High pressure thermal hydrogen compression employing Ti$_{1.1}$CrMn metal hydride material

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Abstract

The use of Ti$_{1.1}$CrMn metal hydride material in a thermal hydrogen compression system is investigated. The thermodynamic properties of the material, initially synthesized and annealed at 900 °C for 48 h (for quantities on the order of 10 kg), are assessed performing pressure–concentration–temperature equilibrium tests for hydrogen absorption and desorption at pressure up to about 900 bar. Results show flat plateaus and reduced hysteresis. The calculated absorption enthalpy and entropy are 20.55 ± 0.13 kJ mol$_{H_2}^{-1}$ and 102.16 ± 3.00 J mol$_{H_2}^{-1}$K$^{-1}$ respectively. The desorption enthalpy and entropy are 22.89 ± 0.45 kJ mol$_{H_2}^{-1}$ and 107.80 ± 10.45 J mol$_{H_2}^{-1}$K$^{-1}$, respectively. The metal hydride achieves a weight capacity of approximately 1.8% at room temperature and maintain an approximately constant weight capacity during the cycling testing. This makes the material a suitable candidate for high pressure hydrogen compressors, achieving pressures on the order of 450 bar at temperatures of approximately 140 °C. The same material composition is synthesized at laboratory scale quantities (on the order of 50 g), applying a modified annealing procedure (1200 °C for 240 h). This allows higher operating pressures to be achieved, but the modified annealing process also produces (at least) an additional phase, namely the C15 Laves phase, present in the material along with the C14 Laves phase. Consequently, two pressure plateaus are present at each operating temperature, reducing the effective material weight capacity available for the compression application. A two-stage hybrid compressor concept is also presented, with the thermal hydride compressor paired with a lower pressure electrochemical unit. In principle, the system can compress hydrogen with a compression ratio of 45 from 10 to 450 bar without any external thermal input and recovering the electrochemical unit waste heat to drive the thermal stage.

Nomenclature

| Term | Definition |
|------|------------|
| Ames | Ames Laboratory |
| DOE  | US Department of Energy |
| GWE  | Greenway Energy, LLC |
| HEX  | Interfaced heat exchanger between the LPS and the HPS |
| HPS  | High pressure section |
| JMC  | Japan Metals & Chemicals Co. Ltd |
| LPS  | Low pressure section |
| MH   | Metal hydride |
| PBI  | Polybenzimidazole |
| PCT  | Pressure composition temperature |
| XRD  | X-ray diffraction |

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Greek letters

\[ \Delta H \] Reaction enthalpy (kJ mol\(_{\text{H}_2}\)\(^{-1}\))

\[ \Delta S \] Reaction entropy (kJ mol\(_{\text{H}_2}\)\(^{-1}\) K\(^{-1}\))

\[ \alpha + \beta \] Two-phase hydrogen absorption/desorption region in the material, with formation of the metal-hydride

Subscripts

abs Absorption
des Desorption

1. Introduction

The use of hydrogen, as an energy carrier, is becoming of worldwide importance for both vehicular applications (e.g. fuel cell automobiles) and for steady state power applications (e.g. ammonia production, backup power systems, energy storage and grid stabilization) [1, 2]. A main technical issue to be overcome to achieve a large-scale hydrogen economy is relative to its capillary delivery [3]. The US Department of Energy (DOE) started a novel initiative, referred to as H2@Scale [1], and identified three main ways to deliver hydrogen, produced in large scale centralized plants [1, 4]. Hydrogen can be transported and delivered in liquid form, using cryogenic tank systems, or in gas form using tube trailers, or by pipeline systems [4]. Each option sees the presence of compression (or pumping) units to achieve the required operating conditions in terms of temperatures and pressures. In particular, the gas delivery options require the integration of the infrastructure with high pressure compression units. The DOE defined a set of techno-economic compression performance targets, including operating pressures (875 bar, with 100 bar pipeline delivery), maintenance cost (4% of the installed capital cost), lifetime (10 y), specific energy consumption (1.6 kWh kg\(^{-1}\)) and cost (uninstalled cost of $275 000 for 100 kg h\(^{-1}\) peak compression flow) [4]. Traditional mechanical compressors are reliable systems for low pressure applications, but at high pressures, required for large scale hydrogen delivery, they suffer from low efficiency, low reliability and increased investment and lifetime costs [4–6]. The repeated transitory operating conditions, intrinsically associated with hydrogen transport and delivery, further decrease the efficiency and the lifetime of the component. Therefore, alternative and reliable compression systems, which can operate at pressures higher than 350 bar and achieve high efficiency and low costs, are required. Two main alternative compression concepts are currently investigated, namely the electrochemical and thermal compression systems.

