Development of turbo chiller using water(R-718) as a refrigerant

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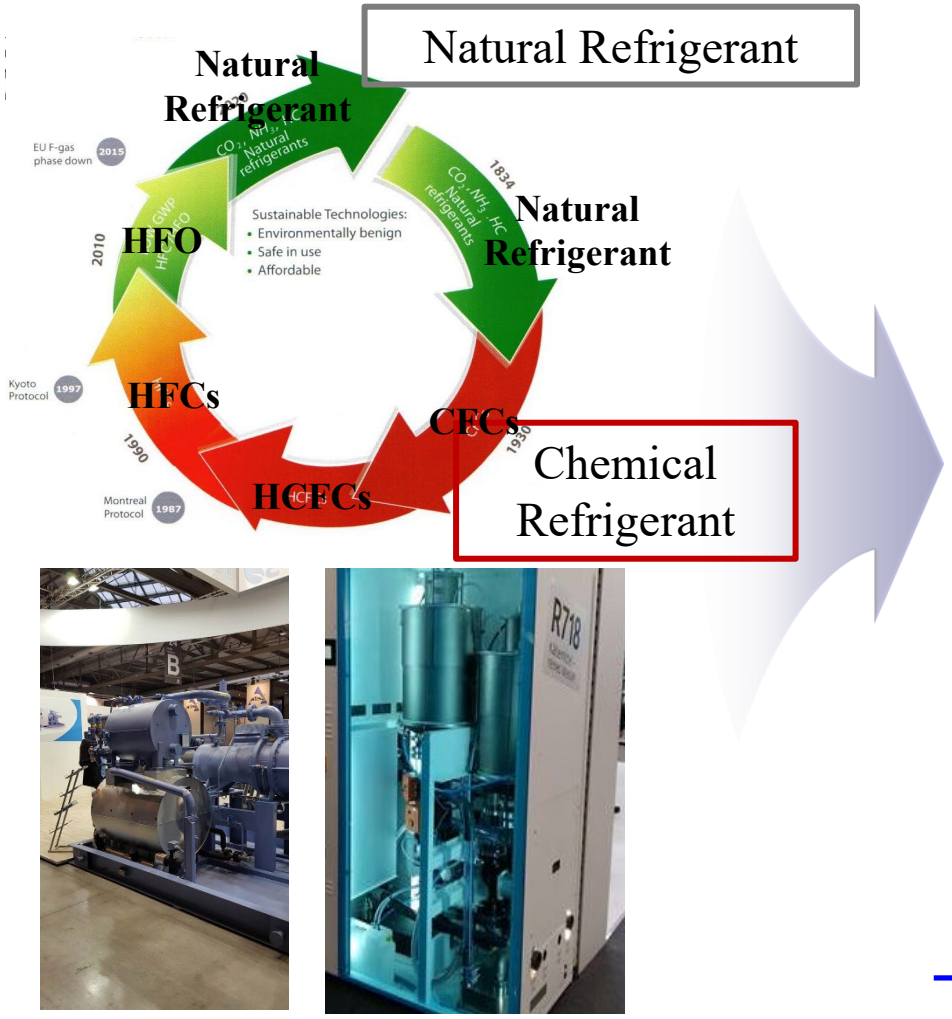
Introduction

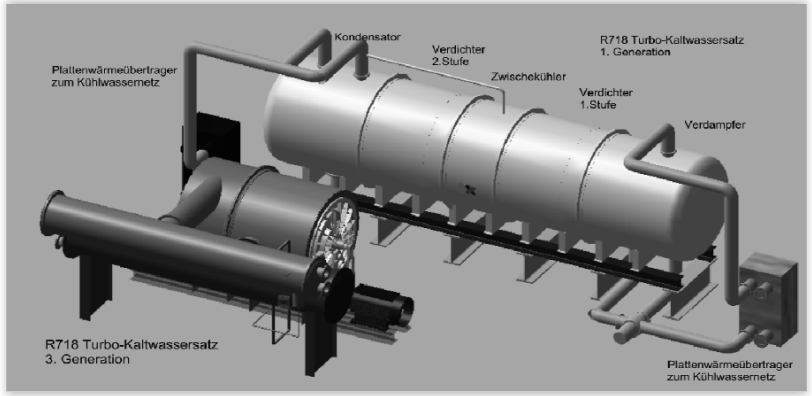


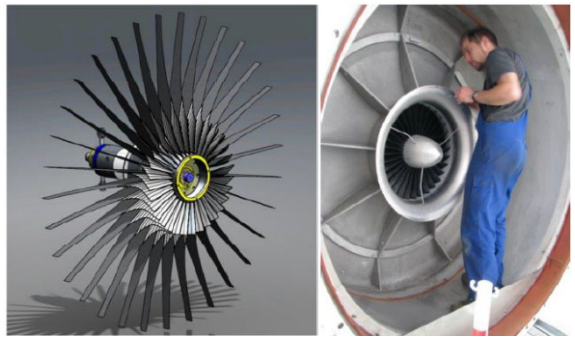
Water

as a refrigerant (R-718)

