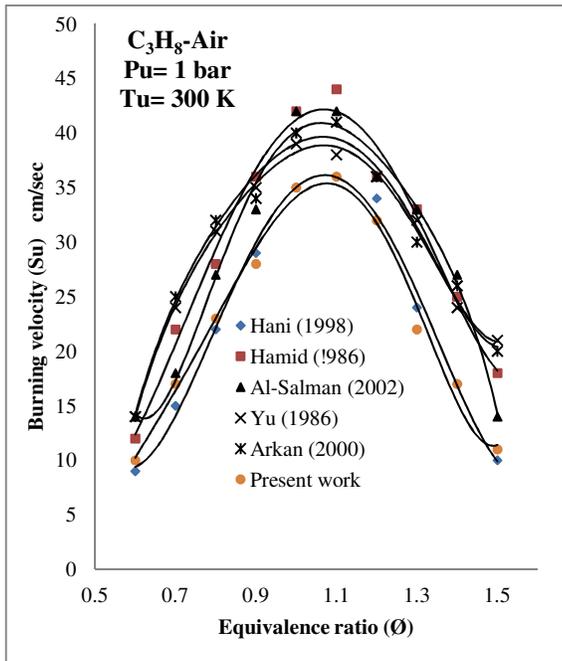
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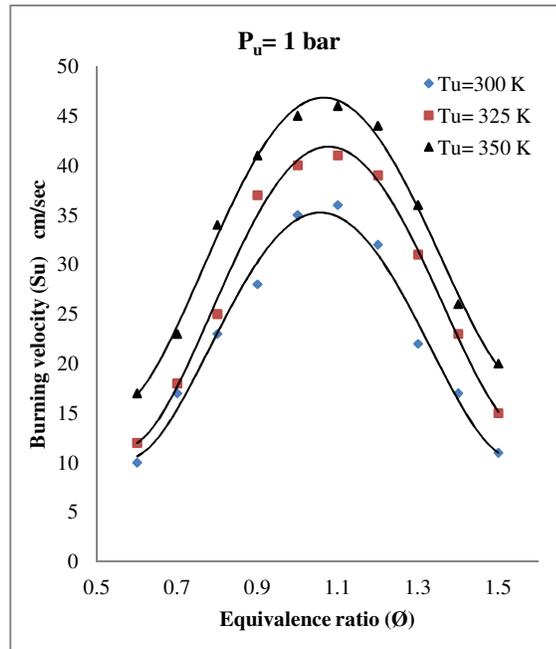
Fig. 7, temperature effect on laminar burning velocity for wide range of equivalence ratios at fixed P=1 bar
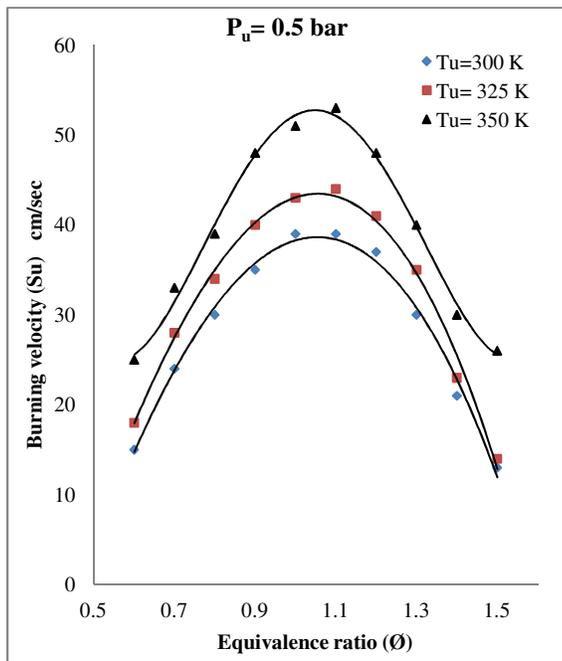
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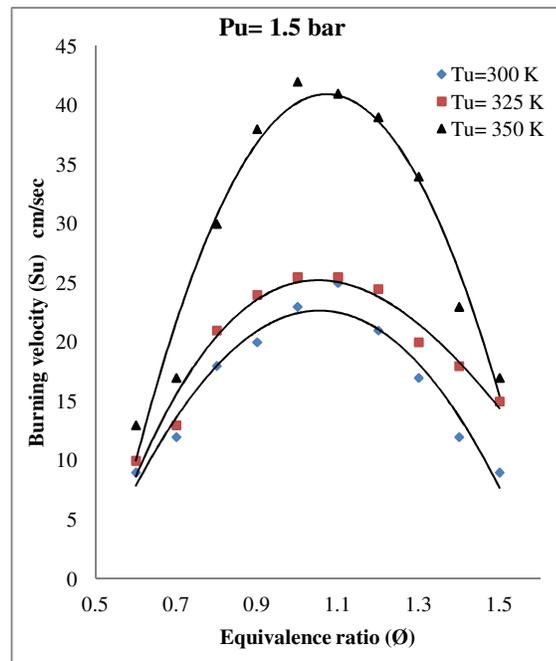
Fig. 9, temperature effect on laminar burning velocity for wide range of equivalence ratios at fixed P=1.5 bar
