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A Study of Thermal Management Systems for Metal Hydride Hydrogen Storage

Chibuzo V. Ikwuagwu[1,*], Ikechukwu E. Okoh[2], Tobechukwu Okamkpa[3], Elochukwu Osuchukwu[4], Isaac Ibeh[5]

[1,3,4,5]Department of Mechanical Engineering, University of Nigeria, Nsukka, Enugu, Nigeria.
[1]Department of Mechanical Engineering, African Centre of Excellence for Sustainable Sower and Energy Development, University of Nigeria, Nsukka, Enugu, Nigeria.
[2]Department of Mechanical Engineering, Michigan Technological University, Houghton, Michigan, United States of America.
chibuzor.ikwuagwu@unn.edu.ng[1], iokoh@mtu.edu[2], tobe.okamkpa@unn.edu.ng[3], elo.osuchukwu@unn.edu.ng[4], isaac.ibe@unn.edu.ng[5]

Abstract: Hydrogen storage represents a critical component in the development of sustainable energy systems, with various methods being explored to address the challenges of storage capacity, safety, and efficiency. Among these methods, metal hydride hydrogen storage systems have emerged as promising candidates, offering high storage capacity at manageable pressures and temperatures. Essential for the optimal functioning and productivity of metal hydride systems is the efficient control of thermal transfer during the absorption and release of hydrogen. This paper presents a comprehensive review that begins by surveying different hydrogen storage methods before narrowing its focus to metal hydrides. Subsequently, the review delves into advancements in heat exchanger technology specifically tailored for metal hydride hydrogen storage. Optimising heat exchanger design parameters and employing systematic methodologies further contribute to improved heat transfer and absorption characteristics. This review underscores ongoing efforts to overcome hydrogen storage challenges and identifies promising avenues for future research and development, emphasising the integration of metal hydrides and advanced heat exchanger technologies.

Keywords: Metal Hydride Reactor; Heat Transfer; Thermal Management; Hydrogen Absorption; Hydrogen Storage; Thermal Conductivity; Heat Exchanger; Sustainable Energy Systems.

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1. Introduction

Hydrogen, a clean and abundant energy carrier, has gained popularity as part of the search for environmentally friendly and sustainable energy sources. Because of its high energy density and adaptability, it is an appealing option for a variety of

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[*] Corresponding author.

applications such as power generation, transportation, and industrial processes. Hydrogen is also used in the pharmaceutical industry and metallurgy for metal reduction and metalworking processes (using an oxyhydrogen flame) [1]. H2 is playing an important role as an energy transporter, storing surplus electrical power generated during off-peak hours. Furthermore, it is gaining popularity in the energy industry for both stationary and portable applications [2]. Nonetheless, a major impediment to its widespread implementation is the lack of effective and dependable storage methods. To address the barriers to widespread adoption of hydrogen as a renewable energy reservoir, a thorough understanding of potential storage approaches, as well as the level of integration of hydrogen into various energy applications, is required. Over the years, various storage methods have been explored in the industry to better store hydrogen, some of which are:

- **Compressed Gas Storage:** This entails pumping hydrogen into tanks under high pressure. This method has a moderate energy density, but the high-pressure requirement presents some challenges, such as limitations in the material used in tank construction and safety concerns in the event of a potential leak.
- **Liquid Hydrogen Storage:** Another method for storing hydrogen is to liquefy it at extremely low temperatures (down to -253°C). This approach provides high energy density, but cryogenic conditions must be combined with specialized storage infrastructure.
- **Solid-State Storage:** This refers to the storage of hydrogen in solid materials, which absorb and release the gas via reversible chemical reactions. Several techniques are used to store hydrogen. One method is metal hydrides, in which metal alloys absorb hydrogen at moderate temperatures and pressures. Chemical hydrogen storage involves using chemical compounds to store and release hydrogen through reversible chemical reactions. Additionally, carbon-based materials, including nanostructured materials such as carbon nanotubes and graphene, are being investigated for their potential in hydrogen adsorption and desorption.

