

DETERMINATION OF EXPLOSION PARAMETERS OF HYDROGEN-  
AIR MIXTURES IN CLOSED VESSEL

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DETERMINATION OF EXPLOSION PARAMETERS OF HYDROGEN-AIR  
MIXTURES IN CLOSED VESSEL

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## **SUPERVISOR'S DECLARATION**

“I hereby acknowledge that the scope and quality of this thesis is qualified for the award of the Bachelor Degree of Chemical Engineering (Gas Technology).”

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*Special Dedication to ALLAH swt my family members that always love me,  
My friends, my fellow colleagues  
And all who always stay with me*

*For all your Care, Support and Believe in me*

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# **DETERMINATION OF EXPLOSION PARAMETERS OF HYDROGEN-AIR MIXTURES IN CLOSED VESSEL**

## **ABSTRACT**

Hydrogen has been proposed as a potential fuel to replace fossil fuels in consideration to reduce carbon emissions. This paper presents experimental data on the characteristics of hydrogen-air explosion in air mixture using 20-L sphere. This data includes the maximum explosion pressure, deflagration index, and the maximum rate of pressure rise. Methods and equations are available to estimate these parameters.

The experimental maximum explosion pressure agrees with the theoretical value estimated using a chemical equilibrium program if the concentration of hydrogen is from 10 % to 75% in air but not close to the flammable limits. Therefore, the maximum pressure can be estimated conventionally by the equilibrium program regardless of the size of the explosion vessel.

Deflagration index for mixture of hydrogen in air, even if normalized by the cube root of the number of vessels explosion, is shown to be sensitive to the vessel volume. The fraction of burnt gas just before the flame contacts the wall has a dominant effect on the deflagration index (Crowl, 2001). From experimental data the deflagration index of hydrogen explosion in 20 L is 212.54 bar.m / sec. The maximum explosion pressure is 2.8 bar at the amount of 22% hydrogen in air and the maximum rate of increase in pressure is 783 bar. Experimental values are different from the theoretical value because there is an error during the experiment run. So, improvements need to be done to get better data experimental procedures in the future.

# **MENGENALPASTI PARAMETER LETUPAN BAGI CAMPURAN HIDROGEN-UDARA DI DALAM BEKAS TERTUTUP**

## **ABSTRAK**

Hidrogen telah dicadangkan sebagai bahan api yang berpotensi untuk menggantikan bahan api fosil dalam pertimbangan untuk mengurangkan pelepasan karbon. Kertas ini membentangkan data eksperimen mengenai ciri-ciri letupan hidrogen udara di dalam campuran udara menggunakan sfera 20-L. Data ini termasuk tekanan letupan maksimum, indeks deflagrasi, dan kadar maksimum kenaikan tekanan. Kaedah dan persamaan telah disediakan untuk menganggarkan parameter ini.

Tekanan letupan maksimum eksperimen adalah sama dengan nilai teori yang telah dianggarkan menggunakan program keseimbangan kimia jika kepekatan hidrogen adalah daripada 10% kepada 75% dalam udara tetapi tidak terlalu dekat dengan had mudah terbakar. Oleh itu, tekanan maksimum boleh dianggarkan biasanya oleh program keseimbangan tanpa mengira saiz sfera

Indeks deflagrasi untuk campuran hidrogen di dalam udara, walaupun normal oleh akar kiub jumlah vesel letupan, ditunjukkan untuk menjadi sensitif kepada jumlah kapal. Nilai pecahan gas dibakar sejurus sebelum kenalan nyalaan dinding mempunyai kesan dominan terhadap indeks deflagrasi (Crowl, 2001). Daripada data eksperimen indeks deflagration dalam sebuah sfera 20 L adalah bernilai sebanyak 15.66 bar.m / sec. Tekanan letupan maksimum adalah 2.8 bar pada jumlah 22% hidrogen di dalam udara dan kadar maksimum kenaikan tekanan adalah 783 bar. Nilai eksperimen adalah berbeza daripada nilai teori kerana terdapat ralat semasa eksperimen di jalankan. Jadi, penambahbaikan perlu lah dilakukan untuk mendapat data eskperimen yang lebih baik pada masa akan datang.



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## LIST OF SYMBOLS

|                 |                             |
|-----------------|-----------------------------|
| P               | Pressure                    |
| T               | Time                        |
| V               | Volume                      |
| K               | Deflagration index          |
| (dP/dt)         | Rate of pressure rise       |
| K <sub>St</sub> | Deflagration index for dust |
| K <sub>G</sub>  | Deflagration index for gas  |
| %               | Percentage                  |

## **LIST ABBREAVIATION**

|      |   |
|------|---|
| NFPA | National Fire Protection Association      |
| ASTM | American Society for Testing and Material |
| FM   | Factory Mutual System                     |
| UFL  | Upper Flammability Limit                  |
| LFL  | Lower Flammability Limit                  |



## **CHAPTER I**

### **INTRODUCTION**

#### **1.1 Background of Research**

In new era, a great deal of effort has been dedicated to the continuing replacement of ordinary fossil fuels by new energy vectors, primarily because of the natural resources dry up and the simultaneous rapid increase of energy demands worldwide. Hydrogen is considered one of the most promising fuels for global use in the future, mainly because it is an energy-efficient, low-polluting and renewable fuel (Rigas et. al., 2005). On the other hand, aiming at environmental benefits such as combination of hydrogen with other gaseous fuels like natural gas is under consideration. One of the major issues affecting the approval of hydrogen for public use is the safety of hydrogen installations such as production and storage units, as well as its applications. Evaluation of hazards connected to the hydrogen storage facilities have been studied by Fotis Rigas & Spyros Sklavounos for many years to reveal potential accidents that hydrogen may yield under certain conditions. In their

previous study, they examine the common hazards arising from hydrogen storage and distribution systems. Hazard analysis was performed based on Event Tree Analysis Method. Moreover, they also do a computational analysis on estimation of the dispersion resulting from liquefied hydrogen spills and this lead to a series of accident types that can cause a severe threat to the property and public safety.

In current works, theoretical and computational safety comparisons between hydrogen and other fuels, do not allow a clear point of view for the safest one to be concluded. Certainly, in the past, there were situation that hydrogen applications gave rise to severe accidents with significant economic and societal cost, show the need of improving safety measures wherever hydrogen is handled. Without doubt, the need for safety measures should be pointed out when failure prevention and public safety are concerned. In the context of combustion the characteristics that give high responsibility for explosion hazards in storage are reactivity and diffusivity of hydrogen. Because of these behaviors it is necessary to contribute in the planning and engineering design for storage, safety and performance in combustion engines and other applications (Law, 2004).

In order to increase the safety measure for handling of hydrogen in closed vessel the explosion parameters should be determined. There are three important parameters which are maximum explosion pressure, rate of pressure rise and deflagration index. Maximum explosion pressure can be defined as the highest value of pressure develops by a deflagration after a series of deflagration test is done over wide range of concentration. This value is normally used to design enclosure and to predict the severity of consequences. From this series of test the value of maximum

rate of pressure also can be obtained. This value is needed in the calculation of deflagration index and also in predicted the violence of the explosion. The deflagration index will show how fast the pressure will rises following the ignition of dust of a known concentration in a container of a specific volume (20 liters). Besides that, deflagration index also will determine whether hydrogen can be classified as hazard class 1, 2 or 3. The higher the deflagration index, the more severe a dust explosion can be. Deflagration index, K can be calculated based on below equation:

$$K = \left(\frac{dp}{dt}\right)_{\max} \times \sqrt[3]{V}$$

Where:

$P$  = pressure, bar

$t$  = time,s

$V$  = volume,m<sup>3</sup>

$K$  = deflagration index, bar.m/s

$\left(\frac{dp}{dt}\right)_{\max}$  = maximum rate of pressure rise, bar/s

## 1.2 Problem Statement

The characteristic of hydrogen such as wide flammability limit and lower source of ignition become the prime factors which contribute to the hazards of the hydrogen. So, these properties of hydrogen will cause threat to the property and public safety. If the explosion parameters in closed vessel cannot be determined it will definitely cause hazard explosion when there is source of ignition in the vessel. There are three parameters need to be studies which are maximum explosion pressure, deflagration index and maximum rate of pressure rise by determining these parameters, hazards risk of using hydrogen can be reduced.

## 1.3 Objectives of Research

The objectives of the study are to:

- a) To investigate on the maximum pressure of explosion,  $P_{\max}$  (bar)
- b) To determine the maximum rate of pressure rise,  $dp/dt_{\max}$  (bar/s)
- c) To study on the deflagration index, K (bar.m/s)

#### **1.4 Scope of Research**

This experiment will run start from at the range of 2% by volume of hydrogen in air until the graph absolute pressure, P and rate of pressure rise,  $dP/dt$  against time is completely plot. The value of explosion pressure and rate of pressure rise of explosion can be determined during the course of single deflagration test. To get the value of maximum pressure,  $P_{max}$  and maximum rate of pressure rise series of test over wide range of concentration should be done. Maximum pressure can be defined as maximum explosion overpressure generated in the test chamber. From the data, the graph explosion pressure and explosion rate of pressure rise against hydrogen concentration will be plot. The value of maximum pressure and maximum rate of pressure rise then will be determined from these graphs. Deflagration index then can be calculated by using the value obtains from the graph.

## **CHAPTER II**

### **LITERATURE REVIEW**

#### **2.1 Introduction**

Explosion could be said as a phenomenon that can happen anywhere likes in the residential area, vehicles, shop lot and many others places but major explosion usually occurs in industries, especially the industries that use lots of chemicals that have a high potential to cause an explosion. This fatal incident not only happen now days but already started a long time before. Where ever explosion occurs it might be cause by the same factor. Every year there's the case of explosion that can be read in the newspapers or widely spread on the internet no matter it's a minor or major explosion. On 17 August, 2009 after the case of large property loss, the insured and insurers of a hydroelectric power plant in North America became involved in subrogation to determine if the event could be characterized as an explosion. The

subject insurance policy provided coverage for explosions, but excluded mechanical breakdowns (Martin et. al., 2000). Therefore, based on the case many researchers are tried to define what is the exactly meaning and the caused of the explosion to classified whether this case can be describe as the explosion or not. The researched done by Martin, Ali and Larry were based on analysis of the accident and describe the necessary characteristic of explosion. Further investigation have been done by many others researcher to find the parameters of the explosion so that safety precaution can be take to prevent any fatality.

## **2.2 Explosions**

### **2.2.1 Definition**

Word of explosion is defined by Webster as a large scale, rapid and spectacular expansion, outbreak, other upheaval. This means that the process occur when a pressure wave of finite amplitude is generated in air by a rapid release of energy. The different types of energy sources can generate pressure waves and thus can be classified as explosives based on the definition. Explosion also can be defined as a sudden expansion of matter into a much larger volume than it formerly occupied (Martin et. al., 2000). Based on the past researcher explosion does not require the passage of combustion wave through the exploding medium, whereas an explosive gas mixture must exist in order to have either a deflagration or detonation.

When vapors, dusts or gases mixed with the sufficient amount of air and ignited explosive combustion might happen (DeHann, 1991).

Based on another sources by Glassman (1977) has defined explosion is a term which corresponds to rapid heat discharge or in other word can be say as pressure rise. An explosive gas or gas mixture is one which will allow rapid energy release, as compared to most stable, low temperature reaction. Glassman also said that it is very regular to confuse between a pure explosion and detonation.

According to Saifol (2008) explosion also can be defined as an event in which energy is released over a sufficiently small period of time and in a sufficiently small volume to generate a pressure wave of finite amplitude traveling away from the source. This energy may have been originally stored in the system as chemical, nuclear, electrical, or pressure energy. However, the release is not considered to be explosive unless it rapid and concentrated enough to produce a pressure wave that can be heard (Saifol, 2008).

By considering the definition found in the safety code standards issued by National Fire Protection Association (NFPA) and the Factory Mutual System (FM) gives a different perspective in the definition of the explosion. National Fire Protection Association has defined the term of explosion as the bursting or rupture of an enclosure or a container due to the development of internal pressure from a deflagration. The word of enclosure can be defined as confined or partially confined volume while deflagration can be said as a propagation of a combustion zone at a



velocity that is less than the speed of sound in the unreacted medium as stated in safety code standards (National Fire Protection Association, 2008).

In other words Factory Mutual System give a definition of an explosion as rapid transformation of potential physical or chemical energy into mechanical energy and involves the expansion of gases. Physical explosion originally from purely physical phenomena, such as rupture of boiler of pressurized container, or from interaction between water and molten or black liquor smelt while chemical explosion originate from a chemical reaction such as flammable vapor air explosion, a dust explosion, or detonation of an explosive or blasting agent. Deflagration is an exothermic reaction that propagates from the burning gases to the unreacted material by conduction, convection, and radiation (Factory Mutual System, 1999).

