The Integration of Ammonia Electrochemical Compressor in Vapor Compression System

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Abstract

An electrochemical compressor was proposed to improve the efficiency of the vapor compression cycle and the reliability of the compressor by eliminating moving parts. The electrochemical compressor designed based on the proton exchange membrane fuel cell can compress ammonia as a working fluid while using hydrogen as a carrier gas by charging a DC voltage to the membrane electrolyte assembly. From the previous research, the transfer ratio between ammonia and hydrogen was found to be 2. The electrochemical compressor stack design was proposed for scaling up cooling capacities. In this study, the thermal management of the electrochemical compressor stack is investigated. For the removal of heat from cathode side, using different types of heat exchanger design is discussed, which includes open channel, microchannel flat tube and metal foam heat exchanger. Then the isothermal compressor efficiency and system COP are modeled when the ammonia electrochemical compressor is used in the vapor compression cycle. The system can potentially be more energy efficient than the conventional vapor compression cycle driven by the mechanical compressor.

Keywords: compressor, fuel cell, heat pumps, vapor compression cycle

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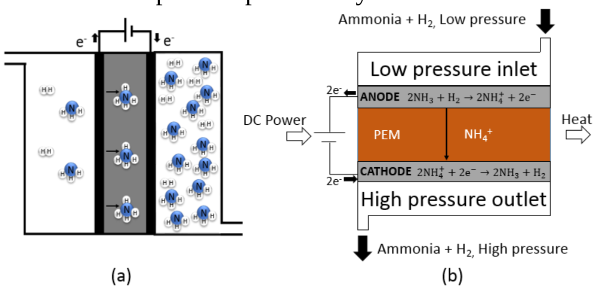
1. Introduction

The usages of HFCs will be globally phased down in the future due to the agreement on Montreal Protocols. Industries are currently actively seeking alternative cooling technologies which use either refrigerants with low GWPs or other environmentally friendly fluids. In addition, the efficiency of mechanical compressors in the vapor compression cycle has considerably impact on the efficiency of refrigeration system. The electrochemical compressor shows a great potential in the vapor compression cycle as it has much higher compression efficiency than the mechanical compressor. Moreover, it has many more advantages such as a simple solid state geometry, no moving parts, no need for lubrication oil and no noise operation. It also works with ammonia which is an environmentally friendly refrigerant and hydrogen as a carrier gas. From the previous research by Tao et al. [1], the transfer ratio between ammonia and hydrogen was found to be 2. Metal hydride electrode was proposed to be attached on both anode and cathode sides to remove the carrier gas hydrogen from rest of the system to improve the heat exchanger performance. The electrochemical compressor stack design was proposed for scaling up cooling capacities. The electrochemical compressor operates by charging the membrane with a DC voltage. Under the influence of external voltage, the membrane can pump ammonia from anode side to the cathode side as illustrated in Figure 1. Based on pressure difference, anode and cathode represent suction and discharge side of the compressor as shown in Table 1. In addition to the membrane, gas distribution channel plates (both anode side and cathode side) and gaskets are the major components, as shown in Figure 1, which are similar to proton exchange membrane fuel cell (PEMFC) design. Thanks to the unique geometric characteristics of electrochemical compressor, heat can be easily removed from the cathode side of the compressor by different heat exchanger designs (Figure 2). In this paper, the thermal management techniques for cathode cooling are discussed. Then the steady state simulation is performed for vapor compression cycle with electrochemical compressor at different operating conditions to estimate its performance.



