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Hydrogen Compression without Moving Parts: A Comprehensive Review of Metal Hydride Compressor Technologies

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Abstract- The transition toward a Hydrogen based energy economy requires safe, efficient and reliable hydrogen compression technologies. Conventional mechanical compressors have limitations like moving parts leading to noise and vibration. They also have gas contamination risks and require high maintenance which makes them less efficient. Metal hydride compressors (MHCs) have emerged as a promising alternative due to solid-state operation, absence of moving components and high operational safety. These compressors operate on the principle of reversible hydrogen absorption and desorption by metal hydrides which enables efficient compression by controlling temperature variations. This article represents a comprehensive analysis of MHC technologies and review the fundamental principles, thermodynamics, material selection and system configurations. Key challenges like heat management, material degradation and kinetics are critically discussed. Integration with renewable energy sources and potential industrial applications are shown to identify future research directions for large-scale deployment in hydrogen infrastructure.

Keywords— Metal hydride compressor; Hydrogen compression; Solid-state hydrogen technology; Thermal sorption; Renewable energy integration; Hydrogen infrastructure..

1. INTRODUCTION

The global energy sector, which is going through a major change caused by climate change mitigation targets and energy security concerns. Along with it, there is also a urgent need to decarbonise industrial and transportation systems. Hydrogen has become a key energy source due to its high gravimetric energy density, useful for many different things and potential for carbon-neutral utilization when it is produced from low-carbon sources [1]. Hydrogen is becoming a key solution for decarbonising hard-to-electrify sectors. Example of these sectors are: steel manufacturing, chemical processing, heavy-duty transport, and long-duration energy storage. These things lead to a rapid growth in global hydrogen demand and infrastructure requirements [2].

The biggest challenge for hydrogen is finding better ways to store and transport it. Hydrogen must be compressed to high pressures because it has property of owing extremely low volumetric energy density at ambient conditions, which is typically in the range of 350–700 bar for practical storage, transport and refuelling applications [3]. Hydrogen compression therefore plays a critical role in the hydrogen value chain, directly affecting energy efficiency, operational safety, and system cost. Conventional mechanical compressors are although technologically mature but suffer from drawbacks such as moving parts, noise, vibration, lubrication-related contamination and high maintenance requirements, which limit their long-term reliability and economic viability [4].

Metal hydride compressors (MHCs) have emerged as a promising solid-state alternative to conventional hydrogen compression technologies. These systems operate through the reversible absorption and desorption of hydrogen in metal hydride alloys under controlled temperature variations, enabling compression without moving mechanical components [5]. This operating principle significantly reduces noise and vibration, minimizes maintenance, enhances operational safety, and delivers hydrogen of very high purity. Metal hydride compressors are also capable of utilizing low-grade thermal energy which is typically between 60 and 200 °C. This allows effective integration with industrial waste heat and renewable thermal energy sources [6].

Despite substantial progress in material development and compressor system design, several technical challenges

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continue to hinder large-scale deployment of metal hydride compressors. System performance is strongly influenced by hydride thermodynamics, reaction kinetics, heat and mass transfer limitations, material degradation during cyclic operation, and alloy cost [7]. Moreover, many existing studies address material behaviour or compressor design independently, with limited discussion on the integration of both perspectives at the system level. In this context, the present review aims to provide a consolidated and forward-looking assessment of metal hydride compressor technologies by integrating fundamental principles, material selection, system configurations, performance characteristics, and real-world demonstrations, thereby identifying key research gaps and future directions for hydrogen infrastructure development [8].

II. WORKING PRINCIPLE OF METAL HYDRIDE COMPRESSORS

Metal hydride compressors operate on the principle of reversible hydrogen absorption and desorption in metal hydride alloys, where temperature variation replaces mechanical motion as the driving force for compression [8]. During the absorption stage, hydrogen is absorbed exothermically by the metal alloy at relatively low pressure and temperature, forming a stable metal hydride phase. Upon heating, the equilibrium pressure of the hydride increases, and hydrogen is released endothermically at a higher pressure, enabling compression in a solid-state manner [9].

