Compressed Hydrogen

Compressed hydrogen is the most common way for fuel cell hydrogen storage.

From: Encyclopedia of Materials: Science and Technology, 2005

Related terms:

Natural Gas, Hydrogen Storage, Compressor, Hydrogen, Liquid Hydrogen, Flux Density, Hydrogen Gas, Natural Gas Engine, Volumetrics

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Assessment of Selected Hydrogen Supply Chains—Factors Determining the Overall GHG Emissions

Anne RödlChristina WulfMartin Kaltschmitt, in Hydrogen Supply Chains, 2018

Compressed transportation

Compressed hydrogen can be transported by trucks in gas cylinders or gas tubes with pressures between 200 and 500 bar. Usually several cylinders or tubes are bundled to modules in a 20▯ or 40▯ container that is mounted on a trailer (tube trailer).

The transport capacities and tank weights are important variables in assessing the GHG emissions and non-renewable energy consumption in hydrogen transportation via truck. Typically, the high weight of the cylinders or tubes limit the maximum hydrogen load that can be transported. A tube trailer with steel cylinders can store up to 25,000 liters of hydrogen compressed to 200 bar (Wystrach GmbH, 2017a), which amounts to around 420 kg of hydrogen.

Currently lighter tank materials (composite materials for gas cylinders or gas tubes) that can be operated at higher pressure are under development in order to increase the hydrogen transport quantities per trailer. For example, superlight cylinder materials consisting of carbon fiber over high-density polyethylene liners (Wystrach et al., 2012) have been investigated. Trailers with such composite cylinders can carry up to 39,600 liters of hydrogen with a pressure level of 200 bar equivalent to about 666 kg of hydrogen (Wystrach GmbH, 2017b).

Recently a jumbo trailer was released that can carry 13,000 m^3 of hydrogen compressed with 500 bar (Linde Group, 2013), which amounts to a transported hydrogen weight of about 1100 kg.

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Electricity and hydrogen as energy vectors for transportation vehicles

J.W. Sheffield, ... R. Folkson, in Alternative Fuels and Advanced Vehicle Technologies for Improved Environmental Performance, 2014

Compressed

Compressed hydrogen must be stored in specially designed tanks capable of withstanding the storage pressures, which can range from 17 MPa to 70 MPa. These tanks are usually made of steel. However, tanks made of carbon fiber lined with aluminum, steel, or specific polymers are used when weight is a consideration. When compressed, the density of hydrogen at 35.0 MPa is about 23 kg/m^3 and at 70.0 MPa is about 38 kg/m^3. This leads to an energy density of 767 kWh/m^3 (27 °C, 35 MPa).

The volume of the storage tank is the biggest challenge, since the density of compressed hydrogen is lower than that of liquid hydrogen. Compression of hydrogen is an energy-intensive process which increases the overall cost. Estimates are about 6.0 kWh/kg for compression to 70 MPa, which leads to the CO_2/kg of hydrogen stored to be high (approximately 1.3 kg of CO_2/kg of hydrogen) (Di Profio *et al.*, 2009). However, compression only consumes a third of the energy that liquefaction does. In addition to the cost of compressing hydrogen, the cost of compressed storage tanks must also be taken into account. The cyclic loading of tanks, which tend to heat up as they are filled with compressed hydrogen, reduces tank life.

Compressed storage is mostly done above ground. However, underground storage is also possible, especially for fuelling stations since it decreases the amount of land used. This reduces the chance of accidents since the storage tanks are isolated, but increases the difficulty associated with inspection and maintenance. There are approximately 600 small-scale compressed hydrogen storage sites in the United States (EIA, no date). Storage capacities range from 100 kg to 1,300 kg and storage pressures range from 1 MPa to 30 MPa Hydrogen fuelling stations in the United

States have storage capacities which range from 10 kg to 150 kg and storage pressures range from 1 MPa to 54 MPa (Fuel Cells 2000 (2011)).

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Hydrogen

Bengt Sundén, in Hydrogen, Batteries and Fuel Cells, 2019

3.4.3.2 Compressed cryogenic gas

Cooling down compressed hydrogen gas means increasing the density and more stored gas in the tank. The system is often cooled down to 77 K with liquid nitrogen, increasing the volumetric capacity by three times compared to non-cooled hydrogen.

It has been found that at this temperature, a pressure of 148 atm is required to store 4.1 kg hydrogen in 100 L at room temperature, instead of 740 atm at room temperature. Drawbacks are that bigger and heavier tanks are needed due to the thermal insulation.

New research findings show that adding adsorbents in the tank further decreases the storage pressure. Only 59 atm are required if the tank is filled with super-activated carbon pellets.