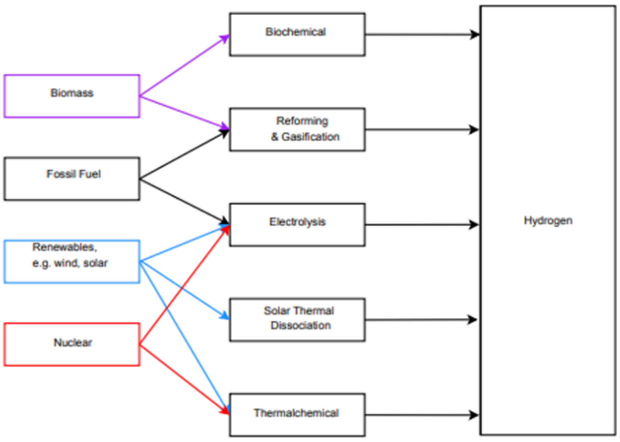


Figure 1: The route of hydrogen production [3]

There is currently a global shift toward renewable energy sources to combat CO_2 emissions, with an emphasis on their potential to mitigate environmental crises due to their low greenhouse gas emissions [4]. However, renewable energy relies on unpredictable natural resources, such as sunlight and wind, necessitating energy storage techniques to manage their intermittency. Worldwide research has made significant contributions to the development of efficient energy storage methods to meet rising energy demands. In the last decade, there has been a rapid development of hydrogen-related technologies ranging from hydrogen production using fossil fuels, biomass, and electricity generated from renewable power sources, to hydrogen storage in both pressurised gas and liquefied forms, and material-based methods, as well as associated hydrogen-powered electricity generation technologies. Figure 1 depicts four primary hydrogen production pathways: renewable, non-renewable, nuclear, and biomass.

2. Review of Literature

The storage of hydrogen is critical to the advancement of hydrogen and fuel cell technologies. There are two main approaches to hydrogen storage: material-dependent and physical-dependent systems. Given hydrogen's exceptionally low boiling point of -252.8°C, physical-based systems typically involve either storing hydrogen in a liquid state at cryogenic temperatures or as a gas, requiring high-pressure containers (ranging from 300 to 700 bar). Unlike fossil fuels, hydrogen is both sustainable and environmentally friendly; however, because of its lightweight and gaseous nature, it presents storage challenges. Hydrogen can be stored in a variety of physical and chemical methods, but because liquefaction requires extremely low temperatures, liquefied hydrogen and cryocompressed hydrogen may have a role in the future of the hydrogen economy. Physical adsorbents have low hydrogen capacities at room temperature, making hydrogen storage impractical [5].

Currently, no hydrogen storage material used exclusively meets all of the required properties, including storage capacity (4.5 wt%), reaction enthalpy (15-24 kJ/mol), kinetics (0.02 g H2/s), cycle life (410,000 cycles), and desorption temperature [6]. However, recent advances, such as the development of reactive hydride composites (RHC), nanoconfinement of hydrides using nanoscaffold materials, the synthesis of novel alkali-alkaline earth composite structures, and the creation of air-stable nanocomposite systems, have shown promise [7]. Despite their conceptual appeal, these materials have yet to address the challenges. Conventional storage systems face safety challenges, jeopardising the future of the hydrogen economy. Metal hydrides have the potential to safely store large amounts of hydrogen in a compact, reversible manner. Unfortunately, due to storage capacity limitations and unfavourable temperatures for hydrogen absorption/desorption, they no longer meet the requirements for practical application.

Chen et al. [8] developed a novel method for storing hydrogen alongside its production by ball milling NaBO2.2H2O or NaBO2.4H2O with MgH2 at room temperature and atmospheric pressure without any additional post-treatment. High yields of NaBH4 were obtained for NaBO2.2H2O (90.0%) and NaBO2.4H2O (88.3%), with hydrogen produced by the splitting of coordinated water in hydrated sodium metaborate. This created a cost-effective loop for producing and storing hydrogen. However, magnesium-based materials are among the most promising options for hydrogen storage due to their numerous properties, including high hydrogen storage capacity and environmental friendliness, even though they have limited thermodynamic and kinetic properties. These properties have recently been improved through modifications such as alloying, composites, and nano-crystallisation [9]. Catalysis has also led to advancements in this area, but hydrogen storage in light-metal-based materials is still far from meeting the needs of practical applications.

Furthermore, additives have been observed to accelerate the dehydriding kinetics of magnesium, with palladium-carbon nanotubes (Pd/CNT) additives superior to micron-sized palladium on activated carbon (Pd/AC). The electrochemical method claims to be the best method of storage because it generates and stores hydrogen in situ at normal pressure and temperature conditions. Various methods can be used to study hydrogen storage through electrochemical means, such as alloys, carbonaceous materials, carbo nano-ions, carbon nanofibers, and carbon nanotubes. On the other hand, research has revealed the potential of porous carbon (PC) nanostructures derived from bituminous coal as an adsorbent for hydrogen storage. X-ray diffraction, Fourier transforms, and infrared spectroscopy were used to identify the PC's well-defined structure and high ultramicroporosity.