Therefore, both NFPA and FM concerned with the both effect on bursting and rupture and cause deflagration in their definition. NFPA does not include non combustion sources in their definition while FM regrouped it into two main categories which are physical and chemical. However, both standards require that the definition for explosion include the rapid expansion of gases (Martin et. al., 2000).

All researchers give their own definition of explosion but all of them concentrated on the same point which is increasing of energy release, rapidly increasing in pressure rise and also deflagration. Therefore, this is the keyword of the explosion.

## **2.2.2 Types of Explosion**

### **2.2.2.1 Dust Explosion**

Combustible materials are materials that are capable of burning in air. Most organic materials and metal and some of non metallic inorganic material will be burn or explode if they contact with sufficient ignition sources (Blair, 2003). Not all small particles will burn. For example, salt and baking soda, no matter how small of fine the powdered, it will not burn if they do not contain combustible material. Coffee creamer, on the other hand, will burn because it contains fat because fat can be categorized as inorganic material. Combustible dusts are can be manufactured or generated when solid combustible are handled or processed due to gradual reductions in the particle sizes and/or segregation of the particles.

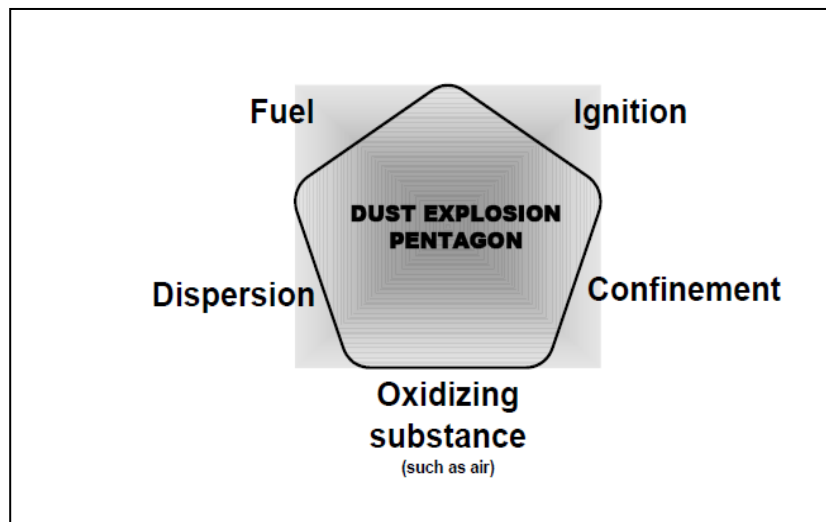
National Fire Protection Association 654 (2006) has defines combustible dusts as a combustible particulate solid that presents a fire or deflagration hazard when suspended in air or some other oxidizing medium over a range of concentrations, regardless of particle size or shape. Awareness of combustible dust hazards is important to ensure employee safety, to ensure proper facility design, and to develop adequate operations and maintenance procedures (National Fire Protection Association, 2006).

They are many factors that influence the possibility and severity of dust explosion. Typically, for dust explosion to take place three conditions must be there which combustible dusts are is suspended, the dust is ignited and dust is confined

such that damaging pressure and accumulate. Based on the researcher the finer the dust particle the more easily the dust oxidizes to give the higher potential for explosion to occur.

#### **2.2.2.1.1 Dust Explosion Pentagon**

Fuel, ignition, oxygen, suspension, and confinement form the five sides of the dust explosion pentagon as shown in Figure 2.1. Like all other fires, a dust fire occurs when fuel is exposed to heat in the presence of oxygen. Removing any one of these elements of the fire triangle eliminates the possibility of a fire. A dust explosion requires the simultaneous presence of two additional elements which are dust dispersion and confinement. Confinement keeps dust particles in proximity after suspension to allowing sufficiently rapid heat transfer to continue propagation. Without confinement, a propagating explosion is not possible, though a large and very dangerous fireball may occur. Suspended dust burns more rapidly, and confinement allows for pressure buildup (Blair, 2003). Remove either the suspension or the confinement elements will terminate an explosion, though a fire may still occur, because the elements of the fire triangle (fuel, oxygen and ignition) exist.



**Figure 2.1** Dust Explosion Pentagon (Blair, 2003)

### 2.2.2.1.2 Dust Explosion Characteristic

The relative explosibility of a given combustible dust is typically expressed using the deflagration index,  $K_{St}$  and depends on several factors. This index is determined experimentally by measuring how fast the pressure rises following the ignition of dust of a known concentration in a container of a specific volume (20 liters). The higher the  $K_{St}$ , the more severe a dust explosion can be. National Fire Protection Association 68 (2002) defines three dust hazard classes, used to indicate relative explosiveness. Class St-1 dusts have a  $K_{St}$  at or below 200 bar-m/sec, St-2 dust  $K_{St}$  values range from 201 to 300 and St-3 dusts have a  $K_{St}$  above 300 bar-m/sec. The following table shows the  $K_{St}$  values and hazard classes for some commonly known combustible dusts.

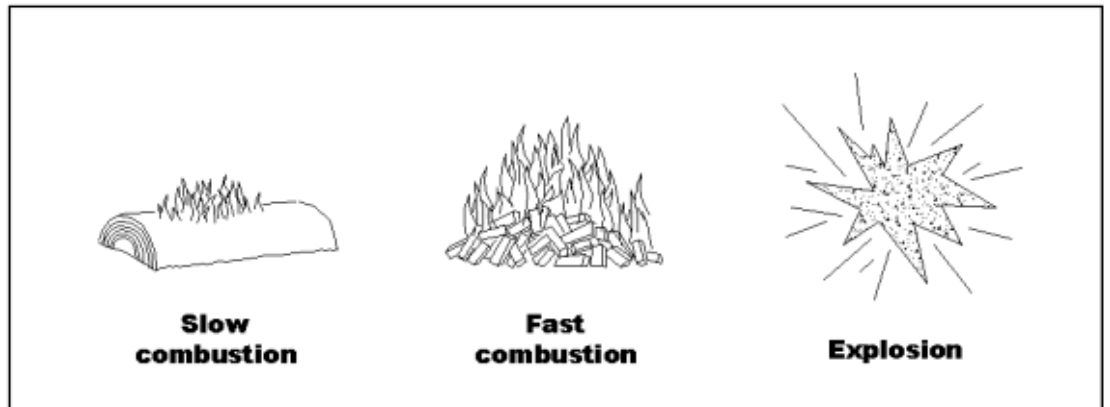
**Table 2.1**  $K_{st}$  value for common combustible dust (Eckhoff, 2003)

| Dust            | $K_{ST}$ ,bar.m/sec | ST class |
|-----------------|---------------------|----------|
| Aluminium       | 400-1100            | 3        |
| Aspirin         | 217                 | 2        |
| Copier toner    | 134-196             | 1        |
| Rubber          | 138                 | 1        |
| Wheat flour     | 87                  | 1        |
| Yellow food dye | 288                 | 2        |

### 2.2.2.1.3 Properties of Explosion Dust

For any combustible solid, the severity and likelihood of an explosion can be quantified based on measurements of various physical properties. Some of the properties are size of particles and dust chemistry and moisture. Both of these properties will be explain more detail in below.

Particle size specific surface area primarily influences the easiness of ignition and the severity of combustible dust explosions. Finely divided particles have a large surface area, which allows them to react rapidly with oxygen when dispersed in air and ignited. Greater surface area correlates with a faster reaction, and more vigorous explosion (Blair, 2003). Figure 2.2 shows sequence of burning when surface area is increasing.



**Figure 2.2** Sequence of Burning based on Surface Area

Based on figure above shows that a large piece of wood burs slowly and release heat over a long period of time. When the wood is cut into smaller pieces, the ignition is easier and the pieces of wood burn faster because the total contact area between the wood and air are high. As the wood is further cut into smaller pieces, ground into sawdust, suspended in air as a confined dust cloud, and ignited, the dust burns very rapidly and may explode.

There so many common dust involved in dust explosion has a particle size of 10 to 50 microns in diameter, similar to baby powder. The table 2 shows the list of the particle sizes for some commonly known materials.

**Table 2.2** Particle Size of Common Materials (Blair, 2003)

| <b>Common Materials</b>                               | <b>Size (micron, <math>\mu</math>)</b> |
|---|--|
| Baby powder, fine silt, red blood cells,<br>cocoa     | 5 to 10                                |
| Pollen, milled flour, course silt, fine<br>human hair | 44 to 74                               |
| Table salt, coarse human hair                         | 105 to 149                             |
| Coarse sand   | 297 to 1000                            |

Particle size influences dust explosion severity and sensitivity to ignition. Most combustible dusts ignite at lower energy and produce a greater rate of pressure rise at smaller particle sizes. Generally, the maximum explosion pressure and rate of pressure rise for any given type of dust will increase as the particle size decreases, and the minimum energy required to ignite a dust cloud decreases with particle size.

Another property of dust explosion is their dust chemistry and moisture. According to Eckhoff (2003) stated that the chemical composition of a material determines properties such as the rate of reaction and the amount of heat released in the reaction and governs the rate at which materials combust. Some dust particles such as polyethylene must be melted and evaporated to vapor form before they burn. This evaporation process can also affect the burning rate. The faster the particle combustion rate, the faster the flame front will move across a dust cloud and yield the greater pressure. Therefore, the sensitivity to ignition, the flame speed, and the

explosion severity are all affected by the composition of the material (Eckhoff, 2003).

The amount of oxygen available to the dust in the dispersed cloud also affects the combustion rate. Therefore, substituting an inert gas such as nitrogen for some of the air in dust-containing equipment can reduce the risk and severity of a dust explosion. Inerting is only practical within process equipment and storage vessels (Blair, 2003).

Moisture content, by acting as a heat sink to slow evaporation and combustion, also has a measurable effect on dust burning rate and explosion severity. Moisture in the atmosphere also reduces the amount of static electricity available for ignition, and makes the dust more difficult to ignite (Eckhoff, 2003)



### **2.2.2.2 Gas Explosion**

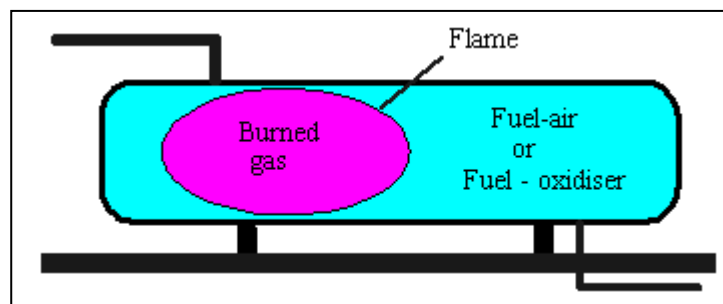
Gas explosion is a process where combustion of a premixed gas cloud such as fuel with air or fuel with oxidiser which causing rapid increase of pressure (Bjerketvedt et. al., 1997). Gas explosions can occur inside process equipment or pipes, in buildings or off-shore modules, in open process areas or in unconfined areas.

The consequences of a gas explosion will depend on the environment in which the gas cloud is contained or which the gas cloud engulfs. Therefore it has been common to classify a gas explosion from the environment where the explosion takes place whether confined area likes vessels, pipes, channels or tunnels. Second place is in partly confined area such are compartment, building or off-shore modules while unconfined area likes process plant and other unconfined areas. It should be pointed out that these terms are not strictly defined. In an accidental event sometimes it's hard to classify the place of the explosion. As an example an unconfined explosion in a process plant may also involve partly confined explosions in compartments into which the gas cloud has leaked (Bjerketvedt et. al., 1997).

### 2.2.2.2.1 Confined Gas Explosion

Confined gas explosions are explosions within tanks, process equipment, pipes, in culverts, sewage systems, and closed rooms and in underground installations. Confined explosions are also called internal explosions. The most two common confined explosion scenarios involve explosive vapors and explosive dusts.

