Design of non-flammable mixed-refrigerant Joule-Thomson refrigerator below -100 ℃

Korea Advanced Institute of Science and Technology
Taejin Park, Junhyuk Bae, Sangkwon Jeong*

Heat Pump Conference 2023
2023.05.15

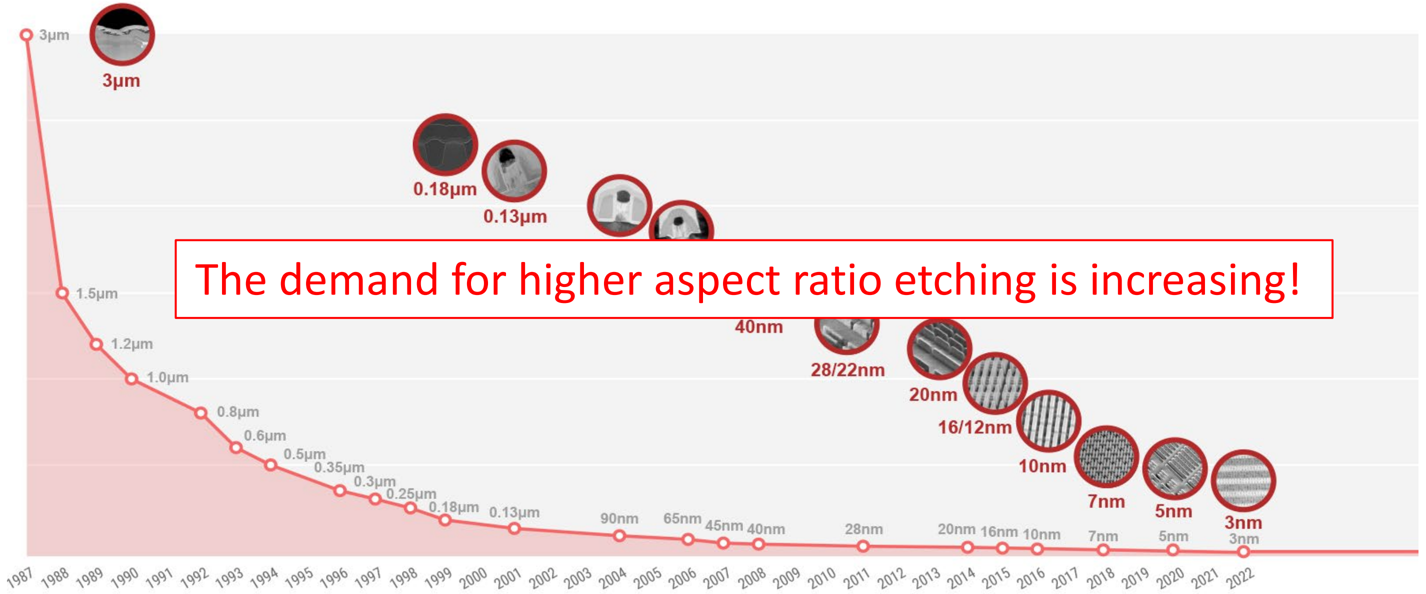
Contents

- **Introduction**
- **Methodology**
- **Results**
- **Discussion**
- **Conclusion**

Introduction

- **Research background**
  - Need to process vast amounts of data exploding with 4th industrial revolution

>>> High density fabrication in semiconductor industry



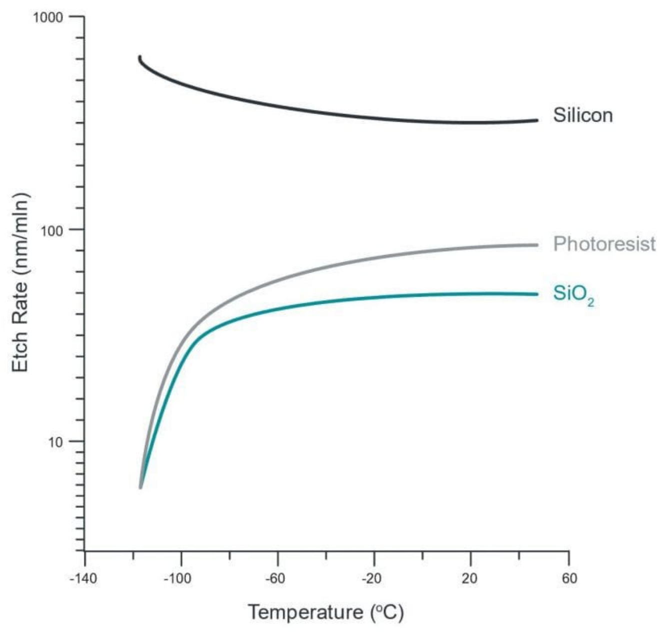
The demand for higher aspect ratio etching is increasing!

1987 <Node availability for semiconductor[1]> 2022

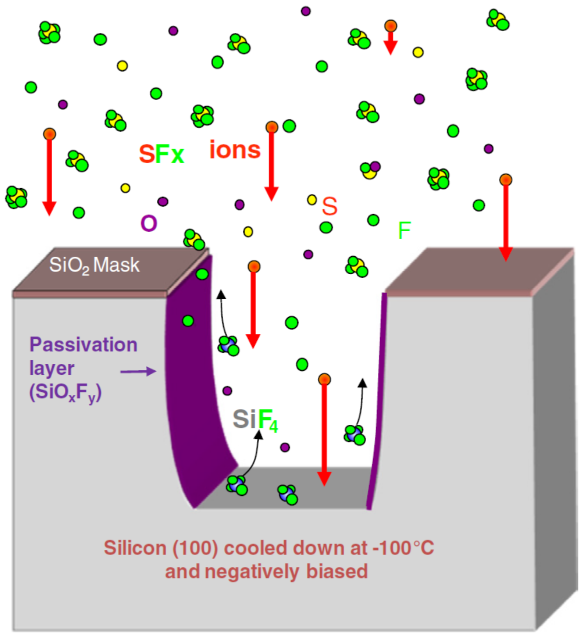
[1]https://www.tsmc.com/english/dedicatedFoundry/technology/logic/l_5nm

Introduction

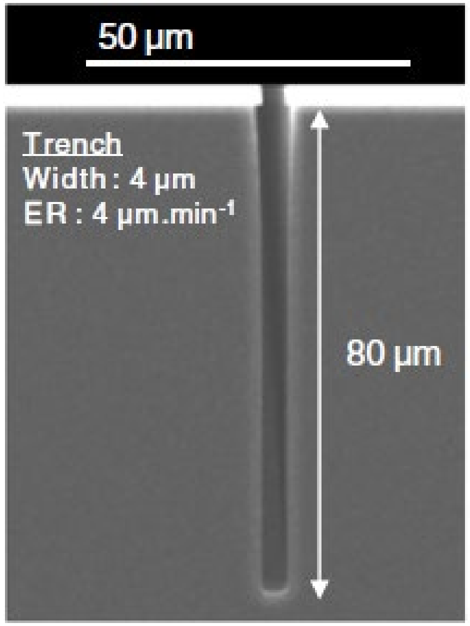
- **Research background**
  - Cryogenic etching is emerging to increase directionality and selectivity of semiconductor IC fabrication.



<Temperature dependence of etch rates[1]>



<Cryogenic etching[2]>



<Trench profile of Si cryo-etching[2]>

[1] https://www.semiconductor-digest.com/understanding-cooling-and-particulate-contamination-challenges-for-next-generation-ale-technologies/ [2] Plasma cryogenic etching of silicon: from the early days to today's advanced technologies

