

## A STUDY OF THE EFFECT OF AMMONIA BLENDING ON BURNING VELOCITY OF LPG AT INITIAL PRESSURE WITH HIGH-SPEED CAMERA

JAAFAR SAMI SHABAN and SAMER. M. ABDULHALEEM  
College of Engineering, University of Babylon- Iraq

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### ABSTRACT

This experiment measures premixed flame laminar speed and burning velocity for LPG, air, and ammonia. A centrally ignited constant volume chamber has been designed and constructed to experimentally investigate stretched flame speed ( $S_n$ ), laminar burning velocity ( $S_u$ ), Markstein length ( $L_b$ ), and ammonia and liquefied petroleum gas are mixed in a combustion chamber with a constant volume of cylindrical shape and volume (0.04899 m<sup>3</sup>), inner diameter 395 mm, and length 400 mm, the flange with a thickness of 12 mm diameter 407 mm and 570 mm both sides made of A Schlieren visualizes and analyzes transparent medium density changes. It detects slight refractive index changes caused by temperature, pressure, or density gradients. The Schlieren method employs light beams' directionality in zones with different refractive indices. Light refracts through transparent materials like air to reach denser regions. These slight changes can be seen with careful light ray manipulation. beginning pressures (100-200-300) kPa, 0.8-1.3 equivalency ratios, and 298 K. In the constant-size combustion chamber and central ignition investigation, increasing starting pressure decreased laminar flame speed, Markstein length, and burning velocity. Valence, 100 kPa starting pressure, and 20% fuel ammonia content were investigated. We notice that  $s_u$  is 27.28 cm/sec cm at valency 0.8 and 38.315 cm/sec at equivalence ratio 1.  $S_u$  rises with valence and then falls. Valence increased at 1.3 equivalence ratios.  $s_u$  32.552 cm/sec At 20% ammonia concentration and equivalency ratios 1,  $s_u$ 's value at 100 kPa is 34.945 cm /sec and at 200 kPa is 28.93 cm /sec, showing how starting pressure increases with pressure. Initial pressure reduces  $s_u$ . Practical experiments showed that ammonia reduces  $s_u$ . The value of  $s_u$ . It was 31.645 cm /sec at 20% ammonia, 200 kPa starting pressure, and 1 equivalence ratio. Same conditions, 30% ammonia,  $S_u$ . 28,935 cm/sec.

**KEYWORDS:** laminar Burning Velocity, flame speed, Ammonia Blending LPG, Markstine length

### 1. INTRODUCTION

Global warming results from increased greenhouse gas concentration (GHGS), in particular, carbon dioxide (CO<sub>2</sub>) in the atmosphere. This atmospheric accumulation of greenhouse gases are largely the result of fossil fuel combustion and other human activities. Many possible reforms were suggested to address this study, and the search for fossil-fuel replacements is a significant task for society.

Various researches were conducted to evaluate alternative fuel's energy efficiency and environmental impact. the use of ammonia gas represents a possible solution for the storage of intermittent renewable energy, Ammonia is considered more suitable for storage and transportation compared to Hydrogen gas because the tanks in which ammonia is stored is light, not expensive and its storage is also safer due to the low pressure. The ammonia energy storage system has great advantages over a wide

range and less restriction of geographical conditions compared to many other conventional energy storage method [1].

The velocity of laminar burning (LBV) The speed where unburned gases travel across in the combustion wave normal the direction of the wave surface the kinetics of chemical reactions, as well as molecular heat and mass transfer, determine it. The flow of the flame front, which is a two-component chemical reaction and temperature that grows in the same direction, is represented LBV. Understanding a wide spectrum of flames requires the capacity to make exact laminar premixed flame measurements.

Despite the fact that the majority of fuel is anticipated to be consumed in turbulent combustion, LBV measurements are still necessary since they are utilized as input data in many turbulent combustion models. Laminar burning velocity is another crucial factor in controlling chemical kinetics [2] The CVM technique has some drawbacks, such as slow and tedious calculations, which might be addressed by employing a data processing system that is quick. The second disadvantage is, that starting a spherical flame takes the least amount of ignition energy, and appropriate non-adiabatic circumstances that occur at the end of burning owing to heat transfer to the chamber walls can be solved by matching the spark gap and the spark energy [3] There are several methods for calculating burning velocity. Installing a quick reaction pressure transducer, in the bomb's outer wall, is one way as the flame expands, a pressure trail forms. Based on the pressure measurements, a computer model is utilized to calculate the burning velocity.

## **2. CALCULATION OF LAMINAR BURNING VELOCITY,**

Three ways for determining laminar burning velocity There are three of them the techniques are as follows: the stagnation plane flame technique, the heat flux method, and the combustion bomb. The process generates various

flame patterns, however getting a clean flame front and flame stability at high pressure is challenging. The heat flux methodology comprises calculating the rate of heat loss as a function of velocity extending the results to zero heat loss for typical spreading spherical flames, as well as the combustion bomb technique is used configuration to estimate the burning velocity [4]. The methods used for LBV computations are based on the flame movement. Stationary procedures are those in which the reactants are placed into Such a thing as the response zone the Bunsen burner, as well as propagation procedures are those that bring the reaction zone into the reactants, such as flame propagation in the tube.

