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METAL HYDRIDE HYDROGEN STORAGE AS A SAFE ALTERNATIVE TO TRADITIONAL HYDROGEN STORAGE METHODS

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Abstract: Safety in hydrogen storage is a key factor for its potential use in modern energy systems. Hydrogen is often referred to as the fuel of the future and therefore poses significant safety challenges due to its high flammability, low molecular density, and ability to easily penetrate various materials. Traditional methods of storing hydrogen include high-pressure storage under high pressures of 35–70 MPa in pressurized vessels and the storage of liquid hydrogen at temperatures as low as -253°C. Metal hydride hydrogen storage tanks are a safe alternative to these traditional storage systems. Hydrogen is a chemically bonded system to metal alloys at pressures under 10 bar(a) and room temperature, eliminating safety risks. During the absorption and desorption of hydrogen, endothermic and exothermic reactions occur, necessitating efficient thermal management. To ensure effective thermal management of the storage tank, various approaches can be applied. One highly innovative solution involves the use of a closed-loop heat pipe (LHP). This system requires no pumping work during operation; thus, it has low energy requirements for operation. The article presents the design of a thermal management system for heating and cooling a metal hydride hydrogen storage tank, along with the development of a physical model of the tank using loop heat pipes. It also discusses the experimental results obtained from measurements on the physical model. Results demonstrate that a well-designed thermal management system ensures optimal operation of the metal hydride storage tank.
Keywords: energy storage, hydrogen storage, loop heat pipe, metal hydride

1. INTRODUCTION

Hydrogen is often considered a potential energy source of the future as it represents a viable alternative to fossil fuels. Hydrogen is an attractive solution for the industrial, transportation, and energy sector due to its potential to decrease reliance on fossil fuels. Furthermore, hydrogen can be produced using renewable energy sources, such as solar, wind, or hydro power, thereby reducing dependence on fossil fuels.

Hydrogen gas has a high energy density per unit of mass, reaching 120 MJ/kg (Usman, 2022). At standard atmospheric pressure and room temperature (25°C), hydrogen has a density of only 0.0824 kg/m³. For comparison, air has a significantly higher density under the same conditions, at 1.184 kg/m³. However, physical and chemical properties—such as low density, high flammability, and wide explosive limit pose significant safety challenges Hydrogen has a very low ignition energy, only 0.02 mJ (Lee et al., 2011), which means that even a static discharge can initiate ignition. A mixture of hydrogen and air is explosive at concentrations from 4% to 75%, as shown in the figure (Fig. 1.). This wide ignition range increases the risk of explosive reactions and therefore working with hydrogen requires increased safety requirements. In addition, its flame is almost invisible, making fires difficult to detect and extinguish. This combination of properties makes hydrogen one of the most dangerous gases to work with. (Panda and Hecht, 2017)