An explosion in a confined space causes the accumulation of high-temperature gases from the by-products of the explosion. These high-temperature gases, if expanding in a space with restricted venting, because the buildup of gas pressures inside the structure (Keenan et. al., 1992)



**Figure 2.3** Confined Explosions with Tank (Bjerketvedt et. al., 1997).

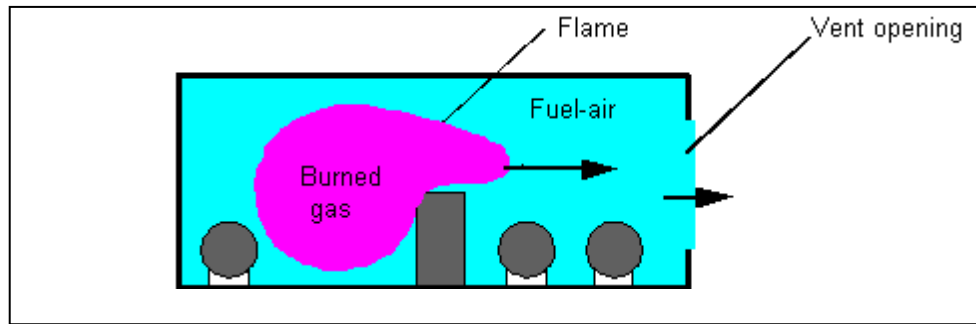
A closed vessel often has very small openings, such as connected pipes, rupture disks or relief valves through which pressure can be relieved during a gas explosion. In this case, the relief process is often too slow to relieve the pressure fast enough, and the vessel may behave like a fully closed vessel with regard to pressure build-up. The pressure build-up will mainly depend on type and concentration of

fuel, the initial pressure, the filling ratio in the vessel, the burning rate, the venting and the oxidiser.

#### **2.2.2.2.2 Partly Gas Explosion**

Partly confined explosions occur when a fuel is accidentally released inside a building which is partly open (Bjerketvedt et. al., 1997). Typical cases are compressor rooms and offshore modules. The building will confine the explosion and the explosion pressure can only be relieved through the explosion vent areas like open areas in the walls or light relief walls that open quickly at low overpressure.

If fuel is accidentally released inside a partly confined area or if combustible gas is traveling into such an area, serious explosions may occur. The consequences of such explosions will depend on several parameters, such as type of fuel, size and concentration of the gas cloud, ignition and geometrical layout such as confinement and obstructing objects. In consequence analyses all these factors have to be taken into account. Variations of these parameters may result in large changes in peak explosion pressure. Below shows the figure of gas explosion in a partly confined area containing process equipment.

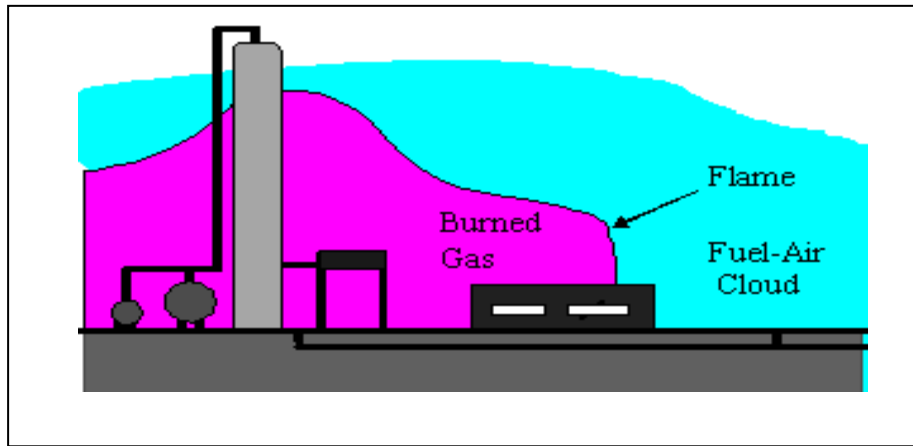


**Figure 2.4** Gas Explosions In A Partly Confined Area Containing Process Equipment.

In a partly confined area with obstacles as shown in Figure 4, the flame may accelerate to several hundred meters per second. The main mechanism of flame acceleration under such conditions is turbulent mixing due to generation of turbulent flow fields ahead of the flame (Bjerketvedt et. al., 1997).

#### **2.2.2.2.3 Unconfined Gas Explosion**

The term unconfined was used to describe explosions in open areas such as process plants. Usually results from spill of a flammable gas spill. These explosions are rarer than confined since dilution occurs. Large scale tests have demonstrated that a truly unconfined, unobstructed gas cloud ignited by a weak ignition source will only produce small overpressures while burning. The term unconfined gas explosions should therefore be used with care. In a process plant there are local areas which are partly confined and obstructed. In case of a deflagration it is these areas that are causing high explosion pressures.



**Figure 2.5** Gas Explosions in a Process Area.

However if an unconfined cloud detonates the explosion pressure will be very high, in the order of 20 barg and in principle independent of confinement and obstructions.

### **2.2.3 Effects of Explosion**

An explosion is a gas dynamic phenomenon there are a variety of effects of the spherically expanding heat and pressure wave. These effects assist the investigator in understanding the dynamics of the explosion and the sequence of events that took place during the explosion.

### **2.2.3.1 Blast Pressure Front Effect**

The initiation of chemical explosives and fuel gases result in the generation of quantities of gases. These gases expand at a high speed and move outward equally in all directions until an obstruction is encountered. They are two types of blast pressure front effect which are positive pressure phase and negative pressure phase.

For positive pressure phase can be divide into two categories which are spherical shape of the pressure wave and rate of pressure rise vs. maximum pressure. For the spherical shape of the pressure wave, generally under ideal conditions the shape of the blast front from an explosion is spherical in nature, moving outward from the origin equally in all directions. However, obstructions or vents will change the configuration of the blast front. The damage caused as a result of the blast pressure front of an explosion is a result of two items. The maximum pressure and the rate of pressure rise. If the rate of pressure rise is rapid, then the containing vessel will not have sufficient time to resist the forces.

For negative pressure phase is a result of the movement outward from the origin of the positive pressure phase, a low pressure area is created. This low pressure area allows the movement back towards the origin of the surrounding air. The negative pressure phase causes additional or secondary damage, and it is common to find the debris moving towards the point of origin or in opposite directions from the positive pressure phase.

### **2.2.3.2 Fragmentation (Shrapnel) Effect**

Containers, structures, or vessels that contain or restrict the movement of the positive pressure fronts may rupture and produce pieces of debris that may travel long distances and cause considerable damage or injury. The distance that they may travel depends on a variety of factors, including the types of fuels involved, the strength of the container, type of initiation, and venting that may be present. Fragmentation is a debris from the container, for example the structure while Shrapnel is a debris that was placed in the area of a device, in order to inflict harm to those in the area.

### **2.2.3.3 Thermal (Incendiary) Effect**

Combustion explosions release quantities of energy that may heat light solid combustibles or gases present to their ignition temperature. Often diffuse fuels (vapors or gases) or high surface to mass solids (example flexible urethane foam cushions or vehicle interiors) are more likely to be ignited as a result of the thermal effects of an explosion. Dense solid fuels are not as likely to be ignited due to the duration of the heating that takes place.

#### **2.2.4 Deflagration**

In a deflagration, the combustion or reaction wave propagates at a velocity less than the speed of sound. Although all combustion (fires) can be defined as a deflagration, the ignition of a fuel-oxidizer mixture or a suspended cloud of combustible dust in a confined environment typically causes a significant and rapid increase in pressure that can cause catastrophic damage. These explosions are typically associated with natural gas or propane releases (gas explosion), gasoline and hydrocarbon vapors (vapor explosion), finely divided fuels (dust explosion), and certain reactive chemicals. These events can occur immediately before, or immediately after a fire and can propagate throughout a facility. Therefore, an engineering investigation of the event typically includes the preceding and subsequent events (Bjerketvedt et. al., 1997).

#### **2.2.5 Explosion Parameter**

Explosions, whether or not followed by fires are destructive phenomena, with major social and economic implications, especially given the current technologies. Therefore, the risk assessment associated with each explosion is the duty of every employer to ensure the safety and health by implementing risk management requirements prescribed by regulations. To assess the risk of explosion and explosion expertise of such events, it is necessary to know the parameters of explosion



characteristics of air mixtures with flammable substances. Development of methods for determining the explosion characteristic parameters of air with combustible substances mixtures increase the capacity of expertise in explosions, the extension of knowledge about the explosion phenomenon and increase the occupational health and safety by using experimental data obtained in developing the explosion proof protection measures (Prodan et. al., 2012).

#### **2.2.5.1 Maximum Explosion Pressure ( $P_{max}$ )**

National Fire Protection Association (NFPA) 69 has defined maximum explosion pressure as maximum pressure developed in a contained deflagration for optimum mixtures (NFPA, 2008). Another standards organization has defined maximum explosion pressure as the maximum pressure reached during the course of deflagration for the optimum concentration of the dust tested. Maximum pressure is determined by a series of test over a large range of concentration (American Society for Testing and Material, 2008). From this definitions maximum explosion pressure is the highest value of pressure which can be reached in closed vessel of one cubic meter after ignition of dust-air mixture of optimal concentration by strong ignition source. The most common values of maximum explosion pressure are 3 to 10 bar, some dust can reach up to 12 bar (VST Engineering, 2012).

The explosion pressure depends also on the shape and volume of the vessel where the explosion occurred and on the concentration of the dust and some other

parameters. The highest value of maximum explosion pressure reaches when the explosion is ignited in optimal concentration. Maximum explosion pressure has strong influence on the construction parameters of devices because if the machine is constructed to be explosion pressure resistant like coal mills in power plant, usually it is not necessary to protect them against explosion (VST Engineering, 2012).

#### **2.2.5.2 Maximum Rate of Pressure Rise $(dP/dt)_{max}$**

According to Prodan et al maximum rate of pressure is a maximum slope of the curve pressure / time during a flammable mixture explosion in a closed vessel (Prodan et. al., 2012). Based on their research explosion parameters plays an important role in the primary phase of explosion risk assessment and consistency assessment stage equipment and also in protective systems planned for use in potentially explosive atmospheres.

Based on American Society for Testing and Material (ASTM) has defined maximum rate of pressure rise as maximum value for the rate of pressure increase per unit time reached during the course of a deflagration time for the optimum concentration of dust tested. It is determined by a series of a test over a wide range of concentration (ASTM, 2008).

### 2.2.5.3 Deflagration Index, $K_G$

The deflagration index is a constant direct proportionality which defines the maximum rate of pressure rise with time of a deflagration in a volume according to the equation :

$$K = \left(\frac{dp}{dt}\right)_{max} \times \sqrt[3]{V}$$

In general,  $K_G$  cannot always be considered a finite property of the explosion mixture as its value depends on the volume and geometry of the test vessel, and on the presence or absence of turbulence. Explosion venting is known to be greatly affecting the reactivity of a mixture particularly for gaseous fuels (Factory Mutual System, 1999).

### 2.2.6 Explosion Prevention and Mitigation

The dust explosion pentagon is the basis for preventing and mitigating (reducing the consequences of) dust explosions. Eliminating the fuel, the ignition source or oxygen for combustion will prevent an explosion. The focus of the NFPA standards is on reducing the likelihood of an explosion by controlling fuel, oxygen and/or ignition source.

When it is not possible prevent dust explosions, it is still possible to limit the amount of damage and injury they cause. The other two sides of the pentagon, confinement and dispersion, provide keys to mitigating the hazard. Dust explosion prevention and mitigation are discussed below.

#### **2.2.6.1 Methods of Explosion Prevention**

The practical focus of dust explosion prevention is to control or minimize the three legs of the explosion pentagon that came from the fire triangle: fuel, oxygen and ignition.

##### **2.2.6.1.1 Fuel**

One of the requirements for a dust explosion is an accumulation of combustible dust. If the fuel is contained within a piece of process equipment or a dust collector, a primary explosion can result. If the dust accumulation is on floors, beams, ceiling tiles or other areas outside of equipment, secondary explosions can occur. As previously discussed primary explosions are often followed by secondary explosions of accumulated dust.

Housekeeping and maintenance play a critical role in minimizing uncontrolled dust accumulations. It is essential to maintain pipes, ducts and equipment to keep dust from escaping into the work environment. Housekeeping includes cleaning dust filters to reduce the amount of fuel accumulated in the dust

collector, and to keep the dust collector working at peak performance. Diligent, regular housekeeping to remove dust accumulations safely,<sup>13</sup> is vital to prevent secondary explosions. Another way to control fuel is to mix an inert material, like rock dust, into the dust. This can prevent an explosible concentration inside dust collection equipment. Coal mining uses a similar method to prevent coal dust explosions.

#### **2.2.6.1.2 Oxygen**

Most dust-carrying or dust-producing operations occur in an air environment. There is more than enough oxygen in the workspace to feed a dust explosion. Contained equipment can sometimes be inerted with nitrogen or other gases, however, to eliminate the oxygen from the dusty space.

Inerting is difficult, however, and is not often the primary means of protection employed. According to Ebadat, inerting is only practical in a closed-loop system. Where several noninerted systems (such as conveyors, hoppers and dryers) are inter-connected, inerting is infeasible (Ebadat , 2003).

