A Study on Isothermal Compression System Applying Electrochemical Compressor

Soyeon Kim*, Minkyu Jung, Donik Ku, Soojin Bae,
Gijeong Seo, Don Kyu Kim, **Minsung Kim†**
Energy Conversion System Lab.
nuri36@cau.ac.kr
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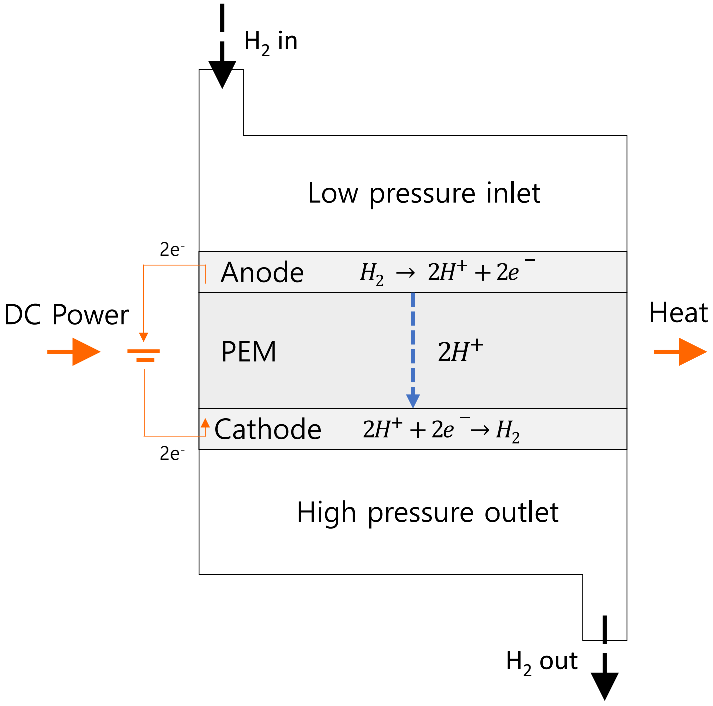
This Document was prepared by staff members of Energy Conversion System Laboratory of Department of Intelligent Energy and Industry in Chung-Ang University, Seoul 06974, KOREA

Electrochemical Compressor (ECC)

➢ Electrochemical compressor

- Compressing refrigerants by electrochemical reaction through the layers of membranes
- H_2, NH_3, HFO refrigerants available using PEM (proton exchange membrane) & Stack in serial for getting high pressure
- High isothermal efficiency (η_{iso} : 0.8~0.9) → by heat loss; discharge temperature ↑ as the # of stage ↑ (in stack)



< Mechanism of electrochemical H_2 compressor >

< Electrochemical compressor cell >

$$W_{isot.comp.} = nFE_{Nernst} = RT_{ECC}\ln\left(\frac{P_{cathode}}{P_{anode}}\right)$$

$$\eta_{isothermal} = \frac{w_{isot.comp.}}{w_{comp}} = \frac{w_{isot.comp.}}{w_{isot.comp.} + w_{heatloss}}$$

$$Heat\ loss = w - w_{iso} = h_{discharge} - h_{discharge,iso}$$

Table Isothermal efficiency of NH_3 ECC cell (experiment)

		ECC (H_2+NH_3) 1-stage
Compression work	Isothermal compression (by equation)	191.52 [kJ/kg]
	Experiment result	206.72 [kJ/kg]
Pressure ratio		3

η_{iso} 93%

Isothermal compression

➢ Vapor Compression Cycle (VCC)

- The largest power consumer in heat pump system
- Carnot VCC : isentropic + isothermal compression
- Isothermal compression at $T_b = T_0$ rejecting ${}_bQ_c$

⇨ **Compressor cooling for approaching isothermal compression**

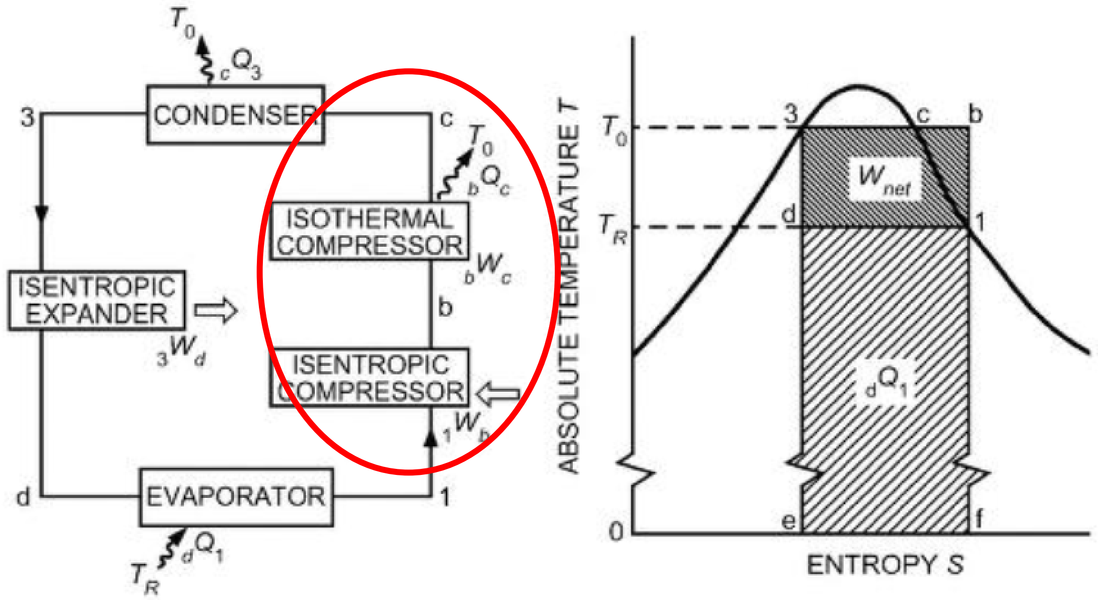


Figure Carnot vapor compression cycle*

*ASHRAE handbook : Fundamentals (2017)