The constant volume was used in this study. approach was chosen among the propagating methods because:

1. A modest quantity of fuel is required for the constant volume approach.
  2. The constant volume approach is used to model the combustion process in a spark ignition engine (SIE)
  3. The constant volume technique provides the most control over the beginning circumstances and composition of the mixture
  4. The constant volume approach Its self-contained and well-suited for high-pressure situations
  5. The constant volume approach can yield local measurements of the burning velocity at each instantaneous pressure value
  6. The method of constant volume A simple flame arrangement with a well-defined flame stretch rate
- ### 2.5 Factors Affecting flame speed and Burning velocity

The mean factors attend of inflame speed and burning velocity and type of fuel, Initial Temperature and Initial Pressure

#### **1. Type of the Fuel**

The flammable mixture includes the air as the maximal part; therefore, the weight of molecular fuel has a low effect upon burning velocity [5].

As well the fuel's molar mass does not have a strong impact on the velocity of the burning, due to the fact that most mixture is considerably more significant. The air is the thermal content of fuel combustion because this affects the temperature of the adiabatic flame where the temperature has maximum impact in relation to burning velocity.

The motility of oxidation reactions is also important and can explain the reason for the difference in burning velocity of some of the fuels that have an adiabatic flame, Temperature [6].

$$S_l = S_{l,ref} \left( \frac{T_u}{T_{u,ref}} \right)^\gamma \left( \frac{P}{P_0} \right)^\beta \quad (1)$$

Where the subscript (ref) represents the reference conditions (Typically  $T_{u, ref} = 298 \text{ k}$ ,  $P_{ref} = 1 \text{ bar}$ ).

The exponent's power for pressure  $\beta$  and temperature  $\gamma$  has been discussed in detail by [8] varying as the fuel type function, oxidizer, and ratio of equivalence.

$$S_u = S_{u,o} \left( \frac{P}{P_0} \right)^{\beta_1} \quad (2)$$

Understanding the equation above has some specific basics in the initial flame speed theories. [10], had indicated negative dependence of  $S_u$  with the pressure by heat and mass balance only. [11], [12] had expanded the theory through the introduction of the rate of total reaction ( $w^\circ$ )

$$S_u = S_{u,o} \left[ 1 + \beta_2 \log \left( \frac{P}{P^\circ} \right) \right] \quad (3)$$

It has been proposed first by [14] with  $\beta_2 = -0.206$  for a stoichiometric meth mix [15] have explained their measurements the coefficient  $\beta_2$  value is 2close to (-0.20) for the equivalence ratio of (0.80-1.20)

In general, the velocity of the burning for the hydrocarbon fuel types is decreased in the case where the atoms of the carbon in molecular fuel are increased [7].

## 2. Initial Temperature

The represents the most important aspect that affects the variety of the burning velocity in general, raising the temperature degree of unburning gas increases laminar burning velocity and allows the flame to spread in a more stable manner. The most common link that represents the initial temperature and pressure effect is

## 3. Initial Pressure

The first pressure impact verification on the velocity of burning has been shown by [9] with the use of the following power – law pressure dependence that has been applied for a range of the pressure of (1bar - 4bar).

explicitly [13] had developed the theoretical approach viewing that mass burning rate  $w^\circ = \rho S_u$  has been directly proportionate to the square root of the rate of the total reaction  $w^\circ$ . Another pressure dependence relation.

## 4. Energy of Ignition

The discharge of the spark results in causing a shock wave, which is succeeded by a slower heatwave.

As there is a difference in the voltage between the electrodes the air in the gap is

ionized and power is generated. This energy might result in increasing the mixture temperature and then the speed of the flame.

For the energy of ignition that is lower compared to minimal power of ignition, the speed of the flame had dropped quickly to 0. The energy values are slightly higher than minimum ignition energy. The flame speed drops to a minimal value, and then increases when the flame has been created as mentioned in [16], [17] found that burning velocity changed little with spark energy and gap wide for hydrogen and propane mixture in the combustion chamber.

### 5. Equivalence Ratio

The correlation between the burning velocity and the equivalence ratio followed between laminar burning velocities except for vibrant fuel-air mixtures. So, it is maximum at slightly more than stoichiometry [18] had studied flames for CH<sub>4</sub> / air mixture and have shown that laminar burning velocity had peaked at  $\phi = 1.08$  [19] have shown that maximum laminar burning velocity for the NH<sub>3</sub> /air flames at all of the initial mixture pressures that have been observed had reached the peak values be  $\phi = 1.10$ .

## 3. EXPERIMENTAL SETUP

A description of the experimental rig the chamber and measuring instruments used to investigate experimentally the effect of ammonia blending ratio with LPG on combustion system safe operation and flame stability is presented. All experiments are conducted in the Mechanical Engineering Department Laboratories at the University of Babylon figures 1 and 2.

### 4. test procedure: -

The mixing process relies on the Gibbs - Dalton Law for partial pressure of each component of the mixture to obtain a precise parity ratio. The mixture was prepared within the mixing combustion chamber. the total absolute pressure (5bar) per test by: -

### 5. combustion chamber preparation processes

To make a homogenous mixture for exact equivalence ratio Ammonia – LPG –air blending, there are steps to prepare the mixing chamber.

### 6. cleaning process

The outer flanges are opened and then the rig lining is cleaned with a clean cloth to get rid of the soot generated after the explosion process if any, as well as cleaning the windows quantize.

### 7. vacuum process

The vacuum process takes place by closing all the valves except the valves of the vacuum pump and the vacuum gauge so that the pump can sufficiently clarify the combustion chamber from any previous air until its pressure reaches approximately (-0.95 bar). After the unloading process, leave the rig for five minutes, noting the pressure transmitter and tracking the pressure to make sure that there is no leakage of the mixture during the injection process inside the combustion chamber.