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APPLICATIONS – TRANSPORTATION | Submersibles: Batteries

Ø. Hasvold, in Encyclopedia of Electrochemical Power Sources, 2009

Hydrogen/Oxygen Fuel Cells

A FC based on compressed hydrogen in carbon fiber composite cylinders and pure oxygen is an interesting alternative for deep submergence underwater vehicles. The system as such is bulky, but the low weight of composite cylinders can make the total performance of a deep-diving AUV very high as the hydrogen storage can have the additional function of buoyancy compensation. A typical AUV for deep-sea survey operation may contain 300–600 L of syntactic foam to achieve neutral buoyancy. Foam density is □500 kg m^{-3} and increases with design depth. This density is comparable with the average density of a composite gas cylinder for hydrogen with a working pressure of 70 MPa. Although it should be recognized that the rating for external pressure is significantly less than the rating for internal pressure, carbon fiber composite is an excellent material for pressure vessels. The land-based interest in FCs for transportation has resulted in a number of commercially available and officially approved composite cylinders for hydrogen storage. This is not the case for compressed oxygen. Storage of oxygen in a large vehicle can be made very weight efficient using liquid oxygen (density 1140 kg m^{-3} at −190 °C), but as the vehicle gets smaller, the relative weight and the volume of the thermal insulation increase, making compressed gas more favorable. Using state-of-the-art composite containers, 50% of the system weight can be oxygen, compared with typically 20% with 300 bar metal gas bottles. The density of oxygen at 30 MPa is 400 kg m^{-3}. An alternative to the use of compressed gas is to store oxygen as a compound that can easily be decomposed to liberate oxygen. Decomposition of HP liberates 0.471 kg of oxygen per kilogram of HP:

[IX]

Because concentrated HP is unstable and the reaction [IX] is highly exothermic, pure HP is not used. Commercial HP solutions contain inhibitors of decomposition (e.g., phosphoric acid); 50% and 70% HP are in routine use by the industry, and 85% concentrations have been used in torpedoes in the Scandinavian countries for many years without accidents.

Off-base operation of FC-powered survey AUVs also requires a minimum size of the mother vessel, as the weight and the volume of the onboard systems for hydrogen generation (electrolyzer or diesel reformer/purifier or bottled hydrogen) may be fairly high.

At present, there is a large interest in hydrogen/oxygen FCs for underwater use. The German AUV DeepC and the Japanese AUV Urashima have been designed with hydrogen/oxygen FCs. The technology is mature for large submarines and space applications, and a miniaturization of the systems for scientific and commercial applications in unmanned submersibles is expected.

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Design and Optimization of Hydrogen Supply Chains for a Sustainable Future

Sofía De-León Almaraz, Catherine Azzaro-Pantel, in Hydrogen Economy, 2017

6.2 Tube Trailer

From a conditioning center, compressed hydrogen can be transported at around 200–250 bar by tube trailers. With the appearance of decentralized, regional production, tube trailers use is a solution for the transition phase toward the use of pipelines (European Commission, 2008). Commercial tube trailers are well established. Generally, transporting CH_2 over the road in high-pressure tube trailers is expensive and used primarily for short distances; it becomes cost prohibitive when transporting farther than about 321 km from the point of production in the study of Dagdougui (2011b). Compressed gas truck delivery is not considered as a long-term delivery solution because their low hydrogen capacity would necessitate too many deliveries (Yang and Ogden, 2013).

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Fuel Cells and Hydrogen Technology

D. Nash, ... V. Ortisi, in Comprehensive Renewable Energy, 2012

Abstract

This chapter is an introduction to compressed hydrogen vessels. It provides a short theoretical background into the principles of design for compressed containers. An emphasis is given as to how to select the container materials, what type of equations shall be used for designing the tanks, and what has to be considered when using openings and nozzles. Latest composites container's characteristics are explained highlighting some of the basic requirements for hydrogen tanks. The most common codes and standards for hydrogen pressurized tanks are summarized, including some of the best industry practices. Issues with connectors and joints are highlighted with some basic safety guidelines summarized. Two case studies are provided, one for the design and manufacture of a hydrogen vessel and the second one for the design of a complete hydrogen system, based on the learnings of the PRE Project.

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Ammonia as a hydrogen energy carrier and its application to internal combustion engines

M. Koike, ... K. Ogasawara, in Sustainable Vehicle Technologies, 2012

3 ENERGY STORAGE IN VEHICLES

For vehicle applications, we compared compressed hydrogen and liquefied ammonia. The current status of the gravimetric and volumetric energy capacity of the storage technologies used for hydrogen is shown in Table 2 (11). The materials and designs of hydrogen storage tanks have been improved considerably such that they can store as much energy as possible in a confined space with the minimum tank weight. On the other hand, heavy steel cylinders are currently used for storing ammonia. Therefore, we substituted a composite tank like that used for storing liquefied petroleum gas (LPG) as the ammonia storage tank, because the physical properties of LPG are similar to those of ammonia.