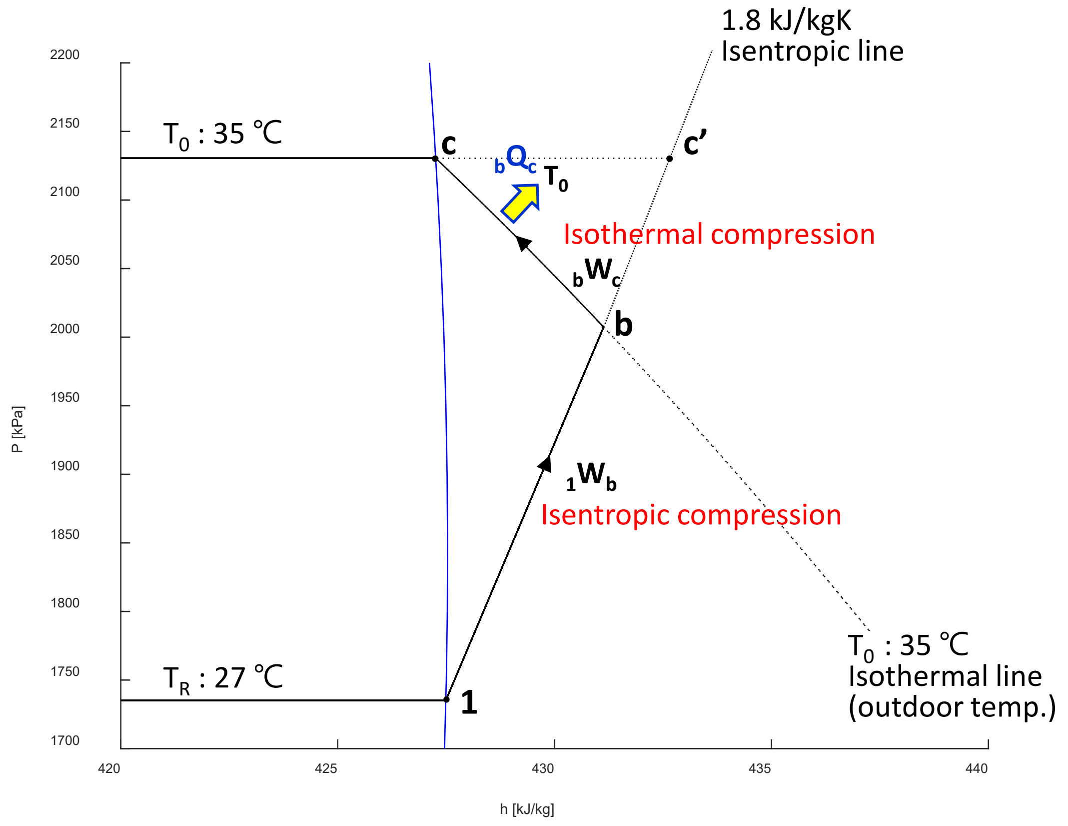


Figure P-h diagram of Carnot vapor compression cycle

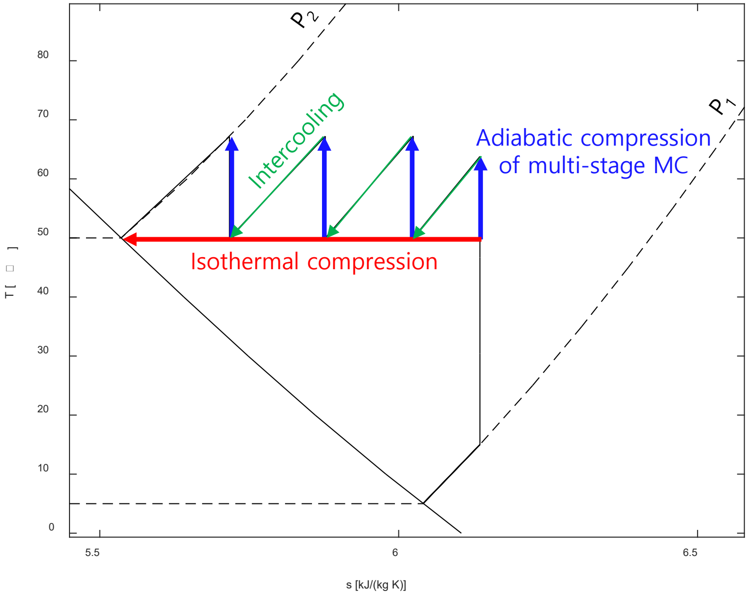
Compressor cooling

➢ Gas compression

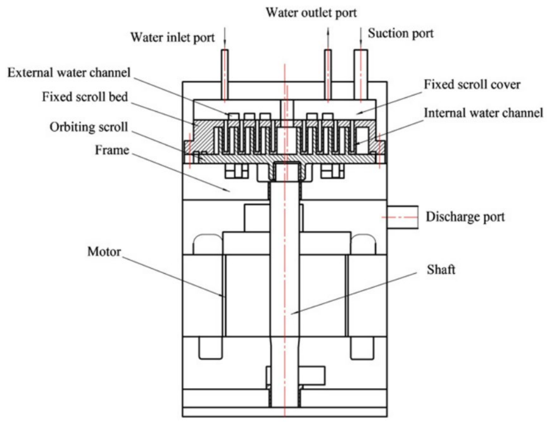
- Cryogenic system(liquefaction cycle), gas turbine cycle, air compression
- External cooling, interstage cooling, water injection, oil-flooded(injection)
- Reducing compression work without condensation

➢ Vapor compression

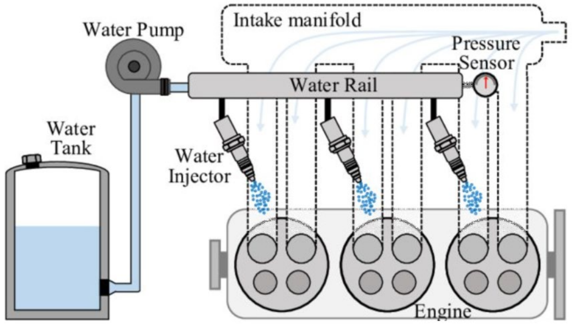
- Trans-critical cycle(sCO_2 cycle), sub-critical cycle
- Refrigerant injection, oil-flooded(injection), external cooling, interstage cooling



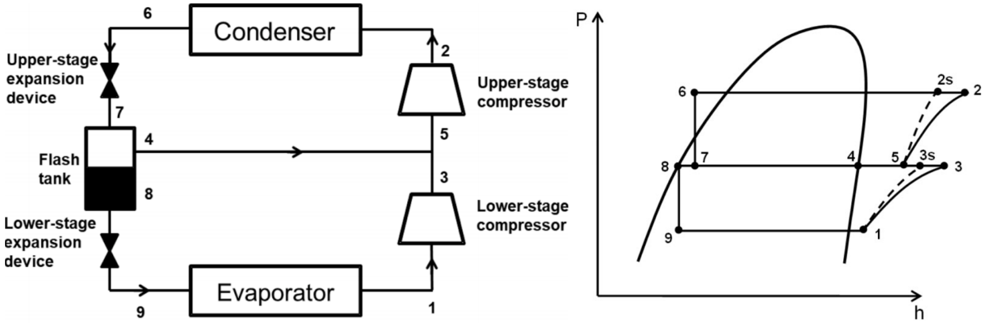
< multi-stage compression with intercooling[4] >



< External cooling of scroll compressor[1] >



< Water injection system for DISI Engine[2] >



< Refrigerant injection for heat pump system[3] >

1. Sun, S., Zhao, Y., Li, L., & Shu, P. (2010). Simulation research on scroll refrigeration compressor with external cooling. International journal of refrigeration, 33(5), 897-906.
2. Millo, F., Gullino, F., & Rolando, L. (2020). Methodological approach for 1D simulation of port water injection for knock mitigation in a turbocharged DISI engine. Energies, 13(17), 4297.
3. Huang, J. M., Chiang, C. P., Chen, J. F., Chow, Y. L., & Wang, C. C. (2007). Numerical investigation of the intercooler of a two-stage refrigerant compressor. applied thermal engineering, 27(14-15), 2536-2548.
4. Lipp, L. (2012). "Electrochemical Hydrogen Compressor," DOE Hydrogen Program.

Practical compression condition

➢ Multi-stage compression & intercooling by outdoor air

- Finite temperature difference between heat source and refrigerant in HX
  → isothermal compression(T_{od}) : cannot compress up to P_{cond}
- Practical compression system : multi-stage comp. & intercooling
- No cooling after final compression stage -> to condenser
- Discharge temperature : $T_{cond} > T_{od}$

