EH2TA

Education in Hydrogen Technologies Area

HYDROGEN STORAGE AND TRANSPORT

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CONTENT

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INTRODUCTION

Hydrogen can be stored in a variety of ways, including as a gas, a liquid, or in a solid form such as a metal hydride or chemical compound. The most common method of hydrogen storage is as a compressed gas in high-pressure tanks. This method has the advantage of being relatively simple and inexpensive, but the storage density is relatively low, so large tanks are required to store a usable amount of hydrogen.

Hydrogen can also be stored as a liquid in cryogenic tanks, which are tanks that are designed to store materials at extremely low temperatures. Liquid hydrogen has a much higher storage density than gaseous hydrogen, so it can be stored in smaller tanks. However, the tanks and equipment needed to store and handle liquid hydrogen are more expensive and complex than those needed for compressed gas storage.

Another method of hydrogen storage is to store it in a solid form, such as in a metal hydride or chemical compound. This method has the advantage of being able to store large amounts of hydrogen in a small space, but it is generally more expensive and less efficient than the other methods.

There are also several methods for transporting hydrogen, including by truck, train, ship, and pipeline. The most common method is by truck, using tanks that are similar to those used for storing hydrogen. Hydrogen can also be transported by train or ship in cryogenic tanks, or it can be transported through pipelines like natural gas.

Overall, the development of effective and efficient methods for storing and transporting hydrogen is an important area of research and development, as hydrogen has the potential to be a way of storing energy.

1 WORK SAFETY DURING STORAGE AND TRANSPORTATION OF HYDROGEN

Hydrogen is a highly flammable gas and must be handled with care to ensure safety. When stored or transported, hydrogen must be kept at high pressures or extremely low temperatures to reduce the risk of explosion. This can make storage and transport more challenging and expensive than for other types of fuel.

One of the key concerns with hydrogen storage is the potential for leaks. Hydrogen can leak from storage tanks and pipelines, which can lead to the formation of flammable or explosive mixtures. To minimize the risk of leaks, storage tanks and pipelines must be designed and constructed to strict safety standards. Regular inspections and maintenance are also crucial to ensure that these systems remain in good working order.

When transporting hydrogen, it is usually done by truck, rail, or ship. Truck and rail transport are typically done in large, specially-designed tanks or containers that can withstand the high pressures or low temperatures needed for hydrogen storage. Shipping hydrogen is usually done in cryogenic liquid form, which requires insulated containers that are designed to keep the hydrogen at extremely low temperatures.

Another key safety concern is the potential for hydrogen fires and explosions. Hydrogen is a highly flammable gas, and if it leaks and comes into contact with an ignition source, it can cause a fire or explosion. To minimize the risk of hydrogen fires and explosions, storage and transport facilities must be located away from populated areas, and must have fire suppression systems in place.

Overall, hydrogen storage and transport requires strict adherence to safety protocols, proper equipment design and maintenance, and emergency response plans are in place to minimize potential hazards. While hydrogen has the potential to be a way of storing energy, it's important that proper safety measures are taken to protect people and property.

Potential risks associated with the storage of compressed hydrogen gas:

- Difficult to identify hydrogen release because the gas is odourless, colourless and tasteless.
- Hydrogen can cause metals to embrittle. This can lead to a reduction in the strength of the material and subsequently to the rupture of the container, resulting in a hydrogen leak.

- Accumulation of hydrogen for long periods of time in confined spaces such as a garage or mechanical workshop, vehicle passenger compartments. Suffocation may occur due to displacement of air by hydrogen.
- Formation of flammable hydrogen-oxygen or hydrogen-air mixtures. Suction of flammable mixture into the ventilation system of a building may lead to detonation.
- Explosion of the container accompanied by a pressure wave can lead to damage to the eardrum, rupture of the container, flying debris, breakage of glass, etc.
- Hydrogen is easily ignited because its MIE is 0.017 mJ (which is 10 times lower compared to other fuels). A static spark can ignite the released hydrogen.
- When pure hydrogen burns, its flames are invisible in daylight.
- Hydrogen burns quickly and does not produce smoke.
- External fire, heat or thermal radiation can cause mechanical rupture of the tank due to thermal decomposition of polymer and composite materials (Hy Responder Lecture 3: Hydrogen storage, 2021, s. 13-14).

General guidelines for working safely with hydrogen gas:

- Follow all safety regulations and guidelines for handling hydrogen gas. This may include wearing personal protective equipment such as gloves, goggles, and flame-resistant clothing.
- Use caution when handling hydrogen gas cylinders or other containers. These should be handled with care to avoid damage to the container, which could lead to a leak or release of hydrogen gas.
- Keep hydrogen gas away from sources of ignition, such as open flames, sparks, and electrical equipment.
- When transporting hydrogen gas, make sure that the gas is contained in a suitable container that is designed for hydrogen gas and is in good condition.
- Store hydrogen gas in a well-ventilated area, away from sources of ignition.
- Use caution when transferring hydrogen gas from one container to another. Make sure that the containers are properly secured and that the transfer is done slowly to avoid spills or leaks.
- In case of a hydrogen gas leak or spill, evacuate the area immediately and ventilate the area to disperse the gas. Do not attempt to repair the leak or spill yourself; instead, call for professional help.
- Regularly check the condition of hydrogen gas containers and equipment to ensure that they are in good working order and do not pose a safety risk.

- Make sure that all workers handling hydrogen gas are properly trained and familiar with the hazards associated with the gas.

Picture no. 1: Warning board.

2 HYDROGEN TRANSPORTATION

INTRODUCTION

Hydrogen can be transported in several ways, including by truck, ship, rail and pipeline.

One common method of transporting hydrogen is by truck, using cryogenic liquid tanker trailers. These trailers are designed to carry liquified hydrogen at extremely low temperatures (-253°C), which reduces the volume of the hydrogen and allows for more efficient transport.

Another option is to transport hydrogen by ship, either as a cryogenic liquid or as a compressed gas. Cryogenic liquid hydrogen can be shipped in specialized tankers, similar to those used for transporting liquified natural gas (LNG). Compressed hydrogen gas can also be shipped in containers that are designed to withstand high pressures.

Finally, hydrogen can also be transported through pipelines, just like natural gas. This method is generally only practical over short distances, as hydrogen tends to leak out of pipelines more easily than natural gas. However, it can be an efficient option for moving hydrogen from a production site to a nearby storage or distribution center.

KEYWORDS

Liquified hydrogen, compressed hydrogen pipeline, container, transport, tanker, train, truck, gas, ship, membrane separation, LOHC

2.1 COMPRESSED HYDROGEN TRANSPORTATION IN CONTAINERS BY ROAD OR RAILS

Hydrogen can be transported in containers by road, either as a compressed gas or as a liquid. When hydrogen is transported as a compressed gas, it is typically stored in high-pressure tanks that are mounted on a trailer or truck. The tanks are typically made of carbon fiber or steel and are designed to withstand the high pressures at which hydrogen is stored.

There are a number of factors to consider when transporting hydrogen by road, including the size and weight of the containers, the potential for leaks or accidents, and the need to follow safety regulations. It is important to ensure that the containers are properly designed and maintained, and that the drivers are trained to handle the containers safely. In addition, it is important to follow all relevant regulations and guidelines.

There are a number of advantages to transporting hydrogen by train, including the ability to transport large quantities of hydrogen over long distances, the relatively low cost of rail transport compared to other modes of transportation, and the reduced impact on the environment compared to other modes of transportation. However, there are also some challenges to consider, such as the need to follow safety regulations and the potential for accidents or leaks. It is important to ensure that the containers are properly designed and maintained, and that the railcars are equipped with the appropriate safety features.

Hydrogen can be transported in tree states. In gaseous state it can mainly be transported in high numbers of small cylinders or stored in several long horizontal vessels.

Platts data shows that while a single truck can carry between 500 kg and 1,100 kg of hydrogen in gaseous form, a truck carrying liquefied hydrogen can carry up to 3,500 kg (S&P Global Commodity Insights, 2021).

These days hydrogen is mostly transported as compressed gas in pressure containers made of iron or carbon tubes composites. Hydrogen in pressure vessels can be transported in pressure cylinders at the pressure of 200 - 300 bars. Hydrogen fueled vehicles use smaller pressure tanks with the pressure 350 or 700 bar for their use.

Picture no. 2: Hydrogen transportation in containers by road.

2.2 LIQUIFIED HYDROGEN TRANSPORTATION IN CONTAINERS BY ROAD, RAIL OR SHIP

Hydrogen can be transported in its liquid form, which is called cryogenic liquid hydrogen (LH2). It must be stored and transported at extremely low temperatures, typically around -253°C. LH2 has a number of advantages as a transportation fuel. It has a high energy density, meaning that a relatively small amount of LH2 contains a large amount of energy. It is also a clean-burning fuel, producing only water when it is burned.

However, there are also a number of challenges associated with the transportation of LH2. It requires specialized and expensive storage and transportation infrastructure, as it must be kept at extremely low temperatures to remain a liquid. It is also a highly volatile fuel, which can pose safety risks if it is not handled properly. Despite these challenges, LH2 has the potential to be an important transportation fuel in the future, particularly for the movement of goods over long distances.

Hydrogen can be transported by road in liquid form in specialized cryogenic tanker trucks, which are designed to carry liquids that are extremely cold, such as liquid hydrogen. These tanker trucks are usually made of stainless steel and are insulated to help maintain the extremely low temperature of the liquid hydrogen. The tanks themselves are designed to withstand the high pressure that is generated by the expansion of the liquid hydrogen as it warms up.

To load the liquid hydrogen onto the tanker truck, it is transferred from a storage tank to the tanker truck using a transfer line. The transfer line is equipped with a series of valves and safety devices to prevent spills and accidents. The tanker truck also has its own safety systems, such as pressure relief valves, to prevent accidents during transportation.