Table 2. Current status of storage technology

	Liquefied NH_3(1 MPa)	**Compressed H_2(70 MPa)**
Volumetric - capacity (g/L)- energy density (MJ/L)	3807.1	242.9
Gravimetric - capacity (wt.%)- - energy density (MJ/kg)	7013	3.54.2

An ammonia tank is expected to carry about 2.5 times as much energy as a hydrogen tank for a given volume. Needless to say, both hydrogen and ammonia have smaller energy densities than conventional gasoline or diesel oil. The same amount of energy as 70 L of gasoline would require a hydrogen storage tank with a volume in excess of 770 L and weighing 530 kg. Ammonia offers the potential to reduce this to 315 L and 172 kg, respectively. This is more critical for freight applications such as heavy duty trucks. To carry the energy equivalent of 400 L of diesel oil would require a truck to carry a 5 kL hydrogen storage tank, with a weight of 3.4 t. In the case of ammonia, this would fall to 2.03 kL and 1.1 t, respectively.

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Hydrogen for Energy Storage

Odne Stokke Burheim, in Engineering Energy Storage, 2017

8.2.2.2 Compressed Hydrogen

When considering hydrogen for cars, hydrogen compressed to 700 bar (in some instances, only 350 bar) is generally considered the most convenient technology.

This is as it meets the requirement for driving range () and sufficiently low fueling time (<3 min).

Compressing hydrogen requires work. The way this is done is by using a series of compressors and a stepwise compression up to the desired compression. The stepwise compression means that the compression is close to isothermal and more efficient [58]. The specific work for compression of hydrogen can therefore be calculated by integrating pressure with respect to volume (Eq. (2.13)). By inserting the viral equation of state, Eq. (8.21), at constant temperature, we obtain the molar work

(8.22)

Equation (8.22) gives the work from compression of hydrogen as a nonideal gas and as a function of the molar volume. This work is obviously negative since it is the input work done on the gas. Equation (8.21) gives the pressure as a function of molar volume, and thus the molar work versus pressure can be obtained. The absolute value of Eq. (8.22) divided by the molar mass of hydrogen is plotted as a function of pressure in Fig. 8.9, the gray line. Also, the ideal gas specific compression work is plotted, dashed black line. We can see that the ideal gas law is suitable up to 100 bar and that, at higher pressures, the viral equation predicts a higher work demand. At 350 bar and 700 bar, this deviation is 6 and 11% more than predicted by the ideal gas law. The viral equation of state is an approximation, also with limitation in precision. Considering isothermal compression is another approximation. Also, these calculations do not account for other irreversiblilites. Allover, the presented analysis therefore only gives a brief introduction to hydrogen compression and the related work. Regardless of the approximations, the analysis is useful as a starting point. Evaluating the work needed for compressing hydrogen, we should compare it to the specific energy content of hydrogen, 33 kWh�kg−1. In this context, around 10% of the work available is spent on compression hydrogen up to 700 bar.

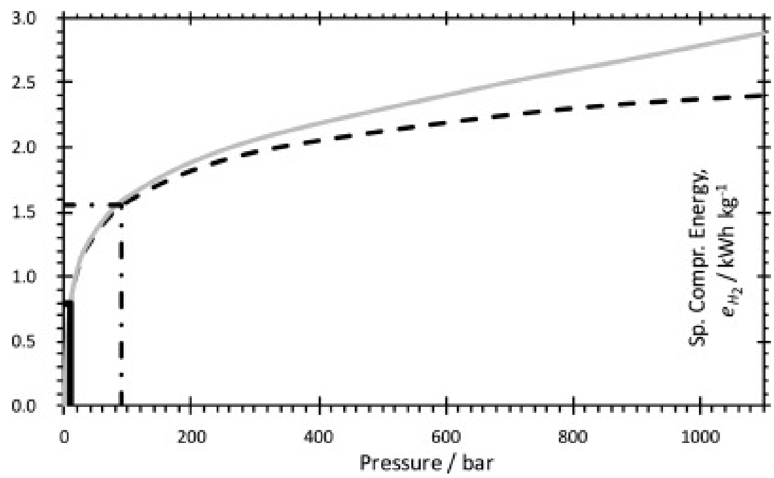

Figure 8.9. Specific work needed for compressing hydrogen from 1 bar, calculated using the viral equation with two terms (gray) and the ideal gas law (black dashed).

