Hydrogen Storage & Measurement Technologies: Recent Progress and The Future

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Abstract

Hydrogen storage is certainly one of the key challenges in developing and implementing a hydrogen economy. Hydrogen storage systems in both on-board and off-board applications should meet minimum requirements in order to achieve consumer's acceptance. Hydrogen storage system, in addition, must be viable, cost-effective, durable, and efficient to meet the needs of a global hydrogen economy.

Introduction

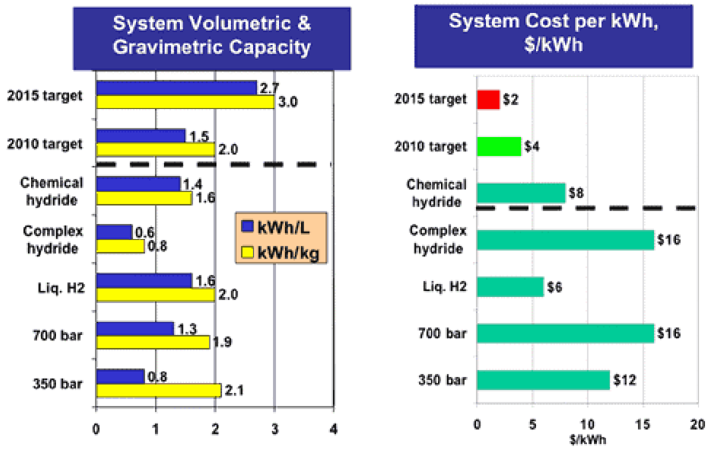
Hydrogen is a substance with high-energy content compared to its weight. This is the reason that hydrogen is naturally the first choice in space travel and very well suited for air travel. On the other hand, the energy content compared to volume is rather low. This poses greater challenges with respect to storage compared to storage of gasoline in which is a liquid. Hydrogen storage is a key technology in transportation, stationary, and portable applications. For transportation, the overarching technical challenge for hydrogen storage is how to store the amount of hydrogen required for a conventional driving range, within the vehicular constraints of weight, volume, efficiency, safety, and cost. Durability over the performance lifetime of the system must also be verified and validated and acceptable refueling times must be achieved. The ability to store the hydrogen effectively, quickly and inexpensively is most important. None of the current approaches to hydrogen storage meets the DOE 2010 or 2015 objectives shown in Figure 1.

Hydrogen Storage Technologies [1,2,3,4]

The DOE hydrogen storage program is focusing primarily on developing on-board storage materials and technologies. The objective of the DOE hydrogen storage activity by 2010 is to develop and verify on-board hydrogen storage systems achieving 2 kWh/kg (6 wt%), 1.5 kWh/L, and $4/kWh. By 2015, develop and verify low cost, off-board hydrogen storage systems, as required for hydrogen infrastructure needs to support transportation, stationary and portable power markets. Possible technological approaches to hydrogen storage are physical storage via compression or liquefaction, and storage in materials via reversible sorption processes or chemical reaction. Researches focusing on several major areas are explained in brief as follows;

1. Compressed Gas Systems

In stationary systems where weight and size are not decisive factors, steel tanks are a good one, but for vehicles, traditional pressure tanks have some problems regarding both weight and volume. There has been considerable breakthrough in the development of new types of composite tanks. Compressed hydrogen tanks [5000 psi (~35 MPa) and 10,000 psi (~70 MPa)] have been certified worldwide according to ISO 11439 (Europe), NGV-2 (U.S.), and Reijikijun Betten (Iceland) standards and approved by TUV (Germany) and The High-Pressure Gas Safety Institute of Japan (KHK). Tanks have been demonstrated in several prototype fuel cell vehicles and are commercially available. Composite, 10,000-psi tanks have demonstrated a 2.35 safety factor (23,500 psi burst pressure) as required by the European Integrated Hydrogen Project specifications. Advanced lightweight pressure vessels have been designed and fabricated. These tank systems have demonstrated 12 wt% hydrogen storage at 70 MPa (~10,000 psi).



* Status was provided by industry developers and includes complete system, i.e. storage material, packaging, and ancillary equipment.

Figure 1. Status and Targets in Hydrogen Storage technologies.

2. Cryogenic Liquid Systems

Liquid hydrogen is in particular interesting for long distance transportation purposes and as fuel in spacecraft and airplanes. In order to cool the hydrogen down, energy equivalent 30~40 % of that in the fuel is needed. Development of a new cooling process that would cut the energy use in half is considered feasible. The German company Linde has developed a tank for liquid hydrogen where the cold from some of the liquid hydrogen is used to cool down the insulation surrounding the tank; this is done with cooling elements. A hybrid tank concept combining both high-pressure gaseous and cryogenic liquid storage is being studied. These hybrid insulated pressure vessels are lighter than hydrides, more compact than ambient-temperature pressure vessels, and require less energy for liquefaction and have less evaporative losses than liquid hydrogen tanks.