### 8. mixing process inside the combustion chamber

The gases are admitted into the combustion chamber after it is completely emptied from the air. Ammonia gas is injected, then liquefied petroleum gas, and then air from the special storage tanks for each gas. The mixture enters into the combustion chamber at required initial pressure, and after that, it closes all the fuses and waits for a period of 10 minutes prior to the ignition for the purpose of stabilizing the mixture, obtaining laminar flame, and sustaining a mixture free of the eddies and turbulence.

### 9. combustion and recoding processes:

The homogeneous mixture was prepared in the preceding steps thereafter.

a. The initial values of the temperature and pressure shall be adjusted on the initial status of the test.

b. The electronic transformer of pressure begins recording the pressure of combustion.

c. Determine the ignition duration (5-second ml).

d. High – Speed camera have to size at the time

of formation (1.2) seconds with 10% pre – operability and the illuminating system begins to lighten

e. Both the ignition logging operators and the camera are moved.

f. The data is recorded and photos are captured. Step (a) has been repeated with a variety of initial conditions.

#### 10. analysis assumption

Laminar burning velocity can be calculated through a series of calculations, from the Schlieren photographs taken during each test. To make use of data from the bomb, many assumptions need to be made. These have been developed by many authors. **Huzayyin et al 2008 [60]** which include

1. The non–burned regular gas is in a state of rest in principle .
2. The total mass and volume of the contents of the receptacle are preserved
3. Pressure is supposed to be regular through flame during combustion analysis

4. The mixture is burning in the middle of the pot with a small temperature entrance.

5. The preface of flame extends to the outside spherically and remains the smooth flame speed is fast enough to buoyancy is negligible

6. The flame front itself is an external heat constant system

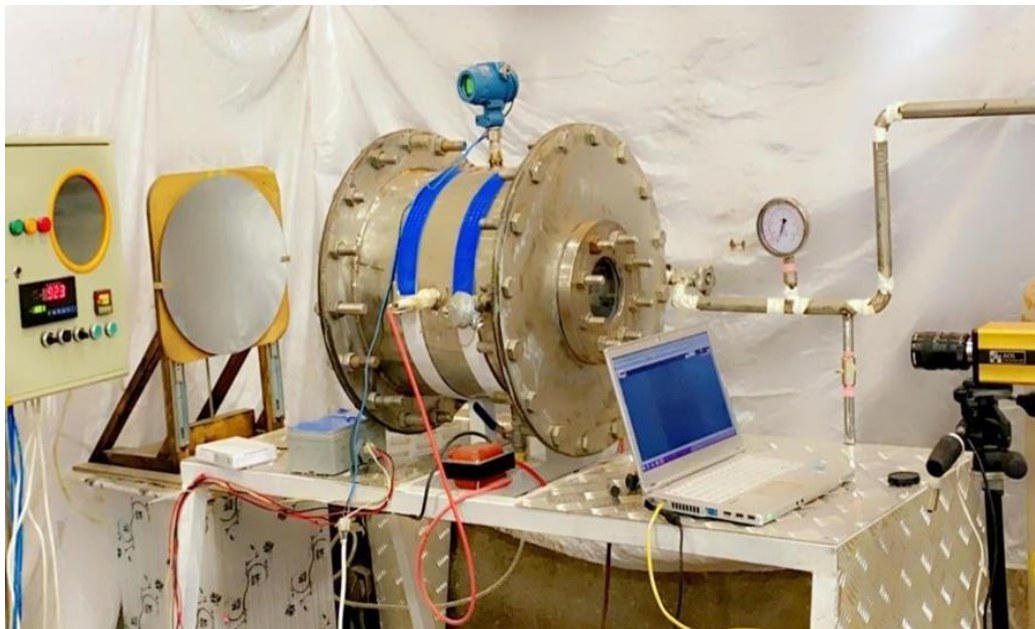
7. The flame front is infinitely thin

8. No chemical reaction and no dissociation occur in the unburned gas.

9. There is no heat transfer between the zones

#### 11. mixing ratio and combustion processes:

A MATLAB program was written to calculate the induction pressures of mixing for Ammonia, LPG fuel, and air according to the blend of ammonia. LPG is a mixture of many types of hydrocarbons (Ethan, propane, butane, and pentane) .The volume percentage of a component of LPG is shown in table (3.1). Analysis of LPG components provided from Hilla Gas plant shown in Appendix (B).



