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Performance Investigation on Electrochemical Compressor with Ammonia

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ABSTRACT

The mechanical compressor on small cooling appliances has considerable energy consumption to the entire vapor compression system. To improve the efficiency of the compressor in the vapor compression system, an electrochemical compressor (EC) was suggested and its performance was investigated. The EC compresses refrigerant by charging an external voltage to the membrane electrolyte assembly (MEA). In this study, ammonia was used as a working fluid due to its high thermodynamic characteristics and electrochemically reactivity with the MEA. This paper mainly focuses on the thermodynamic compression limit at the open loop and the EC performance at the closed loop. The thermodynamic compression limit of the EC at open loop verifies the voltage and compression ratio relationship based on the theoretical Nernst equation. For the closed loop experimental study, the current density of the MEA was investigated with voltage at constant refrigerant charge. The pressure lift across the EC was measured as well. The measured flow rate was in the same order of magnitude of the theoretical values. In conclusion, the ammonia EC can be a new compressor option for the vapor compression system due to its potential energy saving, no moving parts and no lubrication oil.

1. INTRODUCTION

The mechanical compressor used in small cooling appliances such as cooler or freezer has an isentropic efficiency of around 65%. It is also a fairly complicated system with moving parts and lubrication oil. The electrochemical ammonia compressor is proposed to improve the efficiency of vapor compression cycle without using any moving parts and lubrication oil. The electrochemical compressor (EC) pumps gas molecules across a membrane electrolyte assembly (MEA) when charged with an external voltage. The working principle is similar to the reverse of proton exchange membrane fuel cell design. The PEM fuel cell produces electricity by supplying hydrogen and oxygen gases. The EC however, pumps gas by supplying electricity. The electrochemical hydrogen compressor has been built and studied by different groups (Rohland et al., 1998; Strobel et al., 2002; Onda et al., 2007; Gardner and Ternan, 2007; Grigoriev et al., 2011). The focus of this paper is on using the hydrogen transfer feature of proton exchange membrane to let hydrogen drag ammonia across the membrane for compression, which was never been previously reported. The working principle is shown in Figure 1. At the EC suction line, both ammonia and hydrogen are supplied. With the help of Pt catalyst, chemical reactions will take place and the generated NH_4^+ ion will transfer across the membrane with the influence of the electric field. On the other side of the membrane, the NH_4^+ ion will break down to ammonia and hydrogen. The MEA also needs to be humidified to have good NH_4^+ conduction. If the external flow from the EC discharge-side to feed-side is regulated, the gases can be compressed through the EC. Based on the chemical equation shown in Figure 1, the transfer ratio between NH_3 and H_2 is 2:1 due to ionic bonding. The steady transfer rate of NH_3 can be achieved at a constant voltage charge.

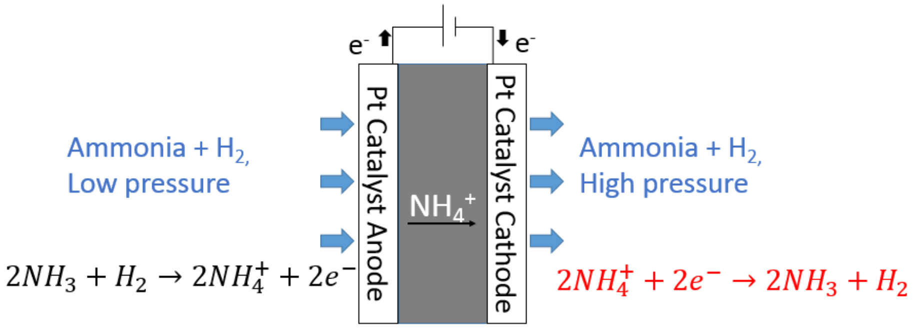


Figure 1: Electrochemical NH_3 compressor using H_2 as carrier gas

2. EXPERIMENTS

2.1 Thermodynamic compression ratio

The EC performance is governed by the Nernst equation, which gives the relationship between pressure ratio and voltage supplied. The discharge pressure is increased by closing the discharge line valve. Therefore, no flow is in the discharge line. The purpose of this experiment is to show that the gas pressure in the suction line and discharge line achieved by the ammonia EC satisfies the Nernst equation. As Figure 2 shows, the EC is charged with constant voltages at 0.05 V, 0.1 V, 0.15 V, and 0.2 V. With the discharge line valve closed, the gas therefore accumulates and pressure builds up. As the pressure increases, the back diffusion across the MEA also occurs at increasing rate. Therefore, eventually the gas transport rate across the MEA will be equal to the back diffusion flow rate and pressure stops building up. The equilibrium pressure and voltage were recorded when pressure in the discharge line was no longer increasing.

