Available online at www.sciencedirect.com

ScienceDirect

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

Accelerating hydrogen absorption in a metal hydride storage tank by physical mixing

*Hui Wang, Ajay K. Prasad, Suresh G. Advani**

Center for Fuel Cell Research, Department of Mechanical Engineering, University of Delaware, Newark, DE 19716, USA

ARTICLE INFO

Article history:
Received 20 March 2014
Received in revised form
3 May 2014
Accepted 6 May 2014
Available online 11 June 2014

Keywords:
Hydrogen storage
Metal hydride
Physical mixing
Mixing rate
Aluminum foam
Heat transfer coefficient

ABSTRACT

A novel method to improve the hydrogen absorption rate in a metal hydride tank is proposed by introducing physical mixing of the metal hydride powder to promote heat removal and accelerate the kinetics of the hydriding process. Experiments were conducted with and without mixing to demonstrate that the hydrogen absorption rate can be improved significantly by mixing. Mixing was achieved by tilting the cylindrical metal hydride tank back and forth by 90° during charging. A mathematical model was also developed to simulate the effects of physical mixing. The model results indicate that physical mixing enhances heat transfer by redistributing the hydride powder from the hot core to the boundary and facilitates heat removal by convection at the tank walls. After validating the model against experimental results, the effect of physical mixing on accelerating hydrogen storage was explored by changing the mixing rate and the convection coefficient at the tank wall, and by increasing the thermal conductivity of the hydride bed by adding aluminum foam. It was found that while higher mixing rates generally improve the absorption rate, the benefits of mixing are reduced for higher convection coefficients, and for higher weight fractions of Al foam. Simulations were also conducted with and without mixing as a function of tank size. The results show that the benefit of physical mixing increases with tank size.

Introduction

Diminishing fossil fuel reserves and increasing greenhouse gas emissions have necessitated the search for carbon free energy sources. Fuel cells have shown the potential to address both of these concerns by converting hydrogen fuel directly to electrical energy in a clean and efficient manner, and are therefore considered a promising power source for automotive and portable applications. Although hydrogen possesses the highest energy content of any fuel on a mass basis, its volumetric energy density is quite low. Therefore, hydrogen storage poses a significant challenge for commercial applications that use hydrogen as the fuel. Current hydrogen storage methods such as compression and liquefaction are not optimal because not only are these methods very energy-intensive and expensive, but they also present safety issues. Metal hydride-based storage has attracted extensive interest because it can absorb and desorb hydrogen at relatively low operating pressures resulting in safety and cost advantages.

* *Corresponding author.*
E-mail address: advani@udel.edu (S.G. Advani).
http://dx.doi.org/10.1016/j.ijhydene.2014.05.029

Moreover, such systems can provide high volumetric storage efficiencies, especially with the development of new metal hydride materials.

For automotive applications in which fuel cells are powered by onboard hydrogen storage systems, the rate of desorption of hydrogen from the metal hydride tank is typically quite slow and therefore more easily accomplished than the charging process which must be completed in just a few minutes. The hydriding reaction during charging with hydrogen is a complicated multi-physics problem involving compressible gas flow in a porous medium, coupled with heat transfer and reaction kinetics. During charging, the exothermic reaction between the hydrogen and the metal releases a substantial amount of heat. The hydriding reaction rate is a function of temperature with higher temperatures reducing or even halting the reaction, hence rapid heat removal from the system is necessary to maintain a high rate of hydrogen absorption within the tank. Therefore, it is imperative to find and apply techniques that promote high heat removal rates.

As the thermal conductivity of most metal hydride materials is quite low, the heat removal rate can be enhanced by increasing the effective thermal conductivity of the metal hydride bed by the addition of conductivity-enhancing materials such as aluminum foam [1,2] or graphite [3,4], or by introducing internal fins to increase the heat transfer area [5,6]. Heat removal can also be accelerated by increasing the convective heat transfer from the tank by fitting it with a cooling jacket containing a recirculating coolant [5,7], or by introducing internal cooling tubes [8–10], heat pipes [11], or a helical coil heat exchanger [12–14]. The tank geometry (size and aspect ratio) also strongly influences the heat removal rate when heat is removed from the tank wall only [15]. While all these methods enhance the heat transfer rate, they require the addition of internal or external components, and/or materials which can displace active hydride material from the tank and adversely impact the gravimetric and volumetric storage efficiencies. Storage efficiency was not considered in these previous studies which only focused on improving the filling rate.