The electrochemical hydrogen compression became a feasible and efficient approach to compress hydrogen with the use of polymer electrolyte membranes (PEM), allowing high differential pressures between anode and cathode side [7]. Today, hydrogen electrochemical compressors are commercially available for pressures on the order of 30–50 bar and flow rates on the order of 0.5–50 SLPM [8–10]. Currently electrochemical compressors are employed at relatively low pressures mainly due to the hydrogen crossover and high resistive losses. This both reduces the efficiency of the electrochemical system and increases the installed costs at high pressures, requiring the development of specific membranes to limit the crossover effect [11, 12]. Additional development is therefore required for the electrochemical compression units to achieve higher pressures and to be used in large scale scenarios.

Another suitable alternative to mechanical compressors for high pressure and large scale applications is represented by thermal compression systems. Metal hydrides are adequate materials that have the potential to be employed in efficient and low cost hydrogen compressors. Metal hydrides can absorb hydrogen and, increasing the operating temperature, can desorb hydrogen at higher pressures, defined by their thermodynamic properties. Depending on the operating conditions (temperature and pressure), different material formulations can be employed. Usually rare-earth based materials (e.g. AB\(_5\) materials such as LaNi\(_{5}\), MnNi\(_{5}\)) or Ti based metal hydrides (e.g. AB or AB\(_2\) materials such as TiFe) are employed for compressor achieving pressures on the order of 100–200 bar at temperatures on the order of 50 °C–100 °C [5, 13, 14]. For higher pressure applications, Ti-based AB\(_2\) materials, usually including Ti, Cr and Mn elements, are generally employed [5, 15, 16]. Some of the Ti-based AB\(_2\) alloys can achieve pressures higher than 700 bar at temperatures on the order of 150 °C–200 °C, making the thermal compression system particularly appealing for high pressure scenarios [5, 17]. In order to achieve large scale penetration of metal hydride thermal compressors the heating/cooling power management is also a fundamental aspect [5, 16].
Greenway Energy (GWE), in conjunction with the Savannah River National Laboratory and Skyre, LLC, has been working on hybrid compression systems, within a DOE funded project. The compressor is comprised of an electrochemical stage, achieving pressures on the order of 100 bar, integrated with a second metal hydride based thermal stage, achieving pressures on the order of 400–900 bar, depending on the material. The behavior of a high pressure Ti-based material (Ti$_{1.1}$CrMn), acquired at industrial level and characterized experimentally up to pressures on the order of 900 bar, will be discussed. The integration of the Ti$_{1.1}$CrMn metal hydride compressor with an electrochemical stage will also be commented. The feasibility of the proposed hybrid system to achieve pressures on the order of 450 bar recovering the waste heat available from the electrochemical stage will also be discussed.

2. High pressure hydrogen compression system

A two-stage compression system is proposed, to compress hydrogen from inlet pressures on the order of 10 bar (i.e. typical operating pressure of water electrolyzers), to pressures higher than 350 bar (i.e. current baseline gas tank storage pressure). The system is comprised of two stages. The low-pressure stage (LPS) works at manometric compression ratios of approximately 10, achieving outlet pressures of 100 bar. The high-pressure stage (HPS) employs metal hydride thermal units to achieve the required operating pressure (>350 bar). The thermal option, employed as the HPS, represents a valid alternative to traditional mechanical compressors, which are affected by low reliability at high pressures. The high-pressure thermal system can also avoid most of the drawbacks associated with the use of electrochemical systems at high pressure (e.g. hydrogen crossflow).

