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Review

Thermal Management Techniques in Metal Hydrides for Hydrogen Storage Applications: A Review

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Abstract: Metal hydrides are a class of materials that can absorb and release large amounts of hydrogen. They have a wide range of potential applications, including their use as a hydrogen storage medium for fuel cells or as a hydrogen release agent for chemical processing. While being a technology that can supersede existing energy storage systems in manifold ways, the use of metal hydrides also faces some challenges that currently hinder their widespread applicability. As the effectiveness of heat transfer across metal hydride systems can have a major impact on their overall efficiency, an affluent description of more efficient heat transfer systems is needed. The literature on the subject has proposed various methods that have been used to improve heat transfer in metal hydride systems over the years, such as optimization of the shape of the reactor vessel, the use of heat exchangers, phase change materials (PCM), nano oxide additives, adding cooling tubes and water jackets, and adding high thermal conductivity additives. This review article provides a comprehensive overview of the latest, state-of-the-art techniques in metal hydride reactor design and heat transfer enhancement methodologies and identifies key areas for future researchers to target. A comprehensive analysis of thermal management techniques is documented, including performance comparisons among various approaches and guidance on selecting appropriate thermal management techniques. For the comparisons, the hydrogen adsorption time relative to the reactor size and to the amount of hydrogen absorbed is studied. This review wishes to examine the various methods that have been used to improve heat transfer in metal hydride systems and thus aims to provide researchers and engineers working in the field of hydrogen storage with valuable insights and a roadmap to guide them to further explore the development of effective thermal management techniques for metal hydrides.

Keywords: metal hydride reactor; heat transfer; thermal management

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1. Introduction

Hydrogen is a well-known, viable alternative fuel and energy storage medium due to its storage capabilities and mobility [1]. Despite having a low energy content, it has high energy density when compared to the traditional fossil fuels. It continues to provide the greatest energy capacity per mass when compared to fossil fuels [2]. The hydrogen economy could be made more efficient by using hydrogen-storing materials with greater energy densities as well as smaller volumes and lesser bulk [2]. Finding innovative materials or new material combinations with high volumetric and gravimetric capacity, rapid sorption kinetics at near to ambient temperatures, and high recycling tolerance is, however, one of the greatest challenges facing modern hydrogen storage systems now.

Metal hydrides are a class of materials that are composed of metal and hydrogen. These materials have received significant attention in recent years due to their high hydrogen-storage capacities, which makes them promising candidates for use in hydrogen-based energy systems. Their high energy density, relatively low cost, and environmental compatibility make them a compelling choice for applications in portable electronics, electric vehicles, and renewable energy systems. However, their development for hydrogen storage applications faces major challenges, including the need to determine suitable materials possessing a high hydrogen-storage capacity whilst being stable, safe, and economically viable. Researchers have been exploring the use of various metal hydrides such as those based on magnesium, aluminum, and titanium to meet the abovementioned criteria. A number of factors can influence the performance of metal hydrides, including the choice of metal, the size and shape of the hydride particles, the purity of the materials, and the presence of impurities. Metal hydrides are being considered for their potential use in hydrogen fuel cells, which are an important component of hydrogen-based energy systems, as they are able to use hydrogen to provide electrical energy through oxidation and reduction. By this technique, fuel cell systems can be made more compact and efficient, as well as more environmentally friendly.

Despite the progress that has been made in the development of metal hydrides for energy storage applications, there are still many areas to be researched. In order to fully realize the potential of this technology, researchers must continue to investigate and understand the fundamental science of metal hydrides and develop new and innovative approaches to optimize their performance. This review article focuses on the development of metal hydrides for energy storage applications and reviews the current state of the field, highlighting recent advances and ongoing challenges in thermal management of metal hydride. A comprehensive analysis of thermal management techniques is documented, including performance comparisons among various approaches and guidance on selecting appropriate thermal management techniques.

Challenges in the Widespread Use of Metal Hydrides

Alongside growing interest, there are many challenges associated with the use and development of metal hydrides. Researchers have struggled to improve and optimize the hydrogen storage performance of metal hydrides. This requires a deep understanding of the fundamental chemical and physical processes that govern their behavior, including hydrogen uptake and release kinetics, thermodynamics, and stability. In particular, metal hydrides can be prone to degradation and corrosion, which can limit their performance and lifespan. Additionally, the cost of producing metal hydrides is still relatively high, making them less attractive for use in commercial bids. Their use in real-world applications can also be limited by factors such as the cost and availability of materials, as well as the complexity and efficiency of the hydrogen release and storage systems. To overcome these challenges, various performance-boosting strategies are being devised; for instance, the development of new synthesizing methods for metal hydrides, as well as the use of novel materials and nanostructures to enhance their hydrogen storage capacity.

Another major challenge hindering the use of metal hydrides for hydrogen storage applications is the effective management of heat during the absorption and desorption of hydrogen. The heat generated during the exothermic absorption process can cause the temperature of the metal hydride to rise, which can lead to thermal instability, decreased hydrogen uptake rate, and reduced cycle life. Similarly, the heat absorbed during the endothermic desorption process can cause a drop in temperature, which can also negatively impact the hydrogen uptake/release kinetics. Therefore, efficient thermal management techniques are crucial to improve the performance and safety of metal hydrides for hydrogen storage applications.

Despite these challenges, the field of metal hydride research is rapidly evolving, and scientists and engineers are working to develop new and innovative approaches to address these challenges. For instance, researchers are exploring the use of nanoscale metal hydrides, which can offer improved hydrogen storage performance due to their increased surface area. Investigations on the use of composite materials are also underway.

Another promising area of research is the development of smart hydrogen storage systems, which can intelligently regulate the release and uptake of hydrogen in response to changing energy demands. These systems have the potential to provide more efficient and effective hydrogen storage solutions for a wide range of applications.

2. Methods

The study of metal hydrides is an important area of research, as it has the potential to play a significant role in the development of sustainable energy systems. The goal of this research article is to explore the current state of research regarding this issue. A comprehensive review of the literature is undertaken to examine the various strategies that have been developed for improving the performance of metal hydrides, as well as exploring the challenges that remain in the development of these materials. Performance comparisons among various thermal management techniques are conducted, and this review provides guidance on selecting appropriate cooling/heating techniques for various types of metal hydride reactors. For the comparisons, the hydrogen adsorption time relative to the reactor size and to the amount of hydrogen absorbed is studied. By providing a comprehensive overview of the current state of metal hydride research, this article serves as a valuable resource for researchers and practitioners in this field and helps advance the development of these materials for practical use in the future.

3. Metal Hydrides

A metal hydride is a compound formed between a metal and hydrogen, in which the hydrogen atoms are bonded to the metal atoms through chemical bonds. Metal hydrides have a wide range of applications as energy storage materials, catalysts, and structural materials. There are various types of metal hydrides, each with their own unique properties and challenges. These include interstitial, substitutional, and complex types. Interstitial hydrides are those in which the hydrogen atoms are located between the metal atoms in the crystal lattice, while substitutional hydrides are those in which the hydrogen atoms replace metal atoms in the crystal lattice. In complex hydrides, the hydrogen atoms form covalent bonds with the metal atoms, resulting in a compound with a more complex chemical structure. Some of the most well-known metal hydrides include sodium aluminum hydride ($NaAlH_4$), magnesium hydride (MgH_2), and titanium hydride (TiH_2). These hydrides can store and release large amounts of hydrogen in a relatively safe and controlled manner, making them ideal for energy storage applications.

One of their main characteristics is the ability to absorb and release hydrogen gas through processes known as hydriding and dehydriding, respectively [2]. This property makes them attractive for use as hydrogen storage materials, as they can store large amounts of hydrogen at relatively low pressures [3]. Metal hydrides can also be used as catalysts in chemical reactions and as structural materials due to their high strength and low density.

