Transactions on Energy Systems and Engineering Applications

Article

A review on thermal management of metal hydride based solid state hydrogen storage devices

Anurag Singh[1,*], R. Shree Pragya[1], Priyaranjan[1], Neeraj Yadav[1], Paramkush J. Nakka[1], Akshat Jain[1] and Prerana[1]

[1] Department of Industrial and Production Engineering, GGV Bilaspur, C.G – 495001, India.

[*] Correspondence: anuragsingh2907@gmail.com

Received: 25 March 2024; Accepted: 30 December 2024; Published: 21 August 2026

Abstract: Metal hydride based solid state hydrogen storage devices have garnered substantial interest owing to their potential in facilitating clean and efficient energy storage for various applications. However, effective thermal management remains a critical aspect influencing their performance and safety. This review comprehensively explores the thermal management strategies employed in metal hydride-based systems, encompassing heat transfer mechanisms, materials design, and engineering approaches. Various thermal management techniques, including passive and active cooling methods, heat exchangers, and advanced modelling techniques, are studied in detail. Furthermore, challenges and opportunities in enhancing the thermal performance and operational reliability of these systems are discussed. The insights provided in this review aim to contribute to the advancement of metal hydride-based solid-state hydrogen storage devices. By highlighting the significance of thermal management, this review provides actionable insights for researchers and engineers aiming to enhance the efficiency, safety, and real-world applicability of metal hydride hydrogen storage devices, thereby contributing to the broader goal of sustainable energy solutions.

1. Introduction

The ever-increasing global population and technological progress intensify our energy demands substantially [1]. Decades of fossil fuel overuse have notably contributed to the greenhouse effect, as well as driving adverse environmental effects. Several nations are racing to achieve net zero emissions, which is only feasible by completely eliminating fossil fuels [2]. This underscores the necessity for an alternative renewable fuel that leaves no harmful by-products. Hydrogen emerges as a prime candidate among other renewable sources such as solar, wind, tidal, geothermal energy etc. [3]. Hydrogen, being the abundant gas in existence, holds a pivotal role in displacing fossil fuels. It has significant potential as a power source,

How to cite this article: Singh, Anurag; Pragya, R. Shree; Priyaranjan; Yadav, Neeraj; Nakka, Paramkush J.; Jain, Akshat; Prerana. A review on thermal management of metal hydride based solid state hydrogen storage devices. *Transactions on Energy Systems and Engineering Applications*, 7(2): 664, 2026. DOI:10.32397/tesea.vol7.n2.664

facilitating the production of clean, eco-friendly energy [4]. Despite its history, including wartime use for destructive purposes, hydrogen has immense potential as an energy source.

2. Hydrogen Economy

Hydrogen economy depends on three major elements: (a) Hydrogen production, (b) Transportation and Storage and (c) Utilisation/End use [5].

One of the key advantages of a hydrogen economy is its versatility. Hydrogen can be produced through various methods, including electrolysis powered by renewable energy sources like solar, wind, or hydroelectric power [6]. Additionally, it can be derived from natural gas through a process called Steam Methane Reforming or through other processes like biomass gasification. This flexibility ensures that hydrogen can be generated using different resources, making it adaptable to diverse geographic and economic conditions. In transportation, the potential for hydrogen Fuel Cell Vehicles (FCVs) is substantial [7]. These vehicles utilize hydrogen gas to produce electricity, powering an electric motor. FCVs offer longer driving ranges and shorter refueling times compared to Battery Electric Vehicles (BEVs) [8]. Moreover, they emit zero harmful pollutants, contributing to cleaner air in urban areas.

Hydrogen can be utilized in industries like steel and chemical manufacturing as a clean feedstock or fuel, reducing their carbon footprint. Moreover, hydrogen serves as an excellent energy storage medium [9]. Excess renewable energy generated during peak times can be used to produce hydrogen through electrolysis, which can then be stored and utilized when energy demand is high. Figure 1 shows the different elements of hydrogen economy such as hydrogen generation, storage, distribution, transportation and application [10].

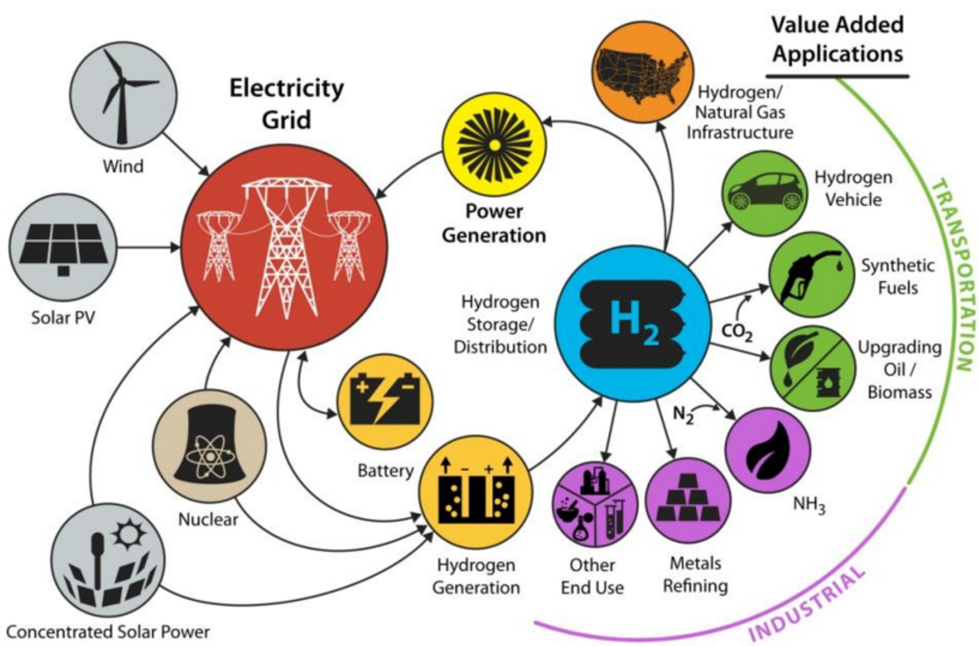

Figure 1. Elements of the hydrogen economy. (Reproduced from Poullikkas A. [10], licensed under CC BY 4.0).

However, challenges persist in realizing a full-fledged hydrogen economy. One major hurdle is the cost associated with hydrogen production, storage, and distribution. Developing efficient and cost-effective technologies for large-scale hydrogen production remains a priority [11]. Additionally, building the necessary infrastructure, including hydrogen refuelling stations and distribution networks, requires substantial investment. Despite these challenges, numerous countries and companies are investing in hydrogen technologies, recognizing its potential to revolutionize the energy landscape [12]. Collaborative efforts among governments, industries, and research institutions are essential to drive innovation, lower costs, and accelerate the transition towards a hydrogen-based economy. In essence, the hydrogen economy represents a promising pathway towards a more sustainable and greener future, offering a versatile, zero-emission energy solution across various sectors while necessitating concerted efforts to overcome technological and economic barriers. A detailed review on the three major elements of hydrogen economy is presented below.

3. Hydrogen Production

Hydrogen finds its primary usage in the production of ammonia (51%), around 31% allocated for oil refining, 10% for methanol production, and the remaining 8% serving various other purposes [13].

Reports indicate a rapid 27.2% increase in global hydrogen demand over seven years, rising from 255.3 billion cubic meters in 2013 to approximately 324.8 billion cubic meters in 2020 [14]. The production of hydrogen deals with procurement of hydrogen gas in its pure state. Hydrogen is not freely available in nature; it must be extracted from the available sources. It is produced through the conversion of materials that contains hydrogen, such as hydrocarbons, water etc. [15]. It is estimated that approximately 96% of the global hydrogen is derived from conventional fossil fuels, distributed as follows: 30% from naphtha reforming, 48% from steam reforming of natural gas, and 18% from coal gasification [16]. To extract hydrogen from these sources, an abundant and continuously available energy supply is required [17]. However, the conventional technologies used for hydrogen production are closely linked to the environmental pollution [18]. This has prompted stakeholders in the energy and environmental sectors to advocate for more sustainable methods of hydrogen production using renewable sources. Therefore, harnessing the potential of renewable energies such as solar, wind, and sea waves in hydrogen production technologies could pave the way for its sustainable production [19].

4. Transportation and Storage

Once hydrogen is generated, it has to either transport to some place for utilization or it has to be stored for future use. Both the aspects are discussed below.

4.1. Transportation

One of the barriers limiting green hydrogen to offset fossil energy carriers is its high cost of production, distribution, and storage [20]. This barrier becomes even more challenging for transport applications where the demand is geographically distributed and, at least in an initial market stage, limited to small-to-medium volumes [21]. One way to limit the cost of the refueling infrastructure is to find ways to compress the hydrogen more efficiently, either by innovative non mechanic compression technologies, such as electrochemical or adsorption compressors [22], or produce hydrogen at higher pressures with, for instance, high-pressure PEM electrolyser [23]. Alternatively, storing hydrogen on-board at significantly lower pressures in metal hydride-based tanks can simplify the hydrogen handling onshore and with that reduce the costs of the refueled hydrogen.

4.2. Storage

Once pure hydrogen is extracted, it must be stored but unlike other conventional fuels, hydrogen cannot be kept in a normal airtight container [24]. Modern technologies enable us to store hydrogen by altering its physical state. There are different methods of storing hydrogen: high pressure gaseous storage, liquid hydrogen storage and solid-state hydrogen storage [25].