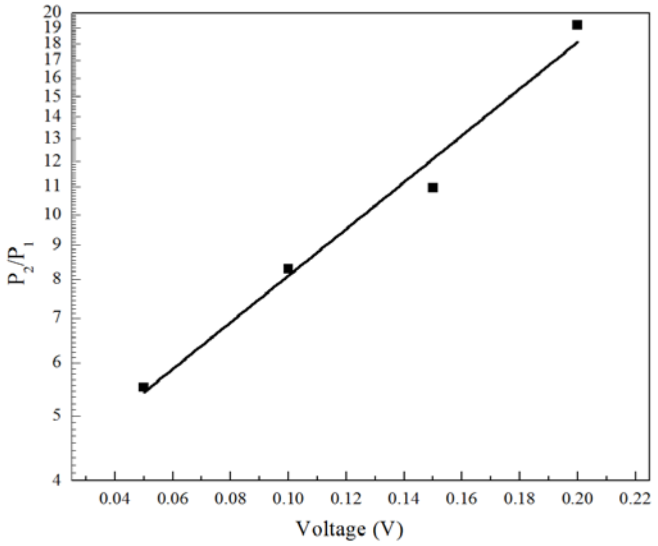


Figure 2: Ammonia EC thermodynamic compression limit

According to the Nernst equation shown in Eq. 1, the log scale of pressure ratio follows linear increase with respect to the cell voltage charge.

$$\boldsymbol{E = \frac{RT}{nF} \ln\left(\frac{P_d}{P_s}\right)} \qquad (1)$$

where P_d represents the discharge pressure, and P_s represents the suction pressure, n represents the number of moles of electrons released by each H_2 molecule transferred across the membrane, E represents the EC cell voltage charge.

The Nernst equation gives the ideal compression voltage needed for reaching the desired partial pressure ratio. In reality, the total cell internal resistance, contact resistance, and anode- and cathode-polarization will be taken into account as parasitic loss. Therefore, the linear relationship shown in Figure 2 deviates from the ideal linear relationship, but the overall trend is still following logarithm.

2.2 Closed loop analysis

In order to test the compressor prototype performance for the potential vapor compression cycle application, a closed loop analysis was performed to test the EC performance in real conditions with discharge line valve partially opened. As previously described, the EC builds up pressure by pumping gas molecules across the MEA, therefore regulating the discharge side flow back to the suction line needs to be regulated. The closed loop analysis gives real time performance of the EC. At this moment, the small EC prototype has only very limited flow rate. In order to have flow rate that is measureable, the EC needs to be scaled up by increasing the MEA surface area and multiply stacks. The system was pulled vacuum before charging 2 bar of mixture of H_2 and NH_3 at 1:2 ratio. Figure 3 shows the closed loop design of EC with suction line and discharged line marked. The suction line uses 6.4 mm diameter tubing and 50 cc cylinder for gas reservoir. The discharge line uses 3.2 mm diameter tubing. Figure 4 shows the closed loop schematic of the ammonia EC. Both suction side (anode) pressure and discharge side (cathode) pressure were measured by pressure transducers. As previously discussed in Section 1, the MEA needs to be humidified to be able to transport both H_2 and NH_3, so that the refrigerant loop was heated by a tape heater to keep temperature constant at 60ºC to have reasonable RH of 70% for enough membrane humidification. For the real refrigeration system, the tape heater can be removed and a suction line humidifier would be installed to maintain the humidity of MEA. The humidity is required at a high level in order to keep the ionic conductivity of proton exchange membrane for high ammonia transfer rate. Water is not interacting with the working fluid but only serves as a need for the membrane. Ammonia as the working fluid will be brought over by hydrogen only. The EC performance at different voltage charges was measured in terms of pressure drop and current.

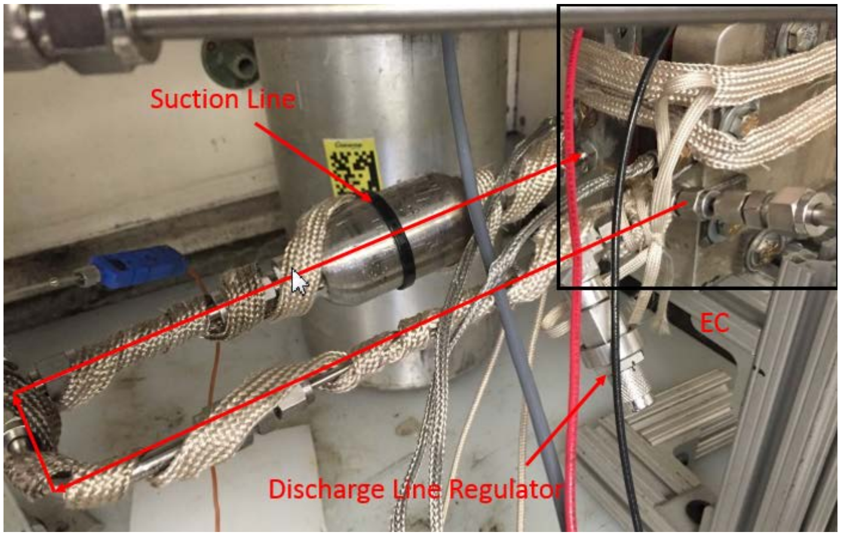


Figure 3: Closed loop analysis with suction and discharge line shown.