The metal hydrides (MH) reaction is denoted by [4,5]:

$$\mathrm{M} + \frac{\mathrm{x}}{2}\mathrm{H}_2 \leftrightarrow \mathrm{MH}_\mathrm{x} \; + \Delta\mathrm{H}. \tag{1}$$

The equilibrium pressure in the system experiences a "plateau" phenomenon during the isothermal reaction phase. The well-known Van't Hoff equation can be used to link this equilibrium pressure to the temperature:

$$\ln(P) = \frac{\Delta\mathrm{H}}{\mathrm{RT}} - \frac{\Delta\mathrm{S}}{\mathrm{R}} \tag{2}$$

where ΔH and ΔS represent the enthalpy and entropy changes, respectively, throughout the process, R is used as the gas constant, and T is the temperature. Equation (2) describes a feature known as the P-C-T or P-C-I property, which varies significantly with different materials.

There are several advantages to using metal hydrides for hydrogen storage:

High capacity: Metal hydrides have a high hydrogen storage capacity, meaning that they can store large amounts of hydrogen in a relatively small volume. This makes them a compact and efficient storage option.

Safe: Metal hydrides are generally considered to be a safe storage option because they do not release hydrogen gas unless they are subjected to specific conditions, such as high temperatures or pressures. This reduces the risk of explosions or fires.

Stable: Metal hydrides are stable and do not react with other materials, making them a safe and reliable storage option.

Reusable: Metal hydrides can be used to store and release hydrogen multiple times, making them a reusable and environmentally friendly storage option.

Lightweight: Metal hydrides are typically lightweight, making them a suitable storage option for applications where weight is a concern, such as in vehicles.

Some of the applications of metal hydrides are provided in Table 1.

Overall, metal hydrides offer several advantages over traditional hydrogen storage methods and may be a more efficient and safe option in certain applications. In Figure 1, hydrogenation enthalpies and entropies of various hydride materials and their suitable applications are provided.

Overall, metal hydrides have the potential to play a significant role in a variety of applications, and their properties and behavior are an active area of research in the field of materials science.

Table 1. Some applications where metal hydrides are used.

References	Technology Area	Engineering System	Pros	Cons	Suggested Hydrides
[6]—Krane et al., 2022	Energy Storage	Two-reactor metal hydride system	• High energy density • Non-toxic and non-flammable suitable for long-term storage. Can be cycled without degradation in capacity • Can operate at a wide range of temperatures and pressures and low environmental impact	• Slow charging • Limited number of experimental validations to support the dynamic model	MgH_2, $TiFeH_2$, $LaNi_5H_6$
[7]—Zhang et al., 2023	Catalysis	Ammonia synthesis	• High catalytic activity and selectivity for ammonia synthesis • Lanthanum hydride species improves the catalytic performance	• Limited understanding of the mechanism behind the improved catalytic performance • Potential deactivation of the catalyst over time	Lanthanum hydride

Table 1. *Cont.*

References	Technology Area	Engineering System	Pros	Cons	Suggested Hydrides
[8]—Lv, Y. et al., 2023	Energy storage	Magnesium hydride conversion electrode	• High energy density • Abundant raw materials and detailed understanding of ion diffusion and hysteresis in magnesium hydride conversion electrodes	• Slow reaction kinetics • Low cycling stability • Challenges in improving ion diffusion and charge transfer kinetics • Limited practical application due to the need for high operating temperatures	Magnesium hydride
[9]—Zhou et al., 2023	Fuel cells	Hydrogen feeding system	• Comprehensive comparison of RE-based and Ti-based multicomponent metal hydrides	• Limited on long-term stability	RE-based and Ti-based multi-component metal hydrides
[10]—Tiwari and Sharma, 2023	Energy storage	Metal hydride reactor and thermocline-based heat storage system	• Proposed a hybrid energy storage system using metal hydrides and thermocline heat storage • Efficient thermal energy storage and release	• Limited discussion on real-world implementation and system optimization • Limited experimental validation	MgH_2
[11]—Alok Kumar, P. Muthukumar, 2022	Hydrogen storage and purification		• Methane poisoning characteristics studied experimentally	• Limited discussion on the impact of methane poisoning on system performance	$La_{0.9}Ce_{0.1}Ni_5$
[12]—Krishnamoorthy et al., 2023	Battery modeling	Lithium–ion and nickel–metal hydride batteries	• Provides efficient battery models for performance studies		Nickel-metal hydride battery
[13]—Zhang et al., 2022	Chemicals	CO_2 capture	• Insight into CO_2 capture by nickel hydride complexes	• Limited discussion of practical applications • Further optimization of the nickel hydride complexes is needed to enhance performance	Nickel hydride complexes

Table 1. *Cont.*

References	Technology Area	Engineering System	Pros	Cons	Suggested Hydrides
[14]—Brestovič, T. et al. 2022	Metal Hydride Compressors	Heat pump-based compression system	• Improved heat transfer efficiency due to the integration of a heat pump with a metal hydride compressor • Utilization of low-temperature heat sources • Increased COP values up to 2.2 in comparison to conventional heat pumps	• The use of metal hydride beds for compression may cause a decrease in the COP • Additional heating of the gas after compression may be required • Low heat transfer rates in the metal-. hydride bed may result in higher operating temperatures, which may negatively impact the overall performance of the system • Limited scalability due to material properties	$LaNi_5$
[15]—Massaro et al., 2023	On-board hydrogen storage technologies	Fuel cell systems for aircraft electrification	• High energy density of hydrogen, which provides high specific energy and range for aircraft • On-board hydrogen storage technologies, such as metal hydrides, offer high storage capacity and low weight • Fuel cell systems provide high efficiency and low noise emissions	• Low volumetric energy density of hydrogen, which requires large storage volumes • Safety concerns due to the high flammability and explosiveness of hydrogen • Limited availability of hydrogen infrastructure	
[16]—Nguyen and Shabani, 2022	Metal hydride hydrogen storage	Standalone solar hydrogen systems	• High volumetric and gravimetric hydrogen storage capacity of metal hydrides • The ability to use renewable energy sources, such as solar energy, to power the metal hydride system • Improved thermal management using phase change materials can enhance system performance	• High cost of metal hydride materials • Slow kinetics for hydrogen uptake and release • Limited cycle life due to material degradation	

Table 1. *Cont.*

References	Technology Area	Engineering System	Pros	Cons	Suggested Hydrides
[17]—Eadi et al., 2023	Hydrogen gas sensing	Pd-Ni alloy thin films	• Pd-Ni alloy thin films exhibit high sensitivity and selectivity towards hydrogen gas detection • The sensing performance of Pd-Ni alloy thin films can be improved by optimizing the deposition parameters • Pd-Ni alloy thin films are a promising candidate for practical hydrogen sensing applications due to their low cost and ease of fabrication	• Pd-Ni alloy thin films can be sensitive to other gases, such as CO and H_2S, which can interfere with hydrogen gas detection • The sensing performance of Pd-Ni alloy thin films can be affected by environmental factors, such as temperature and humidity • Pd-Ni alloy thin films may require periodic calibration to maintain accurate hydrogen gas detection	
[18]—Kumar et al., 2022	Metal hydride-based hydrogen storage	Standalone microgrids	• Metal hydride-based hydrogen storage systems can provide a reliable and efficient means of energy storage for standalone microgrids • Metal hydride systems have the potential for high energy density storage compared to other energy storage technologies • Metal hydride systems are environmentally friendly and have no harmful emissions	• Metal hydride systems can be expensive to manufacture and maintain • The hydrogen uptake and release kinetics of metal hydride systems can be slow, leading to reduced system performance • Metal hydride systems can be affected by temperature and humidity changes, which can reduce system efficiency	MgH_2, $TiFeH_2$, $LaNi_{4.8}Al_{0.2}H_{11.3}$