Introduction

- **Research objective**

<Requirements for Cryo-etching>

✓ **Extremely safe operation**

→ Operation in cleanroom

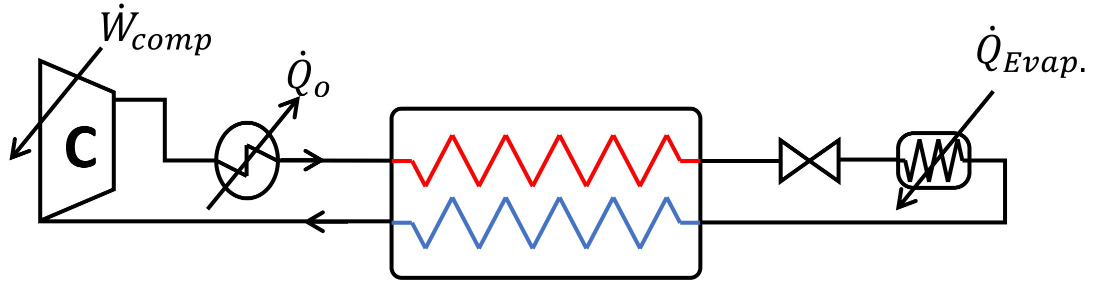
→ **Non-flammable** refrigerant

✓ **High efficiency**

→ Operation of facility all day long

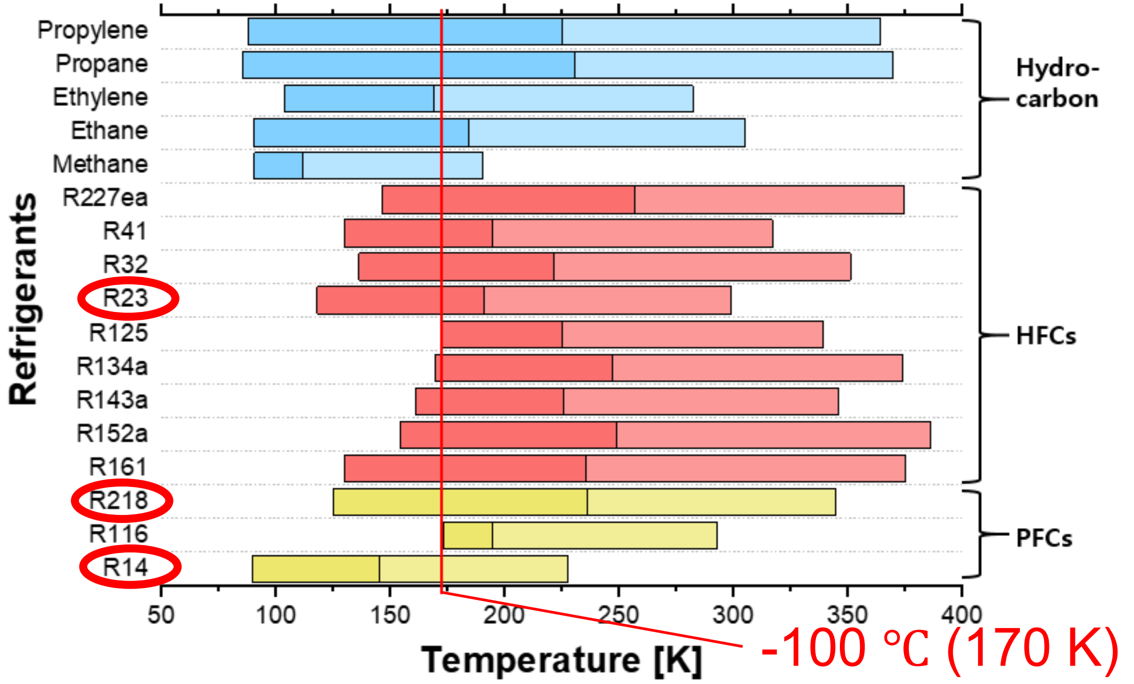
→ **Mixed refrigerant** (MR)

Design of non-flammable MR-JT refrigerator for **-100 ℃**



Methodology

- **Selection of refrigerants**
  - Non-flammable refrigerants (R14, R23 and R218) are selected.

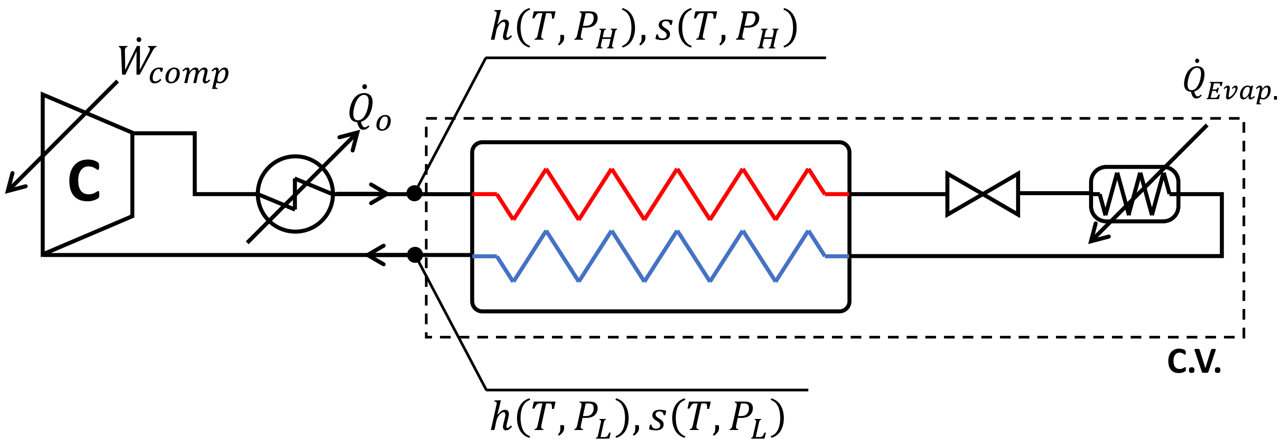


<Liquid-phase range diagram>

Methodology

Determination of MR-composition

✓ Iso-thermal enthalpy difference (Δh_{iso})



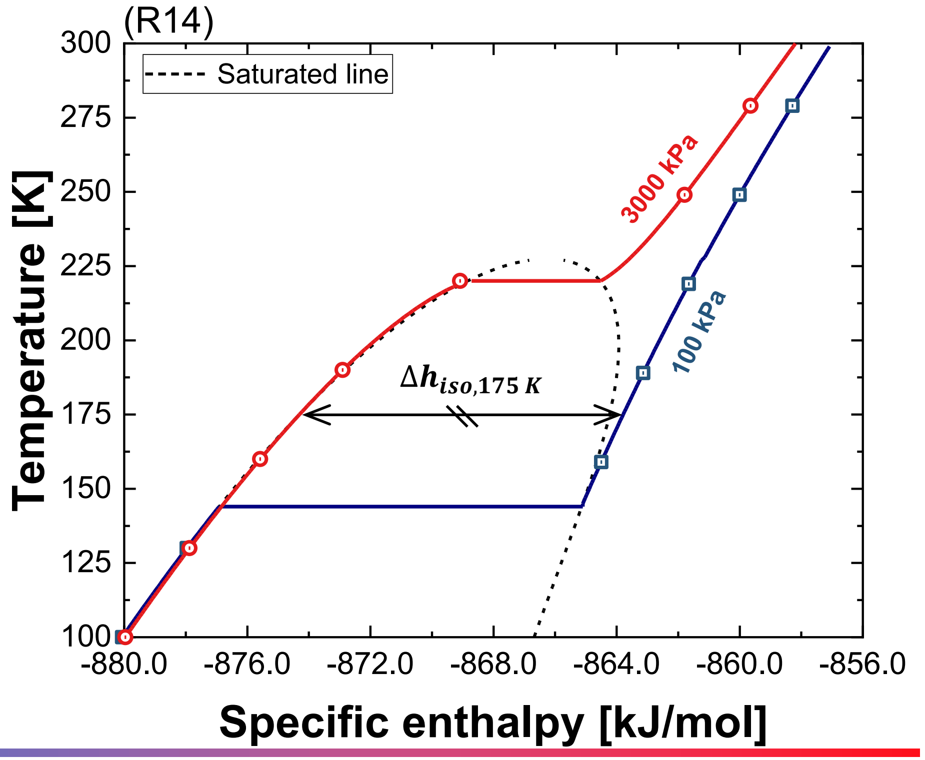
- From energy balance on the control volume, the cooling capacity ($\dot{Q}_{Evap.}$) is determined.

