A STUDY OF NITROGEN DILUTION EFFECT ON THE FLAMMABILITY LIMITS OF METHANE

TENGKU MOHD FADZLI BIN TENGKU AMIN

A thesis submitted to the Faculty of Chemical and Natural Resources Engineering in partial fulfillment of the requirement for the Degree of Bachelor of Engineering

in

Chemical Engineering

Faculty of Chemical and Natural Resources Engineering University Malaysia Pahang

APRIL 2010
ABSTRACT

Explosive/Flammability limits data are essential for a quantitative risk assessment of explosion hazard associated with the use of combustible gas. The present work is to obtain the fundamental explosive data for prevention of the hazards in the practical applications. Experiments have been conducted in a constant volume combustion bomb, and the fuel considered here is natural gas (NG). In this study, the nitrogen ($N_2$) dilution effects on the flammability limits for pure hydrocarbons are explored. The effects of nitrogen on NG–air flammability limits have been investigated. By adding diluents nitrogen ($N_2$) into NG–air mixture, the dilution effects on the flammability limits have been explored as well, and the results are plotted as functions of diluents ratio. From the results, it can be conclude that the range of flammability limits of methane is from 5 vol % until 18 vol %. The effect of nitrogen dilution on the upper flammability limit of methane observed with the reduction from 10 vol % to 30 vol % by increasing the vol % of nitrogen.
ABSTRAK

Batas bahan mudah meletup / terbakar data sangat penting untuk penilaian risiko bahaya letupan kuantitatif berkaitan dengan penggunaan gas yang mudah terbakar. Karya ini adalah untuk mendapatkan data mendasar letupan untuk pencegahan bahaya dalam aplikasi praktikal. Percubaan telah dilakukan di bom pembakaran kelantangan konstan, dan bahan api yang dipertimbangkan di sini adalah gas alam (NG). Dalam kajian ini, nitrogen (N₂) kesan dilusi pada batas hidrokarbon murni mudah terbakar untuk dieksplorasi. Pengaruh nitrogen terhadap batas mudah terbakar NG-udara telah diteliti. Dengan menambah nitrogen (N₂) ke dalam campuran NG-udara, kesan penambahan pada batas mudah terbakar telah dieksplorasi juga, dan keputusan data diplot sebagai fungsi dari nisbah pencair. Dari keputusan experimen, dapat disimpulkan bahawa batas pembakaran metana adalah dari 5 % sampai 18 vol %. Pengaruh dilusi nitrogen pada batas atas metana mudah terbakar diamati dengan penurunan dari 10 % hingga 30 vol % dengan meningkatkan vol % nitrogen.
TABLE OF CONTENTS

CHAPTER TITLE PAGE

TITLE i
DECLARATION ii
DEDICATION iii
ACKNOWLEDGEMENT iv
ABSTRACT v
ABSTRAK vi
TABLE OF CONTENTS vii
LIST OF TABLE xi
LIST OF FIGURE xii
LIST OF ABBREVIATIONS xiii
LIST OF APPENDIX xiv

1 INTRODUCTION

1.1 Introduction 1
1.1.1 Explosion protection 3
1.1.2 Explosion suppression 3
1.2 Background of study 4
1.3 Problem statement 4
1.4 Objective of study 5
1.5 Scope of study 5
2 LITERATURE REVIEW

2.1 Introduction 6
2.1 Experiment methods 11
2.3 Explosion 12
2.3.1 Explosive and explosive Limits 13
2.3.2 Explosion Pressure 14
2.3.3 Detonation 15
2.4 Explosion Suppression 17
2.4.1 Common suppression 18
  2.4.1.1 Inert fire Extinguishing 18
  2.4.1.2 Inert gas suppression system 18
  2.4.1.3 Argonite 18
  2.4.1.4 Carbon dioxide suppression system 19
  2.4.1.5 Foam system 19
  2.4.1.6 Dry chemical suppression 20
2.5 Previous work 20
2.6 20-L Apparatus 21

