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Study of the Hazards in Hydrogen Storage System

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Abstract

Compressed hydrogen becomes a promising fuel, that is called the Green Fuel, and it is the most abundant gas in our life, as well as the source of all kinds of energies. Hydrogen has been considered as alternative energy carrier from the viewpoint of reduction in carbon dioxide emissions due to produce water after combustion process, which none causes any environmental problems' comparison with the other fuels. This gas must be stored in strict safety considerations. Therefore, the main object of this paper is to study the hydrogen hazards that can be occurred in the hydrogen storage systems and focusing on the types of storage tanks and the phase of the hydrogen that can to be stored. The methodology explains the hydrogen storage types, hazards scenarios, and identification all hazards, hazardous events that could lead to the realization of any of the hazards associated with hydrogen all storage systems. This identification includes some the techniques that are applied on the storage systems, such as Swift technique (WHAT IF?), failure mode and effective analysis (FEMA). Moreover, these techniques aim to prevent the failures to the environment, and accidents can cause injuries, fatalities. Besides, providing control procedures with the high level of protection for the storage process by using some instruments, equipment and safety procedures. In this study, the BLEVE scenario was investigated, where storage tank is available on the production site, with 300 Kg, the diameter of fireball was 38.83 m, and the duration may be required to make fireball was 3.012 sec, the distances measured from the point at the ground directly beneath the center of the fireball to receptors for fatalities at 5%, 50%, and 95% are 98, 82, and 68 m, respectively.

Keywords: Hydrogen; green fuel; hazards; WHAT IF; FEMA and BLEVE scenarios.

1. Introduction

Hydrogen fuel is considered from the fuels, that have high flammability during a wide range of temperatures and concentrations, it is colorless and odorless gas, this reason makes the hydrogen is undetectable gas for human [1]. Furthermore, if we compare the hydrogen fuel with the other fuels we will find that the hydrogen has three times of the energy content in comparison with such as gasoline (120 MJ/kg for hydrogen and 44 MJ/kg for gasoline) [2]. Therefore, the storage problem of hydrogen can be arising due to the low volumetric density of this fuel, owing to the physical nature (liquid or gas) and energy density. Therefore, there are many safety requirements should be considered and applied during the operation, transportation, and storage process. The concern modes of hydrogen storage were as compressed and liquid hydrogen tanks; where the hydrogen has to be stored at high pressures to improve the energy density of gas. Consequently, there are many materials requirements have to be considered during the design stage of these storages in order to make sure that the tank integrity [3]. These two ways can be used to increase the value of gravimetric and the capacity of volume storage for the compressed hydrogen gas vessels from their current levels. The first way that includes cryo-compressed tanks which depends on set the pressure and volume at fixed value, and then the tank capacity can increase as the tank temperature decrease [4]. The second way of storage depends on the development of conformable tanks. Therefore, the concepts of conformable tanks can be based on walls supporting structure. The requirements to improve the density energy are the mode of storage will be as liquid hydrogen tanks. The important issues which have to be considered during the hydrogen liquefaction are the energy required for this process, liquid hydrogen can be boiled off, the volume, the weight, and vessel cost. All the studies showed that the energy required for liquefaction process is high and approximately 30% of heating value is required for the liquefaction process [2]. The cost of liquefaction process still needs despite these methods are methods can reduce the energy required. In this situation the hydrogen liquid need to kept and stored at -253 °C [2].

Safety is an important matter for the improvement of hydrogen economy, and a great global effort is being done by different stakeholders for the development of suitable codes and standards concerning safety for hydrogen technologies [5, 6]. Furthermore to codes and standards, different studies have been done about safety aspects of particular hydrogen energy projects [7, 8]. Most of such have been focused on hydrogen production and storage in large facilities, transport, delivery in hydrogen refuelling stations, and utilization. Therefore, there are studies that give the comprehensive information about Hydrogen like, IDEALHY project, which supported by European Union's 7th framework Programmed for the Fuel Cells and Hydrogen Joint Technology Initiative, their paper give the HAZARD Identifications for the new liquefaction process, storage of liquid hydrogen and its transportation by road. This included a review of incidents relevant to these activities. The principal causes of the incidents have been analyzed. Finally, the remaining safety work for the IDEALHY project is outlined [9]. In addition, Gupta, R.B., 2009, was studied the aspects about hydrogen fuel, production storage and transportation. His work gave the valuable information about safety consideration of hydrogen and the possible hazards that can be raised during these processes [2].