Table 1 gives the US Department of Energy (USDOE) targets for on board hydrogen storage system for light-duty fuel cell vehicles.

4.2.1. High pressure gaseous hydrogen storage

High-pressure gaseous hydrogen storage involves confining hydrogen gas at elevated pressures within specialized containers or cylinders, offering a method for compactly storing hydrogen. These storage systems, categorized into different types: type I, II, III, and IV, with varying designs and materials to contain hydrogen gas efficiently. Type I vessels can store around 1 wt.% of hydrogen at pressures ranging from 200 to 300 bar [26]. Type I and type II cylinders frequently have a restriction on hydrogen storage to just 1% or 2% by mass because of the amount of metal needed to withstand the pressure [27]. This limitation renders them impractical for lightweight automotive applications where efficiency heavily relies on weight and volume. Consequently, Langmi et al. [28] have shown recent efforts in developing high-pressure cylinders for light-duty vehicles have focused on Type III and IV cylinders.

Table 1. USDOE targets for on board hydrogen storage system for light-duty fuel cell vehicles [29].

S. No.	Parameter	Units	2020	2025	Ultimate
1.	Gravimetric Capacity • Usable, specific-energy from H_2	kgH_2/kg system	0.045	0.055	0.065
2.	Volumetric Capacity • Usable energy density from H_2	KgH_2/L system	0.030	0.040	0.050
3.	Storage System Cost • Fuel cost	\$/kg H_2 \$/gge at pump	333 4	300 4	266 4
4.	Durability/Operability: Operating ambient temperature Min/max delivery temperature Operational cycle life (1/4 tank to full) On-board Efficiency Min delivery pressure Max delivery pressure	 °C °C Cycles % bar bar	 -40/60 (sun) -40/85 1500 90 5 12	 -40/60 (sun) -40/85 1500 90 5 12	 -40/60 (sun) -40/85 1500 90 5 12
5.	Fill time	Min.	3–5	3–5	3–5
6.	Dormancy time target (minimum until first release from initial 95% usable capacity)	Days	7	10	14
7.	Fuel Quality	% H_2	Meet or exceed SAE J2719		

4.2.2. Liquid hydrogen storage

Liquid hydrogen storage involves maintaining hydrogen in a liquid state at cryogenic temperatures, typically around 21.2 K, stored in specialized cryogenic tanks under ambient pressure conditions [30]. This method is crucial in harnessing hydrogen's energy potential for various applications, especially in transportation and energy sectors. Challenges associated with this storage method include the energy-intensive liquefaction process and minimizing hydrogen boil-off through efficient thermal insulation of storage vessels [31]. According to research by Stetson [32], effective thermal insulation is pivotal to reduce hydrogen boil-off in cryogenic storage systems. Moreover, the work of researcher Züttel [33] emphasizes the significance of advancements in cryogenic storage technologies to enhance the efficiency and practicality of liquid hydrogen storage for widespread application in various industries.

4.2.3. Solid state hydrogen storage

Hydrogen can also be stored in solid form by the absorption process in few alloys and intermetallic compounds. This method involves utilizing specific metals or their alloys capable of retaining gaseous hydrogen [34]. When hydrogen comes in contact with these porous materials, it gets absorbed into the pores and forms metal hydride after the chemical reaction with the hydrogen. This approach offers an efficient means of storing hydrogen at normal atmospheric temperature and pressure unlike the two other methods i.e. large high-pressure tanks or cryogenic setups. Solid state storage of hydrogen also offers safety and ease of transport for applications.

5. Metal Hydride Based Solid State Hydrogen Storage

In metal hydride based solid state hydrogen storage system, a metal is employed that has the capability to absorb and desorb hydrogen as needed [35]. There are several metals, alloys and intermetallic compound that can react with the hydrogen under certain temperature and pressure [36]. Metal hydrides are compounds formed by the reaction of hydrogen with various metals. This process involves the absorption of hydrogen atoms into the crystal lattice of the metal, leading to the formation of a stable hydride. The reaction is often reversible, allowing for the release and uptake of hydrogen depending on temperature and pressure conditions.

The formation of a metal hydride can be represented by a generalized equation:

$$\text{Metal} + \text{Hydrogen} \leftrightarrow \text{Metal Hydride} + \text{Heat}. \tag{1}$$

In this equation, absorption of hydrogen in metals are exothermic process. A large amount of heat is released during absorption process. similarly, when we want hydrogen back from the stable hydride, we have to supply heat and the reaction reverses and hydrogen is released.

This reaction typically occurs at elevated temperatures and pressures. The formation of metal hydrides can vary based on the specific metal involved and the conditions under which the reaction takes place.

For instance, consider the formation of titanium hydride:

$$Ti + H_2 \leftrightarrow TiH_2 + Q. \tag{2}$$

This approach stands as a more efficient and traditional alternative to high-pressure gaseous or liquid hydrogen storage methods. This technique offers increased energy density and improved safety when compared to other storage methodologies. The concept relies on the ability of specific metals to bond with hydrogen atoms, allowing them to absorb hydrogen under certain environmental conditions like temperature and pressure, subsequently releasing it when these conditions change [37]. This process enables a higher degree of control over the absorption and release of hydrogen. Metal hydrides are valued for their ability to store and release hydrogen, making them important in hydrogen storage technologies for various applications, including fuel cells and hydrogen-powered vehicles [38].

5.1. pcT characteristics of metal hydride

The Pressure-Composition-Temperature (pcT) characteristics of metal hydride-based hydrogen storage systems plays a pivotal role in understanding the hydrogen absorption and desorption processes [39]. These characteristics define the relationship between hydrogen pressure, composition, and temperature concerning the metal hydride material. Understanding these characteristics is crucial for optimizing the storage system's efficiency and performance [40]. It allows researchers to determine the operating conditions where hydrogen absorption or desorption occurs most effectively, influencing the design and implementation of metal hydride-based hydrogen storage systems for practical applications in diverse industries, including transportation and energy sectors [41]. Figure 2 depict the pressure-concentration-isotherms (pcT) and the associated van't Hoff plot for an ideal MH system [42]. When hydrogen interacts with metals, the absorption occurs in three distinct phases: α, α+β, and β. At first in the α-phase, which is represented by the initial slope, involves hydrogen adsorption on the metal surface, forming a solid solution within that phase. Shortly after reaching saturation, the α-phase transitions into the β-phase, a process that happens at a constant pressure. This transition accounts for the majority of hydrogen absorption. Once the α-phase converts into the β-phase entirely, further hydrogen absorption leads to the formation of a solid solution within the β-phase. The figure illustrates that even a small amount of hydrogen absorption in the β-phase significantly raises the equilibrium pressure. The region where both α and β phases coexist is termed the plateau region, and the corresponding constant pressure is known as the plateau pressure. Additionally, it can be observed that at higher temperatures, the α+β region decreases in size, resulting in less hydrogen absorption. If the plateau pressure and temperature are plotted as ln$P$ vs $1/T$, a straight line is obtained as shown in the van't Hoff plot [43].

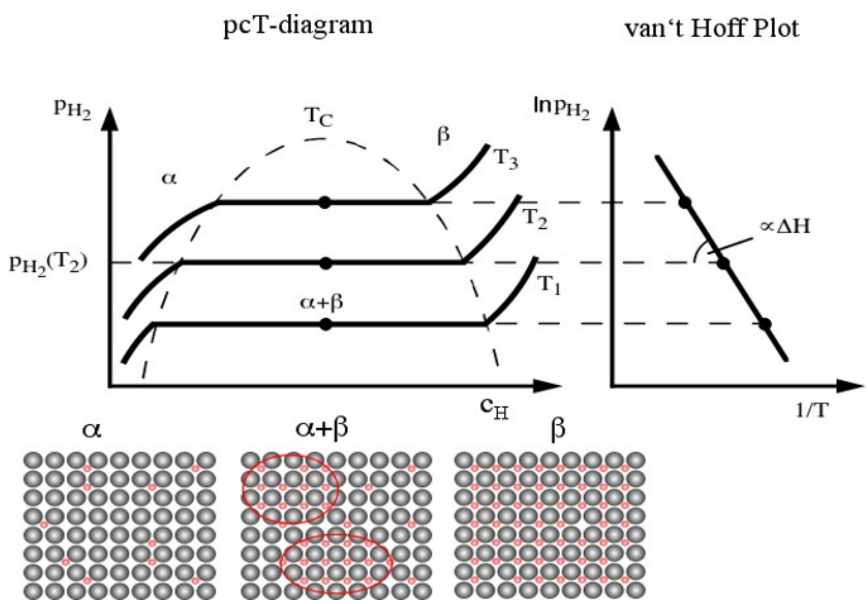

Figure 2. Schematic pcT-diagram and van't Hoff plot of hydrogen absorption in metal hydride (Reproduced from Dornheim [42], licensed under CC BY 3.0.)

5.2. MH storage materials

Materials used for hydrogen storage should have a favourable hydrogenation/dehydrogenation temperature, high volumetric density, good reversible ability, low weight, rapid hydrogen charge/discharge kinetics and easy availability [44]. The most important properties for materials of hydrogen storage are high hydrogen storage capacity and fast reaction kinetics [45]. The solid-state storage of hydrogen in the MHs is the safest method because it can store hydrogen at normal pressure and temperature condition [46]. Based on the count of alloy atoms in a mole of the material, MHs are categorized into four groups: AB, AB_2, A_2B, and AB_5 [47]. Here, A and B denote two distinct elements or groups of elements. 'A' typically signifies the potent hydride-forming element, commonly a rare earth metal, while 'B' signifies the weaker or non-hydriding element, usually a transition metal.