Once the tanker truck is loaded with liquid hydrogen, it can be transported to its destination using the same roads and highways that other vehicles use. The driver of the tanker truck must be specially trained to handle the unique properties of liquid hydrogen and to follow all safety protocols. The tanker truck must also be driven carefully to avoid jostling the tank, which could cause the liquid hydrogen to boil and turn into gas, increasing the pressure inside the tank.

It is important to note that transportation of hydrogen in any form, including liquid hydrogen, comes with certain risks and requires strict safety measures to be in place to prevent accidents.

Transporting hydrogen by ship is a potential option for moving large quantities of hydrogen over long distances. However, there are several challenges that need to be addressed in order to make this a viable option. One challenge is the design of the cryogenic containers that can withstand the rough conditions of being shipped at sea. In addition, there are safety considerations to take into account when handling and storing cryogenic liquids, such as the risk of spills and leaks.

Despite these challenges, there are ongoing efforts to develop safe and cost-effective methods for transporting hydrogen by ship. For example, the European Union's HYFLEET:CUTE project demonstrated the feasibility of using a small-scale vessel to transport hydrogen from offshore production facilities to ports for distribution. In the future, it is possible that hydrogen could be shipped in larger quantities using dedicated vessels that are specifically designed for the transport of cryogenic liquids.

Picture no. 3: Liquified hydrogen transportation in containers ship.

2.3 HYDROGEN TRANSPORTATION BY PIPELINE WITH NATURAL GAS MIXTURE

Hydrogen can be transported by pipeline in a mixture with natural gas, but it requires a specific infrastructure and careful handling. When hydrogen is mixed with natural gas, the mixture is called "hydrogen-enriched natural gas" or "HENG." The concentration of hydrogen in the mixture is typically between 10% and 20%.

One advantage of transporting hydrogen in this way is that it allows for the use of existing natural gas pipelines, which can be more cost-effective than building new pipelines specifically for hydrogen. However, there are also several challenges and considerations to keep in mind when using HENG for transportation.

One challenge is that hydrogen is highly reactive and can corrode certain materials, such as some types of steel. This means that the pipelines used for HENG must be made of materials that are compatible with hydrogen, or they must be coated with a protective layer. In addition, hydrogen has a lower energy content than natural gas, so the heating value of HENG is lower. This means that HENG requires a larger volume to provide the same amount of energy as pure natural gas.

Another consideration is that HENG must be carefully handled and stored to prevent leaks or accidents. For example, HENG must be kept at high pressure to reduce its volume and make it easier to transport. This means that the storage and handling facilities used for HENG must be designed to withstand the high pressures involved.

Overall, while hydrogen-enriched natural gas can be an effective way to transport hydrogen, it requires specialized infrastructure and careful handling to ensure the safety and efficiency of the process.

Hydrogen has a lower heating value than natural gas at the same pressure and volume. Its heating value is about 30 % of natural gas. It will not cause any problems at selling gas to customers as the current price for gas distribution is charged in units of energy (distributed KWh) according to heating value and the used invoice systems has to change the heating value of the gas on the basis of actual measurements.

To provide the same amount of heat it is necessary to deliver more hydrogen than natural gas. An advantage of hydrogen lies in a lower resistance while flowing through pipelines, which means that the mixture of natural gas with hydrogen can therefore flow faster. The present flow rate capacity of pipelines does not pose a limitation for the natural gas and hydrogen mixture as far as the transported heat amount is concerned (Vodíková strategie České republiky, 2021, s. 77-78).

2.4 SEPERATION OF HYDROGEN FROM THE NATURAL GAS MIXTURE USING MEMBRANE GAS SEPARATION

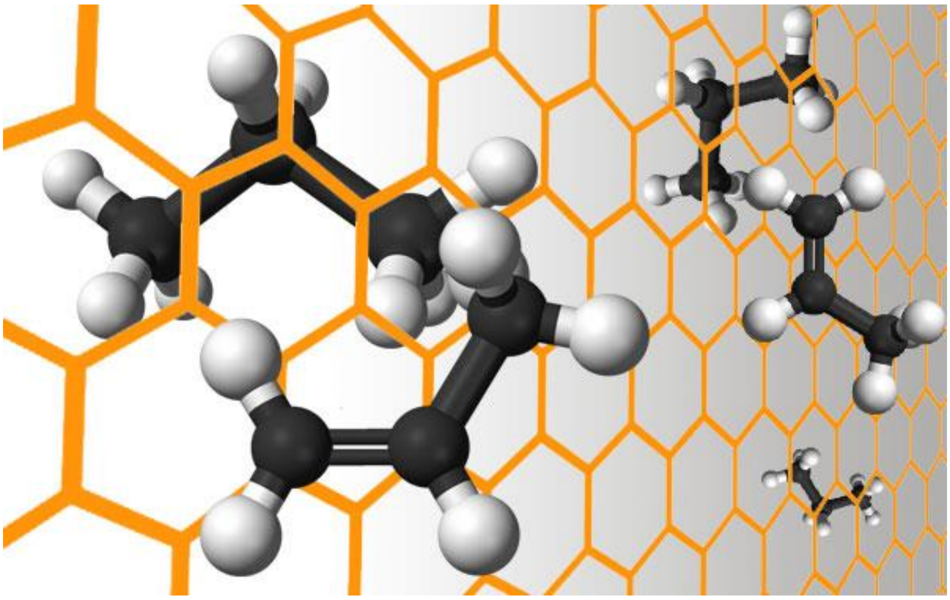
Membrane gas separation is a process in which a gas mixture is separated into its individual components using a membrane. The membrane allows some gases to pass through while preventing others from passing through. In the case of separating hydrogen from a natural gas mixture, a membrane that is selective for hydrogen can be used.

There are several different types of membranes that can be used for hydrogen separation, including polymer membranes, inorganic membranes, and metal organic frameworks (MOF). Polymer membranes are made from polymers such as polysulfones and polyamides, and they are often used for separating hydrogen from natural gas mixtures due to their high selectivity for hydrogen. Inorganic membranes, such as ceramic and glass membranes, are also used for hydrogen separation, but they are generally less selective than polymer membranes. MOF are a relatively new type of membrane that have high surface areas and tunable pore sizes, making them highly effective at separating gases.

The process of separating hydrogen from a natural gas mixture using a membrane typically involves pressurizing the gas mixture on one side of the membrane, while maintaining a lower pressure on the other side. The hydrogen molecules are then able to pass through the membrane and into the lower pressure side, while the other gases are unable to pass through. The separated hydrogen can then be collected and used as a fuel or feedstock for chemical processes.

It's important to note that the efficiency of the separation process can be affected by a number of factors, including the type of membrane used, the pressure difference across the membrane, and the temperature of the gas mixture. In addition, the purity of the separated hydrogen will depend on the selectivity of the membrane and the composition of the starting gas mixture.

It is still a rather new and not well tested process. Nevertheless, using the present gas infrastructure is a great opportunity and it enables significant lowering of costs on H_2 transportation and lowering its final price for a customer. A membrane separator itself is a relatively cheap device which has a potential in scalability. Unfortunately, even here we come across certain imperfection, for example an incomplete gas separation. This technology is also difficult to be used in sections which are branched. In this case, we are talking about a problem which is connected with uneven allocation of hydrogen in constituent branches. It could cause some customers to receive insufficient amount of hydrogen. A risk of a supplied energy shortage is generally obvious even from the whole idea of such a system. For example, if there were only 20 % of pipelines "reserved" for hydrogen, meaning for the only medium carrying energy for the end customer, there would be a significant reduction in accumulative and transferring capabilities of such a pipeline (Galík, 2021, s. 63).



Picture no. 4: Membrane gas separation.

2.5 CLEAN HYDROGEN TRANSPORTATION THROUGH AN EXISTING GAS PIPELINE ADJUSTED TO CLEAN HYDROGEN

It is possible to transport hydrogen through an existing natural gas pipeline by adjusting the pipeline to handle hydrogen gas. This can be done by reducing the pressure of the pipeline, increasing the wall thickness of the pipeline to withstand the higher pressures of hydrogen gas, and adding hydrogen-specific materials to the pipeline to prevent corrosion. The process of adapting an existing natural gas pipeline for hydrogen transportation is known as "repurposing."

This process involves a number of steps, including:

- Cleaning and purging the pipeline: The pipeline must be cleaned and purged of any residual natural gas or other contaminants before hydrogen can be transported through it.
- Inspecting the pipeline: The pipeline must be inspected for any defects or damage that could compromise its integrity during hydrogen transmission.
- Making necessary repairs: Any defects or damage that are found during the inspection process must be repaired before the pipeline can be used for hydrogen transmission.
- Adjusting the pipeline operations: The pipeline's operating pressure and flow rate may need to be adjusted to accommodate hydrogen transmission.
- Adding hydrogen-specific infrastructure: The pipeline may need to be equipped with additional infrastructure, such as hydrogen-specific pumps and compressors, to facilitate the transmission of hydrogen.
- Ensuring safety: It is important to implement safety measures, such as installing hydrogen detectors and emergency shutdown systems, to ensure the safe transmission of hydrogen through the pipeline.
- Replace instrumentation for ATEX IIC class electrical equipment in the Hydrogen plant/pipeline.

One potential advantage of using an existing pipeline for hydrogen transportation is that it can save time and money compared to building a new pipeline specifically for hydrogen. However, there are also some challenges and risks associated with repurposing a pipeline for hydrogen. For example, it is important to carefully assess the condition of the pipeline and ensure that it is suitable for hydrogen transportation. It is also important to consider the impact on the local community and environment during the repurposing process.

The European Hydrogen Backbone study counts with the idea that 75 percent of the hydrogen distribution network should be based on the existing infrastructure, the remaining 25 percent will have to be built up. The EU counts with a shortage of clean hydrogen until 2030 at least, which will mean a need for import (Galík, 2021, s. 62).

Hydrogen can come from many more countries than natural gas. This makes imports less geopolitically dependent.

2.6 PURE HYDROGEN TRANSPORTATION THROUGH A NEW CONSTRUCTED PIPELINE

Hydrogen can be transported through pipelines in its gaseous form, just like natural gas. The construction of a hydrogen pipeline is similar to that of a natural gas pipeline, with some important differences to take into account the unique properties of hydrogen.

