ScienceDirect

Aceves et al. (2006, 2010) at Lawrence Livermore National Laboratory have demonstrated cryo-compressed storage technology in three generations of cryogenic capable pressure vessels. The first-generation (Gen-1) vessels had 135 L internal volume, could store 9.6 kg LH_2, and were designed to operate at 245 atm peak pressure. One of the vessels was installed on a 1992 Ford Ranger pickup truck to power a hydrogen internal combustion engine. The vehicle was refueled successfully with both LH_2 and cH_2. The second-generation (Gen-2) prototype vessel had larger internal volume (151 L), could store 10.7 kg LH_2, and was designed for higher operating pressure (340 atm). It was installed in an experimental Toyota Prius hydrogen hybrid vehicle, which was test-driven for 1050 km on a single tank filled with LH_2. The third generation (Gen-3) vessel is an improved design of the Gen-2 vessel; it has the same internal volume and hydrogen capacity but the total system weight and volume were reduced by 23%.

Aceves et al. (2006, 2010) at Lawrence Livermore National Laboratory have demonstrated cryo-compressed storage technology in three generations of cryogenic capable pressure vessels. The first-generation (Gen-1) vessels had 135 L internal volume, could store 9.6 kg LH_2, and were designed to operate at 245 atm peak pressure. One of the vessels was installed on a 1992 Ford Ranger pickup truck to power a hydrogen internal combustion engine. The vehicle was refueled successfully with both LH_2 and cH_2. The second-generation (Gen-2) prototype vessel had larger internal volume (151 L), could store 10.7 kg LH_2, and was designed for higher operating pressure (340 atm). It was installed in an experimental Toyota Prius hydrogen hybrid vehicle, which was test-driven for 1050 km on a single tank filled with LH_2. The third generation (Gen-3) vessel is an improved design of the Gen-2 vessel; it has the same internal volume and hydrogen capacity but the total system weight and volume were reduced by 23%.

In this chapter, we present integrated thermodynamics, heat transfer, and isomer conversion kinetics models that can be used to evaluate the dynamics of refueling, discharge, dormancy, and storage capacity of cryo-compressed vessels. We also briefly discuss a set of available models that can be used to evaluate the overall efficiency of producing, liquefying, delivering, and pumping LH_2 to the vehicle's storage tank. We use the models to assess the performance of the cryo-compressed hydrogen storage option relative to the near-term and ultimate targets for automotive applications (DOE Targets for Onboard Hydrogen Storage Systems for Light-Duty Vehicles, 2009): 5.5 wt% (7.5 wt%) gravimetric capacity, 40 g/L (70 g/L) volumetric capacity, 5.6 kg usable H_2, 1.6 g/s minimum full flow rate of H_2, 1.5 kg/min (2 kg/min) H_2 refueling rate, 0.05 g/kg maximum H_2 loss rate, and 60% well-to-tank (WTT) efficiency.

In this chapter, we present integrated thermodynamics, heat transfer, and isomer conversion kinetics models that can be used to evaluate the dynamics of refueling, discharge, dormancy, and storage capacity of cryo-compressed vessels. We also briefly discuss a set of available models that can be used to evaluate the overall efficiency of producing, liquefying, delivering, and pumping LH_2 to the vehicle's storage tank. We use the models to assess the performance of the cryo-compressed hydrogen storage option relative to the near-term and ultimate targets for automotive applications (DOE Targets for Onboard Hydrogen Storage Systems for Light-Duty Vehicles, 2009): 5.5 wt% (7.5 wt%) gravimetric capacity, 40 g/L (70 g/L) volumetric capacity, 5.6 kg usable H_2, 1.6 g/s minimum full flow rate of H_2, 1.5 kg/min (2 kg/min) H_2 refueling rate, 0.05 g/kg maximum H_2 loss rate, and 60% well-to-tank (WTT) efficiency.

