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An overview of hydrogen compressors for heat pump systems

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Abstract

Metal hydrides present an alternative heat pump approach to efficiently achieving extreme temperatures, without high GWP refrigerants. These materials work by complexing with hydrogen in order to generate incredible thermal lifts; an alloy of TiCrMn, complexes hydrogen at 90°C and exhausts at approximately -60°C, for example. A drawback of this class of materials is that greater temperature lifts require higher pressure hydrogen. This paper analyzes four methods of producing pressurized hydrogen: two electrochemical systems, one system employing metal hydride compression, and one using conventional mechanical compression. Electrochemical compression makes use of ion selective electrolytes that provide pressurized hydrogen when a potential gradient is applied. Metal hydride compressors operate by reversing the principle behind the metal hydride heat exchangers used in these heat pumps – i.e. releasing hydrogen at pressure when the metal hydride is heated. Mechanical compressors use various designs to move a mass of gas and shrink the volume it occupies, thereby compressing the gas. This paper provides operational data for these four different compression strategies. Heat pump cycles employing these systems are analyzed for critical performance parameters.

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Keywords: metal hydride heat pump; metal hydride compressor; electrochemical compressor; nickel hydrogen battery; hydrogen compressor; metal hydride heat exchanger

1. Background

1.1. Metal Hydride Heat Pump

Metal hydride heat pumps (MHHP) operate using pair(s) of metal hydride heat exchangers (MHHX) to generate heating and cooling. Any compression technology that pumps hydrogen can be utilized to adsorb and desorb hydrogen from the MHHX. Adsorption of hydrogen on to the metal hydride is an exothermic reaction that produces heat, and desorption of hydrogen from the metal hydride is an endothermic reaction and pulls heat from the surroundings.

During the first half of a cycle, high pressure hydrogen flows out of the compressor (I) and adsorbs onto the metal hydride of MHHX A, while low pressure hydrogen is desorbed from the metal hydride of MHHX B and flows into the compressor (II). The coil under low pressure pulls heat from the cooling liquid (III) to generate cooling power on the cold radiator (C), while the coil under high pressure releases heat in the waste heat liquid (IV) to the hot radiator (D). During the second half of a cycle, the hydrogen flow is reversed. High pressure hydrogen flows out of the compressor (II) and MHHX B and low-pressure hydrogen flows out of the MHHX A and into the compressor (I). MHHX A now generates the cooling power (V) for the cold radiator (C) and MHHX B (VI) now rejects waste heat to the hot radiator (D).

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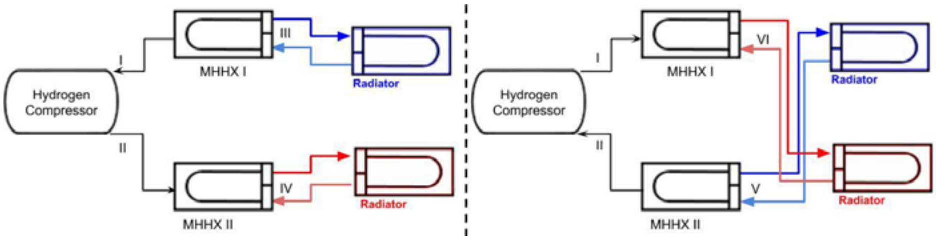


Fig. 1. MHHP configuration and flows during first half-cycle (top) and second half-cycle (bottom)

Different forms of compression were analyzed assuming a room air conditioner (RAC) with a capacity of 2.5 kW of cooling. To improve the economics of the MHHP from the benchtop testing the cycle time was doubled (decreasing the hydrogen flow rate and increasing the mass of the MHHX), and a different metal hydride was selected with a greater heat of formation. This allows for smaller compressors, the most cost critical component in the system. Based on the selected metal hydride, the cycle time, and cooling capacity, the estimated hydrogen flow rate for all systems was 43 SLM.