#### **2.2.6.1.3 Ignition**

Eliminating all sources of ignition is nearly impossible; therefore, the goal is to control them. Process safety expert Trevor Kletz stated “Possible sources of ignition are so numerous that we can never be certain that we have eliminated them completely, even though we try to remove all known sources” ( Kletz, 1994).

The following is a partial list of possible ignition sources for dust explosions<sup>16</sup>. NFPA 654 provides guidance on controlling ignition (NFPA, 2005). The means for controlling them is unique to each type of ignition source.

- Static charge caused by moving particles
- Electrical system faults
- Open flames or sparks (including furnaces, hot work, smoking materials)
- Hot surfaces
- Improperly sealed electrical components

#### **2.2.6.2 Methods of Explosion Mitigation**

Three methods of protection can be determined as isolation, venting and suppression. For isolation method of protection we need to stop the propagation of flame and pressure by stop the spreading of an explosion through ductwork, etc to other areas or process equipment. Venting is the most effective method of protecting structures from explosion severity. It provides overpressure protection from potential industrial explosion hazards by providing a planned pathway for the expanding gases to escape.

##### **2.2.6.2.1 Venting**

Dust explosion vents are analogous to safety valves on reactors. These vents are usually a weak panel designed to rupture if pressure builds inside the protected equipment. This allows the pressure to vent in a more desired direction, rather than exploding the equipment. In some situations, the vented gases are ducted

to a location away from employees, but this creates additional complications. Buildings can be constructed so that if an explosion does occur, the force is directed outside rather than inside where there are employees.

Venting devices are common practice in industry to lessen the potential damage caused by internal gas and dust explosions. Venting is an attractive prospect as it is both economical and practical.

#### **2.2.6.2.2 Suppression**

Engineered systems to suppress an explosion in process are used successfully in some applications. These include a pressure or temperature sensor to detect the earliest stage of the dust explosion, and some form of chemical suppression or inerting to cool or extinguish the moving flame front (Goings, 2002).

Suppression system works in two ways which are chemically by interfering with the explosion's reaction and thermally by removing heat from the deflagration's flame front and thereby lowering its temperature below that needed to support combustion. The important of explosion protection are to protect the equipment, reduce the loss of property and prevent casualties and lastly to the incipient fire before a deflagration ignition occurs so that an explosion can be prevented from developing. Suppression is designed to detect and chemically suppress an explosion in its earliest stages-before an explosion can cause a disaster or become catastrophic.

## **2.3 Hydrogen**

### **2.3.1 Introduction**

Hydrogen has been important feedstock and a fuel in various industrial fields for many years, and is expected to be more diversely and widely utilized as an energy carrier in its three form; compressed gas, cryogenic liquid and metal hydride, in commercial and residential areas. However, hydrogen is one of the most flammable and explosive substance and make some metals brittle. Small and large accidents related to hydrogen have actually occurred due to improper handling or control, although the cause of Hidenburgh tragedy, which was regarded as a representative disaster cause by hydrogen, has been shown no to be related to hydrogen. Adequate handling and safety measure of hydrogen are obviously important for both current and emerging uses of hydrogen as a feedstock and fuel.

### **2.3.2 Properties of Hydrogen**

Hydrogen is by far the most plentiful element in the universe, making up 75% of the mass of all visible matter in stars and galaxies. Hydrogen is the simplest of all elements. You can visualize a hydrogen atom as a dense central nucleus with a single orbiting electron, much like a single planet in orbit around the sun. Scientists prefer to describe the electron as occupying a “probability cloud” that surrounds the nucleus somewhat like a fuzzy, spherical shell (Desert, 2001). Hydrogen is found in the atmosphere at trace levels. It is synthesized from hydrocarbons and from water where



it constitutes the lightest fraction of the H<sub>2</sub>O molecule. Hydrogen gas cannot sustain life.

Hydrogen is a colorless, odorless, tasteless, flammable nontoxic gas. It is the lightest of all gases, with a specific gravity of 0.0695. The hydrogen content of atmospheric air at sea level is 0.5 ppm. Hydrogen has two isomers forms: ortho-hydrogen, in which the two atomic nuclei spin in the same direction; and para-hydrogen, in which they spin in opposite directions. There is no difference in the chemical properties of the two forms of hydrogen, but there are slight differences in physical properties. Gaseous hydrogen is a mixture of 75% ortho-hydrogen and 25% para-hydrogen at room temperature; this mixture is called normal hydrogen (CGA G5, 1991). The following Table 2.3 illustrates the properties of hydrogen.

**Table 2.3** Physical Properties and Characteristic of Hydrogen (Robbins, 2000)

| Physical Properties and Characteristic of Hydrogen |   |
|--|---|
| Property/Characteristic                            | Values (approximate)                            |
| Color  | None  |
| Odor   | None  |
| Toxicity   | Nontoxic  |
| Density, liquid (boiling point)                    | 4.4 lb/ft <sup>3</sup> (0.07g/cm <sup>3</sup> ) |
| Boiling point (1atm)                               | -423.2 F (-252.9°C)                             |
| Critical temperature (188.2 psia)                  | -400.4 F (-240.2°C)                             |
| Stoichiometric mixture in air                      | 29 vol %  |
| Flammability limits in air                         | 4-75 vol %                                      |
| Detonation limits in air                           | 18-60 vol %                                     |
| Minimum ignition energy in air                     | 20μJ  |
| Autoignition temperature                           | 1,085°F (585°C)                                 |
| Volume expansion                                   |   |
| Liquid (-252.9°C) to gas (-252.9°C)                | 1:53  |
| Gas (from -252.9°C to 20°C)                        | 1:16  |
| Liquid (-252.9°C) to gas ( 20°C)                   | 1:848   |

### **2.3.2.1 Unique Properties**

Several unique properties contribute to the hazards associated with gaseous and liquid hydrogen systems:

1. Hydrogen is flammable over a wide range of concentrations.
2. The ignition energy for hydrogen is very low.
3. A single volume of liquid hydrogen expands to about 850 volumes of gas at standard temperature and pressure when vaporized. At 7,000 ft elevation, this expansion rate is increased to approximately 1,000 volumes of gas at standard temperature.
4. Hydrogen is able to reduce the performance of some containment and piping materials, such as carbon steel.

### **2.3.2.2 Flammability Range**

The flammability range of a gas is defined in terms of its lower flammability limit (LFL) and its upper flammability limit (UFL). The LFL of a gas is the lowest gas concentration that will support a self-propagating flame when mixed with air and ignited. Below the LFL, there is not enough fuel present to support combustion; the fuel/air mixture is too lean.

The UFL of a gas is the highest gas concentration that will support a self-propagating flame when mixed with air and ignited. Above the UFL, there is not enough oxygen present to support combustion; the fuel/air mixture is too rich.

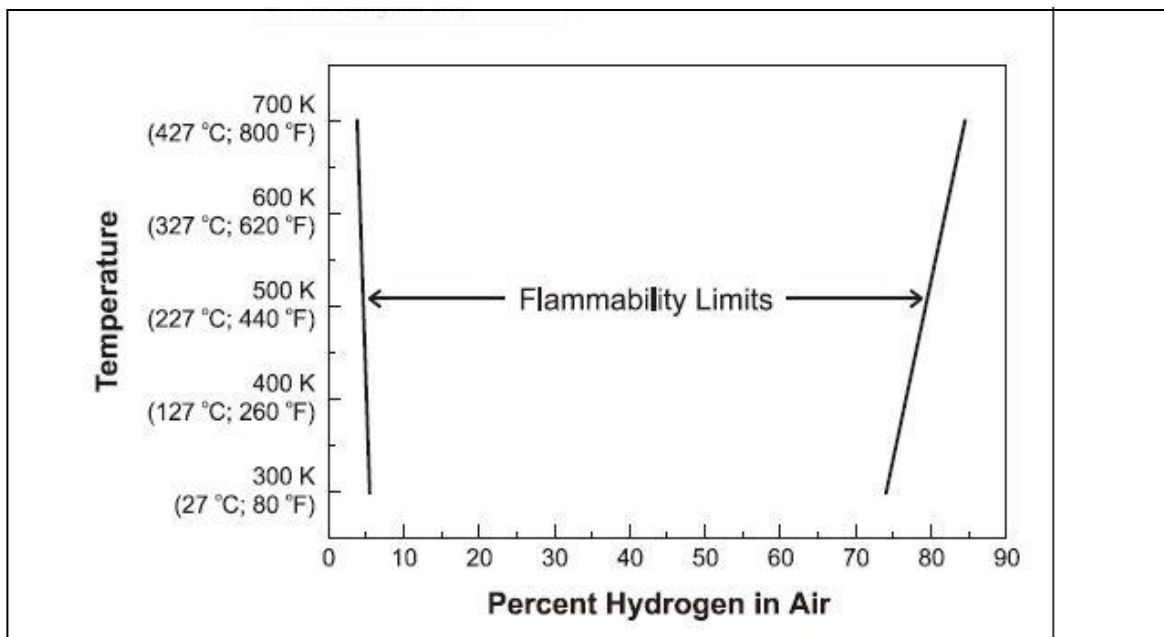
Between the two limits is the flammable range in which the gas and air are in the right proportions to burn when ignited.

A stoichiometric mixture occurs when oxygen and hydrogen molecules are present in the exact ratio needed to complete the combustion reaction. If more hydrogen is available than oxygen, the mixture is rich so that some of the fuel will remain unreacted although all of the oxygen will be consumed. If less hydrogen is available than oxygen, the mixture is lean so that all the fuel will be consumed but some oxygen will remain. Practical internal combustion and fuel cell systems typically operate lean since this situation promotes the complete reaction of all available fuel.

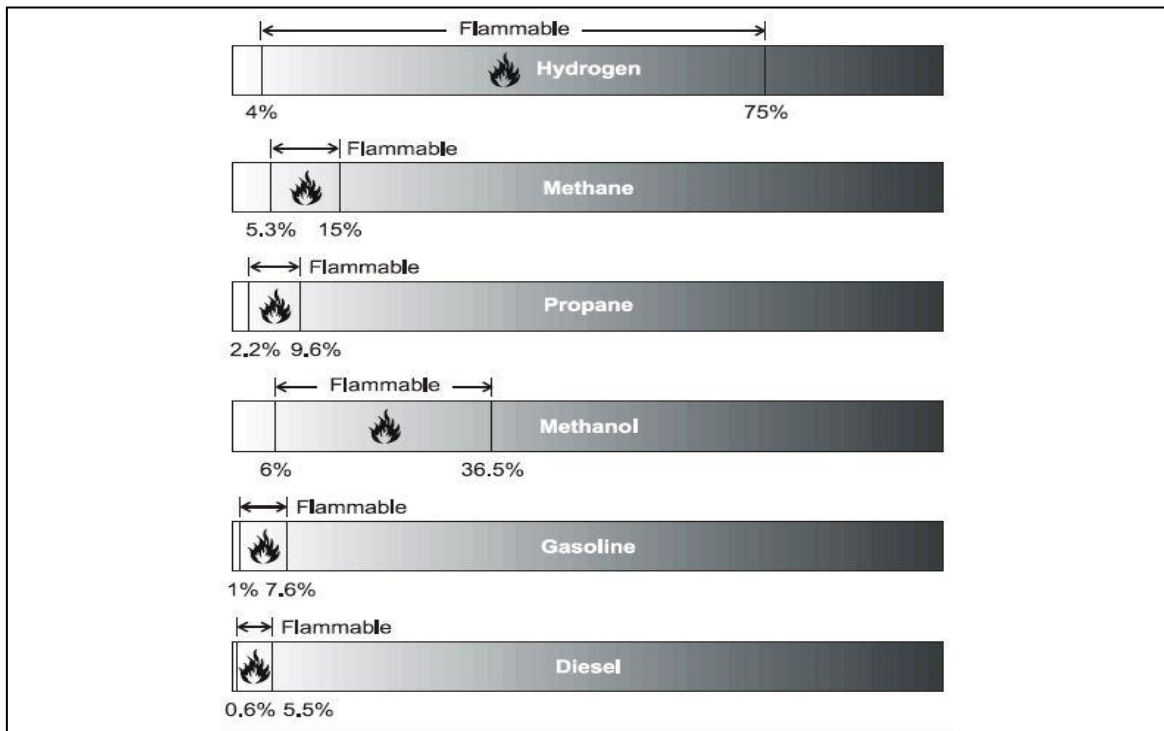
Two related concepts are the lower explosive limit (LEL) and the upper explosive limit (UEL). These terms are often used interchangeably with LFL and UFL, although they are not the same. The LEL is the lowest gas concentration that will support an explosion when mixed with air, contained and ignited. Similarly, the UEL is the highest gas concentration that will support an explosion when mixed with air, contained and ignited. An explosion is different from a fire in that for an explosion; the combustion must be contained, allowing the pressure and temperature to rise into sufficient levels to violently destroy the containment. For this reason, it is far more dangerous to release hydrogen into an enclosed area such as a building than to release it directly outdoors (Hydrogen Properties, 2001).