As a result, it demonstrated remarkable discharge capacity, corresponding to a hydrogen storage capacity of 11.6wt% at ambient temperature. Furthermore, underground hydrogen storage (UHS) in salt caverns has been proposed as a strategy for peak shaving in wind power. According to research, viable and cost-effective solutions for implementing large-scale UHS in regions rich in renewable energy and salt resources may be feasible. Storage hybrids were created by utilising the hydrogen spillover mechanism. This includes the dissociation and chemisorption of H2 on the surface of layered double hydroxides (LDH), as well as the diffusion of H to reduced graphene oxide (rGO) in the presence of o and p-phenylenediamine polymers, which increases the hydrogen storage capacity.

2.1. Stationary and Mobile Hydrogen Storage Applications

Neither physical storage systems (compressed gas, liquid, and cryo-compressed techniques) nor material-based ones (adsorptive materials, metal hydrides, and chemical storage materials) can be considered the best fit for all stationary and automotive applications, implying that a set of complementary solutions offering several options is preferable. Of all commonly used fuels, hydrogen has the lowest energy density, necessitating storage in lightweight systems to accommodate vehicle weight limitations. Furthermore, energy efficiency must be considered, as variations occur during both regeneration and liberation processes. Notably, during hydrogen liberation, energy may be supplied by some of the released hydrogen, resulting in a significantly reduced storage capacity (Table 1).

Table 1: Desorption properties of selected reversible metal hydrides [10]

Hydride	Rev. Capacity (wt% %)	Heat of desorption (kJ/mol H_2)	Temperature for 1 bar (ºC)
Interstitial MH	1-2	~30(~12.4% of LHV)	Near room temperature
MgH_2	7.6	74.5(30.8% of LHV)	300
Mg_2NiH_4	3.6	64.5(26.7% of LHV)	255
$NaAlH_4$ (one step)	3.7	37(15.3% of LHV)	35
Na_3AlH_6	1.9	47(19.4% of LHV)	110
$NaAlH_4$ (two-step)	5.6	40(16.5% of LHV)	-

The ideal storage media for mobility applications should consider safe use, room temperature operation, and high gravimetric and volumetric energy densities.

2.2. Metal Hydrides for Hydrogen Storage

As previously stated, hydrogen can be stored in any of the three primary states of matter: gas, liquid, or solid. It is stored as a compressed gas in pressurised containers or as a liquid in cryogenic tanks. These two methods of storing hydrogen have problems because of the very high pressure (over 700bar) required to compress the hydrogen to a gas in a powerful pressure vessel that can resist explosion, and the high cost and energy involved in liquifying hydrogen (hydrogen liquifies at about 20K). A highly effective method of hydrogen storage is to store it in a solid form, such as in a metal hydride. This occurs in two steps: physical absorption and chemical absorption. During physical absorption, hydrogen molecules (H2) separate into single atoms (H-). The metal's surface absorbs these single atoms. Chemical absorption occurs when smaller hydrogen atoms react with metal to form metal hydride compounds at high pressure and low temperature. The smaller hydrogen atoms are incorporated into the metal's crystal structure, effectively filling the gaps between the larger metal atoms.

2.3. History of Metal Hydride for Hydrogen Storage

Thomas Graham immersed a zinc plate in dilute sulfuric acid, causing hydrogen gas to be released from the zinc plate's surface. However, no occlusion occurred. But then, using a thin palladium plate immersed in sulphuric acid and brought into contact with the zinc plate, the palladium became charged with hydrogen, which was then transferred to its surface. Graham found that the palladium absorbed 173 times its volume of hydrogen in an hour at 12°C. He then washed and dried the palladium plate before placing it in an exhausted glass tube. After two months, the glass tube was opened, and no hydrogen was found to have evaporated from the palladium at the cold temperature of 12°C. However, when palladium was heated to temperatures above 100°C, hydrogen was released from the metal. Thomas Graham's experiment established the basis for metal hydride hydrogen storage [11].