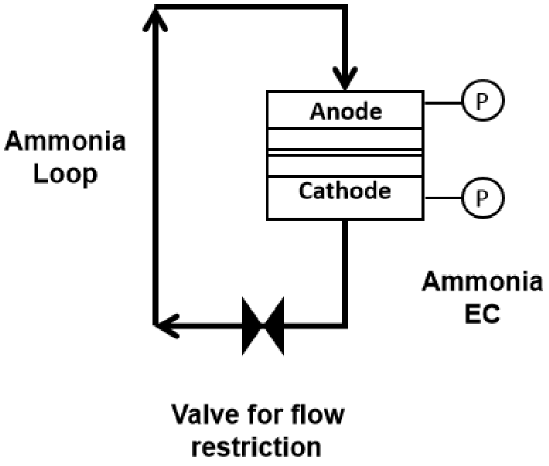
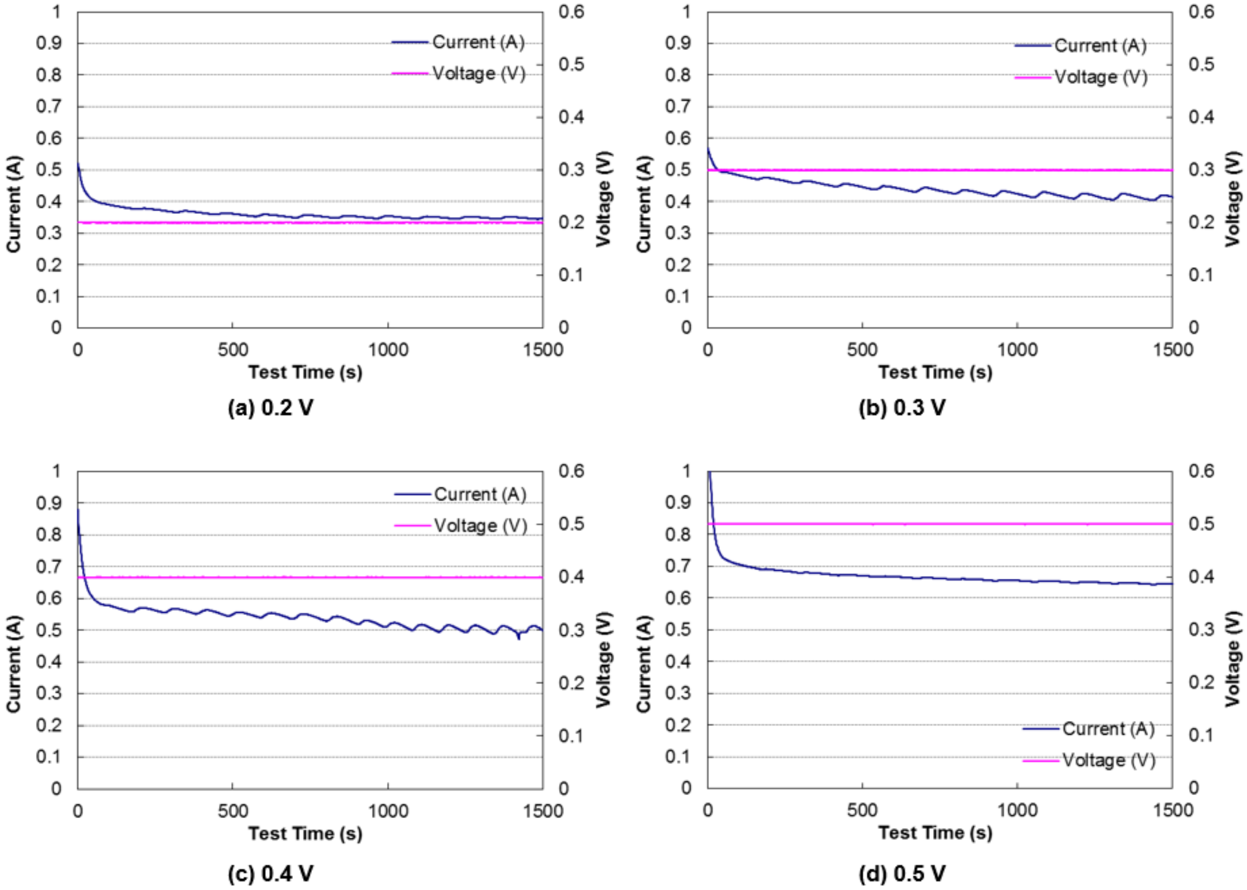