**Fig.( 1):-**photograph of the combustion chamber and all the accessory required for the rig

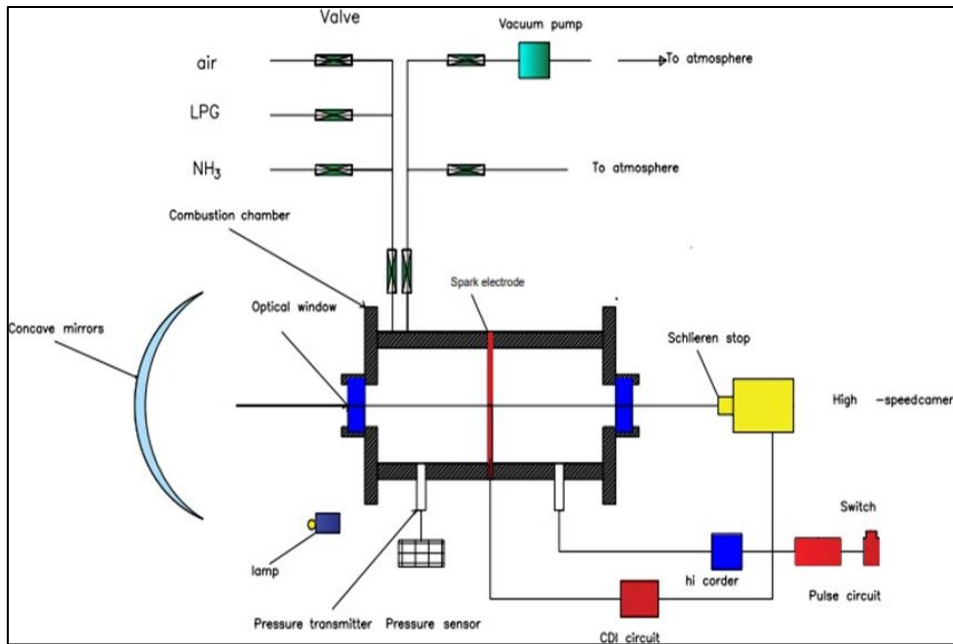


Fig.( 2):-A schematic diagram for the experimental rig setup

## 12. validation

Figures (4.1a) show a comparison between the results obtained from present work with results obtained of other researchers. Figure (4.1a) display the relation between equivalence ratio

and burning velocity for pure NH<sub>3</sub> with the initial pressure at 100kPa and temperature 298K. it shows a comparison between the results of present work and the results

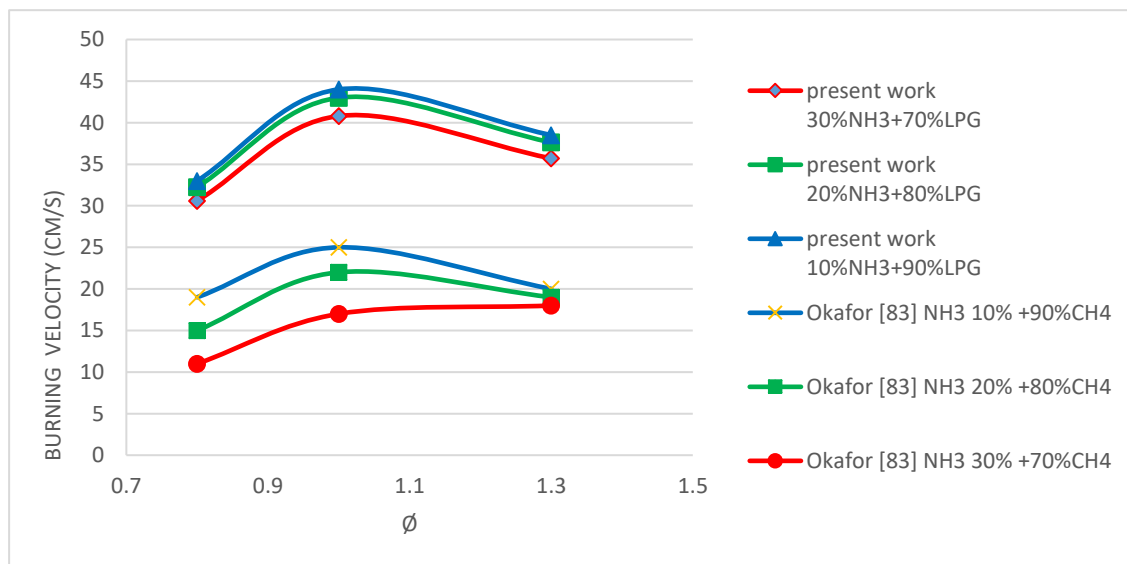
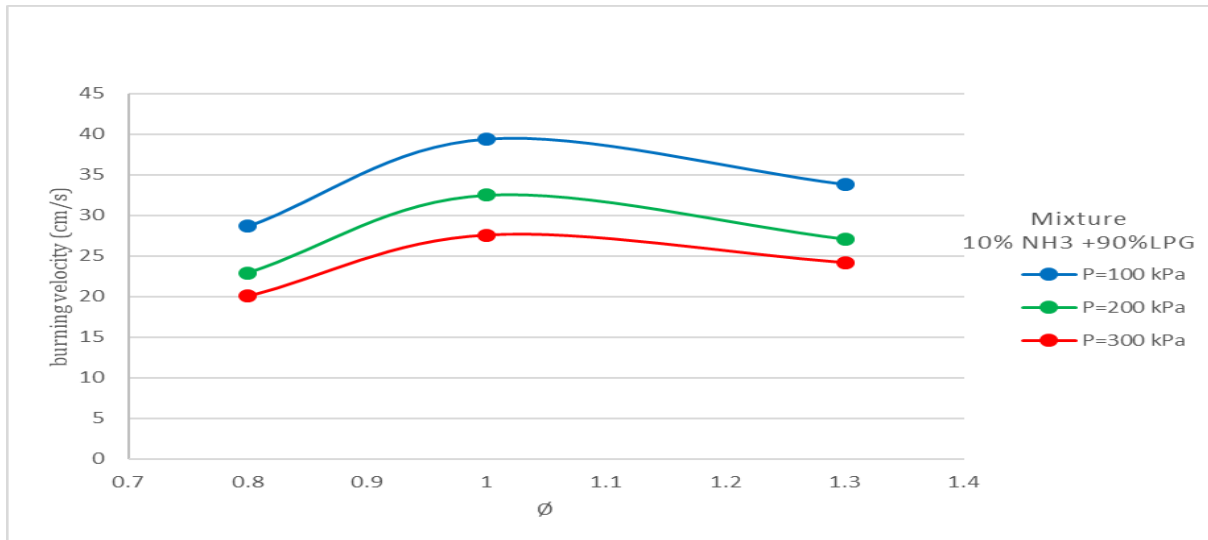