Hydrogen is flammable over a very wide range of concentrations in air (4 – 75%) and it is explosive over a wide range of concentrations (15 – 59%) at standard

atmospheric temperature. The flammability limits increase with temperature as illustrated in Figure 2.3.1. As a result, even small leaks of hydrogen have the potential to burn or explode. Leaked hydrogen can concentrate in an enclosed environment, thereby increasing the risk of combustion and explosion. The flammability limits of comparative fuels are illustrated in Figure 2.3.2 (Hydrogen Properties, 2001).



**Figure 2.6** Flammability Limits of Hydrogen with Temperature



**Figure 2.7** Flammability Limits of Comparative Fuels

### 2.3.2.3 Ignition Sources

The autoignition temperature is the minimum temperature required to initiate self-sustained combustion in a combustible fuel mixture in the absence of a source of ignition. In other words, the fuel is heated until it bursts into flame. Each fuel has a unique ignition temperature. For hydrogen, the autoignition temperature is relatively high at 1085 °F (585 °C). This makes it difficult to ignite a hydrogen/air mixture on the basis of heat alone without some additional ignition source (Hydrogen Properties, 2001).

Ignition energy is the amount of external energy that must be applied in order to ignite a combustible fuel mixture. Energy from an external source must be higher than the autoignition temperature and have enough time to heat the fuel vapor to its ignition temperature. Common ignition sources are flames and sparks. Although hydrogen has a higher autoignition temperature than methane, propane or gasoline, its ignition energy at  $1.9 \times 10^{-8}$  Btu (0.02 mJ) is about an order of magnitude lower and is therefore more easily ignitable. Even an invisible spark or static electricity discharge from a human body (in dry conditions) may have enough energy to cause ignition. Nonetheless, it is important to realize that the ignition energy for all of these fuels is very low so that conditions that will ignite one fuel will generally ignite any of the others (Hydrogen Properties, 2001).

There are many types of ignition sources which are hot surface, flames and hot gases, mechanically generated sparks, electrical apparatus, stray electrical currents, static electricity and lightning. There are three types of prevention and protection option for explosion which are primary explosion protection. This means that we need to prevent any hazardous explosive atmosphere. For secondary explosion protection, it's important to avoid any ignition sources from hazardous material and places and lastly tertiary explosion protection is reducing the effect of explosion.

#### **2.3.2.4 Embrittlement**

Constant exposure to hydrogen causes a phenomenon known as hydrogen embrittlement in many materials. Hydrogen embrittlement can lead to leakage or catastrophic failures in metal and non-metallic components.

Because of its small molecular size, hydrogen can easily pass through porous materials and is capable of being absorbed by some containment materials, which can result in loss of ductility or embrittlement. At elevated temperatures, this process is accelerated. Because of the possibility of hydrogen embrittlement of some materials, piping and component materials that are not subject to this form of degradation should be selected. Recommended materials include 300-series stainless steels, copper, and brass.

The mechanisms that cause hydrogen embrittlement effects are not well defined. Factors known to influence the rate and severity of hydrogen embrittlement include hydrogen concentration, hydrogen pressure, temperature, hydrogen purity, type of impurity, stress level, stress rate, metal composition, metal tensile strength, grain size, microstructure and heat treatment history. Moisture content in the hydrogen gas may lead to metal embrittlement through the acceleration of the formation of fatigue cracks (Hydrogen Properties, 2001).



### **2.3.3 Hazards of Hydrogen**

#### **2.3.3.1 Flammability and Explosivity**

The primary physical hazards associated with hydrogen gas are its flammability and explosivity. This is because hydrogen can form a flammable mixture with air over a wide range of concentrations from 4% until 75%, and very low energy is needed to ignite hydrogen-air mixtures. Once hydrogen is ignited, the reaction can proceed either by deflagration (subsonic propagation) or detonation (supersonic propagation). Deflagration in a closed volume can cause a pressure increase of almost eight times the initial pressure. Detonation from a low-energy ignition source is possible in hydrogen-air mixtures of 18% until 60% volume that are well mixed and confined. Although hydrogen air mixtures have the same calorific value per pound as TNT, the rate of energy release is much slower for hydrogen-air mixtures. Hydrogen detonations, although rare, are characterized by pressure increases so rapid that pressure relief devices are usually ineffective (Robbins, 2000).

#### **2.3.3.2 Fire Hazards and Related Damage**

A fire hazards means an existing or potential condition or situation that may result in a fire. Most fire hazards in handling of hydrogen result from formation of flammable mixture with air through its accidental or inadvertent leakage that is attribute to mishandling or mechanical failures of equipment, construction materials, erosion, physical abuse, improper maintenance or collision.

When leaked hydrogen ignites in an open space, it usually deflagrates with a flame propagating as an expansion wave at a relatively fast velocity below the speed of sound, or it can burn as an open flame or fireball near its leaking site. In the case of totally or partially confined spaces, the flammable mixture deflagrates mostly by ignition. Under more explosive conditions, the deflagration can transform to a detonation, in which combustion waves coupled with shock waves propagate at supersonic speeds (Itsuki, 2001).

It is obvious that these deflagrations and detonations also cause fires. Explosive hazards and damage based on deflagration and detonation phenomena are described in later subsections.

### **2.3.3.3 Effect on Health**

Hydrogen is nontoxic and has even been used as filler for oxygen sources for underwater diving. The primary health effect associated with hydrogen is the possibility that it could displace air in a poorly ventilated or confined space, resulting in asphyxiation. However, because it is flammable at only 4% in air, the most significant concern should be the physical hazard of flammability and the possibility of burns resulting from fires and explosions. When working with liquid hydrogen, there is an additional health hazard of cryogenic burns (Itsuki, 2001).

Although hydrogen is non-toxic hydrogen still can act as a simple asphyxiant by displacing the oxygen in the air. Oxygen levels below 19.5% are biologically inactive for humans. Effects of oxygen deficiency may include rapid breathing, diminished mental alertness, impaired muscular coordination, and faulty judgment, depression of all sensations, emotional instability and fatigue. As asphyxiation progresses, dizziness, nausea, vomiting, prostration and loss of consciousness may result, eventually leading to convulsions, coma and death. At concentrations below 12%, immediate unconsciousness may occur with no prior warning symptoms.

In an enclosed area, small leaks pose little danger of asphyxiation whereas large leaks can be a serious problem since the hydrogen diffuses quickly to fill the volume. The potential for asphyxiation in unconfined areas is almost negligible due to the high buoyancy and diffusivity of hydrogen (Hydrogen properties, 2001).

### **2.3.4 Safety Measure in Handling Hydroge**

#### **2.3.4.1 Pressure Relieve Devices**

In any pressurized system, each component of the system must have a pressure rating that equals or exceeds the maximum allowable working pressure (MAWP). The MAWP is the maximum pressure at which a system is safe to operate. This is the maximum setting for the primary pressure relief device.

Hydrogen cylinders must be equipped with pressure-relief devices to release the gas at or below the MAWP. The relieving capacity of the pressure relief device must be sufficient to prevent the system pressure from increasing more than 10% above the MAWP. The type of pressure relief device used consists of a frangible disk combined with a backing of low melting point fusible metal designed to burst under a combination of high temperature and excessive pressure.

Pressure-relief devices are also necessary on all volumes where liquid hydrogen or cold hydrogen gas can be trapped, and on vacuum insulation spaces surrounding liquid hydrogen. It is important that the discharge of pressure-relief devices is vented outdoors in a way that avoids impingement of escaping gas on adjacent equipment, structures, or personnel. Vents shall not discharge where hydrogen can accumulate, such as below eaves of buildings.

#### **2.3.4.2 Valves**

To allow for maintenance activities and emergency response, isolation valves are required. An isolation valve shall be installed at an accessible location in a hydrogen pipeline so that hydrogen flow can be shut off when necessary.

A special type of isolation valve is the emergency isolation valve (EIV), which provides an automatic or manual means for stopping the hydrogen flow in an

emergency. EIVs are used on systems where branch or multiple distribution lines feed different facilities, and are located outside each building to permit emergency isolation of the system.

In some systems, excess flow valves may be necessary to ensure that the flow rate of the hydrogen gas does not exceed specifications. Check valves prevent reverse flow, which could result in contamination of the hydrogen gas system. All of the valves described in this section must be gas tight and made of materials suitable for use with hydrogen.

#### **2.3.4.3 Electrical Equipment**

Because of the extremely low energy required to ignite flammable mixtures of hydrogen gas, exercise caution must be done when using hydrogen around electrical equipment. All flexible hoses and piping systems must be electrically grounded. The National Fire Protection Association has established standards for the specifications of electrical equipment intended to be used around hydrogen gas. The Occupational Safety and Health Administration have also established specifications for electrical equipment used around indoor hydrogen gas systems with a gas volume capacity greater than 400 cubic feet. Contact your area safety engineer for assistance in ensuring that these standards are followed.

#### 2.3.4.4 Hydrogen in Gas Cylinder

The following are some safe-handling guidelines that have been established by the Compressed Gas Association for using hydrogen gas cylinders. By following these guidelines you can help assure the safety of your hydrogen gas operations:

1. It is very important to secure all compressed gas cylinders in an upright position so that they cannot be knocked over.
2. Hydrogen gas cylinders should never be used if pressure has not been reduced by a suitable regulator at the cylinder, or at the outlet of the header valve of a cylinder manifold. Use only regulators intended to be used with hydrogen and never force connections that do not readily fit together.
3. Never crack a hydrogen cylinder valve to remove dust or dirt from fittings prior to attaching a regulator. While this practice may be acceptable for other gases, with hydrogen there is a risk of self-ignition.
4. Once the regulator is attached, be sure that the regulator adjusting screw is in the closed position before opening the cylinder valve. When opening the valve, turn the hand wheel slowly so that the hydrogen does not enter the regulator suddenly. Never use a wrench, hammer, or other tool to open or close the hand wheel.
5. When opening the cylinder valve to extract content, turn the hand wheel all the way open and then back toward the closed position one quarter turn. When the work is finished, turn the cylinder valve off and be sure to bleed off all remaining hydrogen from the regulator before removing it from the cylinder.

### 2.3.5 Hydrogen Fueled Cell

Explosions in hydrogen-air gaseous mixtures in close area are a well recognized hazard, due to the high pressure and high rate of pressure rise reached quickly after ignition by local sources with various energies. Such processes may damage a vessel without a proper venting or explosion-suppressing device. The cause is the fast delivery of the combustion heat that cannot be compensated by the slow heat dissipation through conduction, convection or radiation, before contact of the flame front with the walls (Molkove et. al., 1999). Knowledge of pressure-time variation during explosion of hydrogen air mixture in enclosures is a very important component of safety recommendations for a wide range of human activities; connect to the production, storage or uses of hydrogen. Understanding of hydrogen air combustion in closed and vented vessel is necessary for modeling of unwanted deflagrations at containment building when nuclear reactor accidents scenarios are considered. It should be important also in the near future for hydrogen fueled vehicles industry aim to decide zero emission problems (Razus, et. al., 2006).

Clean combustion has become an important aspect in the last few decades. In addition, combustion of hydrocarbon fuel always generates undesired products that can be categorized as pollutants. Some examples of pollutant species are soot, carbon monoxide (CO), sulphur and nitrogen oxides (SO<sub>x</sub> and NO<sub>x</sub>) which are highly toxic and can cause acid rain. However combustion of hydrogen-oxygen generates less pollutant without CO<sub>2</sub> emission. The world's climate nowadays is in dangerous situation and something should be done to reduce the emission of CO<sub>2</sub> (Liu, 2006). Hydrogen is an attractive alternative fuel. However, unlike coal, gas or oil, hydrogen

is not a primary energy source. Rather, its role mirrors more closely that of electricity as a secondary ‘energy carrier’, which must be produced using energy from another source and then transported for future use where its latent chemical energy can be fully realized. Hydrogen can be obtained from diverse resources, both renewable (hydro, wind, wave, solar, biomass and geothermal) and non-renewable (coal, natural gas and nuclear). It can be stored as a fuel and used in transportation and distributed heat and power generation systems using fuel cells, internal combustion engines or turbines, with the only by-product at the point of use being water. The ability of hydrogen to replace fossil fuels in the transportation sector could address one of the world’s major environmental problems (Edwards et. al., 2007).