The first stage can employ traditional mechanical intercooled systems, or low pressure metal hydride systems, or electrochemical systems. The selection was based on the available waste heat and its availability temperature. The proposed two-stage compressor is particularly efficient only if the high pressure thermal stage, comprised of metal hydride materials, can be driven by recovering the available waste heat from the LPS, without any external heat input. Given the operating pressure ranges, employing Ti-based metal hydride material, a target temperature of 150 °C was set as the minimum temperature value required to drive the metal hydride HPS [18].

The waste thermal power from mechanical intercooled compressors is insufficient to provide the required heating power (i.e. approximately 20–30 kJ mol$^{-1}$ for typical Ti–Cr–Mn metal hydrides [5, 13]) at temperatures of approximately 150 °C. Using a one-stage mechanical compressor, the waste heat useful to drive the metal hydride unit is on the order of 3–5 kJ mol$^{-1}$, i.e. approximately 10%–20% the power required to drive the thermal compression. This makes the integration between a mechanical unit and a metal hydride unit not effective nor practical. A low-pressure stage, comprised of metal hydride materials, could be paired with the high-pressure metal hydride unit. In principle, this solution has the advantage of eliminating the electric input. However, both metal hydride stages operate approximately at the same temperatures both for charging and discharging. Therefore, the thermal power required to drive the high-pressure system cannot be recovered directly from the LPS and needs to be provided either externally or through increasing the LPS waste heat temperature (e.g. using heat pumps). This solution will increase both the installed costs and the lifetime costs, with additional reduction of the overall system efficiency. The integration of the metal hydride HPS with an electrochemical LPS has the potential to recover directly the waste heat from the electrochemical compressor and drive the thermal unit. A hybrid compression system configuration is shown in figure 1. The low-pressure stage, comprised of an electrochemical system, oxidizes molecular hydrogen (H$_2$) at the anode, producing protons and electrons. The protons pass through a proton–exchange membrane and recombine at the cathode to deliver hydrogen at the required pressure (approximately 100 bar). The high-pressure stage employs two metal hydride reactors, working in parallel in opposite absorption/desorption phase and achieving pressures higher than 350 bar. The first half of a cycle sees one metal hydride absorbing exothermically hydrogen at approximately 100 bar (inlet pressure) and room temperature. The parallel metal hydride desorbs endothermically hydrogen at the required outlet pressure (i.e. higher than 350 bar) operating at temperatures on the order of 130 °C–150 °C. The second phase of the cycle sees the process reversed between the two parallel hydriders. This approach assures the flow continuity with hydrogen compressed between approximately 10 bar and >350 bar. Using Nafion® or Polybenzimidazole (PBI) membranes, the heat rejected by the electrochemical stage can be available at temperatures on the order of 130 °C–170 °C [5, 16] and reused to drive the endothermic desorption reaction in one of the metal hydride reactors.