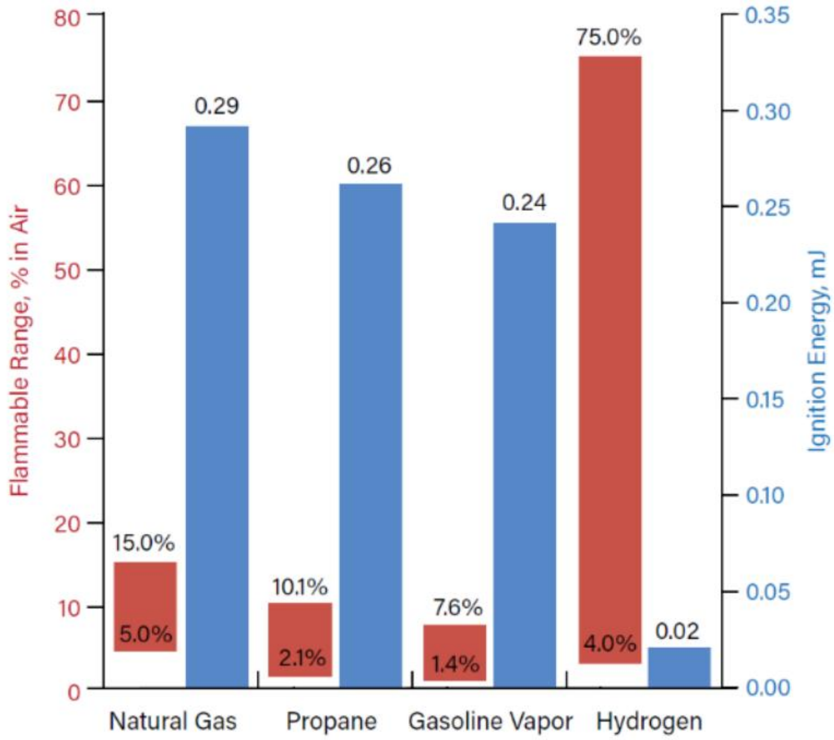

Fig.1. Flammability limits of hydrogen and other gases. Source: Perelli and Genna, 2022

Molecules of hydrogen easily escape through materials that can typically hold other gases. A device that is air-tight may not necessarily be hydrogen-tight, necessitating the use of specialized materials to ensure safety. This factor must be carefully considered in the design of such systems to minimize the likelihood of hydrogen leaks. Traditional methods of storing hydrogen in pressurized vessels or in liquid form have significant drawbacks, including high energy demands and safety risks associated with extreme pressures of up to 70 MPa (Usman, 2022). These factors not only increase costs but also pose safety challenges related to the storage and handling of hydrogen.
Metal hydrides are compounds that can store hydrogen through reversible chemical reactions, where hydrogen is absorbed into the metal lattice structure to form stable hydrides. This process involves hydrogen occupying interstitial sites within the metal structure, often within polyhedral configurations formed by hydride-forming and non-

forming elements (Morinaga and Yukawa, 2002). By adjusting temperature and lowering pressure, the stored hydrogen can be released. The interactions between hydrogen gas and metal in these compounds facilitate smooth absorption and desorption of hydrogen, allowing for safe handling and reducing the risk of leaks often associated with other hydrogen storage methods. Metal hydride hydrogen storage tanks therefore offer an innovative alternative to conventional systems that depend on extreme pressures or cryogenic conditions. These tanks provide stable hydrogen storage and improve operational safety.

2. ANALYSIS OF CURRENT HYDROGEN STORAGE TECHNOLOGIES

Hydrogen, as a promising fuel for the future, requires efficient and safe storage methods. The most widely used methods include high-pressure gaseous hydrogen storage, liquid storage, and hydride storage, most commonly in metal hydrides. However, all three methods bring specific advantages and challenges, especially in terms of safety and energy consumption.

Hydrogen gas storage in high-pressure vessels at pressures of 35–70 MPa is one of the most common methods due to its simple principle. However, safety remains an issue in high-pressure storage. High pressure increases the risk of leaks. These vessels must be designed to withstand high pressures, using special alloys and composite materials that provide high strength and resistance to cracking.

Liquid hydrogen is another storage option, that offers a higher energy density by volume compared to gaseous hydrogen. However, the liquefaction process requires cooling of the hydrogen to an extremely low temperature of -253°C. The safety challenges associated with liquid hydrogen are significant and relate to its extremely low temperatures. One of the main challenges is the risk of failure of refrigeration systems. In the event of a cooling system failure, liquid hydrogen will begin to evaporate rapidly. In the process, its volume increases more than 800 times, leading to a sharp increase in tank pressure. Another risk is the brittleness of the materials at extremely low temperatures. Many materials, such as ordinary steel, lose their strength and elasticity at these temperatures, which can lead to cracks and subsequent leaks of liquid hydrogen.