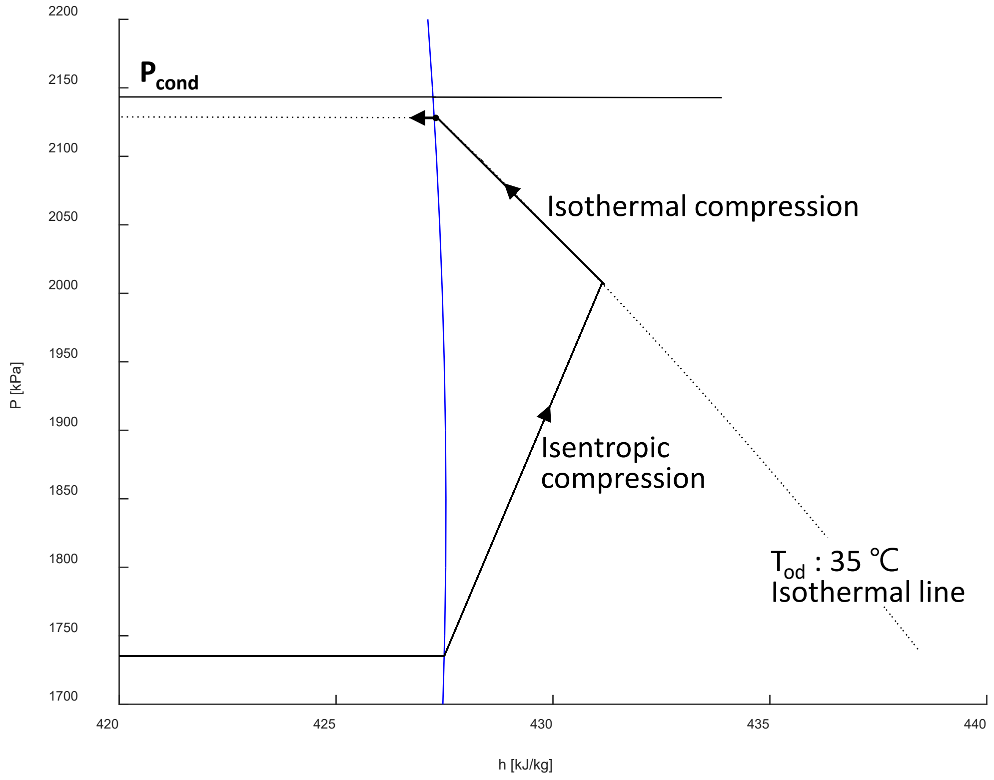


Figure Multi-stage compression & intercooling cycle

➢ Heat pump system simulation

- System modeling to determine cycle design points
- Comparing with single-stage compression cycle
- Cooling / heating mode of heat pump system
  → Performance analysis according to T_{OD}, T_{ID} conditions

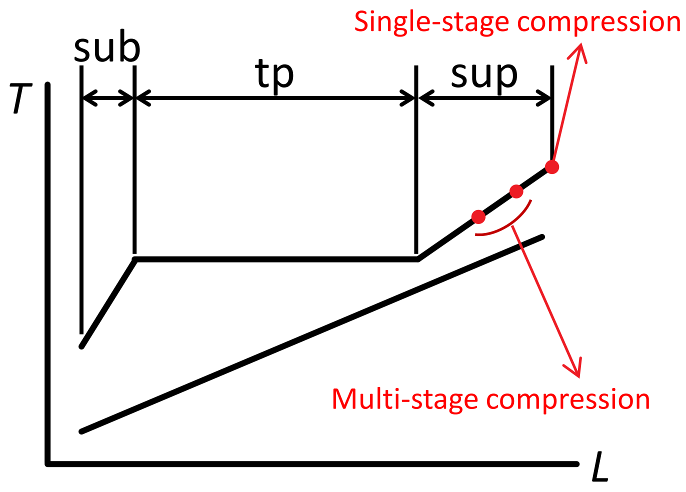
Heat pump simulation

➢ On-design simulation (cycle determination)

- Fundamental analysis for cycle design
  - Based on operating conditions**(temperature)** or design conditions(capacity)
  - **Determination cycle points** using key design parameters
  - Steady-state analysis & constant superheat/subcooling
  - Not considered component sizes in analysis

➢ Heat exchanger

- **LMTD** (Log Mean Temperature Difference) model
  - Average temperature difference based on the **inlet/outlet conditions** in HX
  - Applying for each section **2-phase**, and **subcooling** conditions
  - Suitable model when the cycle is defined by a given temperature difference : typically LMTD 8-10 ℃ (evaporator), 10-15 ℃ (condenser)



Condenser

$$\frac{1}{\Delta T_c} = \frac{\dot{Q}_{tp,c}}{\dot{Q}_c \Delta T_{tp,c}} + \frac{\dot{Q}_{sub,c}}{\dot{Q}_c \Delta T_{sub,c}} = \frac{1}{\dot{Q}_c} \sum \frac{\dot{Q}_i}{\Delta T_i}$$

Evaporator

$$\frac{1}{\Delta T_e} = \frac{\dot{Q}_{tp,e}}{\dot{Q}_e \Delta T_{tp,e}} + \frac{\dot{Q}_{sup,e}}{\dot{Q}_e \Delta T_{sup,e}} = \frac{1}{\dot{Q}_e} \sum \frac{\dot{Q}_i}{\Delta T_i}$$

On-design simulation (Cycle determination)