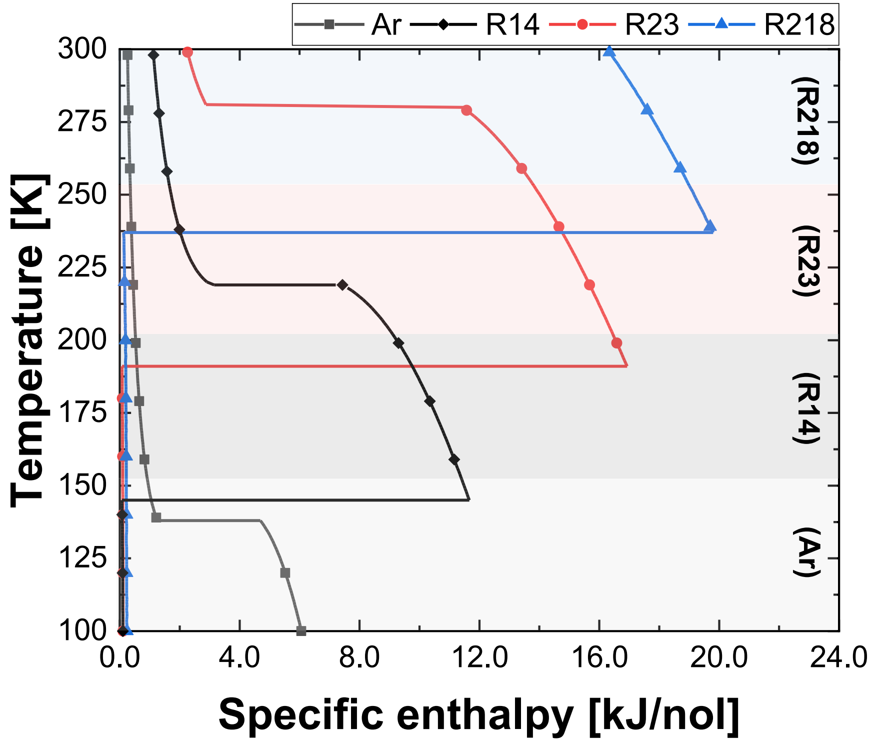
$$\dot{Q}_{Evap.} = \dot{m}\Delta h_{iso} = \dot{m}[h(T, P_L) - h(T, P_H)]$$

Methodology

Determination of MR-composition

✓ Δh_{iso} (pure refrigerant)

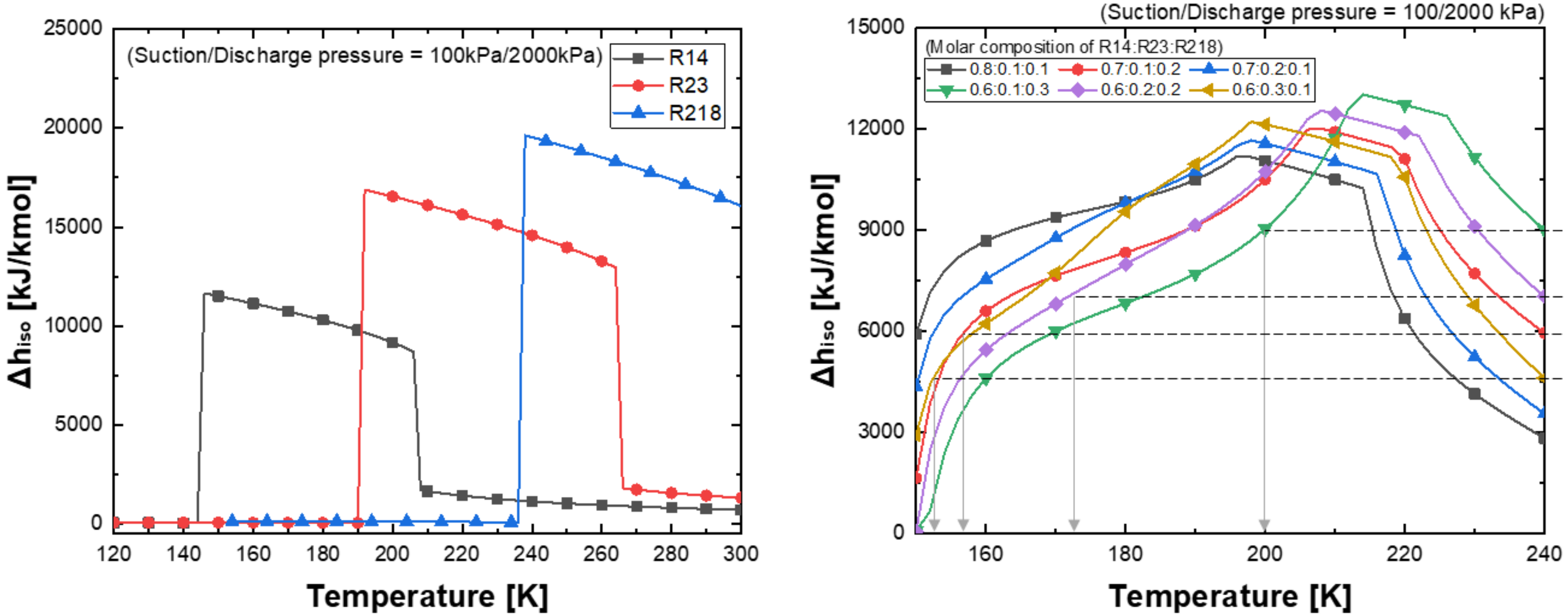




✓ 'Δh_{iso}' of each pure refrigerant is distributed over the different temperature range.

Methodology

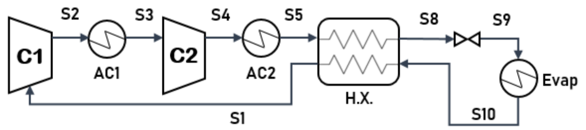
- **Molar composition for mixed refrigerants**
  - The molar composition ratio of R14 should be larger than R23 and R218.
  - A precooling cycle is beneficial for narrowing the temperature range.



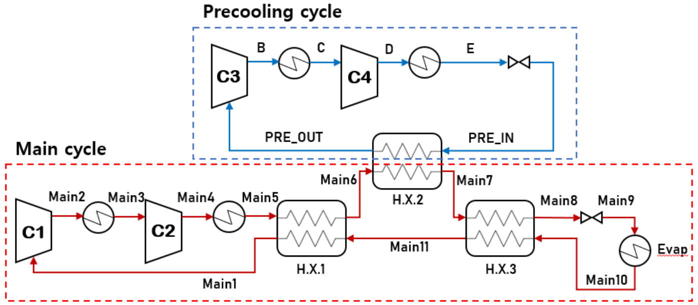
<Isothermal enthalpy difference for R14, R23 and R218>

Methodology

- **Cycle descriptions**
  - Single-stage MR (SMR) cycle
  - Cascade MR cycle: main cycle + precooling cycle with R410A



<SMR cycle>



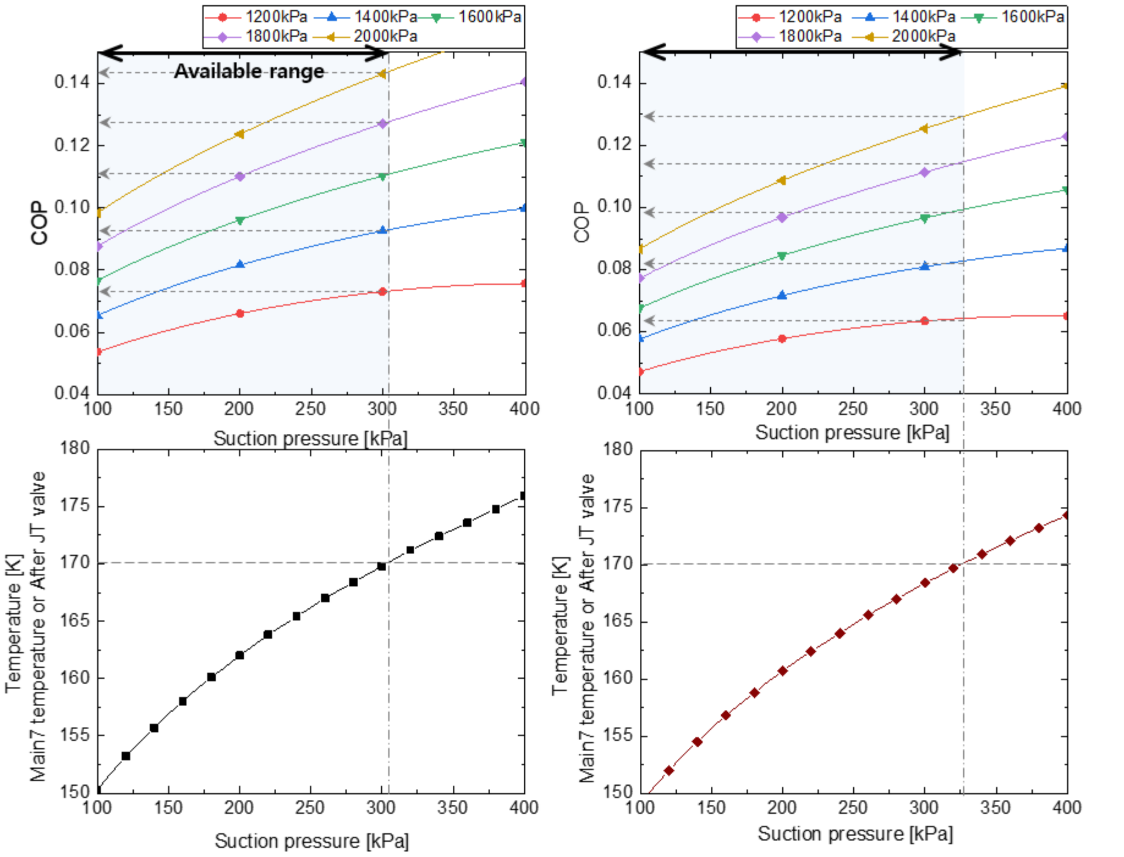
<Cascade MR cycle>

Simulation constraints for Aspen HYSYS V8.0

	Specification	Min	Max	Variation
Main cycle	Lower(suction) pressure [kPa]	100	500	40
	Higher(discharge) pressure [kPa]	1800	3400	200
	Mass flow rate [kg/s]	1	1	-
Precooling cycle	Higher(discharge) pressure [kPa]	1750	1750	-
	Temperature [K]	230	250	5

