SAFETY ASPECTS OF HYDROGEN TECHNOLOGIES

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ABSTRAKT

Vodíkové technologie skýtají jistou možnost pro transfer energetického mixu směrem od uhlovodíkových zdrojů vůči méně zdrojům produkujícím méně CO_2. Tyto technologie – tak jako jakékoliv ostatní – v sobě skrývají určitá bezpečnostní rizika vyplývající z charakteristik samotného vodíku jako chemické látky, ale také ze způsobu její výroby, transportu, skladování a použití.

Tento článek se zaměřuje na určení rizika exploze – konkrétně jejího rozsahu, velikosti a dopadu na lidi a konstrukce. Riziko exploze je vyhodnoceno pro konkrétní use-case, kdy je uvažován únik vodíku ze zásobníku. Jsou uvedeny základní charakteristiky vodíku a způsoby jeho uchovávání. Dále jsou popsány metody určení rizika exploze konkrétního use-case uchovávání vodíku. Výsledky modelu jsou uvedeny následně. Výsledky jsou dále rozebrány v kontextu proběhlých havárií vodíkových úložišť.

KLÍČOVÁ SLOVA

Vodík • Technologie • Bezpečnost • Risk Assessment • Consequence Analysis

ABSTRACT

Hydrogen technologies represent an opportunity for a transfer of the energy mix towards less CO_2 emitting sources. These technologies - like any other - carry certain safety risks arising from the characteristics of the chemical itself, but also from the way it is produced, transported, stored, and used.

The paper focuses on determining the risk of an explosion - specifically its scope, magnitude and impact on people and structures. The explosion risk is evaluated assuming specific use-case of a hydrogen storage tank. Basic hydrogen characteristic and storage methods are presented. Methods for determining the explosion risk of a specific use-case of hydrogen storage are described. The results of the model are presented subsequently. The results are further discussed in the context of past hydrogen storage accidents.

KEYWORDS

Hydrogen • Technologies • Safety • Risk Assessment • Consequence Analysis

1. INTRODUCTION

When designing any engineering structure, transportation facility or public building, specifics of the building and its operations should be examined. More in the previous works of the author (Kostalova 2022, Kostalova 2021). Hydrogen as a foremost candidate for solving the European emission policies – not only as a chemical substance itself – moreover the technologies coming together with the substance – is posing new risks and challenges for the engineers.

Moreover, as the public is not yet familiar with the modern technologies, the safety concerns may play a part in argumentation against hydrogen. Key thing is to comprehend the shortcomings of the technologies and put the assets to the forefront to develop a safe system. The system may include the transport – shall it be trucks or pipelines, hydrogen production – obtaining it directly from fossil fuels or by dividing water molecules via electrolysis, or hydrogen storage (the means of storage are given following).

1.1. Hydrogen storage means

The choice of the volume of the hydrogen storage is connected to the use and way of storing the substance. Two basic ways exist. As hydrogen is a gas in standard conditions with a very low density – 0.084 kg/m^3 (air is 1.205 kg/m^3) - more condensed phase is sought by:

1. Liquefying the hydrogen. The phase transition of hydrogen is dominated by low temperatures such -250°C. The main risk assessment the ratio of the final volume to the initial is 847 from liquid to gaseous state. That can result in a final pressure of 177 MPa in a closed tank if loss of coolant accident happens. (Molkov, 2012)
2. Compressing the hydrogen in gaseous phase. Current hydrogen-driven automobiles carry storage (hydrogen tank) with pressurized hydrogen with up to 700 bars (~70 MPa). Other use cases can however only use pressure of 35 bars.

The paper considers the latter mean of storage for further examination.

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Figure 1: *Visualisation of 3 compression use cases with a same amount of hydrogen – 5 kg. From the left – 700 bar, 350 bar and 1 bar. Visualized by the author.*

1.2. Understanding hydrogen

Understanding the characteristics and behaviour of the substance is the key for assessing potential risks (Molkov, 2012):

- Hydrogen is colourless, odourless, and insipid. These characteristics make the leak difficult to detect.
- The flammability range of hydrogen is wider compared to most hydrocarbons, i.e., 4% to 75% by volume in air at STP (standard temperature and pressure).
- Low density of 0.084 kg/m^3. More condensed way of storage is then sought (as previously mentioned). Asset of this characteristics is, that in the case of leakage a rather fast buoyancy occurs. This fact minimizes the risk of clustering of hydrogen (when the storage is in unconfined place).
- Diffusivity is two orders higher than gasoline - D=6.1E-05 m^2/s compared to that of gasoline 6.348 E-07. That needs to be paid attention when assessing a leakage in confined places (e.g., diffusion to gypsum panels in the confined room).
- High TNT equivalent. 1 g of hydrogen is energetic equivalent of 28.65 g of TNT.
- Auto-ignition temperature is above 510° C.
- Low energy of ignition source. Ignition sources - mechanical sparks from rapidly closing valves, electrostatic discharges in ungrounded particulate filters, sparks from electrical equipment, catalyst particles, heating equipment, lightning strikes near the vent stack, should be eliminated.
- Hydrogen can cause a significant deterioration of the metals' mechanical properties. Choice of the material for the tanks, combination of materials and welds of the steel tanks are the aspects to be properly examined before the use

1.2.1. Joule-Thomson effect – asset or a challenge?

The Joule-Thomson effect is present phenomenon at situations where compressed gases expand to standard pressure area. Most gases cool when expanded across a porous plug – the example may be CO2 extinguishers (for this reason CO_2 extinguishers have a special hose which protects the hand from being frozen by the gas).