Table 1. *Cont.*

References	Technology Area	Engineering System	Pros	Cons	Suggested Hydrides
[19]—Tian et al., 2022	Hybrid rocket propulsion	Solid-fuel additives	• Addition of metal and metalloid solid-fuel additives can improve the combustion performance of hydroxy-terminated polybutadiene-based hybrid rocket motors • Metal and metalloid additives can increase the density and specific impulse of the rocket motor • Additives can also reduce the nozzle ablation rate, which can extend the lifetime of the motor	• The effect of the additives on the mechanical properties of the motor is not well understood • The production and processing of the solid-fuel additives can be expensive and difficult • The use of metal and metalloid additives may require additional safety measures due to the potential for increased reactivity and flammability	
[20]—Lee et al., 2022	Hydrogen storage	Magnesium hydrogen tank	• The two-in-one flexible high-temperature micro-sensor developed in this study can provide real-time monitoring of surface temperature and strain of magnesium hydrogen tanks • The sensor is low-cost, lightweight, and can be easily integrated into existing tank designs • Real-time monitoring of tank conditions can improve safety and performance in hydrogen storage systems	• The study focuses solely on the development and testing of the micro-sensor and does not address other aspects of hydrogen storage technology • The use of magnesium as a hydrogen storage material has some drawbacks, including low hydrogen storage capacity and high reactivity with air and moisture	MgH_2

Table 1. *Cont.*

References	Technology Area	Engineering System	Pros	Cons	Suggested Hydrides
[21]—Sezgin et al., 2022	Hydrogen energy systems	Underwater applications	• Hydrogen fuel cells are a promising power source for underwater applications due to their high efficiency, low noise, and zero emissions • Hydrogen can be stored in metal hydride tanks, which have high energy density and can operate at low pressures • Hydrogen systems can provide longer endurance and greater range than traditional battery-powered systems	• The high cost and complexity of hydrogen systems may limit their adoption in some applications • The need for refueling infrastructure and the limited availability of hydrogen fuel may also be barriers to adoption	TiFe, $LaNi_5$, AB_2 ($MmNi_{3.6}Co_{0.7}Mn_{0.4}Al_{0.3}$), MgH_2, $LiBH_4$
[22]—Kailiang Ren, Jiajia Miao, et al., 2022	Electrochemical energy storage	Batteries	• $LaFeO_3$ coated with C/Ni exhibited superior electrochemical performance at high temperatures compared to bare $LaFeO_3$ • The coating with C/Ni helps to increase the conductivity of the material and improves its electrochemical properties	• The preparation of the C/Ni-coated $LaFeO_3$ requires additional processing steps • The long-term stability of the coating is unknown	NiMH
[23]—Dinesh Dashbabu, E. Anil Kumar, I.P. Jain, 2022	Hydrogen compression	Metal hydride hydrogen compressor	• Metal hydride hydrogen compressor with Al-substituted $LaNi_5$ hydride can effectively compress hydrogen • Study provides a comprehensive thermodynamic analysis of the compressor	• The performance of the compressor decreases at higher operating temperatures • The thermal conductivity of the metal hydride decreases with increasing Al content	$LaNi_5H_6$-xAlx

Table 1. *Cont.*

References	Technology Area	Engineering System	Pros	Cons	Suggested Hydrides
[24]—Sayantan Jana et al., 2022	Heating and cooling	Embedded cooling tube type metal hydride reactor	• High thermal conductivity • Energy-efficiency • Rapid heating/cooling • Absence of moving parts • Long life cycle	• Limited by heat transfer efficiency • Relatively low hydrogen storage capacity • Higher cost compared to conventional systems	Mg_2NiH_4, Top of Form bottom of form
[25]—Singh et al., 2022	Renewable energy	Reversible SOFC, hydrogen storage, rankine cycle, absorption refrigeration	• Novel energy storage system design based on multiple technologies	• Need for further testing and optimization	$LaNi_{4.8}Al_{0.2}$, MgH_2, Ni-MH alloy, CaH_2
[26]—H. Chang, Y.B. Tao, H. Ye, 2023	Hydrogen and thermal storage	Sandwich reaction bed filled with metal hydride and thermochemical material	• Proposed a new sandwich reaction bed for hydrogen and thermal storage • Conducted numerical simulations to investigate the performance of the system under different operating conditions	• No experimental validation of the numerical results was conducted	

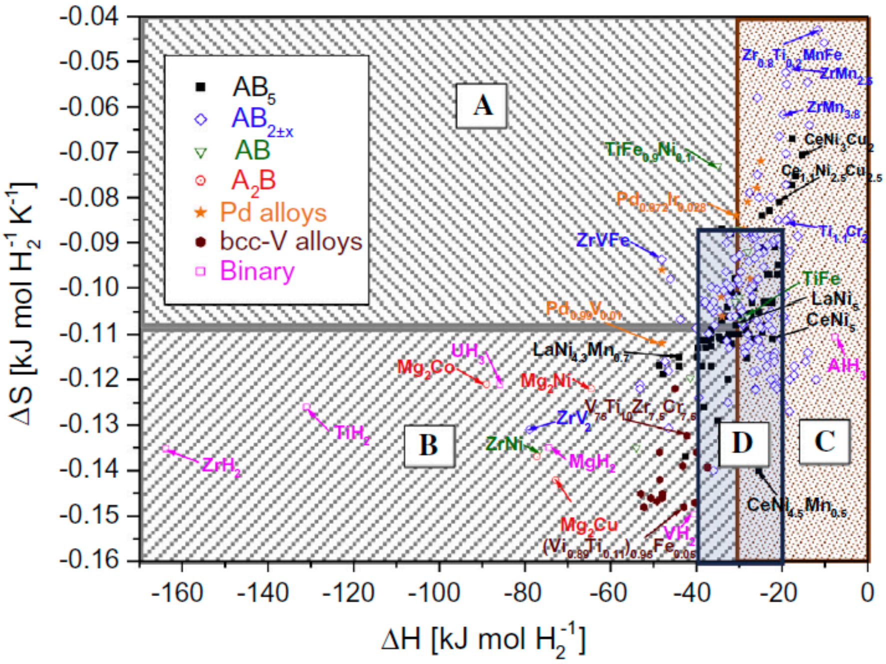

Figure 1. Hydrogenation enthalpies and entropies of various hydride materials and their suitable applications: (**A**) heat pumps, (**B**) heat storage, (**C**) hydrogen storage, (**D**) hydrogen compression [27].

Type AB_5 metal hydrides (for which $LaNi_5$ serves as the paradigm) and type AB_2 metal hydrides are the most well known for hydrogen absorption (such as Mn_2Zn). The AB_5

group has excellent hydrogenation ability at ambient temperature. However, its hydrogen capacity is typically in the range of 1 to 1.5 wt%. Metal hydrides based on magnesium (Mg and Mg_2Ni) display unacceptably slow rates of hydrogenation and dehydrogenation even after significant activation at 673 K (400 °C) [28].

4. Reactor House Shape Optimization

The metal hydride reactor provides the region where the materials are filled. In other words, it acts as a packed bed-type vessel, which serves to enhance mass and heat exchange in the metal hydride bed. There have been several metal hydride reactor designs built over time, and the main geometric configurations of these reactors can be divided into three types: tubular reactors, disc reactors, and chamber reactors.

4.1. Tubular Reactors

In this type of reactor, hydrogen is normally fed via a central artery. As indicated in Figure 2, the heat exchange between the reaction bed and the heat source/sink can be accomplished through the outer surface of the tube wall. The annular space between the artery and the wall is densely packed with metal hydride materials. The tubular reactor has been in use since the early applications of metal hydrides in heat pump systems [29], and its design has evolved over time. To allow effective radial heat transmission, the outside diameter of a single tube unit should normally not exceed 30 mm [30–34]. The length of the tube must be increased to store a given volume of metal hydride. The tube unit's aspect ratio, which is defined as the ratio of cylinder height to diameter, is often more than 10. Although circular cross-sectional tubes are the most common, Veerraju et al. [35] contend that elliptical tubes may be superior due to their compact structure and lower hydraulic loss. Because standardized tubing may be utilized, this reactor is very simple to manufacture and maintain. It also has a high bearing pressure and excellent sealing. Furthermore, the tube units are modular and self-contained, making it very easy to scale up the reactor by adding more units. Small-scale studies are best performed with a single tubular reactor [31,34,36], but larger applications can benefit from tube columns or banks. The literature [37–40] contains descriptions of tube units in parallel, square, and hexagonal configurations.

