Experimental research of metal hydride heat storage reactor processes

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Abstract. The results of the experimental research of thermal, mass exchange and dynamical characteristics of processes inside the low temperature metal hydride (MH) thermal energy storage system are presented. Single stage pressure driven MH heat storage system of closed cycle concept was studied and tested. Intermetallic compound (IMC) LaFe 0.1Mn 0.3 Ni 4.8 in the quantity of 5 kg was used as main hydrogen storage/heat emitter element in the reactor. Nominal maximum hydrogen capacity of the reactor is 850 st.l. with though resulting effective volume of cycled hydrogen ended up to be around 240-250 st.l. The reactor type and intermetallic alloy, which were used in the series of experiments, proved to be somewhat suitable for the task, but more advanced heat exchange design along with selection of different type of IMC promise to increase the cycled effective volume along with the system dynamics, resulting in greater thermal energy power output.

1. Introduction
Decreasing supplies of fossil fuels, growing concern about global warming, and the accelerating rise in energy demand have made the power-producing areas to shift their focus from conventional sources of energy to renewable ones. The Paris Agreement, signed by 195 countries in a struggle against global warming, demands that each of the participating nations plans and implements actions to mitigate climate change. When a perfect scenario would make provision for the complete transition from fossil fuels to renewable energy, only about 23% of the potential global renewable energy needs to be harnessed [1], leaving vast moment for improvement and innovation.

Along with other renewable sources, solar energy is the most exuberant and should be given the highest possible priority [2]. Mainly, Solar Photovoltaic (SPV) and Concentrated Solar Thermal Power (CSTP) systems are used to harness solar energy [3]. However, more like SPV power, CSTP is affected by seasonal and location characteristics of solar insolation, which also varies significantly during the course of a single day at a particular site, therefore limiting the period of effective electricity generation to about 7 to 8 h per day. One very promising option for resolving this issue in the case of CSTP is the integration of a thermal energy storage system (TESS). Thermal energy storage systems become relevant when the heat supply and its demand do not overlap. Heat can be stored in the form of sensible, latent and chemically stored heat. Mainstream thermal energy storage systems mostly utilize Phase Change Materials (PCMs) [4-6] and sensible heat storage materials such as cast steels, concrete, fire bricks, etc. From different variants of thermal energy, thermo-chemical energy acts as the promising one due to the high energy density of
chemical reactions comparing to sensible or latent heat. There is a variety of accessible thermochemical energy storage materials such as salt hydrates, carbonates, metal hydroxides, metal hydrides etc. [7]. The key advantages of reversible thermo-chemical thermal energy storage systems over the two aforementioned traditional ones can be summarized as follows:

- Higher energy density due to use of chemical reaction heat
- Stable chemical compounds preserved at an ambient temperature without diminishing provide long-term storage
- Can be adopted for heat transport over long distance
- Regeneration of the stored heat is possible with the lack of stored heat exergy deteriorating
- Can be adopted for various useful heat transformation operations like heat pumps, refrigeration, thermal amplification, heat transforming, reversible low-temperature energy storage, etc.

Metal hydride thermal energy systems are considered as reversible chemical heat storage systems, able to store thermal energy in the estimate range of 2 MJ/kg [8]. In metal hydride thermal energy storage system, useful heat is released when the hydrogen is introduced into the system at certain pressure and temperature. The rate of thermal energy release and the temperature can be managed by altering the hydrogen supply pressure and gas flow parameters. When the external heat is available, hydrogen could be regenerated from metal hydride and stored back in to a container. Main scientific and technical questions of development and constructing efficient MH devices though are tied with handling the thermal and mass transfer peculiarities inside the MH volume. Inefficient ways of managing the heat transfer inside the IMC volume combined with high thermal effect of reaction result in crisis events characterized by rapid decreasing of reaction dynamics [9]. Thus, intensification of thermal transfer between IMC and coolant is crucial to achieve maximum thermal energy power output possible.

2. Materials and metal hydride reactors
Varying an IMC composition allows one to compose an alloy of needed sorption/desorption pressure in a temperature range of 0 to 100°C to meet needed requirements for reversible thermal energy storage. AB5-type hydrides can achieve necessary parameters to be utilized in a model thermal energy storage system. LaFe(Mn)0.1Mn0.3Ni4.8 composition was chosen on the basis of readily availability in our facility along with its acceptable pressure-content-temperature characteristics, which allow us to utilize it in a thermal energy storage system in a comparatively low temperature range (0-100°C).