Here are some key considerations for the construction of a hydrogen pipeline:

- Materials: The materials used for the construction of the pipeline must be able to withstand the corrosive nature of hydrogen. Carbon steel, for example, is not suitable for use in hydrogen pipelines, as it can corrode over time. Instead, materials such as stainless steel, aluminum, or special alloys such as inconel or hastelloy can be used.
- Pipe diameter: The diameter of the pipe should be chosen based on the desired flow rate and pressure of the hydrogen. As hydrogen has a lower density than natural gas, the required pipe diameter may be larger for a given flow rate.
- Welding: Welding is a critical step in the construction of any pipeline, and special precautions must be taken when welding hydrogen pipelines. Hydrogen can form flammable mixtures with air, so it is important to purify the air around the welding area and use shielding gases to prevent the formation of explosive mixtures.
- Safety systems: Hydrogen pipelines must have a number of safety systems in place to prevent accidents and leaks. These can include overpressure protection, leak detection systems, and emergency shutdown systems.
- Permitting: As with any major construction project, building a hydrogen pipeline will require obtaining the necessary permits and approvals from relevant government agencies.

Overall, the construction of a hydrogen pipeline requires careful planning and attention to detail to ensure the safe and efficient transport of hydrogen.

Transportation through gas pipelines is realized in case of cumulation of many producers and customers in one location. In the world there are many rather large networks, the most important one probably in Germany where the total length of network exceeds 200 km. The operational pressure in this network is 2.5 MPa, the transportation capacity of the network is 50 mil. m^3 per hour. The pipeline has a diameter of 20 cm and it is placed one meter under the ground. The operational loss is about 1%. In the USA (Texas), there is a network 96 km long with similar parameters. Other two smaller are, for example, in France, the UK and other countries. There are more than 1000 km operational hydrogen pipelines in the world (Šváb, 2006, s. 25-26).

Picture no. 5: Hydrogen transportation by pipeline.

2.6.1 THE EUROPEAN HYDROGEN BACKBONE

The European Hydrogen Backbone (EHB) is a proposed infrastructure project that aims to support the use of hydrogen as a clean energy source in Europe. It is intended to be a comprehensive network of hydrogen production, storage, and distribution facilities that will be built across the European Union (EU). The goal of the European Hydrogen Backbone is to enable the widespread adoption of hydrogen technologies in the EU, particularly in sectors where it is difficult to decarbonize using other technologies.

The European Hydrogen Backbone is expected to be a key element of the EU's efforts to decarbonize its energy system and to meet its climate and energy targets. It is intended to support the development of a number of sectors, including transport, industry, and power generation.

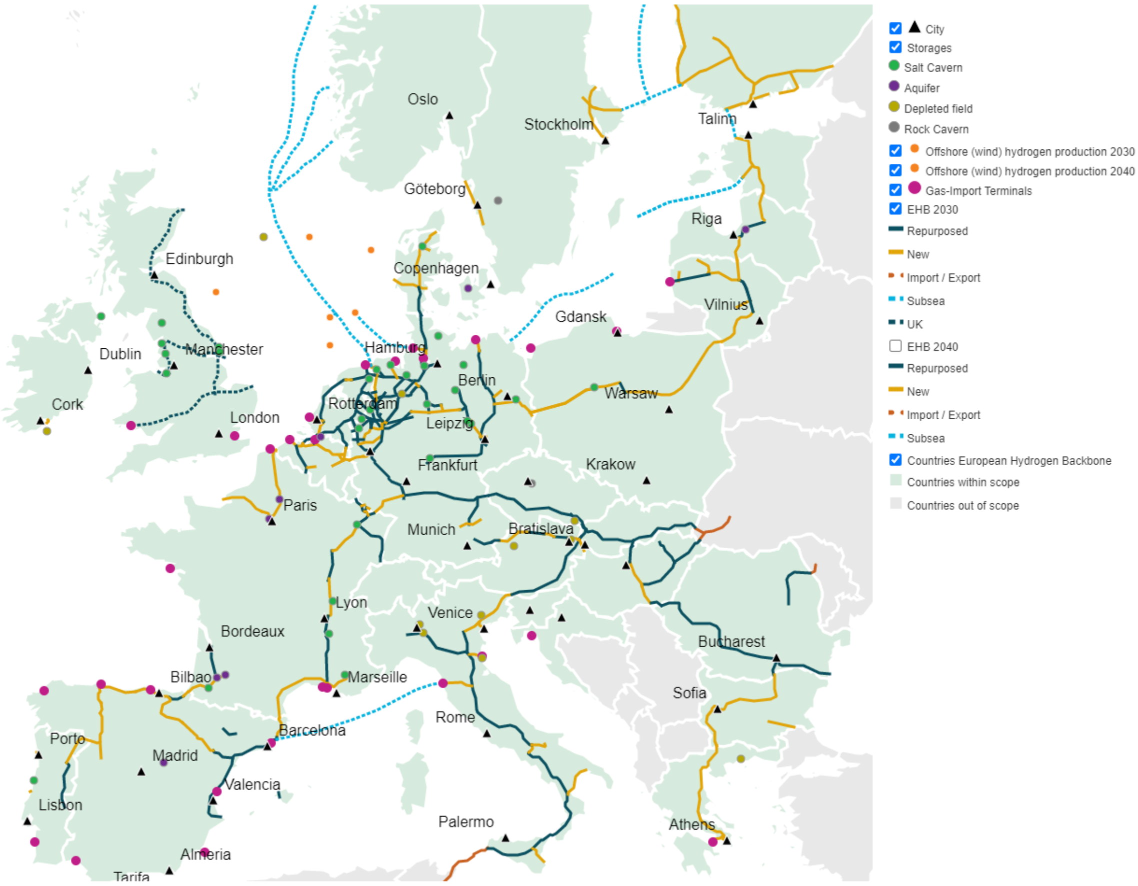
The specific details of the European Hydrogen Backbone, including the exact location of production, storage, and distribution facilities, have not yet been finalized. However, the European Commission has identified a number of key challenges that must be addressed in order to make the European Hydrogen Backbone a reality. These challenges include:

- Developing cost-effective and efficient production technologies: Hydrogen can be produced using a variety of technologies, including electrolysis, steam methane reforming, and biomass gasification. However, these technologies are currently relatively expensive and inefficient, and improvements will be needed in order to make the production of hydrogen competitive with other energy sources.
- Building the necessary infrastructure: In order to support the widespread use of hydrogen, a comprehensive network of production, storage, and distribution facilities will be needed. This will require significant investment in infrastructure, including pipelines, storage tanks, and filling stations.
- Ensuring the safety and reliability of hydrogen systems: Hydrogen is a highly flammable gas, and care must be taken to ensure that hydrogen systems are safe and reliable. This will require the development of appropriate safety standards and the establishment of robust safety procedures.
- Overcoming regulatory barriers: The development of the European Hydrogen Backbone will require the coordination of efforts across a number of different countries and sectors. This will require the development of a regulatory framework that is conducive to the development of hydrogen technologies.

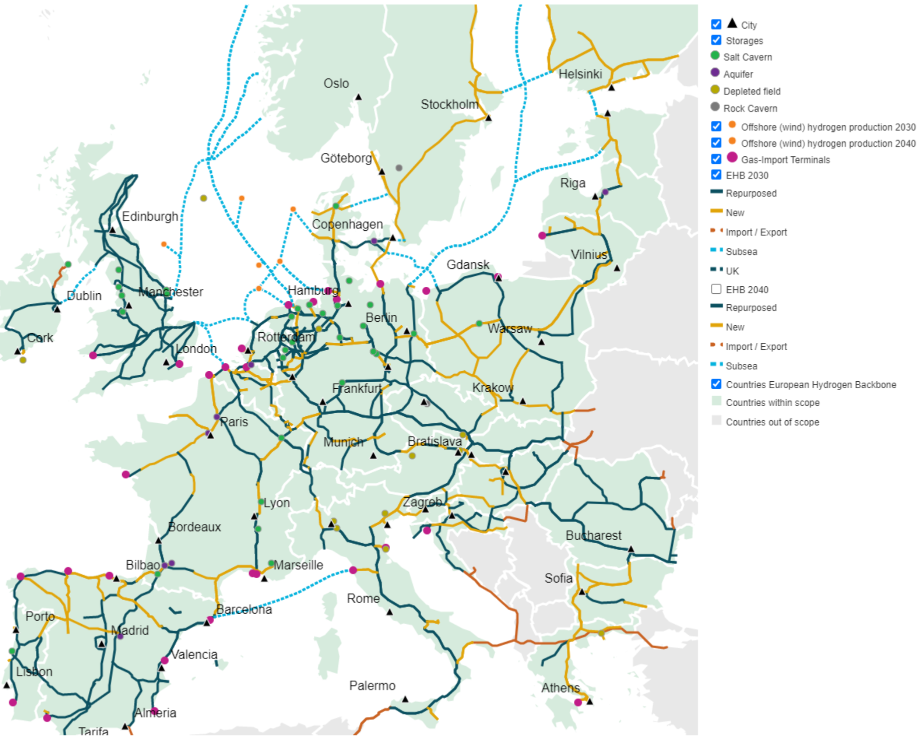
Overall, the European Hydrogen Backbone is ambitious and complex project that will require significant investment and coordination in order to be successful. However, if successful, it has the potential to play a major role in the decarbonization of the EU's energy system and the achievement of its climate and energy targets.

Total investment costs of the envisaged 2040 European Hydrogen Backbone are expected to range from €27 to €64 billion, covering the full capital cost of building and retrofitting the backbone. This compares to the hundreds of billions in investments in green hydrogen production that the EC Hydrogen Strategy foresees, already for the period up to 2030. The 22,900km backbone will consist of 75% retrofitted pipelines, with diameters ranging between 60-120cm, and will provide 3-13 GW (LHV) transport capacity per pipeline. In the medium case, 60% of the total investment costs will be dedicated to pipeline works and the remaining 40% will be spent on compression equipment.