2.4. Improvements on Metal Hydride for Hydrogen Storage

When using metal hydrides to store hydrogen gas, it is critical to consider several key material properties. These include the connection between pressure and temperature (pressure-temperature relationship) for reversible hydride creation, the ability to effectively store hydrogen, the speed (kinetics) of both storing and releasing hydrogen, the longevity of the storage material, and the chemical stability of the material whether hydrided or dehydrided. Years of research into hydrogen storage in a solid state have been focused on identifying materials with these properties, as the absence of any of these properties reduces the material's efficiency. Various metal hydrides are used for reversible solid-state hydrogen storage. They include magnesium alloys, intermetallic compounds, and complex hydrides.

2.5. Magnesium-based alloys and intermetallic compounds

They are employed in hydrogen storage systems because of their capability to absorb and release hydrogen gas at low pressures and temperatures. This characteristic renders them well-suited for applications in fuel cells and various other hydrogen-based technologies. When hydrogen reacts with intermetallic compounds, it forms solid solutions, either crystalline or amorphous, of hydrogen within the compounds or in the resulting hydrides. They are used in hydrogen storage systems because they can absorb and release hydrogen gas under low pressures and temperatures. This characteristic makes them ideal for use in fuel cells and other hydrogen-based technologies. When hydrogen reacts with intermetallic compounds, it forms solid hydrogen solutions within the compounds or the resulting hydrides, which can be crystalline or amorphous. These compounds produce intermetallic hydrides. Magnesium alloyed with lanthanum and nickel (Mg-Li-Ni) has been shown to absorb over 7% mass of hydrogen and desorb up to 6% mass of hydrogen with no activation required. In a separate experiment, it was discovered that the onset temperature for hydrogen absorption decreased as the iron content in magnesium-iron alloys increased and the nickel content increased in magnesium-nickel alloys. An investigation into the hydrogenation of the ternary nitride, LiMgN, discovered that doping the nitride with Titanium(iii)chloride resulted in the storage of 8.0wt% hydrogen.

Titanium hydride, titanium oxide, and niobium oxide were used as catalysts at the same time to change the activation energy and kinetic properties of MgH2. As a result, the rate of hydrogen absorption and desorption increased, while the activation energy and operating temperature decreased. A study investigating the impact of Ni-based additives on the dehydrogenation process of MgH2 revealed that these catalysts led to a 50% reduction in activation energy and decreased the decomposition temperature of magnesium hydride by up to 27°C. Similarly, Nickel (Ni) nanoparticles were used to improve the reversible dehydrogenation of the 2LiBH4+MgH2 system. The study found that a small amount of Ni significantly promoted the decomposition of MgH2, whereas a large amount of Ni was required to decompose LiBH4. Mg-Li-Al alloy, produced through ingot casting and reactive ball milling, was used to store hydrogen gas. The resulting complex hydride had a storage capacity of 10wt% hydrogen and a desorption temperature of 65°C.

A study of nanostructured composite materials - Mg-Ni, Mg-Ni-La, Mg-Ni-Ce, and Mg-LaNi5 - found that these magnesium-based materials have accelerated hydrogenation kinetics at low temperatures, but require a high temperature for dehydrogenation. Ti0.47V0.46Mn and Ti0.50V0.51Mn alloys were created through arc melting. At 120 bar of H2 and 303K, the alloys' hydrogen sorption capacities were 1.53 and 1.56 wt% hydrogen. A study on magnesium processing techniques for hydrogen storage assessed the storage capacity of both mechanised and manually filed magnesium chips. The chips demonstrated faster hydrogenation and dehydrogenation kinetics. However, it was discovered that the mechanised chips had a slight delay before hydrogen absorption. To improve the low-temperature dehydrogenation of MgH2, palladium (Pd) and nickel (Ni) nanoparticles were added to magnesium hydride. This composite material had a desorption temperature that was 150K lower than pure MgH2. With the addition of copper (Cu) and cobalt (Co), Mg2Ni improved its hydrogen storage properties. Adding more copper or cobalt improved the alloy's storage capacity.

2.6. Complex Hydrides

Traditional metal hydrides are primarily composed of heavy metal elements, resulting in low gravimetric hydrogen storage capacities. Meanwhile, complex hydrides are composed of lighter elements such as lithium (Li), aluminium (Al), and sodium (Na), resulting in high hydrogen storage capacities, densities, and low dehydrogenation pressures and temperatures. These light elements have notably high energy densities, but they are difficult to manage in terms of safety and stability. Despite its theoretical capacity to store approximately 7.9wt% of hydrogen, the storage of hydrogen in Lithium aluminohydride or lithium alanate (LiAlH4) is rarely used due to the high cost of lithium and the difficulty of extracting the stored hydrogen. Ball-milling with titanium compounds during a doping procedure can release some of the stored hydrogen. Zang et al. [12] investigated the dehydrogenation behaviour of $LiAlH_4$, and TiF3 was used as a catalyst. As a result, the lithium alanate sample began releasing hydrogen at 35°C, with the peak dehydrogenation rate occurring at approximately 108°C, as opposed to the pristine alanate's initial and peak temperatures of 145°C and 179.9°C, respectively.

