Experimental study on electrochemical compression of ammonia and carbon dioxide for vapor compression refrigeration system

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ARTICLE INFO

ABSTRACT

After the establishing of Montreal Protocol Agreement, industries are seeking alternative refrigerants to replace HFCs with high GWP. Meanwhile, the efficiency of vapor compression refrigeration system still remains as a challenge. In this study, we propose an electrochemical compressor for the vapor compression refrigeration cycle running with ammonia or carbon dioxide as its working fluids. The single unit electrochemical compressor prototypes for both refrigerants were developed and their performances were demonstrated with a potential isothermal compression efficiency of 90%. The system level performance was modeled for both refrigerants with coefficient of performance of 5.1 for ammonia refrigeration and 3.9 for carbon dioxide refrigeration. The scaled-up compressor design with improved gas distribution channels and internal heat exchangers was also demonstrated for the system. Since the electrochemical compressor does not use any moving parts, it does not need to use lubrication oil as well as produce any noise or vibration. Moreover, it can potentially approach an isothermal compression for even higher energy efficiency and thus improve the system performance.

Étude expérimentale sur la compression électrochimique d'ammoniac et de dioxyde de carbone pour un système frigorifique à compression de vapeur

1. Introduction

The refrigeration industry is currently facing a main environmental challenge because of using high global warming potentials (GWP) refrigerants and low efficient systems. The direct environmental challenge mainly involves the utilization of high GWP HFCs, which are widely adopted in 170 million refrigerators and freezers in the United States (US DOE, 2016). Most of the currently used HFCs are greenhouse gases with high GWP, which means the release of these gases into the atmosphere would cause the rise of earth surface temperature. In October 2016, country leaders around the world have agreed to pass the Montreal Protocol Kigali Amendment, aiming to phase down HFCs by 80% by the year of 2050 (Montreal Protocol Handbook, 2016). Therefore, HVAC industry is actively seeking alternative refrigerants with low GWPs to replace high GWP HFCs. On the other hand, the efficiency of small-scale cooling appliances has always been holding back by the mechanical gas compressors in the system, typically with isentropic efficiency of 65%. The mechanical compressors are the major energy consumer in the vapor compression refrigeration cycle (VCRC) and their efficiency enhancement is saturated due to limitations in heat transfer and manufacturing tolerances. The electrochemical compression technology is developed to address these challenges. The electrochemical compressor (EC) has a great potential of achieving an isothermal compression efficiency greater than 90%, and it works with environmentally friendly refrigerants such as ammonia (NH_3) and carbon dioxide (CO_2). It also operates without using lubrication oil and does not cause any noise and vibration.

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Nomenclature

COP	coefficient of performance
CO_2	carbon dioxide
DC	direct current
E	cell voltage V
EC	electrochemical compressor
F	Faraday's constant
HFC	hydrofluorocarbon
HVAC	heating, ventilation and air conditioning
GWP	global warming potential
MH	metal hydride
n	number of electrons transferred
NH_3	ammonia
P	partial pressure Pa
PEM	proton exchange membrane
Q	cooling capacity W
R	ideal gas constant
T	temperature K
U	electric voltage charge V
VCC	vapor compression cycle
W	work input W

Greek Letters

η	Compressor efficiency

Subscript

0	reference state
EC	electrochemical compressor

The EC was first proposed and studied by General Electrics in the 1980s (Sedlak et al., 1981). The idea was based on charging DC voltage to an ion exchange membrane, which is mainly proton exchange membrane (PEM), so that hydrogen molecules can be pumped across the membrane. Nafion is typically used as the PEM and the pressure of the compressed hydrogen can be as high as 100 MPa according to the works by Lipp and Patel (2011) and Bouwman (2014). After their initial study, more groups have worked on electrochemical hydrogen compressor and improved its performance (Rohland et al., 1998; Strobel et al., 2002; Gardner and Ternan, 2007; Onda et al., 2007; Grigoriev et al., 2011). However, the application in the past are only limited to hydrogen purification and concentration for fuel cell systems.

In order to apply the concept of electrochemical hydrogen compression to produce cooling and heating effects, researchers utilized the unique property of metal hydride (MH), which allows metal hydride to reversely react with hydrogen and generate thermal effect. In the past, there are mainly two major types of MH heat pump that have been developed and studied (Takeda et al., 2009; Muthukumar and Groll, 2010). The first type is called heat driven MH heat pump. It takes advantage of the reaction pressure and temperature differences of two kinds of MH compound materials. The heat pump is designed by connecting two types of MH reactors. When heated, the first reactor releases hydrogen at low pressure and temperature (provided by waste heat or solar radiation) and is utilized as a driving force to increase the hydrogen pressure of the second reactor. The second reactor then absorbs hydrogen at higher pressure and releases heat at higher temperature which can be used for heating purpose. On the other hand, when slightly cooled, the first reactor absorbs hydrogen at high pressure and temperature, which therefore reduces the hydrogen pressure of the second reactor. The second reactor then desorbs hydrogen at lower pressure and temperature to provide cooling. This type of the MH heat pump usually has lower performance
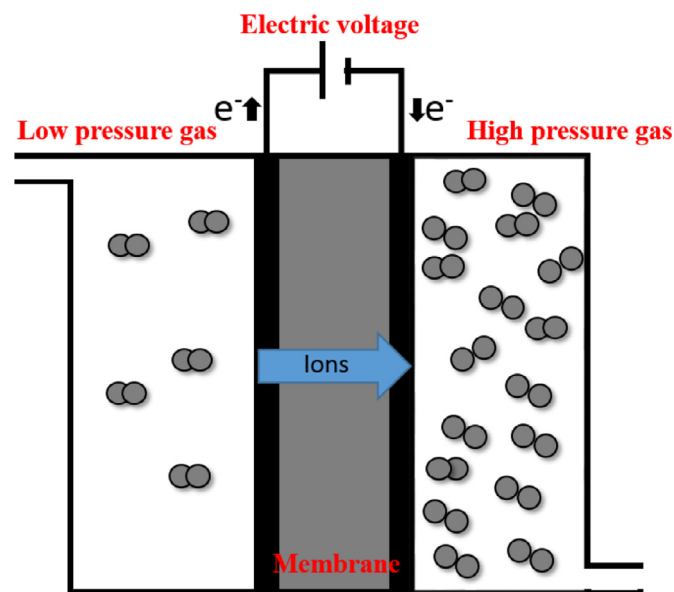