Results

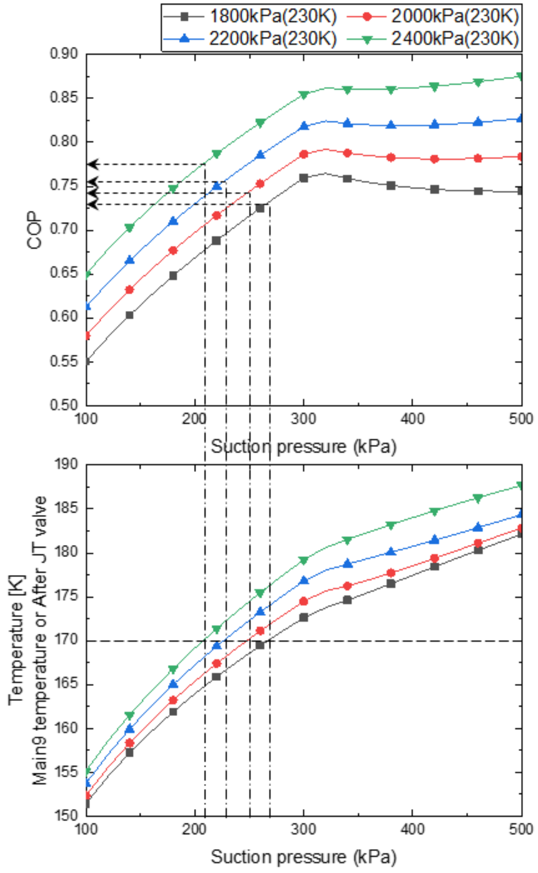
- **Simulation results**
  - SMR cycle



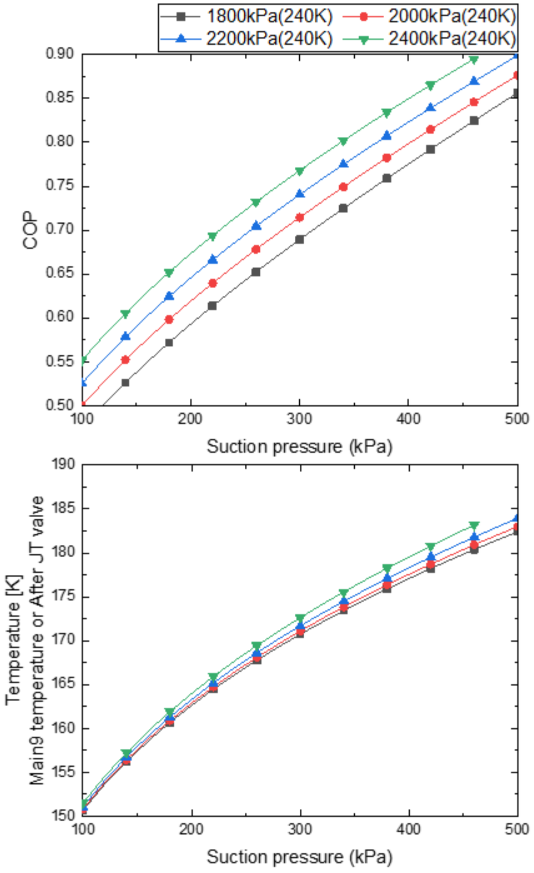
<R14:R23:R218 = 0.7:0.1:0.2> <R14:R23:R218 = 0.75:0.1:0.15>

Results

- **Simulation results**
  - Cascade MR cycle

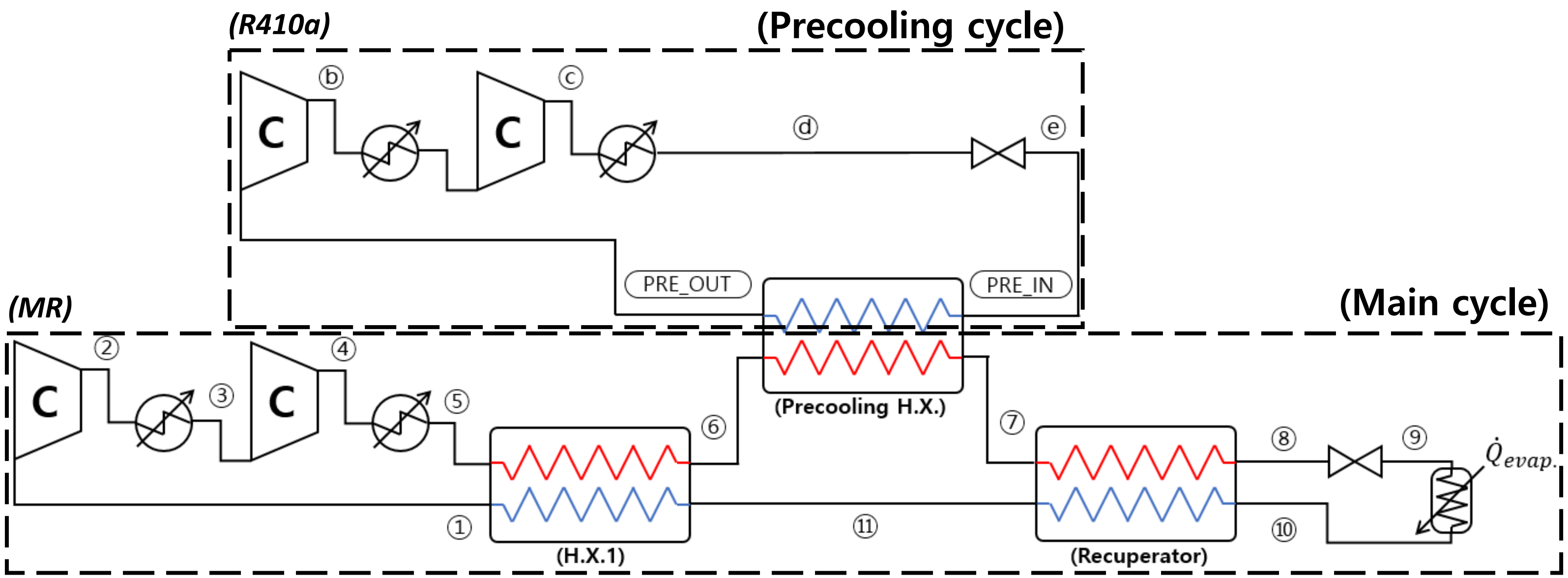


<Tpre = 230 K>



<Tpre = 240 K>

Results



- ✓ Equation of state (EOS) : Peng-Robinson
- ✓ Compression process
  - 2-stage compression process (compression ratio equal)
  - Isentropic efficiency : 80 %
- ✓ Heat exchanger
  - Minimum temperature approach : 3 K
- ✓ $COP = \frac{\dot{Q}_{Evap.}}{\dot{W}_{comp\_main} + \dot{W}_{comp\_pre}}$

Results

- **Simulation results**
  - Cascade MR cycle
    - Maximum COP = 0.785 for R14:R23:R218=0.7:0.1:0.2

Subdivided cases for several molar compositions

Case	Composition		
	R14	R23	R218
(1)	0.8	0.1	0.1
(2)	0.7	0.1	0.2
(3)	0.7	0.2	0.1
(4)	0.6	0.1	0.3
(5)	0.6	0.2	0.2
(6)	0.6	0.3	0.1