Both high-pressure and liquid storage methods are associated with significant energy requirements. Compressing hydrogen to a pressure of approximately 70 MPa requires energy that represents approximately 13-18% of its total calorific value (Møller et al., 2017). This means that to compress a given quantity of hydrogen, energy equivalent of 13-18 % of the energy contained in the hydrogen itself must be used. In comparison, the process of liquefying hydrogen is even more energy intensive, requiring up to 30-40 % of its calorific value (IDTechEx, 2023). When hydrogen is stored in pressurized vessels, a 26 litre container is required to store 1 kg of hydrogen when the hydrogen is compressed to 70 MPa. In comparison, when storing hydrogen in liquid form, a volume of 14 litres is required to store the same amount of hydrogen at a pressure of 78.8 MPa. In contrast, in a metal hydride storage tank using the $LaNi_5$ compound, at a hydrogen content of 1.2% (Zhu et al., 2019) by weight in the compound, 82.33 kg of the compound is required to store 1 kg of hydrogen, which corresponds to a volume of 10.36 litres of the compound. Although the mass is higher in the case of metal hydride, the advantage is that we are working with significantly lower pressures and temperatures compared to compressed or liquid hydrogen. This results in higher handling safety, and lower energy requirements.

Metal hydride storage tanks are one of the safest alternatives for hydrogen storage. With the right metal hydride compound, hydrogen chemically bonds to metal alloys at pressures under 10 bar(a) and temperatures below 200°C. The process is reversible; once heated, the hydrogen is released back into the gas phase. Due to their ability to absorb and desorb hydrogen under controlled conditions, metal hydrides minimize safety risks, making them an innovative solution for future hydrogen-based energy systems.
When storing or expelling hydrogen from a metal hydride storage tank, thermal management, or cooling and heating of the metal hydride alloy with respect to the actual process, plays an important role. In the case of hydrogen absorption into the metal hydride alloy, the hydrogen chemically bonds with the metal, which is an exothermic process. In this mode, heat is generated, which needs to be efficiently dissipated. Conversely, in the case of desorption of hydrogen from the metal hydride alloy, heating is required to release the hydrogen from the lattice, thereby releasing the hydrogen from the metal hydride metal lattice. Various methods can be used to cool and heat the heat transfer medium with efficient thermal management.
A potentially promising solution for thermal management appears to be the solution of heating and cooling of the heat transfer medium by a closed loop heat pipe (LHP), which does not need pumping work, which means that the circulation of the heat transfer medium works on the gravity principle.

3. METAL HYDRIDE AS A SAFE AND EFFICIENT SOLUTION FOR HYDROGEN STORAGE APPLICATIONS

Hydrogen storage in metal hydrides has specific technological requirements. In order to to ensure their safety and reliable functionality, it is essential to have the correct thermal management, including the heating and cooling process. Energy consumption for metal hydride storage is on the order of 5–15% of the energy contained in the hydrogen itself, in depending on the type of alloy used and the storage conditions. Metal hydrides require reheating to release the hydrogen, which means additional energy requirements if no other heat source is available, for example in the form of waste heat from the fuel cell, etc. The advantage is greater safety and stability in storage, which makes metal hydrides an attractive option in a variety of applications.

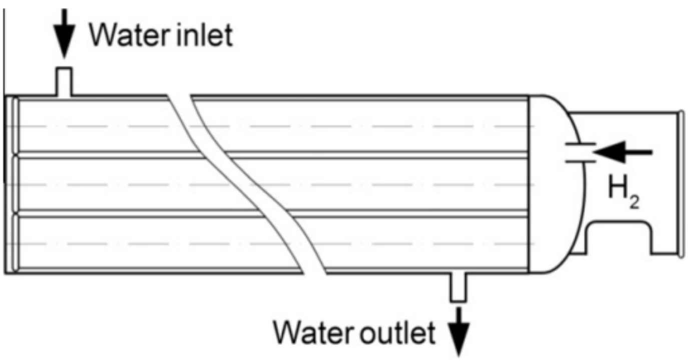

Fig. 2. Tubes with metal hydride alloy with water-based thermal management. Soruce: Brestovič et al., 2015