Fig. 1. The working principle of electrochemical compressors.

and has COP less than 1 (Zhong and Glanville, 2014). The compressor driven MH heat pump usually has two identical MH reactors interconnected to generate heating and cooling at the same time by increasing the pressure of the hydrogen-absorbing reactor and decreasing pressure of the hydrogen-desorbing reactor with a mechanical compressor (Takeda et al., 2009; Muthukumar and Groll, 2010). The compressor driven MH heat pump has been studied by various groups and produced COPs ranging from 2.6 to 4.3 (Kim et al., 1997; Park et al., 2001, 2002; Mazumdar et al., 2004; Magnetto et al., 2006).

Inspired by the compressor driven MH heat pump, Tao et al. (2015) studied the performance of electrochemical hydrogen compressor coupled with MH for heat pump purposes. The EC works similarly as mechanical compressor to create a pressure difference between the absorbing and desorbing reactors. They concluded that the system is 20% more efficient than the mechanical compressor driven system.

Since most of previous eletrochemical compression researches focused on hydrogen compression, further studies are needed for compressing other fluids especially those can be applicable to VCRC. Therefore, this paper focuses on how to electrochemically compress natural working fluids such as NH_3 and CO_2 based on the discovery by Tao et al. (2017) that the EC can also compress other types of gas refrigerants such as NH_3 and CO_2, depending on the kind of ion exchange membrane inserted in the compressor. The EC was evaluated based on its compression ratio, flow rate and efficiency on the single unit. The scaled-up compressor with multiple units in parallel was modeled in the refrigeration system based on COP and cooling capacity. The compressor design was also proposed with heat exchangers embedded to cool down the refrigerant on the discharge side, so that the compression process can achieve isothermal to further increase its efficiency.

2. Working principle of electrochemical compression of NH_3 and CO_2

Fig. 1 shows the working principle of any type of ECs. When the ion exchange membrane electrode assembly (MEA) is charged with a DC voltage, the gas refrigerant molecules on one side of the membrane are split into ions and electrons. The ions are transferred across the ion exchange membrane due to the voltage
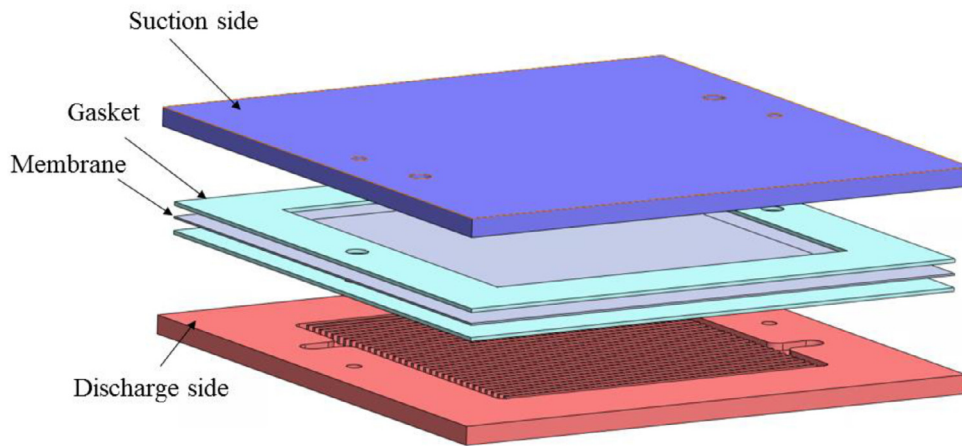
Fig. 2. Single unit electrochemical compressor structure.

charge while the electrons travel in the external circuit. Both ions and electrons are recombined on the other side of the membrane to regenerate the gas refrigerant molecules. If constant voltage is provided to the MEA and an expansion device controls the gas flow from the EC discharge side to EC suction side, the gas refrigerant molecules are continuously consumed on EC suction side and re-generated on EC discharge side so that a pressure difference across the membrane can be maintained. Since the membrane remains stagnant during the compression process, there is no moving part involved so that no lubrication is required, and no noise and vibration are generated.

For the electrochemical compression of NH_3, the EC uses H_2 as a carrier gas to bring NH_3 across the ion exchange membrane. When both NH_3 and H_2 are fed to the anode, two chemical reactions take place at the same time (Eqs. (1) and 2). The first reaction is the split of H_2 into protons (H^+) and electrons (e^-). NH_3 molecules then combine with protons to form the ammonium ion (NH_4^+), which gets transferred across the ion exchange membrane (Tao et al., 2017).