Figure 4: Schematic of EC closed loop

The EC single cell was charged with a voltage for 1,500 seconds and the current was measured as well as the pressure lift from the suction side to the discharge side. Figure 5 shows the current versus voltage graphs. As the voltage charge increases, the current increases as well. The EC was able to maintain constant pressure lift at fixed voltages. The flow rate across the EC can be calculated based on the current by using the Faraday's Law.



(a) 0.2 V

(b) 0.3 V

(c) 0.4 V

(d) 0.5 V

Figure 5: Current versus voltage at voltage charge

The pressure lift was measured at the suction line and discharge line by partially opening the metering valve. Table 1 shows the pressure lift with respect to different voltage charge. The pressure lift of a single EC unit is very low. However, it is expected to increase linearly as the number of units in the stack increases for scale up. The evaporating and condensing temperatures of ammonia are 5°C and 45°C at 5 bar and 18 bar, respectively. For the future development, 1 EC with multiple units in the stack for the required pressure lift will be built and tested for a 200 W cooling system.

Table 1: Pressure lift versus voltage charge

Voltage (V)	Pressure lift (kPa)
0.2	19
0.3	23
0.4	26
0.5	30

2.3 Flow rate measurement

The transfer rate was measured and calculated using titration and results were shown in Table 2. The experimental flow rate was calculated by the amount of hydrogen and ammonia determined by titration over time. The theoretical flow rate was calculated based on the Faraday's Law in Eq. 2.

$$\frac{dn_e}{dt} = \frac{I}{nF} \tag{2}$$

where I is the current, n_e is the number of electrons transferred per molecule, in this case n is equal to 2 for hydrogen and 1 for ammonia, and F represents the Faraday's constant.

The results in Table 2 show that the measured flow rate is in the same order of magnitude with the theoretical flow rate. The discrepancy between the measured and theoretically predicted flow rates may be caused by H_2 and NH_3 cross over, which is a common phenomenon associated with proton exchange membrane.

Table 2: Comparison between measured flow rate and theoretical flow rate

Measured Current (A)	Theoretical flow rate H_2 (g/s)	Theoretical flow rate NH_3 (g/s)	Measured flow rate H_2 (g/s)	Measured flow rate NH_3 (g/s)
0.14	1.45e-06	2.47e-05	1.85e-06	3.22e-05
	1.45e-06	2.47e-05	1.72e-06	3.16e-05
	1.45e-06	2.47e-05	1.78e-06	3.29e-05

2.4 EC scale up calculation

Since the flow rate for a single cell of EC is small, the proper scale up is needed in order to have enough flow rate to provide enough cooling capacity for the size of a cooler. The mass flow rate of EC ($\dot{m}$) can be calculated in Eq. 3.

$$\dot{m} = \frac{dn}{dt} * M_{NH_3} = \frac{I}{nF} * 17 \tag{3}$$

$$I = I_d * np * S \tag{4}$$

where I_d represents the current density of each cell, np represents the number of cells in parallel, S represents the surface area of each cell.

The scale up is going to be based on the stacking up plates design. Based on the theoretical calculation, in order to provide 200 W of cooling capacity, ammonia flow rate needs to be at 0.2 g/s, which requires 70 cells to be connected in parallel, forming an EC stack. The scaled up EC is estimated to have surface area of 100 cm^2 for each cell and the overall size is 10 cm x 10 cm x 70 cm.

3. CONCLUSIONS

A small prototype of the electrochemical compressor working with ammonia was investigated. The open loop thermodynamic compression ratio was measured based on the voltage and compression ratio with discharge line valve closed. The open loop analysis shows the logarithm of compression ratio is in linear relationship with voltage charge. The closed loop analysis gives the actual EC performance when ammonia from the discharge line is fed back to the suction line. Both current and pressure lift increase with voltage charge. The EC can be a new compressor option for the vapor compression cycle.

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NOMENCLATURE

E	EC cell voltage charge
EC	electrochemical compressor
F	Faraday's constant
I	current
I_d	current density of each cell
$\dot{m}$	mass flow rate
MEA	membrane electrolyte assembly
n	number of moles of electrons released by each H_2 molecule transferred across the membrane
n_e	number of electrons transferred per molecule, in this case n is equal to 2 for hydrogen and 1 for ammonia
np	number of cells in parallel
P_s	suction pressure
P_d	discharge pressure
S	surface area of each cell

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