

**THE EFFECT OF NITROGEN DILUTION ON THE FLAMMABILITY
LIMITS OF HYDROGEN ENRICHED NATURAL GAS**

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ABSTRACT

Nitrogen dilution is a common procedure for ensuring safety in used of the flammable gas like hydrogen enriched natural gas which has higher burning velocity. The objective of this study is to determine the flammability limits of hydrogen enriched natural gas to the combustion and to determine the correlation of nitrogen dilution towards the hydrogen enriched natural gas. The experiment was performed in a 20L closed vessel of explosion unit. The mixtures were ignited by using spark permanent wire that place at the centre of the vessel. The pressure-time variation data during the explosion of the natural gas/hydrogen/air mixture after nitrogen is added in a vessel was recorded. Since the explosion vessel does not allow direct visual observation of the flame, the explosion vessel uses an indirect measurement of the flame propagation which is the explosion pressure. The explosion pressure data is use to determine the flammability limits of hydrogen enriched natural gas. In this study, the result shows that the flammability limits of natural gas/hydrogen/air mixture are changed after nitrogen is added into the mixture. When 7 % volume of nitrogen is added into the natural gas/ hydrogen/ air mixture, the upper flammability limit is changed from 16 % to 14 % volume of natural gas. Then, nitrogen diluted from 7 % volume up to 9 % volume of nitrogen reduces the upper flammability limit of hydrogen enriched natural gas from 14 % to 11 % of natural gas by volume. So, the range of the flammability limits also reduced when the volume of nitrogen is increased.

ABSTRAK

Pencairan nitrogen adalah prosedur untuk memastikan keselamatan semasa penggunaan bahan mudah terbakar seperti gas asli campuran hidrogen yang mempunyai kelajuan pembakaran yang lebih tinggi. Tujuan penyelidikan ini adalah untuk menentukan had pembakaran bagi gas asli campuran hidrogen dan untuk mengenalpasti hubungkait di antara pencairan nitrogen dengan gas asli campuran hidrogen. Eksperimen ini dijalankan di dalam 20 L bekas letupan yang tertutup. Campuran gas akan dicucuh dengan menggunakan wayar percikan tetap yang terletak di tengah bekas letupan. Variasi tekanan-masa semasa letupan campuran gas asli, hidrogen, nitrogen dan udara direkodkan. Data tekanan letupan digunakan untuk menentukan had pembakaran gas asli campuran hidrogen. Dalam penyelidikan ini, keputusan menunjukkan had pembakaran campuran gas asli, hidrogen dan udara bertambah setelah gas nitrogen ditambah ke dalam campuran. Apabila 7 % isipadu nitrogen ditambah ke dalam campuran gas asli hidrogen dan udara, had pembakaran maksimum telah berubah daripada 16 % isipadu kepada 14 % isipadu natural gas. Kemudian, pencairan nitrogen daripada 7 % isipadu meningkat kepada 9 % isipadu nitrogen telah mengurangkan had pembakaran maksimum untuk gas asli campuran hydrogen iaitu daripada 14 % kepada 11 % isipadu gas asli. Maka, julat had pembakaran berkurang apabila isipadu nitrogen bertambah.

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LIST OF ABBREVIATIONS

NG	:	Natural gas
CH ₄	:	Methane
H ₂	:	Hydrogen
N ₂	:	Nitrogen
O ₂	:	Oxygen
LFL	:	Lower Flammability Limit
UFL	:	Upper Flammability Limit
NO _x	:	Nitrogen oxide
CO	:	Carbon monoxide
CO ₂	:	Carbon dioxide
HCNG	:	Hydrogen enriched Compressed Natural Gas
UEL	:	Upper Explosive Limit
LOC	:	Limiting Oxygen Concentration
P _{exp}	:	Explosion Pressure
P _{max}	:	Maximum Explosion Pressure
Θ _{exp}	:	Explosion Time
t _v	:	Ignition Delay Time
IE	:	Ignition Energy
P _m	:	Corrected Explosion Pressure