Fig.( 4.1) b. behavior of the result obtained by Okafor [83]

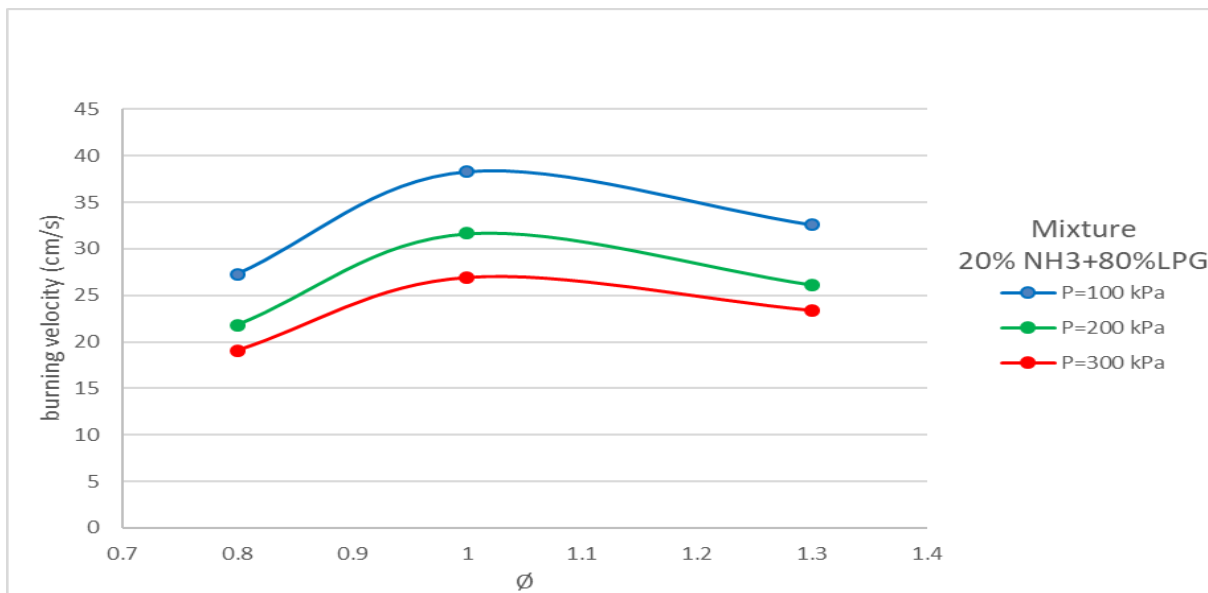
### 13. RESULTS AND DISCUSSION

Laminar burning velocity LBV is a significant

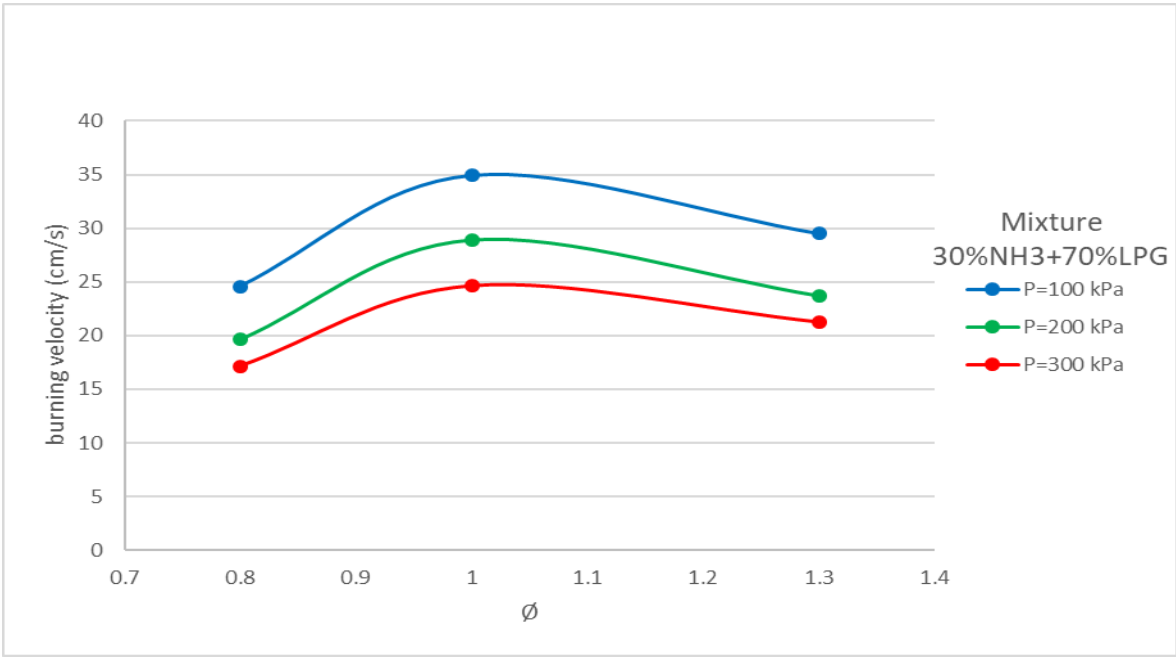
restriction of a combustible mixture because it contains the necessary information regarding its exothermicity, reactivity, and diffusivity.



