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Effects of heat exchanger design on the performance of a solid state hydrogen storage device

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ABSTRACT

Heat exchanger design plays a significant role in the performance of solid state hydrogen storage device. In the present study, a cylindrical hydrogen storage device with an embedded annular heat exchanger tube with radial circular copper fins, is considered. A 3-D mathematical model of the storage device is developed to investigate the sorption performance of metal hydride (MH). A prototype of the device is fabricated for 1 kg of MH alloy, $LaNi_5$, and tested at constant supply pressure of hydrogen, validating the simulation results. Absorption characteristics of storage device have been examined by varying different operating parameters such as hydrogen supply pressure and cooling fluid temperature and velocity. Absorption process is completed in 18 min when these parameters are 15 bar, 298 K and 1 m/s respectively. A study of geometric parameters of copper fins (such as perforation, number and thickness of fin) has been carried out to investigate their effects on absorption process.

Introduction

Disadvantages and inadequacies of conventional non-renewable energy sources have involved researchers from all around the world to find an alternative. Hydrogen has been considered as a promising candidate, but its poor energy density by volume (0.0898 g/L) has made its storage a major bottleneck towards the hydrogen economy. Conventional methods to store hydrogen in its physical form such as high pressure gas storage and liquefaction (cryogenic storage) are very unsafe and energy intensive. Solid state storage of hydrogen in metal hydride (chemical storage) is gaining importance due to several advantages such as compactness and safety due to normal temperature and pressure operations. The storage device must be designed to absorb sufficient amount of hydrogen within a short interval of time. Absorption/desorption process of hydrogen is associated with considerable heat release/uptake, but poor thermal conductivity of MH decelerates the process and increases the charging/discharging time. Previous studies clarify that an effective heat management system for the storage device can significantly increase the absorption/desorption rate to reduce the charging/discharging time. Various inner and outer heat

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exchanger designs have been investigated theoretically and experimentally in the literature and the former has generated a lot of interest amongst the researchers.

Combined heat and mass transfer phenomenon controls the charging time of metal hydride. Ben Nasrallah et al. [1] tested the validity of the assumptions made to simplify the heat and mass transfer analysis of the hydrogen storage device by comparing the numerical results with and without the assumptions for $LaNi_5$. They concluded that the local thermal equilibrium between solid and gas is valid under almost all conditions. The effect of pressure variation in the storage device and convection heat transport term can be neglected. The effect of concentration variation can be seen only during desorption process, whereas it can be neglected during the absorption process. Ram Gopal and Srinivasa Murthy [2,3] experimentally investigated the performance of a cylindrical hydrogen storage device for different heat transfer fluid temperatures. Mohan et al. [4] simulated the performance of $LaNi_5$ based hydrogen storage device with embedded filters and heat exchanger tubes. They found bed thickness to be a major parameter controlling the sorption reaction. Mellouli et al. [5] conducted experiments on a storage device equipped with a spiral heat exchanger tube and concluded that the heat exchanger which provides more heat transfer area reduces the charging time significantly. Muthukumar et al. [6] studied the heat and mass transfer process in a 2-D model of an annular cylindrical hydrogen storage device. Mellouli et al. [7] presented a 2-D mathematical model of a storage device and investigated the effect of adding metal foam with the MH material. They found that aluminum foam increases the heat transfer rate and hence reduces the charging time by 60% for 90% storage of hydrogen. Askri et al. [8] examined the storage device incorporating a concentric heat exchanger tube with fins and a good improvement in the performance was found. Mellouli et al. [9] compared the effects of spiral tube heat exchanger with and without fins on charging time and 66% improvement for 90% hydrogen storage is reported for the former design. Anbarasu et al. [10] experimentally investigated the absorption performance of $LmNi_{4.91}Sn_{0.15}$ based solid state hydrogen storage device with 36 and 60 embedded cooling tubes. They investigated the effects of different operating parameters on absorption rate and absorption capacity. The reduction in absorption time for storage device with 60 tubes was quite significant (37.5%) as compared to 36 cooling tubes. Souahlia et al. [11] conducted the experimental studies on two different designs of storage device, first one with finned concentric heat exchanger tube embedded inside the MH bed and the second one with conventional concentric heat exchanger jacket, using $LaNi_5$ as a storage media. A good absorption rate was found for first design. Mandhapati and Kumar [12] presented a systematic study to optimize the heat exchanger design using CFD modeling for three different shell and tube heat exchanger configurations. They concluded that a helical coil heat exchanger is useful to get a high heat transfer coefficient because of high turbulence and consequently the enhanced absorption rate. Linder et al. [13] experimentally investigated the effects of main influencing parameters on the dynamics of a MH reaction bed using $LmNi_{4.91}Sn_{0.15}$ as a hydriding material. They used capillary tube bundle heat exchanger and a very fast charging time of about 100 s was obtained for 1 g of MH at water flow rate of 5 l/min. Anbarasu et al. [14] presented the simulation analysis of a cylindrical MH storage device with embedded cooling tubes. They first simulated the 2-D model to optimize the number of embedded cooling tubes. The study was then further extended to develop a 3-D model to predict the sorption performance of $LmNi_{4.91}Sn_{0.15}$ under different operation conditions of supply pressure, hot fluid temperature and effective thermal conductivity. Several other heat exchanger mechanisms such as helical coil heat exchanger with Al foam [15], heat pipe [16], embedded cooling tubes [17], finned multitubular tank [18] and finned spiral heat exchanger and lateral heat exchanger [19] for storage devices were investigated in the recent past. The effects of different operating variables such as hydrogen supply pressure, heat transfer fluid temperature and overall heat transfer coefficient were studied by many researchers [2,4,5,7,8,11,12,17–19] and it was concluded that a good choice of these parameters is necessary to improve the sorption performance. Mazzucco et al. [20] reviewed the recent works on heat management systems of hydrogen storage device focusing on the limitations and performance improvement of each system.

All the above studies indicate a strong dependence of charging/discharging time of MH storage device on its heat exchanger design. However, a proper numerical study of heat and mass transfer process in a solid state hydrogen storage device with experimental validation and investigation of effects of different heat exchanger configurations is limited. The objectives of this work is to study experimentally and theoretically the hydrogen absorption process in a solid state hydrogen storage device with an embedded heat exchanger of novel design. The effects of different geometric parameters of the fins and various operating conditions on absorption performance were investigated vis-à-vis reduced charging time.

Experimental analysis

Description of hydrogen storage device

The proposed design of MH hydrogen storage device is shown in Fig. 1. It is a cylindrical device with embedded finned heat exchanger assembly. The cross sectional view of storage device at different sections are shown in Fig. 1(a). The dimensions of the storage device are given in Table 1. According to the capacity of device, 1 kg of MH, $LaNi_5$, is filled inside the cylinder. A circular opening on the cylinder serves as an inlet/outlet port for hydrogen gas. Unit cell of packed MH bed is shown in Fig. 1(b). Heat exchanger design employs two concentric stainless steel tubes with copper fins as shown in Fig. 2(a). Water is used as a heat transfer fluid which enters into the heat exchanger through the inner tube from top of the storage device, and is redirected through a concentric annular outer tube from bottom to top. In order to increase the heat transfer between the fluid and MH bed, thirteen radial circular copper fins are equally spaced on the periphery of outlet tube. Design of the circular copper fin is presented in Fig. 2(b). Holes are punched in the fin to reduce the total weight of the heat exchanger assembly. Three PT-100 sensors are inserted inside the device, each to a different depth of 50, 90 and 130 mm from