While 75% of the total network or almost 18,000km will consist of retrofitted infrastructure, this represents only around 50% of the total investment, which shows the value of making use of existing pipelines (European Hydrogen Backbone Report, 2020, s. 11).

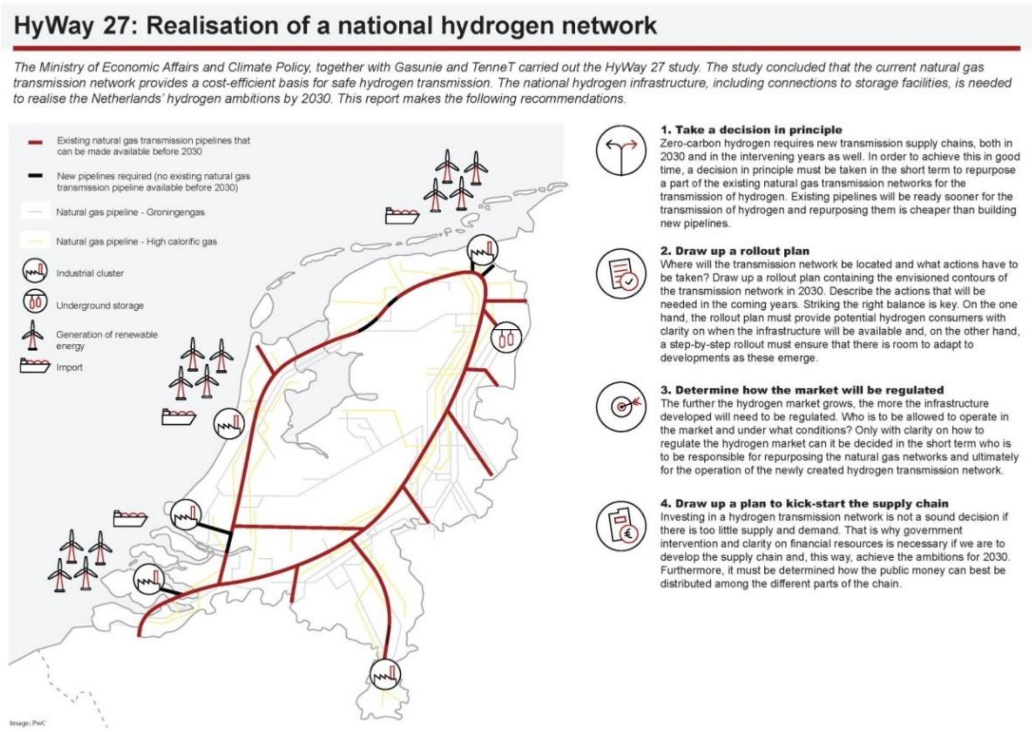


Picture no. 6: The European Hydrogen Backbone 2030.



Picture no. 7: The European Hydrogen Backbone 2040.

2.6.2 EXAMPLE OF THE REALIZATION A NATIONAL HYDROGEN NETWORK



Picture no. 8: HyWay 27 infographics.

2.7 LOHC

Liquid organic hydrogen carriers (LOHC) are organic compounds which can absorb and release hydrogen through chemical reations. Therefore, LOHC can be used as a storage medium for hydrogen. Basically, every unsaturated compound (organic molecules with double or triple bonds) can bind hydrogen during hydrogenation.

LOHC are materials that can store hydrogen in a liquid form, potentially making it easier to transport and use as a fuel. When hydrogen is dissolved in a LOHC, it becomes a stable and relatively safe storage material. The hydrogen can be released from the LOHC by heating it or by applying a small amount of pressure.

There are several different types of LOHC that have been developed, including pyridine-based LOHC, amine-based LOHC, and alcohol-based LOHC. These materials have different properties and may be more or less suitable for different applications.

One advantage of LOHC is that they can store hydrogen at relatively high densities, making it possible to transport large amounts of hydrogen in a small volume. This could make them useful for applications such as fuel cell vehicles, where the hydrogen needs to be stored on board the vehicle.

LOHC are still an active area of research, and there are many challenges to be addressed before they can be widely used. For example, further work is needed to improve the efficiency of the storage and release process, and to find materials that are stable and safe over long periods of time.

In 2020 Japan constructed the first international chain of hydrogen suppliers in the world between Brunei and Kawasaki City. It uses LOHC technologies on the toluene basis. Hyundai Motor is investing into the development of stationary and board systems LOHC.

2.7.1 EXAMPLE OF USING LOHC IN PRACTICE

Hydrogenious LOHC Technologies

Hydrogenious LOHC Technologies is a German company that specializes in developing liquid organic hydrogen carrier (LOHC) technology for the storage and transport of hydrogen. The company's LOHC technology uses a special class of organic compounds called cycloalkanes to store hydrogen in liquid form at ambient temperatures and pressures. The stored hydrogen can then be easily transported and used as a fuel source for vehicles or in industrial processes. The technology has the potential to greatly increase the efficiency and feasibility of hydrogen fuel use.

Picture no. 9: Stationary LOHC infrastructure – StoragePLANTS by Hydrogenious.

Picture no. 10: Stationary LOHC infrastructure – ReleasePLANTS by Hydrogenious.

SUMMARY

Hydrogen can be transported in gaseous or liquid form.

Gaseous hydrogen: Gaseous hydrogen can be shipped in pressurized or refrigerated tanks on specialized ships. These tanks are designed to store hydrogen at high pressures and low temperatures to minimize the volume of the gas. Shipping gaseous hydrogen by sea is a relatively new development and is currently limited to small quantities.

Liquid hydrogen: Liquid hydrogen can be shipped in cryogenic tanks on specialized ships. These tanks are designed to store hydrogen at temperatures below -253°C and at high pressure to keep it in a liquid state. Shipping liquid hydrogen by sea is more common than shipping gaseous hydrogen, but it is still relatively limited due to the high cost of the specialized ships and handling equipment.

Hydrogen delivery refers to the transportation and distribution of hydrogen from a production or storage site to a point of use or sale. There are several methods for delivering hydrogen, including pipeline, tanker truck, rail and on-site generation.

Pipeline: Hydrogen can be transported through pipelines just like natural gas, but the infrastructure for hydrogen pipelines is currently limited.

Tanker truck: Hydrogen can be transported by tanker truck, either in its gaseous or liquid form. When hydrogen is transported in its liquid form, it must be kept at a temperature of -253°C and at high pressure to remain a liquid. This requires specialized tanker trucks and handling equipment.

Rail: Hydrogen can also be transported by rail, either in its gaseous or liquid form. However, rail transport is not commonly used for hydrogen due to the high cost of specialized railcars and handling equipment.

On-site generation: In some cases, hydrogen can be produced on-site at the point of use using natural gas, water electrolysis, or other methods. This can be a convenient option for users who need a small amount of hydrogen on a regular basis and are located near a natural gas supply.

Regardless of the delivery method, hydrogen must be handled carefully as it is highly flammable and can be dangerous if not handled properly.

Method	Advantages	Disadvantages
Compressed hydrogen transportation in containers by road or rails	- No need to build special infrastructure (pipelines) - Transport capacity can be scaled well to requirements on a small scale	- High weight and volume tanks - The pipeline also functions as an accumulator hydrogen storage tank - Small mass transport capacity
Liquified hydrogen transportation in containers by road, rail or ship	- No need to build infrastructure (pipelines) - Possibility of transporting larger volumes	- Large liquefaction losses - Small mass transport capacity
Hydrogen transportation by pipeline with natural gas mixture	- Existing natural gas infrastructure (and biogas/bio-methane) - Continuity of supply - Lower costs compared to transport by road/rail - Natural storage capacity	- A limited ratio of admixture to a certain percentage - The maximum hydrogen concentration is given by compatibility of the connected end devices (e.g. CNG, boilers, etc.)
Seperation of hydrogen from the natural gas mixture using membrane gas separation	- Use of the existing pipeline network - Relatively cheap technology - Scalable technology	- Hydrogen back separation is not 100% - Can only be used on sections without branching - New technology
Clean hydrogen transportation through an existing gas pipeline adjusted to clean hydrogen	- Means to import large volumes hydrogen - Flexible balancing according to immediate country needs - Active transmission system operator in the latest approaches to decarbonise the EU gas sector - Experience in hydrogen operation in Europe, e.g. Benelux region	- Low level of transport experience of pure hydrogen in pipelines in the region Central Europe
Pure hydrogen transportation through a new constructed pipeline	- Means of importing large volumes of hydrogen - Flexible balancing according to the immediate need in the country - Experience in operating hydrogen pipelines in Europe, e.g. Benelux region - Importing 'cheap' hydrogen from the regions with significantly lower production costs	- High investment costs for construction compared to the use of existing infrastructure - Problems with securing rights land rights, EIA, nature protection and landscape
Liquid organic hydrogen carriers (LOHC)	- Transportation at normal temperature and pressure - Easy liquid handling - High hydrogen content both in terms of both by weight and volume - Great flexibility in terms of what is transported of quantity and distance transported	- Hydrogen storage and recovery is expensive - New technology

Table no. 1: Comparison of hydrogen transport methods.