These reactions in anode are:

$$H_2 \rightarrow 2H^+ + 2e^- \tag{1}$$

$$2NH_3 + 2H^+ \rightarrow 2NH_4^+ \tag{2}$$

When NH_4^+ reaches the cathode side of the membrane, it is converted back to NH_3 and proton, proton will then receive an electron and reproduce H_2 at higher pressure (Eqs. (3) and 4).

These reactions in cathode are:

$$2NH_4^+ \rightarrow 2NH_3 + 2H^+ \tag{3}$$

$$2H^+ + 2e^- \rightarrow H_2 \tag{4}$$

The standard voltage charge in order to make the reactions happen is 200 mV. And for each H_2 molecule transferred across, there are two molecules of NH_3 accompanied. Therefore, the over-all compression reaction ratio is shown as follows:

$$2NH_3 + H_2 \text{ (at } P_1) \rightarrow 2NH_3 + H_2 \text{ (at } P_2) \tag{5}$$
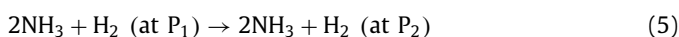
The hydrogen carrier gas can be removed by either phase separation at the condenser outlet or absorbed by MH electrode at the cathode side of the proton exchange membrane.

The electrochemical compression of CO_2 works in similar principle to that of NH_3. Except that O_2 is used as a carrier gas to bring CO_2 molecules across the ion exchange membrane. The ion exchange membrane in this case, conducts negatively charged anions instead of positively charged ions. When both CO_2 and oxygen

(O_2) are fed to the cathode side of the membrane, facilitated by the $CaRuO_3$ catalyst, only one chemical reaction takes place (Eq. (6)), which is the combination of O_2 and CO_2 to form the negatively charged CO_3^{2-} ion (Vega et al., 2012).

This reaction in cathode is:

$$O_2 + 2CO_2 + 4e^- \rightarrow 2CO_3^{2-} \tag{6}$$

The CO_3^{2-} ion is then transferred from cathode to anode under the voltage charge. When the ion reaches the anode, it is converted back to O_2 and CO_2 (Eq. (7)).

This reaction in amode is:

$$2CO_3^{2-} \rightarrow O_2 + 2CO_2 + 4e^- \tag{7}$$

The standard voltage charge to make this reaction take place is around 1.2 V. And for each O_2 molecule transferred across, there are two molecules of CO_2 accompanied. Therefore, the overall electrochemical compression process can be represented in the following reaction (Eq. (8)).

$$O_2 + 2CO_2 \text{ (at } P_1) \rightarrow O_2 + 2CO_2 \text{ (at } P_2) \tag{8}$$
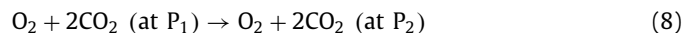
The O_2 carrier gas can be handled by either phase separation at the gas cooler outlet or absorbed by perovskite electrode on the anode side of the anion exchange membrane.

3. Experimental study and results of NH_3 and CO_2 ECs

The experimental setup and results of single unit EC are discussed in detail next. And the system performance with EC for VCRC is modeled and COP is calculated and compared with the conventional system. The concept of electrochemical compression of both NH_3 and CO_2 has been experimentally verified. With the verification on a single EC unit, the scaled-up design of the EC stack is presented at the end. In order to verify the feasibility of electrochemical compression for both refrigerants, two conditions should be met. The first is the transfer ratio between the refrigerant molecule and carrier gas molecule. The second condition is that the compression ratio and voltage charge must satisfy the Nernst relationship. In this work, we have successfully verified both conditions and the experimental study is discussed in detail. The electrochemical compression unit is mainly composed of gas distribution channels and ion exchange membranes with gaskets for preventing leakage. Fig. 2 shows the single EC unit structure. The gas distribution channels evenly distribute the gas refrigerant and the carrier gas on the surface of the membrane electrode. The channels are made of either graphite or stainless steel to facilitate electric conductivity. From preliminary investigation, we found out that due to corrosion issue, the graphite channels are only suitable for operating conditions with voltage under
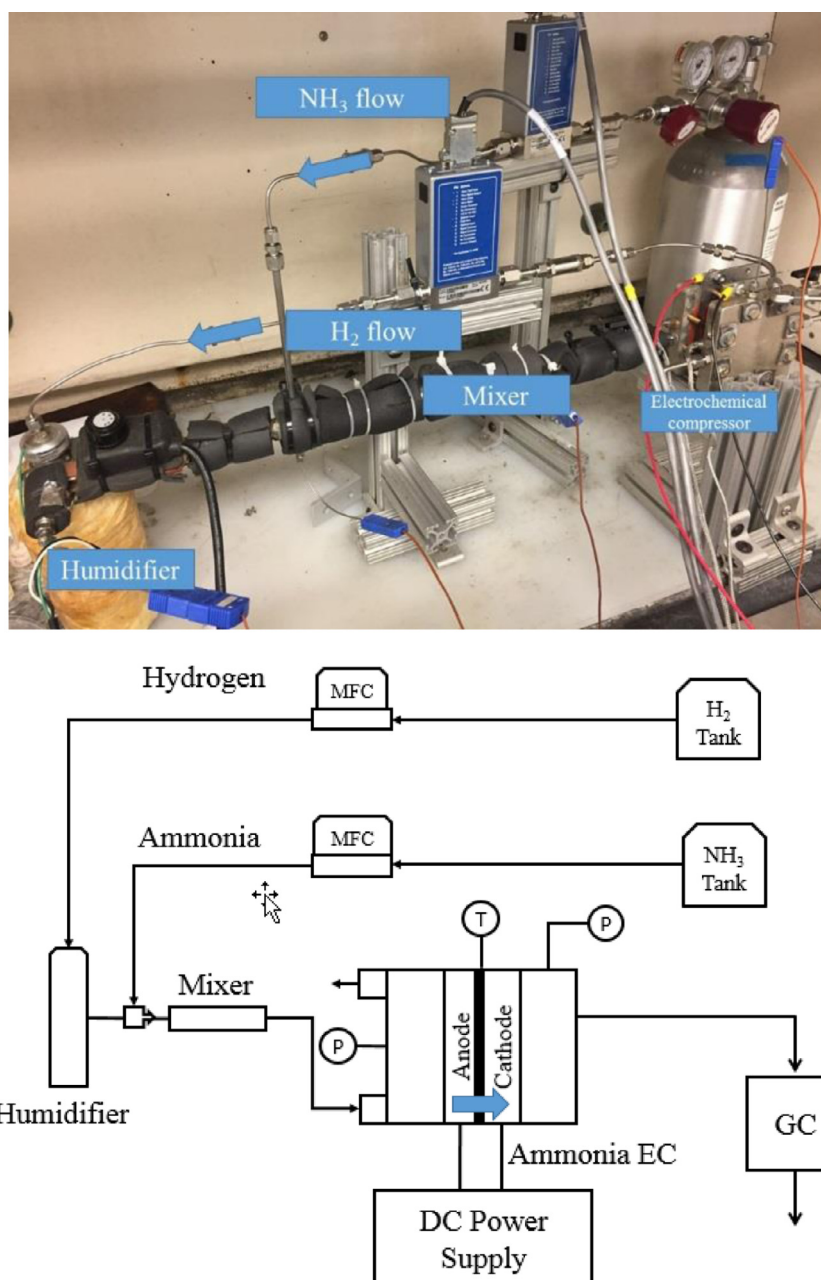
Fig. 3. Test facility for EC discharge stream concentration measurement and its schematic diagram.