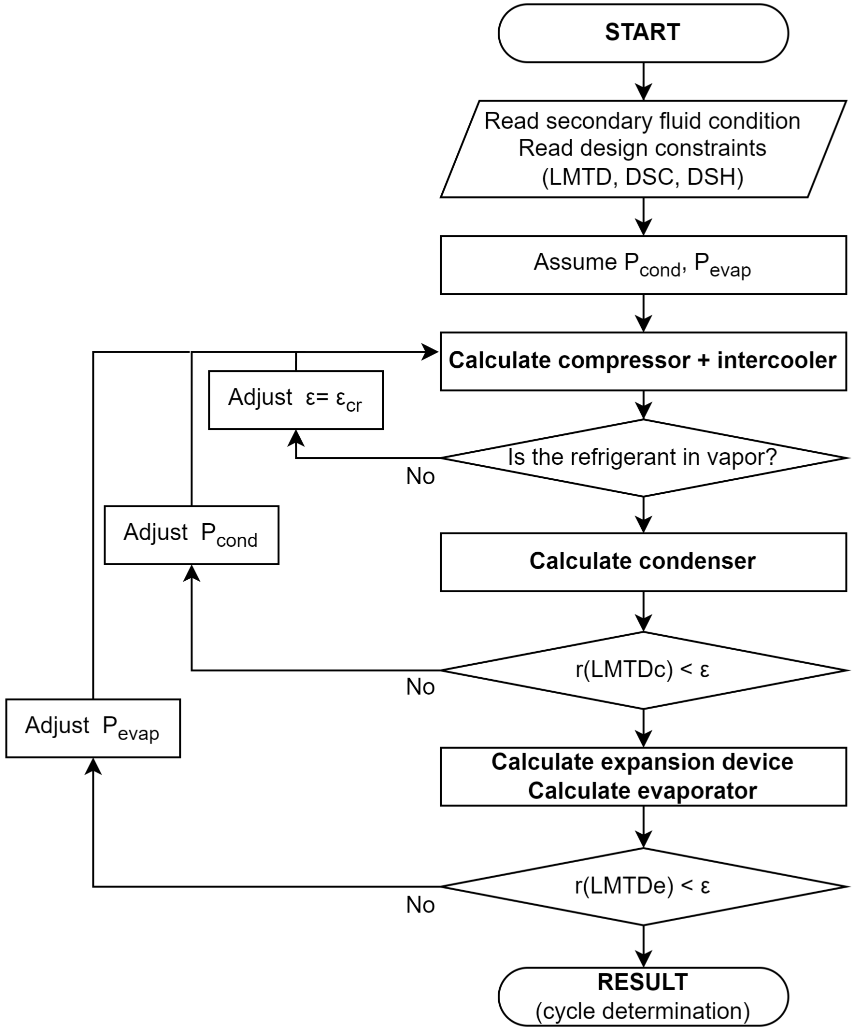
14th IEA HEAT PUMP CONFERENCE

➢ Heat pump cycle simulation

Table Design parameters for the heat pump

Parameters	Values
Degree of superheating [℃]	5
Degree of subcooling [℃]	5
LMTD for condenser/evaporator [℃]	8
Temperature difference of water in condenser/evaporator [℃]	8
***Compressor isentropic efficiency (η_{isen}) [-]**	0.83
Effectiveness of intercooler (ε) [-]	0.9
Number of compressors for multi-stage compression [-]	1~10
**Heat source temperature for cooling mode [℃]	35 (308K)
**Heat sink temperature for cooling mode [℃]	27 (300K)
**Heat source temperature for heating mode [℃]	20 (293K)
**Heat sink temperature for heating mode [℃]	7 (280K)

*ASHRAE handbook : HVAC Systems and Equipment (2016)
** AHRI standard 210/240-2017



Simulation result

➢ Cooling mode (T_{OD} : 35℃, T_{ID} : 27℃)

- 4-stages compression cycle
- Intercooling heat source : 35℃ air
  - Cooling effect starts after the compression stages when the T > 35 ℃
- COP improvement (COP=$Q_{evap}/work$)
  - isentropic comp . + isothermal comp. (at T_{cond}) : 22.1 kJ/kg
  - Cooling capacity by compressor cooling : constant

Table Comparing performance of heat pump cycle in cooling mode

η_{isen}	0.83		1	
# of stages	Single-stage Compression	4-stage Compression	Single-stage Compression	4-stage Compression
$T_{discharge}$	68.27 [°C]	53.06 [°C]	64.88 [°C]	52.16 [°C]
Compressor work	27.6 [kJ/kg]	- 3.7 % 26.56 [kJ/kg]	22.9 [kJ/kg]	- 4.1 % 21.96 [kJ/kg]
Cooling capacity (Q_{evap})	162.28 [kJ/kg]	= 162.28 [kJ/kg]	162.28 [kJ/kg]	162.28 [kJ/kg]
COP	5.88	+ 3.9 % 6.11	7.08	+ 4.3 % 7.39