1.2. Proton Exchange Membrane (PEM) Based Electrochemical Compression

Proton exchange membrane (PEM) electrochemical compression (ECC) is a method of hydrogen compression that is a derivative of fuel cell technology. It is a solid-state compression technology that offers the benefits of no moving parts, no noise, and high efficiencies. Pressure lifts are generated by transporting hydrogen in its ionic form as protons.

A PEM, depicted in Figure 2, is sandwiched on either side by a catalyst and a gas diffusion layer. A voltage is applied to the membrane electrode assembly (MEA) to drive the hydrogen compression reaction. Hydrogen contacts the catalyst/membrane interface at the anode of the system and reacts to form protons and electrons. The protons transport across the membrane, as the membrane is ion-selective and allows cations to transport across. The protons recombine with the electrons at the catalyst/membrane interface of the cathode to form hydrogen. The method of applying a potential to the MEA allows for high pressure hydrogen to be generated from a low-pressure hydrogen feed.

The overall standard potential for the system is 0.00 V, however this assumes an ideal case with no pressure differential and perfectly balanced half cells. The overpotential, or additional energy, that must be applied due to the pressure differential is given below.

$$V = \frac{RT}{2F} * ln\left(\frac{P_{cathode}}{P_{anode}}\right);\ Anode: H_2 \rightarrow 2H^+ + 2e^-, E^\circ = 0.00\,V;$$
$$Cathode: 2H^+ + 2e^- \rightarrow H_2, E^\circ = 0.00\,V;\ Overall: H_{2,low} \rightarrow H_{2,high},\ E^\circ_{total} = 0.00\,V$$

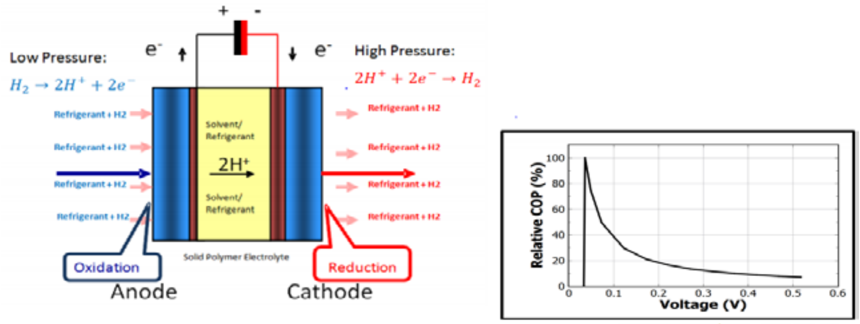


Fig. 2. Proton exchange membrane electrochemical compressor proton flow diagram (left) and COP curve (right)

When operating the cell at low pressure differentials the voltage required is very close to 0.00 V, i.e. the system efficiency is very high. However, some heat pump applications require pressure ratios of >10x, decreasing the overall efficiency of the PEM ECC. From Figure, the COP of an ECC system exponentially increases at cell voltages <0.1 V. In order to make PEM ECC-MHHP systems viable, the current density (proportional to the hydrogen flow per unit area) must be increased at low voltages.

The development of PEM ECCs has been focused on decreasing the weight and volume and increasing the current density, to improve the economic viability and the energy efficiency of the system. Additionally, combined PEM ECC-MHHP systems have been successfully run for initial analysis.

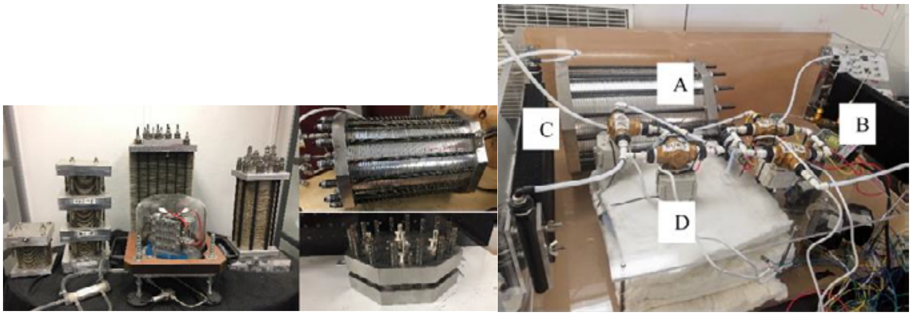


Fig. 3. Left: A selection of PEM-ECCs; Right: Proof-of-concept 250 W PEM ECC-MHHX