Sodium alanate ($NaAlH_4$) is a complex hydride that has reversible storage applications. In theory, sodium alanate can reversibly store up to 5.5wt% hydrogen. However, practical reports show a storage capacity of 5 wt%. A team of researchers from the Institute of Technology, Kjeller, Norway studied NaAlH4 and Na3AlH4. Mechanical grinding and chemical modification of both alloys resulted in a storage capacity of 3.0wt% for NaAlH4 at temperatures ranging from 80°C to 140°C, while Na3AlH4 had a maximum storage capacity of 5wt% between 150 and 180°C. Another complex hydride is lithium borohydride (LiBH4). It is a high-capacity complex hydride designed for solid-state hydrogen storage applications, capable of storing up to 18.5 wt%. However, the LiBH4 structure's strong and highly directional covalent and ionic bonds result in high desorption temperatures, slow kinetics, and low reversibility. This makes large-scale use of lithium borohydride impractical. In an attempt to modify lithium borohydride for hydrogen storage, metal oxides and chlorides were added. When TiO2 was used, 9wt% hydrogen was desorbed from LiBH4 between 100°C and 600°C, while 8wt% hydrogen was absorbed at 600°C and 70 bar of hydrogen. A new coupled system of lithium borohydride and calcium hydride (LiBH4/CaH2) designed for hydrogen storage had a storage capacity of more than 11wt%. The reaction is thus:

$$6LiBH_4 + CaH_2 \leftrightarrow 6LiH + CaB_6 + 10H_2$$

In practice, 9wt% of hydrogen was stored with TiCl3 as a catalyst. Zivar et al. [2] created a new type of complex hydride by ball milling lithium borohydride (LiBH4) and urea (CO(NH2)2) in a 1:1 molar ratio, yielding LiBH4•CO(NH2)2. The dehydrogenation properties of the product were investigated. LiBH4•CO(NH2)2 produced up to 8wt% hydrogen at temperatures below 250°C.

3. Heat Exchangers for Metal Hydride Hydrogen Storage

Heat exchangers play an important role in regulating temperature fluctuations during hydrogen absorption and desorption. Recent research efforts have focused on designing, optimising, and evaluating various heat exchangers to improve the efficiency and efficacy of metal hydride reactors. This section provides a comprehensive overview of recent research focusing on heat exchangers within hydrogen storage systems using metal hydrides.

3.1. Heat Exchangers Designs and Configurations for Hydrogen Storage in Metal Hydrides

To manage their thermal requirements, metal hydride hydrogen storage systems require efficient heat exchanger design. Proposed a methodical approach to heat exchanger construction that ensures compactness and manufacturability while meeting demanding fill-time criteria. They met the strict weight, volume, and manufacturability requirements while dealing with the enormous challenge of dispersing the massive amounts of heat generated by the exothermic reaction of hydrogen with metal hydride. Following a series of engineering decisions aided by computational modeling, they completed a design for the heat exchanger, as shown in Figure 2. This design successfully meets the critical 5-minute fill time requirement for refueling 5 kg of hydrogen, demonstrating the feasibility of using high-pressure metal hydrides (HPMHs) in compact and lightweight hydrogen storage systems. Tiwari and Sharma [13] conducted an experimental study to assess the efficiency of a spiral heat exchanger integrated into a metal-hydride reactor. The findings show that higher values of the heat transfer coefficient (achieved through increased water flow) result in shorter absorption durations but have no discernible effect on hydrogen storage capacity.

Furthermore, the scientists demonstrated how using a heat exchanger significantly reduces the reactor's charge and discharge times. The study also looked at how several parameters affected reactor performance, such as hydrogen tank volume, applied pressure, and cooling fluid mass and temperature. Visaria and Mudawar [16] investigated the effectiveness of a coiled-tube heat exchanger in a high-pressure metal hydride (HPMH) hydrogen storage system [14]. The primary goal was to investigate how different heat exchanger designs performed in terms of maximising hydrogen storage capacity while maintaining realistic fill times. The study discovered that a coiled-tube heat exchanger can effectively remove significant amounts of heat generated during the hydriding reaction (Figure 2). The findings showed that using a cooling tube embedded in the powder inside the storage vessel resulted in effective cooling during the hydriding process and heating during the dehydriding reaction of the surrounding hydride powder.