This paper was highlighted the importance of considering some accident conditions related to the plant capacity and operating severity, location, and stock level of hazardous substances in intermediate vessels. This study applies the BLEVE scenario to evaluate the influence of various accident conditions on the effects (radiative heat flux and consequences (P% of fatalities)) on the human at various distances from source.

2. Methodology

The methodology was addressed the hazards and safety issues, which can arise during the storage systems from risk of fire to explosion. In addition identification some techniques can be applied to minimize the possible causes that may lead to hazards. FMEA and What If?, which are most techniques are applied.

2.1. The hazards and safety issues of hydrogen storage

The availability of any kind of ignition sources can cause accidents of fire or explosion in different components of hydrogen systems. These sources of ignition can be mechanical sparks as a result of closing valve rapidly or can be electrostatic discharge which can happen due to ungrouding the equipments. As well as it can be from welding or cutting operation in the area where the hydrogen stored. As it known the release of hydrogen (gas or liquid) can make flammable mixtures which can cause the hazards of fire or explosion. Therefore it will be very difficult to control the hydrogen in this situation of release, because the hydrogen can be diffused rapidly and increase the rate of dispersion with air. Additionally, the evaporation of hydrogen liquid can rapidly produce flammable mixtures and if these mixtures with air were ignited that can make accidents with ignitions to be occurred. BLEVE or flash fire can be happened with an external energy of heating to liquid hydrogen storage. These accidents can cause injuries, fatalities and property damage. Therefore, high level of protection should be applied to prevent these accidents from occurring.

2.2. Hazard Identification

Hazards identification is the first step in risk management and the most critical step in a risk assessment. The main objective of the hazards identification is to identify the all the potential hazards such as fire, explosion and toxic that could arise during the storage of the liquid systems. There are various techniques to indentify hazards and their major purpose is to identify the hazards themselves or indentify the failure cases that might initiate the

hazards. The choice of technique depends on the purpose of the study and to some extent the type of industries and process [10]. The techniques in this paper include, what if and FMEA, although FMEA is the method adopted to identify the potential hazards of hydrogen storage.

2.2.1. Failure Modes and Effect Analysis (FMEA)

The method focuses mainly on the individual component of a system, how they fail and the effect of their failures to the system and environment. The procedure follows as listed below [11, 12]. Describe the system: List system items, Identify faults for each item, determine the effects on other items the following items would be considered in the proposed FMEA. However, Table 2.1 the written report below describes the application of FMEA technique on hydrogen system with required actions to reduce the accidents failures [13, 14].

2.2.2. SWIFT technique (what if?)

The performance of SWIFT technique can be done by asking comprehensive questions about the possible hazards in the process and these questions will be started by (what if?). The benefits of this technique are considered the most hazards and its causes, and the ability of this application by one person who has good experience or more than one person (team), which depends on the complexity of the processes. In addition, the advantage of this method can be done in short time by simply way. After the assessment has been done, the expert should write his recommendations clearly, that should include the actions that must be taken to protect the system from the failures. This is some accidents which should be asked as the following [13]:

- What if the operating pressure increased inside the hydrogen's tank? Is the tank designed to operate under high pressure value?
- What if the pressure increased inside the vessel, is there any safety valve can open to relief the pressure inside and is there any ventilation system in the space to prevent the formation of flammable mixtures?
- What if the hydrogen released due to high pressure or external impact, is there any gas detection system in the area with the emergency alarms? And what if the accident occurred is there any flame detector?
- What if the pressure increased in the pipes due to high flow? Is there any alarms connected with the flow meter to show that the pressure increased, and is the flanges, gasket, and all the joints designed to resist the high pressure values

3. Case Study and Discussion

There are many accidents can occur during the process industry, as BLEVE scenario, this accident can happen owing to storage tank failures due to corrosion, or external impact which leads to tank rupture. These reasons cause rapidly leakage of flammable liquid and drop the pressure inside the vessel that includes liquefied hydrogen gas.