3. Storage in Materials

There are a few generic routes for the storage of hydrogen in materials: sorption in simple metal hydrides, adsorption in carbon and non-carbon materials, and chemical reaction in complex metal hydrides and chemical hydrides.

3.1. Reversible metal hydride storage systems

Conventional high capacity metal hydrides require high temperatures (300~350 °C) to desorb hydrogen, but sufficient heat is not generally available in fuel cell transportation applications. Currently existing low temperature hydrides, however, show low gravimetric energy densities and require too much space on board or add significant weight to the vehicle. Researchers are developing low-temperature metal hydride systems that can store 3~5 wt% hydrogen. Alloying techniques have been developed that result in high-capacity, multi-component alloys with excellent kinetics, even though at high temperatures. Further researches are required to identify alloys with appropriate kinetics at low temperatures. Hydrogen can be stored in the form of a hydride at higher densities than by simple compression. Using this safe and efficient storage system depends on identifying a metal with sufficient adsorption capacity operating under appropriate temperature ranges. Alanates are considered to be the most promising of the complex hydrides studied to date for on-board hydrogen storage applications. They have focused on an extensive research to increase the storage capacity of the materials, extend the durability and cycle lifetime and uptake and give reproducibility. A thorough thermodynamic and kinetic understanding of the alanate system is needed in order to serve as the basis for systematically exploring other complex hydride systems. Engineering studies, in addition, must be initiated to understand the system level issues and to facilitate the design of optimized packaging and interface systems for on-board transportation applications.

3.2. Reversible carbon and non-carbon nanomaterials storage systems

According to several research groups, carbon nanostructures such as nanofibers, nanotubes and fullerenes have shown promising abilities to adsorb / absorb hydrogen. Carbon materials present a long-term potential for hydrogen storage and several carbon nanostructures are being investigated with particular focus on single-wall nanotubes(SWNTs). However, the amount of storage and the mechanism through which hydrogen is stored in these materials are not well-defined. Fundamental studies are directed at understanding the basic reversible hydrogen storage mechanisms and optimizing them. Therefore, combined experimental and theoretical effort is needed to characterize the materials, to understand the mechanism and extent of hydrogen sorption, and to improve the reproducibility of the measured performance. These efforts are required to obtain a realistic estimation of the potential of these materials to store and release adequate amounts of hydrogen under practical operating conditions. Researches on other new materials such as polymers, inorganic nanomaterials, and inorganic-organic compounds (MOFs), and concepts to meet long-term targets, are undertaking.

3.3. Chemical hydride storage systems (regenerated off-board)

An approach for the production, transmission, and storage of hydrogen using a chemical hydride slurry or solution as the hydrogen carrier and storage medium is being investigated. There are two major embodiments of this approach. Both require some degree of thermal management and regeneration of the carrier to recharge the hydrogen content. Significant technical issues remain regarding the regeneration of the spent material and whether regeneration can be accomplished on-board. Life cycle cost analysis is needed to assess the costs of regeneration. In the first embodiment, a slurry of an inert stabilizing liquid protects the hydride from contact with moisture and makes the hydride pumpable. At the point of use, the slurry is mixed with water and the consequent reaction produces high purity hydrogen. An essential feature of the process is recovery and reuse of spent hydride at a centralized processing plant. Research issues include the identification of safe, stable, and pumpable slurries and the design of the reactor for regeneration of the spent slurry. The second, and most advanced, embodiment is sodium borohydride ($NaBH_4$). The sodium borohydride is combined with water to create a non-toxic, non-flammable solution that produces hydrogen when exposed to a catalyst. The borohydride system has been successfully demonstrated on prototype passenger vehicles such as the Chrysler Natrium.

4. Measurement and Evaluation Technologies for Hydrogen Storage/Discharge Materials

For the measurement of hydrogen storage/release amount, volumetric method using P-C-T apparatus is predominantly applied to in the area of hydrogen storage in a variety of materials. Recently gravimetric method is also used in this area. Newly designed, coupled and combined, and more rigorous measurement methods depending on application ranges and types of storage materials, will be developed sooner or later.

Conclusion

Energy efficiency is a challenge for all hydrogen storage approaches. The energy required to get hydrogen in and out is an issue for reversible solid-state materials. Life-cycle energy efficiency is a challenge for chemical hydride storage in which the by-product is regenerated off-board. For compressed and liquid hydrogen technologies, the energy associated with compression and liquefaction must be considered. Low-cost materials and components for hydrogen storage systems are needed, as well as low-cost, high-volume manufacturing methods. Analyses of the full life-cycle cost and efficiency for hydrogen storage systems should be also accomplished. Applicable codes and standards for hydrogen storage systems and interface technologies, which will facilitate implementation/commercialization and assure safety and public acceptance, should be established.

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