Experimental study of the Laminar burning velocity and Markstine length of NH$_3$ – LPG- air premixed flames

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ABSTRACT

A pilot study on pre-mixed ammonia NH$_3$ / LPG / air in a centrally flame fixed volume chamber at different initial pressure was conducted [100, 200, 300] Kpa and initial temperature of (298K) and in addition to the rate of parity that has been tested for air/fuel mixture Ø (0.8,1,1.3) and the realization blends of concentration (0, 0.1, 0.2, 0.3) by volume and LPG concentration in start from

(1, 0.9, 0.8, 0.7) sequentially where applying Daltons Law of gasses, experimental data of the stretch flame rate, laminar burning velocity, laminar flame speed, and laminar burning velocity for ammonia as well as LPG.

The fixed volume chamber was designed and constructed as a special consideration for this study as I consider it to be the most accurate for the measurement of the laminar burning velocity. and access to control data has been used for the ignition of the mixing chamber and high–speed photography.

The experimental results showed that the impact of adding ammonia becomes apparent ammonia mixture of 30% and LPG greater than 70%. When pressure mixture initial at 100 Kpa. at Ø = 1 1 The laminar burning velocity from (34.945– 24.64 cm /sec), the laminar flame speed of mixture (LPG – NH$_3$ – air) reduces from (3.95 – 3.63) cm/sec, the Markstine length (2.52– 1.71) for the stoichiometric mixture at the atmospheric pressure. When the initial pressure is increased from (100-300) Kpa, the speed of the Laminar flame speed of the mixture (LPG– NH$_3$- Air) and flame radius of 20 mm combination is reduced (1.858 – 1.536) m/s, and the Laminar burning velocity is reduced from (24.56-17.16) cm/s for the lean mixture.

For a rich mixture, the laminar flame speed of the (LPG – NH$_3$ – Air) mixture values (2.572 to 2.054) m/sec, Laminar burning velocity values (29.492 to 21.256) cm/s, and Markstine length values (0.18 to 0.126) mm. the reaction is a rich Ø = 1.3 and the ammonia concentration is 20% of the fuel, at pressure mixture initial (100 -200- 300 Kpa) the laminar flame speed was obtained when the flame radius was (25) mm from (2.88, 2.326,2.092) m/sec, respectively. The laminar burning velocity values (32.552–26.104 - 23.336) cm /sec, respectively.

Introduction

Due to its high hydrogen weight of (17.70%) of ammonia offers potential as one of hydrogen energy carriers [1] 2013. Ammonia is being frequently utilized as a fertilizer currently. Since the ammonia distribution's infrastructure has already been developed and the ammonia manufacturing technology, namely the Haber–Bosch process, has been popular, using ammonia as a carrier of hydrogen energy could be beneficial. A new method for creating ammonia using renewable energy sources, like solar energy, has lately been investigated [2] 2010. Ammonia also has the potential to be a carbon-free fuel. Yet, ammonia hasn't been indicated as fuel due to its lower intensity values of combustion, meaning slower velocity for laminar burning, lower calorific value, and narrower range of the flammability. As a result, the basic flame properties of ammonia flame had received insufficient attention.

Hydrogen-added ammonia flames were explored for improving the lower combustion intensities related to ammonia [3] 2010, [7] 2013. Lee et al. [3, 4] 2010 conducted an experimental study on the laminar burning, the significant increase in laminar burning velocities with hydrogen replacement is observed especially under fuel – rich conditions, due to the increased amount of hydrogen atom2. Flame properties of ammonia/air pre-mixed flames were lately investigated. Haykawa *etal*., [8] 2015, numerically and experimentally examined pre-mixed ammonia/air laminar flames at atmosphere and increased pressures the maximum laminar burning velocity peaks around an equivalence ratio of 1.1 for all initial mixture pressure conditions2. Due to the decrease of NO by ammonia, the formation of NO from ammonia/air flames has been decreased in rich mixes, according to numerical and experimental findings. Furthermore, it was established that as pressure rises, NO generation reduces because of the increase in the consumptions of OH and H radicals that play a significant part in NO formation.