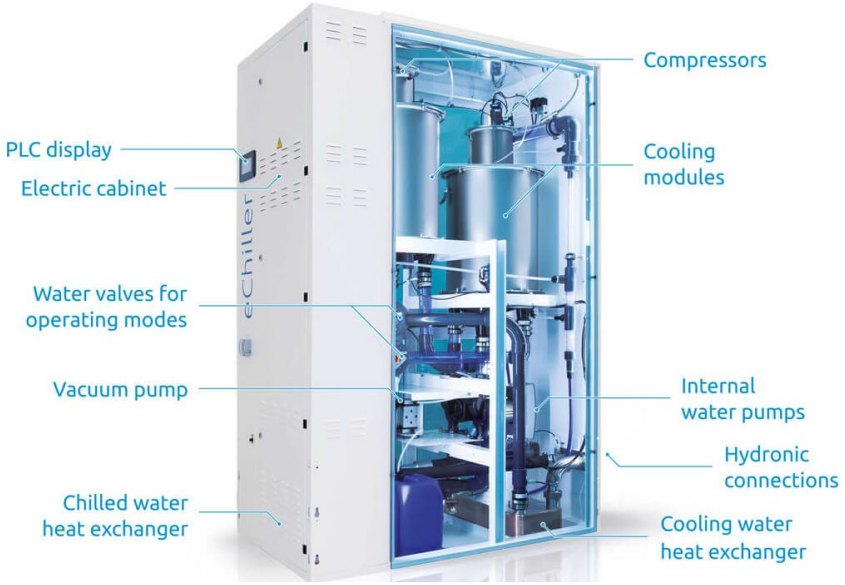
→ R-718 chiller project

Introduction

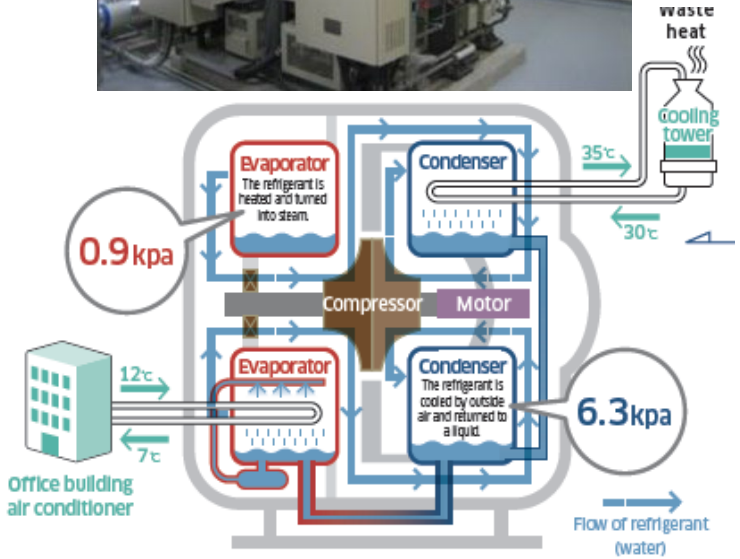




800 kW(ILK)



300 kW(Energy Efficiency)



350 kW(Kawasaki)

Overview of project

- Development of the turbo chiller using water as a refrigerant (TRL 3 → 5)
  - Design of the cycle (350 kW, COP 5.1)
  - Design and manufacture of compressors(turbo)
  - Design and manufacture of heat exchangers (evaporator, condenser, intermediate cooler etc)