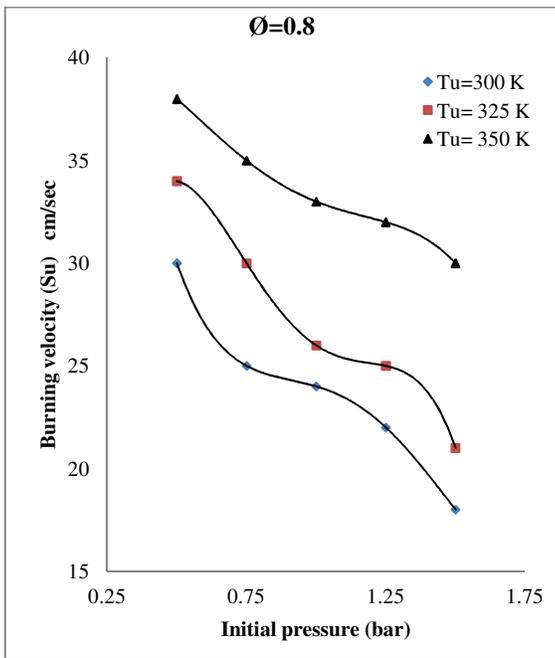
Fig. 10, pressure effect on laminar burning velocity for mixture equivalence ratio= 0.8 and variable temperatures
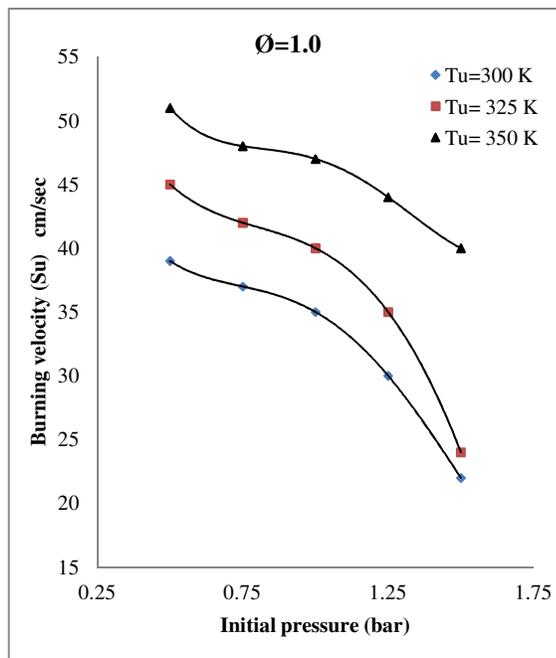
Fig. 11, pressure effect on laminar burning velocity for mixture equivalence ratio= 1.0 and variable temperatures
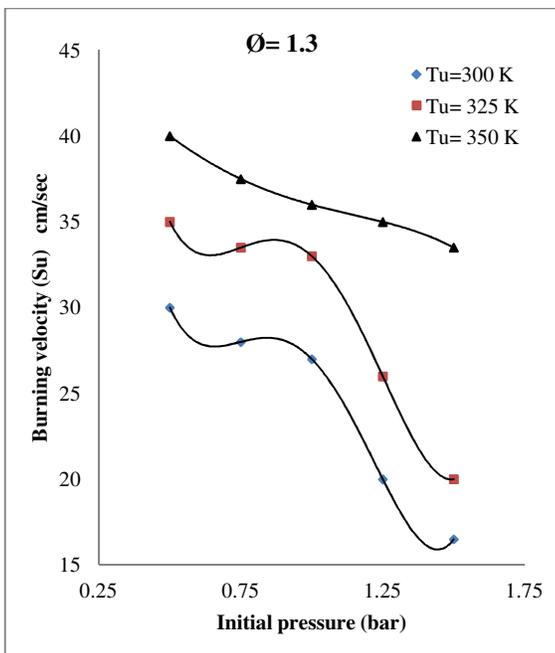
Fig. 12, pressure effect on laminar burning velocity for mixture equivalence ratio= 1.3 and variable temperatures
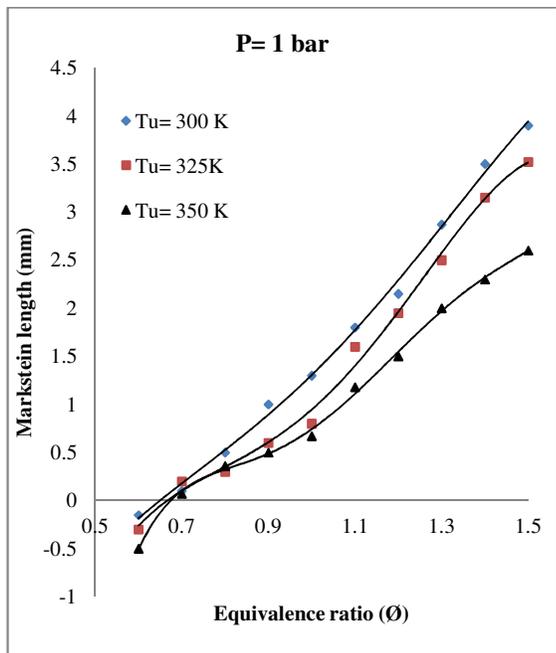

