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Development of Separate Sensible and Latent Cooling System Using Electrochemical Compressor

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Abstract

Separate sensible and latent cooling systems offer superior energy efficiency performance compared to conventional vapor compression air conditioning systems. In this paper we describe an innovative non-vapor compression system that uses electrochemical compressor (ECC) to pump hydrogen between 2-metal hydride reservoirs to provide the sensible cooling effect. The heat rejected during this process is used to regenerate the ionic liquid (IL) used for desiccant dehumidification. The overall system design is illustrated. The Xergy version 4C electrochemical compressor, while not designed as a high pressure system, develops in excess of 2 MPa (300 psia) and pressure ratios > 30. The projected base efficiency improvement of the electrochemical compressor is expected to be ~ 20% with higher efficiency when in low capacity mode due to being throttleable to lower capacity with improved efficiency. The IL was tailored to maximize the absorption/desorption rate of water vapor at moderate regeneration temperature. This IL, namely, [EMIm].OAc, is a hydrophilic IL with a working concentration range of 28.98% when operating between 25 – 75 °C. The ECC metal hydride system is expected to show superior performance to typical vapor compression systems. As such, the combined efficiency gains from the use of ECC and separate and sensible cooling would offer significant potential savings to existing vapor compression cooling technology. A high efficiency Window Air Conditioner system is described based on this novel configuration. The system's schematic is provided. Models compared well with actual operating data obtained by running the prototype system. Finally, a model of an LiCl desiccant system in conjunction with the ECC-based metal hydride heat exchangers is provided.

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Keywords: electrochemical compressor; separate sensible and latent; ionic liquid; high efficiency; window air conditioner.

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1. Introduction

Heat pumps employing electrochemical compressors are a transformative and disruptive platform technology. Electrochemical compression can serve as a basis for heat pumps in different ways; in virtually all cases, ECC's show high operating efficiencies and other benefits such as noiseless operation, and the ability to operate without the use of Global Warming Potential (GWP) working fluids [1-3]. It is also important to recognize that mechanical compressors, an incumbent technology with over 100 years of refinement, supports a multibillion dollar global industry which has consistently improved the performance of these units' year after year, with large engineering and development teams. This paper explores the application of electrochemical compressors for use in window air conditioning systems. The work has been supported by the Department of Energy (DOE)'s BENEFIT program [4]. The program has the following 3 goals:

- Achieve a COP > 4
- Achieve an incremental installed price premium < \$ 70/kBTU (when manufactured at scale)
- Set up a high-volume supply chain to be able to provide low cost components to meet commercial unit targets

2. System Components

The novel system configuration employs the following unique features: an electrochemical compressor, 2 metal-hydride heat exchangers, and the liquid desiccant latent cooling subsystem. Below are detailed descriptions of the different system components.

2.1. Electrochemical compressors

Electrochemical Compressors (ECC) can employ many different working fluids and thermodynamic cycles. In their simplest form, the compressors can compress hydrogen, via proton pumping. With hydrogen as the working fluid, an electrochemical hydrogen compressor is supplied with hydrogen to the anode, and compressed hydrogen is generated at the cathode. When operated at low 'voltages', ECCs provide very high compression efficiencies (Fig. 1). In one configuration, these compressors can be combined with metal hydride heat exchangers to provide heating and cooling as shown in (Fig. 2).