800 mV, while the stainless-steel channels are good for high voltage charge from 1.2 to 1.6 V. Therefore, graphite channels can be used for NH_3 EC, while stainless steel channels can be used for CO_2 EC. When both sides of the membrane electrodes are charged with a voltage, it pumps refrigerant and carrier gas mixture in a fixed transfer ratio across the membrane to the other side. On the other side, the gas distribution channel discharges refrigerant and the carrier gas mixture at an elevated pressure. Experimental studies were conducted to measure the transfer ratio between the refrigerant gas and carrier gas. The testing setup and schematic diagram in Fig. 3 show that both gas refrigerant and carrier gas pairs (NH_3/H_2 and CO_2/O_2) are fed with controlled flow rates. The carrier gas stream goes through the humidifier first and then merges with the refrigerant gas. They are both mixed in the inline static mixer and fed to the inlet of the EC. The compressor takes the mixture stream on the inlet and discharges the mixture on the outlet at an elevated pressure. Finally, the discharged mixture stream is fed to a gas chromatography for concentration analysis. The concentration ratio of NH_3/H_2 must be equal to 2.0 to meet the proposed stoichiometric coefficient in Eq. (5). Similarly, the concentration ratio of CO_2/O_2 must be equal to 4.0 to meet the proposed stoichiometric coefficient in Eq. (8). The GC analysis results are shown in Table 1. The gas transfer coefficient represented by the concentration ratio for NH_3/H_2 is 2.0, which satisfies the proposed Eq. (5). And the transfer ratio represented by CO_2/O_2 concentration ratio is around 4.0, which satisfies the proposed reaction Eq. (8). The reason for CO_2/O_2 to be less than 4.0 is that there would be additional side reaction with water which brings down the stoichiometric coefficient as the catalyst selectivity on CO_2 and O_2 is not 100%. An improvement on the catalyst selectivity is currently undergoing and will be updated in the future.

The second condition needs to be verified is the pressure ratio and voltage relationship. If electrochemical compression is truly

Table 1
Gas chromatography test results of ECs.

Compression/ carrier gas	Voltage charge (V)	Suction side gas flow rate (sccm)		Discharge side gas composition (mol.%)		Transfer ratio (mol/mol)
		Compression gas	Carrier gas	Compression gas	Carrier gas	
NH₃/H₂	0.2	100	50	0.61	0.30	**2.0**
	0.2	100	50	0.83	0.40	**2.0**
	0.2	100	50	0.74	0.37	**2.0**
CO₂/O₂	1.2	50	50	0.88	0.24	**3.6**
	1.2	50	50	0.73	0.21	**3.4**
	1.2	50	50	0.88	0.23	**3.8**
	1.2	50	50	0.61	0.16	**3.9**
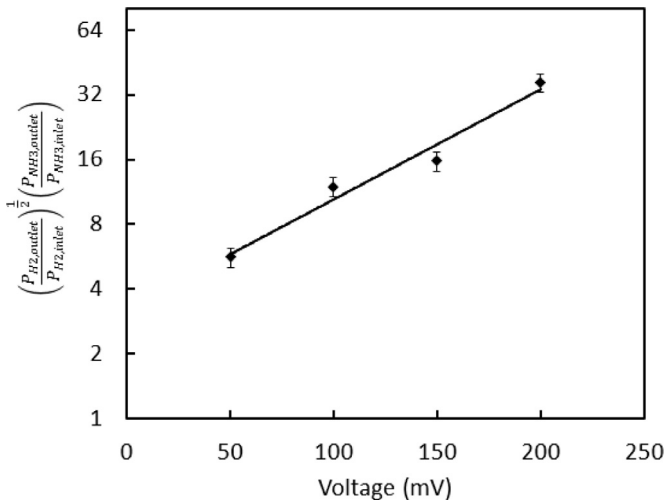
Fig. 4. Partial pressure ratio versus voltage charge based on Nernst equation for NH_3 EC with H_2 as a carrier gas.