Miller *etal*. [9] & Lindsetedt *etal*. [10] 1992 presented thorough reaction approaches for ammonia flames, while Konov [11] 2009 & Tiane *etal*. [12] 2009 suggested reaction approaches for C reactions, such as N chemistry, for ammonia combustion. A very essential parameter for the pre-mixed flames and the validation of the mechanisms of reaction is laminar burning velocity. Zakanov *etal*. [13] 1978, Takezawa *etal*. [14] 2008, Pfahl *etal*. [15] 2000 have all studied laminar burning velocity values of the ammonia/air

pre-mixed flames. Laminar burning velocity regarding ammonia/air pre-mixed flames is lower in comparison to it in the hydro-carbon flames, like propane/air and methane/air flames, according to their findings. Takezawa *etal*. [14] 2008 & Pfahl *etal*. [15] 2000 explored flames that spherically propagate in combustion chamber of constant volume to determine the value of laminar burning velocity. In spite of the fact that the flame stretch was known to take place for laminar flames that spherically propagate because of thermo-diffusive effects Williams FA. [16] 1985, the implications of flame stretch on the speed of flame have not been taken into account in those investigations. Furthermore, all tests have been carried out at an atmospheric pressure.

For the purpose of understanding the essential properties of premixed flames, spherically-propagating pre-mixed flames in a combustion chamber of constant volume have been extensively studied. [17–20] Hayakawa and Kitagawa et al., Kitagawa [17,18] 2011 explored spherically-propagating turbulent and laminar flames for hydrogen and isooctane up to 0.5 MPa initial mixture pressure in a large combustion chamber of constant volume. [19] Tse *etal*. 2000 used two concentric cylindrical vessels to study flame propagation up to 60atm.

energy device mixing **ammonia gas with LPG was chosen because of the latter's most important specifications**

LPG and Ammonia has many advantages such as: -

	LPG	Ammonia
1.	**Lower Heating value LHV=45.5 MJ/kg**	**Lower Heating value LHV=18.8 MJ/kg**
2.	**Higher Heating Value HHV = 49.3MJ/kg**	**Higher Heating Value HHV = 22.5MJ/kg**
3.	**Boiling point for LPG = -44 ˚C**	**Boiling point for NH_3 = -33.34 ˚C**
4.	**Octane number for LPG = 106 - 110**	**Octane number for NH_3 = 130**