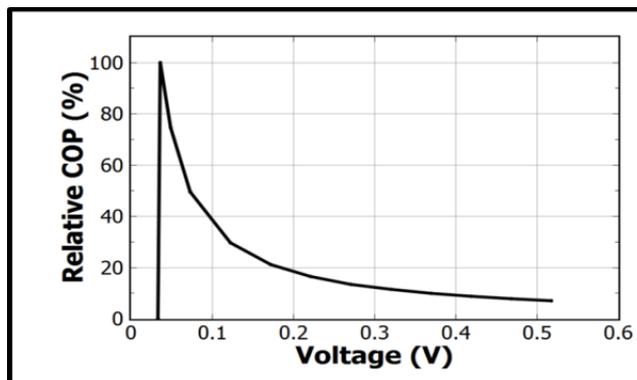


Fig. 1. ECC relative COP (COP/COP_{Carnot}) at various cell voltage

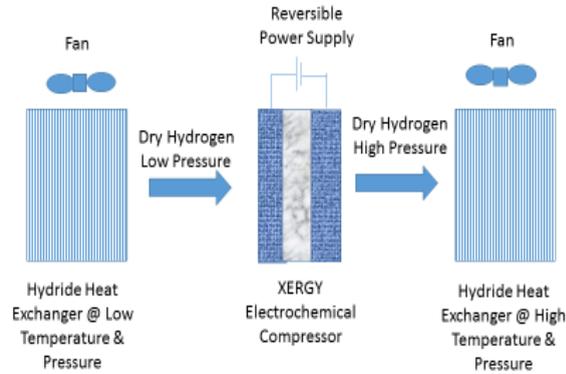
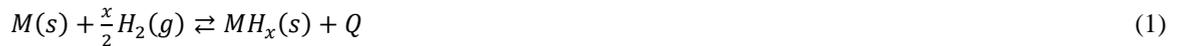


Fig. 2. ECC combined with metal hydride heat exchangers

2.2. Metal Hydride Heat Exchangers

Metal hydrides are metallic compounds, in which one or more hydrogen centers have nucleophilic, reducing, or basic properties. For heat pumps, we utilize the reversible heat-driven reaction of a hydride-forming metal/alloy, or intermetallic compound (IMC) with hydrogen gas:



In Eq.1, M is a metal or alloy (e.g., V or a BCC solid solution based upon it), or an IMC (AB₅, AB₂, etc.); (s) and (g) relate to solid and gas phases, respectively, and Q is the reaction enthalpy. The overall process performance is strongly dependent on the intrinsic features of metal hydride reaction including its thermodynamic and kinetic characteristics, as well as composition, structure and morphology of the solid phases (M, MH_x) involved in the process. These features are mainly related to fundamental aspects of hydride materials. For a given compressor operating voltage (eg .05v/cell) system efficiency (COP) is linearly related to the enthalpy of adsorption varying from 2 to 8 for hydride enthalpy of absorptions of 20 to 80 kJ/mole H₂.

Equilibrium of the metal hydride reaction is characterized by an interrelation between hydrogen pressure (P), concentration of hydrogen in the solid phase (C) and temperature (T). PCT diagrams can be generated to characterize specific hydride-forming materials. These provide the thermodynamics of its interaction with gaseous hydrogen. At low hydrogen concentrations ($0 \leq C < a$) hydrogen atoms form an interstitial solid solution in the matrix per Henry–Sieverts law. When the value of C exceeds concentration of the saturated solid solution, precipitation of the hydride (β -phase with hydrogen concentration) occurs. The system then exhibits a first order phase transition at a constant hydrogen pressure, $P = P_P$ ($a \leq C \leq b$). This pressure is called the plateau pressure in the metal–hydrogen systems. The process is almost exactly (100%) reversible, with slight differences as the concentration changes. This is termed hysteresis, and is a source of efficiency loss (<5%). Hydrogen compression ratio (PH/PL) for hydrides can vary in the range 10–50. Xergy’s one-stage ECC’s, are sufficient to drive hydride systems.

Depending of the type and composition of the hydride-forming material, the equilibrium hydrogen pressures vary in a very broad range, from below 1 bar to exceeding 1 kbar at room temperature. Most of the lower-pressure compression alloys (PH < 200 bar at TH < 150 °C) belong to the AB₅-type intermetallic compounds

while significantly higher, >1 kbar, hydrogen pressures can be generated using AB₂-type compounds. Indeed, the AB₂ compounds have significantly higher enthalpy of adsorption and higher percentage hydrogen storage capacity, see Fig.3. Xergy has built systems with a wide range of commercial AB₅ compounds. With AB₂ compounds, a much higher thermal exchange capacity is feasible which would lead to smaller heat exchangers.