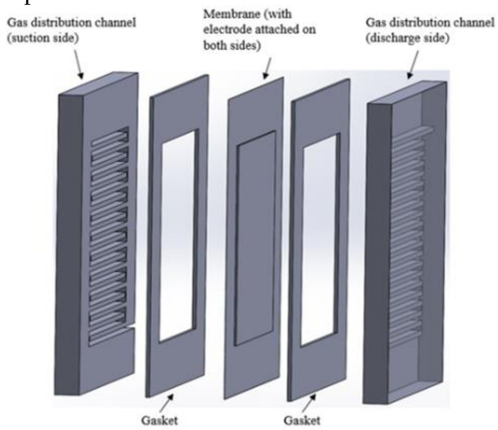


Figure 1: (a) Electrochemical ammonia compression (b) Reaction mechanism

Figure 2: The explode view of a single electrochemical compressor unit

Table 1: Anode and cathode roles in electrochemical compressor

Anode	Cathode
Low pressure	High pressure
Suction side	Discharge side

2. Thermal management of electrochemical compressor

Convective air cooling of the cathode side is commonly used in small fuel cells. However, this requires an open structure at the cathode sides, and may increase the volume of the stack [2]. The gas distribution channel in the discharge side of the electrochemical compressor can be made of either graphite or steel [3]. Then the heat generated in the discharge side of the compressor can be removed by heat exchangers installed adjacent to the discharge side (Figure 3). Here we propose applying three types of heat exchangers based on similar applications in the PEMFC.

First type is open channel design. Air is flowing through these open channels to cool down the high temperature discharge gas. Cooling channel size depends on the heat load to be removed and pressure drop allowed. A separate cooling plate can be inserted in between two cathode discharge sides, so that heat is removed (Figure 3) or channel geometry can be embedded in cathode wall. This cooling strategy was used for PEMFC stacks in the range between 100 W to 2 kW [4]. The advantage of this method is that air is the only working fluid involved, which reduces the complexity of the EC system. Schmidt et al. applied this technique on a 35-unit automobile fuel cell stack with active cooling area of 310 cm^2 [5]. Cooling air temperature ranges from 25°C to 50-80 °C from inlet to outlet. They proved the feasibility of air cooled stacks. Sohn et al. built a 500 W PEMFC stack with air cooling and find out that with optimized design and operation, cooling fan consumes only 10 W of power [6]. Matian et al. proposed thinner cooling channel plates to reduce the stack size, but found out that there is a tradeoff between plate thickness and pressure drop and recommends an optimization [7].

Second option is using the microchannel flat tube. The microchannel heat exchanger is recognized as the next generation heat exchanger over the conventional fin-tube heat exchangers due to its improved heat transfer on the refrigerant side, a reduced air side flow resistance and a reduced volume. The major difference to the open channel heat exchangers is that the microchannel heat exchanger requires higher density fluids than air due to its smaller flow area. The smaller tube diameter, however, increases the heat transfer area and improves the system performance. Garrity et al. did an experimental study on 56-channel aluminum microchannel evaporator cooling plate on PEMFC cathode side with HFE-7100 as refrigerant [8]. The channel has a cross sectional area of 1x1 mm and length of 115 mm. The study concluded that microchannel plate has a thermal capacity of 32 kW/m^2 at mass flow rate of 30 g/s, and is able to completely handle the heat flux rejected by the PEMFC, with refrigerant pressure drop ranging from 200 to 800 Pa. It is also indicated that the microchannel evaporator requires an external heat sink for refrigerant condensation which would potentially increase the complexity of the system.

Third option is using the metal foam heat exchanger. The metal foam has the advantage of large heat transfer area per volume. Boomsma et al. showed that the metal foam heat exchanger has thermal resistance 2 to 3 times lower than the commercially available heat exchangers and consumes the same pumping power [9]. Odabaee did an experimental study on metal foam heat exchangers with size of 5 x 100 x 100 mm and 95% porosity for PEMFC thermal management and found out that the air cooled metal foam heat exchanger requires half of the pumping power compared to water cooled fuel cell systems for the same amount of cooling capacity at same operating conditions and created a uniform temperature distribution across the cathode plates [10]. For heat flux of 1 kW/m^2, the air flow rate was 0.0024 kg/s and the approach temperature was 1.7°C. However, there is also concerns about the increase of pressure drop across the heat exchanger which will increase the fan power requirements.