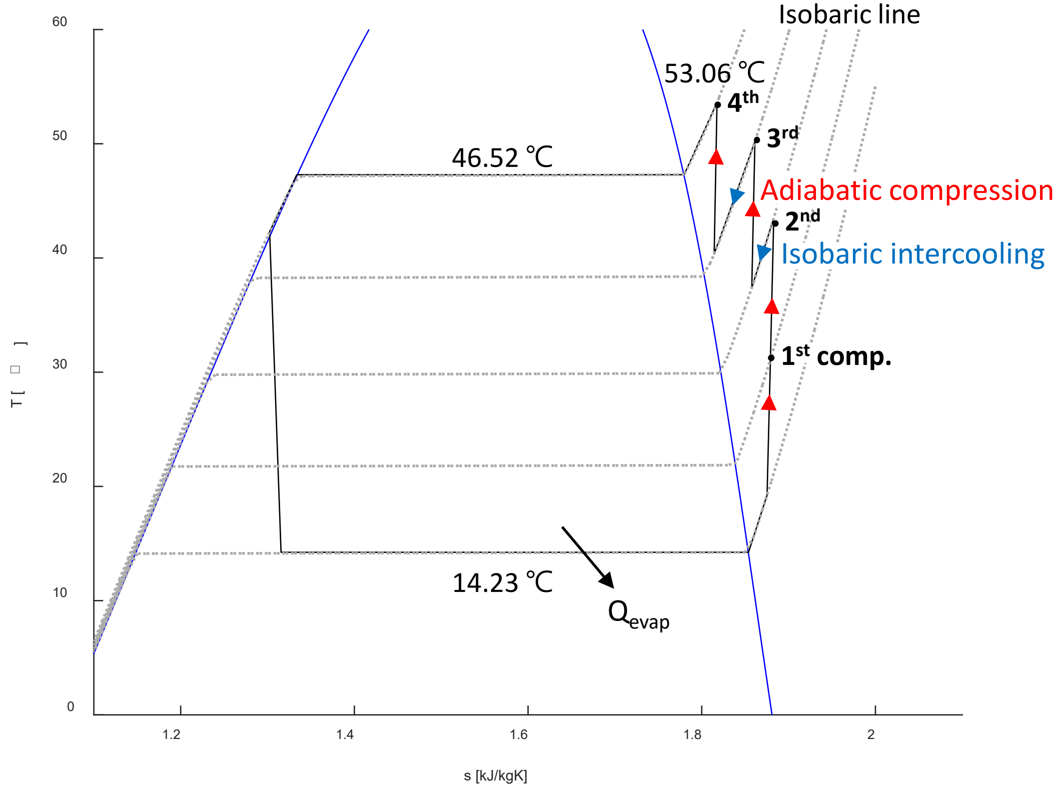


Figure 4-stages compression heat pump cycle in cooling mode

Simulation result

➢ Cooling mode (T_{OD} : 35℃, T_{ID} : 27℃)

- 4-stages compression cycle
- Intercooling heat source : 35℃ air
  - Cooling effect starts after the compression stages when the T > 35 ℃
- COP improvement (COP=$Q_{evap}/work$)
  - isentropic comp . + isothermal comp. (at T_{cond}) : 22.1 kJ/kg
  - Cooling capacity by compressor cooling : constant

Table Comparing performance of heat pump cycle in cooling mode

η_{isen}	0.83		1	
# of stages	Single-stage Compression	4-stage Compression	Single-stage Compression	4-stage Compression
$T_{discharge}$	68.27 [℃]	53.06 [℃]	64.88 [℃]	52.16 [℃]
Compressor work	27.6 [kJ/kg]	(- 3.7 %) 26.56 [kJ/kg]	22.9 [kJ/kg]	(- 4.1 %) 21.96 [kJ/kg] (Isothermal comp. at T_{od} : 14.72 kJ/kg)
Cooling capacity (Q_{evap})	162.28 [kJ/kg]	(=) 162.28 [kJ/kg]	162.28 [kJ/kg]	162.28 [kJ/kg]
COP	5.88	(+ 3.9 %) 6.11	7.08	(+ 4.3 %) 7.39