3 METHODOLOGY

3.1 Material selection 23
  3.1.1 Methane gas 23
  3.1.2 Nitrogen 25
3.2 Experiment Apparatus 26
  3.2.1 20-L-Apparatus 26
  3.2.2 Measurement and Control System
         KSEP 332 27
3.3 Experimental condition 27
  3.3.1 Pressure and temperature 27
  3.3.2 Ignition 28
3.4 Research Parameter 29
3.5 Experiment stages

3.5.1 Run the Methane Explosion by Using Explosion Unit

3.5.2 Determine the Methane Lower Flammability Limit (LFL) and Upper Explosion Limit (UFL)

3.5.3 Carry out methane explosion in the presence of suppression agent (Nitrogen gas)

3.5.4 Collecting data and Record data

3.5.5 Analysis data and make a Comparison

4 RESULTS AND DISCUSSION

4.1 Introduction

4.2 Result and discussion

4.2.1 Methane + Air

4.2.2 Methane + 10 % nitrogen

4.2.3 Methane+ 20 % nitrogen

4.2.4 Methane + 30 % nitrogen

4.2.5 Graph Pm[bar] vs vol %

4.2.6 Graph dP/dt[Bar/s] vs vol %

4.3 Comparison data with previous studies

5 CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

5.2 Recommendation

REFERENCES

APPENDIX
## LIST OF TABLE

<table>
<thead>
<tr>
<th>TABLE NO</th>
<th>TITLE</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.3.1</td>
<td>The flammability limit of some gaseous</td>
<td>13</td>
</tr>
<tr>
<td>2.5</td>
<td>Previous work to determine flammability limit for methane-air</td>
<td>20</td>
</tr>
<tr>
<td>3.3.2</td>
<td>Test condition of experiment</td>
<td>28</td>
</tr>
<tr>
<td>3.4 (a)</td>
<td>The concentration (Vol%) of Methane and Air</td>
<td>29</td>
</tr>
<tr>
<td>3.3 (b)</td>
<td>The concentration (Vol%) of Methane and Air for 10% diluted nitrogen</td>
<td>30</td>
</tr>
<tr>
<td>3.4 (c)</td>
<td>The concentration (Vol%) of Methane and Air for 20% nitrogen diluted</td>
<td>30</td>
</tr>
<tr>
<td>3.5 (d)</td>
<td>The concentration (Vol%) of Methane and Air for 20% nitrogen dilution</td>
<td>30</td>
</tr>
<tr>
<td>4.2.1</td>
<td>Result for Methane + Air</td>
<td>36</td>
</tr>
<tr>
<td>4.2.2</td>
<td>Result for Methane + Air + 10% Nitrogen by volume</td>
<td>37</td>
</tr>
<tr>
<td>4.2.3</td>
<td>Result for methane + Air + 20% Nitrogen</td>
<td>38</td>
</tr>
<tr>
<td>4.2.4</td>
<td>Result of Methane + Air + 30% Nitrogen</td>
<td>38</td>
</tr>
</tbody>
</table>
# LIST OF FIGURE