A benchtop prototype AC unit was designed and built using a nominal 250 W MHHX as a proof of concept. The main system components are (a) PEM ECC, (b) cold-side radiator, (c) hot-side radiator, (d) pair of MHHX, heat exchange fluid line (the white plastic tubing in Figure 3), and hydrogen line (the metal piping). The heat exchange fluid line is designed to transfer the heating and cooling from the MHHXs to the appropriate radiators. The cold side radiator cools down the space, while the hot side radiator dumps heat to the ambient air. The hydrogen line has valving to change which MHHX is feeding to the inlet and outlet based on the cycle.

During testing the outlet pressure of the compressor ranged from 13.8-20.7 bar (200-300 psia), and the inlet ranged from 3.44 (50 psia) to near vacuum. The average temperature drop across a MHHX under low pressure was about 3.56°C, providing a cooling load of 174 W (of the expected 250 W). After "breaking-in" the PEM ECC, a process that took about 50 minutes, the PEM ECC performed as expected for about 20 minutes, until the humidifier ran out of water and the performance of the system dropped. During the time that the PEM ECC performed as expected, its average power consumption was 163 W. Although the COP of this run, ~1, is less than that of the incumbent technology, the benchtop prototype provided a standard system design for the RAC systems, and there are many variables to optimize to improve system efficiency. The system run also provided a basis for hydrogen compression analysis of the other compressors.

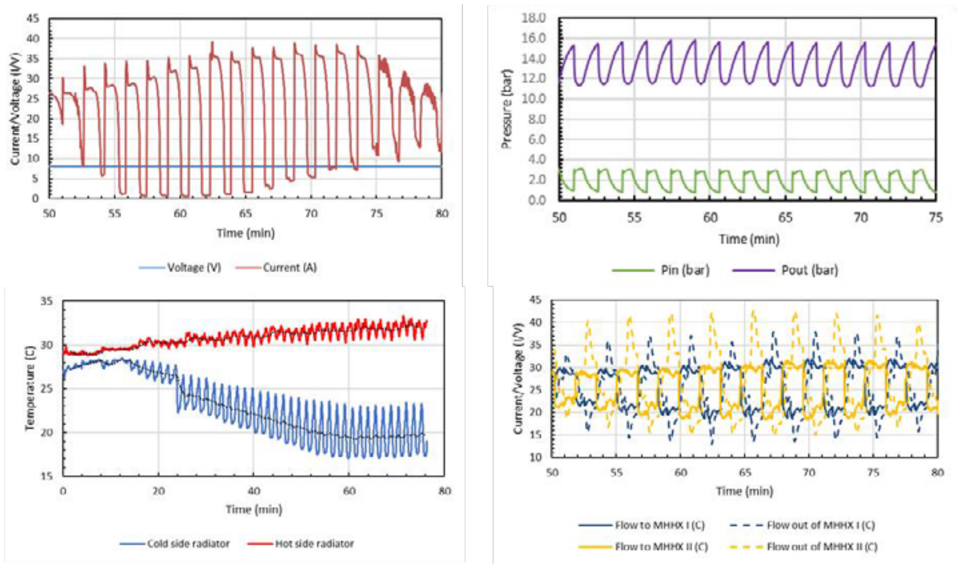


Fig. 4. (Clockwise from top left) Power consumption; ECC pressure differential; MHHXs' temperature; and Cooling during proof-of-concept runs