Different approaches can be used for the thermal management of a metal hydride reservoir, i.e. to ensure hydrogen absorption and desorption. One of them is cooling and heating by circulating water (Fig. 2.), which circulates around the outertube space in a radial direction to ensure optimal heat transfer to the metal hydride alloy. For cooling and heating, Peltier cells were used in this case, which can both heat and cool the water depending on the polarity of the DC electric current supplying the Peltier cells. (Brestovič et al., 2015)

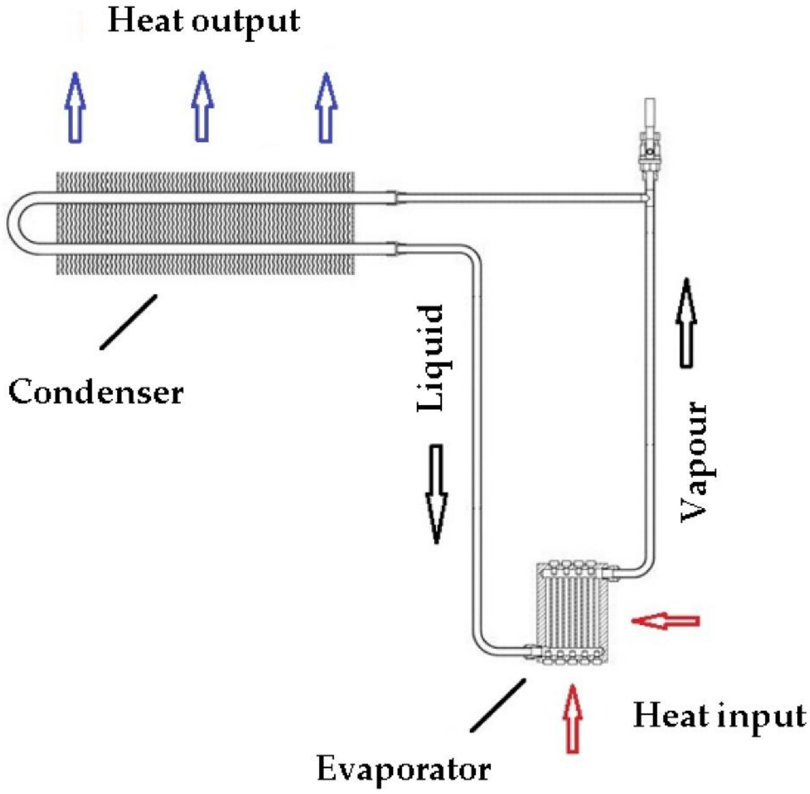

Fig. 3. Working principle of heat transfer via a Loop heat pipe. Source: Polačiková et. al., 2022

One of the innovative ways to realize the heating and cooling of a metal hydride storage tank is the use of a closed loop heat pipe. A closed loop heat pipe (Fig. 2.) is a passive device for efficient heat transfer that operates on the principle of phase change—evaporation and condensation of the working medium. This system is made up of two main parts: an evaporator and a condenser, which are interconnected. In the evaporator, the working medium is exposed to a heat source, which causes it to evaporate. The vapours of the working medium move towards the condenser, where they are cooled and reliquefied. The liquefied medium is returned by gravity back to the evaporator in a liquid state. This cycle is repeated, ensuring a continuous transfer of heat from the source to the point where the heat needs to be removed. The loop heat pipe is a very efficient device that does not require active pumps to move the working fluid.

Our approach to implementing thermal management is to utilize the properties of closed loop heat pipes. By utilizing the phase changes of the working substance (evaporation and condensation), we can provide efficient thermal management with a minimum amount of additional added energy. This approach reduces the operating costs of hydrogen storage, which is a significant advantage over thermal management with circulating water. Thermal management using the LHP system was tested using a physical model to simulate the thermal processes in a metal hydride storage tank. To verify the correct functioning of the heating and cooling of the metal hydride storage tank, as well as the safe behaviour of this system, it is necessary to verify its functionality on a physical model.

Within the application of thermal management by the LHP system, the design of the heating medium for heating the metal hydride hydrogen storage tank, the design of the physical model of the heating of the metal hydride storage tank using closed loop heat pipes, and the results obtained from the experimental measurements on the physical model have been carried out.

