INDIAN INSTITUTE OF TECHNOLOGY GUWAHATI
SHORT ABSTRACT OF THESIS

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SHORT ABSTRACT

In the present energy scenario, increase in global warming and energy demand are two major issues growing at an alarming rate, despite various measures being taken to control them. With the depletion of fossil fuels and drastic rise in greenhouse gases emissions, there is an urgent need for shifting towards clean and renewable energy based technologies, which generate near zero emission of greenhouse gases. Hydrogen is such a fuel (energy carrier) that contains an enormous amount of energy per unit mass and meets all the above criteria. Storage of hydrogen is the most challenging task in Hydrogen Economy. Solid state hydrogen storage in the form of metal hydrides (MH) offers several benefits over the other modes of storage. In addition, interaction of hydrogen with MH offers multiple thermal management applications for which MH can be tailor made, offering high volumetric energy density. A rigorous research work is being carried out to implement MH in on-board applications, which demands compact and lighter in mass MH reactors. Further, there is a minimal issue of leakage as hydrogen in MH is a solid solution. Another major advantage of MH based storage system is the availability of auxiliary cooling effect during discharge of hydrogen. The major bottleneck for the commercialization of MH based systems is its low gravimetric storage capacity. This induces the need for focused research in the field of MH based thermal machines.

The widely preferred cooling mechanism is the one based on vapour compression refrigeration system (VCRS), which utilizes chemicals as working fluid and high grade energy input for its operation. There is a dire need for sorption based mechanism that utilizes low grade energy such as MH based thermal machines. However, they offer low COP and low specific alloy outputs. Compressor driven metal hydride based cooling systems (CDMHCS) are a preferable alternative, and can compete with VCRS as green energy alternative by utilizing input power sourced from renewable energy. Another comparative advantage of CDMHCS is that it employs hydrogen as working fluid, which is ecofriendly in contrast to most of refrigerants. There is a profound lack of practically adaptable strategy when it comes to the design of compact reactors with enhanced heat transfer characteristics. Some of the devised approaches are too complex and demand higher manufacturing cost. Improvement in heat and mass transfer characteristics of metal hydride bed is highly emphasized. Numerous experimental investigations were conducted to study the effect of various parameters on the performance of the MH based thermal machines. However, experimental investigations conducted on industrial scale MH based hydrogen storage and cooling systems are very limited. Experimental investigations reported on CDMHCS were quite inadequate compared to the demand of these systems. There is a great scope for improvement in terms of its COP and specific cooling output.

The major objectives of the present research have been framed to address this research gap: (i) to select alloys that are suitable for operation in near ambient conditions and are better candidates for metal hydride based storage and cooling systems; (ii) to develop a novel design methodology that balances the enhanced heat transfer characteristics of the hydrogen storage or thermal management systems against the parasitic thermal mass; (iii) to predict and analyze the storage performance and heat transfer characteristics of reactor designed based on developed methodology using valid numerical model; (iv) to develop an experimental set-up and conduct parametric and performance investigations on MH based cooling system considering industrial scale reactor; and (v) to develop an experimental set-up and conduct performance investigation on metal hydride based compressor driven cooling system, employing the designed reactors.

A novel set of arithmetic correlations are developed as a base guiding principle for the design of cylindrical reactors with embedded cooling tubes (ECT). The underlying principle of this design methodology is to evenly distribute the ECT within the MH bed, thereby reducing bed thickness

while balancing the design against the resulting parasitic thermal mass of the empty reactor. Performance of these designed reactors are analysed by developing thermal models and solving them numerically. While modelling the MH reactor, gas transport phenomenon within MH bed, combined heat and mass transfer characteristics arising from absorption and desorption reaction, variable wall convective boundary at ECT interface and variation of hydrogen concentration within the bed are taken into consideration. Based on the proposed design methodology, lab scale prototype with 41 ECT reactor is designed and compared with 60 ECT and 55 ECT reactors. The absorption performance of these reactor designs are analysed considering 4 kg of $MmNi_{4.7}Fe_{0.3}$ at supply condition of 50 bar, 25 °C and 24 lpm HTF flow rate, while the desorption performance is analysed at 25 °C and 15 lpm of HTF flow rate. The influence of reactor design is found to be more prominent towards the temperature distribution within bed than the hydriding rate. The bed temperature variation within bed of 41 ECT reactor is seen to be uniformly distributed as opposed to the cases of 55 ECT and 60 ECT reactors. During desorption, the drop in average bed temperature of 41 ECT reactor is observed to be sharper which results in HTF outlet temperature of 23 °C. Through the design methodology, industrial scale reactors with 50 kg alloy capacity are developed and their storage performance is analysed numerically. By selecting the best design among them, the effects of varying supply pressure (5 to 35 bar), absorption temperature (20 °C to 35 °C) and HTF flow rate (10 lpm to 35 lpm) on the hydriding performance of $LaNi_{4.7}Al_{0.3}$ (50 kg) are analysed. Among the designs, 6 inch reactor with 99 ECT depicts best hydriding rate and heat transfer characteristics. It achieves total hydrogen storage capacity (HSC) of 1.29 wt% in 2060 s, while 80% of HSC is attained within 430 s. The numerical results are validated against experimental results and good agreement is observed between them.