2-Experimental procedure

Figures (1,2) depicts experimental setup utilized in the present work, which included a cylindrical combustion chamber of constant volume with length of 40 cm, inner diameter of 39.5 cm, two oppositely facing quartize glass windows of 10 cm and 14 cm in diameter, and optical access into chamber. The combustion mix quantities have been created in the chamber with the use of a QYB02 Series Pressure Transmitter and a Digital panel meter A-Series with enhanced high precision, based on the needed partial pressure of component gases. Table 1 summarizes the experimental conditions, including, initial pressure initial temperature, and equivalence ratio. For each one of the studied conditions, experiments were conducted at least three times. The difference between minimum and maximum values of experimental data was characterized as experimental fluctuation. Schlieren photography was 576*500 lams for 4000 tyros per second, total registration time is 1.1 seconds, and 10% of the time is designated as pre-operatingthe operators to guarantee that all actions are captured while operating the operators, the ignition unit, and the camera. All experimental are conducted in the mechanical engineering department laboratories of the university of Babylon. the complete setup of the chamber.
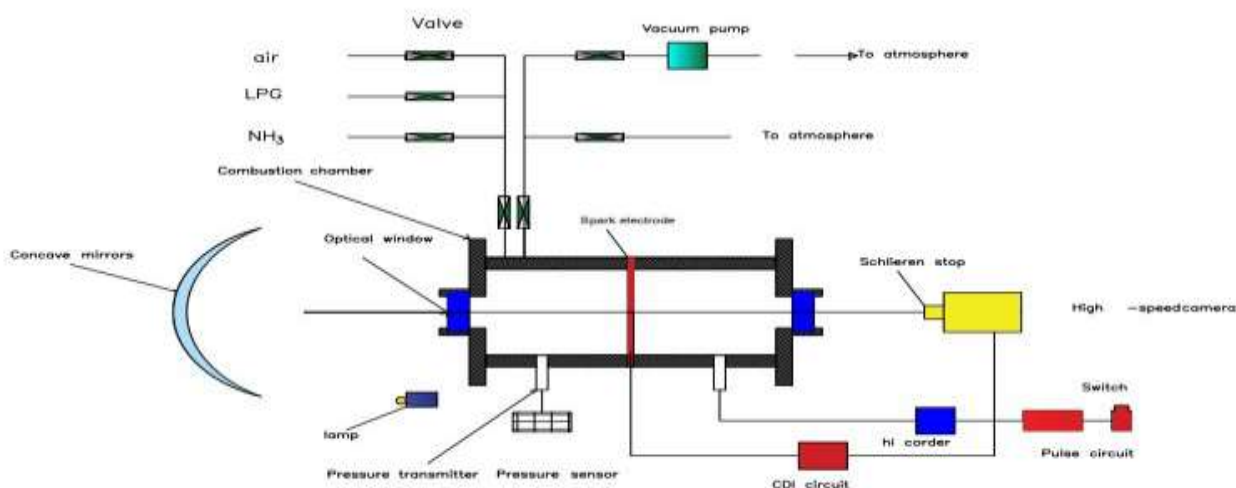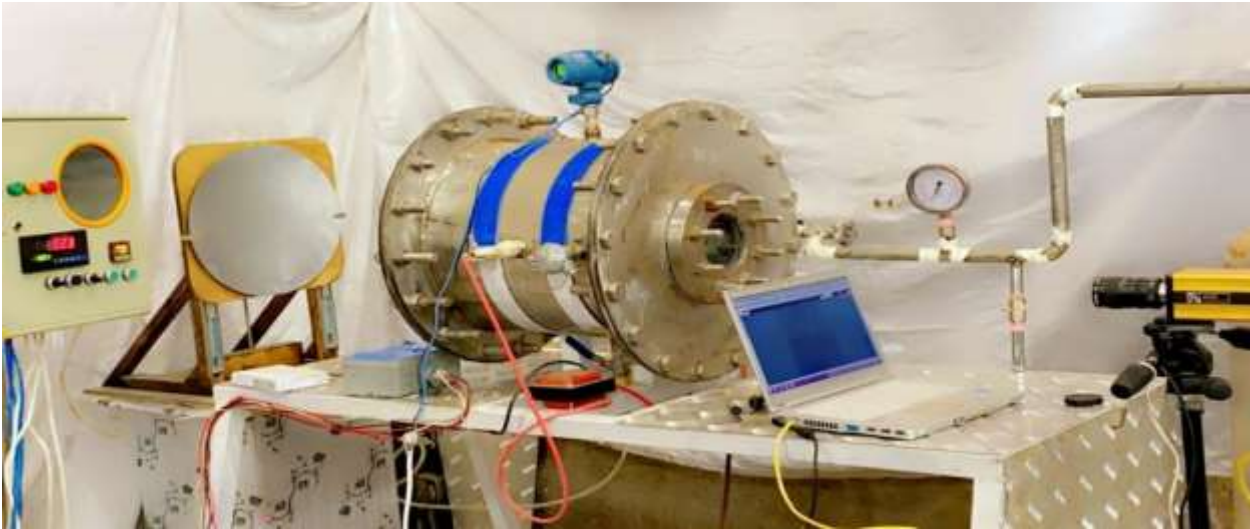

Figure (1) Schematic of experimental setup

Figure (2) The experimental apparatus used in the study

Table 1

Examined conditions

Initial pressure p_i Kpa	100, 200, 300
Initial Temperature K	298
Equivalence ratio (Ø)	0.8, 1, 1.3

The data was generated from experimental radius vs. time value by tracing flame front for consecutive frames with the use of Tracker software (Tracker version 4.87) [23] 2016. The line segment slope that connects 2 neighboring radii vs. the time point is considered as the instantaneous flame speed, i.e.

$$S_n = \frac{dr}{dt} \tag{1}$$

$$S_n = \frac{r_{j+1} - r_j}{t_{j+1} - t_j} \tag{2}$$

Because of the irregularity of the flame front shape, the data are always scattered due to this method, making it complicated to perceive a distinct pattern.