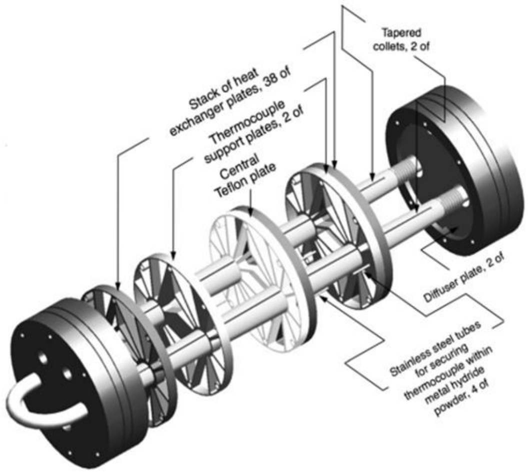


Figure 2: Three-dimensional depiction of heat exchanger assembly [14]

Singh et al. [15] used a combination of experimental and numerical simulation studies to show that heat exchanger design has a significant influence on the absorption rate and temperature evolution of a metal hydride MH bed. The findings revealed that the number and arrangement of fins have a significant impact on heat transfer and, as a result, absorption properties. Furthermore, the study found that the hydrogen supply pressure has a significant influence on the absorption process, with higher pressures resulting in faster absorption rates and temperature convergence with the cooling fluid (Figure 3).

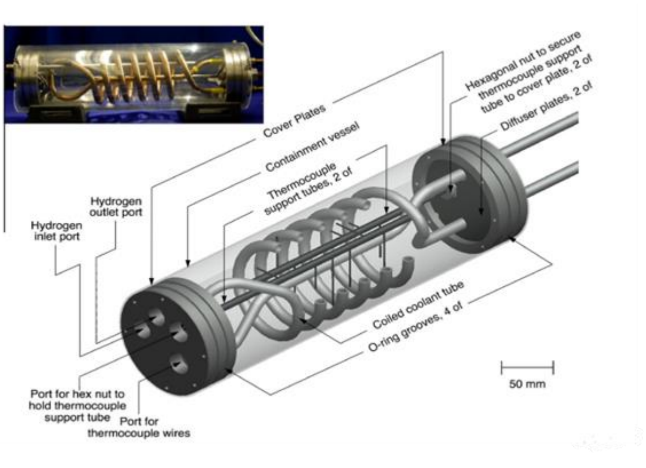
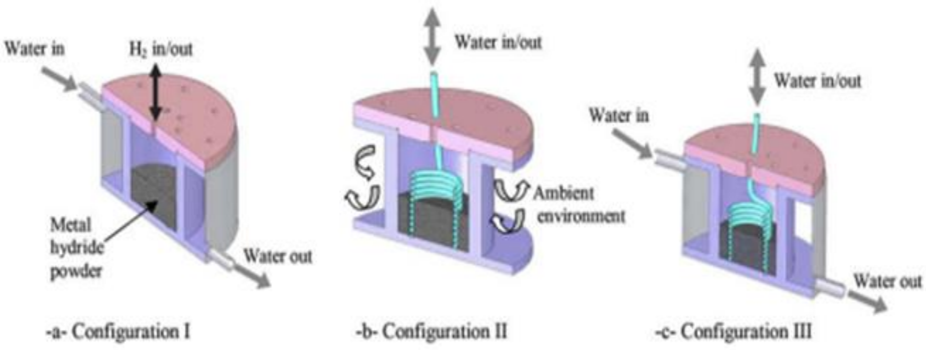


Figure 3: 3-D illustration of containment vessel/heat exchanger assembly [16]

Kikkinides [17] discovered that minimising temperature variations within the bed increases the hydrogenation rate. They investigated a concentric tube heat exchanger and a concentric annular ring heat exchanger, assuming equal temperatures for the solid and fluid phases of the bed. The results revealed a slight improvement with the tube heat exchanger, but a significant improvement with the annular ring setup, which reduced 99% storage time by 60%. They determined that the best position for the annular ring was halfway between the centre and the wall. Placing it closer to the outer surface accelerated uptake, resulting in approximately 90% storage. The study presented the problem as a dynamic optimisation task, with control variables such as cooling fluid flow rate, temperature, and hydrogen charging profile. Heat exchangers are essential for improving absorption and desorption processes. They suggested three combinations:

- A reactor composed of two concentric cylinders, the outer one facilitating coolant flow and the inner one containing metal hydride
- The incorporation of a spiral heat exchanger within the reactor, in addition to free convection cooling by ambient air.
- A combination of the first two configurations (Figure 4).

