14th IEA Heat Pump Conference
15-18 May 2023, Chicago, Illinois

A Study on Isothermal Compression System Applying Electrochemical Compressor

Soyeon Kim[a], Minkyu Jung[a], Donik Ku[a], Soojin Bae[a], Gijeong Seo[b], Dong Kyu Kim[c], Minsung Kim[a,b*]

[a]Department of Intelligent Energy and Industry, Chung-Ang University, 84 Heukseok-ro Dongjak-gu, Seoul 06974, Republic of Korea
[b]School of Energy Systems Engineering, Chung-Ang University, 84 Heukseok-ro Dongjak-gu, Seoul 06974, Republic of Korea
[c]School of Mechanical Engineering, Chung-Ang University, 84 Heukseok-ro Dongjak-gu, Seoul 06974, Republic of Korea

Abstract

Electrochemical compressor (ECC) can produce pressurized refrigerant through electrochemical reaction, and ion selective electrolytes. It can be an ideal replacement for mechanical compressor (MC) that have low compression efficiency and noise problem caused by driving parts. Considering the piston rotating at high speed about 25~30 RPS, it is very difficult to cool the incoming fluid and the gas pressure and temperature increase due to adiabatic compression. However, ECC is prone to lowering temperature of the discharge side as it does not have a driving part, and the surface area of membrane is wide. Therefore, since sufficient inter-cooling can be performed by attaching heat exchangers on multi-stage compression, an isothermal compression process can be achieved. It means, since it is not compressed by volume reduction, compression close to isothermal compression is possible. In this study, a performance of the isothermal compression refrigerator system using ECC is compared with the mechanical compression system. When cooling the ECC with outside air, adiabatic compression is implemented at the compression front-end and isothermal compression at the rear-end.

Keywords: isothermal compression; Electrochemical compressor; mechanical compressor; refrigeration cycle; multi-stage compression;

1. Introduction

The efficiency of refrigeration systems has improved a lot over the past decades due to the rapid increased in cooling loads caused by abnormal climate. The Carnot refrigeration system achieve the highest possible cycle efficiency, which consists of two isentropic processes and two isothermal processes. However, this cycle is not feasible due to various unavoidable irreversibility such as friction, pressure drop, throttling expansion, etc.[1] In particular, the mechanical compressor consumes a lot of energy and the increase in the irreversibility by superheated vapor compression makes it difficult to achieve the refrigeration system closer to the Carnot system.[2] Because the compressor consumes a lot of work in the refrigeration cycle, it is a well-known fact that if isothermal compression is achieved, the efficiency of entire system can be greatly improved. [3] To implement the isothermal compression with the mechanical compressor (MC), it is natural to proceed with multi-stage compression and intercooling. The concept of intercooling is that isothermal compression can theoretically be performed if a cooling step is applied in between each compression stages, and the number of stages becomes infinite. However, in many studies, there is a lack of analysis on how much compression work can be reduce by multi-stage compression and intercooling in practical case. Therefore, in this paper, an analysis of that with MC is included.

The another most potential method to make isothermal compression in the refrigeration cycle is the using electrochemistry.[4] That is called Electrochemical Compressor (ECC), and it can attain an isothermal

* Corresponding author. Tel.: +82-2-820-5973 ; fax: +2-82-3280-5867.
E-mail address: minsungk@cau.ac.kr.

compression efficiency greater than 90%. In ECC, the low GWP refrigerant can be used because the gas that can permeate through the ion exchange membrane in an ion state can be used as cycle refrigerants. It also has no moving parts, so the compression process can be performed without lubrication oil, noise, or vibration. Therefore, in this study, a mechanical multi-stage compressor using intercooling and an ammonia refrigeration system with ECC are analyzed, and a practical cycle modeling considering heat exchanger is conducted.

2. Isothermal compression of multi-stage intercooling compression

2.1. Comparison of configuration and work with number of stages

In this chapter, an ideal case that can make isothermal compression using mechanical compressors (MCs) is analyzed. The intercooling is carried out between each stage of the MC, and this cooling is performed at the outside air or condenser temperature, so that adiabatic compression can be realized in the front-end of compression and isothermal compression in the rear-end compression. The intercooling proceed as the condenser temperature, and ideally, the effectiveness of the heat exchanger is set to 1. The cycle condition is shown in the Table 1. In an ammonia refrigeration cycle in which the evaporator temperature is 5 ℃, the condenser temperature is 50 ℃, and in the case of a 6-stages MC with an isentropic efficiency of 0.75 at each stage to approach practical cycle [5], and assuming that the degree of superheat (DSH) is 5 ℃, the cycle as shown in the diagram below the compressor of cycle is composed.