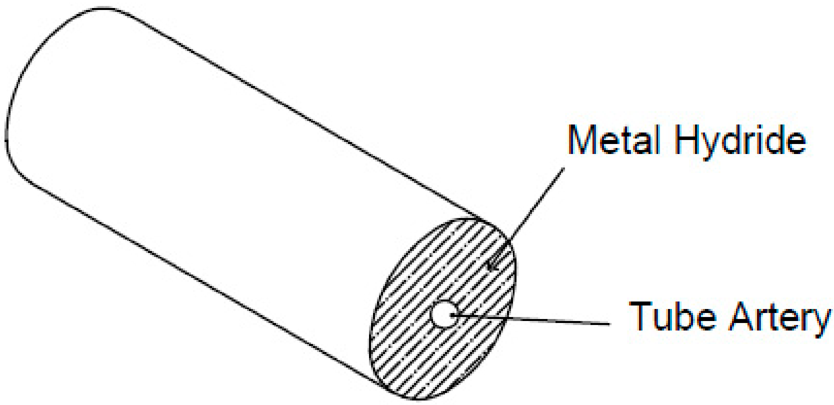

Figure 2. A typical tubular reactor.

4.2. Disc Reactors

The reaction bed of the disc reactor is flat [41,42], and the aspect ratio is significantly less than one. In a common design, heat exchange occurs on one side of the reactor while hydrogen flows axially into or out of the reactor through the screen that covers the metal hydride layer. It offers a large heat transfer surface and quick reaction kinetics for a thin bed. A single disc, on the other hand, can only carry a certain amount of metal hydride. Furthermore, due to the structure's location of mass and heat elements on either side, increasing capacity by adding more disc units is technically tough.

Several studies have attempted to address this issue; a Chinese research group [43,44], for example, created a novel configuration known as an annulus–disc reactor. Figure 3 shows an example of annulus–disc reactor. In such a reactor, hydrogen flows through tubes that penetrate the annulus–disc components and allow radial mass transfer with metal hydride. The units contain metal hydride. The outside surfaces of the annulus–disc units undergo simultaneous heat transfer. The number of annulus–disc units can be adjusted to vary the capacity of this type of reactor. Meanwhile, a rapid reaction rate was achieved by correctly managing the dimension and separation of annulus–disc units.

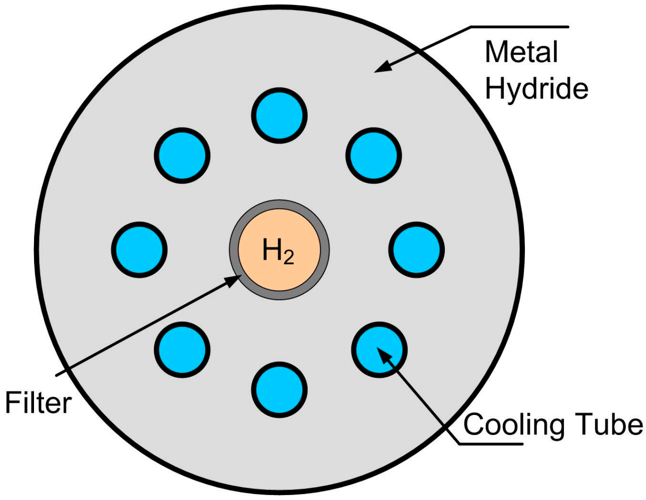

Figure 3. Cross-section of an annulus reactor.

4.3. Chamber Reactors

The reaction bed in a tank or chamber metal hydride reactor is a large cylinder or cube chamber, allowing more metal hydride to be packed than in the preceding two types of reactors. Hydrogen may easily enter and escape the reactor via the arteries [45,46] or the surrounding outer filter [47–50]. Heat exchange in the metal hydride bed is frequently provided by a few embedded components, such as spiral coils [45,51], heat pipes [52], and conventional tube bundles [48,50,53,54]. Dehouche et al. [55] and Meng et al. [56] proposed the use of the micro-channel technique in the metal hydride tank reactor because it can achieve intensive heat transfer in a limited area. Figure 4 presents a schematic of the latter authors' micro-channel reactor. The forced flow of fluid in the multiple circular microchannels in this type of reactor allows uniform temperature distribution and reaction [56]. The micro-structure design has the advantage of directing the fluid flow for heat transmission using electrokinetic or capillary force, which saves the cost of external pumps while considerably enhancing heat transfer.

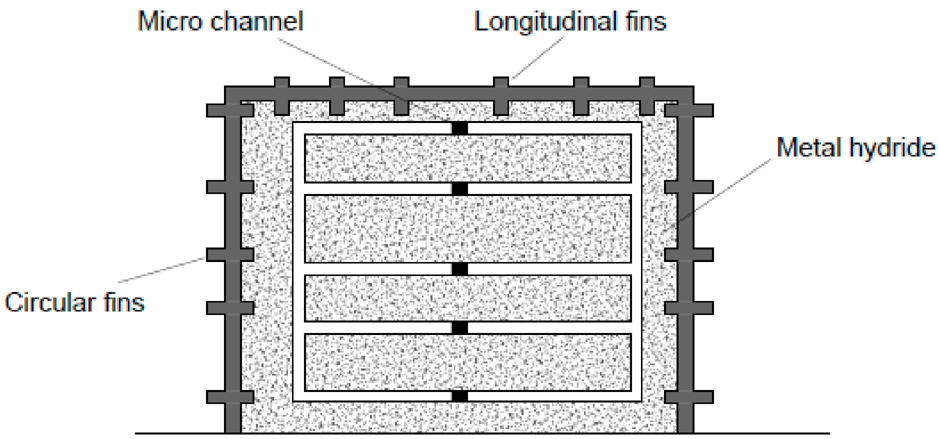

Figure 4. Schematic of micro-channel reactor.

The tank reactor's most important characteristic is its high capacity. As a result, it is recommended for environments where more metal hydride materials are required to achieve the appropriate output. To meet the requirements for excellent performance, the number and placement of heat and mass transmission devices must be carefully evaluated as the bed dimension increases [53,54]. Fortunately, the highly developed computational fluid dynamics (CFD) approach [56–58] is a powerful tool for completing this task. It should be emphasized that these configurations have also been combined to create novel hybrid reactor designs. One example is the so-called bottle reactor [59,60], which is a hybrid of a tubular and a tank reactor. The disc reactor has mostly been employed for kinetic measurements [61,62].

5. Heat Transfer Techniques

Heat transfer in metal hydrides typically involves the transfer of heat between a metal hydride material and its surroundings. This can be achieved through several different techniques, including conduction, convection, and radiation. Other techniques that may be used to transfer heat in metal hydrides include phase change materials, which absorb or release heat as they change from a solid to a liquid or from a liquid to a gas, and thermoelectric materials, which can convert heat into electricity or vice versa.