CHAPTER 1

INTRODUCTION

1.1 Background of the Study

With recent dramatically increased crude oil price, the inevitable decline in petrol resources and the increasing concern of environmental protection, investigation on alternative fuel has attracted more and more attention. Natural gas is regarded as one of the most promising clean fuels. Due to its unique tetrahedral molecular structure, the main constituent of natural gas which is methane has narrow operational limits and is relatively difficult to be ignited. Consequently the utilization of natural gas can increase the severity of cyclic variations under fuel-lean conditions, leading to low thermal efficiency and high unburned hydrocarbon emissions. One of the effective methods to improve its lean operation is to add fuels with faster burning velocity. Hydrogen seems to be the best candidate, which is difficult to be used directly by transport engines due to the safety, storage and economics reason. (Haiyan et al 2009)

With respect to the safety issues, dilution with inert gas like nitrogen is a common procedure to ensuring safety in use of flammable gas like hydrogen enriched natural gas. Inerting is the process of adding an inert gas to a combustible mixture to reduce the concentration of the oxygen below the limiting oxygen concentration for the purpose of lowering the likelihood of explosion. (Chen et al 2009)

The concentration of O₂ in air at which the atmosphere will no longer support combustion known as Limiting Oxygen Concentration (LOC) for combustion. LOC

values vary depending on the material involved and the inert gas used. LOC test is usually performed in the 20 – L – sphere vessel. (Ebadat, 2002)

Knowledge of the explosion hazard of natural gas is important to ensure the safety in industrial and domestic applications that produce or use flammable mixture like natural gas. Nitrogen dilution to the fuels reduces the burning velocity remarkably by reducing the thermal diffusivity and flame temperature of the mixture.

The effect of combustion of natural gas also depends on the hydrogen fraction of the fuel. But in this study, there is only a consideration about the effect of several range of nitrogen dilution to the constant amount of hydrogen in natural gas. The result in this study also can be used in understanding the combustion characteristic based on the effect of different amount of nitrogen dilution to the hydrogen enriched natural gas.

1.2 Problem Statement

One of the major problems associated with applying hydrogen in natural gas-air mixture in the industry is the combustion- induced disaster such as fire and explosion. It is because hydrogen has relatively fast burning velocity and low ignition energy. (Chenglong et al 2009)

With the rapid increase of the industries, the explosion accident regarding to flammable chemical or gases has been seen to be one of the most serious accidents that occur nowadays. This accidental damage has been causing many serious damages in the industries.

Most of combustible chemical can cause explosion when they are mixed with an oxidant like O_2 and then ignite with an energy source like electrical source. There are a lot of these flammable chemicals in the Chemical Engineering Industries such as NG storage and LPG storage.

So, for ensuring the safety in use of flammable gas like H_2 enriched NG, dilution with nitrogen is a better solution. The process can reduce the concentration

of oxygen below the limiting oxygen concentration for the purpose of lowering the likelihood of explosion. (Chen et al 2009)

Nitrogen dilution process can reduce the burning velocity and increase the Lower Flammability Limit (LFL) of that hydrogen enriched natural gas. (Prathap et al 2008)

1.3 Objective of Study

- a) To determine the flammability limits of natural gas in combustion.
- b) To determine the effect of nitrogen dilution on the hydrogen enriched natural gas.

1.4 Scope of Study

This study is conducted to determine the effect of nitrogen dilution on the flammability limits of H₂ enriched NG in a constant volume spherical vessel with a volume of 20 L by using conventional spark ignition system which is located at the centre of the vessel.

In this study, CH₄ with 96 % purity is used to replace the NG. CH₄ can be used to indicate the properties of NG since the major component in NG is CH₄. The study of the flammability limits was focusing on the effect when N₂ gas was added into the mixture of H₂ enriched NG.

The experiment was run two times with different volume of N₂ which is 7 % volume and 9 % volume with a constant volume of H₂. The enrichment of H₂ in the mixture is 3 % volume of H₂. The LFL and UFL of H₂ enriched NG were determined at concentration from 1 % volume to 14 % volume.

1.5 Significant of Study

In this study, the effect of N_2 dilution on the flammability limits in H_2 enriched NG was investigated. Addition of N_2 is said can reduce the flammability limits of NG/ H_2 /air mixture.

The rationale of this study is natural gas is one of the clean fuels nowadays. It has the potential to be the favourite fuel based on the environmental and resources aspect and capability to overcome Cold Start Phenomenon. But, H_2 enriched NG is very easy to flame and explode if we do not take a proper action to control the hydrogen ratio. Dilution with inert gas like N_2 is a common procedure to ensuring safety in use of flammable gas like NG.