When Joule-Thomson coefficient is positive, the cooling occurs. That, for hydrogen, applies for temperatures around -220 °C. At room temperature the coefficient is negative which means, that unlike majority of the gases, hydrogen slightly warms up when going from high pressure to lower pressure area. (Molkov, 2012)

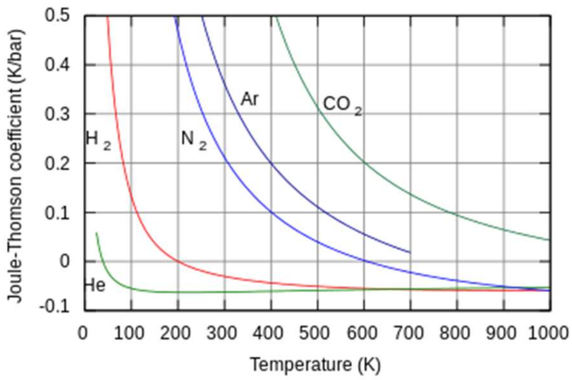

Figure 2: *Joule-Thompson coefficient dependency on temperature.*

Yet, the warming up is only few degrees Celsius. That is – the ignition temperature is not reached unless it was already close to it.

2. METHODS

A situation of discharge of hydrogen from its storage in 50.000 l cylinder is modelled to determine the risks of an explosion.

ALOHA (Areal Locations of Hazardous Atmospheres) developed by Office of Emergency Management and Emergency Response Division is used for purposes of the paper. The modelling program estimates threat zones associated with hazardous chemical releases. Threat zone is an area where a hazard – such an explosion – exceeds user-specified level of concern.

The scenario assumes a hydrogen storage. The storage is a cylinder 2.3 m in diameter and 12 m long. The volume of the cylinder is 50 m^3. The hydrogen is used for the purposes of hydrogen-driven vehicle filling. The operative pressure in the cylinder is 350 bar.

Then, relief valve is incorporated. Diameter of the relief valve is 12 mm. In case the pressure in the storage starts to rise and reaches a critical value, the relief valve releases the overpressure below the critical value. The scenario assumes discharge of the whole amount of the storage – that is – valve stays open. The cause of the valve opening is not further examined in the paper.

Figure 3: *Hydrogen tank, taken from its producer's offer. (Chart Industries, 2023)*

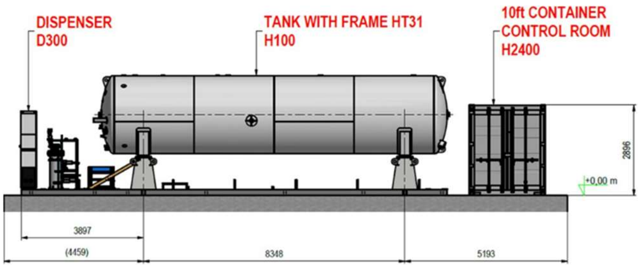

Figure 4: *Commercial picture and visualisation of assumed hydrogen tank. (Chart Industries, 2023)*

The hazardous area of a vapor cloud explosion is modelled. The scenario assumes a wind of 3 m/s. The location is an industrial site within suburb neighbourhood.

3. RESULTS

The results of the modelling of a hazardous scenario when a controlled discharge of a hydrogen from storage occurs.
The flow rate is given in the Figure 5. The scenario assumes that the discharge is not burning as it leaks from the tank.

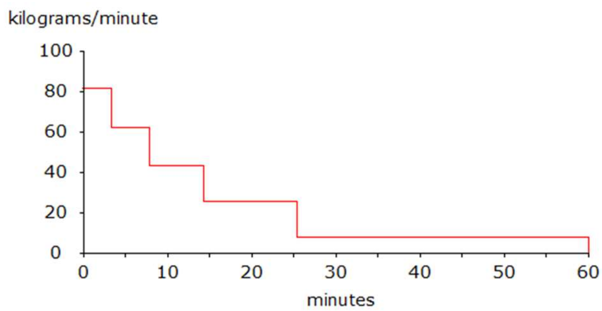

Figure 5: *Flow rate kg/min of the hydrogen discharge from the tank.*

The overpressure from vapor cloud explosion is given in Figure 6. There are 3 levels of concern - with the specific values of overpressure given in Table 1. The overpressure at Level 1 is strong enough to shutter glass in the hazardous area. The overpressure at Level 2 may cause serious injuries. Level 3 may destruct buildings in the hazardous area.