REVIEW QUESTIONS

1. What are the known basic methods for hydrogen transport?

2. What is the usual pressure in containers when transporting compressed hydrogen?

3. What is the temperature of liquid hydrogen?

4. What is the typical concentration of hydrogen when transported in natural gas pipelines?

5. What is membrane separation?

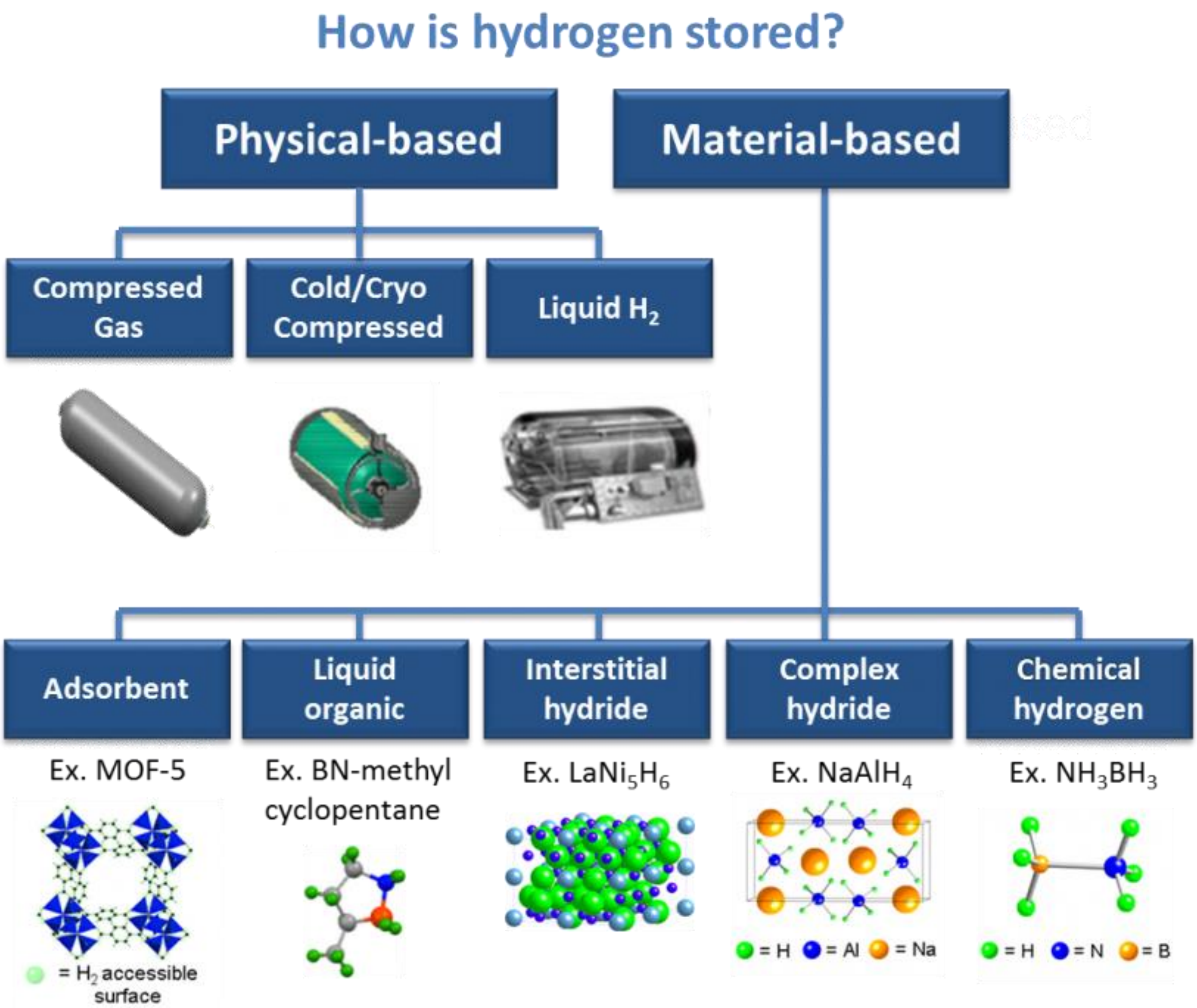
6. What do you know about The European Hydrogen Backbone project?

7. Explain what the acronym LOHC means.

3 HYDROGEN STORAGE

INTRODUCTION

Hydrogen can be stored in various ways, including as a gas, a liquid, or in a solid form. Each method has its own advantages and disadvantages, and the most appropriate method for a particular application will depend on the specific requirements and constraints of that application.



Picture no. 11: Hydrogen storage methods.

One way to store hydrogen is as a gas, which can be done by pressurizing it in a tank or cylinder. This is a simple and relatively cheap method, but the storage density is relatively low, so a large volume is required to store a significant amount of hydrogen. Additionally, high pressure tanks can be heavy and may require special handling and safety measures.

Another way to store hydrogen is as a liquid, which can be achieved by cooling it to a temperature below its boiling point. Liquid hydrogen has a very high storage density, so it is possible to store a large amount in a relatively small volume. However, the cryogenic temperature of liquid hydrogen (-253°C) requires the use of specialized insulation and thermal management systems, which can be expensive.

Hydrogen can also be stored in a solid form, by adsorbing it onto the surface of a porous material. This method has the advantage of being relatively simple and safe, and it can achieve a high storage density. However, the rate at which hydrogen can be adsorbed and desorbed from the storage material can be slow, which may limit the practical usefulness of this method in some applications.

Other methods of hydrogen storage, such as chemical storage and metal hydride storage, also exist. These methods involve the use of chemical compounds or metals that can reversibly react with hydrogen to form stable compounds, which can then be stored until they are needed. These methods can achieve high storage densities and are relatively safe, but they may be limited by the rate at which hydrogen can be absorbed and released, as well as by the cost and availability of the storage materials.

KEYWORDS

Compressed hydrogen, pressure tank, liquid hydrogen, crygenic storage tanks, underground containers, gas structures, hydrides of hydrogen, metal hydrides

3.1 COMPRESSED HYDROGEN STORAGE

Due to the low density of hydrogen it is necessary to store it compressed in pressure tanks. They have to be pressure and destruction resistant and correct tight (tightened with torquewrench) to avoid leaking. Hydrogen is a gas with the smalles molecule and therefore it is necessary to use special materials for its storage. When hydrogen gets in contact with virginal steel or aluminium so called hydrogen embrittlement occurs which can worsen the durability of pressure cylinders which again requires the use of some special materials. Pressing hydrogen itself is energetically demanding. Hydrogen is a very badly compressable gas. It has reversed the Joule-Thompson coefficient, therefore much more energy is needed on its compression than with other gases. For stationary storage of hydrogen there are used large quantity steel pressure tanks or composite (Vodíková strategie České republiky, 2021, s. 81).

The Joule-Thomson effect, also known as the Joule-Kelvin effect, is the temperature change of a gas or liquid as it expands or is forced through a small opening or porous material. This effect is named after James Joule and William Thomson (Lord Kelvin).

The Joule-Thomson effect can be observed when a high-pressure gas is allowed to expand through a small opening or porous material. As the gas expands, its temperature decreases. This is because the expansion of the gas does work on the surroundings, which requires energy. The energy needed for this work is taken from the internal energy of the gas, causing its temperature to drop.

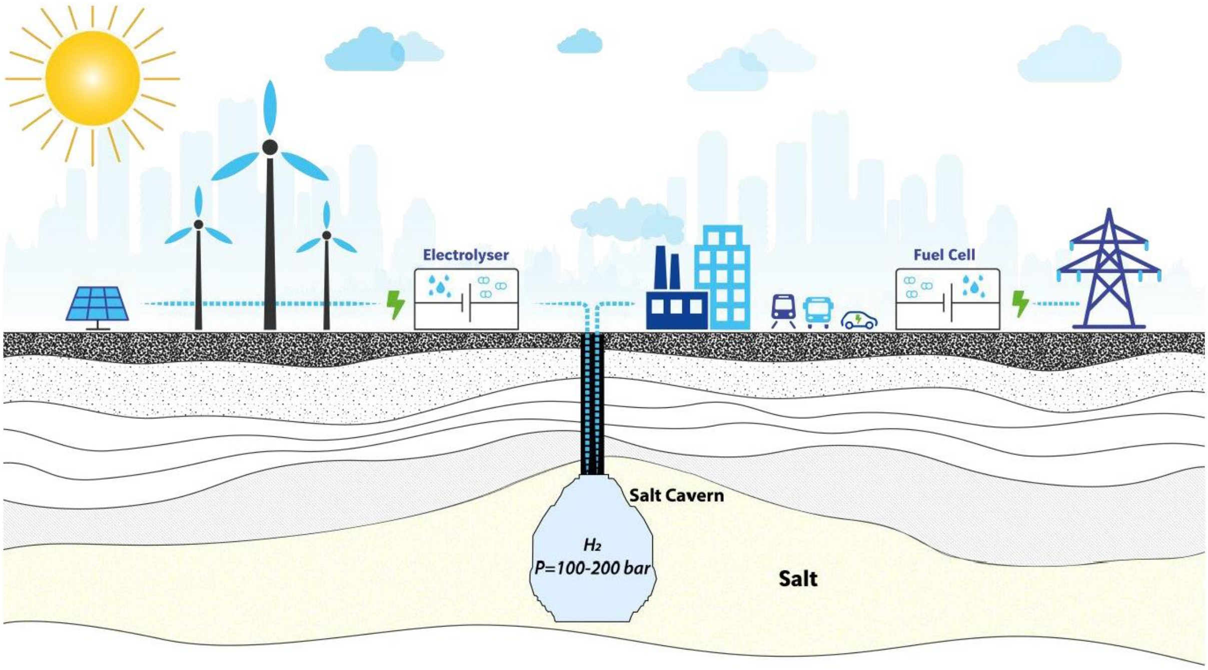
The Joule-Thomson coefficient is a measure of the temperature change of a gas or liquid as it expands. The coefficient is positive for most gases, which means that the temperature of the gas decreases as it expands. For liquids, the Joule-Thomson coefficient can be either positive or negative, depending on the specific properties of the liquid.

The Joule-Thomson effect has practical applications in refrigeration and air conditioning, as well as in the oil and gas industry, where it is used to measure the temperature and pressure of natural gas at various stages in the production process.

For stationary application steel weldless cylinders from low-carbon or alloyed steel are usually used. They are made at volumes ranging from several litres up to approximately 50 l for common application. For mobile applications there are usually used some composite pressure containers. They are made at volumes from tens of litres up to approximately 300 l. A typical operational pressure is 350 bar, in the newest applications it is 450 – 700 bar. In many applications, the cylindrical shape is slightly deformed depending on the needs for installation into storage space of a vehicle. If one wants to store hydrogen in high pressure tanks, first, it has to be compressed at a required pressure. For compressing hydrogen piston compressors are mainly used. The energy necessary for hydrogen compression at 350 bar reaches approximately 30% of energy from a fuel (Krátky, 2012, s. 37).