3- Evaluating the laminar burning velocity and Markstein length

The following approach Markstein length and laminar burning velocity have been acquired via density gradient appears within combustion chamber in a case when the radius of the flame is directly measured through schlieren photography, the radius of the flame may be in shadow image, unlike the actual image because the photographic image does not display the edge of the flame directly

Flame radius is measured from Schlieren photography and laminar flame speed (S_n) from radius – time of flames based on

The stretched flame speed (S_n) has been evaluated with the use of the

$$Sn = \frac{dRsch}{dt} \tag{3}$$

R_{sch}= represent radius of the flame that has been acquired from Schlieren images and t its time.

S_n is the stretched the laminar flame speed of the spherical flame The laminar flame speed (S_n) from calculated the radius – time of flames [24]

Stretch is specified as Lagangian time derivation of logarithm of the area (A) of any small element on surface at any location on the flame's surface [25].

$$\alpha = \frac{d(lnA)}{dt} = \frac{1}{A}\frac{dA}{dt} \tag{4}$$

It is possible to deduced the rate of expansion of an externally propagated spherical flame according to the following equation

$$\alpha = \frac{1}{A}\frac{dA}{dt} = \frac{2}{ru}\frac{dr}{dt} = \frac{2}{ru} Sn \tag{5}$$

where A = $(4\pi r_{sch}^2$, for spherically flame) represents flame's front area. There's a linear link between speed of flame spread and rate of expansion in the pre-pressure period, as shown by the equation below;

$$S_l - S_n = L_b \alpha \qquad (6)$$

The un stretched propagation velocity might be acquired as intercept at α=0 value in flame speed diagram against α. the unburned gas Markstine length L_b, represents negative slope of Sn – α fitting curve [25]. Markstine length then may be characterized as a reduction in burning velocity value for each one of the unit stretches.

4- Experimental results

4.1 Flame observations

Figure. 2 illustrates the Schlieren images of a spherically spreading ammonia/LPG/air pre-mixed laminar flames at the elapsed time from ignition at initial mixture pressure of 100 Kpa (Ø =0.80, 1, 1.30) equivalence ratios. the shape of flame at Ø=0.8, ammonia concentration 10%, LPG concentration 90%, a regime of hot gas that has been produced by electric spark may be noticed between the spark electrodes at t=0ms. At t = 4 ms, the hot gas regime's boundary became obscure. After then, at t = 8 ms, the hot gas boundary appears to vanish. This means that the flame does not spread across the chamber in this case. At initial pressure 100 Kpa and Ø= 1.3, a similar event was seen. According to Panchen's Law, as initial pressure of the mix rises, the voltage near the spark rises as well. Lefebvre and Bilal [28] shown that if the spark gap is constant, released energy of electric spark is increased by increasing pressure value. Even though ignition energy was not measured in this work, it has been thought to be increased as initial mix pressure rises. For all of the initial mix pressure values that have been examined, spherically propagating pre-mixed flame had spread throughout chamber for (0.8, 1.0, and 1.30) equivalence ratios. The flame radius at Ø=1.0 was bigger than that at Ø= 0.8 and Ø= 1.3 after 4 ms from ignition. until t = 2 ms, the center of the spherical flame has been close to the gap between the spark electrodes. The spherical flame's center then traveled upward in the combustion
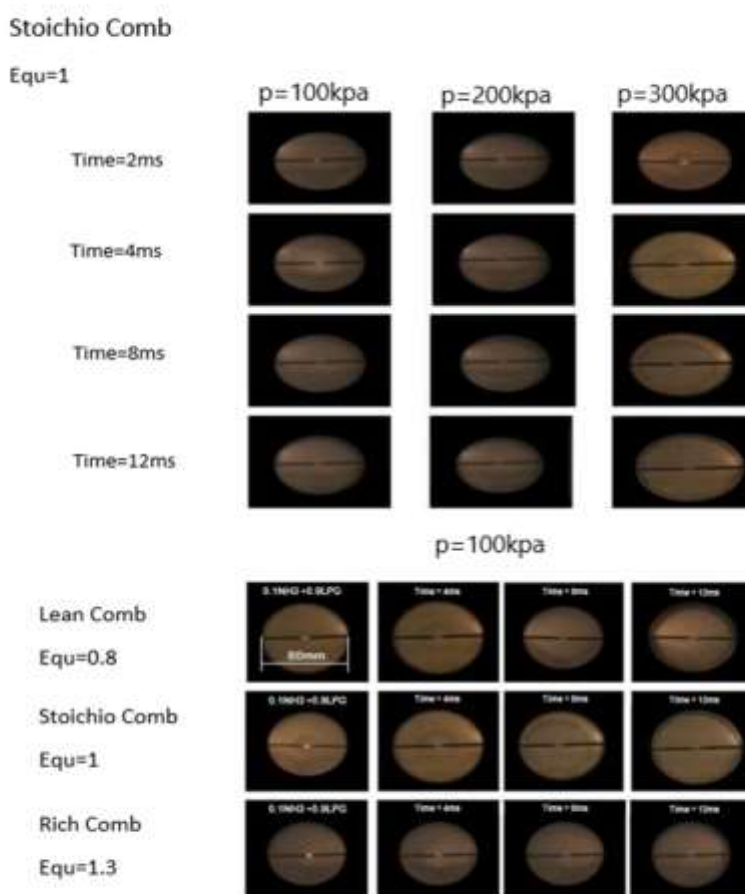
Figure. 3 Schlieren image of ammonia /Lpg / air pre-mixed flame