> Read full chapter

> Read full chapter

Metal hydrides: Modeling of metal hydrides to be operated in a fuel cell

Metal hydrides: Modeling of metal hydrides to be operated in a fuel cell

Evangelos I. Gkanas, in Portable Hydrogen Energy Systems, 2018

Evangelos I. Gkanas, in Portable Hydrogen Energy Systems, 2018

5.2.2 Compressed hydrogen storage

5.2.2 Compressed hydrogen storage

A major drawback of compressed hydrogen storage for portable applications is the small amount of hydrogen that can be stored in commercial volume tanks, presenting low volumetric capacity. Even at high pressures (over 70 MPa), the compressed hydrogen storage presents low volumetric density (lower than 40 kg H_2 m^{-3}) (Sandrock, 1999). In addition, the energy content of the compressed hydrogen is less

A major drawback of compressed hydrogen storage for portable applications is the small amount of hydrogen that can be stored in commercial volume tanks, presenting low volumetric capacity. Even at high pressures (over 70 MPa), the compressed hydrogen storage presents low volumetric density (lower than 40 kg H_2 m^{-3}) (Sandrock, 1999). In addition, the energy content of the compressed hydrogen is less

than the energy content of the gasoline that occupies the same volume (Serdaroglu et al., 2015). Another critical issue is directly related with the safety of storing hydrogen in such large pressures. The possibility of large pressure drops inside the gas cylinder when hydrogen release is necessary (e.g., during the charging of the tank within a hydrogen fuel cell vehicle) is another factor that needs to be considered, as well as the high cost for compression.

than the energy content of the gasoline that occupies the same volume (Serdaroglu et al., 2015). Another critical issue is directly related with the safety of storing hydrogen in such large pressures. The possibility of large pressure drops inside the gas cylinder when hydrogen release is necessary (e.g., during the charging of the tank within a hydrogen fuel cell vehicle) is another factor that needs to be considered, as well as the high cost for compression.

> Read full chapter

Single and Polystorage Technologies for Renewable-Based Hybrid Energy Systems

Zainul Abdin, Kaveh Rajab Khalilpour, in Polygeneration with Polystorage for Chemical and Energy Hubs, 2019

6.1.2 Liquid

Traditionally, liquid hydrogen storage is technically viable at small scales and has been trialed in vehicles but has been overtaken by compressed hydrogen storage. Its potential role in energy systems is not established; nonetheless, cryogenic storage at the scale of many metric tons of liquid is a well-established technology in the space industry. Liquefied hydrogen is considered a promising candidate for large-scale export of pure hydrogen. Kawasaki Heavy Industry (Japan) is moving forward with the construction of small liquefied hydrogen carriers, initially at the 200-t scale [75].

Liquid hydrogen suffers from unavoidable losses from boil-off owing to heat flow into the reservoir from the exterior. Furthermore, hydrogen liquefaction constitutes a parasitic load consuming around 35% of the LHV energy content of the liquefied hydrogen. It is best suited to centralized liquefaction plants with their attendant economies of scale. Remaining challenges include the total system volume and weight, the high cost of the tank, and the ortho-para conversion [76].

> Read full chapter

Introduction to hydrogen storage

N.T. Stetson, ... C.C. Ahn, in Compendium of Hydrogen Energy, 2016

1.2.1 Compressed hydrogen

requirements of these automotive systems based on the guidance from SAE J2579 hydrogen system standard (United Nations Global Technical Regulations, 2015).

requirements of these automotive systems based on the guidance from SAE J2579 hydrogen system standard (United Nations Global Technical Regulations, 2015).

> Read full chapter

Hydrogen Storage and Transport Technologies

In Science and Engineering of Hydrogen-Based Energy Technologies, 2019

Development of Technology for High Pressure Gas Hydrogen Containers

In the development of high-pressure technology for compressed-hydrogen container system, the following five items have been investigated and put to practical use.

Selection of Liner Material

Research was conducted on hydrogen embrittlement behavior under a super high-pressure hydrogen environment and hydrogen embrittlement resistant materials were selected.

Selection of Metallic Materials for Parts

Embrittlement tests of metallic materials used for parts, such as valves of 70 MPa class for compressed hydrogen storage system, were carried out and materials presenting no problem in practical use were selected.

Development of Sealing Material

Sealing performance was evaluated for rubber O-rings. As a result, no-leakage sealing material was developed.