Inerting process which is adding an inert gas to a combustible mixture can reduce the concentration of O_2 for the purpose of lowering the likelihood explosion. The characteristics of N_2 which is one of the inert gas can reduce the concentration of O_2 in air by dilute it into the mixture.

CHAPTER 2

LITERATURE REVIEW

2.1 Natural gas

Natural gas (NG) is composed almost entirely of methane although it does contain small amounts of other gases like ethane, propane, butane, and pentane. Methane (CH_4) is composed of a molecule of one carbon atom and four hydrogen atoms. NG is colorless, non-toxic, invisible and odorless, although an odorant is added known as mercaptan. This odorant is an important safety measure because it provides a distinct smell which is much like the smell of rotten eggs, in the event of a gas leak.

NG is lighter than air and rapidly dissipates into the air when it is released. When NG burns, a high-temperature blue flame is produced and complete combustion takes place producing only water vapor and carbon dioxide (CO_2). It has a heating value of about 1000 BTUs per cubic foot. However, when it burns improperly, it can produce carbon monoxide (CO) which is a deadly and poisonous gas.

NG has a flammability range of approximately 5 to 15 %. That means that any mixture containing less than 5 % or greater than 15 % NG to air would not support combustion. NG when mixed with air and exposed to an ignition source is combustible.

Industrial applications for natural gas are many including those same uses found in residential and commercial settings like heating, cooling, and cooking.

Natural gas is also used for waste treatment and incineration, metals preheating (particularly for iron and steel), drying and dehumidification, glass melting, food processing, and fueling industrial boilers. Natural gas may also be used as a feedstock for the manufacturing of a number of chemicals and products. Gases such as butane, ethane, and propane may be extracted from natural gas to be used as a feedstock for such products as fertilizers and pharmaceutical products.

2.2 Hydrogen (H₂) Enriched NG

The use of H₂ as a supplemental fuel in conventional combustion engines has generally shown decreased pollutant emissions primarily due to the lean burn characteristics of H₂ and a reduction of carbon in the fuel. The advantage of a lean burn operation is its greater thermal efficiency due to its higher specific heat ratio and combustion efficiency. But although lean burn has a lot of advantages it is also associated with several difficulties including slower flame propagation speed and increased ignition energy of the fuel-air mixtures.

H₂ addition is thought to be an ideal approach to compensate these problems since H₂ has relatively fast laminar burning velocity and low ignition energy Karim et al. theoretically studied the H₂ as additive in NG fuelled internal combustion engines. Their results showed that the addition of H₂ into NG could decrease the ignition delay and combustion duration at the same equivalence ratio. Liu et al. investigated the influence of the excess air ratio and H₂ fraction on the emissions characteristics of a spark ignition engine fuelled with NG/H₂ blends. Their results showed that the excess air ratio has a significant effect on the NO_x, CO, and CO₂ concentration for both pure NG and NG/H₂ blends. Huang et al. investigated experimentally the combustion characteristics in a direct-injection spark-ignited engine fuelled with hydrogen-enriched compressed natural gas (HCNG) blends under various ignition timings and lean mixture conditions. The results indicated that ignition timing is an important parameter for the engine performance, combustion and emissions. The concept of investigations of engine operations that is based on the second law of thermodynamics is not a new technique. Availability is also called as 'exergy'. Rakopoulos et al. investigated the effect of mixing hydrogen into natural

gas for direct-injection, diesel engine combustion from the second law perspective. They used a single-zone computational model of the engine operation for the investigations. Their results showed that second-law efficiency increases and irreversibility generation decreases (as a percentage of the totally injected fuel availability) with increasing engine load. Rakopoulos et al. investigated the effects of H₂ enrichment on the second law analysis of natural and landfill gas combustion in diesel engine cylinders. They indicated that H₂ may have particularly attractive characteristics with regard to entropy generation during its use as a fuel, because its combustion reaction is one of a combination of two relatively simple molecules into a more complicated one. Rakopoulos and Michos investigated the generation of combustion irreversibilities in a spark-ignition engine under biogas–hydrogen mixtures fueling. They found that the addition of increasing amounts of H₂ in biogas promotes the degree of reversibility of the burning process mainly during the combustion of the later burning gas, due to the incurred increase in its combustion temperatures. (Hakan Ozcan 2009)