taking place, the pressure ratio across the membrane and voltage charge would satisfy the Nernst Equation (Tao et al., 2017). When the membrane electrode can maintain a pressure difference due to electric voltage charge, the pressure difference and voltage charge are in natural log relationship as shown in Eq. (9).

$$U_{Nernst} = E_0 + \frac{RT}{nF} \ln \frac{p_2}{p_1} \qquad (9)$$

where the p_2 and p_1 represent the partial pressure of each gas in discharge and suction stream.

Therefore, the Nernst equation can be derived for both NH_3 and CO_2 ECs, respectively.

$$U_{Nernst} = E_0 + \frac{RT_{EC}}{nF} \ln \left(\left(\frac{P_{H2,\ discharge}}{P_{H2,\ suction}} \right)^{\frac{1}{2}} * \left(\frac{P_{NH3,\ discharge}}{P_{NH3,suction}} \right) \right) \qquad (10)$$

$$U_{Nernst} = E_0 + \frac{RT_{EC}}{nF} \ln \left(\left(\frac{P_{O2,\ discharge}}{P_{O2,\ suction}} \right)^{\frac{1}{2}} * \left(\frac{P_{CO2,\ discharge}}{P_{CO2,suction}} \right) \right) \qquad (11)$$

The tests were performed with discharge side valve closed to let the pressure build up until it is no longer increasing. While NH_3 EC was charged with four different voltage levels (50, 100, 150 and 200 mV), pressure ratios and voltage charges were measured. Note that even though the system has reached steady state and the pressure is no longer building up, there is still measureable current across the membrane to overcome the back diffusion of gas molecules. The major error source would be leakage of the electrochemical compression cell body. Different trials at same voltage charge may generate various pressure level at 5% of error. The experimental uncertainty is shown in Figs. 4 and 5. The resulted relationship satisfies the natural log Nernst equation as shown in Fig. 4. Similarly, when CO_2 EC was charged with three different voltage levels (2.2, 2.3, and 2.5 V), the pressure ratios were measured and calculated, and the natural log Nernst relationship was satisfied as shown in Fig. 5.

As Fig. 4 shows, the EC is able to compress NH_3 from 0.1 to 1 MPa in a single stage, showing a compression ratio of 10, which is considered to be sufficient for NH_3 refrigeration cycle. On the other hand, the highest pressure achieved by EC for CO_2 compression from 0.1 MPa in a single stage was 0.62 MPa. In this case, a multiple stage unit needs to be built to have enough discharge pressure for CO_2 transcritical refrigeration cycle. The CO_2 EC is still
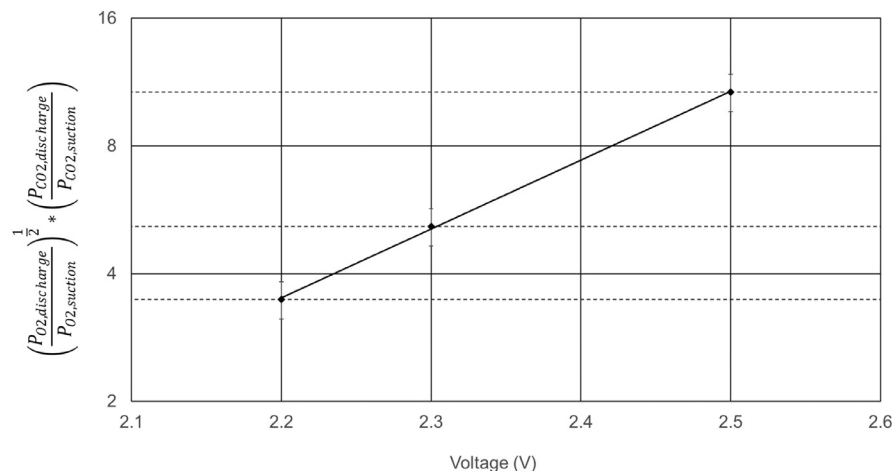
Fig. 5. Partial pressure ratio versus voltage charge based on Nernst equation for CO_2 EC with O_2 as a carrier gas.

Table 2

Performance comparison between the conventional CO_2 refrigeration system and the EC CO_2 refrigeration system.