Several authors have studied different types of metal hydrides. Prasad and Muthukumar [48] conducted experiments on annular porous metal hydride ($La_{0.7}Ce_{0.1}Ca_{0.3}Ni_5$) reactor equipped with radial fins. They investigated absorption characteristics at varying supply pressures (ranging from 5 to 20 bar) and desorption characteristics at different inlet temperatures of the heat transfer fluid (HTF), varying between 30 °C and 50 °C. they concluded that $La_{0.7}Ce_{0.1}Ca_{0.3}Ni_5$ exhibited a steadier desorption rate and higher storage capacity compared to $LaNi_5$.

TiFe intermetallic stands as a promising material due to its reversible hydrogen storage capability and favourable temperature and pressure conditions. It can be used for hydrogen absorption and release, within temperature ranges of around 30°C to 70°C [45]. This material operates effectively at low pressures of around 10–20 bar [49]. Notably, TiFe possesses several advantageous attributes, including abundant natural occurrence, exceptional cycle stability, non-toxicity, low cost, and a high volumetric density of approximately 0.096 Kg H_2 per litre of the system, as highlighted by studies conducted by Sandrock et al. [50] and Srinivasan with Demirocak [51]. TiFe demonstrates a moderately high capacity of 1.9 wt%, proving to be relatively more cost-effective compared to other AB_5 alloys as reported by Reilly and Wiswall [49] and Sandrock [52].

Table 2 gives some of the metal hydride materials tested by the researchers and their storage capacity at particular operating temperature and pressure conditions. Khandelwal et al. [53] investigated the use of MgH_2-based composites for solid-state hydrogen storage, where MgH_2 stands out, due to its abundance, cost-effectiveness, lightweight nature, and theoretical storage capacity of 7.6 wt%. Their study demonstrated that adding 5 wt% of aluminium and annealing the material at 450°C resulted in the best mechanical strength and cyclic behaviour. Furthermore, their work involved incorporating catalysts (graphite & Nb_2O_5) into the MgH_2 powder, observing that ball-milling with Nb_2O_5 catalyst exhibited the fastest kinetics and improved mechanical stability. However, the close compactness of powder particles during milling led to local overheating, hindering hydrogen flow. A computational analysis of metal hydride reactor for thermal energy storage using $LaNi_5$ as material were conducted by Aswin et al. [54]. The study involved examining hydrogen absorption within porous bed at temperature and pressure ranges of 400°C and 40 bar in materials akin to magnesium. Quantitative and qualitative analyses were employed to enhance the reactor's design. $LaNi_5$ served as the active material. The researchers observed that maintaining a temperature of 303 K, using water cooling with hydrogen pressure at 3 bar and a velocity of 0.05 m/s, led to increased reacted mass of hydrogen, directly proportional to time. Achieving optimal cooling or heating times aided in completing the reaction, and determining the maximum spacing between tubes facilitated this. Additionally, it was concluded that enhancement in heat transfer in the reactor could be achieved by incorporating fins, increasing the number of tubes, and improving heat conductivity.

Table 2. Types of materials with their storage capacity, temperature and pressure.

S. No.	Material	Author(s)	Hydrogen storage capacity (wt%)	Temperature (K)	Pressure (bar)
1	$La_{0.7}Ce_{0.1}Ca_{0.3}Ni_5$	Prasad et al. [48]	1.51 (during activation) 1.35 (after 20 cycles)	303–323	5–20
2	MgH_2	Khandelwal et al. [53]	7.6	723	6.0795
3	$Ti_{1.1}CrMn$	Visaria and Mudawar [55]	1.3	275.5–294	280
4	$MmNi_{4.6}Al_{0.4}$	Muthukumar et al. [56]	9.8	–	20
5	$LaNi_5$	Ranong et al. [57]	5.6	–	100
6	TiFe	Sujan et al. [45], Reilly et al. [49], Sandrock [52]	1.9	303–343	10–20

Figure 3 depicts the hydrogen gravimetric capacity of different storage materials for hydrogen fuel as a function of hydrogen release temperature [58].

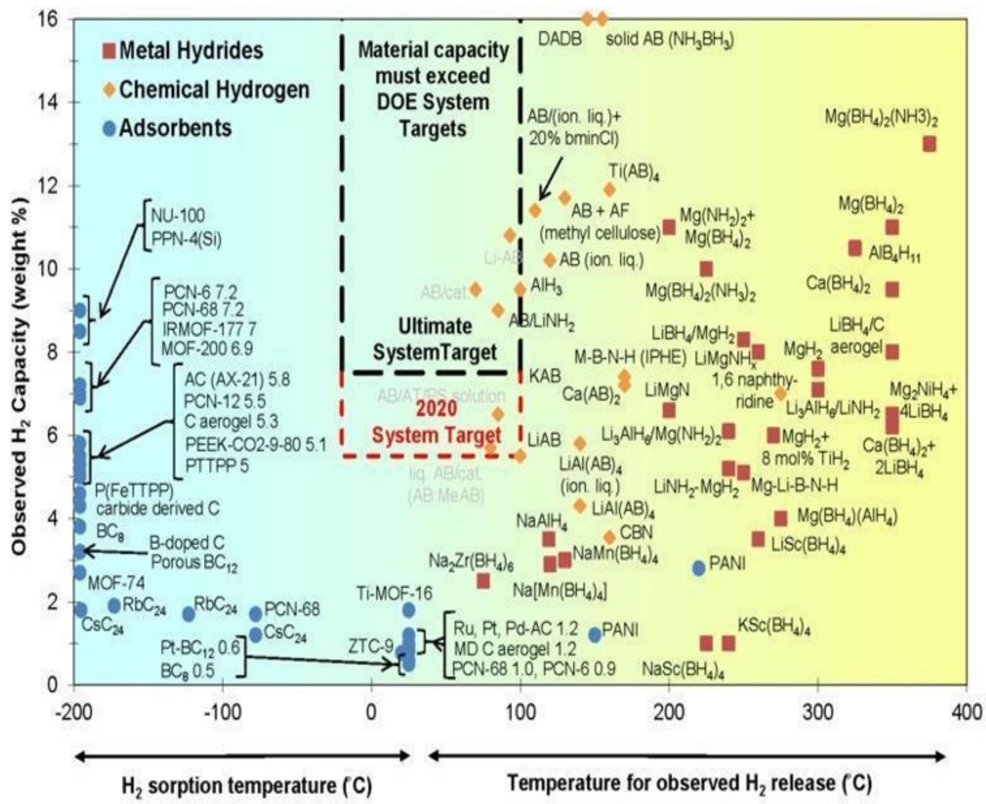

Figure 3. Hydrogen gravimetric capacity of different storage materials as a function of hydrogen release temperature. Source: U.S. Department of Energy [58].

6. Thermal Management of MH Based Hydrogen Storage Device

As discussed earlier, thermal management plays a crucial role in the performance of a metal hydride-based hydrogen storage device (MHHSD). In this section, various methods investigated by several researchers, to manage the heat in MHHSD has been discussed.

6.1. Components of solid hydrogen storage

Metal hydride based solid state hydrogen storage devices contain several components which include:

Metal hydride materials – These are the intermetallic compounds or alloys which form a bond with hydrogen to store it within themselves.

Container design – The containers are used as storage tanks to store metal hydrides. Their designs have a major effect on the performance of MHHSD.

Heat exchanger – This component is used for cooling or heating (facilitates heat exchange between heat transfer fluid and metal hydride bed) of metal hydride bed.

Heat Transfer Fluid – This is used to exchange the heat between fluid and hydride bed. Some of the methods to manage the heat in the MHHSD are presented in the Figure 4.

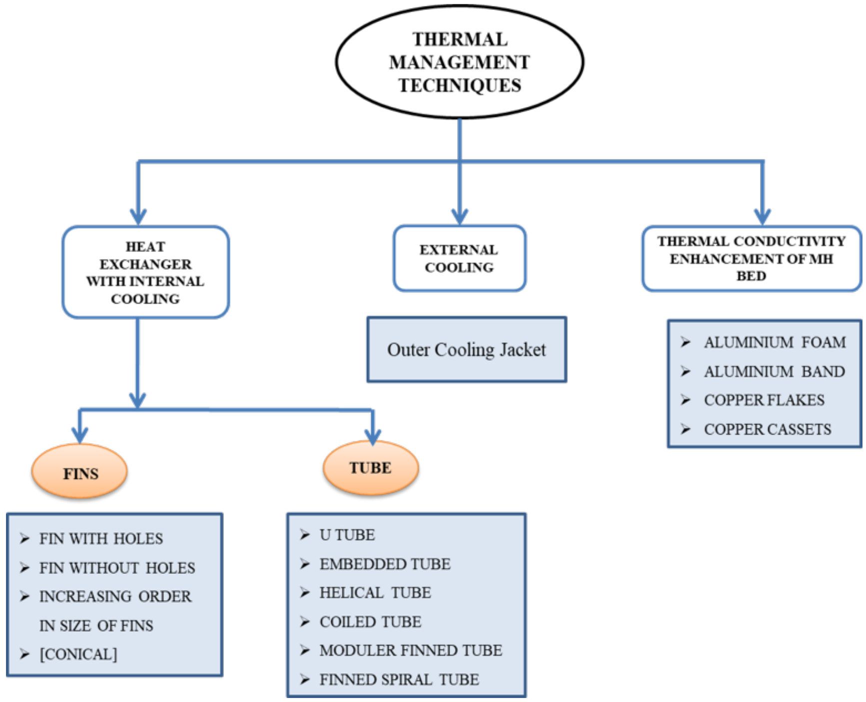

Figure 4. Thermal management techniques in MHHSD.