Fuel cells are considered to be the green power sources for the 21st century, and may make the “hydrogen economy” a reality. The main driving force for fuel cell research, development, and commercialization is the increasing concern about global pollution caused by energy emissions, especially from transportation and stationary applications. The biggest advantage of proton exchange membrane fuel cells (PEMFCs) over internal combustion engines in automotive vehicles is the fact that PEMFCs produce zero emissions when using hydrogen as the fuel and air as the oxidant (Cheng et. al., 2007). Fuel cells directly convert the chemical energy in hydrogen to electricity, with pure water and potentially useful heat as the only byproducts. Hydrogen-powered fuel cells are not only pollution-free, but also can have more than two times the efficiency of traditional combustion technologies (Fuel Cell Technologies Program, 2010).



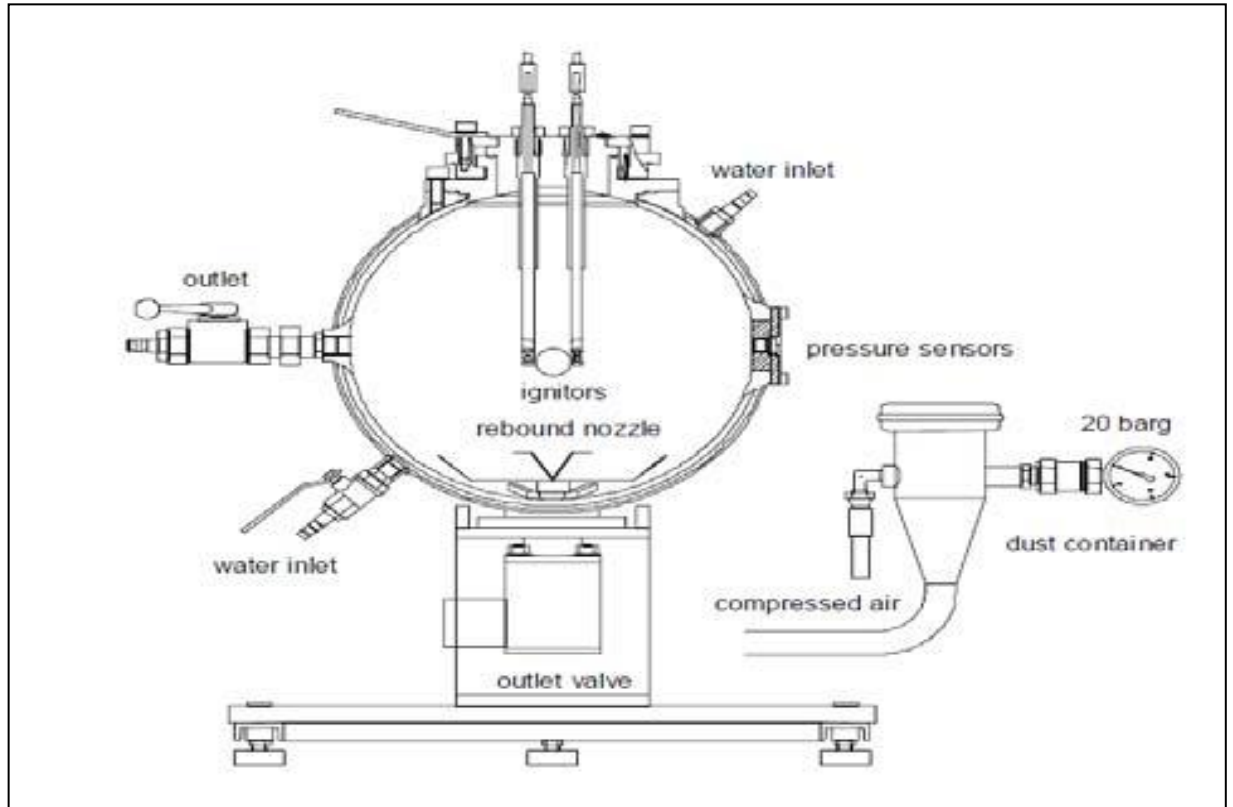
## **CHAPTER III**

### **METHODOLOGY**

#### **3.1 Introduction**

A test chamber is a 20 liter hollow sphere made of stainless steel. The ignition source is located at the centre of the sphere. On the measuring flange, two "Kistler" piezoelectric pressure sensors are installed. The top of the cover contains holes for the lead wires to the ignition system. The opening provided for ignition which is controlled by the KSEP 320 units of 20 liter spherical vessel. A comprehensive software package KSEP 6.0 is used to allow a safe operation of the test equipment and an optimum evaluation of the explosion test results. The KSEP 332 unit uses piezoelectric pressure sensor to measure the pressure as a function of time and controls the valves as well as the ignition system of the 20 liter spherical vessel. The measured values to be processed by a personal computer are digitized at high resolution. The use of two completely independent measuring channels gives good security against erroneous measurements and allow for self checking. For the determination of combustible gases or vapors, the test is accomplished in a quiescent

state for which the ignition delay time is  $t_v = 0$  s. A cross-sectional diagram of the experimental 20 liter spherical vessel is shown in Figure 3.1.

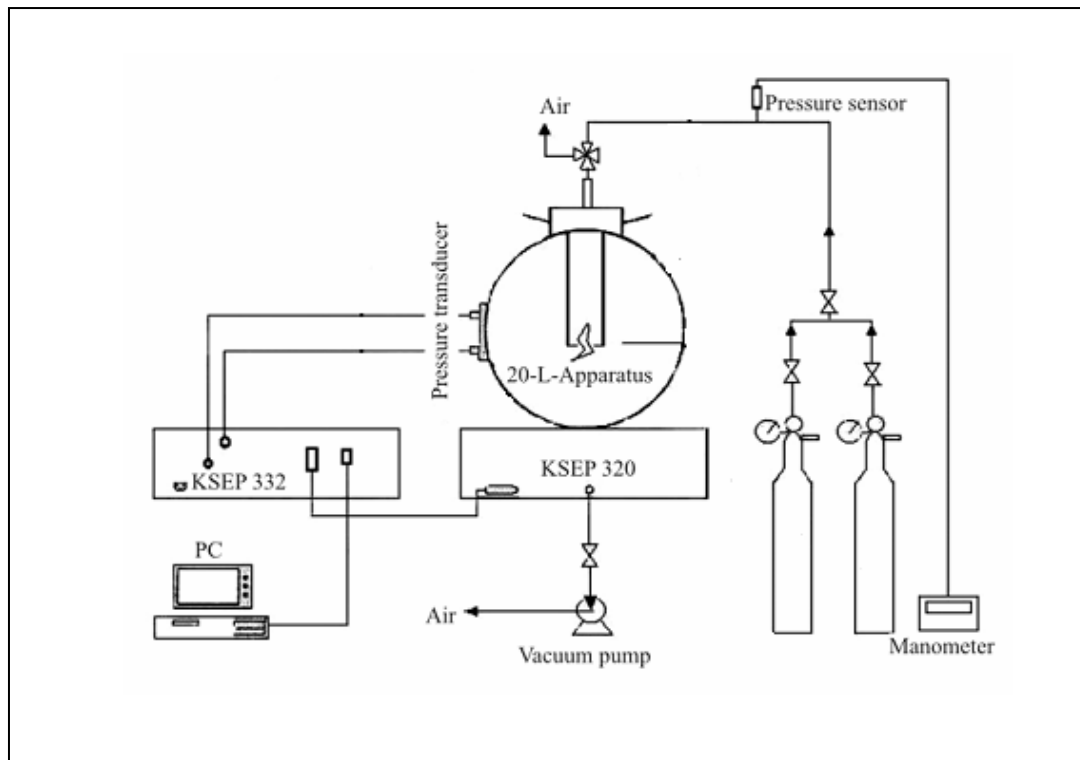


**Figure 3.1** Cross Sectional Area for 20L Spherical Vessel

### 3.2 Framework of Study

The explosive limits of hydrogen/air were investigated at hydrogen concentration from 2% to 30 % vol. The initial pressure in the 20 liter spherical vessel was regulated to 1 bar abs. A water jacket was used to dissipate the heat of explosions or to maintain the testing temperatures. It is necessary to keep the operating temperature at approximately 20 °C which was achieved by water cooling whereby the operating temperature would correspond to room temperature. Water is

circulated and the outlet temperature of the cooling medium never exceeds 25 °C. Ignition is achieved by a permanent spark which is placed at the centre of the vessel. Since the experiment was conducted under quiescent conditions, the ignition energy and ignition delay were set to 10 J and 0 s respectively. The igniter releases 10 J independently of pressure or temperature. The pressure evaluation after ignition was measured by a Kistler 701A piezoelectric pressure transducer connected to a Charge amplifier ( Kistler 5041B ). Figure 3.2 shows the schematic diagram of experimental setup where the equipment was closely placed to the hydrogen gas tank and computer system.



**Figure 3.2** Schematic Diagram of Experimental Set Up

### **3.3 Explosion Text Mechanism**

#### **3.3.1 Dust Explosion Test**

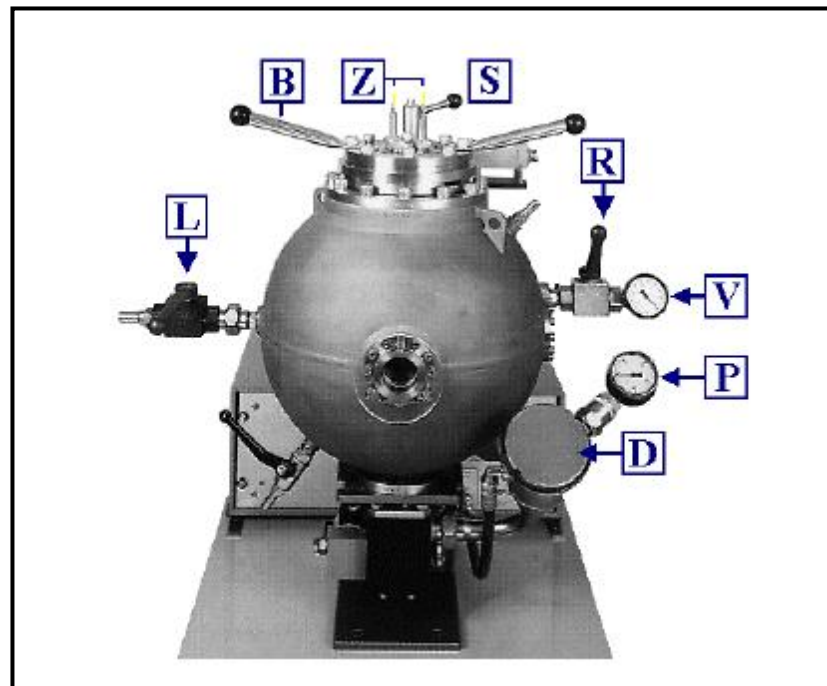
First, the vessel is vacuumed to  $-0.6\text{MPa (g)}$ , then dust sample in the dust vessel is dispersed into the test chamber by compressed air. After a pre-defined ignition delay (normally 60 ms), two pyrotechnical igniters (with energy totally 10kJ) was used to try to ignite the dust cloud. The pressure history in the chamber is recorded by the pressure sensor and data acquisition system.

Explosion pressure,  $P_{\text{exp}}$  and normalized rate of pressure rise ( $dP/dt$ ) can be obtained by analysis of the pressure history curve. Explosion tests are carried out at different dust concentration, and  $P_{\text{max}}$  and  $(dP/dt)_{\text{max}}$  are maximum value of  $P_{\text{exp}}$  and  $(dP/dt)$  respectively.

#### **3.3.2 Gas Explosion Test**

The mechanism of gas explosion test is similar with that of dust explosion test, and the difference is that the way of sample introduction. Fuel gas and air are introduced by fuel gas and air inlet. The dust vessel can be used as a turbulence generation system.

### 3.4 Experimental Testing Preparation



**Figure 3.3** Gas Fire Explosion Unit

First the safety switch (S) is opened. Then the bayonet-ring (B) over anti-clock wise is turned to open the cover sphere. The cover sphere is lifted off to clean up inside the explosion chamber. The chamber is cleaned up by using gas vacuum cleaner. After cleaning, the burn out igniter is removed and the electrode rods are cleaned. The burn out igniter is replaced with a new igniter; the igniter is fitted in parallel to the electrode rods. After finished, changing new igniter the cover sphere on the vessel is raised and the bayonet-ring (B) is turned into the final position. The ignition line (Z) is connected. The ball valve (L) and the valve at pressure gauge is then opened. After that the ball valve (R) is opened and the vacuum pump is started. The sphere is then evacuated to 0.8 bar absolute. The pressure indication is observed at 0.2 bar at pressure gauge. After complete the evacuating, hydrogen gas and compressed air is supplied to the sphere. Pressure indicator will turn to 0 bar. Later both ball valve

L and R and valve at pressure gauge are closed. Then, software KSEPT 6.0 is opened. In the software the function for gas/solvent is selected. Then, the volume percent fuel gas composition is set started with 2%. After that, the button ok is click and the test started. Software will running the experiments and data will be recorded.