4. PHYSICAL MODEL OF HEATING AND COOLING OF A METAL HYDRIDE STORAGE TANK USING LOOP HEAT PIPE

The physical model of the metal hydride storage tank (Fig. 4) was designed as a system with integrated heating and cooling system. The model, made of stainless steel, does not work with real metal hydride, but uses pure monopropylene glycol as the circulating medium to simulate the metal hydride alloy. The metal hydride tank consists of two parts which, when assembled, form a so-called field system. On the outer surface of the field tubes, heating by condensation and cooling by boiling take place. The key element of the simulation is the thermal management system, which ensures the correct functioning of the storage tank. This design therefore serves as a physical model of the metal hydride stack, which allows testing and analysis of its properties.

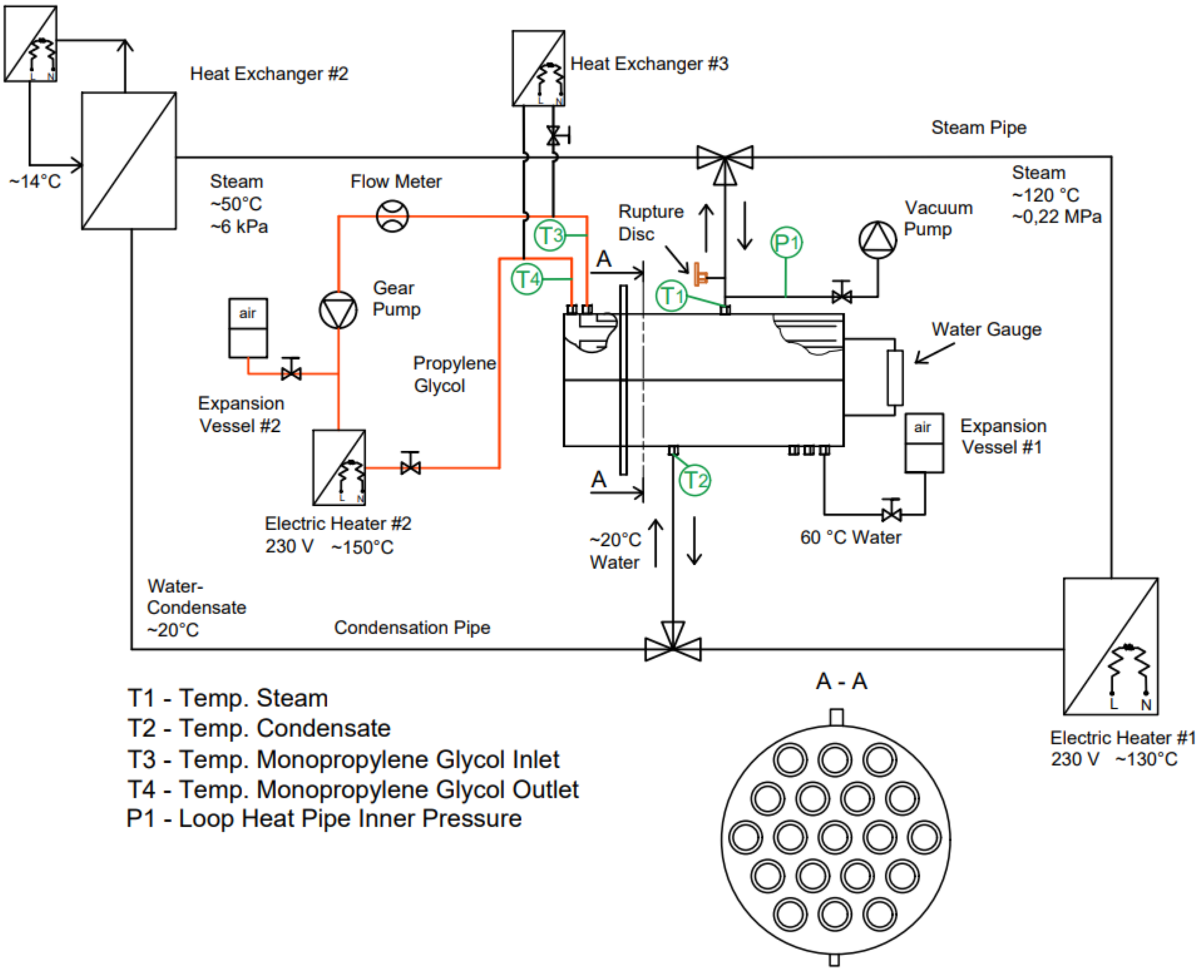

Fig. 4. Schematic diagram of thermal management using a loop heat pipe

The function of the system (Fig. 4.) is based on the control of the heat flux during the heating and cooling phases. The monopropylene glycol circuit is shown in orange to

simulate a metal hydride alloy. Since heat pipes operate most efficiently in a single-component environment, a vacuum of approximately 6 kPa was created in the loop heat pipe system to achieve optimum conditions for circulating the heat transfer medium. The system can be divided into a heating circuit, a cooling circuit, and a monopropylene glycol circuit, with the heating or cooling process controlled by three-way valves. Thermofrost P monopropylene glycol, which is characterized by its high boiling point, was used to simulate the metal hydride charge.
The heating phase started by circulating the monopropylene glycol, which represents the metal hydride charge of the metal hydride reservoir. Electric heater #1 generates steam from the distilled water, which passes through a three-way valve into the interior of the tank. The outer surface of the field tubes is surrounded by distilled water currently. As the steam increases the pressure in the system, water from the interior space is forced into Expansion Tank #1.