6.2. Heat exchanger design

Heat exchangers are pivotal devices in various industries, enabling the transfer of heat between fluids for processes like cooling and heating [59]. Heat exchangers play a critical role in MHHSD by facilitating the crucial thermal management necessary for optimal performance. Enormous amount of heat is released/required during the exothermic absorption/endothermic desorption process. This heat has to be managed quickly to facilitate further absorption/desorption process [60]. A heat exchanger efficiently regulates temperatures by facilitating heat transfer, ensuring that the metal hydride beds operate within the desired temperature ranges for effective hydrogen absorption and release. By maintaining these ideal temperatures, heat exchangers enable faster reaction kinetics and enhance the storage capacity and longevity of the metal hydride-based hydrogen storage system, thereby contributing significantly to its overall efficacy [61]. Various types of heat exchanger designs such as Finned tube heat exchanger, coiled tube heat exchanger, helical coil heat exchanger, Mini-channel heat exchanger, shell and tube heat exchanger etc. have been investigated by researchers either experimentally or by simulation.

Singh et al. [62] examined a MH based hydrogen storage device with an annular finned tube heat exchanger using copper fins and water as a heat transfer fluid. It was found that design parameters such as fin thickness, fin number, and fin perforation significantly affect the hydrogen absorption and desorption rates. They also investigated the effect of different operating parameters on the performance of MHHSD. In another paper, Singh et al. [63] tried to improve the design introduced in the previous paper by inserting 80g of copper flakes to the metal hydride bed. The addition of copper flakes enhances thermal conductivity by 0.08 W/mK and improves sorption performance by 11%, while it also increases the system's weight. In another study two U tube heat exchanger having perforated circular copper fins inserted in a cylindrical MHHSD filled with 1 kg of $LaNi_5$ was experimentally analyzed by Singh et al. [64]. The authors emphasized the importance of optimising heat exchanger design parameters to enhance the absorption performance. Factors like fin thickness, tube diameter, fin perforation, and the use of copper flakes are studied for their impact on hydrogen sorption performance. Visaria and Mudawar [55] investigated the challenges related to heat generation during the hydriding process and the amount of hydrogen that can be stored in a high-pressure MHHSD incorporating coiled tube heat exchanger design. In the second part of their previous research, Visaria and Mudawar [65] explored a 3D numerical model of the coiled-tube heat exchanger for high-pressure metal hydride hydrogen storage. They compared the experimental data with model predictions, highlighting the impact of coolant temperature and pressure on the filling time. Mellouli et al. [66] did a study with the help of a 2D mathematical model to enhance heat and mass transfer in MHHSD, particularly through the use of finned spiral tubes. It was concluded that the addition of fins accelerates heat transfer and reduces charging time in the storage tank. Tong et al. [67] investigated the application of coiled-tube heat exchangers for efficient hydrogen storage which highlighted the impact of heating water temperature, outlet pressure, and heat transfer coefficients on hydrogen storage capacity and dehydriding rates. Yuan et al. [68] did a study on the importance of cleaner hydrogen storage alternatives and delves into the components of hydrogen storage alloy reaction vessels, with a focus on heat exchange structures. They presented a structural model, mathematical equations for heat exchange, mass conservation, and thermodynamic properties of hydrogen storage alloys. Visaria and Mudawar [69] worked on tube fin and coiled fin heat exchanger to release hydrogen gas from high pressure metal hydride. Wang et al. [70] investigated a MHHSD incorporating helical coiled tube heat exchanger and aluminium foam to improve the thermal performance of the storage device. They analyzed the performance of the device for different configuration of the fin arrangement and Al foam. It was found that 5% of aluminium foam is sufficient for optimum performance. Mou et al. [71] investigated MH reactor's performance loaded with 640g of $LaNi_5$ with the helical coiled heat exchanger. Meng et al. [72] performed both simulation and experiment analysis on metal hydride reactor with a mini channel. Their focus was on the performance of mini channel reactor for heat and mass transfer processes. The reactor was effective to achieve the optimal heat transfer, which has a huge advantage over the other reactor types, particularly in controlling thermal resistance.

Raju and Kumar [73] investigated three different designs with shell and tube heat exchangers using alanate as the metal hydride material. The first configuration included alanate in the shell with coolant flowing through interconnected finned tubes, second: alanate in the shell with coolant in a helical tube, and third: alanate in tubes with coolant in the shell. They found that the helical coil heat exchanger exhibited superior heat transfer rates due to the turbulence in the coolant fluid. Mellouli et al. [66] focused on understanding the process of hydriding in metal hydride reactors. They observed that higher heat transfers near the reactor wall resulted in increased hydride formation rates in that area while the thermal mass of the wall did not have any significant impact on the reaction. They proposed a cooling system involving a concentric heat exchanger tube with fins and flowing cooling fluid. They concluded that increasing fin diameter reduces hydriding time. They also investigated the dynamic behaviour inside various metal hydride tank designs, where, the optimization results showed an 80% improvement in storage time with a design featuring a concentric heat exchanger tube equipped with fins and flowing cooling fluid. Askri et al. [74] used a 2D mathematical model for optimizing heat and mass transfer in MHHSD. They studied the effects of fin arrangement, its thickness, pitch and length on the charging process performance. It was observed that shifted fins have better mass absorption capacity of hydrogen with respect to aligned fins and fin pitch affects the mass absorption inversely. Dhaou et al. [75] experimentally investigated two different configurations of MHHSDs: first contained a simple heat exchanger while the second one had a finned spiral heat exchanger. Their focus was to study the geometry and operating parameters influencing the charging process. It was concluded that the later configuration is more suitable as it reduces the charging time of reactor with enhanced performance. Souahlia [59] performed experimental and comparative study on MHHSD. They considered two types of metal hydride containers, one with finned spiral heat exchanger and another with finned tube heat exchanger. When the two designs were compared based on some parameters, the tank which had finned spiral heat exchanger showed better results.

Heat exchanger design for various MHHSDs investigated by different authors are summarized in Table 3.

Table 3. Heat exchanger design for various MHHSDs.

S.No.	Year	Author(s)	Design Specification	Summary
1	2012	Visaria and Mudawar [69]	High pressure metal hydride storage device with two heat exchanger designs, a modular tube fin heat exchanger and a coiled tube heat exchanger	This study examined the dehydriding reaction within these heat exchanger designs for high pressure metal hydride systems
2	2015	Singh et al. [62]	Internal concentric annular heat exchanger fitted with radial circular copper fins	The copper fins raised the absorption rate and shortened the charging duration
3	2017	Singh et al. [64]	Two U tube heat exchanger with perforated circular fins, combined with copper flakes to raise the effective thermal conductivity	Adding copper flakes improved the thermal conductivity of the system
4	2017	Singh et al. [63]	Storage device fitted with an internal heat exchanger having circular fins	The arrangement accelerated the hydrogen sorption process
5	2012	Visaria and Mudawar [55]	Coiled tube heat exchanger assembly used in a high pressure metal hydride storage system	The coiled arrangement improved heat transfer through localized cooling and shortened the charging time
6	2010	Mellouli et al. [66]	Finned spiral tube heat exchanger placed inside a cylindrical metal hydride hydrogen storage device	Fins attached to the cooling tubes increased the contact area, which sped up heat transfer and reduced the charging time
7	2022	Yuan et al. [68]	Spiral mini channel heat exchanger examined for its effect on hydrogen absorption and desorption performance	The spiral geometry provided a greater contact area and improved heat transfer
8	2012	Wang et al. [70]	Helical coil tube heat exchanger placed inside a cylindrical hydrogen storage device, with aluminium foam added to raise the thermal conductivity	At higher aluminium foam content, the hydrogen storage density became less sensitive to changes in coil pitch
9	2023	Mou et al. [71]	Helical coil heat exchanger embedded within a cylindrical hydrogen storage device	The hydrogen absorption process was governed by factors such as the pressure difference and the rate of heat removal at different stages
10	2013	Meng et al. [72]	Mini channel metal hydride reactor developed for various metal hydride based applications	The study concentrated on mini channel reactors and their role in heat and mass transfer. It showed that such reactors support effective heat transfer within a metal hydride bed and prevent the formation of local hot spots

(continued on next page)

(continued from previous page)

S.No.	Year	Author(s)	Design Specification	Summary
11	2012	Raju and Kumar [73]	Three shell and tube heat exchanger arrangements were compared. In the first, metal hydride filled the shell while the heat transfer fluid moved through straight parallel tubes. In the second, metal hydride filled the shell while the fluid moved through helical tubes placed within the hydride bed. In the third, metal hydride was placed inside the tubes while the fluid flowed through the shell	The second design, based on a helical coil arrangement, produced higher gravimetric and volumetric hydrogen storage densities than the other two arrangements
12	2009	Askri et al. [74]	Four metal hydride tank configurations were studied: a plain cylindrical tank, a cylindrical tank with external fins, a cylindrical tank with a concentric cooling tube, and a cylindrical tank with a finned concentric cooling tube	The thermal mass of the tank wall was found to be negligible, and raising the wall conductivity had little effect on storage time. When a finned concentric cooling tube carried flowing coolant, heat transfer improved enough to cut the storage time by nearly eighty percent
13	2010	Dhaou et al. [75]	Finned spiral tube heat exchanger fitted inside a metal hydride vessel	This arrangement reduced the charging time
14	2011	Souahlia et al. [59]	Two metal hydride container designs were compared, a finned spiral copper coil and a coaxial tube fitted with circular fins	The finned spiral heat exchanger removed heat more effectively than the finned tube heat exchanger
15	2022	Prasad and Muthukumar [76]	Two configurations were studied, a large scale annular metal hydride reactor and a reactor fitted with additional fins	The configuration with extra fins gave better performance

Larpruenrudee et al. [77] focused on enhancing the performance of metal hydride hydrogen storage systems by introducing a novel heat exchanger; a semi cylindrical coil with a central return tube, emphasizing to improve heat transfer in central area of storage system. Numerical simulations proved a 30% reduction in absorption duration compared to traditional semi-cylindrical coil heat exchangers. Additionally, the combination of the design with cooling jackets further reduced absorption time by 51%.