PCT-isotherms of sorption and desorption processes were obtained via Siverts method (figure 1) [10].

Experimental research of thermal processes in the MH hydrogen accumulation and purification systems were conducted employing experimental rig 12-04 of JIHT RAS in the laboratory of hydrogen energy technologies [11-16].

Experimental rig (figure 2) consists of gas ramp, electromagnetic valves (EV), pressure sensors (PS), gas flow regulator (FR) and metal hydride reactor RSP-3 №3 (figure 3). Measuring equipment and gas flow regulators are operated via PC block based on LabView system.
Figure 1. PCT curves of the AB₅ alloys used at a temperature of 25.0 °C.

Figure 2. Diagram of the part of experimental rig 12-04 of the JIHT RAS utilized in the research along with basic schema of the concept.
3. Results and discussions

Analysis of performance of MH single stage pressure driven thermal energy storage system should be focused on its main characteristics – working capacity of hydrogen. Due to inherent properties of MH, in accordance with its PCT-diagram, one cannot fully discharge the whole capacity into a closed system. Eventually, the pressure levels inside the MH device and a gas tank would reach equilibrium, defined by the temperature one can put the MH device into, after which no more gas could be put into the desorption process. This so-called “first-stage pressure” should define most of the working capacity amount. But in order to obtain accurate data about working capacity the sorption-desorption cycle should be repeated at least once.

First stage of experiments consisted in desorption of fully charged RSP-3 reactor (850 st.l of hydrogen in MH with an approximately 1.4 st.l of free volume above the MH bed) into a standard 40.1 gas cylinder. Gas tank and gas pipeline were preliminary vacuumed up to $1.2 \times 10^{-5}$ bar. Coolant fluid (water) flow was set to 0.110 st.l/sec. with a temperature of, at first, 83.0°C with an additional rising up to 90.0°C. Such temperatures allowed us to reach up to 7.6 atm in the gas line, which is an equivalent of 304 st.l. of hydrogen inside the gas cylinder.

Second stage of experiments consisted of discharging the hydrogen from the gas tank into preliminary cooled RSP-3 reactor. System temperature was cooled to the temperature of 13.0°C, after which the gas valves were opened with a virtually no limits on the gas flow. Coolant fluid flow was set to 0.110 st.l/sec. Total amount of hydrogen absorbed reached ~238 st.l., with maximum temperature of exhaust water of 17.1°C. The obtained experimental data is represented on figure 4.

![Figure 3. Reactor Type 3 (RSP-3) (pipe board).](image)

![Figure 4. a – first stage. b – second stage.](image)
On figure 4a position “1” points out the moment when EV-3 and EV-4 are opened to let built-up pressure inside the MH device drop down into the gas storage volume. Position “2” points out the moment of a water temperature switched to 90.0°C, and position “3” points out the end of the desorption process with closing of all vents, leaving the gas tank on achieved pressure.

As could be seen on figure 4b, the pressure equilibrium during the sorption was established on ~0.15 MPa, resulting in 60 st.l of dead weight hydrogen inside the gas cylinder. Thus, the working capacity of this particular setup could be evaluated as ~240 st.l H₂, but one more cycle was conducted to reaffirm the results.

Third stage (first part of the new cycle) consisted in desorption of partially charged reactor RSP-3 into the gas cylinder with 60 liters of hydrogen in it. Coolant flow was of 0.117 l/min, with a temperature of, again, 80.0 and 90.0°C. Overall system pressure reached almost 8 atm. Thus 260 st.l of hydrogen were discharged into the gas tank.

Fourth stage (second part of the new cycle) was conducted the same way the second one was, but with water cooled down to 12.0°C. Amount of hydrogen absorbed (~238 st.l) and max coolant temperature achieved (~17.0°C) made clear that the cyclic stable mode of operation was successfully achieved.

The thermal energy storage system was able to reach 2 kW peak power output during the initial part of sorption process. Changes of instantaneous power over time are represented below in the figure 5.

![Figure 5. Thermal power of the experimental device.](image)

4. Conclusion
Though only 28% of total reactor capacity was employed into cyclic work, the concept of single stage pressure driven system worked within expected parameters. The dynamics of reaction could be vastly improved by implementing more efficient design of MH reactor, where much emphasis is to be put on thermal exchange intensification. The IMC, adopted for this study, is hardly suitable for a practical application, so another type of alloy should be put into consideration or even be developed anew with a goal to maximize cyclic working capacity within estimated operational conditions.
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