Development of 70 MPa Class Hydrogen Container

The manufacturing technology for 70 MPa class hydrogen containers was specified. This technology was implemented with the intention of reducing costs. As a result, tanks with resistance to practical problems have been developed.

Development of Temperature Prediction Model for Gas and Container During Filling

Development of Temperature Prediction Model for Gas and Container During Filling

When rapidly filling high-pressure hydrogen containers with hydrogen, the hydrogen temperature in the container rapidly increases, and there is a concern about the bad influence it might have on the container integrity. Therefore, in order to improve the prediction accuracy, large capacity data on thermal property values is introduced, and a model was constructed.

Based on this, high-pressure resistant hydrogen tank, up to 82 MPa, shown in Fig. 5.11, has been developed and is currently in practical use. Fig. 5.12 shows the developed simulation model.

Figure 5.11. Ultra-high-pressure hydrogen gas tank. Based on http://www.jfe-con.jp/product/hpc/fcv.html, http://www.hydrogencarsnow.com/index.php/hydrogen-fuel-tanks/.

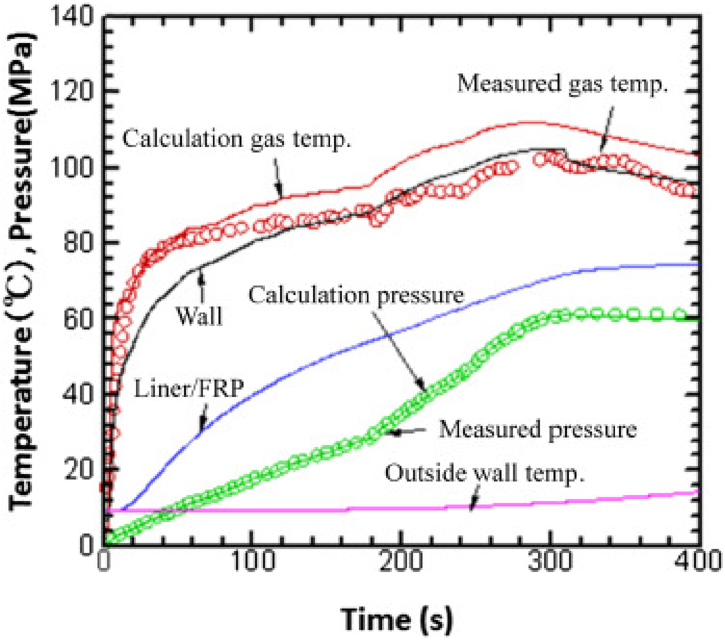

Figure 5.12. Developed simulation model for hydrogen charging.T. Nejat, Transportation fuel hydrogen, Based on Energy Technol. Environ. 4 (1995) P2712–P2730.

Figure 5.12. Developed simulation model for hydrogen charging.T. Nejat, Transportation fuel hydrogen, Based on Energy Technol. Environ. 4 (1995) P2712–P2730.

> Read full chapter

Hydrogen

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

2.5.2 Uses as an energy storage medium

Seen as a storage medium, gaseous hydrogen is convenient in underground stores such as aquifers or flushed-out salt extrusions, requiring only a better lining compared with present use of the same geological formations for natural gas storage. The low volume density makes hydrogen storage in manufactured containers somewhat expensive, but compressed hydrogen storage is still considered a convenient solution for many applications in industry and for at least the first generations of fuel cell hydrogen vehicles and household-size generators. These and other storage options were described in Section 2.3, including liquefied and molecularly trapped hydrogen stores.

It is possible for hydrogen to play a role as storage medium in connection with several types of energy systems, independent of whether or not hydrogen is also used as a general energy carrier. Renewable energy systems require energy storage in order to become self-contained solutions, and hydrogen satisfies a range of the storage requirements of such systems, particularly if an affordable fuel cell becomes available for recovery of energy in the form of electricity. As just mentioned, just about any future energy system would derive benefits from access to hydrogen energy storage.