Fig. 13, temperature effect on Markstein length for mixture wide range of equivalence ratios
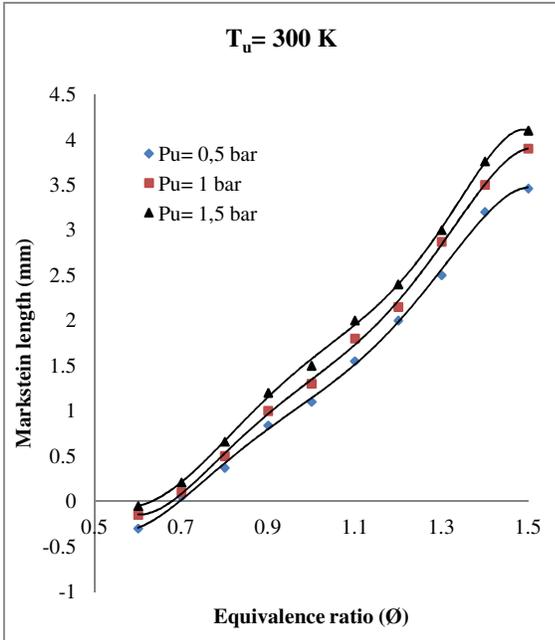
Fig. 14, pressure effect on Markstein length for wide range of mixture equivalence ratios
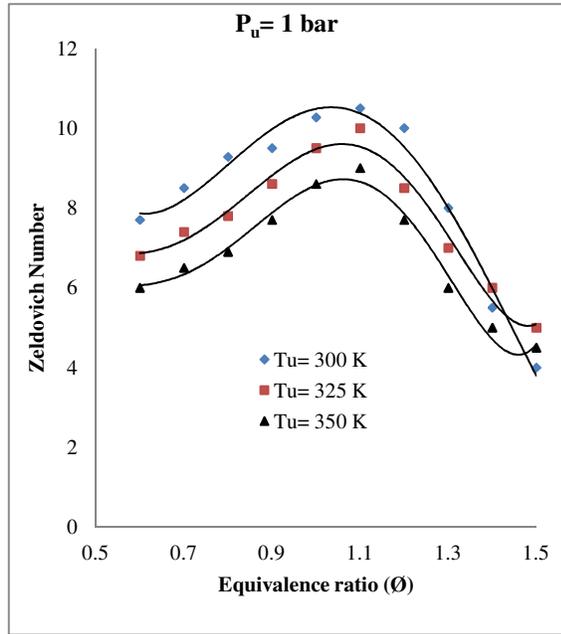

Fig. 15, temperature effect on Zeldovich number for wide range of equivalence ratios
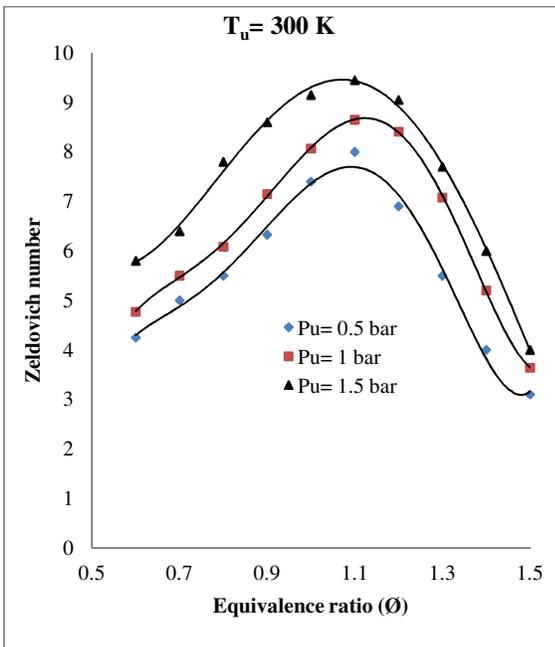

Fig. 16, pressure effect on Zeldovich number for wide range of equivalence ratios