<table>
<thead>
<tr>
<th>FIGURE NO</th>
<th>TITLE</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1 (a)</td>
<td>Illustration of the terminologies and notations</td>
<td>9</td>
</tr>
<tr>
<td>2.1 (b)</td>
<td>Flammability curves of methane for different inert gases</td>
<td>10</td>
</tr>
<tr>
<td>2.3.2</td>
<td>Schematic represents flammability limit</td>
<td>15</td>
</tr>
<tr>
<td>2.6</td>
<td>Schematic diagrams of 20-L-Apparatus</td>
<td>22</td>
</tr>
<tr>
<td>3.2.1</td>
<td>Schematic diagram of experimental set up</td>
<td>26</td>
</tr>
<tr>
<td>3.5</td>
<td>Experiment stage of experiment</td>
<td>31</td>
</tr>
<tr>
<td>3.5.1</td>
<td>Gas Fire Explosion Unit</td>
<td>32</td>
</tr>
<tr>
<td>4.2.5 (a)</td>
<td>Pm [Bar] vs vol % of methane</td>
<td>40</td>
</tr>
<tr>
<td>4.2.5 (b)</td>
<td>Pm [Bar] % vs vol % methane + 10 % nitrogen dilution</td>
<td>40</td>
</tr>
<tr>
<td>4.2.5 (c)</td>
<td>Pm [Bar] % vs vol % methane + 20 % nitrogen dilution</td>
<td>41</td>
</tr>
<tr>
<td>4.2.5 (d)</td>
<td>Pm [Bar] % vs vol % methane + 30 % nitrogen dilution</td>
<td>41</td>
</tr>
<tr>
<td>4.2.6 (a)</td>
<td>dP/dt [bar/s] vs vol % methane + air</td>
<td>42</td>
</tr>
<tr>
<td>4.2.6 (b)</td>
<td>dP/dt [bar/s] vs vol % methane +10 % nitrogen dilution</td>
<td>42</td>
</tr>
<tr>
<td>4.2.6 (c)</td>
<td>dP/dt [bar/s] vs vol % methane +20 % nitrogen dilution.</td>
<td>43</td>
</tr>
<tr>
<td>4.2.6 (d)</td>
<td>dP/dt [bar/s] vs vol % methane +30 % nitrogen dilution.</td>
<td>43</td>
</tr>
<tr>
<td>4.2.6 (e)</td>
<td>Flammability Limit Methane vs. Nitrogen Volume %</td>
<td>44</td>
</tr>
<tr>
<td>4.3</td>
<td>Flammability curves of methane for different inert gases</td>
<td>45</td>
</tr>
<tr>
<td>17</td>
<td>Graph pm vs vol % and dP/dt vs vol % of methane + air</td>
<td>49</td>
</tr>
<tr>
<td>18</td>
<td>graph pm vs vol % and dP/dt vs vol % of methane + air + 10 % nitrogen</td>
<td>51</td>
</tr>
<tr>
<td>19</td>
<td>graph pm vs vol % and dP/dt vs vol % of methane + air + 20 % nitrogen</td>
<td>53</td>
</tr>
<tr>
<td>20</td>
<td>graph pm vs vol % and dP/dt vs vol % of methane + air + 20 % nitrogen</td>
<td>55</td>
</tr>
<tr>
<td>21</td>
<td>Experiment set up to check gas/air mixtures</td>
<td>58</td>
</tr>
<tr>
<td>22</td>
<td>Pressure course: definitions curve</td>
<td>60</td>
</tr>
</tbody>
</table>
LIST OF ABBREVIATIONS

NG  Natural gas
CH$_4$  Methane
N$_2$  Nitrogen
CO$_2$  Carbon Dioxide
Vol%  Volume percent
STP  Standard temperature pressure
P$_{\exp}$  Explosion pressure
$t_1$  Ignition time
dP/dt  Rate of pressure rise
(dP/dt)$_{\text{max}}$  Max. rate of pressure rise
$K_{\text{max}}$  Product specific constant
LFL  Lower Flammability Limit
UFL  Upper Flammability Limits
$P_{\text{m}}$ [bar]  Pressure maximum
# LIST OF APPENDICES

<table>
<thead>
<tr>
<th>APPENDIX</th>
<th>TITLE</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Data from computer</td>
<td>50</td>
</tr>
<tr>
<td>B</td>
<td>Manual of 20-L-Apparatus</td>
<td>58</td>
</tr>
<tr>
<td>C</td>
<td>Technical Data of 20-L-Sphere</td>
<td>63</td>
</tr>
</tbody>
</table>
CHAPTER 1