There are various parameters which can influence the heat transfer in the metal hydrides. For example, heat transfer in metal hydride systems may be improved by increasing the surface area between the metal hydride bed and the heat transfer fluid. Numerous studies on increasing surface area by adding fins have been reported [63,64]. Figure 5 shows a cross-section of a six-finned reactor. Mellouli et al. [65] recommended metal hydride tanks equipped with finned spiral tube heat exchangers for use in fuel cell systems. Compared to metal hydride tanks without circular fins, the time required to obtain 90% hydrogen storage was cut by 66% because the fins provided effective heat transmission. Cylindrical reactors with u-shaped heat transfer fluid tubes brazed with circular fins [66] and uniformly positioned multiple copper tubes equipped with evenly brazed cylindrical shape pin fins on the perimeter of tubes [67] have both led to a notable improvement in the hydrogen storage capabilities. A cylindrical reactor with an exterior heat transfer fluid jacket and rectangular copper fins was recently developed by Gupta and Sharma [68]. According to their modelling, the fins decreased the bed's maximum temperature increase during the formation of metal hydride by 22.3 °C and its maximum temperature reduction during the breakdown process by 6.8 °C. A numerical analysis by Raju and Kumar [69] compared three designs: a shell and tube heat exchanger with lanate on the tube side, an internal helical heat exchanger, and a cylindrical reactor to study the potential enhancement in hydrogen storage. In terms of performance, the internal helical heat exchanger variation outperformed the other two types.

5.1. Phase Change Fluid Flow Designs

The metal hydride bed's temperature increases because of heat release during the hydride formation process. As a result, the equilibrium pressure of the gas inside the reactor increases, consequently decreasing the rate of reaction. For the heat transfer fluid to continue hydride production, heat must be removed effectively. It is also recommended that the rate of heat transfer to the metal hydride bed be high enough to permit quick and continuous hydrogen gas desorption. Therefore, for effective heat and mass transmission in the metal hydride system, the heat transfer fluid's characteristics and flow rate are crucial. Heat transfer fluids have been made from air, water [70,71], oils [53,72], and phase change materials (PCM) [73–75]. Since increasing the heat transfer fluid flow rate improves the convective heat transfer coefficient and hence increases the rate of heat transfer, numerous studies have been conducted to optimize the heat transfer fluid flow rate.

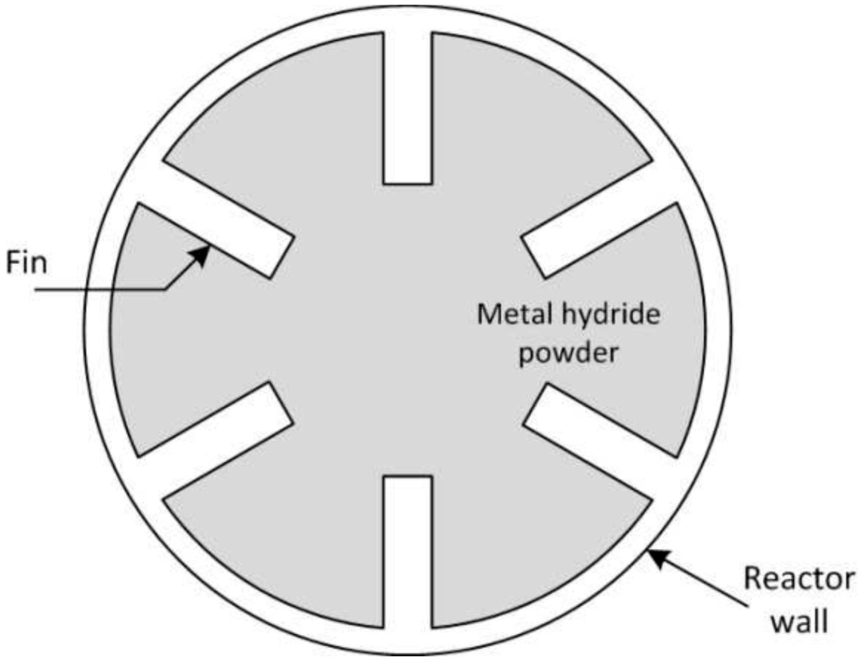

Figure 5. Cross-section of six-fin reactor.

According to Mellouli et al. [51], raising the heat transfer fluid flow rate significantly shortens the time needed to store hydrogen. The storage period decreased by 44% with an increase in the overall heat transfer coefficient from 750 $Wm^{-2}K^{-1}$ to 1250 $Wm^{-2}K^{-1}$, according to their experiment on a reactor with $MmNi_{4.6}Al_{0.4}$ [76]. While greater heat transfer rates and the outlet temperature of the heat transfer fluid are priorities for thermal storage applications, the quick evacuation of heat from the metal hydride bed is the key objective for hydrogen storage applications. The thermal potential of heat transfer fluid must be utilized in metal hydride-based applications over a long residence period at a significant flow rate.

Water has historically been utilized as the heat transfer fluid in metal hydride systems designed to operate at low temperatures (70 °C), but in high temperature applications, air, oils, and PCMs have been used [53,72–75]. Wang et al. [72] and Mosher et al. [53] employed oils as a heat transfer fluid in metal hydride systems running at 150 °C. Heat transfer qualities have improved because of the use of PCMs in metal hydride systems [73,74]. More recently, nanofluids have been suggested for use in metal hydride systems as heat transfer fluids. Al_2O_3-H_2O, CuO-H_2O, and MgO-H_2O nanofluids were employed by Urunkar and Patil [77] with successful outcomes. As a result, the heat transfer fluid and its flow characteristics have a big influence on the quality of functioning of metal hydride systems. The selection of a suitable heat transfer fluid is based on the application and operating temperature of the metal hydride system. Table 2 shows some examples of phase change material techniques.

Table 2. Some examples of phase change material techniques.

Reference	Thermal Management Technique	Observations
[77]—Rahul U. Urunkar, Sharad D. Patil (2021)	Use of various nanofluids for enhancing heat and mass transfer in metal hydride reactor for hydrogen storage	• Addition of Al_2O_3, TiO_2 and CuO nanoparticles to water in the cooling loop of the reactor significantly enhanced the heat transfer rate and decreased the reactor temperature, improving the performance of the system.

Table 2. *Cont.*

Reference	Thermal Management Technique	Observations
[78]—Syedvali Pinjari et al. (2023)	Acid functionalized carbon nanotubes	• Acid functionalized carbon nanotubes were effective at storing hydrogen at room temperature, with a high maximum sorption capacity of 4.43 wt%. • Analysis of sorption kinetics revealed a diffusion-controlled mechanism to be the dominant factor. • This discovery suggests that acid functionalized carbon nanotubes could be a promising candidate for hydrogen storage.
[79]—Atef Chibani et al. (2022)	Phase change material incorporated in porous media (metal foam)	• Heat and mass transfer analysis revealed improved hydrogen desorption performance from the metal hydride by incorporating a phase change material in porous media (metal foam) form.
[80]—Huy Quoc Nguyen et al. (2022)	Organic phase change material	• Employing organic phase change material can enhance the thermal management of metal hydride hydrogen storage, reducing thermal losses and increasing the hydrogen release rate. • The study also showed the potential of using a numerical model for optimization of the system.
[81]—Atef Chibani, Slimane Merouani, Noureddine Gherraf, Yacine Benguerba (2022)	Phase change material–metal foam-based latent heat storage system	• The results of thermodynamic and kinetic analyses of hydrogen absorption in large-scale metal hydride reactor coupled to thermal energy storage system indicated that using a phase change material–metal foam-based latent heat storage system can enhance the hydrogen absorption rate and reduce the thermal fluctuations in the metal hydride reactor.
[82]—Atef Chibani, Aissa Dehane, Slimane Merouani, Cherif Bougriou, Djemaa Guerraiche (2022)	Melting/solidification of phase change material in a multi-tube heat exchanger in the presence of metal foam	• Using metal foam with smaller pore sizes enhances the heat transfer and reduces the time for melting and solidification of PCM.
[83]—A. Chibani, S. Merouani, N. Gherraf, I. Ferhoune, Y. Benguerba (2022)	Phase change material with nano-oxide additives	• Using PCM with nano-oxide additives enhanced heat transfer during hydrogen desorption from metal hydride. • Significant enhancement of hydrogen desorption rate and reduction in desorption time with the addition of nano-oxide additives. • Higher thermal conductivity and latent heat capacity of the PCM with additives contributed to better heat transfer during the desorption process.
[84]—Atef Chibani et al. (2022)	Metal hydride-phase change material reactor with nano oxide	• The addition of nano-oxide additives to the phase change material improves the charging process of the metal hydride reactor by enhancing the heat and mass transfer rates.