According to their testing, configuration 3 performed 70% better than configuration 1. This was attributed to the specialised heat exchangers' ability to accelerate heat transfer to and from the hydride bed. Faster reaction kinetics were associated with the spiral exchanger's placement near the domain's centre and evenly spaced from its edges [18]. Furthermore, studies on commercial metal hydride heat exchangers reveal operating characteristics and absorption kinetics, which inform design decisions for practical applications [19].



-a- Configuration I -b- Configuration II -c- Configuration III

Figure 4: Metal-Hydrogen storage vessels with different heat exchanger configurations [18]

Souahlia et al. [20] conducted an experimental study using a finned spiral heat exchanger in a stainless steel 316-L test reactor. They examined the impact of the cooling system's shape and operational parameters on the metal hydride reactor's performance. To provide context, the study also included trials on a basic reactor. Their findings revealed that installing a spiral heat exchanger resulted in a significant decrease in hydriding time. The debate emphasised the importance of variables such as hydrogen tank volume, applied pressure, cooling fluid mass flow, and temperature in determining reactor performance.

3.2. Optimisation of Heat Exchanger Designs

To improve storage density and thermal control in metal hydride hydrogen storage systems, heat exchanger designs must be optimised. Raju and Kumar [21] used computational fluid dynamics to optimise heat exchanger designs for metal hydride-based hydrogen storage systems. Three different heat exchanger designs were showcased: a helical coil heat exchanger, a straight parallel tube heat exchanger joined by aluminium fins, and a shell and tube heat exchanger with aluminium in the shell. Each design's performance was evaluated based on the amount of hydrogen stored during a 10.5-minute refuelling period, which was standardised for the bed's weight and volume. When compared to other designs, the helical coil heat exchanger had higher gravimetric and volumetric densities. The excellent heat transfer coefficients and adherence to the standard length of metal hydride heat exchangers were cited as reasons for this.

The study provided useful information for future design considerations, emphasising the importance of improving heat exchanger designs to achieve high storage densities and effective thermal control for vehicle hydrogen storage systems. Garrison et al. [22] presented an in-depth analysis of the optimisation of metal hydride-based internal heat exchangers for hydrogen storage tanks. To maximize the amount of hydrogen stored inside the hydride, the scientists developed unit cell models that consider heat transport and reaction kinetic constraints while optimizing designs for both transverse and longitudinal fins (Figure 5). According to the findings, the ideal longitudinal fin design is 20 mm in length, 1.5 mm spacing, and 0.5 mm thickness. Similarly, the ideal transverse fin design is 10 mm long, 1.5 mm wide, and 20 mm thick. These designs are adaptable to different hydrogen feed conditions and pressure levels, making them useful for a wide range of hydrogen storage applications.

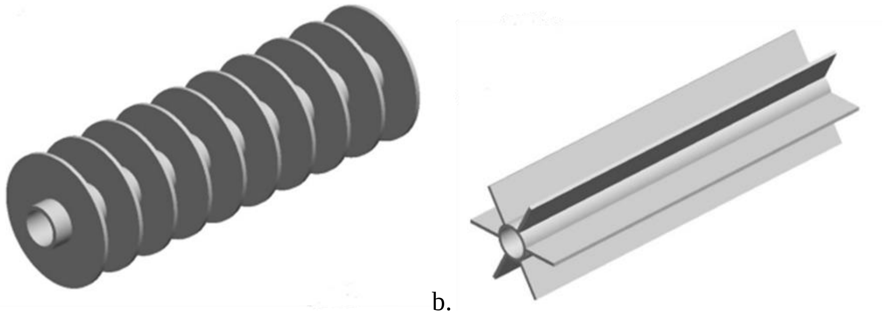
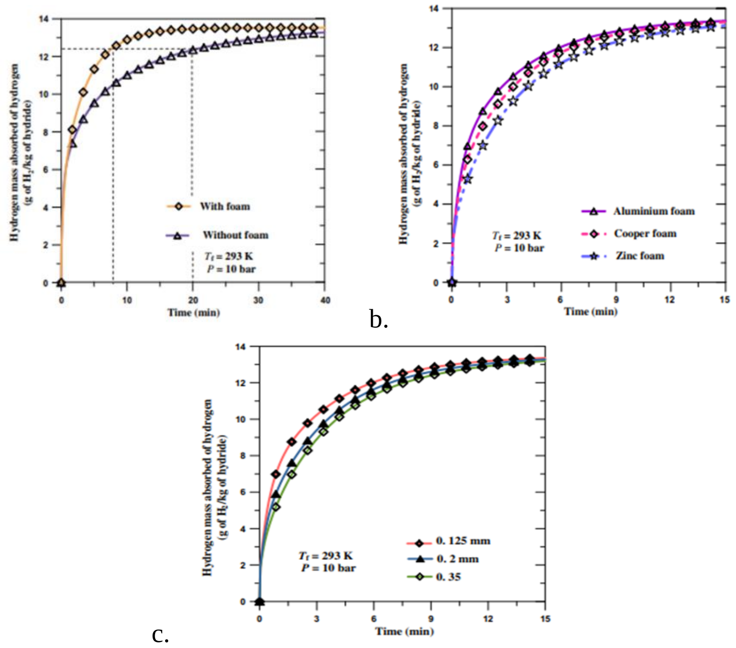