2.3 Nitrogen (N₂) Dilution

Dilution with inert gas like N₂ is a common procedure for ensuring safety in the use of flammable gas. The procedure of dilution with inert gas like N₂ can be understood in two different ways. One is dilution of fuel with inert gas, and the other is dilution of air with inert gas. (Shigeo et al 2006)

N₂ dilution to fuel reduces the burning velocity remarkably by reducing the thermal diffusivity and flame temperature of the mixture. With increased N₂ dilution, flame speed decreases. N₂ dilution results in substantial reduction of laminar burning velocity. The reasons for the substantial reduction of burning velocity due to N₂ dilution in the fuel at a given equivalence ratio are the decrease in heat release and the increase in heat capacity of the mixture with dilution. (Prathap et al 2008).

The dilution effect of N₂ is very different for compounds of ethylene, dimethyl ether and ammonia. This may be understandable because these compounds have very different flammability characteristics from the usual fuel compounds like NG. For example, ethylene has a tendency to explosive decomposition, dimethyl

ether has a tendency to produce cool flames and ammonia is extremely weak in its flammability compared to usual fuel compounds like NG. (Shigeo et al 2006).

2.4 Flammability Limits

Flammability limits, also called flammable limits, or explosive limits give the proportion of combustible gases in a mixture, between which limits this mixture is flammable based on the range shown in figure 2.1. Gas mixtures consisting of combustible, oxidizing, and inert gases are only flammable under certain conditions. The lower flammable limit (LFL) (lower explosive limit) describes the leanest mixture that is still flammable, i.e. the mixture with the smallest fraction of combustible gas, while the upper flammable limit (UFL) (upper explosive limit) gives the richest flammable mixture. Increasing the fraction of inert gases in a mixture raises the LFL and decreases UFL.

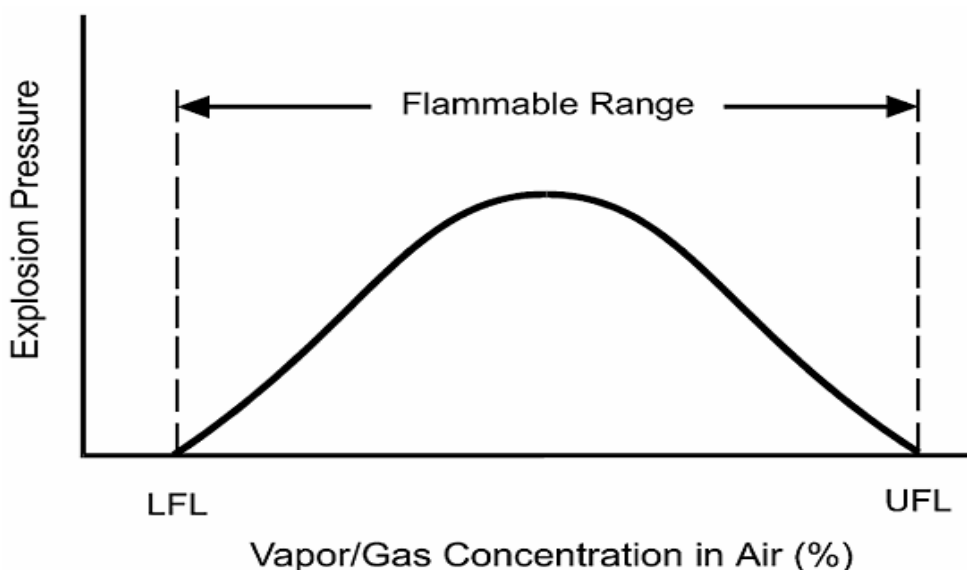


Figure 2.1: Schematic represents flammability limit

Flammability limits data are essential for a quantitative risk assessment of explosion hazard associated with the use of combustible gas. The present work is to obtain the fundamental flammability data for prevention of the hazards in the practical applications. Knowledge of the explosion hazards of gaseous fuels is of importance to ensure the safety in industrial and domestic applications that produce

or use flammable mixtures. There is no question that the flammability limits is a most widely used index for representing the flammability characteristics of gases. In accordance with generally accepted usage, the flammability limits are known as those regions of fuel–air ratio within which flame propagation can be possible and beyond which flame cannot propagate. And there are two distinct separate flammability limits for the fuel–air mixture, namely, the leanest fuel-limit up to which the flame can propagate is termed as lower flammability limit (LFL), and the richest limit is called as upper flammability limit (UFL). There are several criteria to determine the flammability limits. First is inspection of the visualization of the flame kernel produce by the spark, namely visual criterion. Second is the measurement of the pressure or temperature histories in the vessel and appropriate pressure or temperature rise criteria can be used to designate flammability rather than the purely visual observation of the flame development. (Liao et al 2005)

H₂ enrichment is a possible option to extend the flammability limits because H₂ has a wider flammable mixture range, lower ignition energy, faster flame propagation rate compare to NG. These characteristics help to improve the lean burn capability (Fanhua et al 2008).

