Available online at www.sciencedirect.com

ScienceDirect

Current Opinion in Chemical Engineering

Hydrogen storage for fuel cell vehicles

Hyun Tae Hwang and Arvind Varma

The concerns over diminishing resources and the environmental impact of burning fossil fuels have focused attention on the development of alternative and sustainable energy sources for transportation applications. In this context, hydrogen is an attractive option to replace current hydrocarbon-based systems. A major obstacle for the development of hydrogen powered fuel cell vehicles is the lack of safe, light weight and energy efficient means for on-board hydrogen storage. During the last fifteen years, significant effort has been made to develop effective hydrogen storage methods, including hydrogen tank, sorbents and metal/chemical hydrides. In the present article, we concisely review the current status of each on-board hydrogen storage technology, along with its advantages and disadvantages, and offer a perspective for future developments.

Addresses
School of Chemical Engineering, Purdue University, 480 Stadium Mall Drive, West Lafayette, IN 47907, USA

Corresponding author: Varma, Arvind (avarma@purdue.edu)

Current Opinion in Chemical Engineering 2014, **5**:42–48

This review comes from a themed issue on **Reaction engineering and catalysis**

Edited by **Marc-Olivier Coppens** and **Theodore T. Tsotsis**

http://dx.doi.org/10.1016/j.coche.2014.04.004

Introduction

Hydrogen is a potential clean and environmentally friendly energy carrier because, in proton exchange membrane (PEM) fuel cells, hydrogen protons released at the anode transfer through the electrolyte, to react with oxygen at the cathode to produce water while work is generated in the external circuit via electron transfer from the anode to the cathode. In this context, hydrogen is an important alternative to address some adverse aspects of the current hydrocarbon liquid fuels for transportation applications. It has high energy density on a mass basis as compared to gasoline (120 MJ/kg for hydrogen vs. 44 MJ/kg for gasoline). Unfortunately, it has poor volumetric energy density (0.01 MJ/L for hydrogen at STP vs. 32 MJ/L for gasoline), which presents significant difficulty in storing large quantity of hydrogen for vehicle applications. A critical challenge for the development of fuel cell vehicles is how to store hydrogen on-board for a driving range (>500 km or 300 miles) on single fill with the constraints of safety, weight, volume, efficiency and cost [1–3].

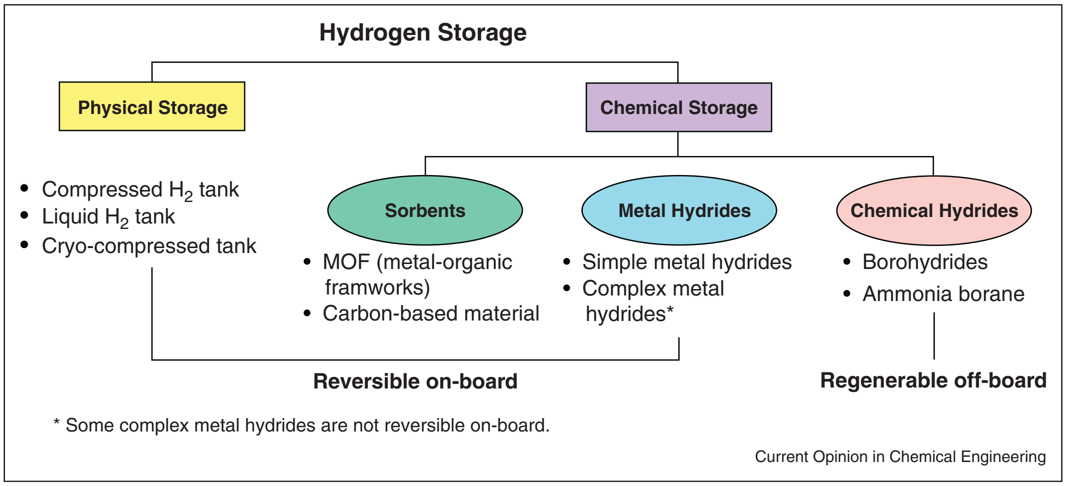
As illustrated in Figure 1, current approaches for on-board hydrogen storage include compressed hydrogen gas, cryogenic and liquid hydrogen, sorbents, metal hydrides, and chemical hydrides which are categorized as either 'reversible on-board' or 'regenerable off-board'. The U.S. Department of Energy (DOE) has set a 2017 requirement of 5.5 wt% H_2 and 40 g H_2/L for gravimetric and volumetric system targets, respectively, as well as cost, while the ultimate targets are more stringent (see Table 1) [4]. The difference between ***system*** and ***material-based*** capacities is noteworthy. Evaluation of a hydrogen storage ***system*** includes all associated components such as tank, valves, piping, insulation, reactants, among others, while ***material-based*** value accounts for only reactants or materials possessing hydrogen. For example, the material-based capacity of compressed hydrogen tank is 100% because it contains pure hydrogen, while system capacity drops to ~5 wt% when all associated components mentioned above are accounted for. In the present article, approaches including sorbents, carbon-based materials, metal hydrides and chemical hydrides provide material-based values unless otherwise noted because these technologies have not been adopted in actual vehicles yet. Apart from gravimetric and volumetric targets, DOE has also addressed the challenges associated with various approaches in terms of meeting key system performance targets, including cost, charge and discharge kinetics, and durability. There are advantages and disadvantages for the different approaches and currently no technology meets all the requirements. In the present paper, the current status of each on-board hydrogen storage method is discussed concisely, along with its advantages and disadvantages. For an extensive review of the topic, the reader is referred to the recent article by Durbin and Malardier-Jugroot [5••].