INTRODUCTION

1.1 Introduction

Knowledge of the flammability limits of gaseous mixtures is important for the safe and economic operation of many industrial and domestic applications that produce or use flammable mixtures. Flammability limits indicates the region of fuel–air mixture ratios within which flame propagation can be possible while outside that flame cannot propagate. There are two distinct separate flammability limits for a mixture which are lean limit or lower flammability limits (LFL) and rich limit or upper flammability limit (UFL) (S.Y. Liao, 2005). In other words, combustion will take place and be self-sustaining only if fuel and air are mixed within the upper and lower flammability limits. Flammability limits have been discussed extensively in the combustion literature. There are several criteria to determine the flammability limits. A successful attempt can be determined by one or a combination of the following criteria: (1) inspection of the visualization of the flame kernel produced by the spark, namely visual criterion, and (2) measurements of pressure or temperature histories in the vessel and appropriate pressure or temperature rise criteria can be used to designate flammability rather than the purely visual observation of flame development.
Basically, a successful ignition would induce a rapid pressure increase and temperature rise within a short time, as well as produce a propagating flame front that could be readily observed. Previous gas flammability limits data were obtained mainly in flammability tubes, in those tests, a gas mixture in a vertical tube was ignited and flame propagation was inspected by a visual criterion. The wall quenching has a significant effect on the flammability measurement in flammability tube. The larger size of combustion charmer can minimize wall effects and can allow for the potential use of stronger igniters to ensure the absence of ignition limitations, so most of the flammability measurements are conducted in closed chambers recently. And more attentions are being given to the effects of environmental parameters, such as the vessel size, initial temperature and pressure on the fundamental characteristics. Moreover, the theoretical studies are carried out for providing analytical predictions about the flammability limits. With the growing crisis of energy resources and the strengthening of pollutant legislations, the use of natural gas (NG) as an alternative fuel has been promoted recently; natural gas is being regarded as one of the most promising alternative fuels for industrial and domestic applications. The chemical composition of natural gas varies from field to field, but the main chemical component of natural gas is believed to be methane. There is a large volume of flammability limits data available for fuels, such as methane, ethane, propane, butane, etc. But to the best of our knowledge, no work has been reported so far on the flammability limits of NG–air mixture.

Therefore, the present work is promoted purposely. The experiments are made systematically to determine the flammability limits of NG–air mixture in a constant volume combustion bomb, using conventional spark ignition system. The explosion pressure traces are recorded and an appropriate pressure rise criterion is used to define the flammability limits.
1.1.1 Explosion Protection

Explosion protection is used to protect all sorts of buildings and civil engineering infrastructure against internal and external explosions or deflagrations. It was widely believed until recently that a building subject to an explosive attack had a chance to remain standing only if it possessed some extraordinary resistive capacity. This belief rested on the assumption that the specific impulse or the time integral of pressure, which is a dominant characteristic of the blast load, is fully beyond our control. Avoidance will make it impossible for an explosion or deflagration to occur, for instance by means of consistent displacement of the O₂ necessary for an explosion or deflagration to take place, by means of padding gas (CO₂ or N₂), or, by means of keeping the concentration of flammable content of an atmosphere consistently below or above the explosive limit, or, by means of consistent elimination of ignition sources. Constructional explosion protection aims at pre-defined, limited or zero damage that results from applied protective techniques in combination with reinforcement of the equipment or structures that must be expected to become subject to internal explosion pressure and flying debris or external violent impact.

1.1.2 Explosion Suppression

Explosion suppression provided a method for extinguishing a growing fireball and relies on early detection of an incipient explosion. This is most commonly achieved by ‘set-point’ pressure detection.

Explosion suppression is often used it is not possible to protect by containment or explosion relief venting and particular where the pressure and flame of the explosion cannot be vented to a safe location. Explosion suppression is particularly important is cases where loss of process containment could cause the emission of toxic dust or other substances harmful to the people or surroundings.
1.2 Background of Study

This project is mainly focuses on the suppression system as the main alternative to prevent or mitigate explosion from occur especially in industrial. According to National Fire Protection Association (NFPA), the grouping that might be considered ‘industrial’ are basic industry, utilities, manufacturing and many of the storage properties, NFPA statistics for the 1990 (Karter, 1991) indicate that there were 22,000 fires and explosion in the combined categories of basic industry, utilities and manufacturing. An additional 39,500 fires and explosion in the storage properties are also recorded. (Zalosh, 2002)

Early detection and protection system are very important to be considering in every industry in order to prevent fires and explosion from occur. In this project, the Nitrogen gas as the suppression agent will apply to the explosion to test and determine the effect to the explosion limit. As the fuel source, natural gas (NG) will be use due to its properties and potential in the occurrence of explosion.