Picture no. 12: Hydrogen pressure tanks.

Next option of hydrogen storage in a gaseous form is to store it in underground storage sites. They are usually some extracted salt mines or caves of natural gas and empty gas field. In the world this method is used on several places, for example in Amarillo in Texas (850 mil. m^3), in French Beynes (330 mil. m^3), in English Billington (2.2 mil. m^3). Other storage sites can be found, for example, in Germany and Holland (Krček, 2010, s. 20).



Picture no. 13: Hydrogen storage in salt cavern.

3.2 LIQUID HYDROGEN STORAGE

There are several key factors to consider when designing a system for storing liquid hydrogen.

One important factor is the material of the storage tank. The tank must be able to withstand the extremely low temperatures of the liquid hydrogen (-253°C) and the pressure that is generated inside the tank as the hydrogen gas expands and contracts. Stainless steel and aluminum are commonly used materials for hydrogen storage tanks, but they must be specially treated to make them resistant to corrosion and cracking at low temperatures. The tank must also be designed to prevent heat from entering the tank, as this can cause the hydrogen to vaporize and increase the pressure inside the tank. This is typically achieved through the use of insulation, such as foam or vacuum-insulated panels.

Another important factor is the size of the storage tank. The tank must be large enough to hold a sufficient amount of hydrogen to meet the needs of the application, but it must also be small enough to be practical for the intended use. For example, a tank that is too large may be too heavy or take up too much space, while a tank that is too small may not be able to hold enough hydrogen to be practical.

Finally, it is important to consider the safety of the storage system. Liquid hydrogen is a flammable gas, so it is important to ensure that the storage system is designed to prevent leaks or spills, and that it is equipped with safety features such as pressure relief valves and emergency shutdown systems.

For storage are used multilayer vessels with very good insulation properties with maximal overpressure 5 bar. These vessels have to be equipped with pressure relief mechanism which regulates maximal safe overpressure. During hydrogen storage in cryogenic tanks there is some gradual evaporation caused by heat transfer from its surroundings and the pressure grows inside the vessel. To prevent a destruction of the tank the excessive pressure has to be controlled by releasing the evaporated hydrogen. For commonly used tanks the losses can reach up to 3% of the content per day (depending on the quality of the tank). In some applications the waste hydrogen is held and pressured into additional pressure cylinders. Liquefaction is a technologically and energetically demanding process (Krátky, 2012, s. 38).

The minimum theoretical energy to liquefy hydrogen from ambient (300 K, 1.01 bar) conditions is 3.3 kWh/kg LH2 or 3.9 kWh/kg LH2 with conversion to para-LH2 (which is standard practice). Actual liquefaction energy requirements are substantially higher, typically 10-13 kWh/kg LH2, depending on the size of the liquefaction operation. Novel liquefaction methods such as an active magnetic regenerative liquefier may require as little as 7 kWh/kg LH2. For comparison, the lower heating value (LHV) of hydrogen is 33.3 kWh/kg H_2. Compression energy requirements from on-site production range from approximately 5 - 20% of LHV. Liquefaction (including conversion to paraLH2) with today's processes requires 30 - 40% of LHV, while theoretical energy requirements for 700 bar and LH2 storage span a range of only 4-10% of LHV respectively (DOE Hydrogen and Fuel Cells Program Record, 2009, s. 1)

Picture no. 14: Liquid hydrogen tank.

3.3 HYDROGEN STORAGE IN UNDERGROUND CONTAINERS IN A MIXTURE WITH METHANE OR AMMONIA

Hydrogen can be stored underground in containers in a mixture with methane or ammonia, a process known as "hydrogen gas injection." This method is used to store excess hydrogen produced during times of low demand, so that it can be recovered and used as a fuel or feedstock when needed. There are several benefits to this approach:

- Safety: Hydrogen gas injection allows hydrogen to be stored underground in a controlled environment, which reduces the risk of leaks and accidents.
- Efficiency: Hydrogen can be stored in high densities when it is mixed with methane or ammonia, which allows more hydrogen to be stored in a smaller volume.
- Sustainability: Hydrogen gas injection can help to reduce greenhouse gas emissions by allowing excess hydrogen to be stored and used as a fuel rather than being released into the atmosphere.

There are several challenges to implementing hydrogen gas injection, including the need to develop suitable storage containers and the cost of building and operating the storage facilities. However, this approach has the potential to play a significant role in the future of hydrogen storage and distribution.

Hydrogen gas injection involves storing excess hydrogen in underground containers in a mixture with methane or ammonia, a process that can help to reduce greenhouse gas emissions and improve the efficiency of hydrogen storage. Here is a more detailed explanation of how this process works:

- Hydrogen is produced through a variety of methods, including electrolysis, steam methane reforming, and biomass gasification. During times of low demand, excess hydrogen is produced and must be stored until it is needed.
- The hydrogen is injected into underground storage containers, where it is mixed with methane or ammonia. The methane or ammonia helps to increase the density of the mixture, allowing more hydrogen to be stored in a smaller volume.
- The hydrogen-methane mixture is stored underground, typically at a depth of several hundred meters. The storage containers are designed to withstand the pressure and temperature conditions at this depth.
- When the hydrogen is needed, it is recovered from the storage containers and separated from the methane or ammonia. This can be done through a variety of methods, including pressure swing adsorption and cryogenic distillation.

- The purified hydrogen can then be used as a fuel or feedstock in a variety of applications, including transportation, power generation, and industrial processes.

3.4 HYDROGEN STORAGE IN HYDRIDES

Hydrogen can be stored in hydrides, which are materials that can absorb and release hydrogen gas. There are several types of hydrides, including metallic hydrides, covalent hydrides, and ionic hydrides.

Metallic hydrides are formed when hydrogen gas reacts with a metal to form a solid compound. These compounds have a high capacity for hydrogen storage, but they tend to be heavy and bulky, and they require high pressures to release the hydrogen.

Covalent hydrides are formed when hydrogen atoms bond covalently with other atoms to form a compound. These compounds have a moderate capacity for hydrogen storage and can be released at lower pressures than metallic hydrides.

Ionic hydrides are formed when hydrogen ions bond with other ions to form a compound. These compounds have a high capacity for hydrogen storage, but they are generally not as stable as metallic or covalent hydrides and tend to decompose at high temperatures.

There are several challenges to using hydrides for hydrogen storage, including the cost and difficulty of producing and handling the hydrides, as well as the low efficiency of the hydrogen release process. Researchers are working on developing new materials and methods to overcome these challenges and make hydrogen storage in hydrides more practical and cost-effective.

At normal temperature, hydrides are stable, not dissolving and they are relatively safe hydrogen tanks. Their disintegration occurs at high temperatures, in the process hydrogen is released and it is brought to a fuel cell.

The observed parameters with these systems are mainly temperature at which the desorption of hydrogen from a material happens, weight capacity of absorber (in case of the whole system), volume capacity of absorber and last but not the least, the price and the system complexity.

One of the requirements is to make the decomposition at temperatures slightly higher (150 - 200°C) not to consume excessive energy amount by hydride heating.

There has been designed efficient systems capable of absorption of high amounts of hydrogen. With different types of hydrides, there are different amounts of hydrogen which the materials can absorb.

Some hydrides are easily processed liquids at a room temperature and atmospheric pressure, some are firm substances.

These materials have good volumetric energy density, but with respect to their weight their energy density is not ideal. However, for example, for some compounds with light metals, as magnesium, the overall weight of the system results only 30% higher in comparison with the systems for liquefied hydrogen storage. These unfavourable parameters are compensated by a greater need for the thermal desorption high temperature, low pressure of produced hydrogen and last but not the least, a high price of hydrides.

Another important quality is reversibility, or the capability of a material to reabsorb new hydrogen after having used up the stored hydrogen. This is connected with "recharging" of hydrides and their repeated use similarly as with batteries (Krátky, 2012, s. 41).

3.4.1 METAL HYDRIDES

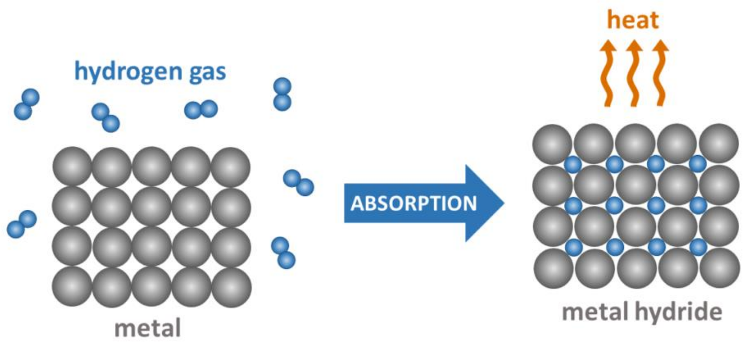
Hydrogen can be stored in metal hydrides, which are compounds formed between hydrogen and a metal. The hydrogen is stored within the metal lattice and can be released through a process called dehydrogenation, which involves heating the metal hydride to a high temperature. There are several types of metal hydrides that can be used for hydrogen storage, including intermetallic compounds, complex metal hydrides, and simple metal hydrides.

Intermetallic compounds are formed between two or more metals and can store a large amount of hydrogen in their lattice. They are generally stable and can be used for long-term hydrogen storage. However, they often require high pressures or high temperatures to release the hydrogen, which can be challenging to achieve in practical applications.