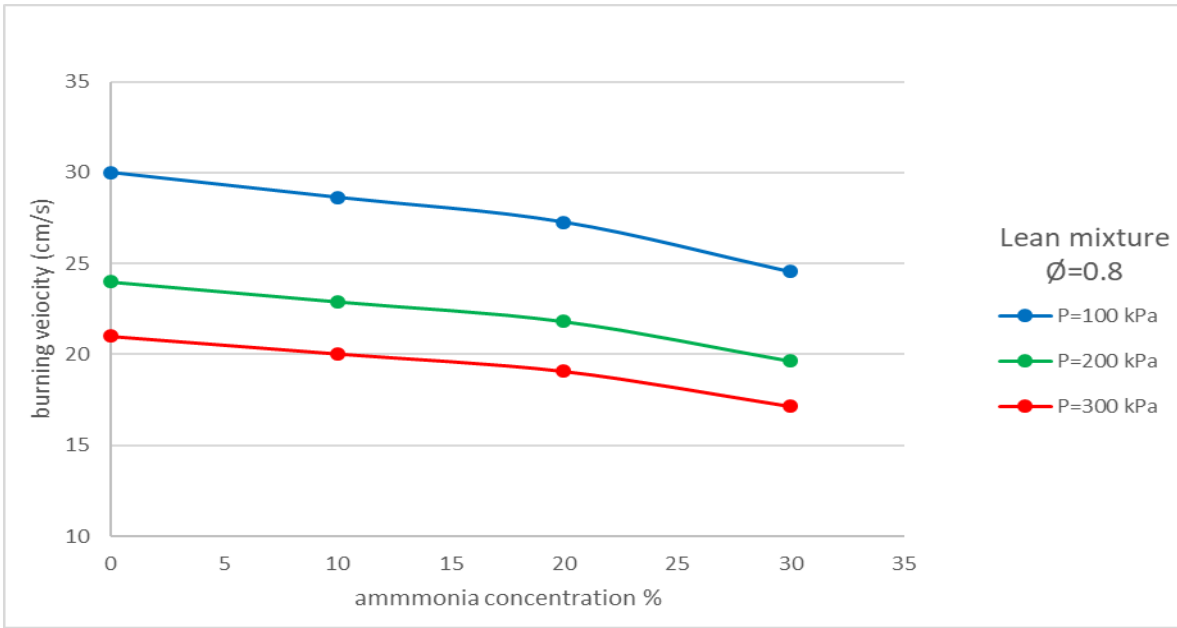
**Fig.( 3)**:-shows burning velocity with equivalence ratio of mixture 10% NH<sub>3</sub> and 90% LPG at initial pressures 100, 200, 300 kPa



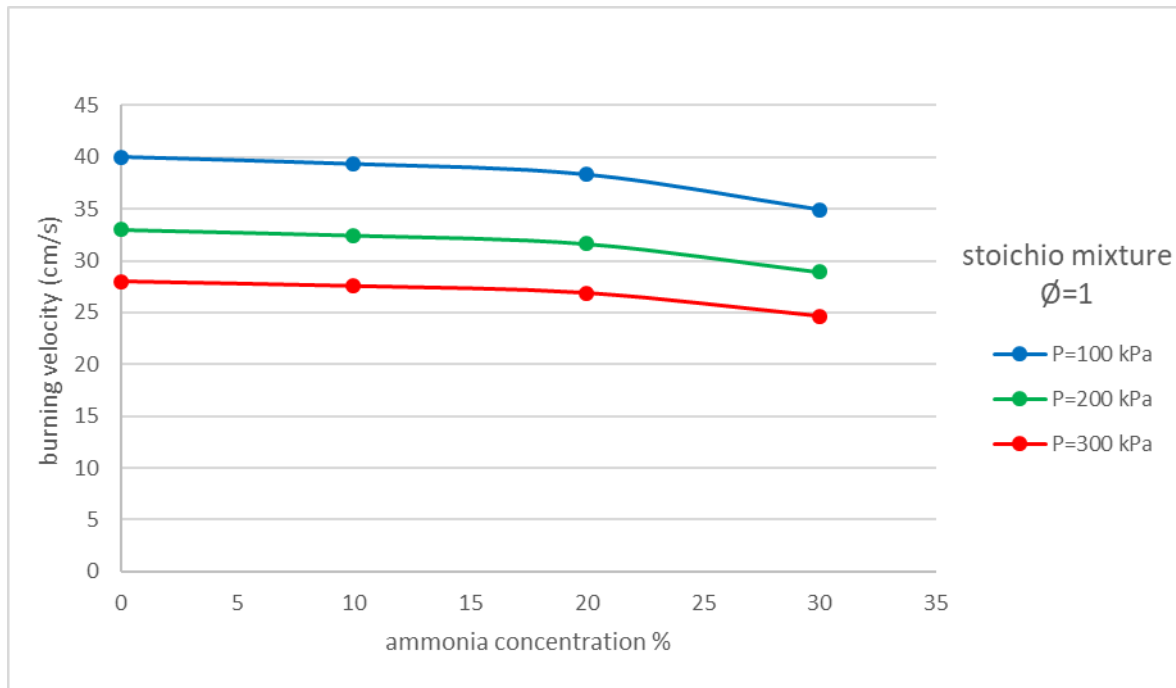
**Fig.( 4)**:-shows burning velocity with equivalence ratio of mixture 20% NH<sub>3</sub> and 80% LPG at initial pressures 100, 200, 300 kPa