Table 1. Ammonia refrigeration cycle conditions and result

Parameters	Value
Condenser temperature [℃]	50
Evaporator temperature [℃]	5
Isentropic efficiency of MC (η_{isen})	0.75
Suction superheat [℃]	5
Number of stages	6
W_{comp} of single-stage MC [kJ/kg]	280.9426
W_{comp} of multi-stage MC [kJ/kg]	263.1342
Work reduction [%]	6.34
COP increase [%]	6.78

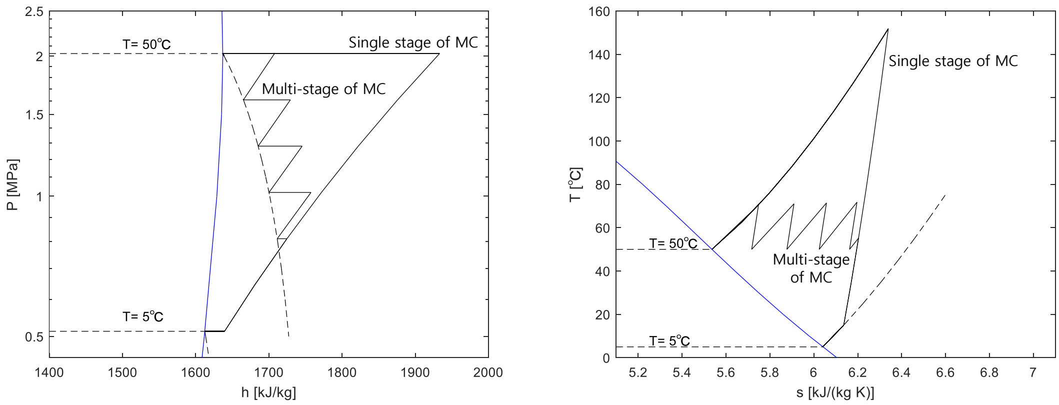

Fig. 1. Diagram of 6-stage MC and 1-stage MC with different configuration (left : *P-h* diagram, right : *T-s* diagram).

The single-stage MC consumes the work about 280.94 kJ/kg, multi-stage MC's work input is 263.13 kJ/kg, so the work reduction from single to multi stages is 6.34%. COP of multi-stage MC can improve approximately 6.78% higher than single MC in standard vapor compression. If the number of stages becomes infinite, isothermal compression can be achieved theoretically.

Consider the case where the number of stages is 100, like the T-s diagram in Fig. 2. If adiabatic compression occurs at the front-end and multi-stage intercooling compression is performed at the rear-end, isothermal compression can be theoretically implemented at the rear-end. As the number of stages increases, the amount of work required by the compressor will decrease. As shown in Fig. 2, isothermal compression is realized at the latter stage of compression, and the effect of approaching the Carnot efficiency can be obtained. The convergence value of work under the current conditions is about 256.6 kJ/kg in Fig. 3.

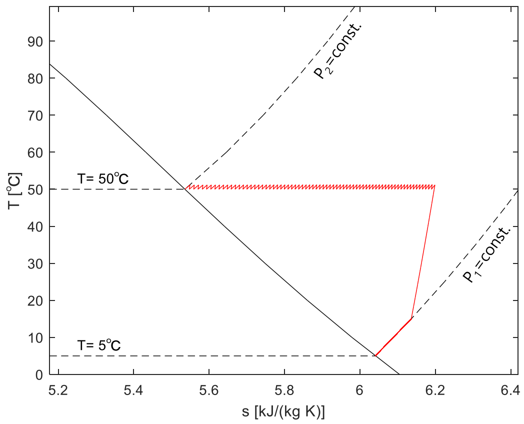

Fig. 2. Configuration of isothermal compression with 100-stage MC.