Schlieren images of an ammonia/Lpg/air pre-mixed flame with equivalency ratio of Ø=1 at investigated initial mix pressure levels are illustrated in Figure 3. The size of spherical flame shrank with an increase of initial mix pressure. It's possible to conclude that in the case where initial mix pressure has been increased, flame speed decreases due to the higher density which mean more chemical heat (oxidation) need to propagation of flame.

4.2 Laminar burning velocity and Markstein length

In combustion chamber of constant volume, flame propagation might be divided into 3 phases: an aquasi-steady period, an ignition-affected period, and chamber-affected period [20] 2009. Laminar burning velocity is an example of a precise fuel combustion characteristic that is required for effective design of combustion device. The Laminar burning velocity data is critical for validating and fine-tuning the reactive mechanism.
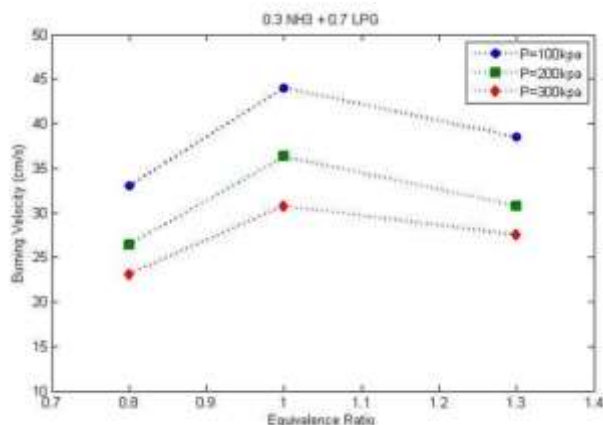

Figure. 4 the relation between laminar burning velocity U_1 and ratio **of** equivalence Ø. (**E$_{NH3}$ = 30% E$_{LPG}$= 70%**) at initial pressure of 100,200,300 kpa
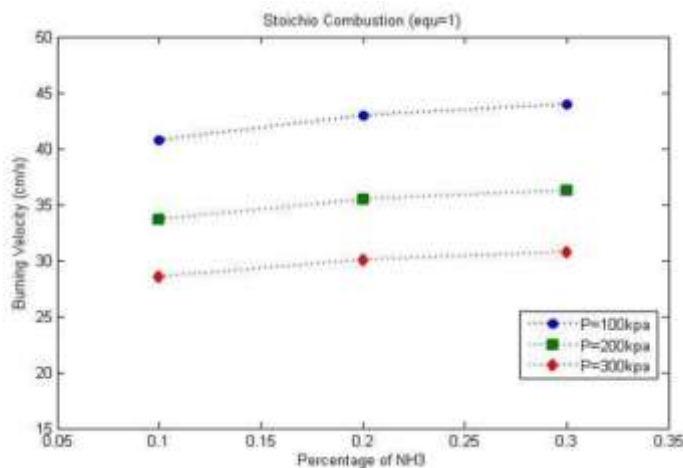
Figure. 5 the relation between laminar burning velocity U_1 and Percentage of ammina. (E$_{NH3}$ = 30% E$_{LPG}$= 70%) at Ø =1 at initial pressure 100,200,300 kpa