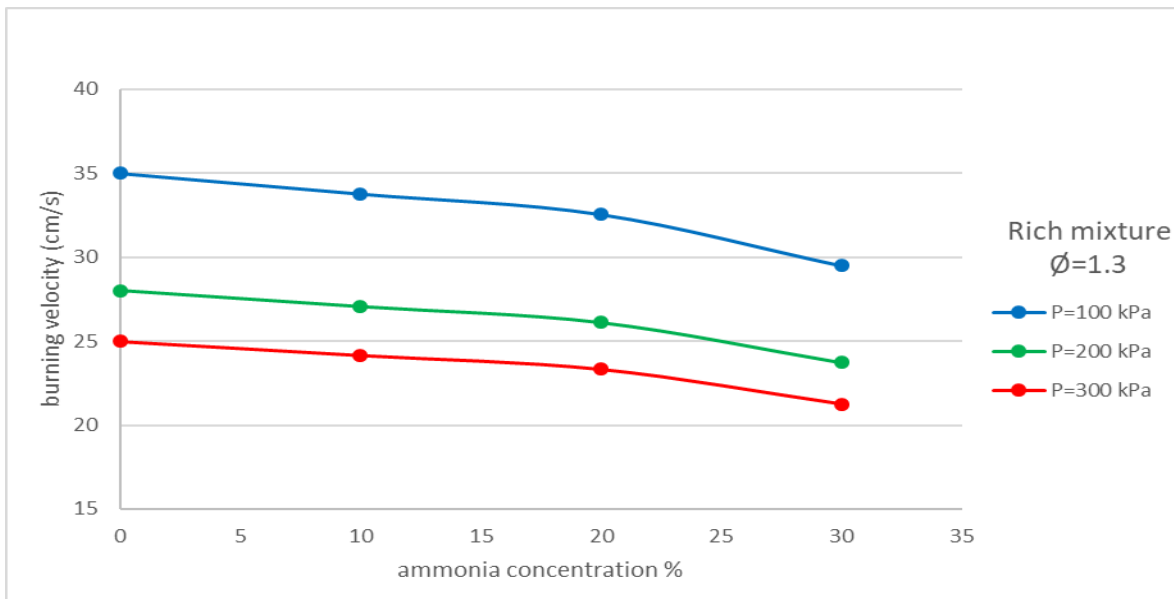
**Fig.( 5):-**Shows burning velocity with an equivalence ratio of mixture 30% NH<sub>3</sub> and 70% LPG at initial pressures 100, 200, 300 kPa



**Fig.( 6):-**Shows burning velocity with ammonia concentrations 0, 10, 20 and 30 % at Lean mixture initial pressures 100, 200 and 300 kPa at  $\phi=0.8$



**Fig.( 7):**-shows burning velocity with ammonia concentrations 0, 10, 20 and 30 % at Stoichio mixture initial pressures 100, 200 and 300 kPa at  $\phi = 1$



**Fig.( 8):**-shows burning velocity with ammonia concentrations 0, 10, 20 and 30 % at Stoichio mixture initial pressures 100, 200 and 300 kPa at  $\phi = 1.3$

#### 14. Effect Of Initial Pressure On Laminar Burning Velocity

Laminar burning velocities for NH<sub>3</sub>-LPG – air mixture with the temperature of 298 K, at 0.1, 0.2 and 0.3 MPa. The results show that Laminar

burning velocity decrease as the initial pressure increases to determine the cause of the initial pressure effect, the temperature is insensitive to changes in the first pressure figure (3), (4) and (5) Shows the result when

initial pressure increases Laminar burning velocity decrease that effect initial pressure increases density increases also and comical combustion It increases combustion reactions therefore laminar burring velocity decrease.

### 15. Effect With Equivalence Ratio and Effect of Ammonia Gas Percentage

Figure, (6), (7) and (8) shows the result when the  $E_{LPG} = 0$  and  $E_{NH_3} = 100\%$ , the lowest value of the laminar burning velocities is on the lean mixture, and the highest value when it reaches the stoichiometric mixture and begins to decrease on the rich mixture.

Whenever the concentration of ammonia exceeds 10% the increase in the laminar burning velocity value begin. Figure (3), (4) and (5) when the concentration of ammonia gas increases the laminar burning velocity begins to decrease clearly. That is the higher value of  $u_l$  and its highest value at a concentration of 10% of ammonia. The stoichiometric mixture has the highest value for the laminar burning velocity.

### 16. RECOMMENDATIONS

1. Using a proportion of ammonia gas more than 30% to mix with liquefied petroleum gas, provided that the combustion chamber is larger, with a stronger external structure, and larger dimensions, because the heat generated during the experiment at a pressure of 300 Kps very high, and the cause of a fire inside the combustion chamber with vibration and a loud explosion sound within Safety measures taken inside the laboratory are stopped at a concentration of ammonia 30% and LPG 70%.
2. Re-experiment using turbulent combustion instead of Laminar combustion and calculating the effect of ammonia gas when mixed with liquefied petroleum gas and studying the properties.
3. Investigation the effect of ignition energy on flame speed and stage of flame formation.