3.1. Case study

The produced hydrogen by reforming process is liquefied gas in the production site and the amount of hydrogen according to the design project "Hydrogen filling station for fuel cell vehicles" which belongs to 3rd year MEng group at Sheffield University is 300Kg [15]. The stored conditions must be under low temperature about -253 °C and pressure is 22 Mpa [15]. This storage feeds the filling station that may locate in the city centre. Hydrogen can be delivered as a liquid in tank trucks. Therefore, Liquid hydrogen is warmed in the vaporizer in order to be converted to gas before being fed to the compressor. Figure 3.1 illustrates the production process of hydrogen is called SMR, that produces the hydrogen to be used in the filling station. SMR uses the methane with rate 0.41 kg/sec, and steam with 0.87 at high temperature about 750-800 °C, which is carried on in the reformer. Furthermore, the process includes liquefaction step to convert the 300kg of H_2 gas to be stored in liquid phase at low temperature -253°C, therefore the quantity of LH_2 must be divided to be 150 kg/day to feed the filling station [15].

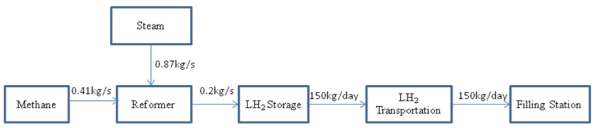

Figure 3.1: Flow chart of hydrogen storage tank in the production site [15]

3.2. Case Study Calculations

It is very necessary to calculate the diameter of fireball in case the accident BLEVE [16], because there

Table 2.1: FMEA (Hydrogen Storage System) [12, 14]

No	Item	Function	Failure Mode	Failure effects	Actions required
1	Inner Storage Tank	Store liquid H_2	• Mechanical failure due to corrosion or H_2 embrittlement • Overfilling of the tank • Overpressure of the tank	• Release of H_2 liquid, eventual pool formation, potential for pool fire • Vacuum loss between inner and outer tank • Release of H_2 liquid, eventual pool formation, potential for pool fire. • Rupture and subsequent release of H_2, potential for fire.	• Proper material selection, regular inspection such as pressure test. • High level trip • Pressure control system
2	Valve	Control flow of H_2 from the tanker into the storage tank	• Mechanical failure • Valve leakage • Valve stuck	• Release/leak of H_2, potential for fire • Same as above • Overpressurisation of the trailer tanker, possible rupture potential for fire/explosion	• Maintenance • Maintenance • Pressure control system
3	Seals	Prevent leakage	• Mechanical failure	• Release of H_2, potential for fire/explosion	
4	Flanges	Connection	• Non alignment	• Release of H_2, potential for fire/explosion	• Leak detector
5	Pressure Relief System	Relief excessive pressure from the system	• Mechanical failure • Spurious Opening • Fails to open on demand	• Release of H_2, potential for fire • Same as above • Overpressurisation of the storage tank, possible rupture, potential for fire.	• Regular inspection • Same as above • Same as above
6	Outer jacket	Store liquid H_2	• Insulation failure	• Over-pressurisation of the inner tank, possible release from the relief system, potential for fire.	• Proper material selection, regular inspection
7	High pressure storage tank	Store gaseous H_2	• Mechanical failure due to corrosion or H_2 embrittlement • Overpressure of the tank	• Release/leak of high pressurized H_2, potential for jet fire, flash fire, VCE • Release/leak of high pressurized H_2, potential for jet fire, flash fire, VCE • Rupture and subsequent release of high pressurized H_2, potential for jet fire, flash fire, VCE	• Proper material selection, regular inspection such as pressure test, load test. • High pressure trip and pressure relief valve.
8	Pressure relief on storage tank	Relief excessive pressure from the system	• Mechanical failure • SpuriousOpening • Fails to open on demand	• Release/leak of high pressurized H_2, potential for jet fire, flash fire, VCE	• Regular inspection, maintenance

are a huge amount of the thermal radiation must be founded which affects on the human, the calculated diameter (D), and height (H) (from the centre of fireball to ground) in this case is 38.83 and 29.12m respectively, which were estimated from the following Equations [11]:

$$D = 5.8\left(M^{1/3}\right) \tag{3.1}$$

$$H = 0.75\,(D) \tag{3.2}$$

where: the M is the amount of liquefied hydrogen. The required duration to make the fireball accidents is 3.012 sec was calculated from:

$$t = 0.45\left(M^{1/3}\right)\ for\, M < 30,000\, kg \tag{3.3}$$

These calculations include the determination of safety distances X fatalities by trial and errors by using the table in the module of applied hazard and emergency planning [5]. Indeed, the thermal radiation, I must determine depends on the percentage of fatality from the following Equation 3.4:

$$Y = -14.9 + 2.6ln\left(I^{1.5} \times t\right), for\, 5, 50, 95\% fatalities \tag{3.4}$$