A: hydride forming element; **B:** non hydride forming element

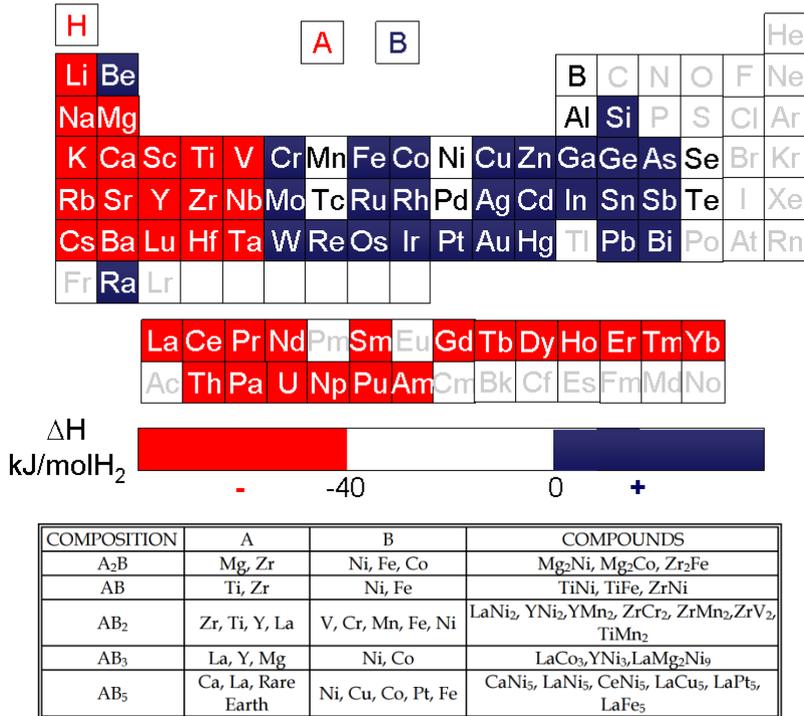


Fig. 3. Hydride and non-hydride forming elements in the periodic system of elements (top) and typical examples of intermetallic hydrides (bottom)[5].

Proper hydride selection is critical to designing useful metal hydride heat exchangers. For durable performance, hydride systems must remain dry. ECC-driven hydride heat exchangers are dual modular systems. A schematic of a potential ECC-based Metal Hydride heat Exchanger (MHX) system is shown in Fig. 3a. Fig. 3b shows a prototype picture of a system with air heat exchangers. In Fig. 4a when using membranes that require hydration to function, the valves would be an appropriately controlled parallel system for (1) water removal and (2) water addition to the hydrogen stream, i.e. a desiccant bed for hydrogen pumped toward the hydride bed and a humidifier for the hydrogen gas being pulled from the hydride bed. The system can also be reduced to one ECC by appropriate plumbing and three-way valves.

Xergy first pioneered the concept of an electrochemical compressor driven metal hydride system in 2014, and the concept was demonstrated in collaboration with a team sponsored by Xergy at the University of Delaware (U.D.). This work resulted in a publication by Fornari et al, in November 2014 at U.D. Since then Xergy has built several advanced ECC-driven heat pumps and filed a family of patents based on this technology.

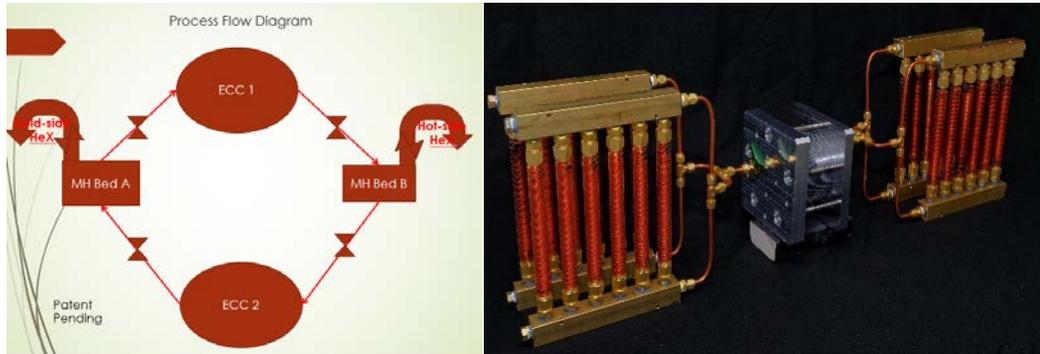


Fig. 4. (a) A schematic for a potential ECC-based MHX. (b) Picture of prototype ECC-based MHX built by Xergy.