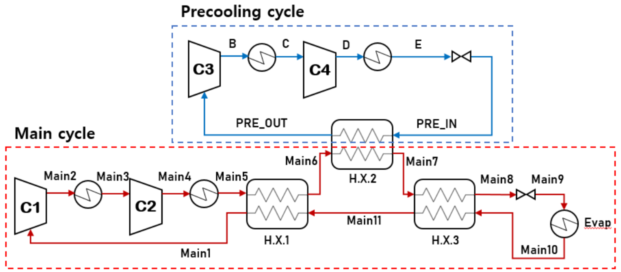
Case	Composition		
	R14	R23	R218
(1-1)	0.7	0.1	0.2
(2-1)	0.75	0.1	0.15
(3-1)	0.75	0.05	0.2
(4-1)	0.75	0.15	0.1

Results

- **Simulation results**
  - Cascade MR cycle
    - Maximum COP = 0.785 for R14:R23:R218=0.7:0.1:0.2

CASE	Main cycle Suction pressure [kPa]	Discharge pressure [kPa]	Precooling cycle Mass flow rate [kg/s]	Suction pressure [kPa]	Temperature [K]	COP
(1-1)	198.67	2600	0.476	134.4	230	0.7847
(2-1)	249.57	2800	0.479	134.4	230	0.7784
(3-1)	220.00	2600	0.458	134.4	230	0.7787
(4-1)	284.28	2800	0.501	134.4	230	0.7767

Main cycle mass flow rate = 1.0 kg/s



Discussion

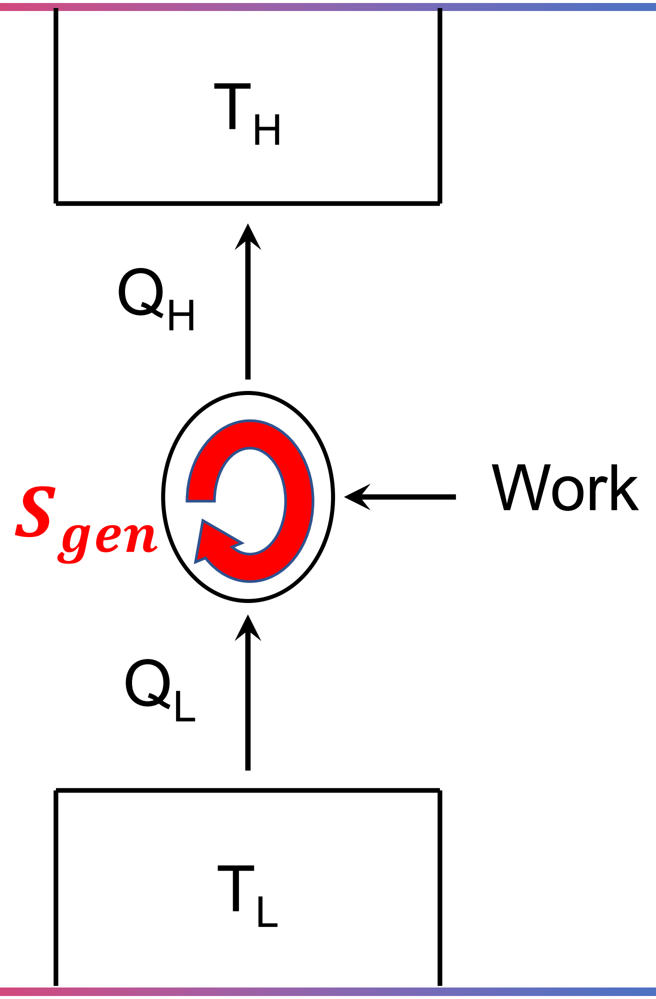
Fundamentals of heat pump or entropy pump

- Work (W) – transport of energy only
- Heat (Q) – transport of energy and entropy

- 1st law of thermodynamics

$$Q_H = Q_L + W$$

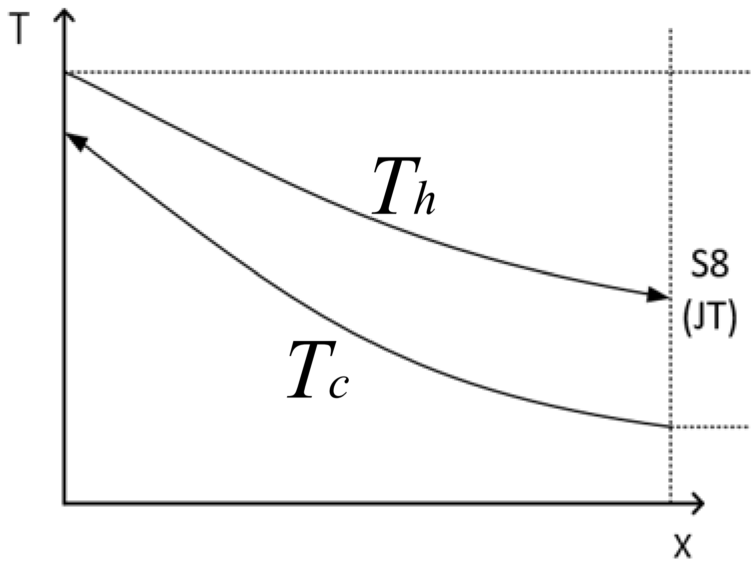
- 2nd law of thermodynamics $\frac{Q_H}{T_H} \geq \frac{Q_L}{T_L}$