$$F = H\,(D/2)^2 / \left(X^2 + H^2\right)^{3/2} \tag{3.5}$$

where: F is the view factor of fireball for vertical surface, the heat intensity is:

$$I = F \times E \times \tau \tag{3.6}$$

where: τ is the coefficient of atmospheric transmission, E is the radioactive emissive flux (energy/area time) which calculated from:

$$\tau = 1 - 0.056\, ln\,(x)\,,\ and \tag{3.7}$$

$$E = R \times M \times H/\pi \times (D_{max})^2 \times t \tag{3.8}$$

Where: R is the radiative fraction of the heat of combustion (unit less).
However, in case of 5% fatality, Y= 3.36 and by using Equation 3.4 to evaluate the I from Equation 3.6, then the safety distance which is measured from the point at the ground directly beneath the center of fireball on the receptors is 98 m, but this distance was decreased to 82 and 68 m for 50% and 95% fatality respectively. However, the other results of calculations were summarized in Table3.1. Beside, Figure 3.2 illustrates the fireball dimensions, which are the diameter (D), the height (H), the resultant flux, and the distance (X). These dimensions affect on the receptor, who will receive both the vertical and horizontal radiation, only horizontal radiation will affect on the human due to small fireball.

Table 3.1: The calculation's results of fireball on the receptor

Fatality, %	Duration, t Sec	Y	I, Kw/m^2	Distance, X meter
5%		3.36	91.86	98
50%	3.012	5.00	148.83	82
95%		6.64	239.98	68

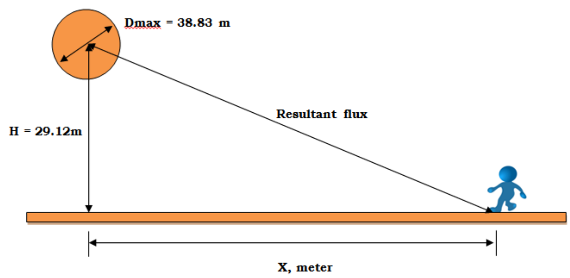

Figure 3.2: The effect of fireball on the receptor

From the fireball effect calculations, the receptor will receive the only horizontal radiation not vertical, which can affect on the people, because the fireball will not rise too much owing to small diameter 38.83m and the quantity of hydrogen compared to the other hydrocarbons that can be stored in big amounts. However, it is known to increase the safety considerations, there are some ideas about safety requirements to prevent mitigate of the hydrogen release. It is called Protective and Preventive method must be taken into considerations, to prevent the accidents such as fireball during the production or storage situations that have the flammable materials namely hydrogen (gas or liquid). These accidents affect on people who live or work nearby storage systems, because the hydrogen burns with invisible flame. The system should provided by following issues that should be taken during storage process such as, equipment design and pipelines; This means that the selection of material design of pipelines & storage should be done under high level of standard specifications. These materials must have resistance against corrosion due to environments conditions and affect of hydrogen embrittlements. Thus, the main problem such as release and risk of hydrogen release can be raised if the equipment and pipelines leakage. On other hand, the emergency shutdown system (ESD) is a part of "Automatic protection system" which is installed in process to reduce the hazard events in the process by stopping automatically the operation of unit that includes failures may affect on the people and environments. Although, the gas & flame detection and alarms is necessary to action due to hydrogen fuel can burn with invisible flame; this reason make high level of attention should be consideration. The different types of detectors are very important in chemical industries as the aim of installing these detectors is to give warning before flammable mixture formed, which cause fire & explosion [16].

4. Conclusion

It is clear that there are many hazards storage system can be raised and affect on the people who live or work in these areas, these hazards in this process can be presented because fails in some procedures operation or maintenance, or human errors. The application of hazard identification techniques in done depending on the personal knowledge, but the in fact the performance of these techniques requires good information and experience that should be provided from project management to team work. In this paper, the two techniques are applied which are FEMA and WHAT IF?, which showed the possible causes that may lead to hydrogen release and accidents and giving the required actions to be considered to avoid and prevent the accidents. However, there are also some other techniques can be applied before loading and uploading process the hydrogen fuel, this technique very effective method that is called (HTA) "Hierarchical Task Analysis", as well as the technique of T.A "Task Analysis" can be very useful to identify the possible causes of hazards related to human errors and the human factors that plays important point in the investigation the accidents.

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