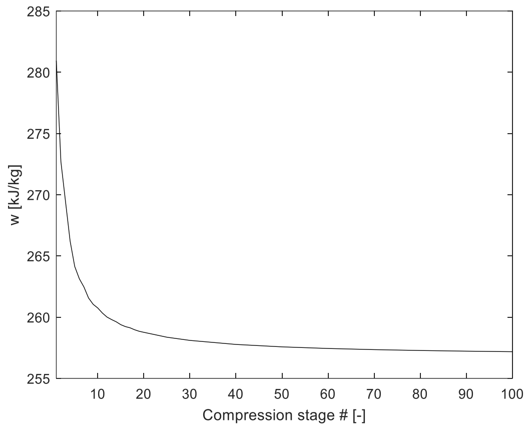

Fig. 3. Work variations according to the stage number of MC.

2.2. Practical cycle of intercooling multi-stage MC

Practical cycle is considered including heat exchanger modeling with compression model. The cycle analysis conditions used for this are shown in Table 2. The simulation model was developed using MATLAB, and the thermal properties were loaded from the REFPROP data base. [6]

Table 2. Practical cycle analysis conditions

	Variables	Value
Main cycle	Refrigerant	Ammonia
	Refrigerant mass flow rate [kg/s]	0.02
Heat exchanger	Condensing water mass flow rate [kg/s]	0.3
	Evaporating water mass flow rate [kg/s]	0.3
	Condensing water inlet temperature [°C]	30
	Evaporating water inlet temperature [°C]	25
	Condensing water inlet pressure [kPa]	101.325
	Evaporating water inlet pressure [kPa]	101.325
	Degree of superheating [°C]	5
	Degree of subcooling [°C]	5
	Heat exchanger length [m]	10
	Finite volume [-]	50
Compressor	Stages of multi-stage MC	6
	Intercooling air temperature [°C]	35
	Isentropic efficiency of MC	0.75

A copper double pipe heat exchanger was used to analyze the heat phenomenon of the two fluids with counter flow, and for the more physically approaching the practical refrigeration cycle the finite volume method (FVM) was used which is one of the most popular numerical methods used to solve heat transfer problems. [7-8] The secant method was used as a numerical analysis method of cycle. The Secant method is similar to Newton's method. Newton's method finds a solution using the gradient at a given point, while the Secant method finds a solution at the gradient of two given points. Unlike Newton's method, which requires knowing the exact function form, the secant method makes it possible to derive a solution without knowing the exact function of the given graph. The method of finding the approximate value of the solution by the secant method is as follows.

$$x_n = x_{n-1} - y_{n-1}\frac{x_{n-1}-x_{n-2}}{y_{n-1}-y_{n-2}}\ , \quad n = 2, 3, \cdots \tag{1}$$

x_0 and x_1 are assumed to be random values from the beginning. The desired solution can be found by repeating the above formula until the approximate value falls within the error range of the actual value. In this simulation, assuming P_{cond} and P_{evap} by changing the values of T_{cond} and T_{evap}, the calculation is repeated until the results of each heat exchanger analysis and the enthalpy of cycle point 3 (condenser outlet) and point 4 (evaporator inlet) converge within 1% of the error range.

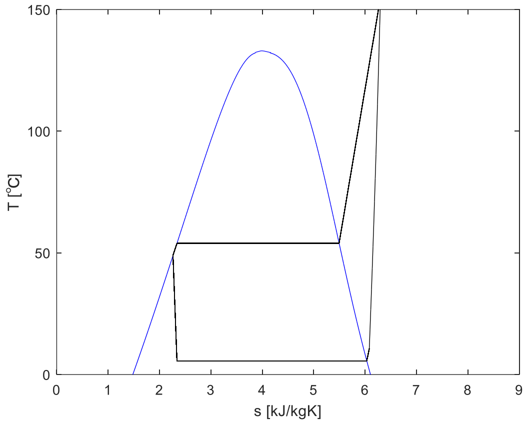

Fig. 4. T-s diagram of cycle with single-stage mechanical compressor.

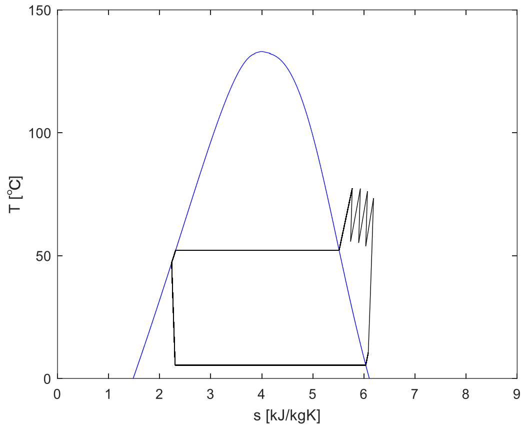

Fig. 5. T-s diagram of cycle with multi-stage mechanical compressor and intercooler.