In this work, we explore a new approach to accelerate heat removal by introducing physical mixing of the hydride powder during charging. Mixing is achieved during experiments by tilting the cylindrical storage tank back and forth by 90° approximately every 5 s. As heat is only removed by convection from the tank walls, mixing enhances heat transfer by redistributing hotter and less saturated hydride powder from the tank's core towards its boundary. This approach benefits the filling rate in three ways: (i) the temperature at the core drops to the average temperature of the tank if the powder is mixed uniformly, which increases the volume of the hydride bed that can undergo reaction at that instant, thereby accelerating the reaction; (ii) the hydrogen density (mass of absorbed hydrogen per unit volume of metal hydride) near the boundary is also reduced to the average hydrogen density, which increases the absorption rate of the near-wall portion of the hydride bed; and (iii) the wall tank temperature increases, increasing the convective heat removal rate.

In our experiments, we employed a manual mixing method by continuously tilting the tank back and forth by 90° to demonstrate a measurable improvement in the filling rate. In our model, we assumed that the hydride bed is uniformly mixed throughout its volume at prescribed intervals. In addition, we studied the effect of enhancing the effective thermal conductivity of the bed by adding aluminum foam, and the effect of the convective coefficient at the tank's outer wall. The effect of mixing rate, Al foam percentage, and convective coefficient are explored in the parametric study section. The mathematical model was validated by confirming that the predicted results are in good agreement with

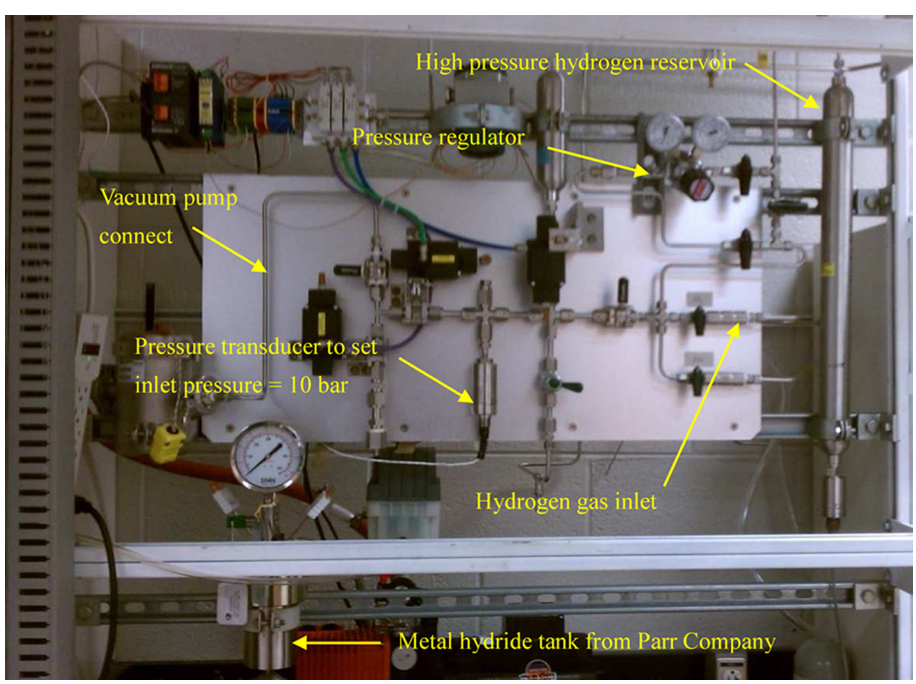

Fig. 1 – Photograph of the experimental apparatus.