The cooling phase took place immediately after the temperatures stabilized after the heating phase. During the cooling phase, the LHP uses the principle of boiling the liquid at reduced pressure. The system pressure was again set to 6 kPa and the water from Expansion Tank #1 was drained back into the interior of the tank. During this process, the tank flooded with water, allowing cooling to begin. The monopropylene glycol circulated through the field tubes, transferring heat. As the water reaches boiling point (33.8°C), it begins to form vapor nuclei on the surface of the tubes. The generated steam rises to Heat Exchanger #2, where it condenses to condensate at about 20°C when cooled with cold water (temperature approximately 14°C). The condensate is then returned to the storage tank, and the cycle repeats.

5. RESULTS AND DISCUSSION

During the heating and cooling process, the monopropylene glycol flow rate was adjusted to achieve the maximum heat output that was possible within the system's capacity, based on the results of previous experiments. A Yokogawa AFX010G flowmeter, capable of accurately measuring the flow rate of low electrically conductive liquids, was used to ensure the flow rate was accurately adjusted to optimize the performance of the heating system designed to produce steam. The high heat capacity of the storage tank and the LHP heat pipe system meant that the entire heating process took over 3 hours. After stabilization of the system, we achieved heating the monopropylene glycol to 105°C at a constant flow rate of 125 l/h and steam production of approximately 113°C. Figure 5. shows the maximum temperatures and pressures at which the system stabilized after 230 minutes of heating at constant flow.
The same procedure was used to cool the metal hydride storage tank, with the flow rate adjusted to match the output of Heat Exchanger #2. The time required to stabilize the temperature in the system was 250 minutes. At the beginning of the measurement, the pressure was reduced to approximately 6 kPa to remove air that is not essential for the function of the loop heat pipe and to lower the boiling point of the working substance in the LHP. After stabilization of the system, the temperature difference of the monopropylene glycol was approximately 8°C, and the monopropylene glycol was cooled from 76°C to 68°C at a flow rate of 300 l/h. The temperature of the generated steam was stable at 65°C.