Eisapour et al. [78] numerically analysed hydrogen absorption process in a cylindrical metal hydride bed conisting Mg_2Ni material using ANSYS FLUENT software. MHHSD was fitted with a central straight return tube to manage the heat inside the MH bed. They observed a significant improvement in heat exchanged between metal alloy and cooling fluid using central straight return tube. The temperature reduction favoured hydrogen absorption. It was found that the absorption time was reduced by 24% for 90% of storage capacity. Also, it was concluded that loading pressure and initial pressure are inversely proportional to the absorption time.

6.3. Effects of design and operating parameter

Reactor design parameters affect the overall absorption/desorption characteristics of the metal hydride bed. Several authors have investigated the effects of the design parameters on sorption characteristics of solid-state hydrogen storage device. Singh et al. [62–64] explored various reactor design aspects such as fin number, fin thickness, fin perforation, insertion of copper flakes, heat exchanger tube diameter and fin length, demonstrating their respective impacts on heat transfer and absorption characteristics. They also highlighted the direct correlation between increased hydrogen supply pressure and absorption rates, while lower cooling fluid temperatures and higher velocities were associated with reduced charging times. Mellouli et al. [66] findings emphasized on the significance of fin length and pitch in absorption rates and storage time. Effect of design Parameters in sorption characteristics of metal hydride are summarized in Table 4.

Table 4. Effect of design parameters in sorption characteristics of metal hydride.

S. No.	Design parameter	Authors	Ranges	Results/effects
1	Number of fins	Singh et al. [62]	3, 7, 10, 13	By increasing number of fins, the rate of heat transfer increases due to which absorption characteristic improves.
2	Fin thickness (mm)	Singh et al. [62]	0.5, 1, 1.5	It improves the heat transfer kinetics which improves the sorption characteristics.
3	Fin perforation	Singh et al. [64]	42 holes of (2 mm)	It helps in reducing weight and improves heat transfer.
4	Copper flakes	Singh et al. [63]	80g	It increases the effective thermal conductivity between the fins.
5	Diameter of heat exchanger tube (mm)	Singh et al. [62]	3.4, 4.4, 5.4	Increasing the tube diameter helps in improving the heat transfer parameter.
6	Length of fins (mm)	Mellouli et al. [66]	5, 10, 13	For 13 mm the rate of absorption is rapid in comparison to others.
7	Effects of fin pitch (mm)	Mellouli et al. [66]	5, 10, 15	Decreasing the fin pitch reduces the storage time.

6.4. Design of storage tank

An analysis of performance of hydrogen storage containers having embedded cooling tubes were done by Muthukumar et al. [56]. They used $MmNi_{4.6}Al_{0.4}$ as hydriding material at industrial scale with the 150 kg capacity. In this analysis it was found that the average temperate of the bed was increasing then decreased exponentially with time. Hydrogen storage capacity was increasing but rate was in direct relation with number of cooling tubes. In the 2-D mathematical model it was found that if containers use outer cooling jacket, then the cycle time would decrease. The findings also suggested that hydrogen is capable of tackling CO_2 emission of automobile industry.

Ranong et al. [57] found that charging time is directly proportional to the reactor but this was not applicable if the reactor's size got doubled. Taking fast refuelling as an important aspect GKSS research centre made a prototype model of hydrogen storage tank and analysed the stress of storage tank at 100 bar pressure [79]. In latest development sodium alanate was found to be lightweight and has a special capability of 5.6% theoretical capacity of hydrogen.

Focusing only on reaction kinetics enhancement, two prototypes were manufactured and tested by Mosher et al. [80], where the first model had 19 kg active material and second one was designed at nominal 1/8th scale with respect to the former one. They contained three components; reactor shell tube, hybrid bed and porous sintered metal tube. Dhaou et al. [75] did experimental and comparative study on metal hydride hydrogen tanks with two storage tanks having different dimensions. The study suggested that hydrogen storage can be improved by choosing good parameters such as pressure and temperature and if better cooling system is considered then kinetic reaction will increase as storage is directly proportional to heat transfer.

Different types of reactors tested by different authors and their observations are summarized in Table 5. A paper by Gambini et al. [81] introduced Liquid Organic Hydrogen Carriers (LOCHs), focusing on their potential for long-term and large-scale storage. The research specifically targets the optimization of LOHC-based batch reactor's thermal design and introduced the novel heat transfer ratio (HTR) for performance evaluation. The optimization process aimed to minimize power consumption while achieving the required HTR, which favour the half-pipe coil reactor design over the jacketed alternative. Figure 5 shows the batch reactor designs.

Table 5. Different types of reactors tested by different authors.

S. No.	Year	Author	Dimensions	Material Capacity (kg)	Observation
1.	2012	Muthukumar et al. [56]	Twenty cooling tubes were used, with eight tubes positioned at a radius of 60 mm and twelve tubes positioned at a radius of 120 mm	150	A water jacket placed around the storage tank reduced the charging time. For a 300 mm diameter industrial scale container fitted with thirty eight cooling tubes, the charging time was found to be 2120 seconds.
2.	2009	Ranong et al. [57]	Outer diameter of 16 mm, reactor element length of 0.5 m, with thirty eight tube bundles	8	The charging time increased with reactor size, but doubling the reactor size did not double the charging time.
3.	2023	Mou et al. [71]	Helical coil heat exchanger with an internal diameter of 4 mm, an outer diameter of 6 mm, a helical pitch of 15 mm, a helical diameter of 38 mm, and four coil turns. The metal hydride bed had a diameter of 50 mm and a height of 80 mm	–	The study identified distinct stages of hydrogen absorption and desorption, governed by the inlet and outlet pressures, which in turn controlled the heat transfer rate.
4.	2011	Souahlia [59]	Tank 1 had a height of 110 mm and a diameter of 80 mm. Tank 2 had a height of 120 mm and a diameter of 60 mm	–	Hydrogen storage performance could be improved by selecting suitable operating parameters such as pressure and temperature.

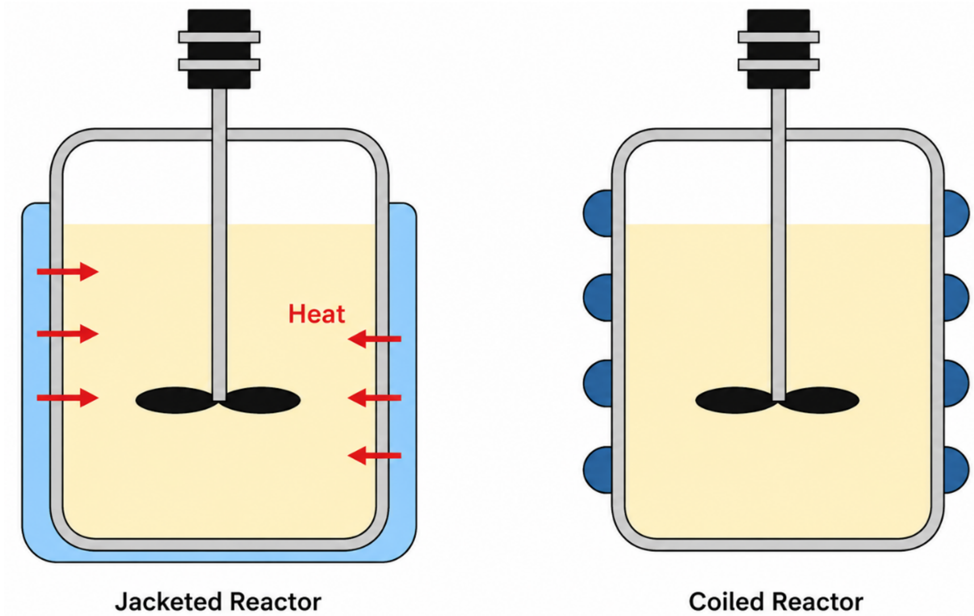

Figure 5. Reactor design: Jacket reactor and coiled reactor [81].

Couteau and Jenny et al. [82] analysed the heat transfer at high pressure while filling hydrogen tank. Their analysis consists of conjugate heat transfer based on energy balance, where type IV tank with a thermocouple tree is used which is depicted in Figure 6.