1.3 Problem Statement

Nowadays many an explosion protection system especially in the process industries as a explosion prevention especially in industries. But there are some disadvantage of some method is the potential of the suppression agent to mitigate the explosion limit especially when dealing with hydrogen and methane, in addition some suppression agent is expensive. There are many methods to prevent fire and explosion such as isolating, venting and suppression. Venting is system release pressure indoor or closed system, especially when dealing with LPG, natural gas and hydrogen where they are high velocity combustion speed and greatest flammable, so its need early method is suppression by using inert gas such as helium, carbon dioxide, nitrogen or argon, in this research, nitrogen is used as a suppression agent, where nitrogen gas is cheaper and easy to get.
1.4 Objectives of Study

The objectives of this study are:

i. To determine the flammability limit of natural gas dilute nitrogen gas mixture in a combustion bomb at atmospheric pressure and ambient temperature.

ii. To determine the effect of nitrogen suppressing on flammability limit of premixed natural gas-air mixture in a combustion bomb at atmospheric pressure and ambient temperature.

1.5 Scope of Study

This study is conducted to determine the flammability limits of premixed fuel-air-nitrogen mixture in a constant volume spherical vessel with a volume of 20 L by using conventional spark ignition system which is located at the centre of the vessel.

In this study methane with 96 % purity is used to replace the natural gas. Methane can be used to indicate the properties of natural gas since the major component in natural gas is methane.

The lower flammability limit (LFL) and upper flammability limit (UFL) of natural gas-air mixture were determined at concentration from 3 vol % to 18 vol %. The effect of nitrogen in natural gas-air mixture was investigated at nitrogen enrichment up 30 vol % nitrogen of fuel by at methane concentration from 3 vol % to 18 vol %.
CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Knowledge of the flammability limits of gaseous mixtures is important for the safe and economic operation of many industrial and domestic applications that produce or use flammable mixtures.

Flammable limits apply generally to vapors and are defined as the concentration range in which a flammable substance can produce a fire or explosion when an ignition source (such as a spark or open flame) is present. The concentration is generally expressed as percent fuel by volume. When the combustion of the fuel is not controlled within the confines of a burner system, the limits of flammability can be called the explosive limits. There are two distinct separate flammability limits for a mixture which are lean limit or lower flammability limit (LFL) and rich limit or upper flammability limit (UFL):

i. Above the upper flammable limit (UFL) the mixture of substance and air is too rich in fuel (deficient in oxygen) to burn. This is sometimes called the upper explosive limit (UEL).

ii. Below the lower flammable limit (LFL) the mixture of substance and air lacks sufficient fuel (substance) to burn. This is sometimes called the lower explosive limit (LEL).
In other words, combustion or explosion will take place and be self-sustaining only if fuel and air are mixed within the upper and lower flammability limits. Usually the LFL and UFL of a combustible material are expressed in volume percentage (vol %) in the literature; however, as the hydrocarbon gas could be taken as an ideal gas at atmospheric pressure, LFL and UFL could be also explained as the molar fraction, which is the expression adopted in this study. To avoid misleading the meaning in formulation, three terminologies are defined here:

i. Fuel mixture the mixture composed of hydrocarbon and air (no inert gas)

ii. Blended gas the mixture composed of hydrocarbon and inert carbon dioxide (no air)

iii. Total mixture-the mixture composed of the blended gas and air.

Many manufacturing processes involve flammable chemicals, and an accident involving a fire or an explosion can occur in storage or process equipment if a flammable chemical exists inside it or if a loss of containment of flammable chemicals occurs. Because the gas mixture of a flammable substance could be ignited only if the concentration of the flammable substance lied within a given range known as the flammability limits, the flammability limits are one of the important features in the development of safe practices for handling a flammable vapour or gas. For this reason, they constitute a crucial issue in research on processing and storing flammable chemicals safely. In the literature, different methods have been proposed to predict the flammability limits of a flammable chemical, especially the lower flammability limit (LFL) of a pure flammable chemical. Industry works with mixtures under many situations, for example, in a reactor or in a distillation column.

The Le Chatelier equation is widely adopted to estimate the flammability limits of a mixture composed of flammable gases. However, complex mixtures composed of flammable gases and non-flammable gases are also formed in process industries, for example, the inverting procedure. Inverting is the process of adding an inert gas to a combustible mixture to reduce the concentration of oxygen below the limiting oxygen concentration (LOC) for the purpose of lowering the likelihood of
explosion. In process industries, the inert gas is usually nitrogen or carbon dioxide, although sometimes steam may be used. As the inert gas does not take part in the reaction mechanism, the method of “calculated adiabatic flame temperatures” is usually applied to estimate the flammability limits of a mixture of fuel and inert gas in the literature Vidal et al.