Overview of project

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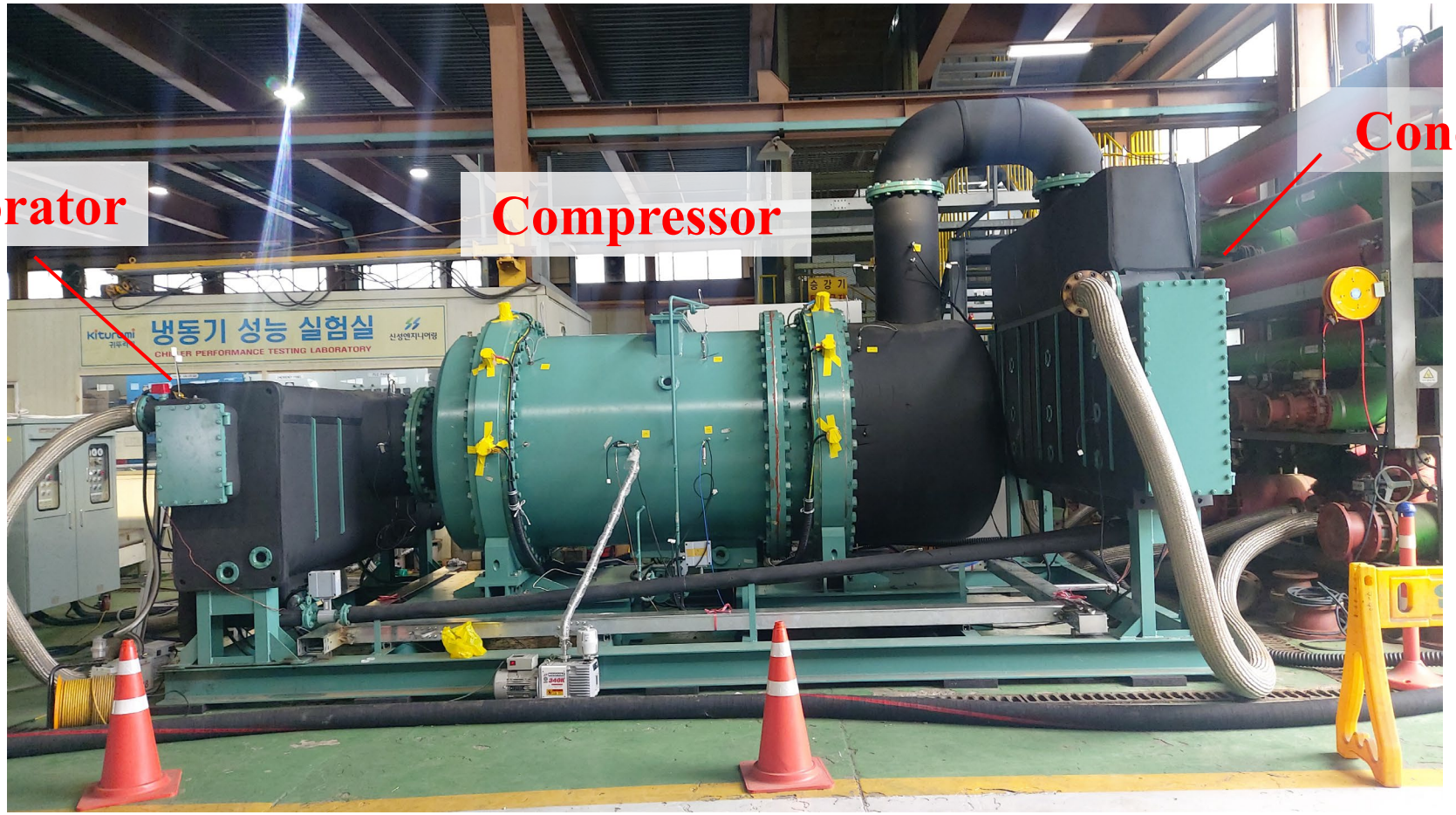