2.4.1 Lower Flammability Limit

The flammable limit of a gas or a vapor is the limiting concentration (in air) that is needed for the gas to ignite and explode. The lowest concentration (percentage) of a gas or vapor in air is capable of producing a flash of fire in presence of an ignition source (arch, flame, heat). At concentration in air below the LFL there is no fuel to continue an explosion. Concentrations lower than LFL are "too lean" to burn. For example, CH₄ gas has a LFL of 4.4 % (at 138 °C) by volume, meaning 4.4 % of the total volume of the air consists of CH₄. At 20 °C the LFL is 5.1 % by volume. If the atmosphere has less than 5.1 % methane, an explosion cannot occur even if a source of ignition is present. When CH₄ concentration reaches 5 % an explosion can occur if there is an ignition source. Each combustible gas has its own LFL concentration. These percentages should not be confused with LFL instrumentation readings. Instruments designed and calibrated to read LFL also read

as percent values. A 5 % displayed LFL reading for CH₄ for example would be equivalent to 5 % multiplied by 5 or 0.25 % CH₄ by volume at 20 °C.

2.4.2 Upper Flammability Limit

Highest concentration (percentage) of a gas or a vapor in air is capable of producing a flash of fire in presence of an ignition source such as arch, flame and heat. Concentration higher than UFL are "too rich" to burn. UFL is also called Upper Explosive Limit (UEL).

2.5 Nitrogen Dilution Effect on the Flammability Limits

Inerting is the process of adding an inert gas to a combustible mixture to reduce the concentration of O₂ below the limiting oxygen concentration (LOC) for the purpose of lowering the likelihood of explosion. In process industries, the inert gas is usually N₂ or CO₂, although sometimes steam may be used. Because the procedure of diluting a combustible gas with inert gas could be also taken as a mixing process of flammable gas and inert gas, Kondo et al. have attempted to modify the Le Chatelier equation so that it could be extended to the case of a mixture of flammable gases and inert gases.

The following assumptions were included in their work.

- i. At LFL, the heat of combustion per mole of a mixture composed of fuel gas and inert gas is equal to the heat of combustion per mole of pure fuel gas times the molar fraction of the fuel gas in the mixture (i.e., adding inert gas to fuel gas does not change the reaction mechanism at LFL)
- ii. The heat release is the same for all limit mixtures at LFL
- iii. The fuel gas would react completely when combustion takes place at LFL
- iv. At UFL, the ratio of the number of moles of O₂ required to burn one mole of the mixture of fuel gas and inert gas to the number of moles of O₂ required to burn one mole of pure fuel gas equals the molar

fraction of the fuel gas in the mixture (i.e., adding the inert gas to the fuel gas does not change the reaction mechanism at UFL)

- v. O₂ would react completely when combustion takes place at UFL
- vi. The heat release is the same for all limit mixtures at UFL.

Usually the LFL and UFL of a combustible material are expressed in volume percentage (vol%) in the literature; however, as the hydrocarbon gas could be taken as an ideal gas at atmospheric pressure, the LFL and UFL could also be explained as the molar fraction. To avoid misleading the meaning in formulation, three terminologies are defined here:

- i. Fuel mixture – the mixture composed of hydrocarbon and air (no inert gas);
- ii. Blended gas – the mixture composed of hydrocarbon and inert nitrogen (no air);
- iii. Total mixture – the mixture composed of the blended gas and air.

The assumptions presumed true in formulation are listed as follows.