3. Experimental characterization of the metal hydride materials

The metal hydride isothermal and cycling characterization were all performed on a custom 2-channel high-pressure Sieverts’ instrument designed, built and employed by GWE (figure 2). The availability of two channels
allowed for expedited analysis and validation of the results at each experimental temperature (figure 3(a)), repeating the measurements multiple times to validate the results. High-pressure gas chromatography pneumatics valves with zero dead volume from Valco, Inc. were used for all valving including the sample reactors (figures 3(b), (c)). Fitting and tubing 1/16’ in size were utilized in order to minimize the dead volume among the components. All system reservoirs and sample reactors (figure 3(c)) are series ‘MS’ micro reactors from High Pressure Equipment® and rated to 1400 bar. Custom made sample holder inserts were also fabricated. The inserts were fitted with a fritted cap and a thermocouple port on the bottom that allowed for easy sample loading and direct sample temperature reading. Regulation of the incoming gas pressure was performed by a Tescom® 26-2000 series venting pressure regulator and ER5000 series electropneumatic actuator with a maximum output pressure of 1000 bar. Omega® thermocouples were used for all temperature measurements. All gas pressure monitoring was performed by Keller America Inc. transmitters. Valueline® series analog transducers were used for the system reservoir and Tescom (accuracy of 0.1% FS), whereas PA33X series digital transducers were used for each channel (accuracy of 0.01% FS). All data acquisition and system operations were performed by National Instrumentation hardware and LabVIEW software. Ultra-high purity grade 5 (99.999%) hydrogen and helium obtained from Airgas® were used for all measurements and calibrations. To achieve the gas pressures required for the isothermal measurements the hydrogen was boosted with a Haskel® two-stage booster pump designed for flammable gases with a maximum output pressure of 1034 bar.

Figure 1. Hybrid compressor system. A low-pressure stage (LPS) employing an electrochemical unit is integrated with a high-pressure stage (HPS) comprised of two metal hydride tanks in parallel.

Figure 2. Piping and instrumentation diagram of the two-channel high-pressure Sieverts’ instrument designed and built by GWE.
Sample loading was performed outside of a glove box inert atmosphere. The as received alloy was not activated prior to shipping and therefore not packed under an inert atmosphere. Prior to each sample loading, the sample reactor along with sample holder insert were calibrated for the empty volume. Upon attaching the reactor filled with sample to the system, the reactor was purged of any air by five cycles of helium and vacuum. Once purged the new sample reactor volume was calibrated. The sample reactor volume was recalibrated after alloy activation for validation.

To activate the metal hydride, the evacuated sample was pressurized to pressures above 400 bar of hydrogen at room temperature. The sample was left under the same conditions until hydrogen absorption started (i.e. sample temperature began to rise). The reactor was allowed to cool down to room temperature and, after the cooling process was completed, exposed to vacuum until no pressure rise was observed when the vacuum valve was closed. The activation steps were repeated until the maximum temperature, reached when hydrogen was added, ceased to increase from the previous activation step.

Isothermal measurements were performed over a range of 22 °C–170 °C. Prior to the start of each absorption portion of the isothermal measurement, the sample was evacuated until no pressure rise was observed when closed to vacuum. With the sample at the desired temperature, hydrogen aliquots were added in a stepwise manner. The equilibrium condition was achieved before proceeding to the next pressure step. The absorption process was stopped once no further increase in gas uptake was observed or a maximum pressure was achieved. The desorption portion was begun allowing for the final data point of the absorption to be the corresponding first data point of the desorption.

The weight capacity of the isothermal measurement for each set temperature was calculated from the molar density as determined by real gas equations of state in NIST REFPROP software [19] at the pressure and temperature of each step. The change in alloy density was also accounted for. With an assumed material volume total variation of 10% during each absorption/desorption isotherm, the material density variation was assumed to be consistent for each absorption/desorption step, i.e. for a total of 10 steps, each isotherm, the alloy density was assumed to change by 1% per step. To test its cycling capacity degradation the metal hydride was cycled between vacuum and 150 bar at room temperature. The sample was evacuated after each absorption test until no pressure increase was observed when closed to vacuum. With the sample evacuated, the channel reservoir was pressurized to 150 bar of hydrogen. Once the pressure had stabilized, the sample valve was opened and the sample exposed to hydrogen. Absorption was determined complete after both the sample returned to room temperature and pressure stabilized.