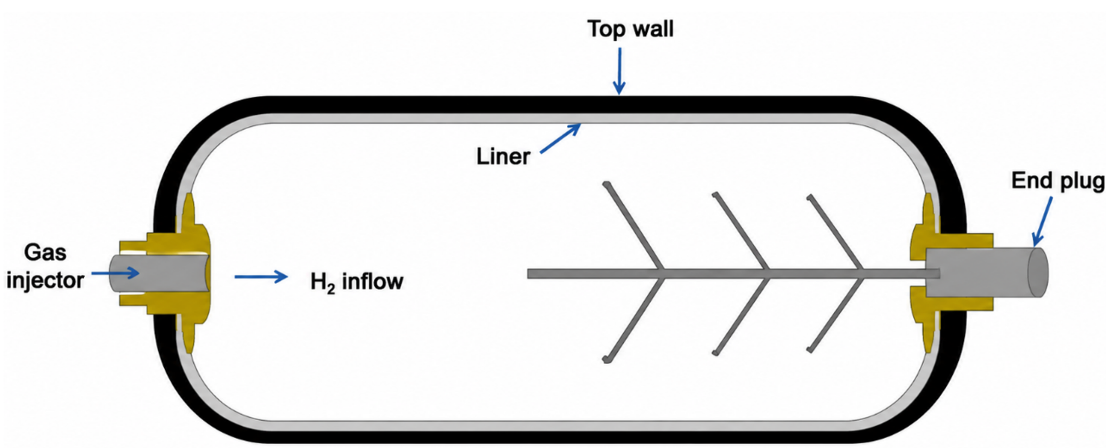

Figure 6. Scheme of the tank with the thermocouple tree [82].

7. Applications of MH

Metal hydride has many applications as it has favorable sorption kinetics. It offers unique properties that make them valuable in heating and cooling systems as well as in hydrogen compression technology [46]. Both the applications are discussed in detail below.

7.1. Metal hydride based heating and cooling system

Metal hydrides are utilized in heat pumps and refrigeration systems due to their ability to absorb and release significant amounts of heat during hydrogen absorption and desorption processes [83]. This reversible reaction allows for efficient thermal energy storage and transfer. In these systems, metal hydrides act as the medium for absorbing heat from the surroundings (during hydrogen absorption) and releasing it when triggered to release hydrogen (desorption), contributing to both heating and cooling functionalities [84]. Muthukumar & Groll [85] reviewed metal hydride-based heating and cooling systems and they concluded that dry sorption systems compete favorably with wet sorption systems for delivering beneficial cooling and heating. In operating principles there were single stage-single effect system and double stage-double effect system. They found that the chosen metal hydride (alloys) based on their properties, highly influence the effectiveness of Metal Hydride Heating and Cooling Systems. These systems should exhibit both high Coefficients of Performance (COPs) and elevated specific power outputs, such as Specific Cooling Power, especially for applications like refrigeration or air conditioning. They included general consideration, reaction bed overall heat transfer in heat and mass transfer aspects.

The commercial viability of these systems, compared to liquid sorption and competing dry sorption alternatives, is uncertain. Nevertheless, their ability to utilize low-quality heat, waste heat, and solar heat presents a significant advantage for Metal Hydride Heat-Driven Systems, along with their other environmental benefits [86].

7.2. Hydrogen compressor

Compressors play a crucial role in solid hydrogen storage systems, making them really important [87]. They are mechanical devices used to increase the gas pressure by reducing its volume, which allows more gas to be stored in smaller containers [88]. By using compressors hydrogen gas is pressurized for hydrogen-powered cars, for storing energy, making it quicker and easier to load and unload hydrogen as required, which is vital for practical and cost-effective way to shift towards cleaner energy sources [89].

Bhogilla and Niyasin [90] explored hydrogen's potential as a transportation energy carrier, particularly in fuel cell electric vehicles (FCEVs). They studied the importance of safe and efficient hydrogen storage and delivery systems, which focuses on metal hydride-based compression. They also discussed the impact of heat source temperature and supply pressure on hydrogen delivery pressure, compression work, and efficiency in a two-stage metal hydride hydrogen compressor. About the importance of material, Goshome et al. [91] investigated the feasibility of a one-stage metal hydride (MH) hydrogen compressor employing $V_{40}Ti_{22}Cr_{38}$ alloy. A practical kg-scale experimental system demonstrates that 1.0 MPa of hydrogen can be compressed to over 10 MPa through hydrogen absorption and desorption at 10°C and 160°C respectively for 30 minutes, achieving a compression rate of 0.23 Nm^3/h. The findings highlighted the potential of BBC alloys for heat driven MH compressors, promising cost reduction, minimal vibration and noise, and lower electric power consumption compared to traditional compressors. The design also affects the efficiency of the compressor. Another study by Toghyani et al. [92] examined the performance of a proton exchange membrane-based electrochemical hydrogen compressor for hydrogen storage, where 3D numerical model was used to assess the impact of operating temperature, pressure, gas diffusion layer thickness, porosity, and channel dimension on the compressor's performance. The result suggested that increasing operating temperature improves cell performance, but GDL porosity has minimal impact. Furthermore, the channel's characteristics significantly influence the compressor's efficiency.

8. Conclusion

The thermal management of metal hydride-based solid-state hydrogen storage devices stands as a critical determinant of their efficiency, safety, and practical viability. This review has highlighted the multifaceted nature of thermal considerations, emphasizing the significance of effective heat transfer mechanisms, materials engineering, and innovative strategies for temperature control. The examination of various thermal management techniques, encompassing both passive and active cooling methodologies, heat exchangers, and advanced modelling approaches, underscores the diverse strategies available to optimize thermal performance. These techniques offer promising avenues for enhancing heat dissipation, minimizing temperature gradients, and ultimately improving the overall performance and longevity of metal hydride-based storage systems. However, challenges persist, including the need for further research in developing materials with enhanced thermal conductivity, the integration of efficient cooling systems without compromising device compactness, and the validation of advanced modelling techniques through experimental verification. Overcoming these challenges will be instrumental in advancing the practical implementation of metal hydride-based hydrogen storage devices.

As the world intensifies its focus on clean energy solutions, the role of thermal management in enabling the widespread adoption of metal hydride-based systems cannot be overstated. Future research endeavours should prioritize comprehensive studies that bridge fundamental principles with practical applications, ultimately fostering the development of robust, efficient, and safe hydrogen storage devices. This review underscores the pivotal role of thermal management in shaping the future of metal hydride-based solid-state hydrogen storage, offering a roadmap for continued advancements in energy storage technologies towards a sustainable and greener tomorrow.

9. Future Research Direction

Future research on metal hydride-based hydrogen storage devices should prioritize the development of advanced materials with higher hydrogen storage capacities, faster reaction kinetics, and enhanced thermal conductivity. Investigating innovative heat exchanger designs and hybrid thermal management systems can further improve efficiency and reliability. Additionally, integrating data-driven modeling and AI-based optimization techniques can enhance system performance and scalability. Efforts should also focus on large-scale implementation and economic feasibility, addressing challenges like cost reduction, material sustainability, and system durability. Collaboration between academia, industry, and policymakers is essential to accelerate the transition of these technologies into real-world applications.

Acknowledgements

The paper was presented in the International Conference on Advances in Renewable and Green Energy Technology (ICARGET 2023).

Funding: This research received no external funding.

Author contributions: Anurag Singh: Conceptualization, Methodology, Supervision, Writing – review & editing; R. Shree Pragya: Writing – review & editing; Priyaranjan: Data curation, Formal analysis, Writing – original draft; Neeraj Yadav: Writing – original draft, Investigation; Paramkush J. Nakka: Writing – original draft, Investigation; Akshat Jain: Writing – original draft, Investigation; Prerana: Writing – original draft, Investigation.

Disclosure statement: The authors declare no conflict of interest.

References

[1] M. Asif and T. Muneer. Energy supply, its demands and security issues for developed and emerging economies. *Renewable and Sustainable Energy Reviews*, 11(7):1388–1413, 2007.

[2] International Energy Agency. World energy outlook 2020. https://www.iea.org/reports/world-energy-outlook-2020, 2020. Licence: CC BY 4.0.

[3] P. Singh, A. K. Agarwal, A. Thakur, and R. K. Sinha, editors. *Challenges and opportunities in green hydrogen production*. Springer Nature Singapore, 2024.

[4] B. Eda, A. A. Elzamar, and S. AlFazzani. Green hydrogen as a source of renewable energy: A step towards sustainability, an overview. *Environment, Development and Sustainability*, 2024.

[5] Ulf Bossel and Baldur Eliasson. Energy and the hydrogen economy. *Methanol Institute, Arlington, VA*, 2003.

[6] S. G. Nnabuife, A. K. Hamzat, J. Whidborne, B. Kuang, and K. W. Jenkins. Integration of renewable energy sources in tandem with electrolysis: A technology review for green hydrogen production. *International Journal of Hydrogen Energy*, 2024.

[7] C. Mendez, M. Contestabile, and Y. Bicer. Hydrogen fuel cell vehicles as a sustainable transportation solution in Qatar and the Gulf Cooperation Council: A review. *International Journal of Hydrogen Energy*, 48(99):38953–38970, 2023.

[8] T. Omatick, D. Zhang, M. S. Blais, M. Mossolly, P. Renzi, R. Kurz, S. Freund, and S. Harvey. Chapter 7 – usage. In *Machinery and energy systems for the hydrogen economy*, pages 251–304. Elsevier, 2022.

[9] P. Breeze. Chapter 8 – hydrogen energy storage. In *Power system energy storage technologies*, pages 69–77. Academic Press, 2018.