According to LeChatelier’s rule:

\[
LFL = \frac{100}{\sum(C_i/LFL_i)}
\]  

(2.1)

Where LFL is the lower flammability limit of mixture (vol. %), \(C_i\) the concentration of component i in the gas mixture on an air-free basis (vol. %), and \(LFL_i\) is the lower flammability limit for component i (vol %).

Inert gas could be obtained. However, prediction models based on adiabatic flame temperature theories typically produce satisfactory results in forecasting LFL, but this is not the case in predicting the upper flammability limit (UFL). Because the procedure of diluting a combustible gas with inert gas could be also taken as a mixing process of flammable gas and inert gas, Kondo et al. have attempted to modify the Le Chatelier equation so that it could be extended to the case of a mixture of flammable gases and inert gases. The following assumptions were included in their work:

i. At LFL, the heat of combustion per mole of a mixture composed of fuel gas and inert gas is equal to the heat of combustion per mole of pure fuel gas times the molar fraction of the fuel gas in the mixture (i.e., adding inert gas to fuel gas does not change the reaction mechanism at LFL). The heat release is the same for all limit mixtures at LFL.

ii. The fuel gas would react completely when combustion takes place at LFL.

iii. At UFL, the ratio of the number of moles of oxygen required to burn one mole of the mixture of fuel gas and inert gas to the number of moles of
oxygen required to burn one mole of pure fuel gas equals the molar fraction of the fuel gas in the mixture (i.e., adding the inert gas to the fuel gas does not change the reaction mechanism at UFL)

iv. Oxygen would react completely when combustion takes place at UFL.

The addition of inert gases influences the LFL and UFL of a fuel-air mixture. Figure 2.1(a) reveals the effect of added inerts on the flammability of methane and air. The left side is the same as the methane side of Figure 2.1 (a) but the right side of Figure 2.1 (a) shows the effect of, for example, added nitrogen on the LFL and UFL and how a flammability envelope is generated. The far right portion of the envelope is termed the nose. At this LFL and UFL values are published for a significant number of fuels for ambient conditions [i.e. 20 °C (68 °F) and 760 mm Hg (14.7 psia)] because room conditions are the easiest conditions to create for flammability testing.

Figure 2.1 (a): Illustration of the terminologies and notations.
As Figure 2.1(b) shows, the change in UFL is usually more obvious than that in LFL when the inert gas is added. It could be found in Figure 2.1 (b) that when the concentration of inert gas is low, the LFL of the methane/inert gas mixture will increase as the concentration of the inert gas increases if the inert gas is carbon dioxide or steam; the LFL of methane/inert gas mixture seems to be irrelative of the concentration of inert gas if the inert gas is nitrogen; and the LFL of methane/inert gas mixture will decrease as the concentration of inert gas increases if the inert gas is helium.

**Figure 2.1 (b):** Flammability curves of methane for different inert gases.
2.2 Experimental Methods

The standardized measurements of flammability limits are usually conducted in the flammability tubes or closed vessels. There are several criteria to determine the flammability limits. A successful attempt can be determined by one or a combination of the following criteria:

i. Inspection of the visualization of the flame kernel produced by the spark, namely visual criterion

ii. Measurements of pressure or temperature histories in the vessel and appropriate pressure or temperature rise criteria can be used to designate flammability rather than the purely also observation of flame development

A successful ignition would induce a rapid pressure increase and temperature rise within a short time as well as produce a propagating flame front that could be readily observed. Previous gas flammability limit data were obtained mainly in flammability tubes which in those test a gas mixture in a vertical tube was ignited and flame propagation was inspected by visual criterion. However, the wall quenching has a significant effect on the flammability measurement in flammability tube.