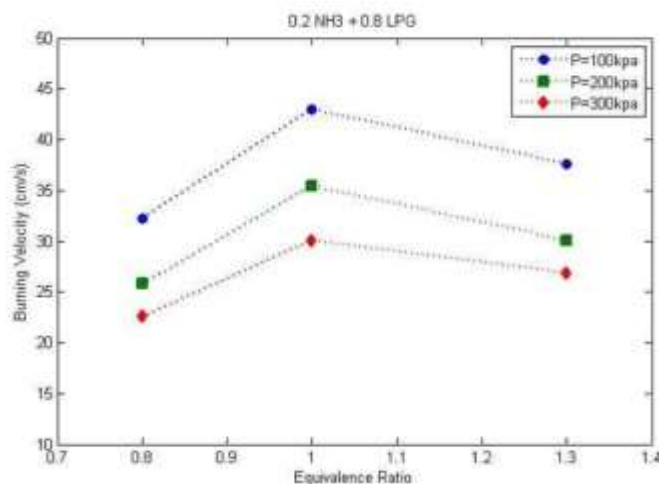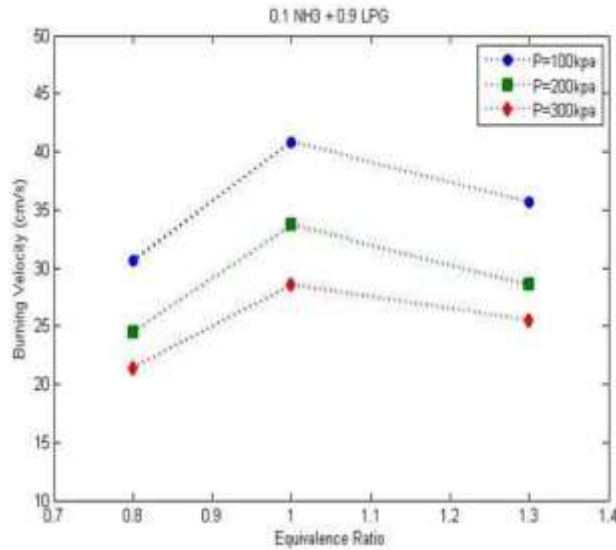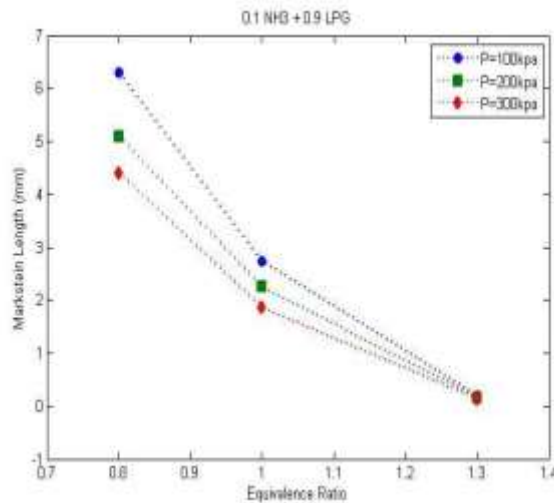**Figure. 6** the relation between laminar burning velocity U_1 and ratio of equivalence Ø. (E$_{NH3}$ = 20% E$_{LPG}$= 80%) at initial pressure of 100,200,300 kpa

Figure. 7 the of relation between laminar burning velocity U_l and ratio of equivalence Ø. (E_{NH3} = 10% E_{LPG}= 90%)

One shows in figure 4 and figure 6, 7 for 0.3 NH_3 + 0.7 LPG and 0.2 NH_3+0.8 LPG and 0.1NH_3 +0.9 LPG respectively its clearly shown that the maximum burning velocity be for a stoichiometric mixture**.** the increase in rich or lean of mixture led to decrease in laminar burning velocity. increasing initial pressure enhance laminar burning velocity due by comparing figure 5 and figure 6 with increase in laminar burning velocity could be recognized.