[10] A. Poullikkas. Perspectives for the development of energy strategies - challenges towards a hydrogen economy in Cyprus. *Green Energy and Sustainability*, 1(2):0004, 2021.

[11] X. Wang, T. Cheng, H. Hong, H. Guo, X. Lin, X. Yang, B. Nie, Z. Hu, and J. Zou. Challenges and opportunities in hydrogen storage and transportation: A comprehensive review. *Renewable and Sustainable Energy Reviews*, 219:115881, 2025.

[12] International Energy Agency. The future of hydrogen. https://www.iea.org/reports/the-future-of-hydrogen, 2019. Licence: CC BY 4.0.

[13] R. Y. Kannah, S. Kavitha, O. P. Karthikeyan, G. Kumar, N. V. Dai-Viet, and J. Rajesh Banu. Techno-economic assessment of various hydrogen production methods—A review. *Bioresource Technology*, 319:124175, 2021.

[14] M. Wang, G. Wang, Z. Sun, Y. Zhang, and D. Xu. Review of renewable energy-based hydrogen production processes for sustainable energy innovation. *Global Energy Interconnection*, 2(4):436–443, 2019.

[15] I. Dincer and C. Acar. A review on clean energy solutions for better sustainability. *Renewable and Sustainable Energy Reviews*, 51:565–585, 2015.

[16] T. Da Silva Veras, T. S. Mozer, D. da Costa Rubim Messeder dos Santos, and A. Da Silva César. Hydrogen: Trends, production, and characterization of the main processes worldwide. *International Journal of Hydrogen Energy*, 42(34):2018–2033, 2017.

[17] W. Iqbal, Y. Hou, Q. Abbas, M. Hafeez, M. Mohsin, A. Fatima, M. A. Jamali, M. Jamali, A. Siyal, and N. Sohail. Assessment of wind energy potential for the production of renewable hydrogen in Sindh Province of Pakistan. *Processes*, 7(4):196, 2019.

[18] W. Raza and M. Bashir. Hydrogen production and its environmental impacts: Conventional and emerging methods. *Journal of Cleaner Production*, 276:123200, 2020.

[19] M. Handwerker, J. Wellnitz, and H. Marzbani. Comparison of hydrogen powertrains with the battery-powered electric vehicle and investigation of small-scale local hydrogen production using renewable energy. *Hydrogen*, 2(1):76–100, 2021.

[20] R. Bhandari and H. Kim. Economic and environmental perspectives of green hydrogen as an energy carrier: Challenges and opportunities. *International Journal of Hydrogen Energy*, 45(26):13339–13352, 2020.

[21] J. Danebergs and S. Deledda. Can hydrogen storage in metal hydrides be economically competitive with compressed and liquid hydrogen storage? A techno-economical perspective for the maritime sector. *International Journal of Hydrogen Energy*, 50:1040–1054, 2024.

[22] G. Sdanghi, G. Maranzana, A. Celzard, and V. Fierro. Review of the current technologies and performances of hydrogen compression for stationary and automotive applications. *Renewable and Sustainable Energy Reviews*, 102:150–170, 2019.

[23] H. Ragnhild, H. Thomas, and Ø. Ulleberg. The case for high-pressure PEM water electrolysis. *Energy Conversion and Management*, 261:115642, 2022.

[24] A. Züttel and A. Remhof. Hydrogen storage: The state of the art and future perspectives. *Materials Today*, 18(8):331–338, 2015.

[25] M. Yang, R. Hunger, S. Berrettoni, B. Sprecher, and B. Wang. A review of hydrogen storage and transport technologies. *Clean Energy*, 7(1):190–216, 2023.

[26] U.S. Department of Energy. Target explanation document: Onboard hydrogen storage for light-duty fuel cell vehicles. https://www.energy.gov, 2021. Accessed: 1 Nov. 2023.

[27] J. O. M. Bockris and W. E. O'Grady. Hydrogen energy: Challenges and prospects. *International Journal of Hydrogen Energy*, 34(22):8816–8823, 2009.

[28] H. W. Langmi, N. Engelbrecht, P. Modisha, and D. Bessarabov. Hydrogen storage. In *Electrochemical power sources: Fundamentals, systems, and applications: Hydrogen production by water electrolysis*, pages 455–486. 2022.

[29] U.S. Department of Energy (USDOE). Hydrogen and fuel cell technologies office: Onboard hydrogen storage systems for light-duty fuel cell vehicles, 2021.

[30] A. Naquash, N. Agarwal, and M. Lee. A review on liquid hydrogen storage: Current status, challenges and future directions. *Sustainability*, 16(18):8270, 2024.

[31] T. Zhang, J. Uratani, Y. Huang, L. Xu, S. Griffiths, and Y. Ding. Hydrogen liquefaction and storage: Recent progress and perspectives. *Renewable and Sustainable Energy Reviews*, 176:113204, 2023.

[32] N. Stetson, S. McWhorter, and C. C. Ahn. Introduction to hydrogen storage. In *Compendium of hydrogen energy, volume 2: Hydrogen storage, transportation and infrastructure*, pages 3–25. Woodhead Publishing, 2016.

[33] A. Züttel. Hydrogen storage methods. *Die Naturwissenschaften*, 91:157–172, 2004.

[34] L. Schlapbach and A. Züttel. Hydrogen-storage materials for mobile applications. *Nature*, 414(6861):353–358, 2001.

[35] J. J. Vajo and R. D. Aines. Hydrogen storage in metal hydrides. In *Hydrogen Energy*, pages 177–201. Springer, 2004.

[36] E. Nemukula, C. B. Mtshali, and F. Nemangwele. Metal hydrides for sustainable hydrogen storage: A review. *International Journal of Energy Research*, 2025(1):6300225, 2025.

[37] A. Das, A. Ghosh, B. S. Bharat, N. Sahoo, U. Shukla, P. Patel, K. Tiwari, S. S. K. Deepak, B. Das, P. Shrivastava, and V. Msomi. Review: next-generation metal hydride systems for sustainable hydrogen storage—kinetics, nanostructuring, and intelligent materials discovery. *Journal of Materials Science*, 61:17697–17760, 2026.

[38] E. I. Gkanas, C. Wang, S. Shepherd, and O. Curnick. Metal-hydride-based hydrogen storage as a potential heat source for the cold start of PEM FC in hydrogen-powered coaches: A comparative study of various materials and thermal management techniques. *Hydrogen*, 3(3):418–432, 2022.

[39] N. A. A. Rusman and M. Dahari. A review on the current progress of metal hydrides material for solid-state hydrogen storage applications. *International Journal of Hydrogen Energy*, 41:12108–12126, 2016.

[40] National Institute of Standards and Technology (NIST). Pressure-composition-temperature (PCT) measurements for hydrogen storage systems. https://www.nist.gov/, 2008.

[41] M. Sahlberg et al. Hydrogen absorption and desorption characteristics of metal hydrides. *International Journal of Hydrogen Energy*, 41(1):41–50, 2016.

[42] M. Dornheim. Thermodynamics of metal hydrides: Tailoring reaction enthalpies of hydrogen storage materials. In *Thermodynamics – Interaction studies – Solids, liquids, and gases*, pages 5772–21662. InTech, 2011.

[43] J. J. Vajo et al. Hydrogen absorption and desorption in metal hydrides. *Journal of Alloys and Compounds*, 402(1–2):80–84, 2005.

[44] M. Balat. Potential importance of hydrogen as a future solution to environmental and transportation problems. *International Journal of Hydrogen Energy*, 33(15):4013–4029, 2008.

[45] G. K. Sujan, Z. Pan, H. Li, D. Liang, and N. Alam. An overview on TiFe intermetallic for solid-state hydrogen storage: Microstructure, hydrogenation, and fabrication processes. *Critical Reviews in Solid State and Materials Sciences*, 45(5):410–427, 2020.

[46] S.-I. Orimo, Y. Nakamori, J. R. Eliseo, et al. Hydrogen storage materials for mobile applications. *Chemical Reviews*, 107(10):4111–4132, 2007.

[47] S. Satyapal et al. Overview of hydrogen storage technologies. *International Journal of Hydrogen Energy*, 32(9–10):1121–1135, 2007.

[48] J. S. Prasad and P. Muthukumar. Performance and energy efficiency of a solid-state hydrogen storage system: An experimental study on $La_{0.7}Ce_{0.1}Ca_{0.3}Ni_5$. *Applied Thermal Engineering*, 216:119030, 2022.

[49] J. Reilly and R. Wiswall. Formation and properties of iron titanium hydride. *Inorganic Chemistry*, 13(1):218–222, 1974.

[50] G. Sandrock. State-of-the-art review of hydrogen storage in reversible metal hydrides for military fuel cell applications. Technical report, SUNATECH INC., 1997.

[51] S. S. Srinivasan and D. E. Demirocak. Metal hydrides used for hydrogen storage. In *Nanostructured materials for next-generation energy storage and conversion: Hydrogen production, storage and utilization*, pages 225–255. Springer, 2017.

[52] G. Sandrock. A panoramic overview of hydrogen storage alloys from a gas reaction point of view. *Journal of Alloys and Compounds*, 293:877–888, 1999.

[53] A. Khandelwal, F. Agresti, et al. Pellets of MgH_2-based composites as practical material for solid-state hydrogen storage. *International Journal of Hydrogen Energy*, 35:3565–3571, 2010.

[54] N. Aswin, P. Dutta, and S. S. Murthy. Computational analysis of metal hydride reactor for thermal energy storage. Technical report, Department of Mechanical Engineering, Indian Institute of Science, Bengaluru, India, 2015.