Prior to determining the tap density of the material, the alloy was separated into varying particle sizes and segregated into separate containers. For tap density measurements, equal weight of each particle size was combined into one container and agitated. Once fully mixed, the powder was transferred into a pre-weighed calibrated volume. The calibrated vessel was tapped 10 times from a distance of 5 cm to allow the material to settle. With the new mass of the calibrated volume the tap density calculated. The material was returned to the original mixture and agitated again before each subsequent measurement.
4. Metal hydride characterization results

A Ti-based material, namely Ti1.1CrMn, was selected as the baseline hydride formulation for high pressure compression systems, having the potential to achieve pressures higher than 350 bar at temperatures on the order of 100 °C–150 °C. This material has been characterized in the past for automotive applications, with experimental results usually available for pressures up to of 100–200 bar [20], extrapolating the thermodynamic data to obtain higher pressures results [21]. The material kinetics has also been characterized widely in the past literature, identifying the main kinetics parameters (i.e. rate constants and activation energies) [22]. For the proposed compression application, the material, produced on large scale, needed to be experimentally characterized over a wider range of pressures. The material was acquired at industrial level from Japan Metals & Chemicals Co., Ltd (JMC). The hydride was synthesized by JMC in a high temperature furnace. After fabrication, the alloy was annealed at 900 °C for 48 h followed by pulverization prior to shipping. JMC provided analysis of the individual metal purity: Ti > 99.4%, Mn = 99.88% and Cr = 99.96%, and quality report of the alloy: Ti = 33.66 wt%, Cr = 31.97 wt%, Mn = 34.37 wt%. The bulk material, as received, was characterized by noticeable particle size inhomogeneity, having average diameters ranging from <45 to 1000 μm with the distribution shown in figure 4.

The average bulk density was also measured following the procedure described in the experimental characterization description section. The average bulk density was equal to 3299 kg m$^{-3}$, oscillating between a minimum of 3116 kg m$^{-3}$ and a maximum of 3426 kg m$^{-3}$ for five different batches of the same JMC material.

Several material samples, with different particle diameters, were analyzed to identify the phases present in the metal hydride. The x-ray diffraction (XRD) profiles are shown in figure 5. The annealed material from JMC showed the presence of a main phase, namely the C14 Laves phase, with an additional peak likely corresponding to what is usually referred to as ‘Cr–Mn’ phase in the literature [23]. The material pressure–composition–temperature (PCT) profiles are shown in figure 6. Results highlight reduced slope in the α+β region of each of the curves within the pressure and temperature range of interest. A weight capacity of approximately 1.8 wt% was achieved absorbing hydrogen at room temperature. Limited hysteresis was also observed in the absorption and desorption profiles shown in figure 6. The maximum hysteresis factor $\psi$, defined as: $\ln\left(\frac{P_\text{abs}}{P_\text{des}}\right)$ [13], was achieved at low operating temperatures with $\psi = 0.34$ at temperature of 22 °C. At higher temperatures (between 110 °C and 170 °C) the hysteresis factor was assessed to be between 0.013 and 0.023, making the Ti1.1CrMn material a valid candidate for high pressure compression systems.

The Van’t Hoff plot, corresponding to the JMC Ti$_{1.1}$CrMn data of figure 6, is shown in figure 7. The profiles were established calculating the fugacity values, corresponding to the pressure data of figure 6, through the fugacity factor relationships adopted in the NIST REFPROP software [19] for the operating temperature and pressure range of interest. Table 1 shows, for each absorption and desorption isotherm, the mid plateau pressure values and the corresponding calculated fugacity values, used in the Van’t Hoff plot.

The values of reaction enthalpy and entropy were evaluated statistically using the fugacity data. The absorption enthalpy and entropy were found to be $\Delta H_{\text{abs}} = 20.55 \pm 0.13$ kJ mol$^{-1}$ and...
The desorption enthalpy and entropy were found to be
\[ \Delta H_{\text{des}} = 22.89 \pm 0.45 \text{ kJ mol}^{-1} \text{H}_2 \] and
\[ \Delta S_{\text{abs}} = 107.80 \pm 10.45 \text{ J mol}^{-1} \text{K}^{-1}. \]

The material was also tested to evaluate its cycling performance. The tests were carried out following the procedure described in the previous section, with hydrogen charged at a pressure of 150 bar at room temperature (22 °C) and the desorption operated under vacuum conditions. The first 20 cycles showed essentially no degradation of the material weight capacity (each cycle reached a weight capacity of approximately 1.7%) (figure 8), confirming the cycling data available in the literature for AB\textsubscript{2} materials \cite{24}.