- (U1) oxygen gas reacts completely at UFL.
- (U2) the stoichiometric relation of a combustion reaction occurring at UFL does not change by the presence of inert gas.
- (U3) the adiabatic temperature rises are the same for all limit mixtures at UFL.
- (L1) the hydrocarbon reacts completely at LFL.
- (L2) the stoichiometric relation of a combustion reaction occurring at LFL does not change by the presence of inert gas;
- (L3) the adiabatic temperature rises are the same for all limit mixtures at LFL

It is well known that the flammable material is the lean reactant when combustion occurs at LFL, while O₂ gas is the lean reactant when combustion occurs at UFL. Thus, assumptions U1 and L1 merely stated that the lean component will be consumed completely in a burning process occurring at flammability limits.

Assumptions U2 and L2 stated that the stoichiometry of the combustion reaction at both lower/upper flammability limits does not change by the presence of inert gas. With the aids of these two assumptions, the heat released for the blended gas from the heat of combustion of pure hydrocarbon could be estimated. These two assumptions are popular assumptions for those works which use the calculated adiabatic flame temperatures to estimate the flammability limits. It should be addressed here that although these two assumptions are very popular in the literature, experimental results do show that the stoichiometry of a combustion reaction occurring at flammability limits might change in the presence of inert gas. The change in stoichiometry could be easily understood from the fact that if an inert gas was added to hydrocarbon/oxidant mixture, the range of concentrations between the UFL and LFL would considerably narrow down and finally converge to a point which is usually known as the inertization point. The lean reactant of a combustion reaction occurring at UFL is different from that of a combustion occurring at LFL; therefore, the stoichiometry of a combustion reaction must change by adding inert gas, because these two flammability limits finally converge to the inertization point. However, it is also obvious that assumptions U2 and L2 are true when the concentration of inert gas is low.

The combustion reaction would continue only if the heat released by the combustion reaction can raise the temperature of the unburned materials to beyond a temperature threshold and this temperature threshold was usually expressed as the adiabatic flame temperature rise of the combustion system. The energy released at flammability limits is deemed to be the one just sufficient to make the temperature of the combustion system reach this temperature threshold. It is widely accepted that inert gas is not involved in the reaction mechanism of a combustion reaction, so it seems reasonable to assume that this temperature threshold like the adiabatic flame temperature rise does not change by adding inert gas. Moreover, it was also reported that the calculated adiabatic flame temperature of LFL was found be around 1400K at different concentrations of inert N_2 for some hydrocarbons. Bases on aforementioned facts, it seems reasonable to assume that the adiabatic flame temperature does not change as inert gas is added to a flammable hydrocarbon, thus assumptions L3 and U3 are adopted in this study. (Chen et al 2009)

2.6 Explosion in Closed Vessel

Knowledge of pressure–time variation during explosions of fuel–air mixtures in enclosures is a very important component of safety recommendations for a wide range of human activities, connected to production, transportation or use of fuels. The characteristic parameters of a closed vessel explosion are the explosion pressure, the explosion time and the maximum rate of pressure rise. The explosion pressure and explosion time were recently defined in the European standard on maximum explosion pressure determination which is

- (i) the explosion pressure, P_{exp} is the highest pressure reached during the explosion in a closed volume at a given fuel concentration
- (ii) the maximum explosion pressure, P_{max} is the highest pressure reached during a series of explosions of mixtures with varying fuel concentration
- (iii) the explosion time, θ_{exp} is the time interval between ignition and the moment when the explosion pressure is attained

Explosion pressures and explosion times are important also for calculating laminar burning velocities from closed vessel experiments, vent area design and characterizing transmission of explosions between interconnected vessels. Recent data on gas explosions were obtained from experiments in a spherical 20 L closed vessel with central ignition, produced by a fusing wire, a pyrotechnical ignitor or capacitive electric sparks. In fact, this is the vessel recommended by the recent European standards, for flammability and explosion pressure measurements. Few data measured according to European standard are however available, especially for mixtures at pressures and/or temperatures different from ambient. (Domnina et al 2006)

CHAPTER 3

METHODOLOGY

3.1 Experimental Apparatus

The experimental 20-L- Apparatus which is 20 Liter Spherical Explosion Vessel was obtained from Adolf Kühner AG and is shown in figure 3.1. The test chamber is a stainless steel hollow sphere with a personal computer (PC) interface.