Based on current testing data, utilizing 25.4 µm membranes would require a total number of 57 cells with an active area of 150 cm^2 to meet a 3-year payback period (on a premium over a conventional, mini-split ductless RAC) for a 2.5 kW air conditioner, operating at 0.12 V per cell and 0.71 A/cm^2. The estimated total power consumption for the compressor is 730 W with a system cost of \$380. The weight, dimensions, and volume of the PEM ECC are 149.7 kg, 25.4 cm x 25.4 cm x 29 cm, and 18.7 L (330 lbs, 10"x10"x11.4", and 1,140 in^2), respectively. Future improvements with the membrane and bipolar plate are required to improve the economics of the system. Extrapolating from the information in Figure 5, with a decrease in thickness to about 10 µm, 0.12 V could provide 1.36 A/cm^2 (capturing 75% of the improved ionic conductivity). The number of cells decreases to 30, with an estimated energy consumption of 730 W and costing \$230. The weight, dimensions, and volume decrease to 65.8 kg, 25.4 cm x 25.4 cm x 12.7 cm, and 8.20 L (145 lbs, 10"x10"x5", and 500 in^3). Further improvements can be made to the system overall to reduce the voltage at the required current level, which would lead to improvements in COP.

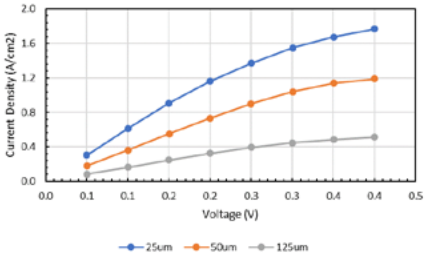


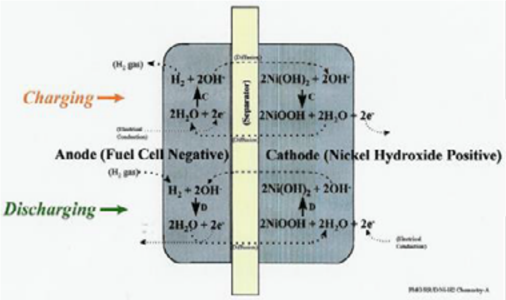
Fig. 5. Potential of improvement to PEM ECC due to membrane thickness

1.3. Alkaline Electrochemical Compression

The anionic electrochemical compression technology analyzed for use in a MHHP is based on well-established nickel hydrogen (Ni-H) battery technology. Going from a cationic to anionic systems greatly reduces the cost of the system. The expensive metal plates in the cationic systems, stainless steel and titanium, can be replaced with cheaper metals like nickel, and the expensive platinum group metals (PGM) can either be replaced entirely with non-PGM catalysts, or reduced in quantity.

The battery technology is used in reverse, where power is put in to compress hydrogen instead of hydrogen expanding to produce power. While the energy density is only about one third as that of a lithium battery, the Ni-H battery has a long life, with cells capable of operating for 15 years at 80% depth of discharge (DOD) in satellite applications [1]. The cells can be designed to operate up to 82.74 bar (1200 psi), so this technology is applicable to MHHPs [2].

The nickel-hydrogen battery combines the positive nickel electrode of a nickel-cadmium battery with the negative electrode of a fuel cell. During charging, water is reduced at the anode to form hydroxyl ions and hydrogen gas. The hydroxyl ions transport through the alkaline electrolyte, typically KOH, and oxidize the nickel hydroxide ($Ni(OH)_2$) to form nickel oxyhydroxide (NiOOH). During discharging the reverse reactions occur, where the NiOOH is reduced back to $Ni(OH)_2$ and hydrogen gas is oxidized to reform water. There are three main architectures for designing a Ni-H battery: individual pressure vessel, common pressure vessel, and bipolar design. For this application we analyzed the bipolar plate design, with a positive electrode made up of porous nickel structure, which is packed with the nickel hydroxide, and a negative electrode like that of a fuel cell, which contains a platinum group metal catalyst with a gas diffusion layer.



$$Negative: H_2O + e^- \leftrightarrow \frac{1}{2}H_2 + OH^-$$
$$Positive: Ni(OH)_2 + OH^- \leftrightarrow NiOOH + H_2O + e^-$$
$$Overall: Ni(OH)_2 \leftrightarrow NiOOH + \frac{1}{2}H_2$$