> Read full chapter

Hydrogen-fueled road automobiles – Passenger cars and buses

J. Wind, in Compendium of Hydrogen Energy, 2016

1.4.3 Hydrogen supply

PEMFC stacks need pure hydrogen in order to operate. Thus, it is necessary to either store pure hydrogen on board the vehicle or to produce it from another fuel carried on board. On-board production of hydrogen has been used mainly in the last century in some FCEV prototypes, such as Daimler's NECAR 3 and NECAR 5 (Mohrdieck et al., 2014). These vehicles used methanol as a fuel and an on-board steam methane reformer to produce hydrogen from methanol. This adds a high degree of complexity to the drive train. This strategy is no longer followed by any car manufacturer; today, all FCEVs use pure hydrogen stored in an on-board hydrogen storage system.

PEMFC stacks need pure hydrogen in order to operate. Thus, it is necessary to either store pure hydrogen on board the vehicle or to produce it from another fuel carried on board. On-board production of hydrogen has been used mainly in the last century in some FCEV prototypes, such as Daimler's NECAR 3 and NECAR 5 (Mohrdieck et al., 2014). These vehicles used methanol as a fuel and an on-board steam methane reformer to produce hydrogen from methanol. This adds a high degree of complexity to the drive train. This strategy is no longer followed by any car manufacturer; today, all FCEVs use pure hydrogen stored in an on-board hydrogen storage system.

Due to the very low volumetric energy density of hydrogen, quite a design effort is needed to store the amount of hydrogen necessary for a reasonable driving range. Several hydrogen storage technologies for FCEVs have been developed and tested. Up to now, the only suitable ways to store significant amounts of hydrogen in a vehicle have been either liquid hydrogen storage or compressed hydrogen storage. A new approach, called cryocompressed storage, is a storage technology that combines both. However, this technology has not yet reached the same technological maturity as the others. Despite the long and intensive design and development work at many research institutes and in industry, no other hydrogen storage technology (such as storage in hydrides) has been developed to the maturity level needed in automotive applications (Sorensen et al., 2005).

A complex and expensive storage system is required to store liquid hydrogen at temperatures below 20.28 K. Even with very good insulation systems using a combination of materials with low thermal conductivity and vacuums, evaporation of hydrogen cannot be prevented totally, leading to considerable hydrogen losses. The hydrogen storage system will be empty after some weeks, even with the best available insulation. This is one of the major drawbacks of on-board liquid hydrogen storage. Another disadvantage is the very high energy consumption needed for the liquefaction of hydrogen, which is in the range of 10 kWh/kg of hydrogen, compared to a total energy content of 33.3 kWh of 1 kg of hydrogen (LBST, 2015).

Today all road vehicle manufacturers are using composite storage tanks to store compressed hydrogen with a pressure of 350 bars or 700 bars. 700-bar storage is used in most passenger cars as the available space is limited. For buses, 350 bars of pressure provides a suitable option due to the greater space available in or on the bus. The compressed hydrogen storage systems consist of one or more composite cylinders, valves, sensors, and regulators. Type IV cylinders consisting of an inner liner made from plastics and a carbon fibre reinforcement filled with resin are used most commonly (Eichseder and Klell, 2012).

> Read full chapter

Due to the very low volumetric energy density of hydrogen, quite a design effort is needed to store the amount of hydrogen necessary for a reasonable driving range. Several hydrogen storage technologies for FCEVs have been developed and tested. Up to now, the only suitable ways to store significant amounts of hydrogen in a vehicle have been either liquid hydrogen storage or compressed hydrogen storage. A new approach, called cryocompressed storage, is a storage technology that combines both. However, this technology has not yet reached the same technological maturity as the others. Despite the long and intensive design and development work at many research institutes and in industry, no other hydrogen storage technology (such as storage in hydrides) has been developed to the maturity level needed in automotive applications (Sorensen et al., 2005).

A complex and expensive storage system is required to store liquid hydrogen at temperatures below 20.28 K. Even with very good insulation systems using a combination of materials with low thermal conductivity and vacuums, evaporation of hydrogen cannot be prevented totally, leading to considerable hydrogen losses. The hydrogen storage system will be empty after some weeks, even with the best available insulation. This is one of the major drawbacks of on-board liquid hydrogen storage. Another disadvantage is the very high energy consumption needed for the liquefaction of hydrogen, which is in the range of 10 kWh/kg of hydrogen, compared to a total energy content of 33.3 kWh of 1 kg of hydrogen (LBST, 2015).