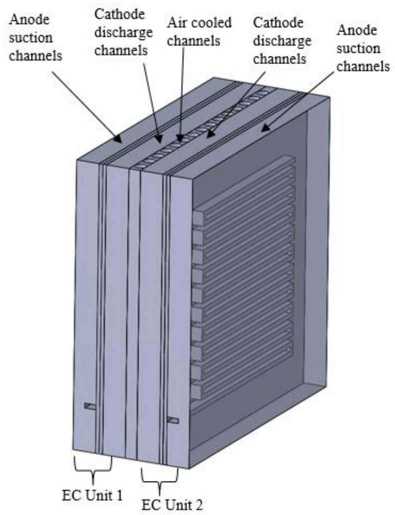


Figure 3: Electrochemical compressor with cooling channels placed in between two cathode discharge sides

3. System performance modeling

The ammonia vapor compression system is modeled with the electrochemical ammonia compressor. The compression process is able to approach isothermal condition by providing enough discharge side cooling. Each electrochemical compressor (EC) unit with 10 cm by 10 cm membrane surface area generates about 3 W of heat. Therefore, it is assumed that this heat is removed by blowing air to the heat exchanger surface. The vapor compression cycle with electrochemical compressor performance is modelled for at 5°C evaporating and 45°C condensing temperatures as follows.

The relationship between compression ratio and voltage for electrochemical compression should satisfy the Nernst equation, which is defined in eq. 1 [11,12].

$$U_{Nernst} = E_0 + \frac{RT_{EC}}{nF} \ln\left(\frac{P_2}{P_1}\right) \quad (1)$$

where P_2 and P_1 represent the partial pressure of compressed gas at both cathode and anode, respectively, P_2/P_1 is the compression ratio, and n is the number of electrons each gas molecule releases, T_{EC} is the operating temperature of the device, and E_0 is the standard hydrogen electrode potential, which is equal to zero.

The electrochemical compression efficiency is defined as the ratio of ideal Nernst voltage over the measured cell voltage to the EC (eq. 2).

$$\eta_{EC} = \frac{U_{Nernst}}{U_{Cell}} \quad (2)$$

The EC cell voltage consists of the theoretical Nernst voltage, Ohmic loss due to total cell internal resistance, and anode- and cathode-polarization as shown in eq. 3.

$$U_{cell} = U_{Nernst} + U_{ohm} + U_{ac} \quad (3)$$

where U_{ohm} of a single EC satisfies the Ohm's law as shown in eq. 4. U_{ac} is small for hydrogen and can therefore be neglected.

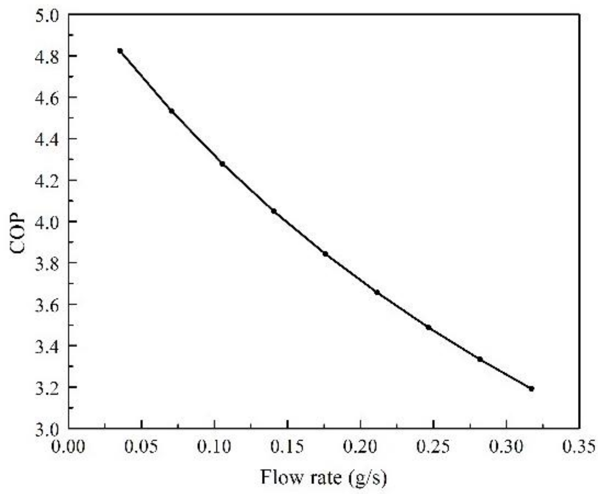
$$U_{ohm} = I_d * R_i \quad (4)$$

where I_d is the current density and R_i is the internal cell resistance. The measured internal cell resistance is about 2 Ω cm^2 during operation.