### **3.4.1 Procedure before Test**

Before the test started, this procedure need to be done. Charge the dust the storage container (D). Then, connect two chemical igniters (each 5 kJ) in parallel to the electrode rods. After that, put the cover on the sphere and turn the bayonet-ring (B) in the final position. Connect the ignition lines (Z). Later, close the safety switch (S). Then, close the ball valve (L). Open the ball valve (R) to the vacuum pump. Evacuate the sphere to 0.4 bar absolute. Indication (V) = **-0,6** bar. Close the ball valve (R) to the vacuum pump. Start an automatic test run.

### **3.4.2 Procedure after Test**

After the test is complete, a few steps need to be follow. First, the ball valve (R) is opened to vent the sphere. After that, the apparatus is rinsed with compressed air by alternately pushing the buttons (I) and (O) on the manual control. Then, the sphere is opened to remove the residue with the vacuum cleaner. Later, the burned-out igniter is removed and the electrode rods are cleaned. After cleaning the rods, the rebound nozzle is cleaned. The dust storage container also needs to be cleaned and the remaining dust is sucked with vacuum cleaner.

### **3.4.3 Purging Pressure after Experiment**

The ball valve L is opened to release exhaust gas and pressure in the sphere. Before opened the ball valve L the ball valve R need to be closed. After that, the ignition line (Z) is disconnected.

### **3.4.4 Shutdown**

The ball valve L is opened to release the pressure from the sphere. The pressure will drop to 0 bar. All the gas supply to the equipment is closed. Lastly, the cover on sphere is opened to clean the inside of the sphere.

## **3.5 Experimental Procedure**

Inspect equipment to be sure it is thoroughly cleaned and in good operational condition. Ensure that the oxygen content of the dispersion air is  $20.95 \pm 0.2$  %. Higher or lower oxygen content will affect the maximum pressure and deflagration index values. The hydrogen gas from the cylinder storage and air from surrounding were fed in to the vessel via the outlet valve and nozzle. The required composition of hydrogen/air mixture was produced readily with the partial pressure procedures. Place the ignition source in the centre of the apparatus. Seal chamber and close all valves. Actuate the timing circuit to conduct the test. The pressure time curve is record on a suitable piece of equipment. The explosion data,  $P_{ex}$  and  $(dP/dt)_{ex}$  can be

obtained from the curve. After the test, open the valve to vent the pressure from the chamber. Open the chamber, remove residue and thoroughly clean the chamber and dispersion system. The initial concentration of hydrogen mix with air that will be feed into the chamber is 10%. This concentration then systematically increases by 10% until 50% or until curve are obtain for both  $(dP/dt)_{ex}$  and  $P_{ex}$  that can clearly indicate an optimum value for both parameters. Two additional test series are run at the concentration where the maximums were found and at one concentration on each side of the maximum.

### 3.5.1 Test Condition

Function = Gas, Solvent

Ignition source = Permanent Spark

Ignition energy IE = 10 J

Ignition delay time  $t_v = 0$  ms

Dispersion pressure  $P_z = 0$  bar (1 bar absolute, no pre-evacuation)

### 3.6 Analysis

Pressure and rate of pressure rise are determined from pressure rise record. The value of  $P_{ex}$  for a test at given concentration, is the highest deflagration pressure (absolute) minus the pressure at ignition (normally 1 bar). The value of  $(dP/dt)_{ex}$  for a given test is the maximum slope of the pressure trace or the highest value on the rate of pressure rise trace. The values for the  $P_{max}$  and  $(dP/dt)_{max}$  are the average of the highest value (over range of concentrations) for each of test series. the deflagration



index,  $K$  is calculated from  $(dP/dt)_{max}$  and the chamber volume,  $V$  using the cubic relationship.

### 3.6.1 Test Evaluation

The explosion indices  $P_{max}$  and  $(dP/dt)_{max}$  are defined as the mean values of the maximum values of each series (total 3 series). Subsequently, the explosion index  $K_G$  is calculated from the above  $(dP/dt)_{max}$ .

$P_{exp}$  [series n] = maximum value of each series

$P_{max}$  = (  $P_{exp}$  [series 1] +  $P_{exp}$  [series 2] +  $P_{exp}$  [series 3] ) / 3

$(dP/dt)_{exp}$  [series n] = maximum value of each series

$(dP/dt)_{max}$  = (  $dP/dt$  [series 1] +  $dP/dt$  [series 2] +  $dP/dt$  [series 3] ) / 3

$K_G$  = 0.27144 x  $(dP/dt)_{max}$

## CHAPTER V

### RESULTS AND DISCUSSION

#### **4.1 Introduction**

Spherical explosion vessel or always know as 20-L-Apparatus, was treated as an ideal apparatus to identify various flammability properties and explosion parameters of flammable materials (Chang and Shu et al). This device does not allow visual observation of the flame, so it uses an indirect measurement of the flame propagation which is the pressure explosion. This is because 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 (Liao et al, 2005). So, deflagration index is used to classify the hazard class for the hydrogen and to determine the severity of the hydrogen explosion. This experimental study has

been done to determine the maximum pressure of explosion, deflagration index and maximum rate of pressure rise. Flame propagation is said to have occurred if ignition is followed by a pressure explosion of 0.1 bar or greater. Based on the result, a pressure of explosion greater than 0.1 bar was observed at a concentration of hydrogen from 2 to 30 percent volume which is sufficient to determine the parameters of hydrogen-air mixture for this study. The data for the

## 4.2 Results

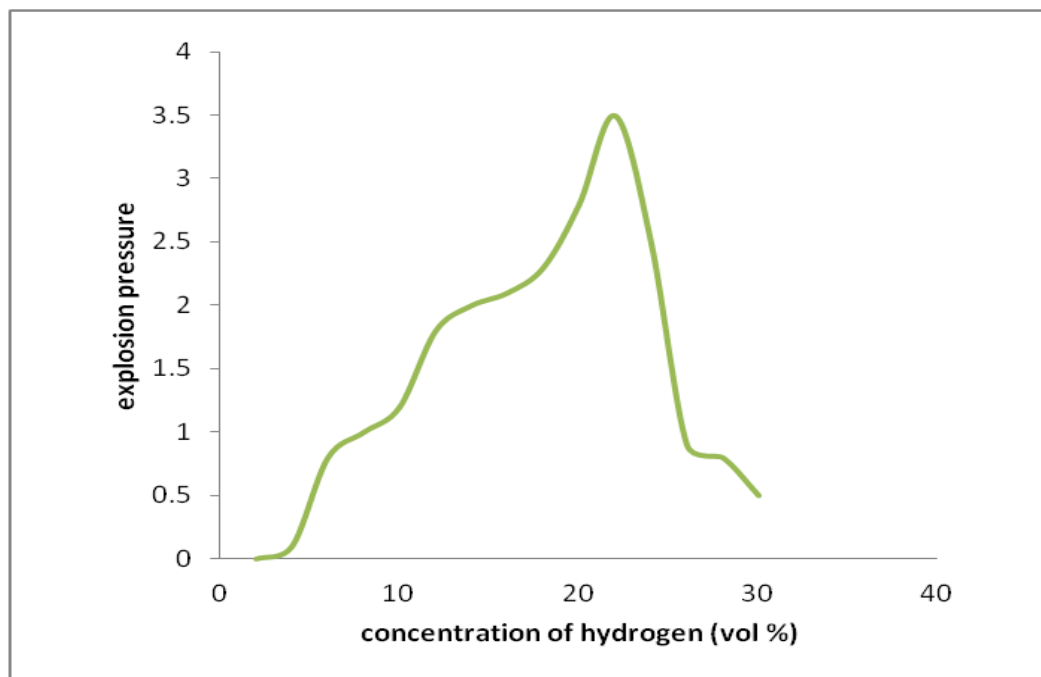
The maximum rate of pressure rise and maximum pressure of explosion were determined at various concentration of hydrogen by volume as shown in Table 4.1.

**Table 4.1** The maximum rate of pressure rise pressure of explosion we at various concentration

| No. | Concentration ( % vol ) |          | P <sub>exp</sub> ( bar ) | dP/dt ( bar ) |
|-----|-------------------------|----------|--------------------------|---------------|
|     | Air                     | Hydrogen |                          |               |
| 1   | 98                      | 2        | 0.0                      | 0             |
| 2   | 96                      | 4        | 0.1                      | 50            |
| 3   | 94                      | 6        | 0.8                      | 110           |
| 4   | 92                      | 8        | 1.0                      | 125           |
| 5   | 90                      | 10       | 1.2                      | 153           |
| 6   | 88                      | 12       | 1.8                      | 187           |
| 7   | 86                      | 14       | 2.0                      | 211           |
| 8   | 84                      | 16       | 2.1                      | 262           |
| 9   | 82                      | 18       | 2.3                      | 278           |
| 10  | 80                      | 20       | 2.8                      | 547           |
| 11  | 78                      | 22       | 3.5                      | 783           |
| 12  | 76                      | 24       | 2.5                      | 761           |
| 13  | 74                      | 26       | 0.9                      | 430           |
| 14  | 72                      | 28       | 0.8                      | 300           |
| 15  | 70                      | 30       | 0.5                      | 90            |

### 4.3 Discussion

From the data collected analysis has been done. Graph of explosion pressure at various concentration of hydrogen in air has been plotted to look at the pattern of the graph in order to compare with the previous study graph's pattern. From the graph one of the explosion parameter which is the maximum explosion pressure can be determine. Figure 4.1 shows the graph of explosion pressure at the various concentration of the hydrogen in air.



**Figure 4.1** Graph of explosion pressure at various concentration of hydrogen in air mixtures

Based on the figure 4.1 it can be clearly seen that in presence of 2% of hydrogen in air will not cause any explosion. This is because the flammability ranges of the hydrogen gas itself. From the properties of hydrogen that already discuss in literature review section shows that the flammability range of for hydrogen gas is from 4% until 75% volume and the explosivity range is from 15% to 59% volume of hydrogen in air (Properties of Hydrogen, 2001).

So, it proved that when the concentration of hydrogen in air is lower than the Lower Flammability Limit (LFL) which is 4% the explosion wouldn't occur although the source of ignition is present. Besides that, the explosion pressure and explosion pressure rise is at 0 bar when concentration of hydrogen is less than lower limit of flammability range.

When the concentration of hydrogen is increase to 4% volume the explosion pressure is seen to be increase from 0 bar to 0.1 bar. This means that the explosion already occurred in the chamber as small fire can be seen through the hole provided on the vessel. As discussed before that the lower flammability limit of hydrogen is 4% volume so only small explosion just occur.

At concentration 4% volume of hydrogen also can be said as a point of ignition. It means that this is the time in which the ignition source occurred in gas-air atmosphere and the energy of this ignition point is higher than lower explosion limit (LEL) of the gas in the atmosphere. From this point relatively slow combustion of

small amount of particles very close (or touching) from ignition source are burning, heating neighbour particles and compressing the atmosphere very close to the ignition source.

The pressure in the vessel starts rising, but relatively slowly because of the volume of burning particles that producing exhaust gases of bigger volume than original atmosphere. This is the reason of why explosion overpressure is small comparing to the whole volume of the vessel.

After the volume of hydrogen in air is increase to 6% volume the explosion pressure increase from 0.1 bar to 0.8 bar. Past researcher state that the explosion pressure will increase until it reach the maximum explosion pressure at optimal concentration of hydrogen gas in air (Bartknecht, 1981). Graph plotted proved that as the concentration of hydrogen increase the pressure also increase.

From concentration 4% volume until 10% volume of hydrogen in air the process of burning starts spreading in chain reaction which every burning particle emblaze several others in the same time. The amount of exhaust gases is bigger and it starts affecting the whole vessel. This phase is about 3-10 miliseconds long and this is the most critical part for the functionality of the explosion protective system - in this phase the explosion should be detected and the explosion protection system should start acting against the explosion.

At the concentration of 12% volume hydrogen in air the explosive mixture is so hot and so compressed, that the ignition and burning spread through the whole volume by extremely high speed. This is the main phase of the explosion. Immediately after this point the pressure rises to the point which is above the static opening pressure of explosion venting systems such as panels, membranes, rupture discs, special valves, and others.