Fig. 6. Alkaline exchange membrane electrochemical compressor electron flow diagram (left) and equations on electrodes (right)

In our proposed system a pair of Ni-H batteries work in tandem, i.e. one is charging while the other one is discharging. This allows for one to provide compressed hydrogen gas to the adsorbing MHHX, while the other is pulling hydrogen gas from the desorbing MHHX. The discharging battery provides most of the electrical power for the charging battery through a step-up converter, and the net difference is provided by an external source. The pair cycles back and forth like the MHHXs, and the discharging battery becomes the charging battery. Therefore, the power consumption of the system is the external voltage at the operational current of the battery providing high pressure hydrogen.

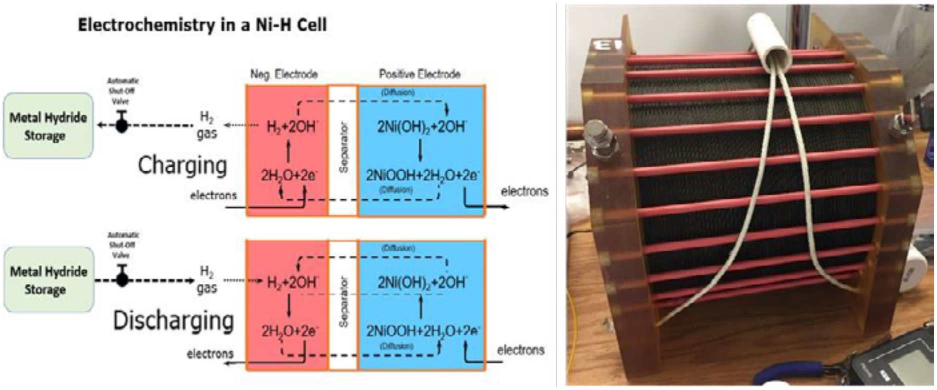


Fig. 7. Electrochemistry in a Ni-H cell (left) and prototype AEM ECC (right)

To meet the demands of a 2.5 kW air conditioner and achieve a payback period of 3 years, each battery will comprise of 228 cells at an active area of 490 cm^2. The discharging battery will operate at a voltage of about 1.25 V/cell at 11 mA/cm^2, and the charging battery will operate at 1.206 V/cell at 11 mA/cm^2, such that the input voltage is 0.044 V/cell. The input power to the system would be 540W with a system cost of $270. The weight, dimensions, and volume of the Ni-H battery system are 40.8 kg, 61 cm x 30.5 cm x 11.43 cm, and 21.23 L (90lbs, 24”x12”x4.5”, and 1,296 in^3), respectively.

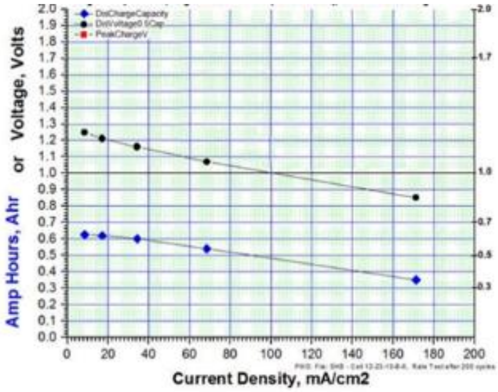


Fig. 8. Performance of NiMH compressor with respect to current density

1.4. Metal Hydride Compression

Metal hydrides (MH) are metallic compounds or alloys that adsorb and desorb hydrogen based on the temperature and hydrogen pressure conditions experienced by the MH. Based on the characteristics of the MH, it will adsorb a certain mass of low-pressure hydrogen at a specific low temperature. Once saturated with hydrogen the hydride is then heated causing the plateau pressure of the hydride to increase (as it is temperature dependent). This increase in plateau pressure causes the hydrogen to desorb from the hydride, allowing for compression of hydrogen gas by the metal hydride compressor (MHC) The temperature of the hydride and the mass of the hydride determines the flow rate, and the output pressure is controlled by the final temperature and the heating rate. Once the hydrogen is completely desorbed the hydride is cooled and then refilled with low pressure hydrogen to start the cycle over again. Figure 9 shows the basic cycle in action.