System	Rated COP	Rate COP improvement [%]	Rated compressor power [W]	Isentropic compression efficiency [%]
Conventional CO_2 refrigeration system	**2.4**	Baseline	88	65
CO_2 EC refrigeration system	**4.0**	67	51	85
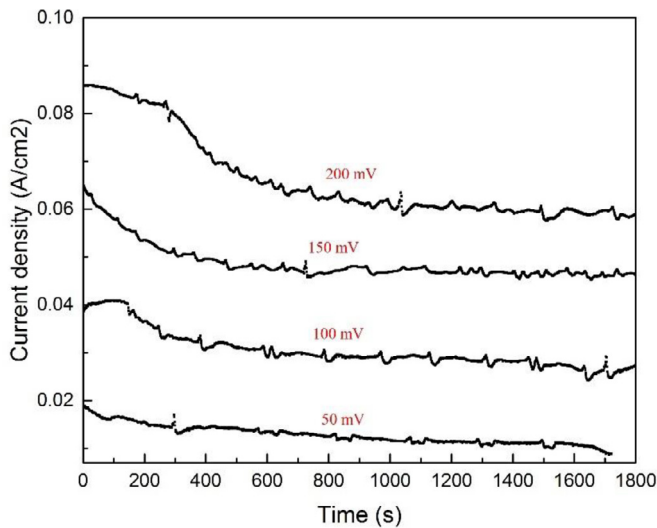
Fig. 6. Current density vs time at constant voltage charge (50, 100, 150, 200 mV) with cathode valve closed, current density decreases eventually stabilizes to reach steady state.

Table 3

Electrochemical compressor size comparison.

Compressor type	EC CO_2	Conventional
MEA area (cm^2)	400	N/A
Size (cm^3)	$20 \times 20 \times 120$	$45 \times 25 \times 70$

under development to improve its performance. The compression efficiency for the CO_2 EC is yet to be optimized in order to reach 90% by improving membrane electrode assemblies.

The data presented in both Figs. 4 and 5 were measured at steady state. It takes about 30 min for the electrochemical compressor to go from transient to steady state. The steady state is determined when current is no longer decreasing and pressure is no longer increasing the discharge side of the compressor (Fig. 6).

4. Discussion on system performance and prototype design

For both electrochemical compression of NH_3 and CO_2, steady state modeling was performed to determine the coefficient of performance (COP) in the VCRC. With the ideal Nernst voltage calculated in Eq. (9), the ideal compression power input can be calculated by multiplying the ideal Nernst voltage and the current as shown in Eq. (12).

$$W_{Nernst} = U_{Nernst} * I \qquad (12)$$

The actual compression work is calculated based on the actual voltage charge multiplied by the current. And the compression efficiency (η_{EC}) is calculated based on the calculated Nernst work (W_{Nernst}) divided by the measured compression work (W_{EC}). The current is cancel out and the compression efficiency can be expressed by the ratio of ideal Nernst voltage (U_{Nernst}) and the measured voltage charge to the EC (U_{EC}) as shown in Eq. (13).

$$\eta_{EC} = \frac{W_{Nernst}}{W_{EC}} = \frac{U_{Nernst}}{U_{EC}} \qquad (13)$$

And the system COP can be calculated from the total evaporator cooling capacity ($Q_{cooling}$) divided by EC work input (W_{EC}) (Eq. (14)).

$$COP = \frac{Q_{cooling}}{W_{EC}} \qquad (14)$$

The NH_3 compression efficiency was measured and calculated to be 90% at 50 mV of voltage charge. The NH_3 refrigeration cycle was then modeled at 5 °C evaporating temperature and 45 °C condensing temperature. For a 200 W cooling capacity, the COP of the system is calculated to be 5.1.

Similarly, the CO_2 system performance was modeled for the transcritical refrigeration cycle at 5 °C evaporating temperature and 37 °C of gas cooler outlet temperature with gas cooler pressure at 10 MPa. The steady state modeling results of conventional CO_2 refrigeration system and CO_2 EC transcritical refrigeration cycle are shown in Table 2. Both conventional and electrochemical refrigeneration systems were modeled at same cooling capacity and operation conditions. Based on the baseline calculation, the conventional CO_2 refrigeration system with 200 W of cooling capacity has a COP of 2.4 with 88 W of rated compressor power and 65% isentropic compression efficiency, while the CO_2 EC transcritical refrigeration system has a COP of 4.0 with 51 W of calculated compressor power with 85% isentropic compression efficiency. With heat removal, the CO_2 EC compressor efficiency can even reach 90%. The higher compression efficiency is due to no irreversible friction loss.

The size of the compressor comparison is listed in Table 3 for a 10.5 kW air conditioning unit. For future improved development for a 10.5 kW air conditioning unit would involve improving membrane current density, which is directly associated with flow rate. Our target is 1 A/cm2 at the 1 V of DC voltage charge. The target current density is achievable by replacing graphite bipolar plates with stainless steel, which has less electric resistance, and improving the catalyst doped on the membrane electrode. Another future development would be reducing the bipolar plate thickness to 1 mm, which can be achieved by stamping. If all of the targets are achieved, a 10.5 kW air conditioning unit would require 1 EC with size of 20 cm × 20 cm × 40 cm for CO_2 compression. The size is comparable to a conventional CO_2 compressor at similar capacity (Emerson Climate Technologies, 2016). Moreover, there will be enough surface area for heat exchange which would enable isothermal compression. Heat can be removed by either passive cooling or active cooling.

And based on the Nernst equation (Eqs. (10) and 11), the semi-isothermal compression efficiency is calculated at constant temperature, which means the compressor discharge gas temperature is equal to the gas cooler outlet temperature without excess amount of superheating. The semi-isothermal compression can be achieved by removing heat from the membrane discharge plate by utilizing its large surface area. And it is modeled by considering the lowered compressor discharge side temperature as compared to what would have been after the isentropic compression process. The potential for electrochemical compressor to reach a semi-isothermal compression is based on its unique design. In general, it is very difficult for mechanical compressors to achieve isothermal operating condition due to limited surface area for heat removal (Wang et al., 2008). The electrochemical compressor compresses refrigerant with layers of membranes. The refrigerants are evenly discharged over a surface area of 20 cm2W^{-1}, which provides large

area for heat removal. The isothermal effect is especially effective for CO_2 compressor because it will also contribute to reducing gas cooling pressure.