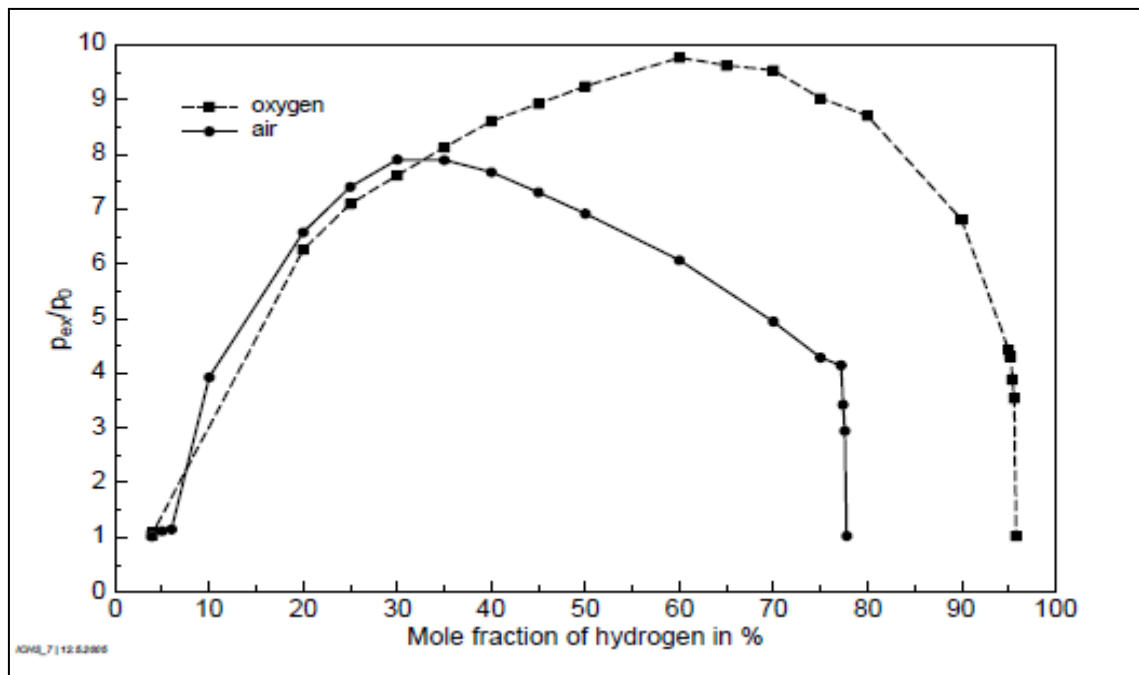
From concentration 12% volume to 22% volume of hydrogen in air is the main phase of the explosion. This is the phase described as explosion. The speed of spreading of the explosion depends on deflagration parameter of the gas and also on original pressure if there is higher pressure before the explosion, so the mixture will need only shorter time to compress and the original temperature. The higher temperature means that the mixture reaches temperature necessary for spreading of the explosion much faster. This period is approximately 10-500 milliseconds long, depending on the volume of explosive atmosphere and its parameters. If there is no protective system acting during the explosion or if the vessel is not explosion pressure resistant, this is the time when it collapses or dispart and the explosion starts to spread to connected devices and to the surroundings of the device.

Figure 4.1 shows that the maximum explosion pressure occurs at 22% volume of hydrogen in air which is the optimal concentration of hydrogen in air. At this concentration the explosion pressure is 3.5 bar. Only a small value of ignition source is needed to cause explosion in the chamber at the optimal concentration of hydrogen.



After the optimal concentration which is from 24% volume to 30% volume of hydrogen in air the pressure seems to decrease from 2.5 bar to 0.5 bar. This is because after all particles of dust are burnt down, the pressure stops rising, reaching its maximum. After this point the mixture starts cooling down and releasing of the pressure by the breaches and holes. This is the point when interesting effect can occur: if the exhaust gases will cool down fast, damaged device is not able to withstand under pressure caused by cooling and shrinkage of the exhaust gases inside and the device collapses inside itself or implodes. This happens usually to silos projected to withstand big overpressure caused by the weight of the material inside, but where the designer never expected under pressure inside the device.

Based on the past researcher, Schroeder et. al.,1999 has done an experiments on the explosion of the hydrogen-air mixtures and hydrogen-oxygen mixtures. Schroeder has collected data on explosion pressure of both mixtures. From the data collected the graph of explosion pressure against mole fraction of hydrogen in air and oxygen has been plotted as shown in Figure 4.2.

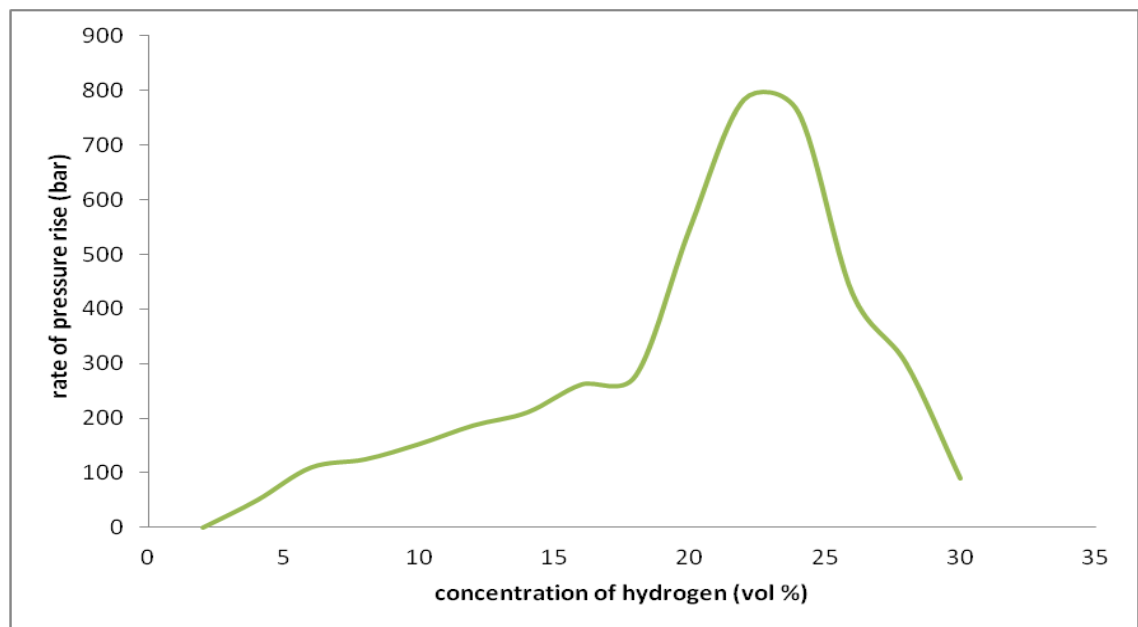


**Figure 4.2** Graph of explosion pressure of hydrogen air and hydrogen oxygen

Based on figure 4.2, comparison can be made on the pattern of the graph. It can be clearly seen that experimental graph and past researcher graph is same. Both of the graph increase on the increasing of concentration of hydrogen in mixtures until reach optimal concentration and decreasing after that because of the pressure release. Based on the pattern, it's same but if compared to the optimal concentration it's different. Optimal concentration of the experimental data is 22% with 3.5 bar of the explosion pressure while from the past researcher the optimal concentration of hydrogen in air mixtures is 30% with 7.5bar of the explosion pressure and optimal concentration of hydrogen in oxygen mixtures is 60% with 9.5 bar of the explosion pressure.

Although the pattern between the experiment graph and past researcher graph is same but the value of the optimal concentration is different. This is because maybe during the experimental procedure the stabilization process after injecting hydrogen gas and air into the chamber is not done. If this stabilization process is not done the hydrogen gas and air will not mix well and when the source of ignition is applied and the explosion occurred in the chamber it might affect the optimal concentration as well as explosion pressure. This is why the optimal concentration for the experiment data is little bit lower if compared to previous experiment.

From the experimental data collected, the graph for the rate of pressure rise at various concentration of the hydrogen gas also has been plotted. The graph is shows in figure 4.3.



**Figure 4.3** Graph of rate of pressure rise at various concentration of hydrogen gas in air mixtures.

Rate of pressure rise is the slope of the curve pressure / time during a flammable mixture explosion in a closed vessel (Prodan et. al., 2012). Based on the figure 4.3 the rate of pressure rise is increase as the concentration of the hydrogen in air is increasing until reach optimum concentration which is 22%. At this concentration the rate of pressure rise is 783 bar. After this optimal concentration the rate of pressure rise decreasing as the explosion pressure decrease due to the release of the pressure in the chamber after explosion has occurred. This parameter is important because the value is needed in the calculation of the deflagration index.

From the data collected, deflagration index can be calculated by using the cubic equation. Based on the calculation, the value of the deflagration index is 212.54 bar.m/s. Based on the researched done by Crowl the maximum value of deflagration index is 950 bar.m/s at 36% volume of hydrogen in air mixture (Crowl, 2009). Crowl also stated that the value of deflagration index will increase as the volume of the vessel increase. The deflagration index is estimated can reach theoretically as high as 17500 bar.m/s. The value of the deflagration index and the optimal concentration of hydrogen in air from the past researched is higher if compared to the experimental data. This is happen maybe during the experiment the mixture of hydrogen gas and the air is not mix well in the chamber. The stabilization process needs to be done before the ignition sources is supply into the chamber.

## **CHAPTER V**

### **CONCLUSION AND RECOMMENDATION**

#### **5.1 Conclusion**

Hydrogen has been proposed as a potential fuel to replace fossil fuels and to reduce carbon emissions. Experiment has been done to find the data on the explosion characteristics of hydrogen-air mixtures in a 20-L sphere. This includes the maximum explosion pressure, deflagration index, and maximum explosion pressure. Methods and equations are provided to estimate these parameters. The result of study in explosion of hydrogen air mixture was analyzed at concentration 2% until 30% volume of hydrogen in air. From the experimental data the value of maximum explosion pressure is 2.8 bar and the value of maximum rate of pressure rise is 783

bar. By using the equation discussed before the value of deflagration index is 212.54bar.m/s.

From the analysis of data can be conclude that the pattern of the graph from the experimental data is same with the previous study.

## **5.2 Recommendation**

Although the project objectives have been fully achieved, several recommendations have been considered for the good of the future. In the future they may be can determine the of explosion parameters of hydrogen mix with air and methane to see the pattern of the graph and also the value of optimal concentration of hydrogen. Besides that, determination of explosion parameters of hydrogen and air at different pressure and temperature also can be done in the future. Other recommendation is to do a theoretical model to estimate the value of deflagration index so comparison can be made between experimental value and theoretical model value. If both methods are done researcher can distinguish which methods can give a better result to compare with past researcher data.

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## APPENDIX A

| No. | Concentration ( % vol ) |          | P <sub>exp</sub> ( bar ) | dP/dt ( bar ) |
|-----|-------------------------|----------|--------------------------|---------------|
|     | Air                     | Hydrogen |                          |               |
| 1   | 98                      | 2        | 0.0                      | 0             |
| 2   | 96                      | 4        | 0.1                      | 7             |
| 3   | 94                      | 6        | 0.8                      | 82            |
| 4   | 92                      | 8        | 1.0                      | 4             |
| 5   | 90                      | 10       | 1.0                      | 153           |
| 6   | 88                      | 12       | 1.0                      | 211           |
| 7   | 86                      | 14       | 2.0                      | 110           |
| 8   | 84                      | 16       | 1.1                      | 284           |
| 9   | 82                      | 18       | 2.3                      | 148           |
| 10  | 80                      | 20       | 2.6                      | 262           |
| 11  | 78                      | 22       | 2.8                      | 365           |
| 12  | 76                      | 24       | 2.1                      | 142           |
| 13  | 74                      | 26       | 0.9                      | 78            |
| 14  | 72                      | 28       | 3.1                      | 783           |
| 15  | 70                      | 30       | 3.1                      | 761           |

**Table A 1** Rate of pressure rise and explosion pressure at various concentration of hydrogen gas in air mixture

## APPENDIX B

### CALCULATION OF DEFLAGRATION INDEX, $K_G$

$$K = \left(\frac{dp}{dt}\right)_{\max} \times \sqrt[3]{V}$$

Where:

$P$  = pressure, bar

$t$  = time, s

$V$  = volume,  $m^3$

$K$  = deflagration index, bar.m/s

$\left(\frac{dp}{dt}\right)_{\max}$  = maximum rate of pressure rise, bar/s

From collected data:

|   |                |
|---|----------------|
| Maximum explosion pressure, $P_{\max}$          | 2.8 bar        |
| Maximum rate of pressure rise, $(dP/dt)_{\max}$ | 783 bar        |
| Volume of vessel                                | 0.02 $m^3$     |
| Deflagration index, $K_G$                       | 212.54 bar.m/s |