Initial development of the electrochemical compressor-based metal hydride system was conducted with commercially available hydride cylinders with heat exchanger capability. Two designs differing in the placement of the heat exchanger coil and the aspect ratio of the units were tested: (1) exterior-wrapped tubes brazed to the high aspect-ratio hydride containing cylinder (Fig.5a), and (2) a coiled tube placed inside a lower aspect ratio hydride cylinder (Fig. 5b). Both designs showed significant deficiencies in heat exchange capability. It is critical that good heat transport be achieved in order to eliminate hot or cold spots while the hydride is sorbing/desorbing. On desorbing/sorbing H_2 the heat exchanger gets very cold, $-7.8^\circ C$ ($18^\circ F$), and hot, $86.1^\circ C$ ($187^\circ F$), with materials we expect to use in the basic heat exchanger. We can employ more expensive and less common materials for special very cold or very hot sink and source requirements and for enhanced COP (higher enthalpy variants).

As discussed earlier, the ECC-MHX consists of one or 2 ECC and 2 beds of MHX with associate valves and control equipment. In the initial configuration that was investigated, the ECC pumped the hydrogen from MHX bed A, thereby reducing its temperature and pressure, to MHX bed b, where H_2 is being adsorbed resulting in significant heat release. A heat exchanger between bed A and the room allows the bed A to provide the cooling effect and another heat exchanger between bed B and water allows bed B to reject heat to the high temperature reservoir. When the desorbing bed A pressure drops to the point that the hydrogen compressor shows signs of insufficient hydrogen supply (approximately 138 kPa (20 PSIG)) all the valves are switched to the opposite sense. Hydride bed B is now connected to the suction side of the ECC and accepts heat from the room air heat exchanger, while hydride bed A is now absorbing hydrogen while dumping heat to the water tank.

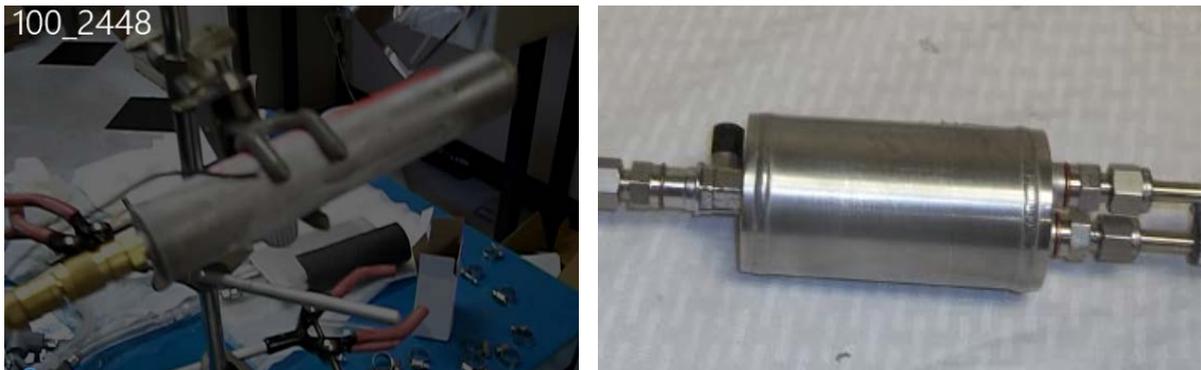


Fig. 5. Hydride cylinders with heat exchanger capability (a) high aspect-ratio hydride with potential for exterior wrap-around coil and (b) a coiled tube placed inside a lower aspect ratio hydride cylinder.

Fig. 6 shows results for COP vs operating voltage. “G” represents the case for higher COP at low voltages and currents (H_2 flow) for steady state maintenance of temperature. Subsequently, we targeted faster heating by operating at higher voltages represented by “T”. The calculated COPs, G=2.8 and T=1.4, are very close to the expected values based on the model.