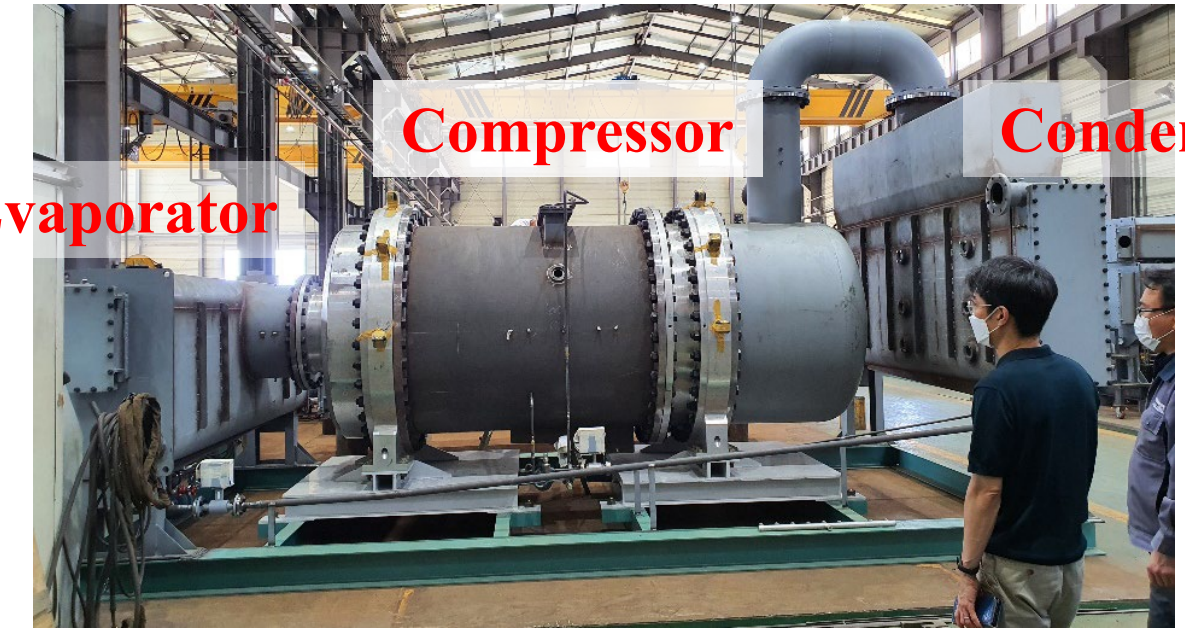
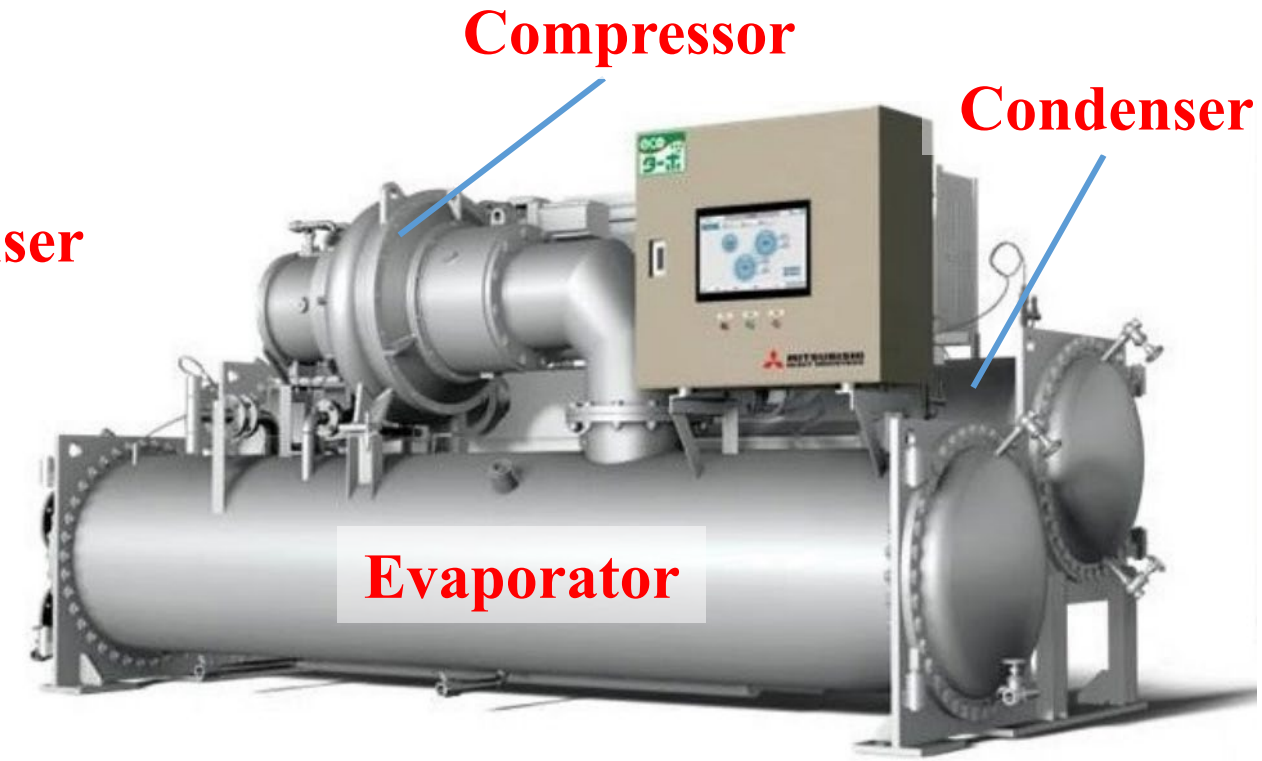