The semi-isothermal compression process can be approached by using inter-stage cooling. The CO_2 transcritical refrigeration cycle with three inter-stage cooling is shown in P-h diagram (Fig. 7). The superheated CO_2 leaving the evaporator is going through three separate compression and inter-stage cooling to achieve the final gas cooler out temperature before entering the expansion valve.
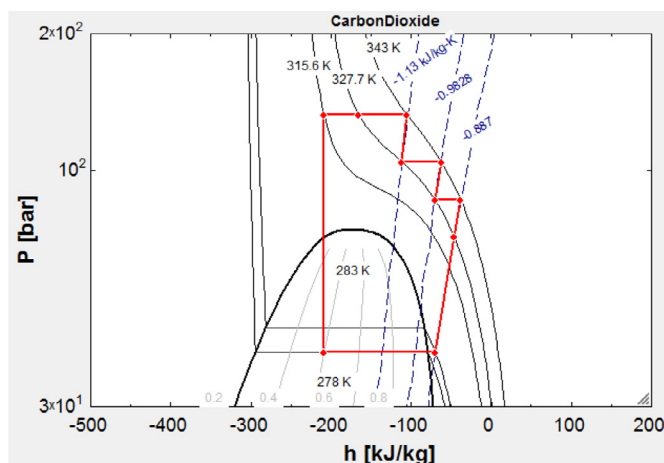

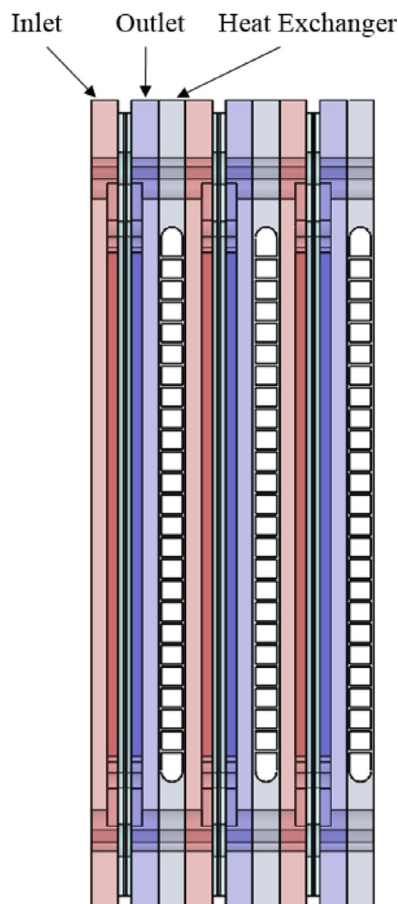Fig. 7. CO_2 transcritical refrigeration cycle with three inter-stage cooling.

Fig. 8. EC units stacked with inserted heat exchangers to reduce the discharge refrigerant temperature and overall compressor power consumption.
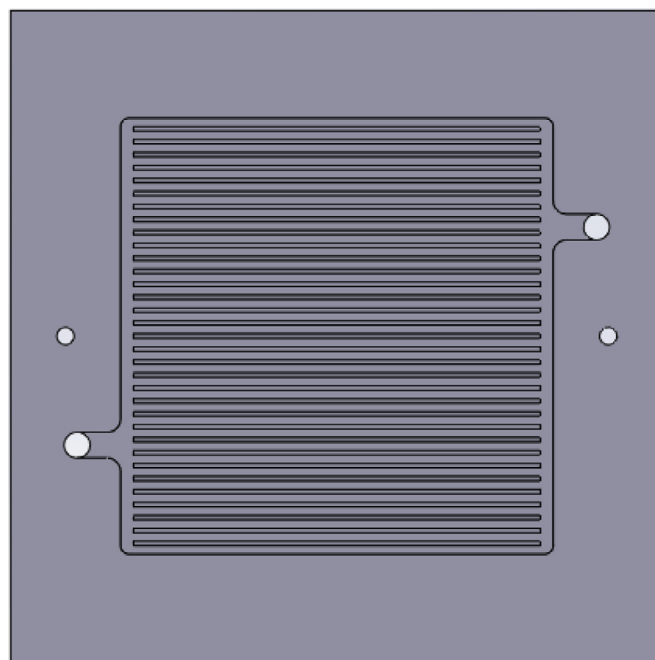

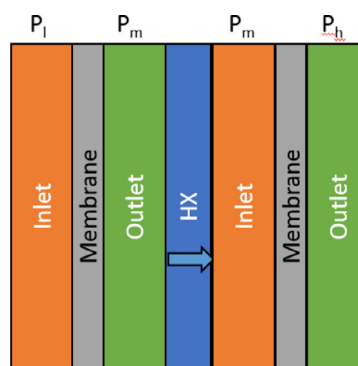Fig. 9. The EC gas distribution channels.

Fig. 10. Serial connection for EC units.

This approach could reduce gas cooling pressure and improve the compression efficiency so that the system COP is improved.