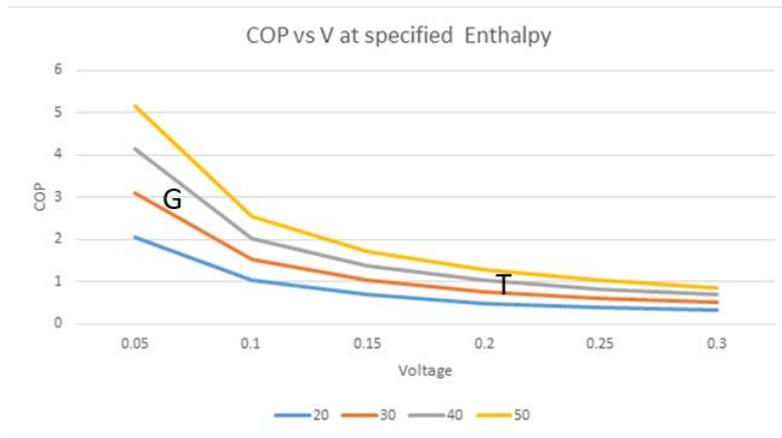


Fig. 6. ECC-MHX Heat Pump Water Heater COP (heating COP) as a function of voltage.

2.3. Liquid Desiccant Subsystem

Air conditioning is used to control both the temperature and the humidity of indoor air to provide the preferred level of thermal comfort. In warm and humid climates, the latent load charged by a dehumidifier for moisture removal could represent up to 88% of the total air conditioning load according to Harriman III [6]. Therefore, air dehumidification can be an energy-intensive process. Liquid desiccant air conditioning (LDAC) has been investigated as a promising alternative to vapor compression (VC) technology because it has lower electricity consumption, a higher system coefficient of performance (COP), a reduced condensate air flow rate, and a reduced VC size [7-14]. LDAC separates the sensible cooling and latent cooling to meet the requirements of humidity and temperature independently. LDAC uses the liquid desiccant to absorb the moisture in the air driven by the difference between the vapor pressure at the surface of the liquid desiccant and that of the surrounding air in order to eliminate the electrical demand of the VC system used for the dehumidification.

In our design, we use the ECC-MHX to provide the sensible cooling and the liquid desiccant subsystem provides the latent cooling. The systems are to be designed such that the waste heat from the ECC-MHX be used as the heat source to regenerate the desiccant solution. The liquid desiccant subsystem consists of 2 heat and mass exchangers (dehumidifier and regenerator) and 4 heat exchangers (solution cooler, solution heater, internal heat exchanger, and air heat recovery). The solution heater and cooler can be combined with the regenerator and dehumidifier respectively to reduce cost. The internal heat exchanger is important to minimize internal heat loss and maintain high efficiency and the ambient air heat recovery heat exchanger can be made of low cost polymer materials to reduce cost. Fig. 7 below shows a schematic of a possible configuration of the liquid desiccant subsystem integrated with the ECC-MHX. In this design, the sensible cooler is cooled by the ECC-MHX and the solution heater is heated by the waste heat of the ECC-MHX.