The thermodynamic properties of the JMC Ti\textsubscript{1.1}CrMn material were significantly different from the data reported in the literature for the same formulation \cite{5,20,25}. The values of the operating pressures (fugacities) are on the order of 42%–58% lower than the corresponding literature data \cite{20,25}. One of the main aspects
The annealing procedure determines the phases in the final material, affecting, in turn, the equilibrium operating conditions (pressure and temperature). The same formulation (Ti\(_{1.1}\)CrMn) was synthesized by Ames Laboratory (Ames), using metal purity on the same order of the JMC material. Particular attention was also paid to the Mn element purity, using additional purification procedures and achieving an oxygen contamination <1 ppm. The material was annealed at 1200 °C for 240 h and sealed in individual quartz tubes. The crystal structure of the Ames Ti\(_{1.1}\)CrMn material, as received after the synthesis, was analyzed comparing the XRD results with the corresponding JMC material data (figure 9). The material synthesized by Ames has (at least) two phases (Laves C14 and Laves C15). The second phase (C15) is known to provide higher equilibrium pressures than the C14 phase, as highlighted for many AB\(_2\) materials, e.g. for the TiCr\(_{1.9}\) (C14 phase) and TiCr\(_{1.8}\) (C15 phase) materials [26–29].

**Table 1.** JMC/Ti\(_{1.1}\)CrMn temperature, pressure and fugacity values for absorption and desorption.

| T (K) | Pressure absorption/desorption (bar) | Fugacity absorption/desorption (bar) |
|------|-------------------------------------|-------------------------------------|
| 295  | 49.1/35.1                           | 50.5/35.8                           |
| 323  | 97.3/83.6                           | 102.8/87.7                          |
| 353  | 176.9/169.8                         | 194.2/185.7                         |
| 383  | 292.6/287.5                         | 338.5/331.8                         |
| 403  | 389.6/380.7                         | 469.4/456.7                         |
| 443  | 631.0/622.6                         | 832.8/818.8                         |
Hydrogen absorption pressure–concentration profiles for three operating temperatures are also shown in figure 10 and compared with the corresponding profiles of the JMC material.

The modified annealing procedure had two main effects on the Ames material: (1) at least two plateaus are visible in the absorption profiles (likely corresponding to the C14 and C15 phases), (2) each material phase absorbs hydrogen at pressures higher than the JMC material (at the same temperatures), with potential for higher weight capacity in the $\alpha + \beta$ region of the material where the flat and extended plateaus occur.

However, the presence of (at least) two material phases makes the management of hydrogen absorption at low pressures more difficult, with likely reduction of the effective material absorption weight capacity. At pressures of approximately 100 bar and room temperature (23 °C) the Ames material can absorb approximately 57% of the hydrogen absorbed by the JMC material under the same operating conditions. Therefore, the JMC material was assumed as the baseline material to be integrated in the hybrid compressor, achieving pressures on the order of 400–500 bar.

5. Hybrid compressor concept

A hybrid compression system, comprised of an electrochemical unit and two parallel metal hydride units, is shown in figure 11. The inlet hydrogen is oxidized at the anode side of the electrochemical unit, connected to the environment through a back-pressure regulator. The actual compression process takes place at the cathode side of the unit, which requires a proper cooling system to maintain the required operating conditions. The cooling power management unit realizes the separation between the pressurized hydrogen (at pressures on the order of
demonstrated the ability to provide waste heat of approximately 4.75 kWh kgH2 shown in another publication, dedicated to the overall hybrid compressor system analysis and design. Heat transfer and compression are required for reliable, efficient economy requires the presence of hydrogen compression systems. Alternatives to traditional mechanical compressors, achieving pressures on the order of 450 bar at temperatures of 140 °C, requiring a heating power of approximately 4.65 kWh kgH2 at 2.5 A cm−2, operating at temperatures of 150 °C–170 °C [16].