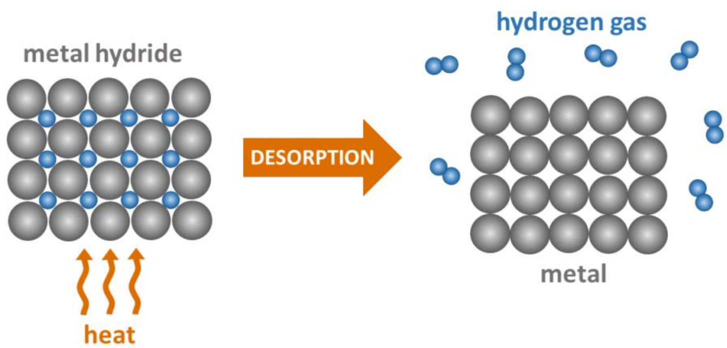
Complex metal hydrides are formed between a metal and a non-metal and can store a moderate amount of hydrogen in their lattice. They tend to release the hydrogen at lower temperatures than intermetallic compounds, but they are not as stable and may decompose over time.

Simple metal hydrides, such as magnesium hydride, can store a small amount of hydrogen in their lattice and release it at low temperatures. However, they are not as stable as intermetallic compounds and tend to decompose over time.

Overall, metal hydrides are a promising option for hydrogen storage due to their high hydrogen storage capacity and the ability to release the hydrogen at relatively low temperatures. However, further research is needed to improve their stability and reduce the cost of producing them.



Picture no. 15: Exothermic hydrogen absorption reaction.



Picture no. 16: Hydrogen desorption reaction from matal hydride.

3.5 HYDROGEN STORAGE IN CARBON-BASED CONTAINERS

Carbon materials, such as graphene and carbon nanotubes, have been studied as a means of storing hydrogen. These materials have high surface area and can physically absorb hydrogen gas, allowing them to store large amounts of hydrogen in a small volume. However, the hydrogen storage capacity of these materials is limited by their surface area and pore size, and they can only store small amounts of hydrogen at a time. Additionally, the process of absorbing and releasing hydrogen from these materials can be slow, making them less practical for use in hydrogen storage applications.

There are several different ways that hydrogen can be stored in carbon materials, including physical adsorption, chemical adsorption, and chemical reaction.

Physical adsorption occurs when hydrogen molecules are attracted to the surface of the carbon material due to Van der Waals forces. This type of hydrogen storage is reversible, meaning that the hydrogen can be easily released from the material by reducing the pressure or increasing the temperature. Physical adsorption can be used to store hydrogen at high pressures (up to about 35 MPa) and at room temperature, but the storage capacity is limited by the surface area of the material.

Van der Waals forces are weak attractive forces that arise between neutral atoms and molecules. They are a type of non-covalent interaction and are caused by temporary fluctuations in electron density. The three types of van der Waals forces are London dispersion forces, dipole-dipole interactions and quadrupole-quadrupole interactions. These forces are responsible for the behavior of gases and liquids and also play a role in the stability of biomolecules and crystal formation.

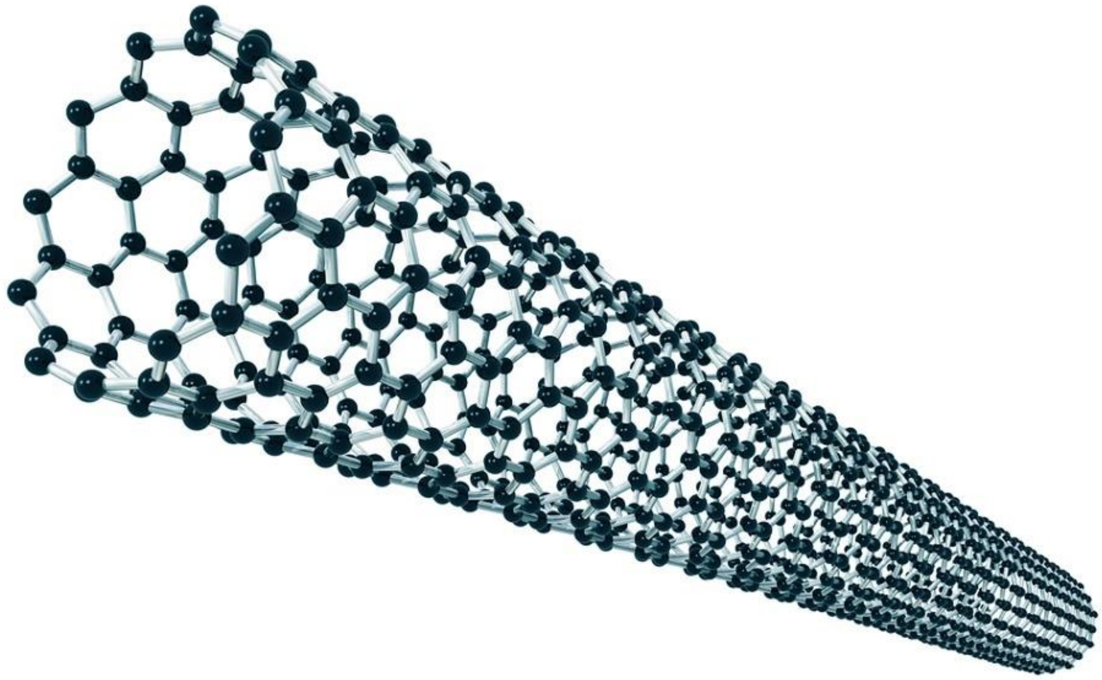
Chemical adsorption involves the formation of a chemical bond between the hydrogen and the carbon material. This type of hydrogen storage is also reversible, but the bond is stronger than the van der Waals forces involved in physical adsorption, so it requires more energy to release the hydrogen. Chemical adsorption can be used to store hydrogen at lower pressures (below 10 MPa) and at lower temperatures.

Chemical reaction involves the formation of a new compound by reacting hydrogen with the carbon material. This type of hydrogen storage is not reversible and the hydrogen cannot be easily released from the material. However, chemical reaction can be used to store large amounts of hydrogen in a small volume.

Overall, carbon materials have several attractive properties for hydrogen storage, including high surface area, high strength, and low weight. However, the storage capacity of these materials is limited and the process of absorbing and releasing hydrogen can be slow, making them less practical for use in many hydrogen storage applications.

Carbon nanostructures include highly porous graphite and carbon nanotubes. Recently, attention has been focused on the study of single-walled nanotubes, which have great potential for hydrogen storage. Many research teams around the world are working on the issue.

The elementary building element of nanotubes is graphite. Nanotubes are formed by one or several layers coiled into the tube of a final length. The diameter of tubes is 0.7 – 3nm (Krček, 2010, s. 22).



Picture no. 17: Carbon nanotubes.

SUMMARY

Compressed hydrogen storage refers to the storage of hydrogen gas at high pressures in order to reduce the volume that it occupies. This can be done in a number of different ways, including the use of high-pressure tanks or cylinders.

Compressed hydrogen storage is that it allows for the storage of a relatively large amount of hydrogen in a relatively small space. This makes it an attractive option for use in vehicles and other applications where space is at a premium. However, it is important to note that the high pressures required for compressed hydrogen storage can pose safety risks, and the tanks and cylinders used to store the gas must be carefully designed and maintained to minimize these risks.

Liquid hydrogen storage refers to the storage of hydrogen in its liquid form, rather than as a gas or solid. To store hydrogen in its liquid form, it must be cooled to a temperature of around -253°C, which is well below its boiling point.

Liquid hydrogen storage is that it allows for the storage of a very large amount of hydrogen in a relatively small volume. This makes it an attractive option for use in a variety of applications, including space travel, where weight and volume are critical considerations.

The low temperature required for the storage of liquid hydrogen makes it difficult to handle and transport, and it requires specialized equipment and insulation to prevent heat transfer and evaporation. Additionally, the low temperature of liquid hydrogen can make it prone to embrittlement of certain materials, which can cause problems with tanks and other storage vessels.

It is possible to store hydrogen in underground containers in a mixture with methane or ammonia, which is a process known as "hydrogen blending." This approach can potentially be used to store excess hydrogen that is produced from renewable energy sources, such as wind or solar power, and then blend it with natural gas for use as a fuel.

Hydrogen blending is that it allows hydrogen to be stored and transported using existing infrastructure, such as natural gas pipelines. This can be more cost-effective and logistically simpler than building new infrastructure specifically for hydrogen storage and transport.

One of the main issues is that hydrogen and methane or ammonia have different physical and chemical properties, which can make it difficult to blend them together in a way that is safe and effective. Additionally, hydrogen is more expensive to produce than methane, so the economics of hydrogen blending may not always be favorable.

Hydrogen storage in hydrides refers to the use of materials that can absorb and release large amounts of hydrogen, known as "hydrides," as a way to store hydrogen. There are several types of hydrides that can be used for hydrogen storage, including metal hydrides, chemical hydrides, and complex hydrides.

Main advantages of hydrogen storage in hydrides is that it allows for the storage of hydrogen in a relatively compact and lightweight form. This makes it an attractive option for use in a variety of applications, such as portable electronic devices and fuel cell vehicles.

Hydrides have a relatively low capacity for hydrogen storage, meaning that a large volume of the material is required in order to store a practical amount of hydrogen. Additionally, the process of absorbing and releasing hydrogen from hydrides is often slow and requires the use of heat, which can be energy-intensive and inefficient.

Hydrogen storage in carbon-based containers refers to the use of materials made of carbon, such as carbon nanotubes or graphene, as a way to store hydrogen. These materials are known for their high surface area and strong chemical bonds, which make them capable of adsorbing and storing large amounts of hydrogen.

One of the main advantages of hydrogen storage in carbon-based containers is that they have a high capacity for hydrogen storage, which means that a relatively small volume of the material is required in order to store a practical amount of hydrogen. Additionally, carbon-based materials are relatively lightweight and strong, which makes them suitable for use in a variety of applications.