Energy saved by starting the compression at 10 and 90 bar compression is also indicated.

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Hydrogen

Bent Sørensen, Giuseppe Spazzafumo, in Hydrogen and Fuel Cells (Third Edition), 2018

2.4.1 Container transport

Hydrogen can be transported in containers of compressed or liquid hydrogen and emerging storage forms in hydrides or other chemical substances, as described in Section 2.3.

Intercontinental hydrogen transport, which may become required if conditions for hydrogen production are geographically distributed in a way different from that of demand, may make use of containers transported on ships, similar to those transporting liquefied natural gas today. Because the density of liquefied hydrogen is so much smaller than that of natural gas, the transportation costs are going to be higher. In addition, there are problems with the leakage from the containers (Section 2.3.2) and safety in case of containment accidents from on-board causes, including those related to hydrogen loading and unloading or caused by ship collisions. Conceptual designs include spherical or cylindrical containers (Abe et al., 1998). Intercontinental transport of hydrogen by ship has been estimated to cost around US$ 25/GJ or US$ 3/kg (Padró and Putche, 1999).

Alternative materials for hydrogen storage during long-range transport are, as mentioned in Section 2.3.5, methanol and higher hydrocarbons. The high-temperature reactions listed in Table 2.4 allow methane and other hydrocarbons to be transformed into producer gases with high hydrogen content, typically with more modest temperature requirements for higher hydrocarbons (such as the decalin mentioned in Eq. (2.63)).

Table 2.4. High-temperature, closed-loop chemical CHO reactions (Hanneman et al., 1974; Harth et al., 1981)

Closed-loop system	**Enthalpy**[a]	**Temperaturerange (K)**
ΔH_0 (kJ mol^{-1})		
$CH_4 + H_2O$ □ $CO + 3H_2$	206 (250)[b]	700–1 200
$CH_4 + CO_2$ □ $2CO + 2H_2$	247	700–1 200

$CH_4 + 2H_2O$ □ $CO_2 + 4H_2$	165	500–700
C_6H_{12} □ $C_6H_6 + 3H_2$	207	500–750
C_7H_{14} □ $C_7H_8 + 3H_2$	213	450–700
$C_{10}H_{18}$ □ $C_{10}H_8 + 5H_2$	314	450–700

a Standard enthalpy for complete reaction.

b Including heat of evaporation of water.

The transport of hydrogen in the form of chemical compounds would seem to reduce losses and costs, relative to transport of liquid hydrogen or voluminous compressed gaseous hydrogen (McClaine et al., 2000).

For shorter distances of transport—for example, from central stores to filling stations—all the forms of transport can in principle be contemplated. The conversion or liquefaction/deliquefaction processes may carry too high energy losses and costs, so that despite the bulkiness of compressed hydrogen, it may be a more acceptable solution.

> Read full chapter

Introduction to hydrogen transportation

R. Gerboni, in Compendium of Hydrogen Energy, 2016

11.2.3 Hydrogen pipelines

Transportation and distribution to single users of compressed hydrogen via pipeline is one of the options that is presently being exploited for the use of hydrogen as an energy vector. As will be seen later, this technology is not always the most convenient and, at the present, the pipeline network for hydrogen transportation is very limited and derived from natural gas technology.

The panorama of hydrogen pipelines is dominated by a few industrial gases companies: Air Products, Air Liquide e Praxair. Other companies share shorter tracks of a few kilometers or operate small networks inside their production plants. Hydrogen is almost always transported to be used in refinery plants or in big chemical plants. The transport of hydrogen to residential consumers is not yet diffused, although some small and specific craft centers, which require hydrogen for their production (e.g., goldsmiths) have started to create local networks to serve their premises with centrally produced hydrogen (usually from electrolysis).

While the most forecasted need for a hydrogen pipeline infrastructure is due to the connection of refueling stations for cars, many have also envisioned the first fuel cell market evolution to head toward residential applications: in this case hydrogen and methane pipelines will be competing, as solid oxide fuel cell (SOFC) is the favorite choice in combined heat and power (CHP) applications. Hydrogen pipelines and storage will also play an important role in future smart grid diffusion in urban areas: as a parallel system to the electrical network and a good energy storage alternative, its adoption will have to be included in the articulated schemes that are proposed for further assessment.

As specified later, codes and standards about hydrogen delivery is still uneven in diffusion: North America, due to the relatively high distribution of hydrogen systems, has provided a number of standards that have local validity. Europe has started a series of initiatives to address safety issues and to develop standards on pipelines, based on the experience gained with natural gas. Single countries have developed local regulations when needed to proceed with demonstration activities and prototypes.