Today all road vehicle manufacturers are using composite storage tanks to store compressed hydrogen with a pressure of 350 bars or 700 bars. 700-bar storage is used in most passenger cars as the available space is limited. For buses, 350 bars of pressure provides a suitable option due to the greater space available in or on the bus. The compressed hydrogen storage systems consist of one or more composite cylinders, valves, sensors, and regulators. Type IV cylinders consisting of an inner liner made from plastics and a carbon fibre reinforcement filled with resin are used most commonly (Eichseder and Klell, 2012).

> Read full chapter

Hydrogen Storage for Mobile Application: Technologies and Their Assessment

Hydrogen Storage for Mobile Application: Technologies and Their Assessment

Lars Baetcke, Martin Kaltschmitt, in Hydrogen Supply Chains, 2018

5.2.3 Cryo-Compressed Hydrogen

Cryogenic hydrogen can also be stored under pressure; this option is called cryo-compressed storage. Besides the storage of liquid hydrogen, this is a storage option characterized by a relatively high volumetric energy density that does not change the chemical appearance of hydrogen.

5.2.3.1 State of Technology

In this storage concept, hydrogen is cooled down to the temperature of liquid hydrogen (20 *K*) and additionally hydrogen is compressed up to a pressure of up to 350 bar or even 700 bar. Under these challenging conditions, an energy density of maximum 7 wt% and maximum 0.07 kg/l may be achieved. This is only possible at the expense of an enormous amount of energy and technological effort to cool and compress hydrogen. Additionally, the demands to the design of a storage vessel containing a fluid at such a low temperature level for a long time and at such a high pressure, are extremely high. To describe it in a simple way, usually a type IV pressure tank (Section 5.2.1) covered with the vacuum insulation typically used for liquefied hydrogen tanks (Section 5.2.2) is needed (Aceves et al., 2010; Brunner et al., 2016).

Due to these challenges, a technically less demanding compromise aims at realizing cyro-compressed hydrogen storage tanks characterized by around 4 bar and 50 K. This leads to a storage density of 5 wt% hydrogen inside the fully-loaded tank (Blagojević et al., 2012). Other concepts currently under development that are in various development stages use different storage parameters to try to optimize the amount of stored hydrogen in relation to the necessary technical effort.

5.2.3.2 Characterization

The cost of a cryo-compressed storage tank is in a range of 12–30 US$/kWh. Due to significant technical uncertainties, these values are more along the lines of the expected cost than the real cost for the few prototypes that exist. The storage efficiency is characterized by values somewhere in between the storage efficiency of liquid and compressed hydrogen; 41% is a realistic order of magnitude for the time being (Stolten et al., 2016; Ahluwalia et al., 2010).

5.2.3.3 Markets and Perspectives

5.2.3.3 Markets and Perspectives

Several attempts have been made to implement and test cryo-compressed storage for mobile applications. This is especially true for application in passenger cars because the high energy density is very attractive for this application. For example, a Toyota Prius has been equipped with a cryo-compressed storage tank and has achieved the longest driving distance so far (1050 km) with a single tank filling for a hydrogen-powered car (Aceves et al., 2010). This storage tank was a specially designed cyro-compressed storage tank filled either with liquid or compressed hydrogen; in the case it is filled with liquid or cryo-compressed hydrogen the storage tank contains 2–3 times more hydrogen than a storage tank of compressed hydrogen.

Cryo-compressed hydrogen storage has some advantages in comparison to other options (e.g., high storage capacity and the technical possibility to fill the storage tank either with compressed, cryo-compressed, or liquid hydrogen. But so far cryo-compressed tanks are not available on the market and the longest possible time without losses if unused is seven days so far; compared to liquid hydrogen storage, this is around seven times longer (Brunner et al., 2016).

