SHORT ABSTRACT

The world is progressing toward renewable energy resources because of the increase in demand for energy, the price of fossil fuels and the global warming effect. A major shift from fossil fuels to renewable energy sources is needed to save the environment from global warming and climate change. Renewable energy sources are often limited for commercial use due to their intermittent nature, i.e., inconsistent energy supply and demand. This issue in concentrated solar thermal power (CSTP) technology can be addressed by integrating a thermal energy storage (TES) system. The excess thermal energy is stored in the TES system during sunshine hours. The stored energy is retrieved for producing electricity during the off-sun hours, making the CSTP plant operate continuously throughout the day and night. Thermal energy can be stored in three different ways: sensible heat storage (SHS), latent heat storage (LHS), and thermochemical energy storage (TCES). The TCES system offers high energy density, wide operating temperatures, and long-term storage among all TES systems. Another promising technology for storing excess renewable energy is in the form of hydrogen. Hydrogen as an energy carrier offers a large-scale, long-term, and seasonal storage of excess renewable energy. The excess electricity produced by renewables (primarily wind and solar PV) during low energy demand periods generates hydrogen using an electrolyzer. The stored hydrogen is utilized in stationary fuel cells for combined power and heat as per the demand.

Metal hydrides (MHs) are the most promising solid-gas TCES reactions for TES and hydrogen storage applications. Metal hydrides (MHs) are compounds formed by the reversible reaction of hydrogen and metal. As per the TES is concerned, MHs have high energy density (up to 2.8 MJ/kg of hydride) and a wide range of operating temperatures (up to 1100°C) with no environmental encroachment. For hydrogen storage, MHs offer higher volumetric storage density at near-ambient conditions. Therefore, this dissertation studies the TES and hydrogen storage aspects of MHs. The main objectives of the present work are (a) to develop a mathematical model for analyzing the absorption and desorption characteristics of the MH reactor, (b) to design a simple, lightweight and efficient MH reactor for large-scale TCES and hydrogen storage applications, and (c) to conduct a detailed experimental study on MH-based TES and hydrogen energy storage systems.

Firstly, the discharging behavior of the tubular reactors filled with magnesium-nickel hydride is analyzed for the heat transfer coefficient of 250 W/m^2-K. Therminol VP1 is considered as a heat transfer fluid (HTF). The drawbacks of a smaller diameter tubular reactor are less energy

storage density and the requirement of a greater number of tubes for the given energy storage capacity. Therefore, an annular MH reactor is proposed to reduce the discharging time of the tubular reactor without a significant drop in its energy storage density. With the proposed annular MH reactor, the discharging time of a 2.5-inch tubular reactor is reduced up to 70%, with only 16% comptonization in gravimetric energy storage density. Also, the average specific discharge power of the 2.5-inch tubular reactor is increased by ~2.5 times with the annular MH reactor.

For real-time TES storage applications, the discharging time of the reactors present near the MH array outlet section is much higher than 360 min (the DOE target's limit). Therefore, radial fins are incorporated in the annular MH reactor to improve the heat transfer characteristics of the reactors present near the outlet section of the MH array. The addition of radial fins reduced the discharging time to 333 min, i.e., 1.93 times lower than the case without fins. Finally, the system level gravimetric storage density of the annular MH reactor with radial fins is 560 kJ/kg of system.

Further, the design of the annular MH reactor is extended to hydrogen storage application with $LaNi_5$ as MH material. The absorption and desorption characteristics of the annular porous MH reactor filled with $LaNi_5$ are investigated. Three reactor configurations are compared to analyze the effect of HTF flow direction and adding radial fins on the absorption and desorption processes. The absorption time of 945 s is obtained with the finned tube reactor under the supply pressure of 15 bar and cooling fluid temperature of 25°C. During desorption, the finned tube reactor achieved a desorption time of 1290 s for the HTF temperature of 50°C. The addition of fins enhanced the absorption and desorption rates by 1.84 and 1.85, respectively.

Based on the numerical results, lab-scale prototypes of the annular MH reactor with radial fins are fabricated. Two MH alloys, namely, $LaNi_5$ and $La_{0.7}Ce_{0.1}Ca_{0.3}Ni_5$ are experimented under different operating conditions for hydrogen storage applications. The developed MH reactor offered a hydride-to-reactor mass ratio of 1.44 with a working pressure of 80 bar. The $LaNi_5$ reactor showed system-level gravimetric and volumetric storage densities of 0.73% and 20.4 kg of H_2 per m^3, respectively. The same for $La_{0.7}Ce_{0.1}Ca_{0.3}Ni_5$ reactor are 0.8% and 22.4 kg of H_2 per m^3, respectively. Further, the $La_{0.7}Ce_{0.1}Ca_{0.3}Ni_5$ reactor offered an energy storage efficiency of 77.54%. Overall, the annular MH reactor with internal radial fins is a promising option for medium to large-scale hydrogen storage applications due to its higher weight ratio, ease of fabrication, savings in pumping power, and better performance.

Further, the annular metal hydride reactor with internal radial fins was experimented for thermal energy storage applications. The magnesium-nickel alloy and air are chosen as MH material and HTF for the experiments. The reactor was filled with 3.76 kg of magnesium-nickel alloy. Firstly, the absorption and desorption characteristics of the magnesium-nickel alloy were studied in a single reactor mode. Magnesium-nickel alloy is activated in the seventh activation cycle, reaching 3.91 wt.%. The alloy absorbed 104, 142, and 143 g of hydrogen in 122, 78.3, and 62.5 min, respectively, under the supply pressure of 10, 20, and 30 bar. Also, the desorption time is approximately two times more than the absorption time, and increasing the desorption temperature has not shown any significant effect on the desorption rate.

Finally, a thermal-driven coupled MH reactor system is studied with two alloy pairs: magnesium-nickel alloy/ $LaNi_5$ and magnesium-nickel alloy/ $La_{0.7}Ce_{0.1}Ca_{0.3}Ni_5$. The charging and discharging times are within 360 min, except for the charging process at 374°C for magnesium-nickel alloy/ $La_{0.7}Ce_{0.1}Ca_{0.3}Ni_5$. In the thermal-driven coupled MH reactor system, the line pressure was influenced by the equilibrium pressure of the hydrogen storage alloy due to its faster reaction kinetics and better heat transfer characteristics. Also, a compressor-driven MH-based TES system is proposed to produce an additional cooling effect in the hydrogen storage reactor.