6.2 * 3.5* 3.4 m^3

Comparison with conventional chiller



R-718 chiller_KIMM

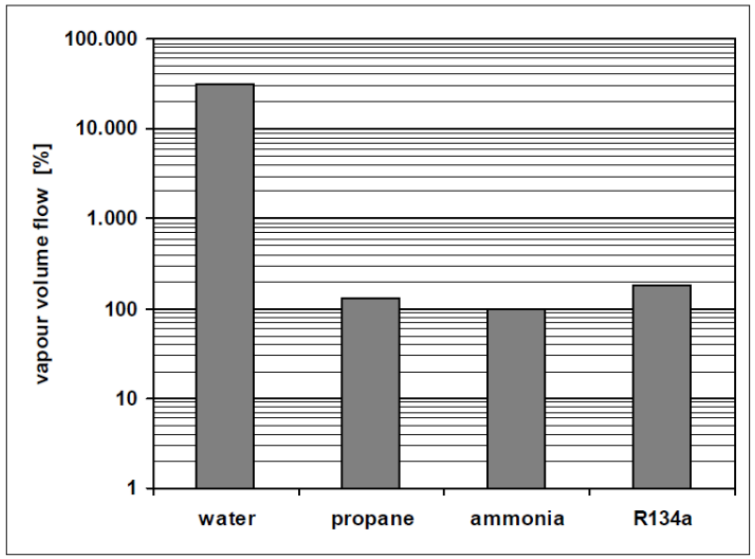


Turbo chiller (Chemical refrigerant)

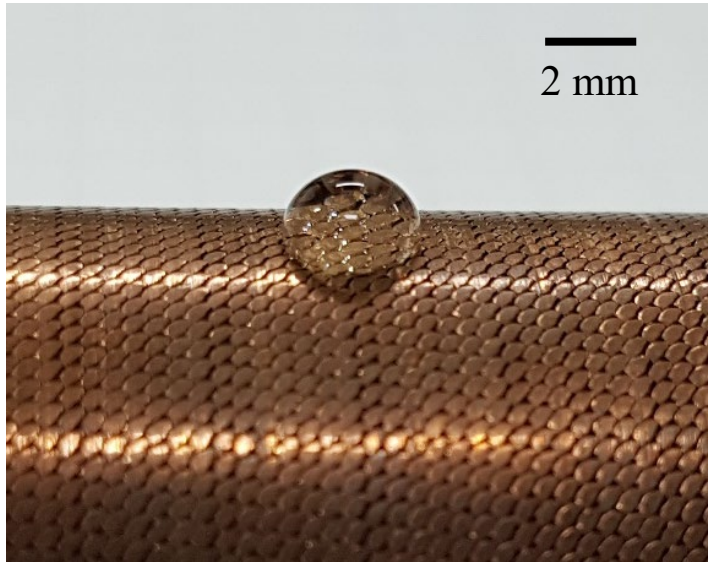
Water as a refrigerant

- **Eco friendly (GWP = 0)**
- **Large latent heat coefficient**

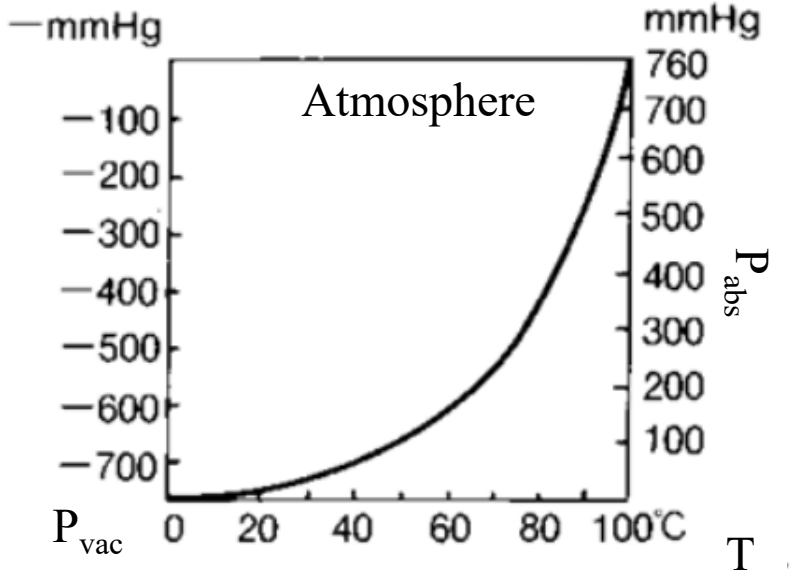
- **Large specific volume**
- **Large surface tension**
- **Phase change : Vacuum state**



Specific volume (Refrigerant)