The industrial exploitation of hydrogen in the chemical sector on a large scale started in 1938 in the Ruhr Basin with the construction of a hydrogen pipeline intended to connect several chemical plants.

Western Europe owns the longest network of pipelines, about 1500 km compared to the existing 900 km in the United States. These values may vary according to sources because there is no agreement on the definition of hydrogen pipeline to be accounted for: some analysts do not consider pipelines with a diameter below a certain value and some others only consider the pipelines connecting production plants with external consumers, neglecting the internal pipelines system into the production facility (Gillette and Kolpa, 2007). The European countries that own the largest part of the hydrogen network are France, Germany, and Benelux (Figure 11.5). Hydrogen pipelines with a smaller length exist in other countries, in particular in Great Britain and Sweden, and projects to connect the Netherlands with Sweden are ongoing.

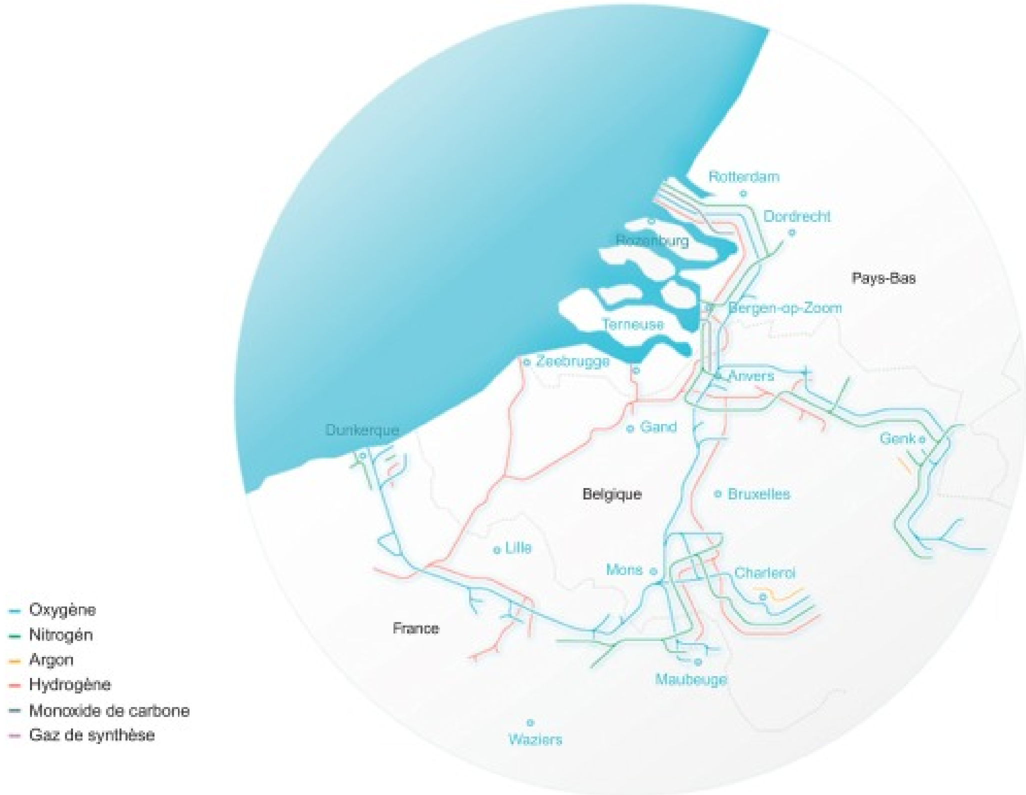

Figure 11.5. European main hydrogen network operated by Air Liquide(map courtesy of Air Liquide).

The existing pipelines are constructed with common steels for general construction. There are no known problems connected with the utilization of these pipelines. The operating pressures vary according to the networks and, in general, are between 0.34 and 10 MPa. Their diameter may vary between 10 and 300 mm. More frequently, the operating pressure is about 1–2 MPa and diameters are about 25–30 cm.

If the pressure remains at low values, embrittlement effects are smaller, which is why conventional steels are used today.

To avoid incurring excessive investment costs, there is the possibility of mixing hydrogen with natural gas and to exploit the existing natural gas network. When the hydrogen share in volume is lower than 20% (which might mean 5–7% in energy content), conventional materials may be used without consequence.

To reduce safety and logistical issues, it is possible to bury hydrogen pipelines, as it is usually done with natural gas pipes. In 1983, Air Products realized the first directional perforation (1.6 km long) through a river to install a hydrogen pipeline in Louisiana.

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