Table 2. *Cont.*

Reference	Thermal Management Technique	Observations
[85]—Elarem, Raja, et al. (2021)	Nanoparticles enhanced phase change material and nanofluid	• The results of the numerical analysis showed that the combined system had higher thermal storage capacity and faster heat transfer rate compared to individual systems, making it a promising option for thermal energy storage applications.

5.2. Adding Cooling Tubes/Water Jackets

Designing metal hydride reactors with embedded cooling tubes (ECT) is one of the most effective techniques to accomplish successful hydrogen storage since it dramatically enhances the heat transfer area. Numerous computational analyses [63,86] and experimental research [87–89] on ECT models have been published. Empirical correlations have been developed to determine the number of ECT required for a particular size of cylindrical reactor, alloy mass, and tube size. Figure 6 shows a reactor diagram of a six-pass finned configuration.

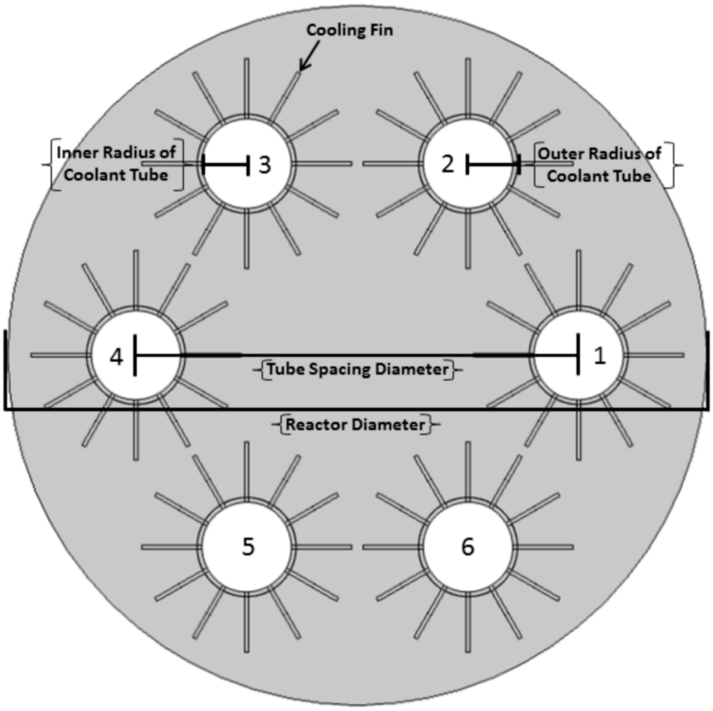

Figure 6. Reactor diagram of a six-pass finned configuration with the tube numbers.

This design was employed for metal hydride applications since it maintained a compact nature while still having a greater heat transfer surface area. The bed thickness was also discovered to be a crucial geometric component for the effective thermal performance of metal hydride systems. The same group also recommend the tube-bundle reactor with plate fins for usage in large-scale systems [90]. Afzal and Sharma [91] and Jana and Muthu Kumar [92] evaluated the performance of tube-bundle model reactors and determined that it was only moderately better than the ECT model.

5.3. Improvement of Effective Thermal Conductivity of Metal Hydride Bed (High Thermal Conductivity Materials)

Only 0.1 $Wm^{-1}K^{-1}$ of heat can be conducted through a typical loose powder bed of metal hydride, and the hydrogenation and dehydrogenation cycles can further pulverize the particles [73]. As a result, the metal hydride bed's effective thermal conductivity can be further diminished, and as the hydride bed has poor heat transport, heat aggregation may take place. This significantly slows down the hydride bed's reaction rate and even prevents hydrogenation and dehydrogenation. The hydrogenation and dehydrogenation times in the hydride bed increase because heat cannot be adequately transported. Enhancing the metal hydride bed's effective thermal conductivity is the key to improving heat transfer efficiency [93,94]. Numerous internal heat transfer augmentation procedures have been devised to boost the effective thermal conductivity of the hydride bed [95]. Compaction, covering with copper, adding high thermal conductivity materials, and constructing internal thermal structures are the key strategies that will be discussed in further depth.

5.3.1. Compaction

Porosity in metal hydride powder beds can significantly reduce their effective thermal conductivity. By mechanically compressing the powder, the internal porosity of the bed can be reduced, and its apparent density increased. This leads to an improvement in both the thermal conductivity and hydrogen storage capacity of the bed [96]. Additionally, compaction can enhance the safety of the powder when it is in contact with air and water. This method is commonly used to densify loose metal hydride powder beds [97]. Dehouche et al. [98] discovered, for example, that compressing $LaNi_{4.8}Sn_{0.2}$, $LmNi_{4.9}Sn_{0.1}$, and $MmNi_{4.7}Al_{0.3}$ powder beds at a maximum pressure of 1.5 metric tons increased apparent density from 3 g cm^{-3} to roughly 6 g cm^{-3} and improved effective thermal conductivity from 0.1 to 1.7 $Wm^{-1}K^{-1}$. Humphries et al. [99] realized a thermal conductivity of 2.08 $Wm^{-1}K^{-1}$ by compacting MgH_2 powder at room temperature in an argon atmosphere at a pressure of 370 MPa. Jepsen et al. [100] increased the apparent density of LiH + MgB_2 to 1.35 g cm^{-3} and lowered the porosity to 20% by compacting the desorbed state under 300 MPa pressure. Thermal conductivity increased to roughly 0.3 and 0.6 $Wm^{-1}K^{-1}$, respectively.

5.3.2. Addition of High Thermal Conductivity Materials

Carbon materials such as graphite powder [101,102], carbon nanotubes (CNTs) [103–105], carbon bars [106–108], and expanded graphite [63,109–111] are used as thermal conductivity reinforcement materials for hydride beds because of their high thermal conductivity and lack of reactivity with hydrides. Materials made of metals, including powder and foam copper powder [112], aluminum foam [91,113,114], and copper foam [115,116] are other alternatives. Metal-based high thermal conductivity materials are frequently added to the AB_5 alloy powder bed due to their equivalent densities. Due to the small variation in metal hydride density, the distribution of metal-based reinforcing materials during the mixed addition and hydride bed hydrogenation/dehydrogenation processes is be uniform. To improve heat conduction, metal-based reinforcing elements are frequently used in metal hydride beds. Carbonaceous and metal foam materials' higher porosity and lower bulk densities have no impact on the hydrogen storage material bed's mass hydrogen storage density. The choice of foam metal is related to the required parameters, such as increased heat transmission and mass hydrogen storage density, because different metal foams have varying thermal conductivity and density. Additionally, the extra particles fill the bed's interstices, creating a heat-conduction channel. Ti_xCr_2-yMn_y was combined by Pourpoint et al. [101] with different CNT and graphite mass fractions. According to the findings, raising the CNTs content from 1% to 5% had little effect on thermal conductivity, which stayed at 0.18 $Wm^{-1}K^{-1}$. This could be explained by the high apparent characteristic size of the CNTs as well as the composites' improved bonding ability and porosity following delivery. The effect of the increased content and powder density may work together to increase the composite material's effective thermal conductivity to about 0.3 $Wm^{-1}K^{-1}$ when 1 and 10% graphite is added. The $La_{0.9}Ce_{0.1}Ni_5$ powders were altered by Park et al. [75] by adding 3 wt% expanded natural graphite, increasing the thermal conductivity from 2.02 to 2.67 $Wm^{-1}K^{-1}$. According to Wang et al. [114], adding 10% Al foam to a large $LaNi_5$ hydride tank (5 kg) increased the hydride bed's effective thermal conductivity and reduced the time to reach 90% hydrogenation saturation by roughly five times. A brief list of metal hydride materials and their thermal conductivity are provided in Table 3.