### REFERENCES

- Wang, Y., Zheng, S., Chen, J., Wang, Z., & He, S. (2018). Ammonia (NH<sub>3</sub>) storage for massive PV electricity. *Energy Procedia*, 150, 99–105.
- Hu Erjiang, Zuohua H, Jiajia H, Chun J, Jianjun Z. Experimental and numerical study on laminar burning characteristics of premixed methane-hydrogen-air flames. *Int J Hydrogen Energy* 2009; 34:4876e88.
- Huzayyin AS, Moneib HA, Shehatta MS, Attia AMA. Laminar burning velocity and explosion index of LPG/air and propane/ air mixtures. *Fuel* 2008; 87:39e57.
- Tang C, Huang Z, Jin C, He J, Wang J, Wang X, et al. Laminar burning velocities and combustion characteristics of propane-hydrogen-air premixed flames. *Int J Hydrogen Energy* 2008; 33:4906e14.
- Abdul Raheem, A. A., Saleh, A. M., & Shahad, H. A. K. (2021). Measurements and Data Analysis Review of Laminar Burning Velocity and Flame Speed for Biofuel/Air Mixtures. *IOP Conference Series: Materials Science and Engineering*, 1094(1), 12029.
- Marshall, S. P., Taylor, S., Stone, C. R., Davies, T. J., & Cracknell, R. F. (2011). Laminar burning velocity measurements of liquid fuels at elevated pressures and temperatures with combustion residuals. *Combustion and Flame*, 158(10), 1920–1932
- Kuo, K. K. (2005). Gaseous diffusion flames and combustion of a single liquid fuel droplet. *Principles of Combustion*.
- Konnov, A. A., Mohammad, A., Kishore, V. R., Kim, N. Il, Prathap, C., & Kumar, S. (2018). A comprehensive review of measurements and data analysis of laminar burning velocities for various fuel+ air mixtures. *Progress in Energy and Combustion Science*, 68, 197–267.
- Unbeholden, L., & Koelliker, E. (1916). Information about the inner core of the Bunsen flame. *Journal Fur Gasbeluchtung Und Wasserversorgung*, 59, 49–57.
- Mallard, & Chatelier, L. (1883). *Recherches*

- expérimentales et théoriques sur la combustion des mélanges gazeux explosifs. Dunod.
- Daniell, P. J. (1930). The theory of flame motion. Proceedings of the Royal Society of London. Series A, Containing Papers of a Mathematical and Physical Character, 126(802), 393–405.
- Nusselt, W. (1915). Die Zundgeschwindigkeit Brenbarer gasgemische. Duet Ing, 59, 872–878.
- Zeldovich, Y. B., & Frank-Kamenetzky, D. A. (1938). The theory of thermal propagation of flames. Zh. Fiz. Khim, 12, 100–105.
- Agnew, J. T., & Graiff, L. B. (1961). The pressure dependence of laminar burning velocity by the spherical bomb method. Combustion and Flame, 5, 209–219.
- Sharma, S. P., Agrawal, D. D., & Gupta, C. P. (1981). The pressure and temperature dependence of burning velocity in a spherical combustion bomb. Symposium (International) on Combustion, 18(1), 493–501.
- Bradley, D., Gaskell, P. H., & Gu, X.-J. (1996). Burning velocities, Markstein lengths, and flame quenching for spherical methane-air flames: a computational study. Combustion and Flame, 104(1–2), 176–198.
- Kwon, O. C., Rozenchan, G., & Law, C. K. (2002). Cellular instabilities and self-acceleration of outwardly propagating spherical flames. Proceedings of the Combustion Institute, 29(2), 1775–1783.
- Andrews, G. E., & Bradley, D. (1972). Determination of burning velocities: a critical review. Combustion and Flame, 18(1), 133–153.
- Hayakawa, A., Goto, T., Mimoto, R., Arakawa, Y., Kudo, T., & Kobayashi, H. (2015). Laminar burning velocity and Markstein length of ammonia/air premixed flames at various pressures. Fuel, 159, 98–106.

## Appendix

### Nomenclature

Symbol	Definition	Unite
A	Flame Surface Area	m <sup>2</sup>
d	Diameter	mm
e	Number of Mole of Component,	mol
J	Ammonia Volume Fraction	
L <sub>b</sub>	Markstine Length	
L <sub>e</sub>	Lewis Number	
M	Mol Mass	kg/mol
P	Pressure	kPa
R	Specific Gas Constant	J/kg.K
r	Radius	mm
R <sub>u</sub>	Universal Molar Gas Constant	J/ mol.K
S <sub>g</sub>	Gas Velocity Ahead of the Flame Front	m/s
S <sub>b</sub>	Stretched Laminar of the Flame Speed	m/s
T	Temperature	K
t	Time	s
S <sub>u</sub>	Laminar Burning Velocity	m/s
V	Volume	liter
x	Mol fraction	

### Abbreviation

Symbol	Definition
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$\phi$	Equivalence Ratio	
$\alpha T$	Temperature Stretch Rate	
$\beta P$	Pressure Dependent Parameter	
$\epsilon$	Flame Stretch Rate	1/s
$\rho$	Density	kg/m <sup>3</sup>

### Greek Symbols

Symbol	Definition
<b>CPM</b>	Constant Pressure Method
<b>CVC</b>	Constant Volume Method
<b>DIB</b>	Di isobutylene
<b>dil</b>	Diluent
<b>ext</b>	Extensional
<b>LBV</b>	Laminar Burning Velocity
<b>LPG</b>	Liquefied Petroleum Gas
<b>Mix</b>	Mixture
<b>Ref</b>	Reference
<b>Sch</b>	Schlieren image