The EC prototype was designed while focusing on the stack design and gas distribution channel design. The multiple EC units are stacked in series for increased pressure lift, and in parallel for increased flow rate. The electrochemical compression process requires energy input into the compressor in the form of voltage charge of 1.2 V, which heats up the device at 500 Wm^{-2} and brings up the temperature of CO_2 discharged. And increased discharge temperature of compressed fluids would eventually compromise the performance of the compressor by increasing its energy consumption. A proper compressor heat removal technique during the compression process could lead to energy savings as high as 28% (Coney et al., 2002). Traditionally, ideas about injecting the refrigerant in liquid or vapor phase to the compressor chamber have proved to be effective to reduce the discharge temperature and improve the compressor performance (Wang et al., 2008). However, the drawback of this idea leads to additional work requirement to compress extra amount of refrigerant and potential lubricant wash out causing severe wear in compressor parts. Other ideas about externally cooling the motor or actively cooling the shell have also been proposed (Wang et al., 2008). However, the compressor usually has limited surface area for heat removal
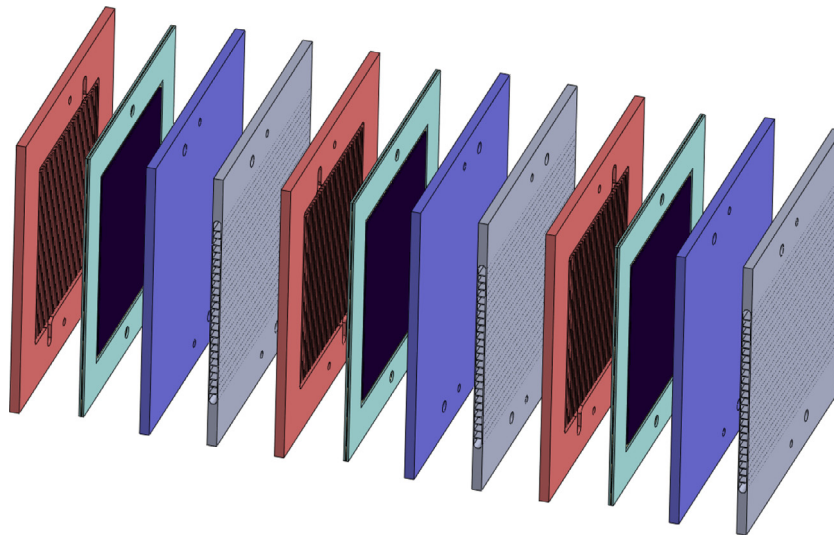
Fig. 11. Exploded view of three EC units stacked in parallel.

which makes it very challenging to cool down. In the EC, however, each unit in the stack has large membrane surface area available for heat removal. Therefore, as an example, microchannel flat tube heat exchangers can be inserted to cool down the discharged refrigerant temperature so the compression process can approach semi-isothermal process (Fig. 8), and not having a significant impact on the compressor volume. The basic concept is embedding the heat exchanger next to the discharge sides of each individual EC unit, so the discharge gas temperature can be reduced. The embedded heat exchangers can also serve as a gas cooler to pre-cool the CO_2 refrigerant before it enters the real gas cooler in the system. Inter-stage cooling can be achieved with multiple stages of compression coupled with heat removal (Fig. 9). As the electrochemical compressors are stacked up in parallel with multiple units to increase flow rate, the performance does not change as each unit is treated as an independent system.

The gas distribution channels in the EC needs to be designed to uniformly distribute refrigerant across the membrane and minimize the pressure drop associated with flow distribution. Fig. 9 shows the example channel design with two inlets on both sides of the plate, connecting to the channels for better flow distribution. The gas distribution channels supply the refrigerant on the surface of the membrane electrode. It not only serves as a flow distributor but also as a mechanical support for the membrane electrode. It is made of stainless-steel to prevent any corrosion issue when O_2 is present as a carrier gas for CO_2 compression, and serves as an electric conductor for electron transport.

In order to achieve inter-stage cooling, the compressor stack is designed to have units connected in series, so that the outlet of the one unit is connected to the inlet of the next unit. The connection is demonstrated in Fig. 10. As shown in Fig. 10, the low-pressure refrigerant coming in at the inlet of the first unit is pumped across the membrane to the outlet. The pressure increases at the outlet and the flow at medium pressure level is cooled by the heat exchanger to the inlet of the second unit. The membrane pumps the medium pressure refrigerant to the second outlet with pressure increased to higher level. If more cooling is required, then another heat exchanger is attached to the outlet of the second unit and so on. The exploded stack view with three units in parallel is shown in Fig. 11. Future work will be focused on the multiple-unit-stack design and flow distribution analysis.

5. Conclusions

In this paper, the electrochemical compression concepts of both NH_3 and CO_2 are proposed. The experimental study verified the feasibility of both compression mechanisms. NH_3 electrochemical compression would achieve a measured isothermal compression efficiency of 90%, at a compression ratio of 2.7 and 50 mV of voltage charge. The compression ratio can also go as high as 10 with a single stage compression. Therefore, it is feasible for NH_3 EC to achieve the desired pressure lift with single stage in the NH_3 vapor compression system for refrigeration purpose. CO_2 electrochemical compression currently can achieve a compression ratio of up to 6.2 with a single stage compression. However, multiple stages must be connected in series to achieve the desired pressure lift. With inter-stage cooling potentially done by microchannel heat exchangers, the compressor can approach isothermal compression for more energy savings with CO_2 as refrigerant. The scaled up compressor design discussed in this paper with improved gas distribution channels and internal heat exchangers will improve the system performance and is part of the future study. In conclusion, the electrochemical compression of NH_3 and CO_2 show great promises for the vapor compression cycle in refrigeration and heat pump systems. The EC can compress natural refrigerants without using any moving parts. And the EC can potentially improve the efficiency of the vapor compression systems.

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