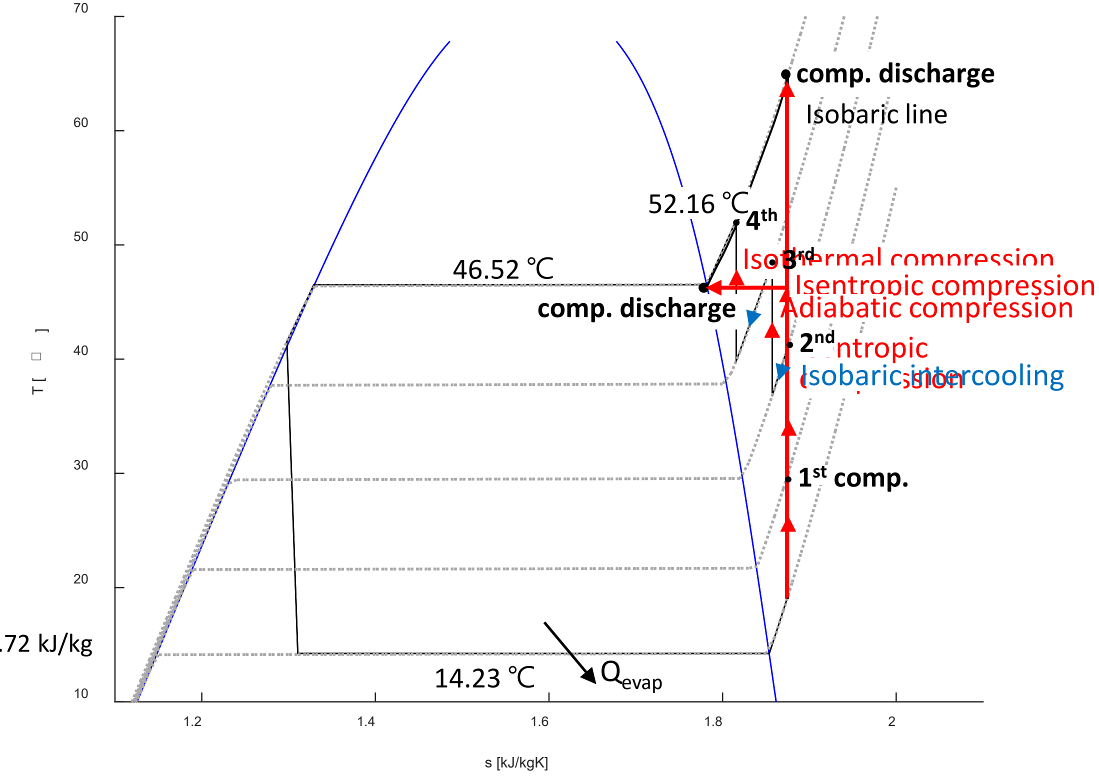


Figure Carnot compression heat pump cycle in cooling mode

Simulation result

➢ **Heating mode (T_{OD} : 7℃, T_{ID} : 20℃)**

- 3-stages compression cycle
- Intercooling heat source : 7℃ air (∴ cooling effect ↑)
  - Cooling effect starts from the stages when the T > 7 ℃
  - Critical effectiveness for design the cycle
- Heating capacity of condenser ↓ (∵ comp. discharge temp. ↓)

⇨ **Work reduction, but less impact than capacity → Not very favorable for heating mode**

Table Comparing performance of heat pump cycle in heating mode

η_{isen}	0.83		1	
# of stages	Single-stage Compression	3-stage Compression	Single-stage Compression	3-stage Compression
$T_{discharge}$	49.82 [℃]	31.76 [℃]	45.15 [℃]	30.51 [℃]
Compressor work	31.76 [kJ/kg]	(- 4.9 %) 30.21 [kJ/kg]	26.36 [kJ/kg]	(- 4.9 %) 25.07 [kJ/kg]
Heating capacity (Q_{cond})	223.89 [kJ/kg]	(- 9.8 %) 201.97 [kJ/kg]	218.49 [kJ/kg]	200.3 [kJ/kg]
COP	7.05	(- 5.16 %) 6.69	8.29	7.99