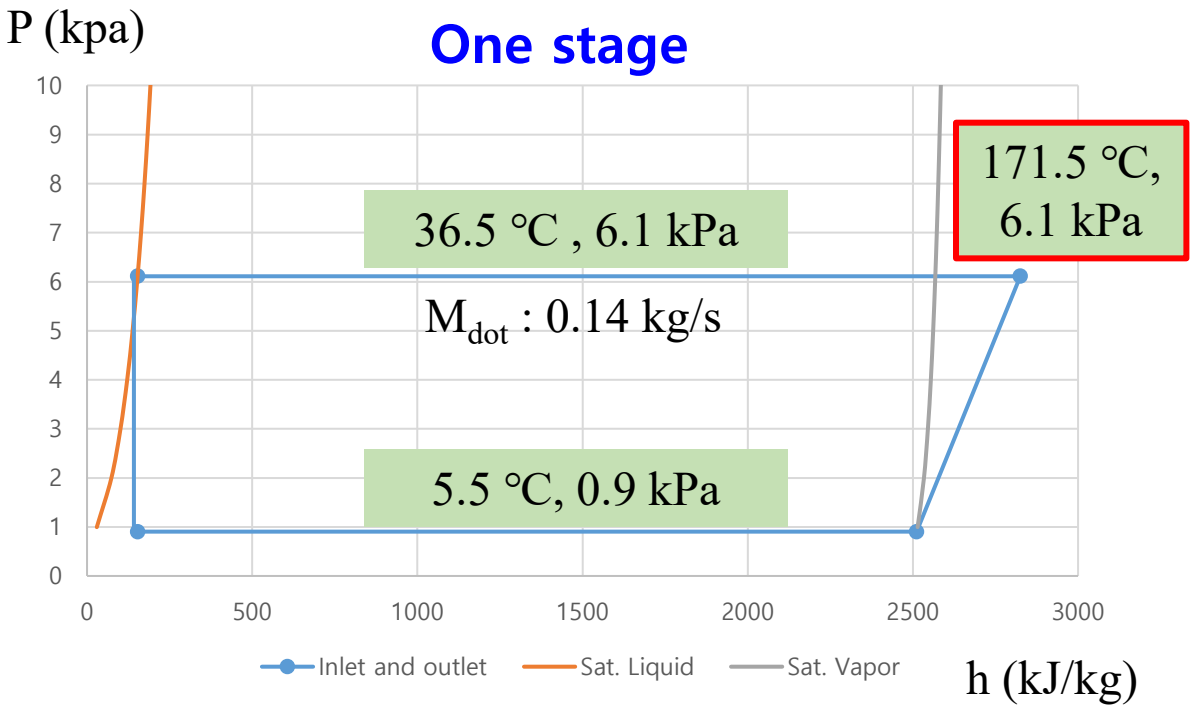


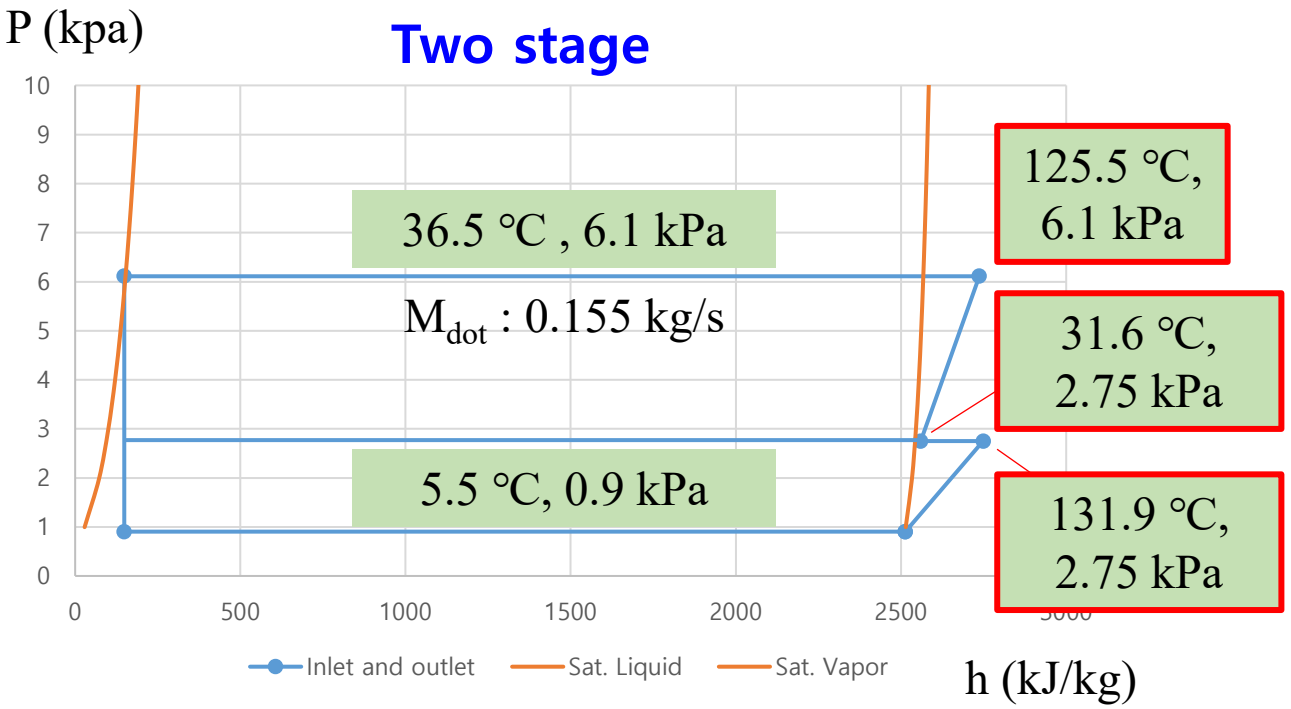
Large surface tension



Phase change pressure

System cycle

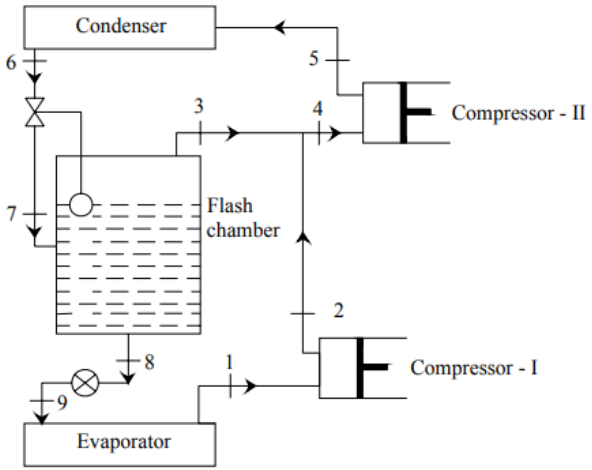


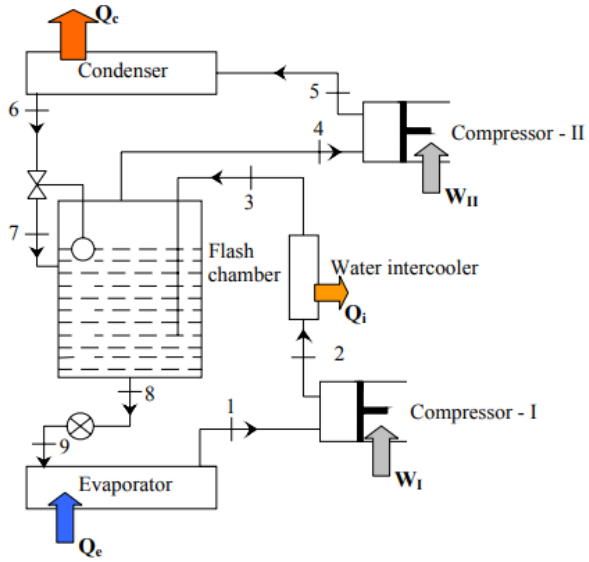


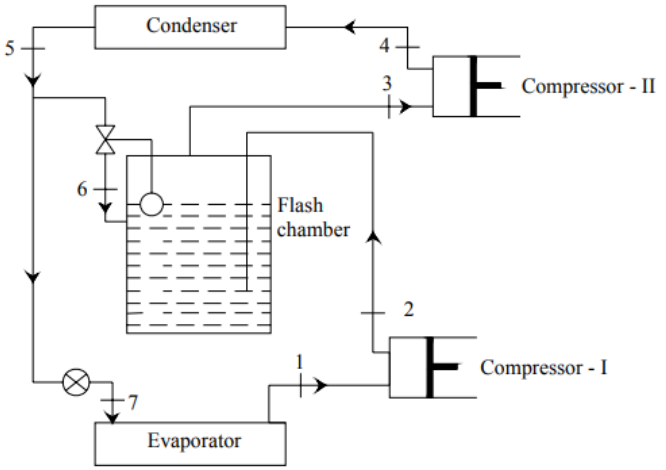
- Two stage, intermediate cooler
- Outlet temperature (Compressor) ↓
- Refrigerant flow rate (Condenser) ↑