Compressed gas

The most commonly used method for hydrogen storage in fuel cell vehicles is compressed hydrogen tanks. Indeed, several prototype vehicles (e.g. Honda FCX Clarity, Toyota FCV, Mercedes-Benz F-Cell, and GM Equinox) with such tanks are already in test use for sale in the near future and manufacturers have estimated the fuel economy using EPA test procedures.

The most important consideration for compressed gas is the material composing the tank. It must be lightweight,

Figure 1



Classification of hydrogen storage methods.

inexpensive and sufficiently strong to meet the required stress, strain and safety specifications [6]. In addition, thermal conductivity of the material must be high enough to manage exothermic heat during filling the tank. Accounting for these requirements, carbon fiber reinforced plastic (CFRP) is promising as material for the compressed gas tank. The CFRP tanks are light-weight and durable, however, they have relatively low thermal conductivity which requires further improvement [7].

For a 300 mile driving range, assuming 50% fuel cell efficiency, 5.6 kg of usable H_2 is required. The CFRP (Type IV, made from carbon fiber with a polymer liner) tanks are estimated to provide 5.2 and 5.5 wt% H_2 for 700 and 350 bar, respectively (Table 2). Compressed gas tanks offer a near-term option for initial commercialization and currently focus on reducing the cost of the carbon fiber composite, which dominates the cost (>65%) of the compressed gas systems. The volumetric capacity (18 and 28 g H_2/L for 350 and 700 bar, respectively) and the cost of tanks, however, are still challenges [4].

Cryogenic storage

The volumetric density of hydrogen can be increased by liquefying it. For example, the theoretical volumetric capacity of hydrogen increases from 24 or 40 g/L (for compressed H_2 at 350 or 700 bar at 300 K) to 70 g/L (for liquid H_2 at 1 atm and 20 K).

When hydrogen is stored as liquid at 1 atm, it must be maintained below its boiling point (20 K). Therefore, effective thermal insulation is essential to maximize the efficiency of the liquid hydrogen (LH_2) tank. Therefore, typical LH_2 tanks consist of metallic double-walled container, where the inner and outer walls are separated by vacuum for thermal insulation purposes.

Despite improved volumetric density, LH_2 storage is not frequently used for several reasons. One of main issues is hydrogen boil-off. The LH_2 can evaporate even with highly insulated tank, which causes hydrogen loss [8].

Table 1

US DOE hydrogen storage performance and cost targets [3].

	Gravimetric, wt% (kWh/kg sys)	Volumetric, g/L (kWh/L sys)	Costs, $/kWh
2017	5.5 (1.8)	40 (1.3)	12
Ultimate	7.5 (2.5)	70 (2.3)	8

Table 2

Estimated performance and cost for different hydrogen storage approaches [3].

H_2 storage system	Gravimetric, wt% (kWh/kg sys)	Volumetric, g/L (kWh/L sys)	Costs, $/kWh
700 bar compressed (Type IV)	5.2 (1.7)	27.7 (0.9)	19
350 bar compressed (Type IV)	5.5 (1.8)	18.5 (0.6)	16
Cryo-compressed (276 bar)	5.8 (1.9)	43.1 (1.4)	12
Metal hydride ($NaAlH_4$)	1.2 (0.4)	12.3 (0.4)	TBD
Sorbent (AX-21 carbon, 200 bar)	4.0 (1.3)	24.6 (0.8)	TBD
Chemical hydride (NH_3BH_3-liquid)	4.0 (1.3)	33.8 (1.1)	TBD