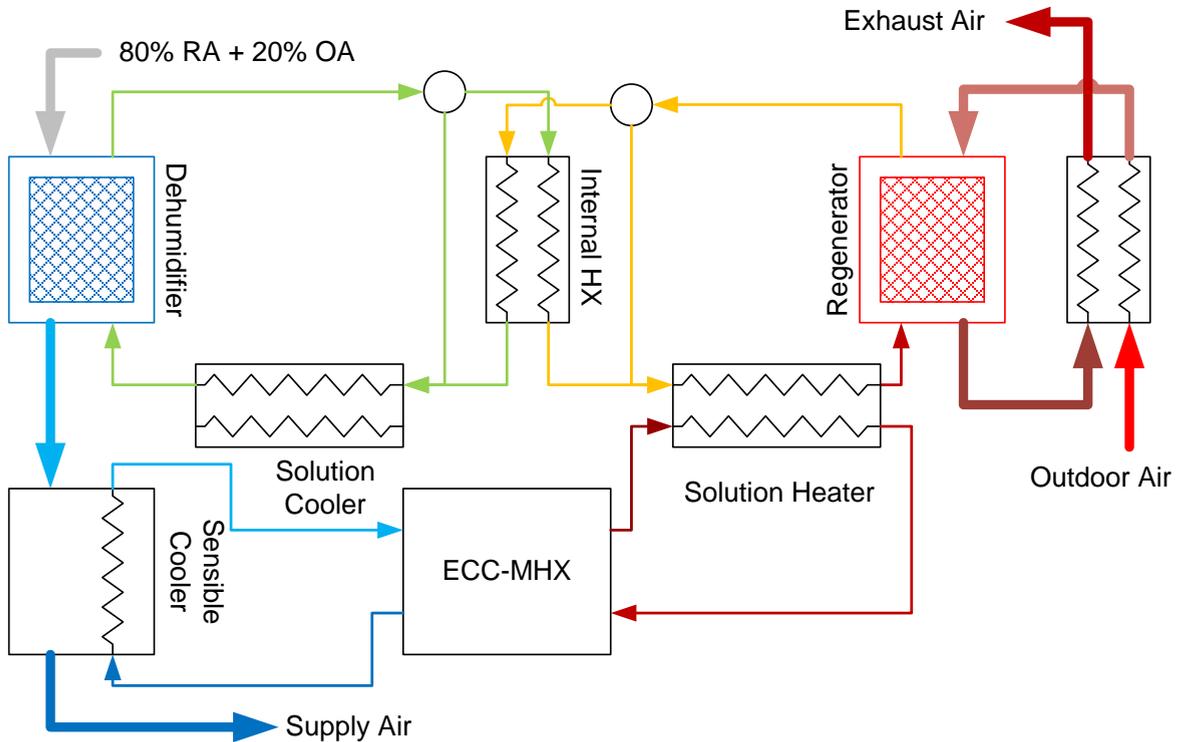


Fig. 7. Schematic of a system configuration of separate sensible and latent cooling employing liquid desiccant subsystem

The case study of the system design in this paper was for a 5.4 kW (18,000 Btu/hr) system with 0.189 m³/s (400 cfm) air volume operated at standard AHRI rating conditions. Twenty percent (80 cfm) of the total air volume was from outdoor air (OA) and was mixed with the 80% return room air (RA) from the space. In a typical vapor compression system, the mixed air (MA) should be cooled down to the dry bulb temperature at 12.78°C (55°F) with the wet temperature at 12.2 °C (54°F), which represents a 0.68 sensible heating ratio (SHR). The total cooling load is approximately 5.4 kW (1.54 cooling tons) while the vapor compression system required 5.856 kW to meet the same load due to the overcooling and reheating process. To provide the same amount of cooling at 5.4 kW, the LDAC system can supply air at the same condition as the typical system or at a higher temperature at 18.3°C (65°F) with relative humidity at 65.8%, if the air volume flow rate is increased to 0.25m³/s (528 cfm).

2.3.1. Ionic Liquid

Historically ordinary (hygroscopic) salts such as NaCl, LiCl, LiBr have been used in HVAC applications as liquid desiccants. Ionic liquids, which are salts comprised of organic cations and inorganic anions or organic anions, become liquid when exposed to room temperature and atmospheric pressure. They have high thermal stability, negligible or no vapor pressure, varied solubility in water, low or no corrosion to metals, and low driving temperatures to achieve dew point temperatures. ILs, therefore, can be used as desiccant materials to remove humidity from environment. A few research groups investigated ILs as potential alternatives to

traditional desiccant liquids used in LDAC [15-17]. There are in fact, bulky, asymmetric organic cations that provide better performance than traditional salt solution in HVAC applications. Organic salts can also be tailored and optimized for specific operating conditions. There are very few other publications available about the ILs used as desiccant liquids. We synthesized 13 different ILs, and performed absorption & desorption evaluations for these candidates. All tests were performed under thermodynamic equilibrium conditions. The objective of the research was to identify an ideal substitute for traditional desiccant liquids among the identified ILs that have good thermal stability, high solubility in water, low or no corrosion to metals, and potential for low cost when manufactured at scale and system performance for the applications of LDAC. First, screening tests were conducted with all 13 candidates for identifying the most promising candidate(s) that can provide the highest vapor adsorption and desorption. Among the 13 different ILs, 1-Ethyl-3-methylimidazolium acetate exhibited the highest capability of absorbing vapor and desorbing water and was identified as the most promising substitute. Its molecular formula is $C_8H_{14}N_2O_2$ and its molar-mass is 170.21 g/mol. It can be abbreviated as [EMIM][OAc] / [emim][OAc] or [C₂MIm][OAc].