Because of these challenges it is unlikely that cryo-compressed storage will become a considerable part of the consumer market in the years to come. Additionally, all currently built refueling stations are designed for the distribution of compressed hydrogen. This might be true for highly specialized fleets of company vehicles (e.g., trains, planes, ships), which might be refueled in only one place or a very limited number of places.

> Read full chapter

Building a hydrogen infrastructure in the EU

M. Steen, in Compendium of Hydrogen Energy, 2016

12.3.4 Large-scale energy storage infrastructure costs

The role of hydrogen storage is to accommodate the intermittency of renewable electricity. The electrolyzers hence have to operate discontinuously and have to be of large capacity for grid support purposes. Low capital costs and the availability of large amounts of excess renewable electricity (in quantity and in time) are hence prerequisites for a favorable business case for hydrogen production. As indicated previously (FCH2JU, 2014a) capital costs for renewable electrolysis are targeted at 2.0 M€/(t/day) and 1.5 M€/(t/day) for 2020 and 2023, respectively, from a current cost of 8.0 M€/(t/day).

previously (FCH2JU, 2014a) capital costs for renewable electrolysis are targeted at 2.0 M€/(t/day) and 1.5 M€/(t/day) for 2020 and 2023, respectively, from a current cost of 8.0 M€/(t/day).

Total capital costs as well as levelized costs per kg for compressed hydrogen storage in different types of geological formations are shown in Figure 12.6 for storage of 7000 ton hydrogen at 140 bar (Sandia, 2011). The FCH-JU target costs for storage at pressures above 80 bar are € 6000/t.

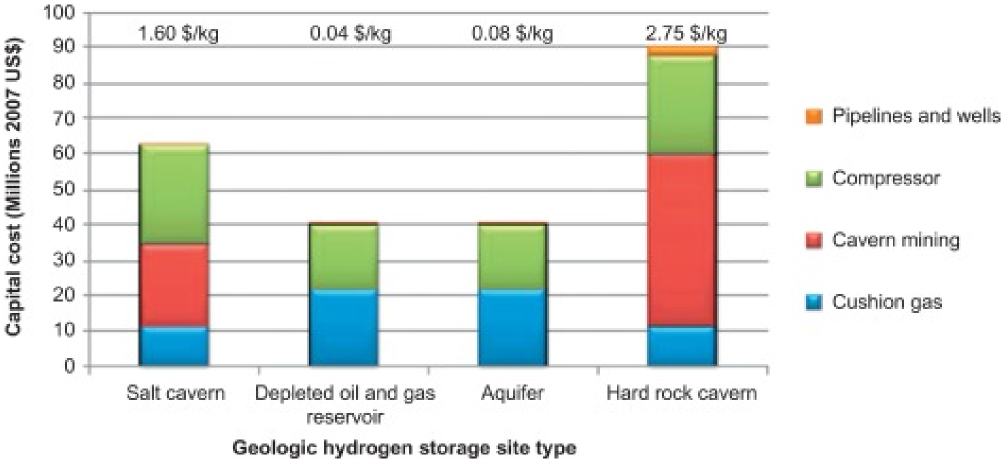

Figure 12.6. Capital cost components and overall levelized costs for hydrogen storage in geological formations (Sandia, 2011).

The overall business case for hydrogen as a renewable energy storage medium depends on the value generated by its use after storage. Converting hydrogen back into electricity for the grid, using fuel cells, suffers from low efficiency (30–35% power-to-power) and capital cost of fuel cell systems. Because of this, competitiveness of hydrogen as a storage option depends on its successful application as a low-CO2 energy carrier in other sectors, most importantly, for hydrogen mobility. This is also apparent from a recent study (FCH2JU, 2014b) which indicates that conversion of renewable electricity to hydrogen for use outside the power sector, i.e., in the gas grid (power to gas), for mobility or in industry has the potential to exploit nearly all excess renewable electricity that would otherwise (have to) be curtailed, thereby substantially contributing to the decarbonization of these sectors. Realizing this potential requires that there is either a demand for hydrogen at the production site or that the hydrogen can be economically transported to a demand center. Because of the volumes involved, pipelines are the obvious choice.

> Read full chapter