Recently, the flammability measurements are conducted in closed chambers. This is because the larger size of combustion chamber can minimize wall effects and can allow potential use of stronger igniters to ensure the absence of ignition limitations (D.M Jiang et al 2005).
2.3 Explosion

An explosion is a rapid increase in volume and release of energy in an extreme manner, usually with the generation of high temperatures and the release of gases. An explosion creates a shock wave. If the shock wave is a supersonic detonation, then the source of the blast is called a "high explosive". Subsonic shock waves are created by low explosives through the slower burning process known as deflagration.

High explosives are explosive materials that detonate, meaning that the explosive shock front passes through the material at a supersonic speed. High explosives detonate with explosive velocity rates ranging from 3,000 to 9,000 meters per second. They are normally employed in mining, demolition, and military applications. They can be divided into two explosives classes differentiated by sensitivity: Primary explosive and secondary explosive. The term high explosive is in contrast to the term low explosive, which explodes (deflagrates) at a slower rate.

Low explosives are compounds where the rate of decomposition proceeds through the material at less than the speed of sound. The decomposition is propagated by a flame front (deflagration) which travels much more slowly through the explosive material than a shock wave of a high explosive. Under normal conditions, low explosives undergo deflagration at rates that vary from a few centimetres per second to approximately 400 meters per second. It is possible for them to deflagrate very quickly, producing an effect similar to a detonation. This can happen under higher pressure or temperature, which usually occurs when ignited in a confined space. A low explosive is usually a mixture of a combustible substance and an oxidant that decomposes rapidly (deflagration), however they burn slower than a high explosive which has an extremely fast burn rate. Low explosives are normally employed as propellants. Included in this group are gun powders and light pyrotechnics, such as flares and fireworks.
2.3.1 Explosive and Explosive Limit

The Flammable Range (Explosive Range) is the range of a concentration of a gas or vapor that will burn (or explode) if an ignition source is introduced. Below the explosive or flammable range the mixture is too lean to burn and above the upper explosive or flammable limit the mixture is too rich to burn. The limits are commonly called the "Lower Explosive or Flammable Limit" (LEL/LFL) and the "Upper Explosive or Flammable Limit" (UEL/UFL).

The lower and upper explosion concentration limits for some common gases are indicated in the Table 2.3.1 below. Some of the gases are commonly used as fuel in combustion processes. The flammability limit of gaseous is show in Table 2.3.1 below:

**Table 2.3.1: The flammability limit of some gaseous.**

<table>
<thead>
<tr>
<th>Fuel Gas</th>
<th>&quot;Lower Explosive or Flammable Limit&quot; (LEL/LFL) (%)</th>
<th>&quot;Upper Explosive or Flammable Limit&quot; (UEL/UFL) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acetaldehyde</td>
<td>4</td>
<td>60</td>
</tr>
<tr>
<td>Acetone</td>
<td>2.6</td>
<td>12.8</td>
</tr>
<tr>
<td>Acetylene</td>
<td>2.5</td>
<td>81</td>
</tr>
<tr>
<td>Ammonia</td>
<td>15</td>
<td>28</td>
</tr>
<tr>
<td>Benzene</td>
<td>1.35</td>
<td>6.65</td>
</tr>
<tr>
<td>n-Butane</td>
<td>1.86</td>
<td>8.41</td>
</tr>
<tr>
<td>iso-Butane</td>
<td>1.80</td>
<td>8.44</td>
</tr>
<tr>
<td>Butylene</td>
<td>1.98</td>
<td>9.65</td>
</tr>
<tr>
<td>Ethane</td>
<td>3</td>
<td>12.4</td>
</tr>
<tr>
<td>Ethylene</td>
<td>2.75</td>
<td>28.6</td>
</tr>
<tr>
<td>Ethyl Alcohol</td>
<td>3.3</td>
<td>19</td>
</tr>
<tr>
<td>Gasoline</td>
<td>1.4</td>
<td>7.6</td>
</tr>
<tr>
<td>Kerosene</td>
<td>0.7</td>
<td>5</td>
</tr>
<tr>
<td>Methane</td>
<td>5</td>
<td>15</td>
</tr>
<tr>
<td>Methyl Alcohol</td>
<td>6.7</td>
<td>36</td>
</tr>
<tr>
<td>n-Heptane</td>
<td>1.0</td>
<td>6.0</td>
</tr>
<tr>
<td>n-Hexane</td>
<td>1.25</td>
<td>7.0</td>
</tr>
<tr>
<td>n-Pentene</td>
<td>1.4</td>
<td>7.8</td>
</tr>
</tbody>
</table>
2.3.2 Explosion Pressure

Knowledge of pressure-time variation during explosions of fuel-air mixtures in enclosures is a very important component of safety recommendations for a wide range of human activities, connected to production, transportation or use of fuels.