The compression efficiency is defined in eq. 5 as the ratio between power of compression and power input. The isothermal compression work is calculated based on eq. 6, dn/dt represents the molar flow rate of ammonia, and R is the gas constant. The real work input is calculated in eq. 7. Figure 4 shows the efficiency values calculated by eq. 8 which is derived by combining eqs. 3, 4, 5 and 6, at different flow rates, which is changed by voltage charge to the membrane. Figure 5 gives the system COP calculated based on eq. 9. As shown in the figures, only at small refrigerant flow rates, the compression efficiency and COP are both high. The major performance loss is due to the irreversible ohmic loss caused by internal resistance. In the meantime, increase of flow rate increases the cooling capacity (Figure 6). Therefore, it is recommended to increase the flow rate by increasing the number of electrochemical compression units in the stack (in parallel), instead of increasing the voltage charge to the membrane. The isothermal compression process achieved by thermal management implemented in PEMFC has less irreversible loss than isentropic mechanical compressor, resulting in higher COP.

$$\eta_c = \frac{W_{compression}}{W_{input}} \quad (5)$$

$$W_{compression} = \frac{dn}{dt} RT_{EC} \log\left(\frac{P_2}{P_1}\right) = \frac{RT_{EC}}{nF} \ln\left(\frac{P_2}{P_1}\right) \times I \quad (6)$$



$$W_{input} = U_{cell} \times I \quad (7)$$

$$\eta_c = \frac{W_{compression}}{W_{input}} = \frac{U_{Nernst}}{U_{cell}} \quad (8)$$

$$COP_{cooling} = \frac{Q_{cooling}}{W_{input}} \quad (9)$$

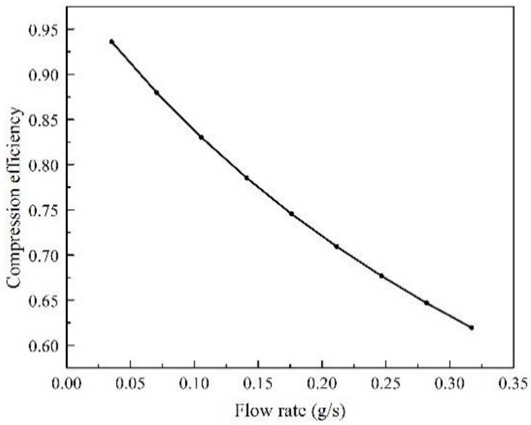
Figure 4: Compression efficiency at different flow rates (5°C evaporating and 45°C condensing temperatures)

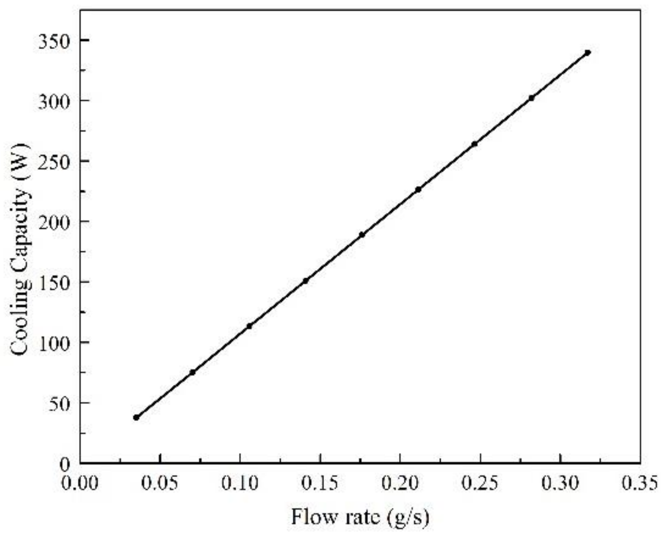
Figure 5: COP at different flow rates (5°C evaporating and 45°C condensing temperatures)

Figure 6: Cooling capacity at different flow rates (5°C evaporating and 45°C condensing temperatures)

4. Conclusions

In this work, the thermal management of electrochemical ammonia compressor was discussed with three types of heat exchangers. Depending on the compressor heating load and operating conditions, open channel,





microchannel heat exchanger and metal foam heat exchangers can be used. Isothermal compression can be achieved by attaching heat exchanger to the cathode discharge side of the EC. Isothermal compression efficiency and system COP were modeled at 5°C evaporating and 45°C condensing temperatures with respect to refrigerant mass flow rate. It is recommended that the voltage charge is kept at a low level and increase the number of units in the stack to increase the flow rate to have the optimum performance.

Acknowledgements

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