Renewable and Sustainable Energy Reviews 91 (2018) 838–860

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

A Bird's Eye view on process and engineering aspects of hydrogen storage

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ARTICLE INFO

Keywords:
Hydrogen storage
Clean fuel
Storage methodologies
Modeling and simulation
Kinetics and thermodynamics

ABSTRACT

Hydrogen as a clean fuel is becoming vital in view of depleting fossil fuels and ever increasing energy demand. Hence hydrogen generation and storage gains immense importance. In this review article, different methods of hydrogen storage viz., physical, chemical and electrochemical in various forms like gas, liquid and solid have been discussed and compared in terms of their efficacy, capacity, operating conditions and other safety aspects. Modeling and simulation studies reported on various aspects of hydrogen storage have been presented and compared vis a vis governing equations, applications, assumptions, merits and demerits. These modeling studies would enable to understand the phenomenon better and to explore new avenues. Kinetic and thermodynamic aspects of hydrogen storage especially employing metal hydrides have been discussed too to understand the mechanism, rate controlling actors and energy aspects. Future challenges and prospects of all the aspects of the review were provided.

1. Introduction

The continued reliance of the world on fossil fuels has had an adverse effect on the ecosystem. The alarming rate at which the world currently consumes fossil fuels would only lead to their depletion and would result in an acute energy shortage in the near future. Furthermore, this continued dependence on fossil fuels for the past several hundred years has also resulted in severe environmental consequences such as global warming and CO_2 pollution. These have and could in the future lead to various disasters such as forest fires, hurricanes among others. Hence it is of utmost importance that the reliance of world energy needs on fossil fuels shift towards a more ecofriendly, easily available, highly efficient and green alternative. Options available at present time in this regard are renewable energies like biomass, biofuels, hydropower, wind power, solar power, and wave power. Energy efficient methods like green chemistry, green transportation – grey water electric motors are also products of such research interests [1] (Fig. 1).

One of the possible solutions for alternative fuel is hydrogen. It possesses several favorable characteristics, i.e., it is non-toxic in nature, it is pollution free (it releases only water vapour), it dissipates quickly into the atmosphere, it is abundant in nature and easier to produce as compared to other methods as it needs only water as a raw material [1,4]. Some other advantages of hydrogen energy also include having relatively lower energy content by volume (4 times less than gasoline), high energy content by weight (3 times more than gasoline), huge chemical energy per mass (142 MJ), 3.2 times less energy density than natural gas, 2700 times less dense than gasoline [3–6]. The efficiency of hydrogen is around 60% while the efficiency of fossil fuels such as gasoline and diesel are only 22% and 45% respectively, which further substantiates hydrogen's potential as a suitable alternative energy source [6,7].

It could play a significant role in fuel cell powered vehicles which could be used instead of normal vehicles, which have been one of the biggest contributors to greenhouse gases emissions. It is both pollutant free and non-toxic and can be easily available. However, one of the drawbacks of this technology is the possibility of violent explosions which could occur if hydrogen comes in contact with air due to its low energy density. So, hydrogen transportation and storage technology need to be further studied and the technology needs to be made safe, compact, inexpensive and more energy efficient [8–10].

Due to its combustible nature (especially when it comes in contact with air) the safety aspects during storage and transportation are of paramount importance. At present many methods are available for this purpose which can be broadly classified into chemical storage, physical storage, electro-chemical methods and “solid hydrogen storage” [4].

Presently two fundamental mechanisms are known to be used for storing hydrogen in materials in a reversible manner: adsorption and absorption. In adsorptive hydrogen storage, molecules of hydrogen maintain its physical forms while in absorptive hydrogen storage, it is chemically bonded to the given material of interest. This leads to bulk storage of hydrogen in materials such as metal hydrides, lithium

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https://doi.org/10.1016/j.rser.2018.04.028
Received 16 February 2017; Received in revised form 23 November 2017; Accepted 14 April 2018

Nomenclature

T	temperature, K
P	pressure, bar
ρ	density, kg/m^3
u	component of velocity vector, m/s
ΔH	enthalpy of formation, J/kg
ΔS	entropy change, J/kg K
E	activation energy, J/kg
Q	heat added or removed, W/m^3
Cp	Specific heat capacity, J/kg K
m	hydrogen mass absorbed or desorbed, kg/m^3 s
µ	viscosity, kg/m K