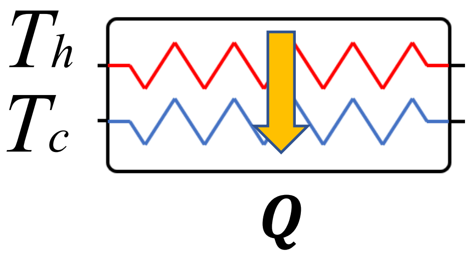
Discussion

- **Intrinsic characteristic of heat exchanger with large temperature gradient**

  → Effect of variable specific heat on exchanger performance



<Temperature distribution in recuperative HX>



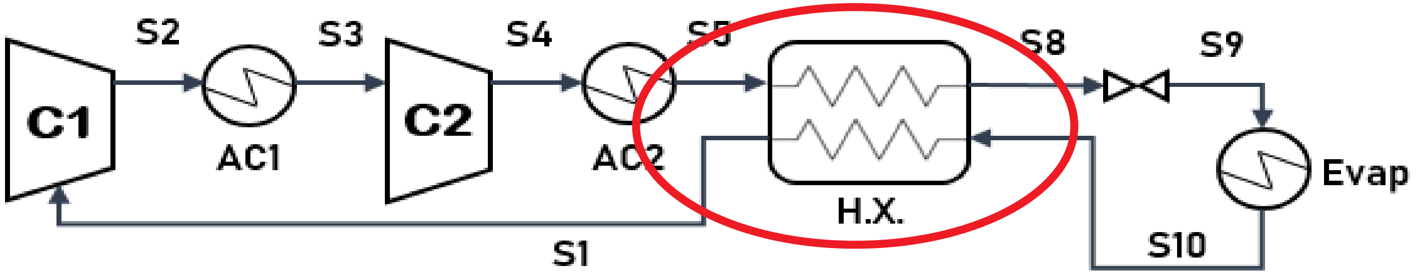
$$d\dot{Q} = -C_h dT_h$$

$$d\dot{Q} = -C_c dT_c$$

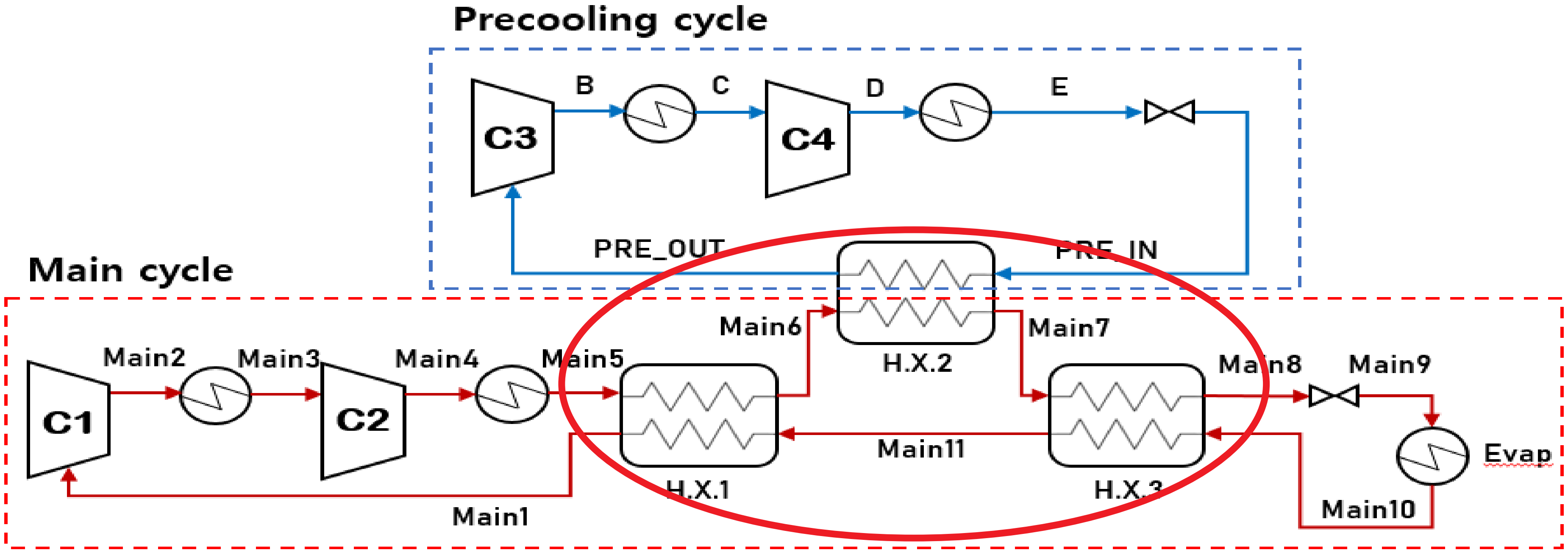
$C = \dot{m}Cp$, the heat capacity rate

$$C_h dT_h = C_c dT_c$$

Discussion



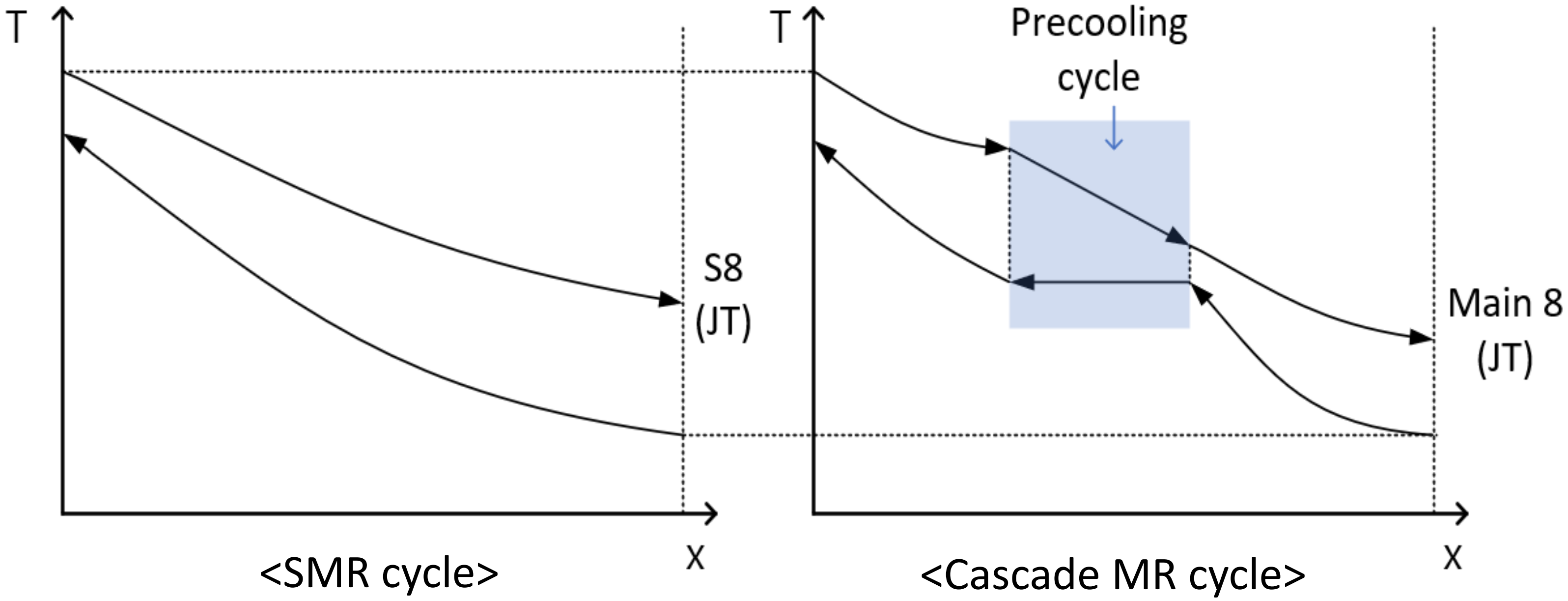
<SMR cycle>

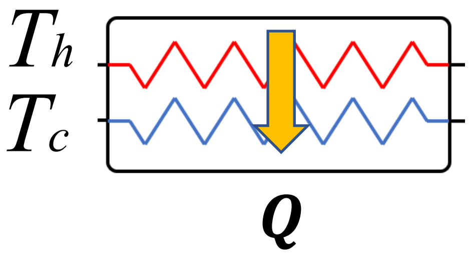


<Cascade MR cycle>

Discussion

- **Entropy generation in recuperative heat exchanger**
  - Benefit of precooling cycle in MR-JT refrigerator





$$S_{gen} = \frac{Q}{T_c} - \frac{Q}{T_h} = \frac{T_h - T_c}{T_h} * \left(\frac{Q}{T_c}\right)$$

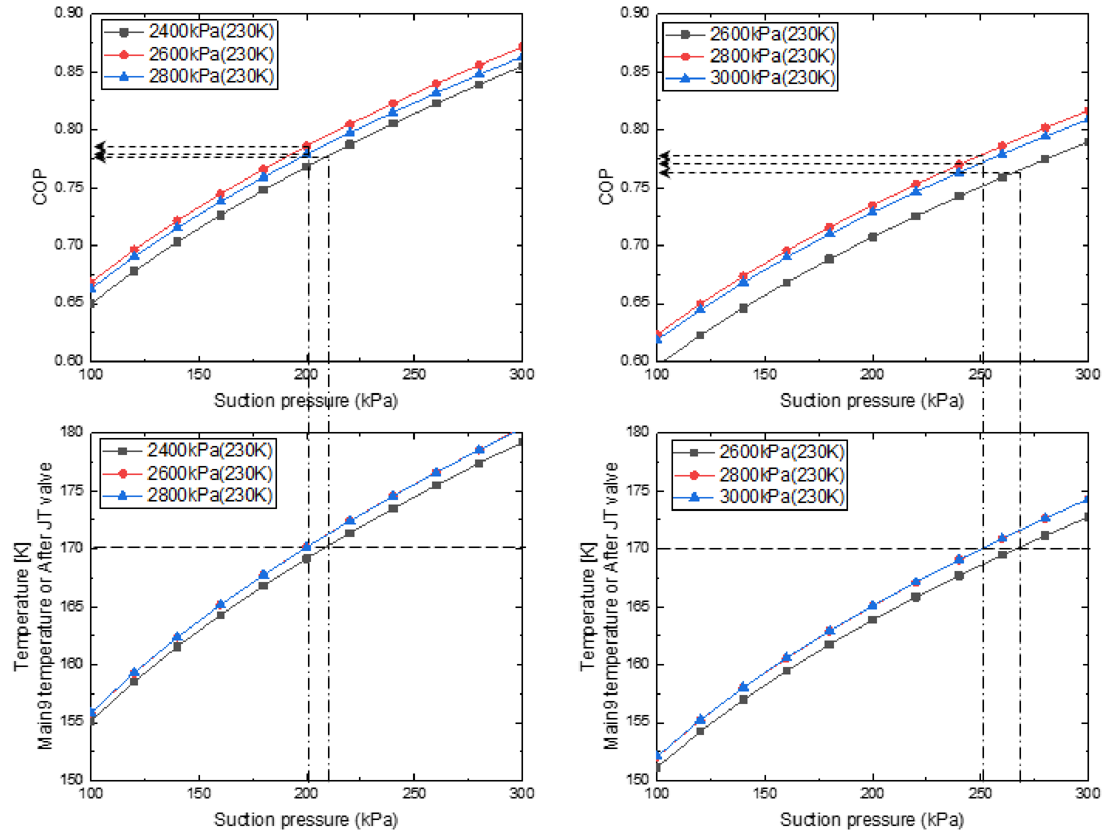
Conclusions

- R14, R23 and R218 are selected as working fluids for MR-JT refrigerator for -100 ℃.
- Single-stage MR cycle and cascade MR cycle are designed and simulated with various conditions.
- Pre-cooling is critical to increase the efficiency of the designed MR cycle.