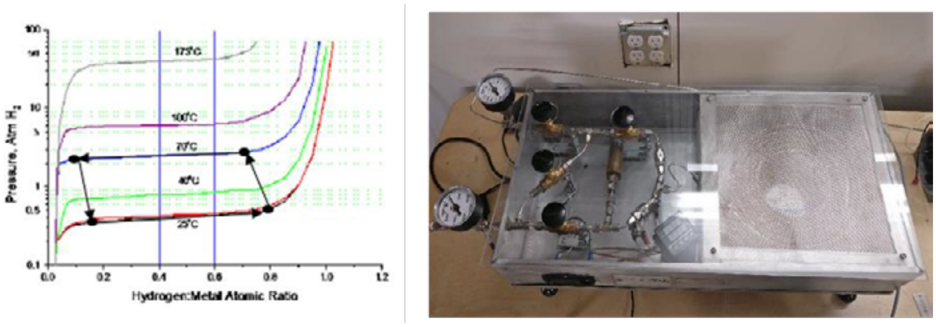


Fig. 9. Metal hydrogen compressor pressure cycle (left) and example compressor (right)

In our proposed system a series of MHCs work in tandem, i.e. some will be adsorbing hydrogen while the others will be desorbing hydrogen. The MHCs that is desorbing hydrogen is heated using a nichrome resistive heating wire, and the MHCs that is adsorbing is cooled down by a fan.

To meet the demands of a 2.5 kW air conditioner, the MHC system will comprise of 20 MHC coils of 1.524 m (5 ft) in length, with 10 producing hydrogen at any time. To achieve the desired pressure and hydrogen output each will need to be heated to 200°C, resulting in a power consumption of ~500 W per coil, or 5000W total. The coils cooling down will be running on a fan system that draws an average 70 W, for a total system power draw of 5500W, at a system cost of $456. The weight, dimensions, and volume of the MHC system are 22.7 kg, 30.5 cm x 61 cm x 25.4 cm (50lbs, 12”x24”x10”, and 2880 in^3), respectively.

1.5. Mechanical Compression

The final method of compression analyzed for the MHHP was a standard mechanical compressor that is already mass manufactured. The type of mechanical compressor selected for testing was an R-22 compressor for a vapor compression (VC) heat pump with a rated cooling capacity of 6,330 kJ/hr (6,000 BTU/hr). This type of compressor is a scroll compressor, with two interleaving scrolls to pump, compress or pressurize fluids such as liquids and gases. Often, one of the scrolls is fixed, while the other orbits eccentrically without rotating, thereby trapping and pumping or compressing pockets of fluid between the scrolls. Another method for producing the compression motion is co-rotating the scrolls, in synchronous motion, but with offset centers of rotation. The relative motion is the same as if one were orbiting.

Fig. 10. R-22 compressor (left) and MHHP employing the same (right)

Connecting the compressor to a hydrogen tank provided a flow rate of ~30 SLPM of hydrogen at a current of 2.4 A and a voltage of 110 VAC. When only connected to a tank the compressor was able to achieve a 12.4 bar (180 psi) maximum from atmospheric pressure. Once it was turned off, a large internal leak caused the sharp increases of the inlet pressure of Figure 11. The compressor was also hooked up to imitate the pressure swings of the MHHP and maintain the 13.8 bar (200 psi) necessary to provide heating and cooling from the MHHXs.