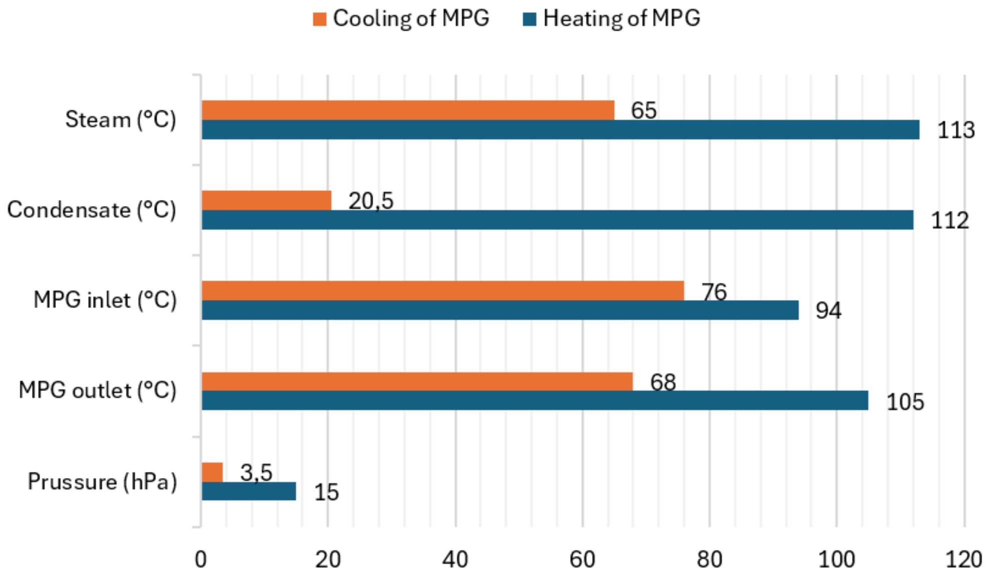

Fig. 5. Peak pressures and temperatures during the cooling and heating processes

It is clear that during cooling we were able to dissipate heat much more efficiently using Heat Exchanger #2 than in the case of heating, when the metal hydride reservoir formed by the field tubes was itself a heat exchanger, given that the difference between the temperature of the steam and condensate was only 1°C in the case of heating but up to 8°C in the case of cooling. Thus, it can be said that the field tubes, which act as a heat exchanger in the heating mode, do not operate with as high an efficiency as a commercially available plate heat exchanger. For this reason, we were not able to reach temperatures higher than 105°C with the 2.2 kW heater when heating the monopropylene glycol. The efficiency with which we were able to transfer the 2.2 kW of power using the LHP never exceeded 65%. It would be worth considering a suggestion to modify the surface of the field tubes to make the heat transfer more efficient or to better thermally isolate the LHP from the surrounding environment. Design modifications considered include increasing the external surface area of the field tubes by adding ribbing made of a highly thermally conductive material such as copper or aluminum.

3. CONCLUSION

Metal hydride storage tanks represent a significant technology in the field of hydrogen storage, mainly due to the low pressures required for hydrogen absorption and desorption. However, this is directly dependent on a properly selected metal hydride alloy that allows proper operation at the selected pressure and temperature conditions. The low system pressures reduce design complexity and safety requirements, making metal hydride storage tanks practical and attractive for a variety of applications.

Experiments have shown that heating by condensation and cooling by boiling can be implemented on the physical model. It has also been confirmed that circulation of the heat transfer medium, distilled water, can be ensured without a circulating pump, which significantly reduces the energy consumption of the whole system and represents a major advantage of LHP technology. Distilled water circulates naturally in the system based on phase changes. During the absorption of hydrogen into the metal hydride alloy, the storage tank needs to be cooled. In LHP cooling, the water boils at negative pressure (below barometric pressure), taking heat from the monopropylene glycol in the evaporator and converting it to steam. This steam is then condensed in the condenser, which can be cooled either actively or passively if it is sized appropriately. In the case of hydrogen desorption from metal hydride, on the other hand, heat must be input, especially in the final stages. In the experiments, steam was generated by boiling water at a pressure of approximately 200 kPa using a 2.2 kW resistance coil. However, this energy could in practice be recovered from the waste heat of the fuel cell, or other sources, which would significantly reduce the energy demand of the system. The fuel cell could thus produce saturated water vapor, which would be used to heat the metal hydride charge.

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