THANK YOU

Appendix

Cascade MR cycle

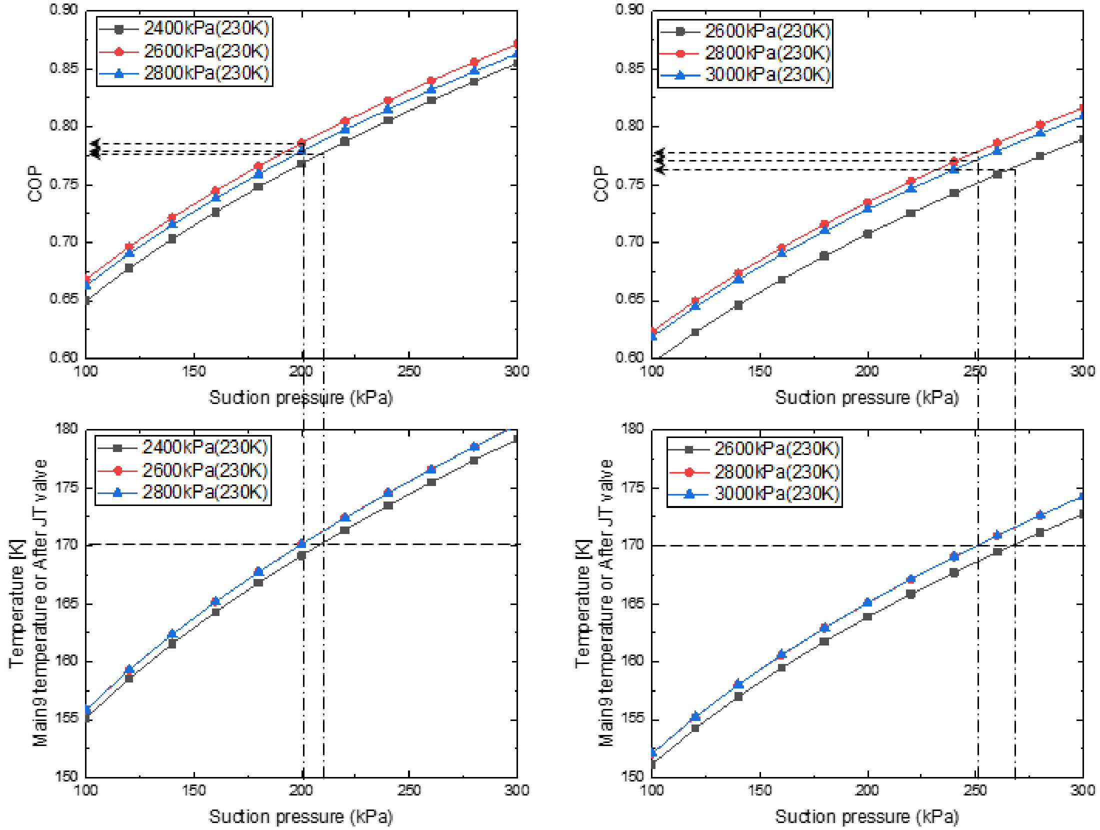


R14:R23:R218 = 0.7:0.1:0.2 (CASE 1-1)

R14:R23:R218 = 0.75:0.1:0.15 (CASE 2-1)

Appendix

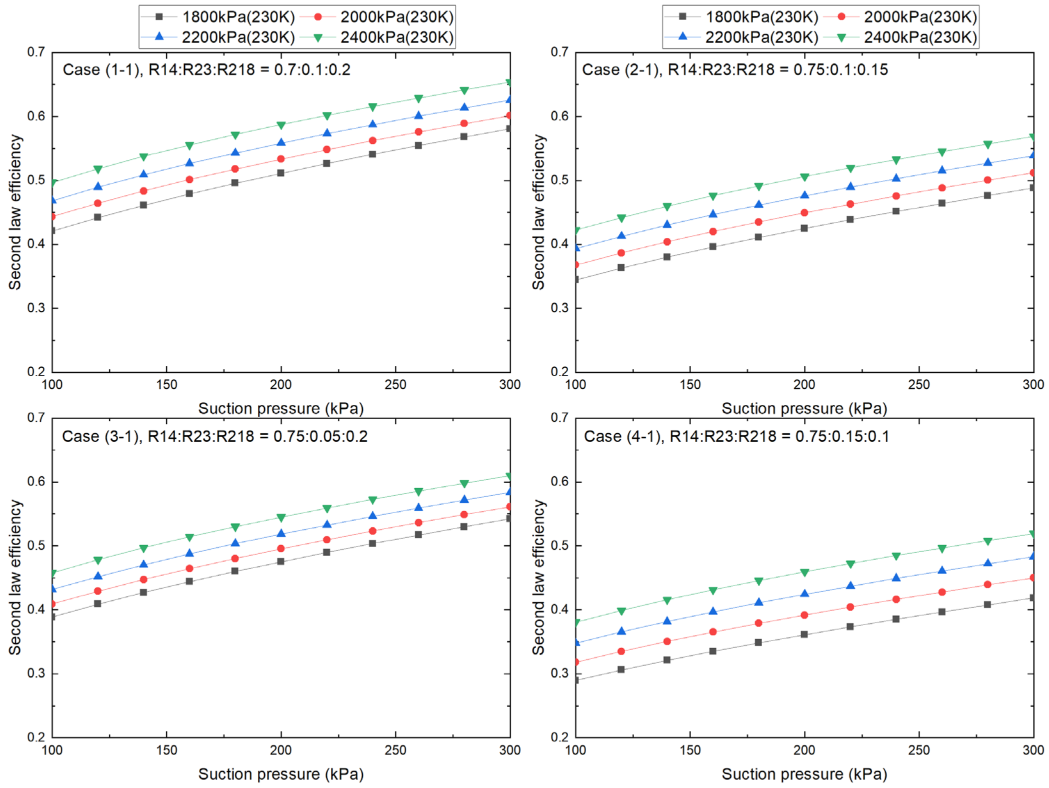
Cascade MR cycle



R14:R23:R218 = 0.75:0.05:0.2 (CASE 3-1) R14:R23:R218 = 0.75:0.15:0.1 CASE(4-1)

Appendix

Cascade MR cycle



The calculated second law efficiencies for four molar compositions

Design of cascade 120 K MR-JT refrigerator

- ✓ The cascade MR-JT refrigerator for 120 K is designed.
- ✓ For the enhancement of the efficiency, an ejector is applied into the cascade MR-JT refrigerator.

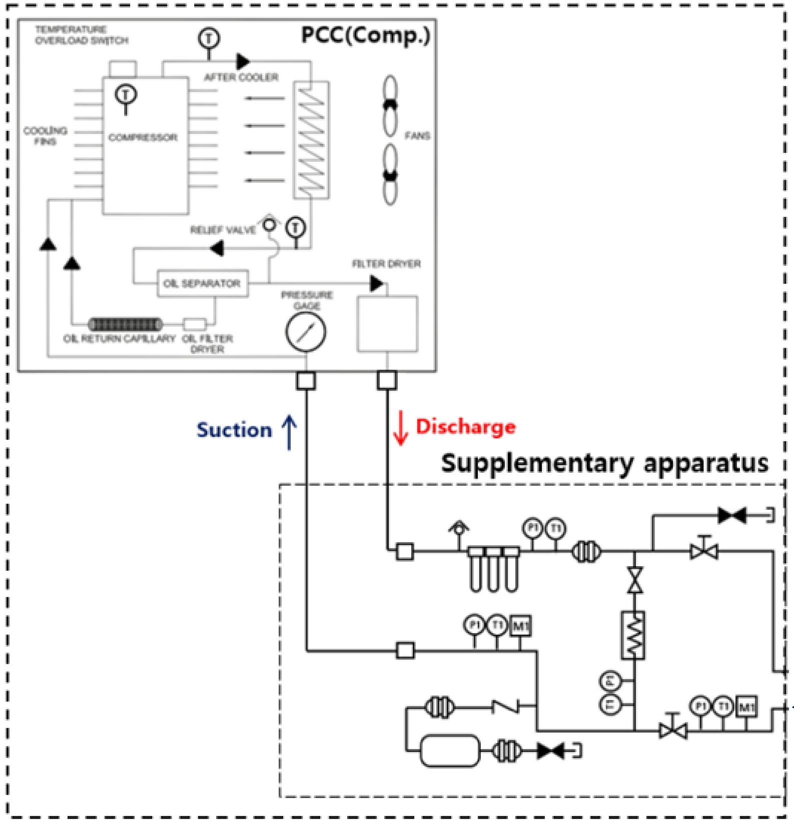
	Cascade MR-JT refrigerator (Without ejector)	Cascade MR-JT refrigerator (with ejector)
Working fluid	Ar + R14 + R23 + R218 = 0.5 + 0.3 + 0.1 + 0.1 (mole)	
$\boldsymbol{COP}_{\mathrm{I}}$	0.3711	0.3776
$\boldsymbol{COP}_{\mathrm{II}}$	46.86 %	47.66 %

Experimental study for MR-JT refrigerator

Experimental apparatus

✓ The compressor unit is subdivided into a PCC device and the supplementary apparatus.