Figure. 8a Correlation between burned gas L_b, Markstein length, and ratio of equivalence Ø. (E_{NH3} = 10% E_{LPG}= 90%)
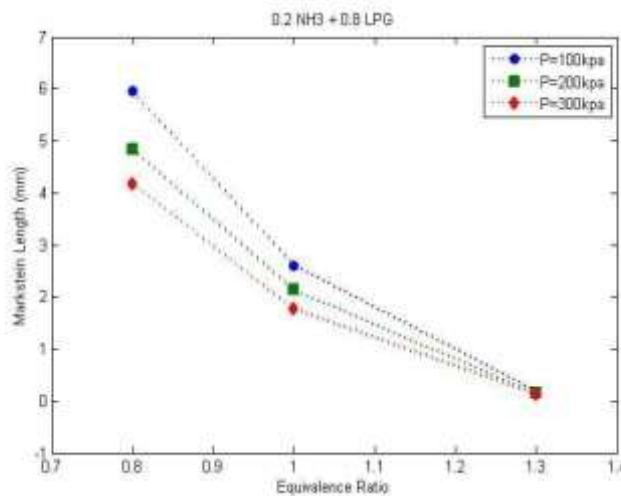
Figure **8b** The relation between burned gas L_b, Markstein length, and ratio of equivalence Ø. (E_{NH3} = 20% E_{LPG}= 80%) at initial pressure 100,200,300kpa
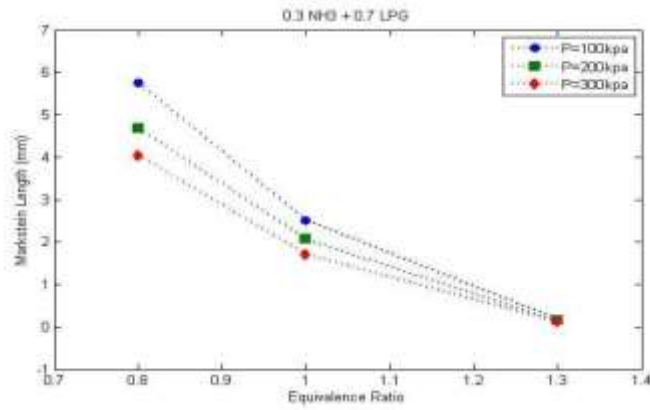
Fig. 8c The relation between burned gas L_b and ratio of equivalence Ø. (E_{NH3} = 30% E_{LPG}= 70%) at initial pressure 100,200,300kpa

Figure 9 a, b and c when ammonia gas is added in different proportion ranging from 10 % to 30 % to LPG at rates ranging between 70% to 90% the burning velocity increases when the percentages of ammonia increases and decrease when the initial pressure increases.

, Markstein length, and ratio of equivalence Ø. (E_{NH3} = 30% E_{LPG}= 70%) at initial pressure 100,200,300 kpa

shows Figure 8 a, b and c the burned gas Markstine length maximum value at lean mixture and minimum value at rich mixture. the value of burned gas Markstine length values at Ø= 0.80 and E_{NH3} = 0.1 % was that 6.3 mm, the value of burned gas Markstine length at P_i = 100 Kpa is larger in comparison to that of 300 Kpa & 200 Kpa.

4.3 effect of addition of ammonia on the burning velocity for mixture

Figure 9 a, b and c when ammonia gas is added in different proportion ranging from 10 % to 30 % to LPG at rates ranging between 70% to 90% the burning velocity increases when the percentages of ammonia increases and decrease when the initial pressure increases.
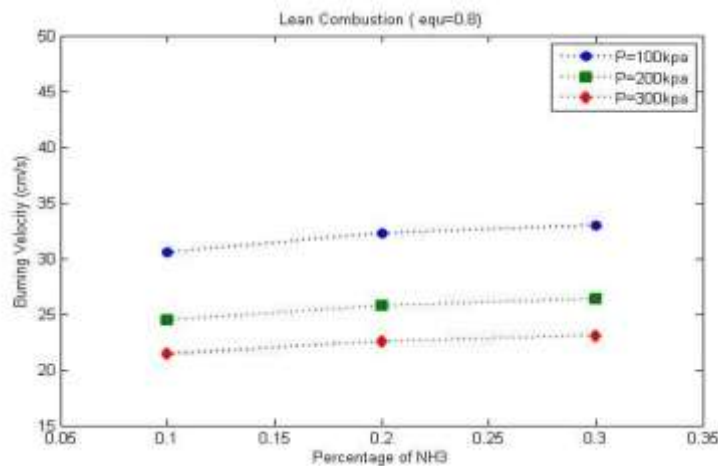