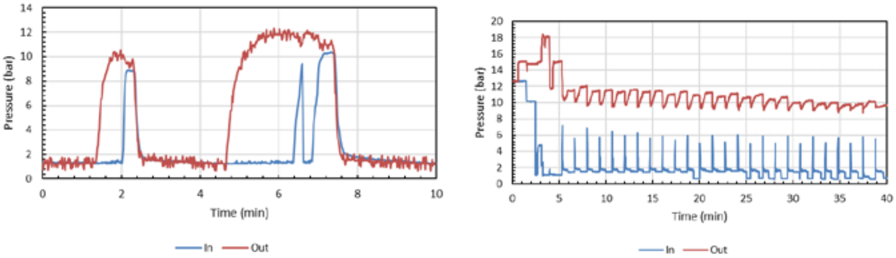


Fig. 11. Compressor when connected to a tank (left) and compressor imitating pressure swings of MHHP (right)

Because the 2.5 kW cooling system requires ~43 SLM of hydrogen and the 6330.4 kJ/hr (6,000 BTU/hr) compressor provided 30 SLM, a compressor sized for ~9074 kJ/hr (8,600 BTU/hr) should provide the requisite flow rate. The power consumption for a mechanical compressor in a MHHP system was estimated from the power consumption of rotary scroll compressors that met or exceeded (by less than 1055 kJ/hr (1000 BTU/hr)) the cooling load requirement. Assuming the power consumption is linear to the output cooling load, the power consumption of the compressors was proportionally decreased by the amount their cooling load exceeded 9073.5 kJ/hr (8600 BTU/hr). The average COP of typical systems employing R-22 is 3.17 [3]. With an average power consumption of 550 W, the average COP of employing a mechanical compressor in the MHHP is 4.52, with a system cost estimated in the range of $50-100. The weight, dimensions, and volume of the Ni-H battery system are 15.4 kg, 22.9 cm x 15.24 cm x 22.9 cm, and 7.96 L (34 lbs, 9”x6”x9”, and 486 in^3), respectively. While these systems were not designed nor optimized for hydrogen flow, they still show strong potential for a high efficiency cooling solution. The MHHX component costs of the RAC is comparable to the non-compressor components of a conventional RAC. Therefore, a RAC utilizing a conventional compressor shows strong potential for an early, low cost MHHX-RAC.

2. Conclusion

Experimental and theoretical data shows that hydrogen compression systems coupled with MHHP technology provides a realistic alternative to standard freon based heat pump systems.

From performance data and techno-economic analysis it is evident that PEM Compressors are highly efficient for low to medium pressure application but require more initial cost. At higher pressures the cost increases even further, limiting the technology to low temperature lift applications. Ni-H compressors provide a better electrochemical alternative with lower cost and higher efficiency than PEM for low to medium pressure application. This is a relatively low TRL technology for hydrogen compression, but with more development, this technology can overcome PEM compressor technology. MHC is the most expensive and least efficient of all the technologies. However, it does allow for much higher-pressure applications. One such application is in extreme temperature systems, such as ultra-low temperature freezers. Because the temperature drop is to -85°C, MHHXs designed for this application require very high pressures (>2000 psi). Mechanical compression of hydrogen offers the most near-term solution to implementation of a MHHP but will not see the advancements that the electrochemical systems will see, in terms of cost reduction and improvements in power consumption, with future development in the electrochemical compression technology.

The Table 1, below, provides a comparison of different hydrogen compression technologies.

Table 1. Summary of hydrogen compression technologies

Compression Technology	System Cost ($)	System Power Consumption (W)	Weight (lb)	Volume (in^3)
PEM ECC	380	730	330	1140
Ni-H	270	540	90	1296
MHC	456	5500	70	2880
Mechanical	50-100	550	34	486

3. Nomenclature

Table 2. Acronyms and abbreviations, defined

Term	Definition	Term	Definition
AEM	Anion Exchange Membrane	MHHP	Metal Hydride Heat Pump
COP	Coefficient of Performance (Wh/Wh)	MHHX	Metal Hydride Heat Exchanger
DOD	Depth of Discharge	PEM	Proton Exchange Membrane
ECC	Electrochemical Compressor	PGM	Platinum Group Metal
MEA	Membrane Electrode Assembly	RAC	Room Air-Conditioner
MH	Metal Hydride	SLM	Standard-Liter per Minute (0°C, 1 bar)
MHC	Metal Hydride Compressor	VC	Vapor Compression

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