Table 3. Metal hydride materials and their thermal conductivity.

Metal Hydride Material	Thermal Conductivity ($Wm^{-1}K^{-1}$)
MgH_2	4.3
$TiFeH_2$	4.6
$LaNi_5H_6$	13.5
$FeTiH_2$	10.0
$CaNi_5H_6$	10.0
$ZrCoH_2$	12.0
Mg_2NiH_4	10.0
$FeTiH_{1.9}$	10.0
Mg_2FeH_6	4.0
$PdH_{0.6}$	71.0
$TiCr_{0.5}V_{0.5}H_2$	8.0
$LiBH_4$	2.4

5.3.3. Innovative High Thermal Conductive Structures

The layout of the heat transfer structure inside the metal hydride layer determines the way in which the high thermal conductivity structure is implemented. The utilization of copper mesh with high porosity (approximately 91%), significant surface area (6882 m^2-m^{-3}), and strong thermal conductivity (389 $Wm^{-1}K^{-1}$) is the focus of the current work [117]. When the amount injected is kept to a minimum, copper mesh does not react with hydride powder, and the hydrogen storage density of the metal hydride hydrogen tank is not greatly affected [118]. To improve powder contact and transform powder–powder contact into powder–copper wire–powder contact, a great number of pores in the powder bed are used as a matrix. In some cases, the powder is encased and crushed within a copper mesh framework. Nagel et al. [117] investigated the thermal conductivity of the $MmNi_{4.46}Al_{0.54}$ powder bed of 0.3–0.4 $Wm^{-1}K^{-1}$with copper wire matrix under a vacuum. In comparison to a bed of pure hydride powder, this hydride bed's effective thermal conductivity was improved by the copper wire matrix's presence by 0.4 $Wm^{-1}K^{-1}$. By combining aerating $LaNi_5$ with high thermal conductivity Al foam, Laurencelle et al. [119] showed that the hydrogen absorption process' difference in hydrogen content at various positions in the hydride bed could be significantly reduced. Additionally, the hydride bed could be expanded from less than 8 mm to 60 mm, and the hydrogen charging could be finished very quickly (15 min). The duration for the hydride bed's peak temperature was lowered from 90 min to 60 min when Romanov et al. [115] introduced $La_{0.9}Ce_{0.1}Ni_5$ to the copper foam matrix and heated the specimen from room temperature to 333 K. Kim et al. [120] used a copper mesh structure to construct a packed bed of La(Ce)Ni_5 powder that required 4.3% of the container's volume. The hydrogen charging experiment proved that a hydride bed with a copper mesh structure could be charged in 73.5% less time.

5.3.4. Other Non-Conventional Methods

Recent advancements in the design of metal hydride reactors include the use of phase-changing materials, heat pipes, and microchannel reactors (PCM). Heat pipes and PCM have been shown to increase system efficiency, albeit each component's performance may differ. The work by Frde et al. [121], in which a U-shaped copper tube with fins was used to improve heat transmission in a system integrated with a PEM fuel cell, is one illustration of the usage of heat pipes in a metal hydride system. The desorption of hydrogen at approximately room temperatures was facilitated by the waste heat from the fuel cell, potentially increasing system efficiency. Another study by Chung et al. [122,123]

also reported that the use of heat pipes led to a 50% improvement in the absorption and desorption behavior of the hydride, making heat pipes a suitable choice due to the small size of the system. Tetuko et al. [124] created a passive system in which a 500 W PEM fuel cell was coupled with a metal hydride reactor using heat pipes. The system employed five metal hydride reactors, each with a diameter of 75 mm and a length of 380 mm, and five heat pipes that were used to remove 880 W to achieve a hydrogen release rate of 2.5 SLPM. It is critical to remember that while this method is effective for absorbing hydrogen, a different heat extraction procedure would be necessary. In a different study by Meng et al. [125], a micro channel heat exchanger was utilized in a rectangular metal hydride tank, and it was shown that the center-to-center distance between the fluid channels significantly affected the heat transfer. The presence of channels that were dispersed evenly led to a more homogenous response front. Mudawwar and Visaria had also patented a metal hydride tank design with a modular heat exchanger that featured microchannel heat exchangers in each of the modules as well as a coiled tube to cool the entire system [126].

Several studies have been conducted on the use of phase-changing materials (PCM) to improve heat transfer in metal hydride systems. Despite the low gravimetric capacity of the PCM alloy due to its weight, Garrier et al.'s [127] use of PCM in a large-scale MgH_2 tank demonstrated that it was still a viable option for stationary applications at massive scales. Darzi et al. [128] evaluated the use of a Rubitherm PCM jacket with a radius of 70 mm around a $LaNi_5$ tank with a radius of 40 mm. They observed that adding 0.6 porosity metal foam to the PCM jacket enhanced thermal conductivity and sped up heat transfer from the metal hydride tank. Additionally, they determined that adding aluminum foam to the PCM jacket significantly reduced the amount of time needed to complete a full charge by 28%. In a metal hydride system with a PCM jacket, Ben Maad et al. [129] focused on the effects of thermal conductivity and melting enthalpy on system performance. They discovered that increasing the thermal conductivity of PCM up to 5 $Wm^{-1}K^{-1}$ significantly increased the hydrogen absorption rate but increasing it beyond this point had no appreciable effect.

5.4. Performance Comparison and Selection

From the different heat transfer methods described in Section 5, the thermal performances are compared between the heat transfer techniques. This study was carried out by evaluating the time elapsed for hydrogen absorption based on three different parameters: the reactor characteristic length, mass of the metal hydride in the reactor, and the amount of hydrogen stored. The characteristic length is defined as the closest distance between the centerline of the reactor and the inner surface of the reactor. For example, in the case of long cylinders, the characteristic length is the inner radius. In the case of a rectangular reactor, the characteristic length would be half of the shortest reactor dimension. Comparison for different heat exchange methods was conducted at 90% reaction time. This method provides a standardized way of characterizing the different cooling methods being investigated. The relative times used for each of these parameters are as follows:

$$\text{Time relative to the characteristic length}: \ tL_c^{-2}$$
$$\text{Time relative to the mass of the metal hydride}: \ tm_{MH}^{-2/3}$$
$$\text{Time relative to the mass of the hydrogen stored}: \ tm_{H2}^{-2/3}$$

where t, L_c, m_{MH}, and m_{H2} are the hydrogen absorption time, the characteristic length of the reactor, the mass of metal hydride, and the mass of the hydrogen, respectively. The characteristic time for cooling or heating of a solid body is $t_c = L_c^2/\alpha$, where α is the thermal diffusivity. When the time elapsed until 90% reaction completion is divided by the characteristic length squared, the quantity characterizes the cooling time compared to the reactor size. This idea can be extended to the relative cooling time to the mass of the metal hydride and to the mass of the hydrogen stored. Since both the mass of metal hydride (m_{MH}) and the mass of the hydrogen stored in it (m_{H2}) must increase as L_c^3, the mass-based cooling time can be defined as shown above.