First, looking at the results of the single MC stage, in this cycle, ammonia has a large vapor compression irreversibility, so it appears as a T-s plot as in Fig. 4. At this time, the condenser temperature and evaporator temperature were 53.99 ℃ and 5.6 ℃, respectively, and the work consumed by the compressor was 309.4576 kJ/kg when the isentropic efficiency was 0.75.

Next is the result when using multi-stage MC including intercooling instead of single MC in the same cycle in the Fig. 5. The effectiveness of the intercooling air heat exchanger between the compression processes was set as an ideal value by obtaining the effectiveness value when the isentropic efficiency is 1 so that the refrigerant at the condenser inlet does not become 2-phase state. When the isentropic efficiency in all stages was given as 0.75, the work input was 230.2457 kJ/kg, which significantly reduced the irreversibility compared to the single-stage MC. As the number of stages approaches infinity, isothermal compression approaches and Carnot efficiency approaches.

In the thermodynamic cycle, the second-law efficiency indicates the degree to which the actual process is close to the reversible process. In this case, the cooling COP can be expressed as the actual performance and the reversible process can be expressed as the Carnot efficiency as shown in the following equation. The second-law efficiency of the multi-stage MC analyzed in this study is 76.77%, and if intercooling and multi-stage compression can be implemented in real, it can be approached close to the Carnot cycle.

$$\frac{COP_R}{carnot\ efficiency} = \frac{Q_{evap}/W_{comp}}{T_{evap}/(T_{cond}-T_{evap})} \tag{2}$$

However, it is actually hard to realize multi-stage compression and intercooling using mechanical compressors.[9] This is why compression using interstage cooling has not been studied much. As shown in Fig. 6, there are studies on two-stage compression with refrigerant injection. [10-11]

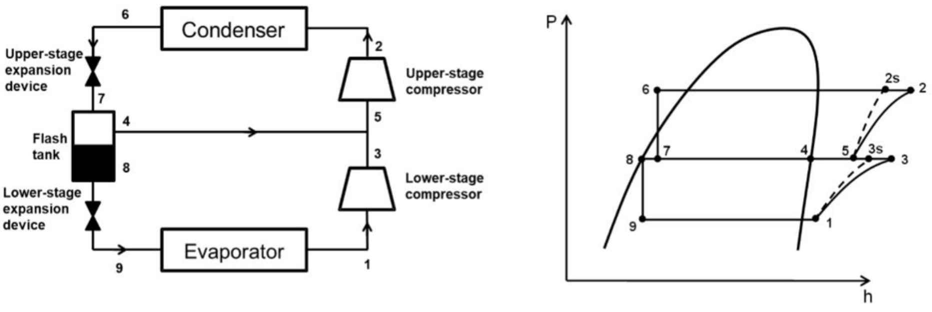

Fig. 6. *Schematic of Two-stage compression cycle (left) with associated P-h diagram (right).[6]*

In contrast, Electrochemical Compressor (ECC) is a technology that compresses gas through an electrochemical reaction and is based on the isothermal compression principle. In the next chapter, the principle of ECC and the practical isothermal compression refrigeration cycle with ammonia ECC are analyzed.

3. Isothermal compression of Electrochemical compressor (ECC)

3.1. Electrochemical Ammonia Compressor

Electrochemical ammonia compressor is an electrochemical compressor that uses the movement of NH_3 from the suction side to the discharge side using H_2 as a carrier gas when the ion exchanger membrane is charged with DC voltage. As shown in Fig. 7, ammonia and hydrogen transfer the membrane at a ratio of 2:1, and the half reaction at each electrode is as follows. [12]

$$2NH_3 + H_2 \rightarrow 2NH_4^+ + 2e^- \quad (anode) \tag{3}$$

$$2NH_4^+ + 2e^- \rightarrow 2NH_3 + H_2 \quad (cathode) \tag{4}$$

Due to the potential difference, H_2 is oxidized to H^+ ions at the anode, and NH_4^+ ions are generated and passed through the polymer electrolyte membrane. At the cathode, NH_3 gas and H_2 gas evolve again. Through pressure sealing on the discharge side, gas compression effect is provided as the number of molecules increases without changing the volume.