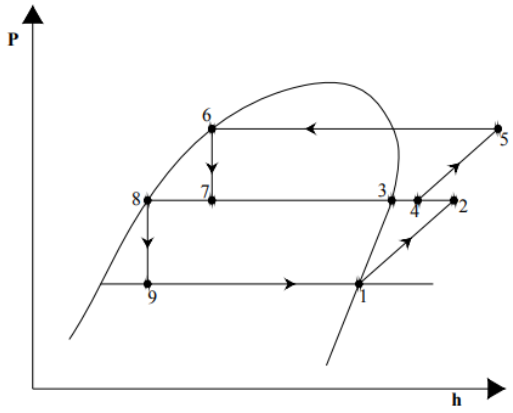
- Q : 350 kW
- M_{dot} : 0.14 kg/s

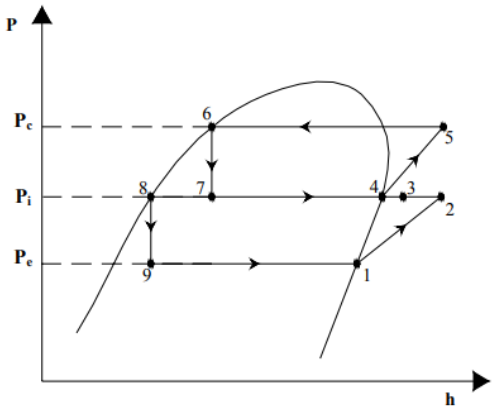
Design of intercooler