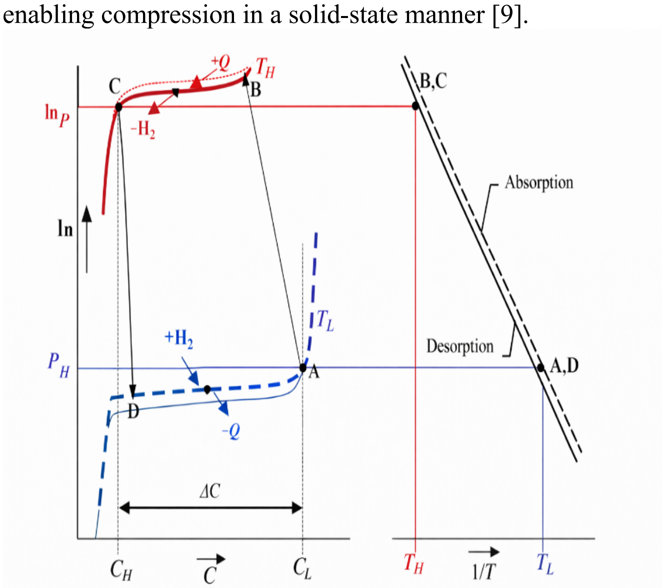

Fig. 1 Principle of operation of a single-stage metal hydride compressor illustrating the absorption–desorption cycle (adapted from [9] under creative common license).

This thermally driven pressure amplification is governed by the intrinsic thermodynamic properties of the metal–hydrogen system which allows precise control over operating conditions. Metal hydride compressors also do not require pistons, diaphragms or lubricants which significantly reduce mechanical complexity [5]. This shows operating principle inherently eliminates vibration, noise, and seal-related leakage issues, resulting in enhanced operational safety and reliability.

Early metal hydride compressors were primarily limited to low or moderate compression ratios due to restricted pressure ranges of available hydride materials. However, the development of cascaded hydride beds and multi-stage configurations has effectively addressed this limitation [10]. Modern systems are capable of achieving outlet pressures suitable for hydrogen refuelling and industrial storage applications by combining hydride materials with progressively higher equilibrium pressures.

The efficiency of this compression process is fundamentally rooted in the Van't Hoff relationship, which defines the exponential increase of desorption pressure with rising temperature [8].

Researchers can engineer "thermal compressors" that utilize low-grade waste heat as the primary energy source by strategically selecting alloys with specific thermodynamic stabilities. The hydrogen discharged from a low-pressure hydride bed is directed into a subsequent bed containing an alloy with a higher plateau pressure in a typical multi-stage configuration. This sequential transfer is coupled with synchronized heating and cooling cycles which allows the system to bridge the gap between ambient suction and high-density storage requirements. Consequently, the absence of moving parts not only ensures high gas purity—free from oil contamination—but also minimizes the Levelized Cost of Hydrogen (LCOH) by leveraging industrial thermal gradients instead of expensive electrical energy [11].

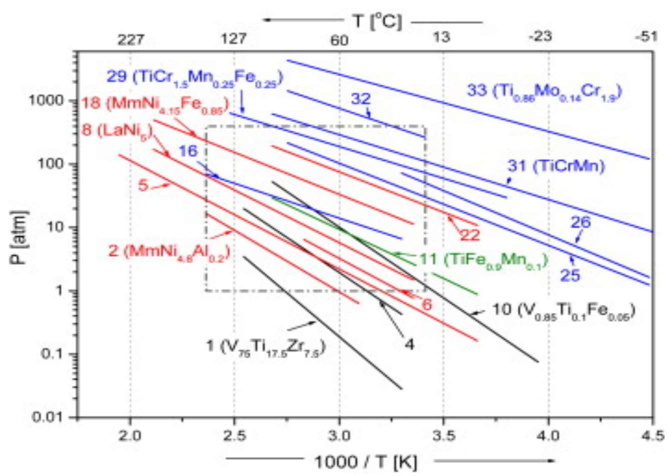

Fig. 2 Van't Hoff plots for selected hydride-forming alloys suitable for H_2 compression (adapted from [8] under creative common license.)

III. THERMODYNAMIC AND KINETIC CONSIDERATIONS

The thermodynamic behavior of metal hydride materials has a very important role in determining compressor performance. Pressure–composition–temperature (PCT) characteristics also define the equilibrium pressure levels achievable during absorption and desorption [8]. While

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parameters such as reaction enthalpy, entropy and hysteresis influence operating temperature windows and energy efficiency. Hydrides with flat plateau regions and low hysteresis are particularly desirable, as they ensure stable pressure output and reproducible performance during repeated thermal cycling [12].

The kinetic limitations often restrict hydrogen throughput and system productivity despite favourable thermodynamics. The slow absorption and desorption rates are frequently caused by inadequate heat transfer rather than intrinsic reaction kinetics [13]. Insufficient heat removal leads to localized temperature rise which reduces hydrogen uptake rates during absorption. While during desorption, inadequate heat supply slows hydrogen release.

The recent studies have focused on enhancing thermal management through improved heat exchanger integration, optimized bed geometry and increased thermal conductivity of hydride beds to overcome these challenges [14]. These strategies address a key research gap by coupling thermodynamic suitability with kinetic efficiency which enable higher cycle frequencies and improved overall compressor performance.