From the analysed reactor designs, lab scale and industrial scale reactors were fabricated for open cycle MH based hydrogen storage and cooling systems (MHHSCS) and closed cycle CDMHCS. The 55 ECT reactor was fabricated and filled with 4 kg of $MmNi_{4.7}Fe_{0.3}$. Upon activation, the hydriding performance of this lab scale prototype was analysed at different supply pressures (10 bar to 70 bar) and absorption temperatures (5 °C to 25 °C). The dehydriding rate and cooling performance of this lab scale reactor were investigated at different desorption temperatures of 5 °C to 30 °C with HTF flow rate of 15 lpm. At 25 °C and 24 lpm flow rate, supply pressure below 40 bar resulted in poor hydriding rate. The storage capacity was increased by ~3.25 times in 676 s when supply pressure was increased from 40 bar to 70 bar. The amount of cooling was increased by 25.5% when desorption temperature was increased from 5 °C to 25 °C at 15 lpm flow rate, with peak output and SCP of 2.3 kW and 279 W/kg of cooling alloy, respectively. The desorption was found to be so rapid that ice formation on the periphery of reactor surface was observed during reaction. When the study was extended to industrial scale reactor, the performance was comparatively low. The effect of varying supply pressure (40 bar to 70 bar) and the effect of varying desorption temperature (5 °C to 25 °C) on the respective absorption and desorption performances of industrial scale model were also investigated. Hydrogen storage capacity of 0.75 wt% (~300 g) was attained by the industrial scale reactor within 364 s. The desorption performance is comparatively slow in the industrial scale reactor, as the bulk of the alloy causes an inherent limitation leading to slower desorption kinetics. At 25 °C and 50 lpm flow rate, 4088.6 kJ of cooling was produced in 3360 s, at an average rate of 1.2 kW. By utilizing two identical lab scale ECT reactors, CDMHCS of different alloys were developed and their performance during quasi continuous cold generation was analysed. The experimental setup of CDMHCS was formulated with two identical 60 ECT reactors filled with 2.75 kg of $LmNi_{4.91}Sn_{0.15}$ to analyse the COP and SCP of the system. The operating parameters including cycle time (4 min to 16 min), cold fluid flow rate (4 lpm to 16 lpm), refrigeration temperature (10 °C to 20 °C) and sink temperature (25 °C to 35 °C) were varied. For $LmNi_{4.91}Sn_{0.15}$ based CDMHCS, increase in cycle time from 4 min to 8 min resulted in corresponding reductions of 43% and 46% in COP and SCP. Similar trend was observed with increase in cold fluid flow rate as well. Increase in refrigeration temperature from 10 °C to 20 °C at sink temperature of 25 °C, resulted in maximum increase in COP and SCP by 64.2% and 70.3%, respectively. The operating condition of 20 °C refrigeration temperature and 25 °C sink temperature with cold fluid flow rate of 8 lpm in 8 min cycle resulted in maximum COP and SCP values of 2.2 and 53.5 W/kg of total alloy, respectively. When the investigation was extended to $La_{0.7}Ce_{0.1}Ca_{0.3}Ni_5$ based CDMHCS, it was noted that the cooling output rate was steady due to steady dehydriding rate of the alloy. Due to this steady rate of desorption, the cooling performance was not as prominent as that of previous system, even though 41 ECT reactor depicted better cooling performance than 60 ECT. Maximum COP of 0.53 and SCP of 66.2 W/kg were achieved at cycle time of 8 min with cold fluid flow rate of 6 lpm, refrigeration temperature of 25 °C and sink temperature of 25 °C.