A large number of studies were found in the literature that investigated the properties of pure [EMIM][OAc] or the solution with little water [18-23]; however, only a few addressed the properties for the aqueous solution of 1-Ethyl-3-methylimidazolium acetate [24]. Based on the literatures, we summarized the data of the thermos-physical properties for the aqueous solution of [EMIM][OAc] and generated the calculation formulations for predicting the thermos-physical properties of the aqueous solution of [EMIM][OAc] by using both thermodynamic principles and statistical methods. The calculation formulations were generated to predict the following thermos-physical properties of the aqueous solution of [EMIM][OAc]: vapor pressures, specific heat capacity, density, and dynamic viscosity.

2.3.2. Results of Liquid Desiccant Subsystem

For our system study and analysis, we used LiCl aqueous solutions as the working fluid in order to make sure we have reliable fluid data for our simulations. After careful study of several components size impact and potential cycle modifications to enhance performance, we concluded that the best system configuration is that shown in Fig. 8. The system consists of seven heat exchangers: two liquid-to-liquid HXs, two air-to-liquid HXs, one air-to-air HX, one liquid desiccant dehumidifier, and one liquid desiccant generator. In this system, $MA1 = MA2 = 0.31$ kg/s (528 cfm). However, MA1 has 80% RA and 20% OA while MA2 has 20% RA and 80% OA. MA1 is the air flow that goes through the dehumidifier, the sensible cooler and eventually provides the space cooling. MA2 is the air flow used for solution cooling. Another 0.2 kg/s of OA are used for the generator from the entering air-to-air heat recovery HX. Hot water at 54°C (129°F) from ECC-MHX waste heat is used to heat the liquid in the liquid-liquid HX. The chilled water at 12°C (54°F) from the ECC-MHX is used to cool the dehumidified air to the desired temperature of 18.3°C (65°F). The air in the dehumidification process is very close to an adiabatic process. The heat gain during dehumidification is only about 0.48 kW. The temperature, flow rate, and concentration of each stream for the dehumidifier and regenerator are summarized in Tables 1 and 2. The heat exchanger capacity for the system components is summarized in Table 3. The LDAC system shown in Fig. 8 only required 5.06 kW of sensible cooling at 12°C compared to the VC system.

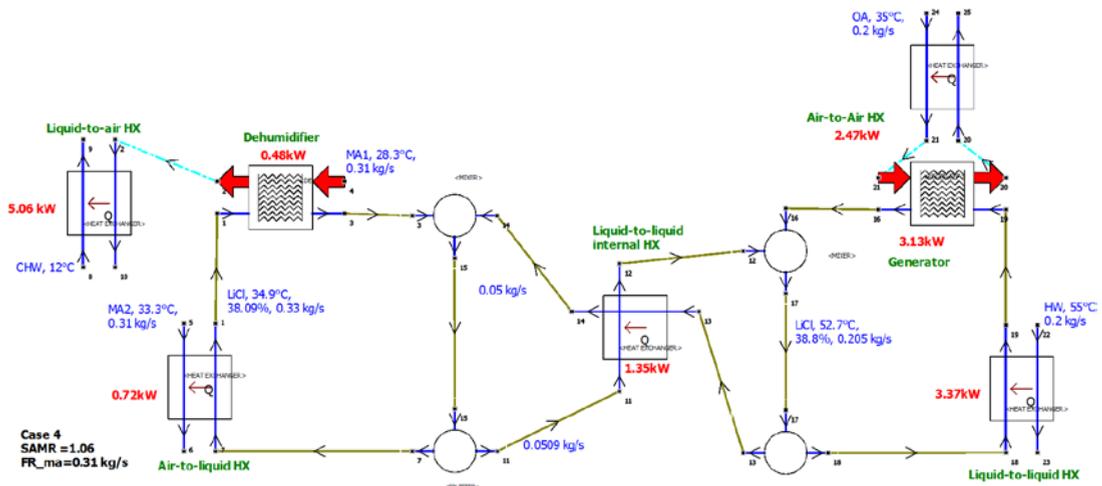


Fig. 7. Hydride cylinders with heat exchanger capability (a) high aspect-ratio hydride with potential for exterior wrap-around coil and (b) a coiled tube placed inside a lower aspect ratio hydride cylinder.