Table 1: *Levels of concern according to the value of overpressure from explosion.*

Level of concern	Overpressure *[psi]*	Overpressure *[bar]*
1	1.0	0.07
2	3.5	0.25
3	8.0	0.55

The results show, the explosive vapor cloud is categorized as Level 1. The overpressure value is greater than 0.07 bar, but not exceeding the 0.25 bar. The area of explosion may reach up to 150 m downwind. The area hovers around 11.500 m^2, or 2.7 acres.

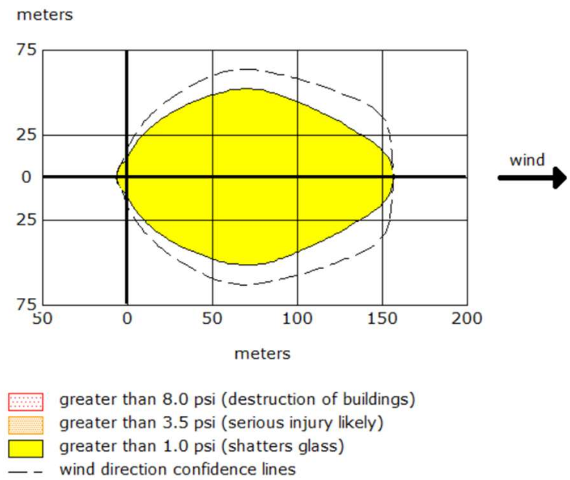

Figure 6: *Overpressure from vapor cloud explosion.*

The modelling programme also exports a .klm file. The .klm file can be incorporated into Google Earth maps to evaluate the impact in the area directly.

Figure 7: *Area of overpressure from vapor cloud explosion incorporated into the Google Earth maps.*

Then a specific precaution may be implemented – e.g., anti-shattering PE layer for windows. The layer does not prevent the glass from breaking due to the overpressure, but it prevents the sharp pieces from flying around at high speed. In case larger overpressure was assumed, special detection and warning system could be designed in case of leakage - to ensure protection of the workers in the area.

4. DISCUSSION

Does controlled hydrogen leakage possess a noteworthy threat? According to the simulation and hydrogen chemical characteristics, the hazard may not be as big as with the hydrocarbon counterparts.

The serious hazard occurs when the hydrogen is ignited in the tank or if the overpressure in the tank is rising faster than the relief valve releases the overpressure (e.g., due to outside heating source).

The latter situation which could lead to profound consequences has already occurred. Thanks to early action of the response teams, no injuries or material damages (except for the truck) happened.

A truck carrying 20 tanks - 0.6 m in diametre and 4 m long – storying gaseous hydrogen under pressure of 500 bar ignited in a habituated neighbourhood. At first, the emergency brigade has not been informed of the hazardous material and approached the burning truck directly. (Los Angeles County Fire Department, 2020)

After the response team discovered what kind of chemical was in place, immediate evacuation process within 0.8 km started – as shown in the Figure 8. The response teams started to cool down the truck from protected places. The idea was to keep cooling the truck to prevent a fast heating of the bottles. In case of fast heating – induced by the fire – the overpressure rise could exceed the speed of the relief valve discharge. (Los Angeles County Fire Department, 2020)

Figure 8: *Picture of the evacuated area in the vicinity of the ignited truck carrying the explosive and flammable gas. (Los Angeles County Fire Department, 2020)*

In case a rapid rise of the pressure and tank rupture, the consequences of mixing very condensed hydrogen with the air could be immerse. (Los Angeles County Fire Department, 2020)

Figure 9: *Picture of the tanks carried of the truck, checked after the burning seized. (Los Angeles County Fire Department, 2020)*

Another incident in occurred at River Plant in Ohio in 2007. The relief valve on a hydrogen tank failed, ignited by an unknown source which led not only to serious material damage, but to eleven injuries from one of which was fatal.

Figure 10: *Damages made by hydrogen explosion at Muskingum River Power Plant's 585-MW coal-fired supercritical Unit 5. (Neville, 2009)*

Hence, hydrogen, if not manipulated correctly, possess a risk. The only need is to understand the risks and manage them – as with any other fuels (e.g., hydrocarbon) or other technologies.

5. CONCLUSIONS

The paper aimed at evaluation of a risk connected to a leakage of hydrogen from its storage.

At first, the hydrogen characteristics – connected to safety - are given to introduce the safety assets and challenges of the substance. The assumptions and method used for the scenario model are given. Then, the results of the model are presented.

Lastly, previous hydrogen storage accidents are discussed and thoughts on comparison to hydrocarbon fuel safety given.

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