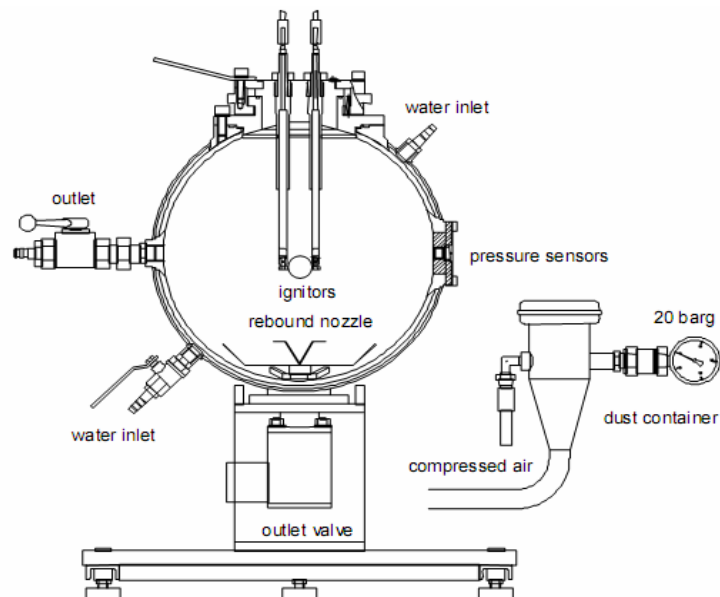


Figure 3.1: Schematic diagram of 20-L-Explosion Vessel
(Ch. Cesana, and R.Siwiek ,2006)

3.1.1 20-L-Sphere

The test chamber is a hollow sphere made of stainless steel with a volume of 20 liters. A water jacket serves to dissipate the heat of explosion or to maintain thermostatically controlled test temperatures. The top of the cover contains holes for the lead wires to the ignition system. The opening provides for ignition which is controlled by the KSEP 320 unit of 20-L-Sphere. The KSEP 332 unit uses piezoelectric pressure sensor's to measure the pressure as a function of time. A comprehensive software package KSEP 6.0 is used to allow safe operation of the test equipment and an optimum evaluation of the explosion test results. The schematic diagram for the experimental set up of the 20-L-Sphere and the software KSEP is shown in figure 3.2.

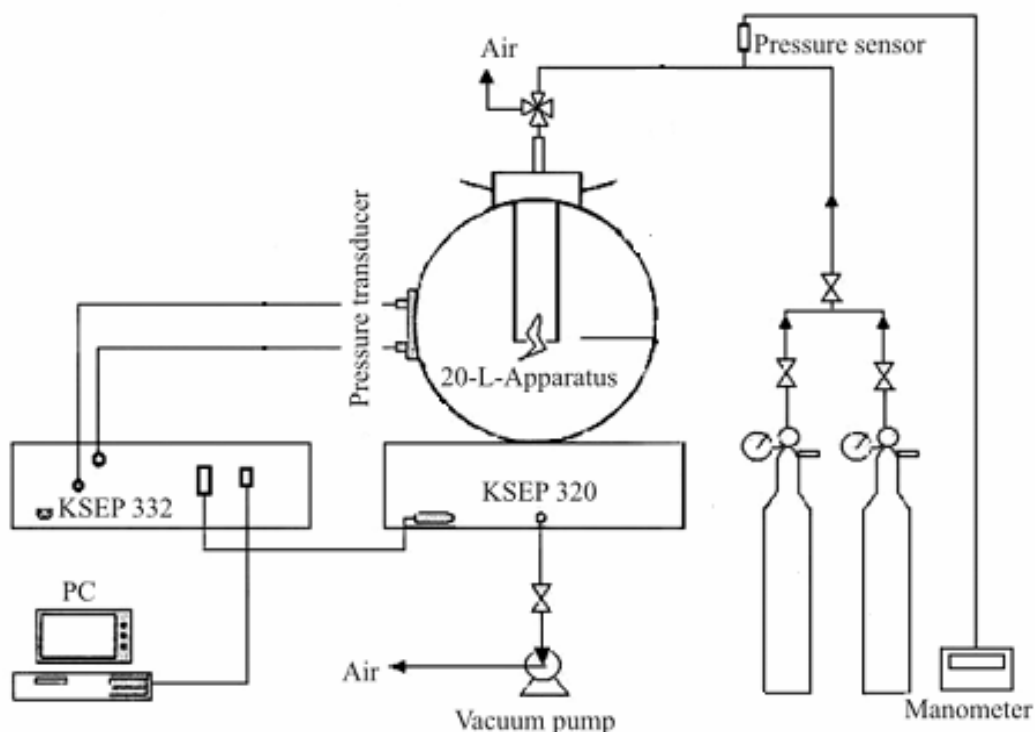


Figure 3.2: Schematic diagram of experimental set up
(Ch. Cesana, and R.Siwiek, 2006)