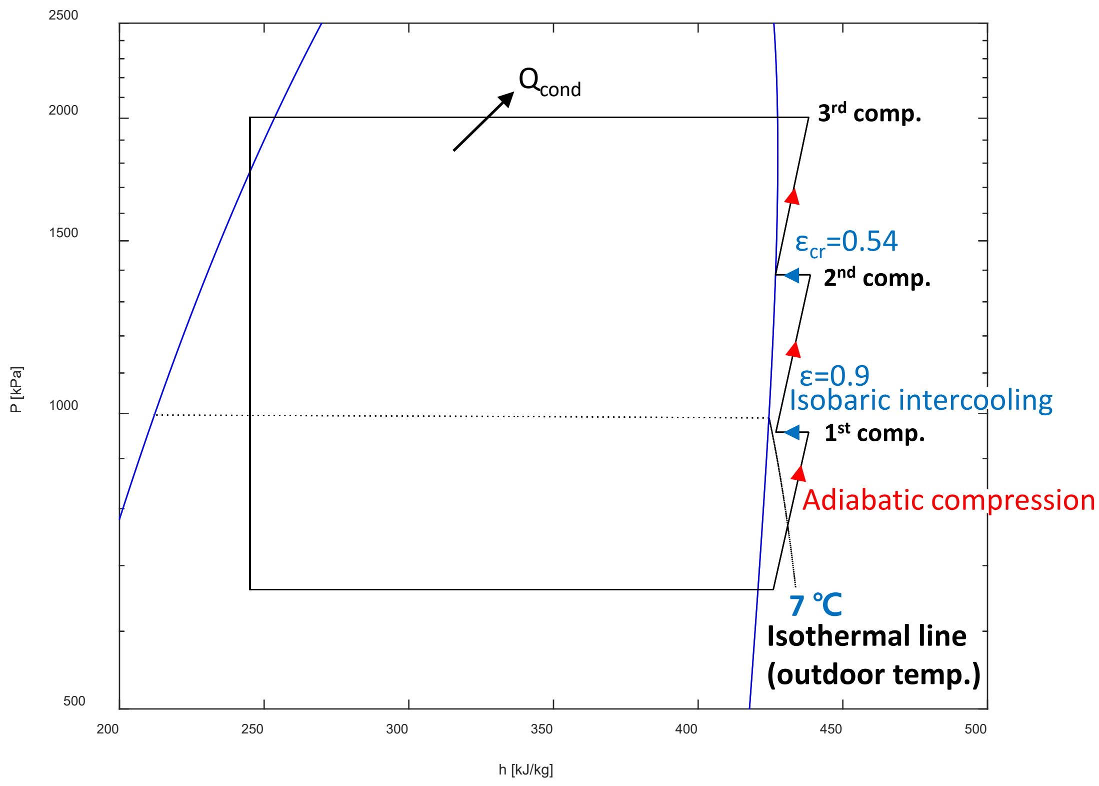


Figure 3-stages compression heat pump cycle in heating mode

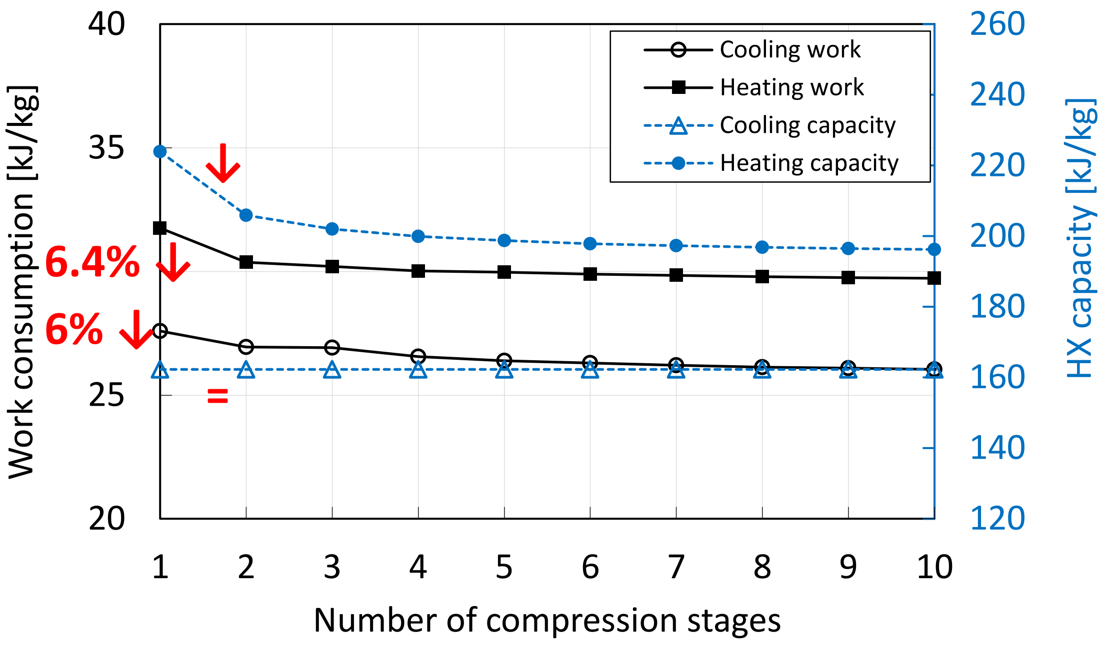
Simulation result

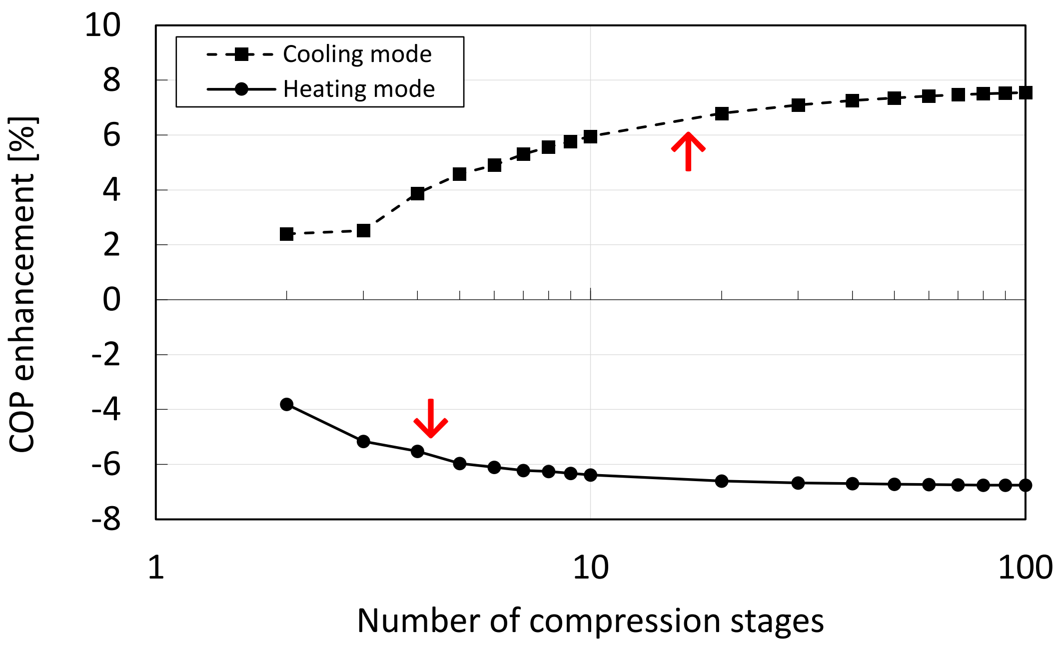
➢ Compressor cooling effect according to number of compressors

- Work reduction rate ↓ even # of compressor ↑
- COP improves in cooling mode, decreases in heating mode as the # of compressor↑

⇨ **(Cooling mode) Number of compressors ↑, and isentropic efficiency ↑ → Compressor cooling impact ↑ (COP ↑)**

⇨ **(Heating mode) Compressor cooling effect can reduce the compressor work, but not much positive effect on COP.**





Closing remarks

- **Electrochemical compressor (ECC)**
  - ✓ Compressor intercooling with outdoor air in ECC stack; isothermal compression efficiency ↑
- **Multi-stage compression and intercooling**
  - ✓ To approach isothermal compression for vapor compression cycle
  - ✓ Design parameters for heat pump simulation (LMTD, η_{isen}, ε) : on-design simulation to determine cycle design points
- **Simulation result**
  - ✓ (Cooling mode) Number of compressors ↑, and isentropic efficiency ↑ → Compressor cooling impact ↑ (COP ↑)
  - ✓ (Heating mode) The compressor work ↓, but also heating capacity ↓ → negative effect on COP (↓)

"THANK YOU"

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