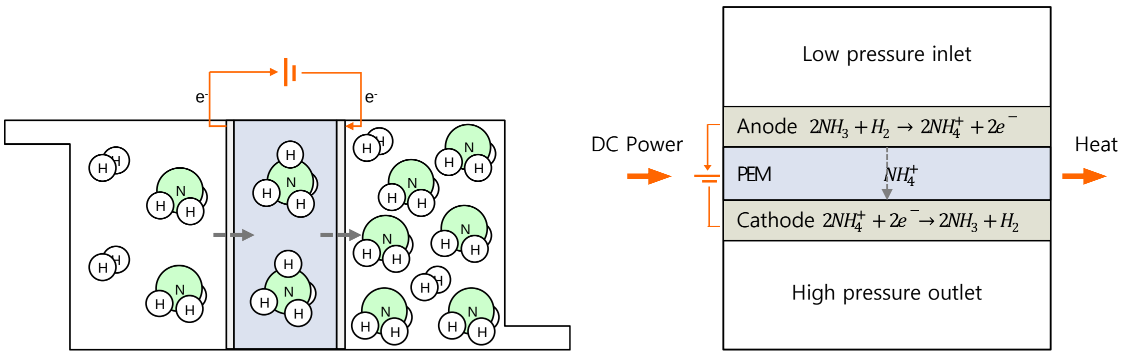

Fig. 7. *Schematic of electrochemical ammonia compressor (left) principle of ammonia ECC (right).*

Unlike traditional MC that is limited by ideal gas law (PV=nRT), the ECC is governed by the Nernst equation and ohmic loss, activation loss, etc. E_0 is standard hydrogen electrode potential, and it is zero because the half reactions on both sides of the membrane are opposite. Where $P_{cathode}/P_{anode}$ is the ratio of pressures across the membrane, and the voltage required for compression is a function of this ratio. [13]

$$V_{comp} = E_{Nernst} + \eta_{ohm} + \eta_{act} \tag{5}$$

$$E_{Nernst} = E_0 + \frac{RT_{ECC}}{nF} ln\,(\frac{P_{cathode}}{P_{anode}}) \tag{6}$$

$$dU = \delta Q + PdV \tag{7}$$

This relationship describes isothermal compression. From a thermodynamic point of view, the internal energy U is a function of Q and W as shown in the equation (7). In the adiabatic process, if the pressure rises without volume change, δQ = 0 and dV = 0, so the change in internal energy is zero. Since internal energy is a function of temperature, isothermal compression can proceed as the temperature change also becomes zero. In addition, since there is no physical driving part, it is a great advantage that there are no problems with noise or lubricating oil.

In comparison with mechanical compressors explained in the previous chapter, the most ideal compression of MC for isothermal compression is adiabatic compression. As can be seen in Fig. 8, multi-stage adiabatic compression is needed intercooling, and it results in high capital and operating cost. The ECC performs isothermal compression like in Fig. 8.

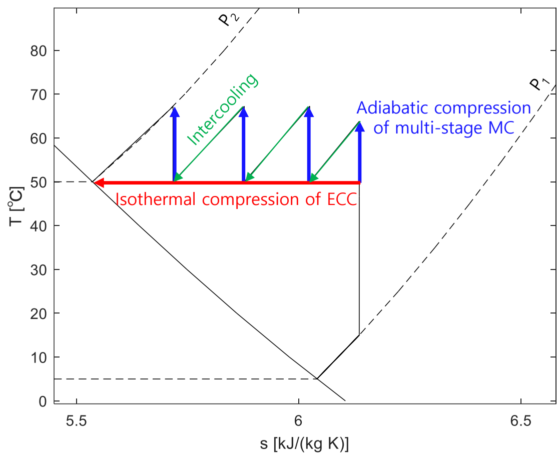

Fig. 8. Compressor temperature profiles during compression with multi-stage MC and ECC. [14]

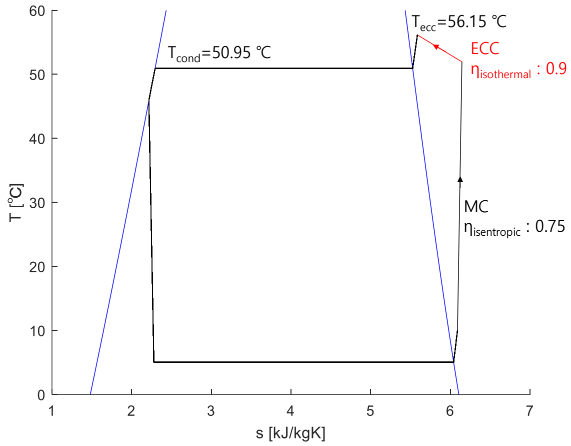

Fig. 9. T-s diagram in practical cycle of semi-isothermal compression using ECC.