For the selection of research papers that were studied for this cooling time analysis, it is observed that the most prominent cooling methods included the use of multiple embedded cooling tubes [70,71,86,88,91,92], single cooling tube configurations [51,89,110], external cooling fluids/jackets [75,76], and phase change materials [73,74,116]. Many of these methods being investigated also implemented and compared the effectiveness of different fin geometries. There were also a few other less common methods investigated, such as physical mixing of the reactor [114] and use of aluminum foam externally [119]. One of the more commonly seen technologies was the use of multiple embedded cooling tubes. For the comparison of characteristic length, the values of tL_c^{-2} ranged from 0.01 to 0.09 s·mm^{-2}. For the mass of the metal hydride in the reactor, the time relative the mass of metal hydride $tm_{MH}^{-2/3}$ ranged from 0.25 to 3.49 s·g$^{-2/3}$. The last range of $tm_{H2}^{-2/3}$ determined, corresponding to the amount of hydrogen stored, was 6.96–68.4 s·g$^{-2/3}$. For reactors using external cooling methods, all three parameters showed a higher value, and higher range of values. For tL_c^{-2}, the values ranged from 0.2 to 0.93 s·g$^{-2/3}$. When observing the metal hydride and hydrogen stored, the values ranged from 1.5 to 7.54 s·g$^{-2/3}$ for $tm_{MH}^{-2/3}$ and 27.13 to 155 s·g$^{-2/3}$ for $tm_{H2}^{-2/3}$. The use of a singular internal cooling tube showed a range of 0.15–0.313 s·mm^{-2} for tL_c^{-2}, 20.0–60.6 s·g$^{-2/3}$ for $tm_{MH}^{-2/3}$, and 427–624 s·g$^{-2/3}$ for $tm_{H2}^{-2/3}$. The last to be analyzed was the use of phase change materials. These reactors displayed the highest ratios for each parameter, which included a range of 3.2–8.25 s·mm^{-2} for tL_c^{-2}, 32.56–83.78 s·g$^{-2/3}$ for $tm_{MH}^{-2/3}$, and 621–3099 s·g$^{-2/3}$ for $tm_{H2}^{-2/3}$. Figures 7 and 8 provide summaries of comparisons between tL_c^{-2} and the other two parameters. The blue squares represent the use of phase change materials, the red squares refer to reactors using multiple embedded cooling tubes, the green triangles refer to the use of a singular embedded cooling tube, and the black dots indicate the use of an external cooling jacket.

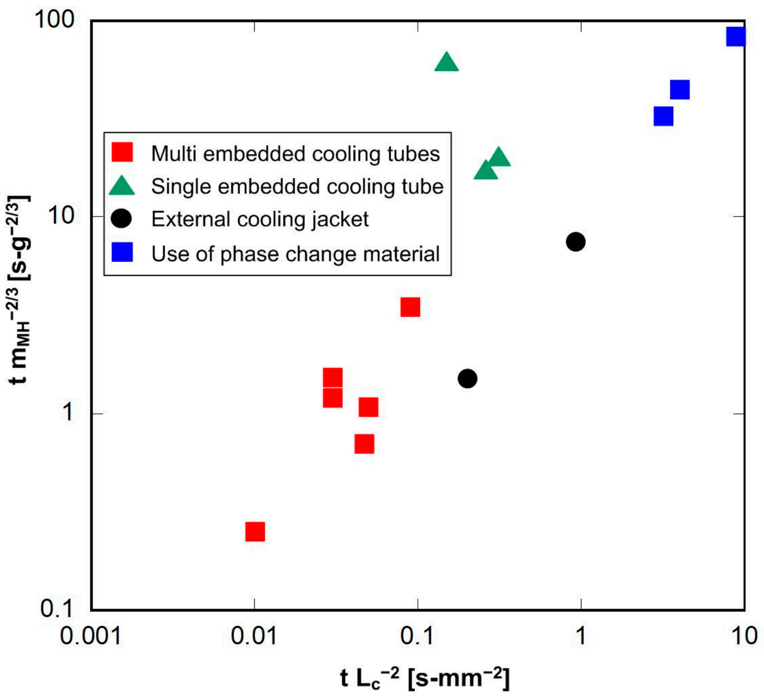

Figure 7. The metal hydride mass-based time vs. the characteristic length-based time.

From this analysis, it is determined that the use of multiple embedded cooling tubes generally causes a low reaction time, as well as a low ratio for each of the three parameters. Slightly higher values for this cooling analysis can be observed with the use of a singular internal cooling tube, or the use of an external fluid. Lastly, large time comparison values for each of the three parameters were detected when using phase change materials as the sole method of heat exchange. Although using a large amount of internal cooling tubes increases the reactor performance, there are other trade-offs to consider such as complexity and cost of manufacturing when compared to the other methods such as the use of an external water jacket. When looking at methods such as phase change materials, it is observed that they do improve heat transfer performance but are generally not as effective as other cooling methods as seen from their higher reaction time. It is also evident from this time-based cooling analysis that some reactor types can have a large range of values present. For example, when looking at the characteristic length parameter for the use of phase change materials, there are values ranging from 3.2 to 8.25 s·mm^{-2}. One of the main factors causing this range in values is that each reactor has different methods of enhancing the thermal conductivity of the PCM, such as copper [116] and aluminum [74] metal foam being mixed with phase change materials to help reaction time. These different enhancement methods provide a wide range of reaction times even though both reactors use phase change materials. Other smaller ranges of values can be caused for many reasons, such as different supply pressures, type of cooling fluid, and selection of different metal hydrides.

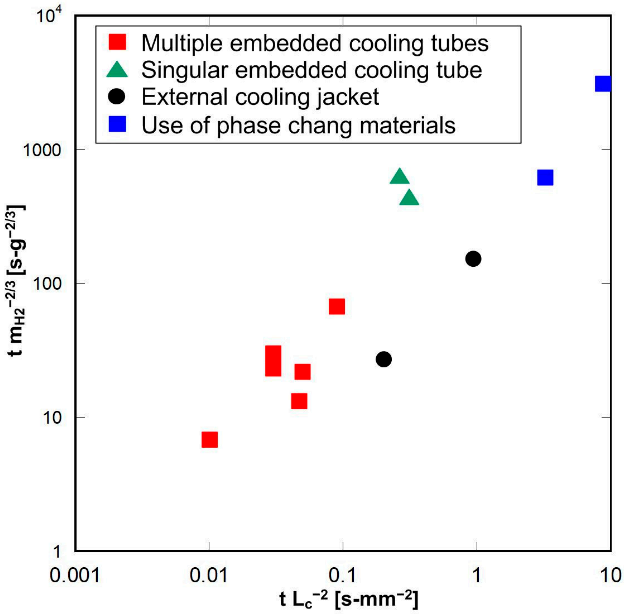

Figure 8. The stored hydrogen mass-based time vs. the characteristic length-based time.

6. Conclusions

Metal hydrides are a promising class of materials with a wide range of potential applications in hydrogen storage and chemical processing. The optimization of the reactor vessel shape and the improvement of heat transfer are key factors in the design and operation of metal hydride systems. The purpose of this review paper was to examine the various approaches to reactor shape optimization, including the use of spiral reactors and cyclone reactors, as well as to consider the various techniques and methods that have been developed to improve heat transfer in metal hydride systems, such as the use of heat exchangers, phase change materials, and porous media.

Several novel approaches to thermal management that have recently appeared were also considered, such as the integration of heat pipes, microchannels, and advanced materials such as graphene and carbon nanotubes and the use of nano fluids, PCM metal foams and PCM nano oxide additives. These innovative systems have shown promise in improving heat transfer and reducing temperature gradients in metal hydrides, which can lead to significant performance and safety improvements.

Overall, there is still significant room for improvement in the design and operation of metal hydride systems. Further research is needed to optimize reactor shapes and heat transfer approaches for specific metal hydrides and applications. In particular, the development of advanced modeling and simulation tools will be critical in predicting and optimizing the performance of metal hydride systems under different operating conditions. Additionally, it will be important to consider the practicality and scalability of different reactor designs and heat transfer methods, as well as the environmental and economic impacts of metal hydride systems. Their use as a hydrogen storage medium has the potential to contribute to the development of a cleaner, more sustainable energy system, but it is important to carefully evaluate the trade-offs and potential drawbacks of this technology.

In summary, the optimization of reactor shape and heat transfer is a critical area of research in the field of metal hydrides. Further studies are needed to fully understand the potential of this technology and to develop practical, efficient, and cost-effective metal hydride systems for a wide range of applications.

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