Symbols

α	Soave function
β,β'	constants in the k-ω model

Subscripts

a	absorption
d	desorption
e	effective
r	radial
z	axial
eq	equilibrium

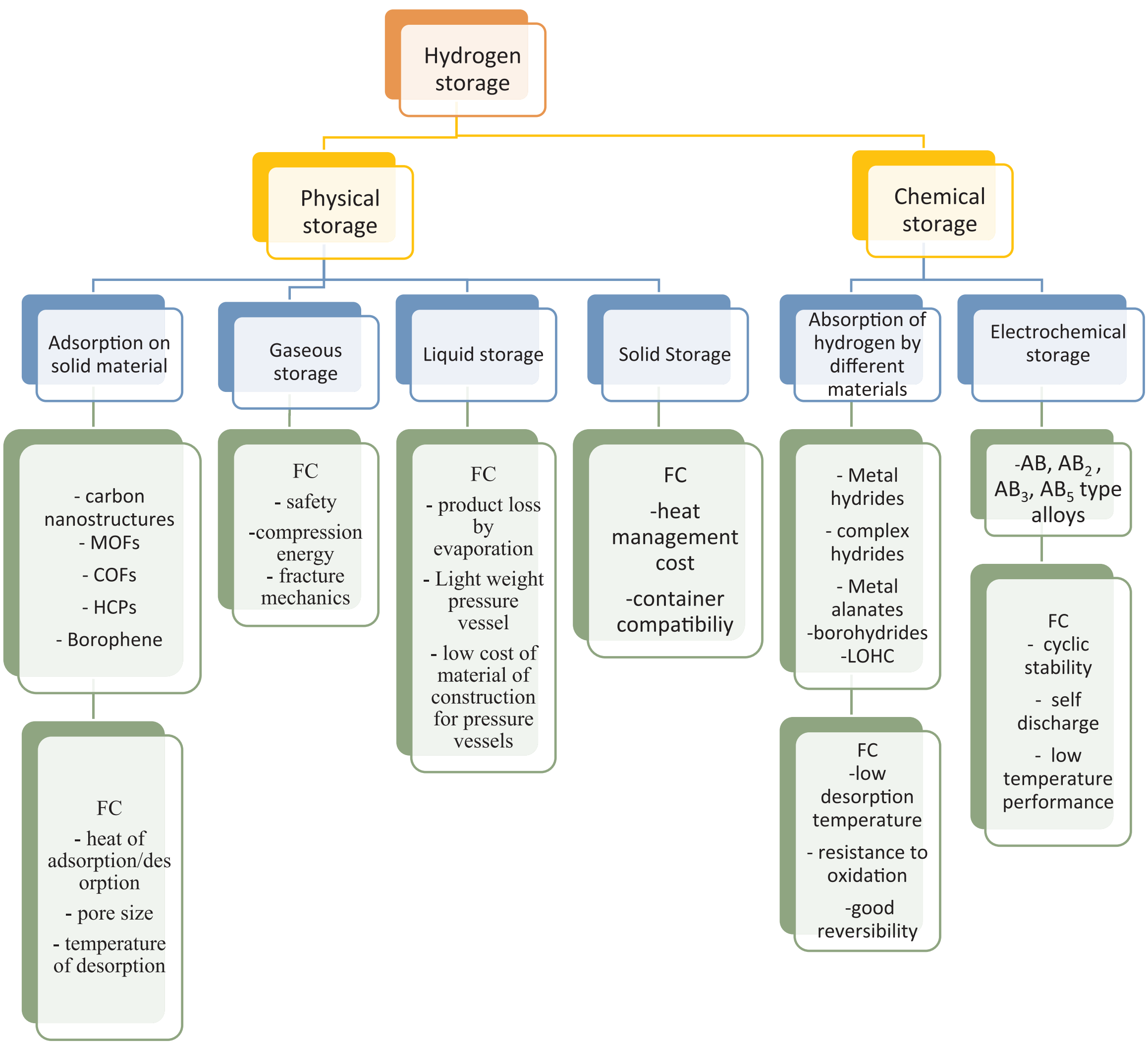

Fig. 1. Hydrogen storage methods. NOTE: FC – Future Challenge.

borohydride, and potassium alanates [11,12]. By finding the kinetic and thermodynamic properties of a system, adsorption can be categorized into physisorption and chemisorption. Since the amount of hydrogen that can be stored by these two methods is very less as compared to DOE (US Department of Energy) targets, another mechanism known as hydrogen spillover is used. In this mechanism, adsorbent material is doped with many metals such as nickel, platinum and ruthenium. Addition of these metals greatly improves the adsorbing properties of material on which hydrogen is to be adsorbed [13]. Another way of storing hydrogen is reversible chemical reactions. However, in multitude of cases backward reactions don't occur at favorable temperature and pressure.

Several comprehensive reviews summarize recent advances in hydrogen storage describing progress made with carbon-based nanostructures and metal organic frameworks based on the physisorption process, and metal or chemical hydrides based on the chemisorption process [12,14,15]. These materials should meet the US Department of Energy's (DOE) recently updated target values for minimum hydrogen storage capacity of 5.5 wt% and 40 g/L with 5 min filling time, at the system level, for commercial viability [16]. Furthermore, the cost of the