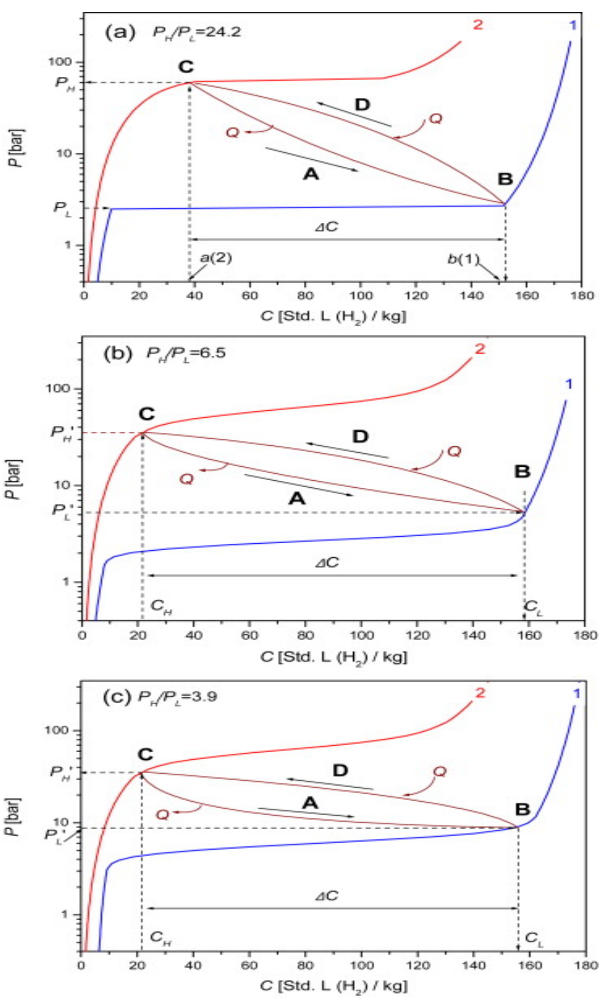

Fig. 3 Pressure–composition isotherms at T_L = 20 °C (1) and T_H = 150 °C (2) for H–$La_{0.85}Ce_{0.15}Ni_5$ system illustrating thermally driven hydrogen compression using metal hydrides: (a) idealised (flat plateaux), (b) idealised (sloping plateaux), and (c) real behaviour (adapted from [8] under creative common license)

Advanced material engineering focuses on the Effective Thermal Conductivity (ETC) of the hydride bed to reduce the gap between theoretical capacity and real-world hydrogen flux. Researchers are increasingly utilizing expanded natural graphite (ENG) matrices, aluminium foams, or internal longitudinal fins to facilitate rapid heat dissipation, since metal hydride powders naturally possess low thermal conductivity. These structural modifications ensure that the exothermic heat of absorption is quickly removed which prevents the system from reaching "plateau pressure" prematurely, which would otherwise halt the hydrogen intake. By optimizing the interstitial heat transfer coefficient within the reaction vessel, the cycle time can be significantly reduced which transform the compressor from a slow and batch-oriented process into a more continuous and high-throughput industrial solution. This synergy between material science and mechanical design is crucial for achieving the power densities required for modern hydrogen energy infrastructure [15].

IV. METAL HYDRIDE MATERIALS: CHALLENGES AND IMPROVEMENT STRATEGIES

Material selection remains a main challenge in the development of metal hydride compressors. AB_5-type alloys which are particularly $LaNi_5$-based systems are among the most widely studied materials, due to their moderate operating temperatures, stable thermodynamics and good reversibility. The elemental substitution within AB_5 alloys enables tuning of equilibrium pressure and improvement of cycling stability which make these materials suitable for low-to-medium pressure compression stages.

For higher pressure applications, A_2B_7-, AB_2-, and BCC-type alloys have attracted increasing attention due to their higher hydrogen storage capacities and pressure capabilities. BCC alloys based on Ti–V–Cr or Ti–V–Mn systems offer significant advantages in terms of hydrogen capacity. However, these materials often suffer from microstructural degradation, pulverization and gradual capacity loss during prolonged cycling, which limits long-term durability [16].

Material degradation addresses and represents a major research gap in metal hydride compressor technology. From recent mitigation strategies which include compositional optimization, microstructural refinement, surface coatings and alloy stabilization techniques are aimed at suppressing pulverization and preserving structural integrity [17]. These approaches provide practical pathways for extending operational lifetime while maintaining high compression performance.