[55] M. Visaria and I. Mudawar. Coiled-tube heat exchanger for high-pressure metal hydride hydrogen storage systems – part 1. experimental study. *International Journal of Heat and Mass Transfer*, 55(7–8):1782–1795, 2012.

[56] P. Muthukumar, A. Singhal, and G. K. Bansal. Thermal modelling and performance analysis of industrial-scale metal hydride-based hydrogen storage container. *International Journal of Hydrogen Energy*, 37(18):14351–14364, 2012.

[57] C. Ranong, M. Hohne, J. Franzen, J. Hapke, G. Feig, M. Dornheim, N. Eigen, J. M. Bellosta von Colbe, and O. Metz. Concept, design, and manufacturing of a prototype hydrogen storage tank based on sodium alanate. *Chemical Engineering & Technology*, 32(8):1154–1163, 2009.

[58] U.S. Department of Energy. Materials-based hydrogen storage. https://www.energy.gov/cmei/fuels/materials-based-hydrogen-storage. Accessed: 15 Jul. 2026.

[59] A. Souahlia, H. Dhaou, M. Sofiene, F. Askri, A. Jemni, and S. Ben Nasrallah. Experimental and comparative study of metal hydride hydrogen tanks. *International Journal of Hydrogen Energy*, 36(21):12918–12922, 2011.

[60] A. Züttel et al. Hydrogen storage in metal hydrides. *Materials Science and Engineering: B*, 100(2–3):80–91, 2003.

[61] M. Afzal, R. Mane, and P. Sharma. Heat transfer techniques in metal hydride hydrogen storage: A review. *International Journal of Hydrogen Energy*, 42:30661–30682, 2017.

[62] A. Singh, M. P. Maiya, and S. Srinivasa Murthy. Effects of heat exchanger design on the performance of a solid-state hydrogen storage device. *International Journal of Hydrogen Energy*, 40(30):9733–9746, 2015.

[63] A. Singh, M. P. Maiya, and S. Srinivasa Murthy. Experiments on solid-state hydrogen storage device with a finned tube heat exchanger. *International Journal of Hydrogen Energy*, 42(23):15226–15235, 2017.

[64] A. Singh, M. P. Maiya, and S. Srinivasa Murthy. Performance of a solid-state hydrogen storage device with finned tube heat exchanger. *International Journal of Hydrogen Energy*, 42(42):26855–26871, 2017.

[65] M. Visaria and I. Mudawar. Coiled-tube heat exchanger for high-pressure metal hydride hydrogen storage systems – part 2. computational models. *International Journal of Heat and Mass Transfer*, 55(7–8):1796–1806, 2012.

[66] S. Mellouli, F. Askri, H. Dhaou, A. Jemni, and S. B. Nasrallah. Numerical simulation of heat and mass transfer in metal hydride hydrogen storage tanks for fuel cell vehicles. *International Journal of Hydrogen Energy*, 35(4):1693–1705, 2010.

[67] L. Tong, C. Yuan, T. Yang, P. Bénard, Y. Yuan, and J. Xiao. Performance estimation of dehydriding process in metal hydride hydrogen storage tank with coiled-tube heat exchanger. *International Journal of Hydrogen Energy*, 28:101633, 2021.

[68] J. Yuan, M. Yao, B. Zhao, Y. Liu, H. Huang, J. Chen, B. Liu, B. Zhang, and W. Ying. Influence of heat exchanger structure on hydrogen absorption-desorption performance of hydrogen storage vessel. *International Journal of Hydrogen Energy*, 32(5):617–624, 2022.

[69] M. Visaria and I. Mudawar. Experimental investigation and theoretical modelling of dehydriding process in high-pressure metal hydride hydrogen storage systems. *International Journal of Hydrogen Energy*, 37(22):5735–5749, 2012.

[70] H. Wang, A. K. Prasad, and S. G. Advani. Hydrogen storage system based on hydride materials incorporating a helical-coil heat exchanger. *International Journal of Hydrogen Energy*, 37(22):14292–14299, 2012.

[71] X. Mou, Z. Bao, and W. Huang. Performance investigation of metal hydride reactor equipped with helically coiled heat exchanger during hydrogen absorption and desorption. *International Journal of Hydrogen Energy*, 38(1):101656, 2023.

[72] X. Meng, Z. Wu, Z. Bao, F. Yang, and Z. Zhang. Performance simulation and experimental confirmation of a mini-channel metal hydrides reactor. *International Journal of Hydrogen Energy*, 38(35):15242–15253, 2013.

[73] M. Raju and S. Kumar. Optimization of heat exchanger designs in metal hydride-based hydrogen storage systems. *International Journal of Hydrogen Energy*, 37(3):2767–2778, 2012.

[74] F. Askri, M. Bensalah, A. Jemni, and S. Ben Nasrallah. Optimization of hydrogen storage in metal-hydride tanks. *International Journal of Hydrogen Energy*, 34(3):897–905, 2009.

[75] H. Dhaou, A. Souahlia, S. Mellouli, F. Askri, A. Jemni, and S. Ben Nasrallah. Experimental study of a metal hydride vessel based on a finned spiral heat exchanger. *International Journal of Hydrogen Energy*, 35(4):1674–1680, 2010.

[76] Prasad J. Sunku and P. Muthukumar. Design and performance analysis of an annular metal hydride reactor for large-scale hydrogen storage applications. *Renewable Energy*, 181:1155–1166, 2022.

[77] P. Larpruenrudee, N. S. Bennet, Z. Lou, R. Fitch, E. Sauret, and M. S. Islam. A novel design for faster hydrogen storage: A combined semi-cylindrical and central return tube heat exchanger. *Journal of Energy Storage*, 71:108018, 2023.

[78] A. H. Eisapour, A. Naghizadeh, M. Eisapour, and P. Talebizadehsardari. Optimal design of a metal hydride hydrogen storage bed using a helical coil heat exchanger along with a central return tube during the absorption process. *International Journal of Hydrogen Energy*, 46(24):14478–14493, 2021.

[79] C. Na Ranong, M. Höhne, J. Franzen, J. Hapke, G. Fieg, M. Dornheim, N. Eigen, J. M. Bellosta von Colbe, and O. Metz. Concept, design and manufacture of a prototype hydrogen storage tank based on sodium alanate. *Chemical Engineering & Technology*, 32:1154–1163, 2009.

[80] D. Mosher, X. Tang, and S. Arsenault. High density hydrogen storage system demonstration using $NaAlH_4$ based complex compound hydrides (annual progress report IV.A.1). Technical report, U.S. Department of Energy, DOE Hydrogen Program, 2006.

[81] M. Gambini, F. Guarnaccia, M. Manno, and M. Vellini. Thermal design and heat transfer optimisation of a liquid organic hydrogen carrier batch reactor for hydrogen storage. *International Journal of Hydrogen Energy*, 48:37625–37636, 2023.

[82] A. Couteau, P. D. Eggenschwiler, and P. Jenny. Heat transfer analysis of high-pressure hydrogen tank fillings. *International Journal of Hydrogen Energy*, 47:3060–3069, 2022.

[83] K. Malleswararao, P. Dutta, and S. S. Murthy. Applications of metal hydride based thermal systems: A review. *Applied Thermal Engineering*, 215:118816, 2022.

[84] P. Muthukumar, A. Kumar, N. N. Raju, K. Malleswararao, and M. M. Rahman. A critical review on design aspects and developmental status of metal hydride based thermal machines. *International Journal of Hydrogen Energy*, 43(37):17753–17779, 2018.

[85] P. Muthukumar and M. Groll. Erratum to "Metal hydride-based heating and cooling systems: A review". *International Journal of Hydrogen Energy*, 35:3817–3831, 2010.

[86] V. K. Sharma and E. A. Kumar. Thermodynamic analysis of novel multi stage multi effect metal hydride based thermodynamic system for simultaneous cooling, heat pumping and heat transformation. *International Journal of Hydrogen Energy*, 42:437–447, 2017.

[87] G. Sdanghi, G. Maranzana, A. Celzard, and V. Fierro. Review of the current technologies and performances of hydrogen compression for stationary and automotive applications. *Renewable and Sustainable Energy Reviews*, 102:150–170, 2019.

[88] J. Zou, N. Han, J. Yan, Q. Feng, Y. Wang, Z. Zhao, J. Fan, L. Zeng, H. Li, and H. Wang. Electrochemical compression technologies for high-pressure hydrogen: Current status, challenges and perspective. *Electrochemical Energy Reviews*, 3:690–729, 2020.

[89] A. M. Elberry, J. Thakur, A. Santasalo-Aarnio, and M. Larmi. Large-scale compressed hydrogen storage as part of renewable electricity storage systems. *International Journal of Hydrogen Energy*, 46(29):15671–15690, 2021.

[90] S. S. Bhogilla and H. Niyas. Design of a hydrogen compressor for hydrogen fuelling stations. *International Journal of Hydrogen Energy*, 44:29329–29337, 2019.

[91] K. Goshome, E. Naruki, and T. Maeda. Demonstration of a single-stage metal hydride hydrogen compressor composed of BCC $V_{40}TiCr$ alloy. *International Journal of Hydrogen Energy*, 46:28180–28189, 2021.

[92] S. Toghyani, E. Afshari, and E. Baniasadi. Parametric study of a proton exchange membrane compressor for electrochemical hydrogen storage using numerical assessment. *Journal of Energy Storage*, 30:101469, 2020.