The characteristic parameters of a closed vessel explosion are the explosion pressure, the explosion time and the maximum rate of pressure rise. The explosion pressure and explosion time were recently defined in the European standard on maximum explosion pressure determination:

i. The explosion pressure, $P_{\text{exp}}$ is the highest pressure reached during the explosion in a closed volume at a given fuel concentration

ii. The maximum explosion pressure, $P_{\text{max}}$ is the highest pressure reached during a series of explosions of mixtures with varying fuel concentration

iii. The explosion time, $\text{exp}$ is the time interval between ignition time and the moment when the explosion pressure attained

Explosion pressures and explosion times are important for calculating laminar burning velocities from closed vessel experiments, vent area design, and characterizing transmission of explosions between interconnected vessels (D. Razus et al 2006).
Based on the pressure time traces three regimes of explosion development or combustion conversion can be identified. The regimes depend on the initial mixture composition, at given conditions as illustrated at Figure 2.3.2. In the first one, marked as 1, the pressure increases fast and smoothly to the maximum value, after ignition. This type of pressure development is seen for near stoichiometric mixtures. In the second regime, the pressure trace is distinctly S shaped (a shoulder). Such type of pressure development is a narrow fuel lean concentration range and in a wider concentration range with fuel rich mixtures. In the third regime the shoulder disappeared, and the increase is low and slow. (A.A.Pekalski, 2005).

![Schematic represents flammability limit](image)

**Figure 2.3.2:** Schematic represents flammability limit

### 2.3.3 Detonation

Detonation involves an exothermic front accelerating through a medium that eventually drives a shock front propagating directly in front of it. They are observed in both conventional solid and liquid explosives, as well as in reactive gases. The velocity of detonations in solid and liquid explosives is much higher than that in gaseous ones, which allows far clearer resolution of the wave system in the latter.
Gaseous detonations normally occur in confined systems but are occasionally observed in large vapour clouds. Again, they are often associated with a gaseous mixture of fuel and oxidant of a composition, somewhat below conventional flammability limits. There is an extraordinary variety of fuels that may be present as gases, as droplet fogs and as dust suspensions. Other materials, such as acetylene, ozone and hydrogen peroxide are detonable in the absence of oxygen; fuller lists are given by both Stull and Bretherick. Oxidants include halogens, ozone, hydrogen peroxide and oxides of nitrogen and chlorine.

In terms of external damage, it is important to distinguish between detonations and deflagrations where the exothermic wave is subsonic and maximum pressures are at most a quarter of those generated by the former. Processes involved in the transition between deflagration and detonation are covered thoroughly by Nettleton.

The simplest theory to predict the behaviour of detonations in gases is known as Chapman-Jouguet (CJ) theory, developed around the turn of the 20th century. This theory, described by a relatively simple set of algebraic equations, models the detonation as a propagating shock wave accompanied by exothermic heat release. Such a theory confines the chemistry and diffusive transport processes to an infinitely thin zone.

A more complex theory was advanced during World War II independently by Zel'dovich, von Neumann, and W. Doering. This theory, now known as ZND theory, admits finite-rate chemical reactions and thus describes a detonation as an infinitely thin shock wave followed by a zone of exothermic chemical reaction. With a reference frame of a stationary shock, the following flow is subsonic, so that an acoustic reaction zone follows immediately behind the lead front, the Chapman-Jouguet condition. Both theories describe one-dimensional and steady wave fronts. However, in the 1960s, experiments revealed that gas-phase detonations were most often characterized by unsteady, three-dimensional structures, which can only in an averaged sense be predicted by one-dimensional steady theories. Indeed, such waves are quenched as their structure is destroyed.