Table 1 Dehumidifier performance assuming NTU = 2.2

Variable	Value	Unit
Solution inlet temperature	34.88	°C
Solution outlet temperature	35.51	°C
Solution flow rate	0.33	kg/s
Solution inlet concentration	38.08	%
Solution outlet concentration	37.97	%
Air inlet temperature	28.3	°C
Air outlet temperature	34.28	°C
Air flow rate	0.31	kg/s
Air inlet humidity ratio	0.0116	kg/kg _{dry air}
Air outlet humidity ratio	0.0086	kg/kg _{dry air}

Table 2 Regenerator performance assuming NTU = 2.2

Variable	Value	Unit
Solution inlet temperature	52.76	°C
Solution outlet temperature	46.99	°C
Solution flow rate	0.2	kg/s
Solution inlet concentration	38.79	%
Solution outlet concentration	38.97	%
Air inlet temperature	46.93	°C
Air outlet temperature	50.41	°C
Air flow rate	0.2	kg/s
Air inlet humidity ratio	0.0142	kg/kg _{dry air}
Air outlet humidity ratio	0.0189	kg/kg _{dry air}

Table 3 Heat exchangers duty

Heat Exchanger	Duty, kW
Dehumidifier	0.48
Regenerator	-3.13
Internal heat exchanger	1.34
Solution cooler	0.72
Solution heater	3.38
Outdoor heat recovery	2.46
Sensible cooler	5.06

3. Overall System Result

This study used an electrochemical compressor to produce chilled water at; and the heat generated during electrochemical compression was used as the heating source in the generation loop. Therefore, electricity was consumed only to compare the recommended LDAC system to the conventional VCR. The COP of the electrochemical compressor for producing chilled water at 12°C (54°F) was assumed to be 5. Therefore, the total electricity demand for generating 5.06 kW chilled water at 12°C (54°F) was 1.02 kW of electric power. Comparably, if a VCR system was used to provide the 5.4 kW of cooling, as discussed in earlier, the electricity demand was 1.677 kW to provide 5.856 kW of total cooling and moisture removal by using 3.5 as the COP (EER = 12) of typical VC system. In addition, the power to be used for the fans and pumps in LDAC which are additional to those used in a typical VCR shall be included in the system performance analysis. The recommended LDAC system primarily consists of two fans for the dehumidifier and the regenerator, and two pumps in the dehumidification and regeneration loops. The fan for the regenerator and the two pumps are assumed as the devices in the LDAC additional to those in the VC system. According to ASHRAE/IES Standard 90.1-2013, fan power rate is 365 W/1000 cfm. To provide a 0.2 kg/s (340 cfm) air flow, the fan power is 0.124 kW. According to ASHRAE 90.1, pump power rate is 22 W/gpm. To provide a 0.33 kg/s (5.23 gpm) of water flow in the dehumidification loop and a 0.21 kg/s (3.33 gpm) of water flow in the regeneration loop, the total pump power is 0.188 kW. As such, the overall energy consumption for the LDAC/ECC-MHX would be 1.332 kW; and the expected energy savings compared to best in class window unit (EER 12) is 21%.

4. Conclusions

A basic framework for a highly efficient, noiseless, vibration free heat pump system without GWP working fluids, and utilizing liquid desiccant to avoid latent heat loads has been provided for a window air conditioner. This concept can clearly serve as a basis for larger heating and cooling applications – where the savings can be significantly larger.

The study presented in this paper identified a system configuration for LDAC coupled with electrochemical compression. The rationale and the process of identifying the system configuration were discussed and illustrated. Five cases of different system configurations were studied and simulated in Sorpsim. The final recommended system configuration was determined based on its 21% energy savings compared to a conventional VC system. The findings in this paper will be the foundation for the upcoming next phase of this study, which includes prototype design, fabrication, testing, and analysis.

Acknowledgements

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