Method	Advantages	Disadvantages
Compressed hydrogen storage	- Compared to batteries, an increasingly convenient form of energy storage for longer periods - Long-term experience	- Losses (leakages) - Hydrogen compression is energy intensive - Technologically no longer practically possible further improvements - Restriction of routes according to ADR conditions
Liquid hydrogen storage	- Higher energy concentration than for compressed hydrogen - Can be handled at low pressure - Good energy content ratio to the weight of the container	- Losses (leakages) - Liquefaction of hydrogen is energetically intensive - Cryogenic storage vessels and transport are very expensive
Hydrogen storage in underground containers in a mixture with methane or ammonia	- High-capacity storage - Existing storage infrastructure - Connection to the gas system - Experience with hydrogen storage as a component of luminescent gas	- Storage of a higher proportion of hydrogen is needs to be technically verified and may vary from tank to tank - Losses (leakages) from storage of higher concentrations of hydrogen mixed with methane or hydrogen alone
Hydrogen storage in hydrides	- Transportation at normal temperature and pressure - Easy handling of solids - High hydrogen content both in terms by weight and volume - Great flexibility in terms of quantity transported and distance transported	- New technology
Hydrogen storage in carbon-based containers	- Very lightweight material - High strength-to-weight ratio - Chemically and thermally stable	- Carbon materials are not completely impermeable to hydrogen - Degrade over time - More expensive and technically difficult to manufacture

Table no. 2: Comparison of hydrogen storage methods.

REVIEW QUESTIONS

1. Explain the Joule-Thomson effect.

2. What is the typical pressure in high pressure hydrogen storage tanks?

3. What mechanism must tanks be equipped with to store liquid hydrogen?

4. Describe the advantages of storing hydrogen in underground storage mixed with methane or ammonia.

5. What types of hydride are suitable for hydrogen storage.

6. Which carbon materials are suitable for hydrogen storage?

4 COMPONENTS

INTRODUCTION

There are several ways to store hydrogen, depending on the type and the desired pressure and temperature conditions. Some common components for storing hydrogen include:

- Compressed hydrogen cylinders: These are high-pressure containers made of steel, aluminum, or composite materials. They are used to store hydrogen that are in a compressed liquid or gaseous state.
- Cryogenic tanks: These tanks are used to store gases that are in a cryogenic (very low temperature) state, such as liquid hydrogen or liquid oxygen.
- High-pressure storage tanks: These are large tanks that are used to store gases at high pressure. They can be made of steel, aluminum, or other materials and are typically used to store hydrogen that are in a gaseous state.
- Pipeline storage: Hydrogen can also be stored in pipelines, which are used to transport the gas from one location to another. These pipelines are typically buried underground and can be used to store gases for long periods of time.

It is important to follow proper safety procedures and regulations when storing hydrogen to minimize the risk of accidents or releases.

KEYWORDS

Compressed cylinders, cryogenic tanks, high-pressure storage tanks, pressure vessels

4.1 PRESSURE TANKS

Hydrogen pressure tanks are containers that are designed to store hydrogen gas at high pressure. They are often made of composite materials such as carbon fiber or fiberglass, which are lightweight and strong enough to withstand the pressure of the gas inside the tank.

Hydrogen gas is stored in pressure tanks in order to increase the amount of gas that can be stored in a given volume. When hydrogen is stored at high pressure, its energy density increases, which allows it to take up much less space. This makes it possible to store large amounts of hydrogen in a relatively small tank, making it an attractive option for use in fuel cell vehicles and other applications where space is limited.

There are several types of hydrogen pressure tanks, including those that are designed to be refilled, and those that are designed to be disposed of after they are emptied. Some tanks are also designed to be used in combination with other types of storage systems, such as cryogenic tanks, which are, used to store hydrogen in liquid form at very low temperatures.

In order to ensure the safety of the gas inside the tank, hydrogen pressure tanks are equipped with various safety features such as pressure relief valves and burst discs. These features help to prevent the tank from rupturing or bursting in the event of an overpressure situation.

Overall, hydrogen pressure tanks are an important part of the infrastructure needed to store and transport hydrogen gas, and they play a critical role in the development and deployment of hydrogen fuel cell technologies.

Pressure vessels can be used both for stationary storage and for mobile hydrogen storage. For static applications, seamless steel cylinders made of low carbon or alloy steel are usually used. They are produced in a wide range of volumes according to the planned use.

With mobile applications, composite pressure vessels are usually used. They are made in volumes ranging from tens of liters up to roughly 300 l. A typical operating pressure is 350 bar, in the newest applications from 450 up to 700 bar (temporary technological limit is 1000 bar).

Cyllinders 12 meters long with outer diameter of approximately 80 cm can be used as tanks for filling stations of hydrogen-fueled vehicles or as tanks for energy surplus from renewable energy (Vodíková strategie České republiky, 2021, s. 111).

The fact that it is a tested technology which is verified and meets all rising requirements on hydrogen storage is considered an advantage. It is suitable for storage of low-scale amount in irregular supplies. With development of hydrogen technologies, the hydrogen storage conditions are going to increase dramatically. One question remains, if the current evolution of technologies will not cause a decline in storage needs and high-pressure hydrogen transportation. A disadvantage of pressure tanks can be their safety aspects and technological limits as for example pressure, material or volume of pressure cylinders (Vodíková strategie České republiky, 2021, s. 111-112).

Picture no. 18: Composite pressure tank.

4.2 CRYOGENIC TANKS

Cryogenic tanks are specially designed storage vessels that are, used to store materials at extremely low temperatures. They are used to store a variety of materials, including gases such as hydrogen, oxygen, and nitrogen, as well as biological materials like human cells and tissues.

Cryogenic tanks are made of materials that are capable of withstanding these extremely low temperatures, such as stainless steel or aluminum. They are also heavily insulated to keep the cold inside and the heat out.

There are two main types of cryogenic tanks: stationary tanks and portable tanks. Stationary tanks are used to store large quantities of materials and are typically installed at a fixed location, while portable tanks are used to store smaller quantities and can be moved from one location to another.

Cryogenic tanks are used in a variety of industries, including the medical, chemical, and energy industries. They are an important tool for storing and transporting materials at extremely low temperatures, and they play a vital role in many scientific and technological applications.

Cryogenic tanks can be used to store hydrogen in its liquid form, at a temperature of -253°C. This is one of the most efficient ways to store hydrogen, as it allows for a much denser storage of the gas.

However, storing hydrogen in a cryogenic tank requires special equipment and careful handling, as the extremely low temperature can be dangerous. The tank must be heavily insulated to keep the hydrogen cold and prevent it from warming up and vaporizing. In addition, the tank must be equipped with safety features such as pressure relief valves to prevent the tank from rupturing due to overpressure.

Cryogenic tanks are typically used to store large quantities of hydrogen, and they are typically installed at a fixed location. They are commonly used in the chemical and energy industries, as well as in research and development settings.

Overall, cryogenic tanks are an important tool for storing and transporting hydrogen, but they require special handling and equipment due to the extreme temperature and pressure involved.

Picture no. 19: Cryogenic tanks.

4.3 HIGH-PRESSURE STORAGE TANKS

High-pressure storage tanks are large pressure vessels that are used to store gases at high pressures. They can be made of a variety of materials, including steel, aluminum, and fiber-reinforced plastics, and are designed to be strong yet lightweight. These tanks are typically used to store gases that are in a gaseous state, such as hydrogen.

High-pressure storage tanks are used in a variety of applications, including fuel storage for hydrogen vehicles. They are generally designed and constructed to meet safety regulations and standards to minimize the risk of accidents or releases of the stored gas.

It is important to follow proper safety procedures when handling and storing high-pressure storage tanks. This includes ensuring that the tanks are stored in a safe location away from sources of ignition, and that they are handled and transported carefully to prevent damage. In addition, it is important to regularly inspect and maintain high-pressure storage tanks to ensure that they are in good working condition and to prevent leaks or other problems.

High-pressure storage can store a large amount of hydrogen in a relatively small space. A great opportunity for high-pressure storage is the strategic area absolutely necessary for the further development of hydrogen and the savings resulting from the extent of possible hydrogen storage. During the construction of high-pressure storage facilities, it is necessary to expect high initial investment requirements. Construction is only worthwhile at the point of production or consumption and is conditioned by hydrogen compression and energy loss. Safety aspects cannot be neglected either (Vodíková strategie České republiky, 2021, s. 115).

SUMMARY

Compressed hydrogen cylinders are high-pressure containers used to store hydrogen gas at pressures ranging from 350 to 700 bar. These cylinders are made of high-strength materials such as steel or composite materials and are designed to be strong yet lightweight. They are commonly used as a fuel for hydrogen vehicles, as a chemical feedstock, and for other industrial and commercial applications.

Cryogenic hydrogen tanks are storage vessels that are used to store hydrogen gas at extremely low temperatures, typically in the range of -253°C or colder. These tanks are made of materials that can withstand the extreme cold and pressure of the stored hydrogen, such as stainless steel or high-strength composites.

High-pressure hydrogen storage tanks are pressure vessels that are used to store hydrogen gas at high pressures. These tanks are made of high-strength materials such as steel or composite materials and are designed to be strong yet lightweight. They are commonly used as a fuel for hydrogen vehicles, as a chemical feedstock, and for other industrial and commercial applications.

High-pressure hydrogen storage tanks have several advantages over other types of fuel storage. They are relatively lightweight, making them well-suited for use in vehicles. They are also easy to refill and can be used in a wide range of temperatures. However, hydrogen is a highly flammable gas, so it is important to follow proper safety procedures when handling and storing high-pressure hydrogen storage tanks. This includes ensuring that the tanks are stored in a safe location away from sources of ignition and that they are handled and transported carefully to prevent damage.

REVIEW QUESTIONS

1. What components do you know for hydrogen storage?

2. What is the difference between a pressure vessel and a cryogenic tank?

3. Where is high-pressure hydrogen storage most often used?

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6 LIST OF IMAGES AND TABLES

7 LIST OF ABBREVIATIONS

EHB - The European Hydrogen Backbone

MIE - minimum Ignition Energy

LNG - liquified natural gas

LOHC - liquid organic hydrogen carriers

LH2 - liquid hydrogen

HENG - hydrogen-enriched natural gas

CO_2 - carbon dioxide

CNG - compressed Natural Gas

MOF - metal organic frameworks

EU - European Union

UK - United Kingdom

EIA - environmental impact assessment

LHV - lower heating value

DOE - design of experiment

ADR - accord dangereuses route