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The focus is shifting toward surface functionalization and the creation of multi-phase alloy architectures to combat the "pulverization" effect. The hydride particles can be shielded from impurities in the hydrogen stream which significantly reduce chemical poisoning by applying thin-film coatings such as electroless nickel plating or fluorination. Furthermore, the introduction of secondary phases through rapid solidification techniques helps in pinning the grain boundaries which restricts the lattice expansion-contraction stress that typically leads to particle cracking [18]. These structural enhancements are combined with the substitution of rare-earth elements with more abundant transition metals which not only improve the mechanical robustness of the beds but also make the technology more economically viable for large-scale industrial deployment. This dual focus on metallurgical stability and surface protection is essential for transitioning metal hydride compressors from laboratory prototypes to reliable and long-term energy storage assets.

V. COMPRESSOR CONFIGURATIONS AND THERMAL MANAGEMENT

The configuration of metal hydride compressors strongly influences their achievable compression ratio and operational efficiency. Single-stage compressors are typically employed for moderate pressure amplification, whereas multi-stage systems utilize cascaded hydride beds operating at progressively higher temperature levels. The double-stage metal hydride compressors significantly enhance pressure amplification while maintaining stable operation [13].

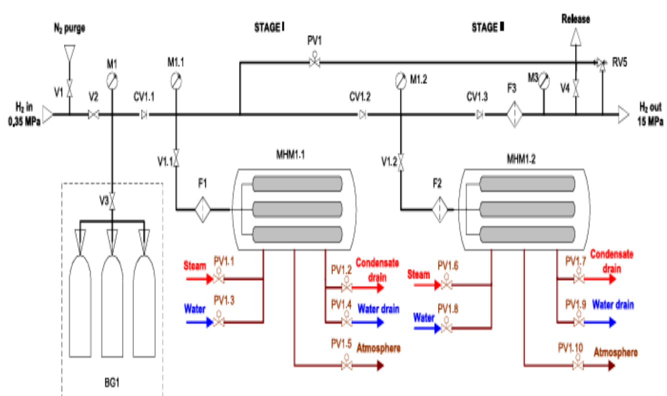

Fig. 4 Multi-stage (two-stage shown) metal hydride hydrogen compressor illustrating cascaded hydride beds and thermal management using steam heating and water cooling. Adapted from Tarasov et al. (2020) [19] under creative common license.

Thermal management is a critical design aspect, as efficient heat exchange is required during both absorption and desorption processes. The insufficient thermal coupling within hydride beds leads to reduce hydrogen throughput and unstable pressure output. To address this issue, modern compressor designs integrate internal heat exchangers, modular hydride beds, and optimized thermal pathways [20].

The ability of metal hydride compressors to utilize low-grade thermal energy represents a key advantage over mechanical systems. Integration with industrial waste heat, solar thermal sources, or heat pumps reduces electrical energy consumption and enhances overall system efficiency [21]. These system-level innovations directly address earlier efficiency gaps and support scalable deployment.

The optimization of the thermal duty cycle is increasingly dependent on the selection and flow dynamics of Heat Transfer Fluids (HTF). The sensible heat generated during the exothermic absorption phase can be partially recovered or redirected which minimize the external energy required for the subsequent desorption stage by implementing a "closed loop" thermal management system [22]. The advanced configurations now utilize phase-change materials (PCMs), integrated within the reactor jacket to buffer temperature swings which ensure that the hydride bed remains within its optimal plateau region for longer durations. The transition from simple jacketed vessels to shell-and-tube or plate-fin architectures has drastically increased the surface-to-volume ratio. This intensification of heat flux not only stabilizes the mass flow rate of hydrogen but also allows for faster switching frequencies between cycles which effectively increase the specific productivity of the compressor without increasing its physical footprint.

VI. CONCLUSIONS

This study has systematically examined metal hydride compressor technologies as a promising solid-state solution for hydrogen compression without moving parts. It is evident that metal hydride compressors address several critical limitations of conventional mechanical compressors which include noise, vibration, gas contamination and high maintenance demands by integrating fundamental working principles, thermodynamic behavior, material characteristics and system-level configurations. Thermally driven absorption–desorption cycles enable effective pressure amplification according to statistical data. This is particularly through multi-stage architectures while operation within moderate temperature ranges allows the utilization of low-grade thermal energy. Compressor performance however remains strongly dependent on heat and mass transfer efficiency, hydride reaction kinetics and long-term material stability during cyclic operation.

The evolution of metal hydride compressors is expected to be driven by advances in durable and cost-effective hydride materials, intelligent thermal management strategies and integrated system design from a futuristic perspective. With emerging approaches such as alloy microstructural stabilization, modular compressor architectures and model-based optimization, this technology also offer clear pathways to overcome existing performance and scalability challenges. The inherent compatibility of metal hydride compressors with renewable and waste heat sources positions them as

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enabling technologies for sustainable hydrogen infrastructure. Metal hydride compressors also have the potential to become reliable, efficient and safe compression solutions which support the long-term realization of a hydrogen-based energy economy with continued interdisciplinary research and successful transition from pilot-scale demonstrations to industrial deployment.

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