a. b.

Figure 5: Heat exchanger designs: (a) transverse cooling fins; (b) longitudinal cooling fins [22]

Nyamsi et al. [23] optimised finned heat exchangers to increase heat transfer and reactor volume efficiency. The study looked at the heat exchanger's analytical approach and numerical simulation, with an emphasis on improving heat transfer and optimising vessel volume efficiency. The technological challenge of heat control is investigated, as well as the possibility of using metal hydrides to store hydrogen. The study also investigated the effect of fin size on heat exchanger performance and developed a semi-analytical formulation for the heat transfer rate from a single fin. The findings showed that, while larger fins can increase hydrogen charging and discharging rates, they can also reduce total hydrogen capacity in terms of volume and gravimetric measurements. They concluded that reducing the fin thickness and increasing its radius could improve the heat exchanger's thermal conduction.

Abdin et al. [24] developed a one-dimensional mathematical model to evaluate transient heat and mass transfer in a metal hydride tank (MHT) with a metal foam heat exchanger. The model's validity was tested by comparing the numerical results to the experimental data. The MHT's charging process was evaluated concerning several geometric and operational factors of the metal foam. The results show that using metal foam extends the MHT's hydrogen storage period while increasing heat transmission. Figure 6 depicts the effects of the base material and metal foam exchanger on storage duration, as well as the impact of pore size on total hydrogen storage. When a concentric tube heat exchanger was added to the hydride bed with aluminium foam instead of the standard container without metal foam, the storage process improved by 75%.



a. b.
c.

Figure 6: Effect of (a) metal foam exchanger on the storage time, (b) base material on the storage time, and (c) pore size on total h2 mass stored [25]

4. Conclusion

This paper provides a comprehensive review of hydrogen storage methods, with a focus on metal hydrides and advances in heat exchanger technology specifically designed for metal hydride hydrogen storage. Several hydrogen storage methods have been investigated, each with advantages and disadvantages. Recent advances in hydrogen storage technologies, such as reactive hydride composites, nanoconfinement strategies, and novel composite structures, indicate promising areas for improvement. Metal hydrides, using physical and chemical absorption processes, offer a promising solution that surpasses the limitations of traditional methods. Significant advances have been made in understanding metal hydride properties, particularly in magnesium-based alloys and intermetallic compounds. Investigations into alloy compositions and catalyst doping have revealed improved storage capacities and kinetics, whereas complex hydrides composed of light elements have high storage capacities and low dehydrogenation pressures.

The discussion includes advancements in heat exchanger technology, which is critical for controlling temperature variations during hydrogen absorption and desorption processes in metal hydrides. Various heat exchanger configurations, including spiral and coiled-tube heat exchangers, have been shown to improve reactor efficiency by shortening absorption times and effectively managing heat release. Optimising heat exchanger design parameters, such as fin configurations and cooling fluid flow rates, can result in better heat transfer and absorption. Furthermore, the use of novel materials such as metal foam promises improved heat transfer in metal hydride tanks. Systematic methodologies have been proposed to address the challenge of dissipating heat generated during hydrogen-metal hydride reactions, resulting in designs that meet stringent fill-time requirements for hydrogen refuelling.

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Ethics and Consent Statement: This research was conducted in accordance with established ethical standards. Informed consent was obtained, and participant confidentiality was maintained throughout the study.

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