A single stage MH compressor, equipped with the JMC Ti1.1CrMn material, can achieve pressures of 450 bar at temperatures of 140 °C, requiring a heating power of approximately 4.65 kWh kgH2. The operating conditions of the metal hydride material are based on the experimental results shown in figures 6 and 7. The heating power, required to desorb hydrogen at higher pressures, was assessed using the model described in [5] with the thermodynamic and physical and chemical data obtained experimentally for the JMC Ti1.1CrMn material. Either using a direct or indirect heat transfer approach the required heating power can be exchanged between the electrochemical unit and the metal hydride reactor, through the HEX heat exchanger (figure 11), achieving pressures of 450 bar in the thermal compression unit without any external heating requirement.

6. Conclusions

Each of the hydrogen delivery scenarios identified by the US Department of Energy for a large-scale hydrogen economy requires the presence of hydrogen compression systems. Alternatives to traditional mechanical compression are required for reliable, efficient and low-cost high-pressure hydrogen compression systems. The use of Ti1.1CrMn metal hydride material in a thermal compression system, to be coupled with a lower pressure electrochemical compression system, has been investigated. The material was synthesized at industrial level (on the order of 10 kg) by JMC and annealed at temperature of 900 °C for 2 d (48 h). The material, as received, was then analyzed to identify the particle size distribution and the phases present in the formulation. A single C14 Laves phase was identified after XRD analysis. The thermodynamic properties of the material were also assessed, performing the equilibrium PCT measurements in a novel high-pressure Sievert’s apparatus developed by GWE. Six isotherm profiles for hydrogen absorption and desorption at pressures up to about 900 bar were identified. Results showed flat plateaus in the α + β region with reduced hysteresis especially at the higher operating pressures of interest. This makes the material an excellent candidate for high pressure hydrogen compressors, achieving pressures on the order of 450 bar at temperatures on the order of 130 °C–150 °C. However, remarkable differences were found between the tested Ti1.1CrMn material and the corresponding data available in the literature for the same formulation. The material was subjected to a modified annealing procedure, at 1200 °C for 10 d (240 h), to achieve higher operating pressures. The material was synthesized and annealed at the specified conditions by Ames and acquired at laboratory scale quantities (on the order of 50 g). The new annealing procedure allowed higher operating pressures to be achieved, as demonstrated by the pressure–composition–temperature profiles, in comparison with the corresponding profiles of the JMC Ti1.1CrMn. The final material formulation also saw the presence of an additional phase (C15 Laves phase), resulting in the presence of, at least, two equilibrium plateau pressures (for different hydrogen concentration) at the same operating temperature. This has a detrimental effect especially for the hydrogen absorption process at lower pressures, reducing the amount of hydrogen that can be absorbed at the same charging pressure and temperature (i.e. reducing the effective weight capacity of the material, available for the compression application). Finally, a two-stage hybrid compressor schematic concept was conceived, with the thermal high-pressure compressor paired with a lower pressure electrochemical unit. In principle, the overall system can compress hydrogen with a compression ratio of 45 from 10 to 450 bar, without any external thermal input and recovering the electrochemical unit waste heat to drive the metal hydride compressor. Results demonstrate that additional research and development aimed to identify metal hydride materials with flat and extended plateaus at high pressures would be beneficial to increase the overall material capacity.
Table 2. Hybrid compressor operating conditions.

| System                      | Temperature range (°C) | Pressure range (bar) | Heat (kWh kg\textsubscript{H\textsubscript{2}}\textsuperscript{−1}) | References |
|-----------------------------|------------------------|----------------------|-------------------------------------------------|-------------|
| Electrochemical system (PBI membrane) | ≈170                   | 10–100               | 4.75 (waste heat)                               | [16]        |
| Metal hydride system (JMC Ti\textsubscript{1.1}CrMn hydride) | 40 (charging)–140 (discharging) | 100–450             | 4.65 (desorption heat)                          | Current work|
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