3.2. Practical case of isothermal compression cycle modeling with ECC

Practical cycle with ECC was analyzed including single-stage MC compressor in the low-pressure compression part. The cycle analysis conditions used for this also are shown in Table 2. For isothermal compression using ECC, MC with an isentropic efficiency of 0.75 was used at the front-end to adjust the condenser refrigerant inlet temperature to the cycle like Fig. 9, and the isothermal efficiency of ECC is set 0.9. Since the compression of ECC is not volume compression but compression due to the increase in the number of molecules at constant volume, so it cannot be represented as a state point in the T-s plot, but it is plotted in a sense of entropy per mass for better understanding.

From eq. (6), the required work to compress from the MC outlet pressure to the condenser pressure is calculated by dividing the isothermal efficiency ($\eta_{isothermal}$). The work equivalent to the remaining work increases the enthalpy of the refrigerant as a loss of ECC like an eq. (8). So, the refrigerant which temperature determined at the ECC outlet with isothermal compression efficiency flows into the condenser. The ECC consumes the work as 155.84 kJ/kg, and total compression work is required as 243.583 kJ/kg, which is confirmed that the work could be reduced compared to single-MC cycle. Compared to Fig. 4, the cycle using ECC takes advantage at work in the superheat vapor compression over the condenser temperature part and performs close to isothermal compression instead of MC cycle which is barely to implement real intercooling and multi-stage systems.

$$w_{thermal,loss} = RT_{ECC} ln\left(\frac{P_{ECC,out}}{P_{ECC,in}}\right) * \frac{(1-\eta_{isothermal})}{\eta_{isothermal}} = h_{ECC,out} - h_{ECC,in} \tag{8}$$

In other words, due to irreversibility caused by cell resistance, overvoltage is required than Nernst voltage, and it generates heat corresponding to remainder of the isothermal compression efficiency. To maintain constant performance, this heat must be removed. Normally, the isothermal compression efficiency of ECC is known to be about 93% [4], but if you make a stack to achieve a high-pressure ratio, you must have a thermal management solution [14].

Fortunately, ECC makes it easy to implement intercooling between unit cells in the stack unlike the MC. Since the gas distribution channels are in contact between the cells, the surface area for heat removal is sufficient. Tao et al. proposed an intercooler design to implement isothermal compression in ECC stack. The intercooling has an open channel design using air or a heat exchanger design using water, so the system is not complicated. Therefore, it can be said that it is the closest process to practical isothermal compression.

The second-law efficiency of the Fig. 9 cycle is 73.87%, which is the closest to the Carnot cycle. However, even in this cycle, the effect of isothermal compression is reduced because MC is used for the front-end compression to satisfy the condenser temperature. Therefore, it is necessary to study refrigerant cycles or membranes with low condenser temperatures for use in refrigeration cycles. ECC has a cation exchange membrane and an anion exchange membrane. Research is being conducted on a low GWP refrigerant that can pass through the membrane in a positive ion state by obtaining H^+ while using hydrogen gas as a carrier gas. The most anticipated refrigerant is the HFO series. The biggest barrier to using ECC as a compressor in the refrigeration cycle is the operating temperature of the ECC. In the case of Nafion membrane, which is the most used, since it is mainly used at 5-60℃, the condenser temperature is around that temperature or rather, it requires heating to apply to the cycle and cooled again after compression. Therefore, it is necessary to increase the potential of the refrigeration system through the development of ECC with high efficiency in the low temperature region.

4. Conclusion

In this paper, the concepts of multi-stage mechanical compressor (MC) with intercooling and electrochemical compressor (ECC) are proposed for practical implementation of the isothermal compression. The most ideal and theoretical compression using MC is adiabatic + intercooling compression. With given isentropic efficiency, the work consumed in the refrigeration cycle of single-stage MC and multi-stage MC with intercooling was compared, and the numerical analysis of the cycle reflecting practical elements was performed. As a result, as the number of stages increases, it becomes closer to isothermal compression and the work can be reduced. However, considering the high-speed rotating piston, it is almost impossible to cool the inflowing fluid, and multi-stage compression using MC is not feasible due to the problem that the pressure and temperature of the gas rise simultaneously due to adiabatic compression.