→ The supplementary apparatus is utilized for the safe operation of the compressor.



(Compressor unit)

(a) PCC compressor

(b) Supplementary apparatus

Experimental study for MR-JT refrigerator

Experimental apparatus

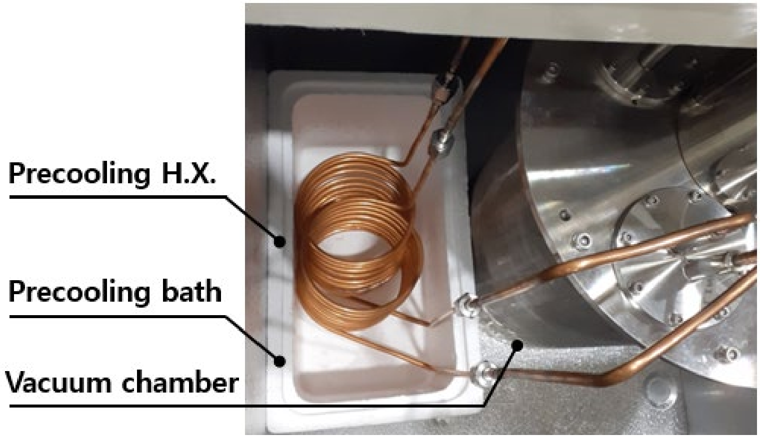
- ✓ Cold box component

  → ***Vacuum chamber*** and ***commercial refrigerator*** for precooling

- ✓ Vacuum chamber is comprised of H.X.1, Recuperator, Evaporator, and JT valve.

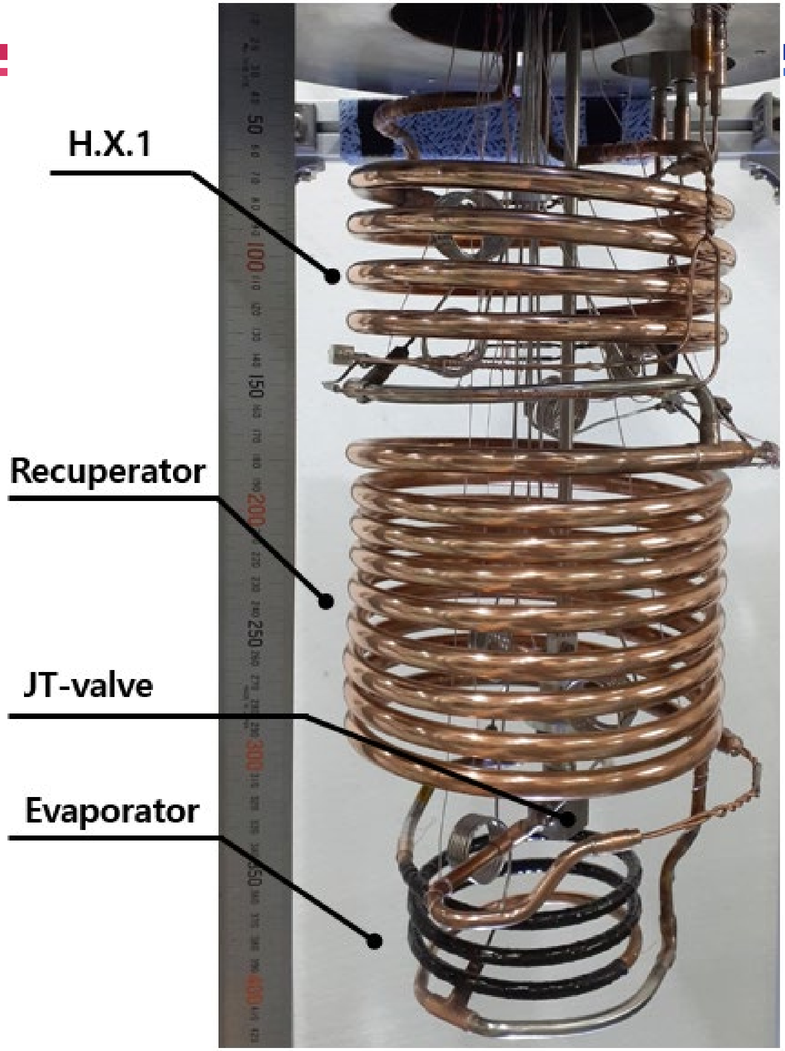
- ✓ The refrigerator contains the vacuum chamber and precooling bath.

  (Precoolant : anit-freezer Novec 7200 by 3M™)



<Inside refrigerator>

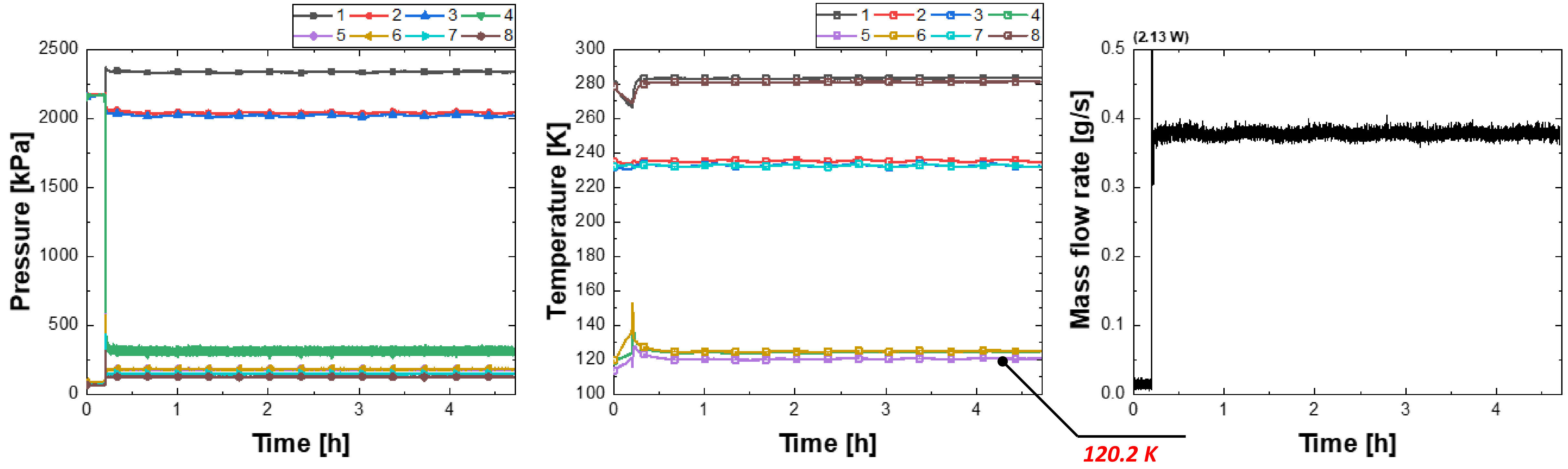
<Bottom view>



<Side view>

Experimental study for MR-JT refrigerator

Experimental result



- ✓ Experimental study was performed at the condition with $P_{dischrage}(P_1) \approx 24\ bar$ and $T_{pre}(T_3) = 230\ K$.
- ✓ After steady state, the minimum temperature $(\mathbf{120.2\ K})$ was achieved with the cooling capacity $(\mathbf{2.13\ W})$.

Experimental study for MR-JT refrigerator

Experimental result

✓ The below graph shows the cooling capacity map according to the lowest temperature.

→ Additional experimental data is required to confirm the performance of the MR-JT refrigerator.