Figure 9a effects of ammonia gas on burning velocity at lean mixture at initial pressure 100,200,300 kpa
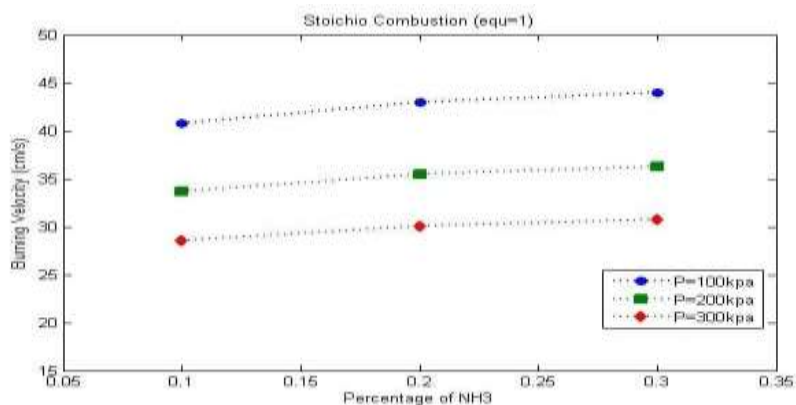

Figure.9b effects of ammonia gas on the values of the burning velocity at Stoichiometric mixture Ø=1 at initial pressure 100,200,300 kpa
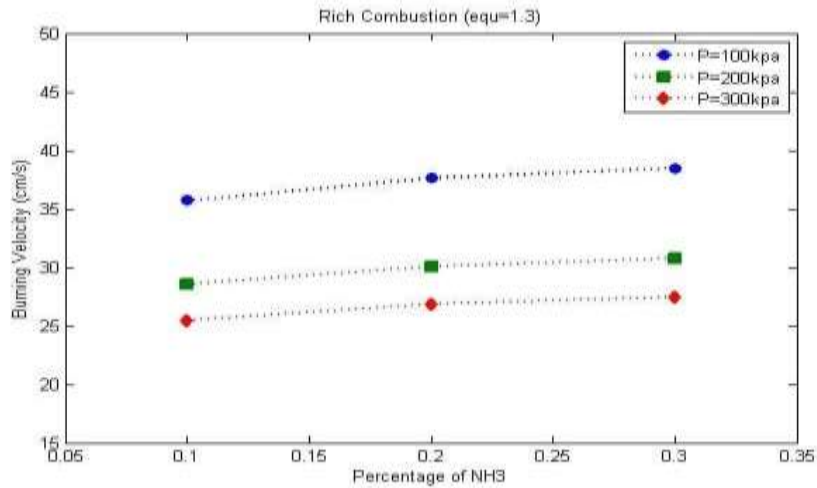
Fig.9c effects of the ammonia gas on burning velocity values at Rich mixture Ø=1.3 at initial pressure 100,200,300 kpa

4. Conclusions

The next conclusions were drawn from the experimental investigation of the mixtures of (NH3 – air) and (LPG – air) and (NH3 – LPG – air) in order to determine the attributes of each mixture:

1-   The value of laminar burning velocity of the mixture (LPG-air) and (NH3-air) at a variety of equivalence ratios and initial pressures reduces with increasing initial pressure, implying that the higher the initial pressure, the lower the laminar burning velocity value, which peaks when the mix is stoichiometric. The (NH3 – air) mix's laminar burning velocity is higher than the (LPG – air) mix's laminar burning velocity. However, when ammonia gas is added to a mixture of (LPG – air) in a variety of the equivalence ratios and at various initial pressure values, the effect is to maintain the value of laminar burning velocity with a slight increase, implying that LBV increases with the decrease of initial pressure and increasing proportion of added ammonia gas to more than 10%, with the highest value when the mixture is stoichiometric.

2-   When studying the properties of LPG-air the Markstein length has the highest value when the mixture is lean and the initial pressure is the lowest and the highest value is the Markstein length when the mix is rich Contrasting to the properties of ammonia and air. When ammonia gas is added to the mixture, its effect is limited to reducing the value of Markstein length, meaning that as the concentration of ammonia increases, Markstein length begins to decrease and reaches its maximum value when the ammonia concentration is less than 20%.

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