On the other hand, since ECC is not compression by volume reduction, compression close to isothermal compression is possible. In addition, there is no driving parts, and the surface area of the membrane is wide, so it is easy to lower the temperature of the discharge side. Therefore, since sufficient intercooling can be performed by attaching a heat exchanger during multi-stage compression, the possibility of implementing an isothermal compression process is high.

However, when applied to the refrigeration cycle, since the condenser temperature must be matched, the temperature of isothermal compression must still be raised using MC at the compression front-end, and it is difficult to approach Carnot efficiency due to the few stages of isothermal compression. In addition, in the case of ECC, the range of refrigeration cycles that can be applied is not expected to be wide because the operating temperature is high at 5-60 ℃. Nonetheless, ECC has potential for low GWP refrigerants and as membrane technology improves, it can potentially improve the efficiency for the vapor compression systems.

Acknowledgements

This research was jointly supported by National Research Foundation of Korea (NRF No. 2019R1A2C108869414) and by Korea Institute of Energy Technology Evaluation and Planning (KETEP) (20202020900290, 20214000000280, 20212050100010) funded by Ministry of Trade, Industry and Energy. This research was also supported by the Korea Environmental Industry & Technology Institute (KEITI No. 2020003060005) Authors sincerely appreciate their supports.

References

[1] Kim T, Lee CY, Hwang Y, Radermacher R. A review on nearly isothermal compression technology. *J Int Refrig* 2022;144:145-62.
[2] Asdrubali F, Desideri U. Handbook of Energy Efficiency in Buildings: A Life Cycle Approach. Oxford, UK : Elsevier; 2019, p. 441–595
[3] Schorer, L., Schmitz, S. 2017. “Onsite hydrogen generation and hydrogen recycling for refuelling FCEVs using an electrochemical hydrogen compressor,” EVS30 Symposium. Stuttgart, Germany.
[4] Tao Y, Hwang Y, Radermacher R, Wang C. Experimental study on electrochemical compression of ammonia and carbon dioxide for vapor compression refrigeration system. *J Int Refrig* 2019;104:180-8.
[5] Ibrahim TK, Rahman M, Alla ANA. Study on the effective parameter of gas turbine model with intercooled compression process. *SRE* 2010;5(23):3760-70.
[6] Lemmon, E. W., Bell, I. H., Huber, M. L., McLinden, M. O., 2018. NIST standard reference database 23: reference fluid thermodynamic and transport properties-REFPROP, Version 10.0, National Institute of Standards and Technology. Standard Reference Data Program, Gaithersburg.
[7] Kim S, Cho Y, Kim MS, Kim M. Characteristics and optimization of supercritical CO2 recompression power cycle and the influence of pinch point temperature difference of recuperators. *Energy* 2018;147: 1216-26.
[8] Na SI, Kim M, Kim MS. Performance simulation of CO2 transcritical cooling system with mechanical subcooling cycle for automobile air conditioning. *J Mech Sci Technol* 2022;36:4797–807.
[9] Coney MW, Stephenson P, Malmgren A, Linnemann C, Morgan RE, Richards RA, Huxley R, Abdallah H. Development Of A Reciprocating Compressor Using Water Injection To Achieve Quasi-Isothermal Compression. *International Compressor Engineering Conference*. 2002; Paper 1508.
[10] Lee D, Seong KJ, Lee J, Performance investigation of vapor and liquid injection on a refrigeration system operating at high compression ratio. *Int J Refrig* 2015;53:115–25.
[11] Huang JM, Chiang CP, Chen JF, Chow YLo, Wang CC, Numerical investigation of the intercooler of a two-stage refrigerant compressor. *Appl Therm Eng* 2007;27:2536–48.
[12] Tao Y, Gibbons W, Hwang Y, Radermacher R, Wang C. Electrochemical ammonia compression. *Chem Commun* 2017;53(41):5637-40.
[13] Nordio M, Rizzi F, Manzolini G, Mulder M, Raymakers L, Annaland MVS, Gallucci F. Experimental and modelling study of an electrochemical hydrogen compressor. *Chem Eng J* 2019;369:432-42.
[14] Lipp, L., 2012. “Electrochemical Hydrogen Compressor,” DOE Hydrogen Program.