3.1.2 Measurement and Control System KSEP 332

The KSEP 332 unit as shown in figure 3.3 uses piezoelectric pressure sensor's to measure the pressure as a function of time and controls the valves as well as the ignition system of the 20-L-Apparatus. 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 allows for self checking. For the determination of combustible gases or vapors, the test accomplished in a quiescent state which is the ignition delay time, t_v is equal to 0 s.

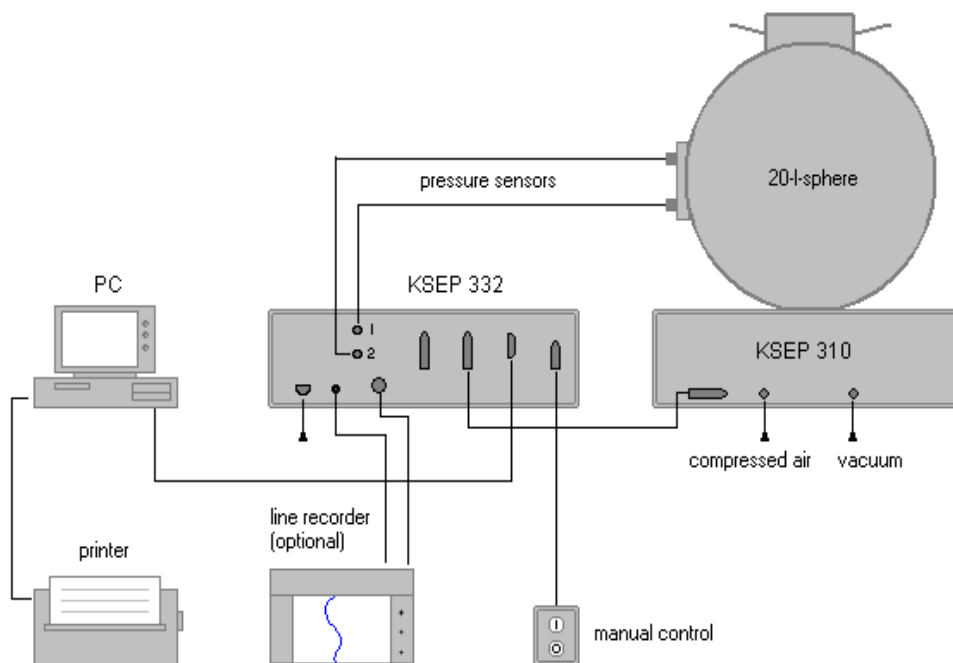


Figure 3.3: Schematic of KSEP 332

(Ch. Cesana, and R.Siwiek, 2006)

3.2 Experimental Condition

The flammability limits of NG/air mixture, NG/H₂/air mixture and NG/H₂/air mixture with N₂ dilution for 7 % volume and 9 % volume of N₂ were investigated at NG concentration from 1 % volume to 14 % volume. The other experimental condition is shown in figure 3.1.

Table 3.1 Test condition of the experiment

Pressure	1 bar absolute
Temperature	Ambient temperature
Mixture state	Quiescent state
Ignition energy	10 J
Ignition delay time, t_v	0 s

3.2.1 Pressure and temperature

The initial pressure in the 20-L-Sphere is regulated to 1 bar absolute. A water jacket to dissipate the heat of explosions or to maintain thermostatically controlled test temperatures. It is necessary to keep the operating temperature at approximately 20 °C by means of water cooling, whereby the operating temperature would correspond to room temperature. Therefore, there is always some flow of water and so that the outlet temperature of the cooling medium never exceeds 25 °C.

3.2.2 Ignition

Ignition is achieved by permanent spark which placed in the centre of the vessel. Since experiment was conducted under quiescent conditions, ignition energy (IE) is 10 J and the ignition delay time is 0 s. The igniter releases 10 J independently of pressure or temperature. The pressure evolution after ignition is measured with a Kistler 701A piezoelectric pressure transducer connected to a Charge amplifier (Kistler 5041B).