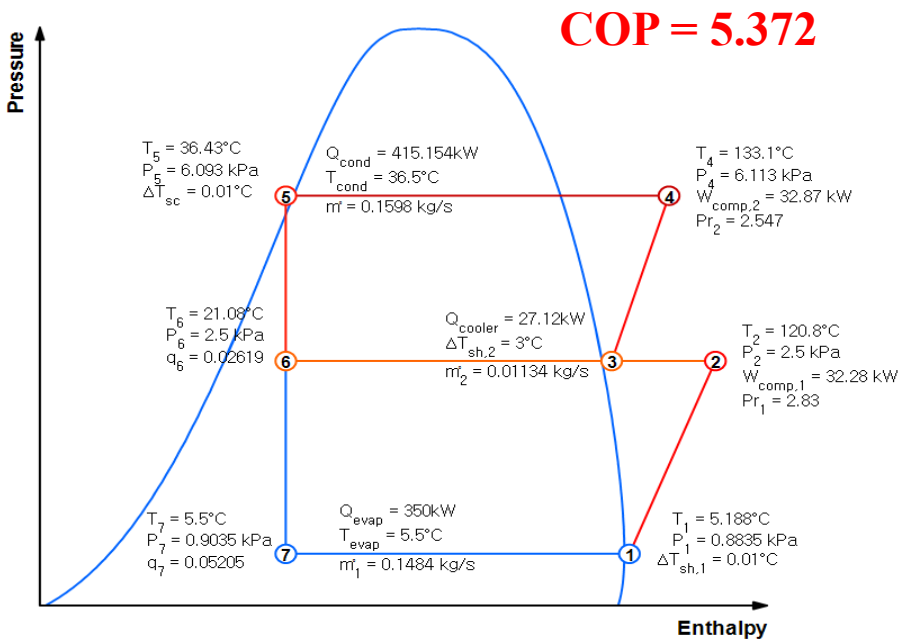


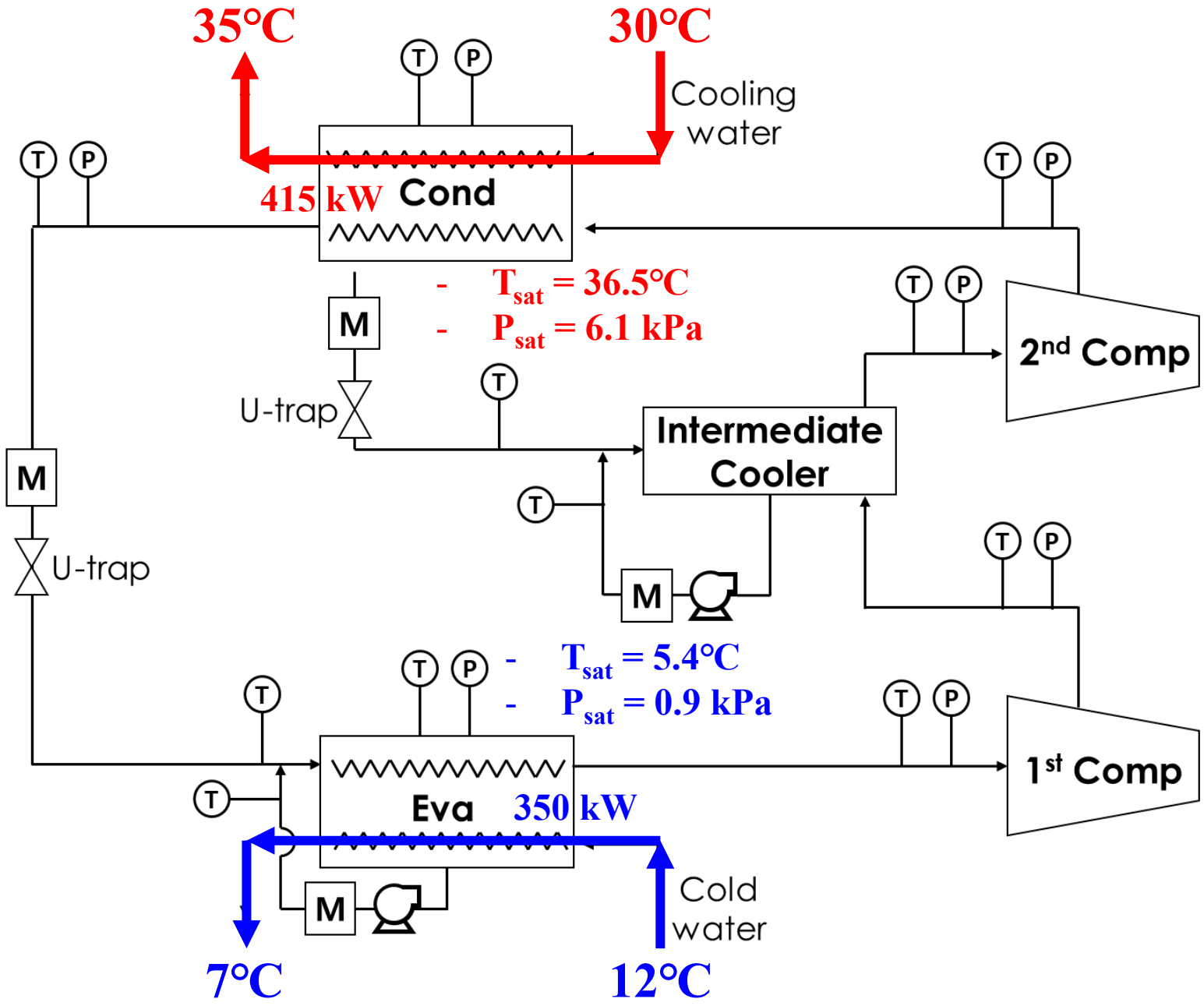


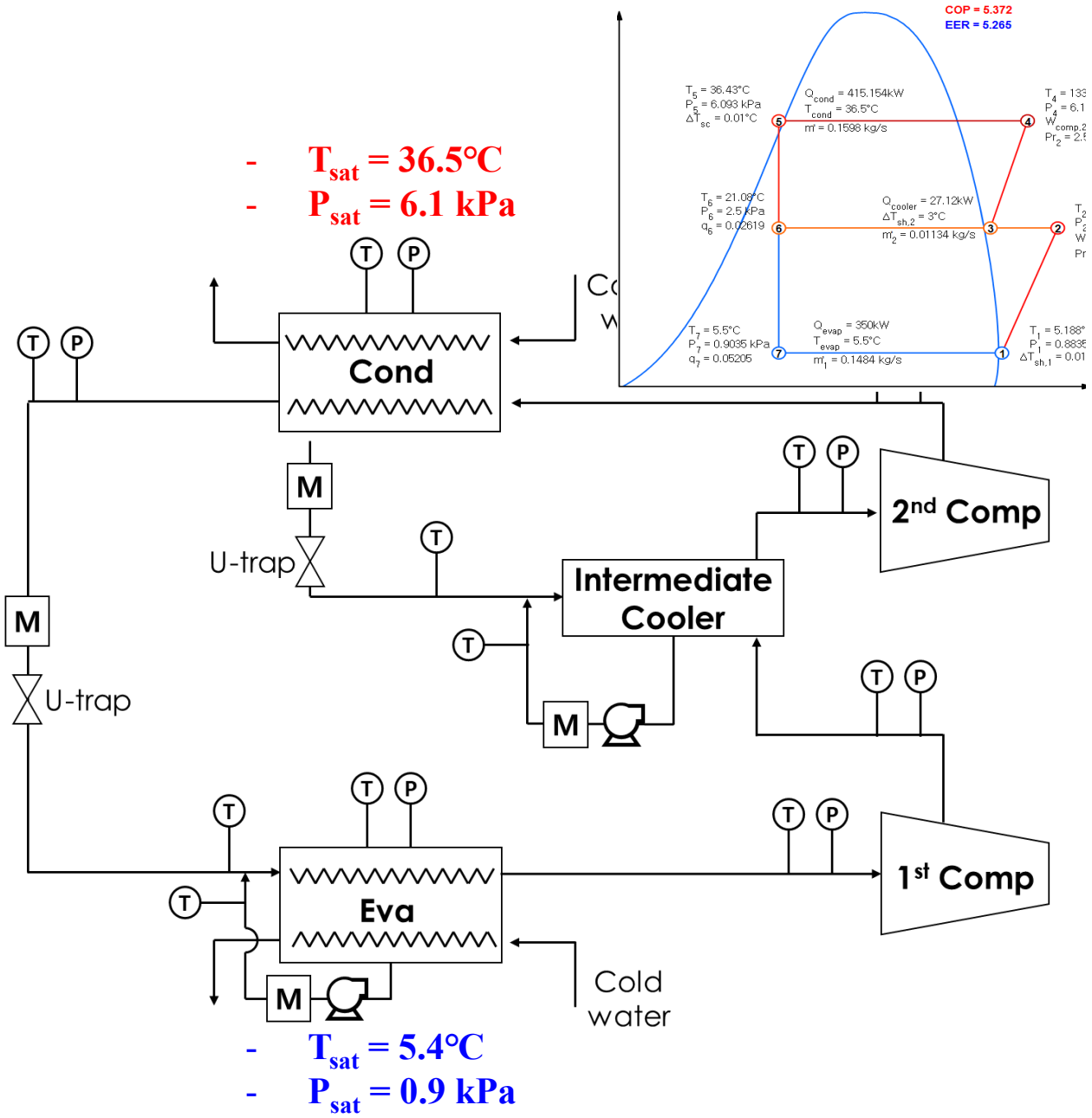


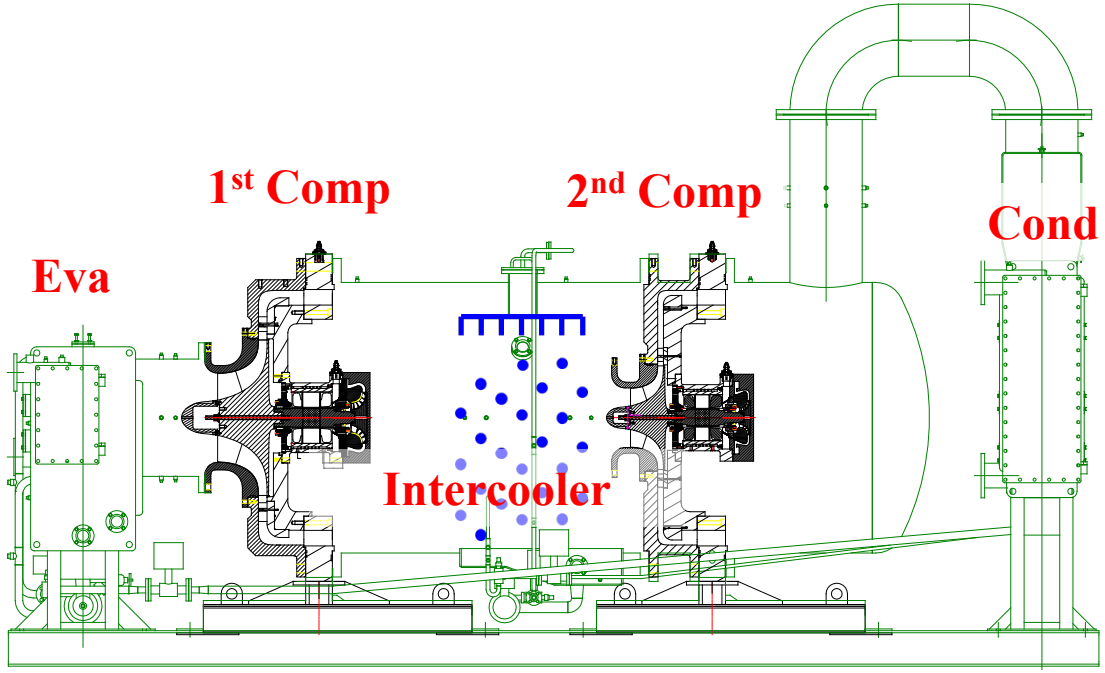


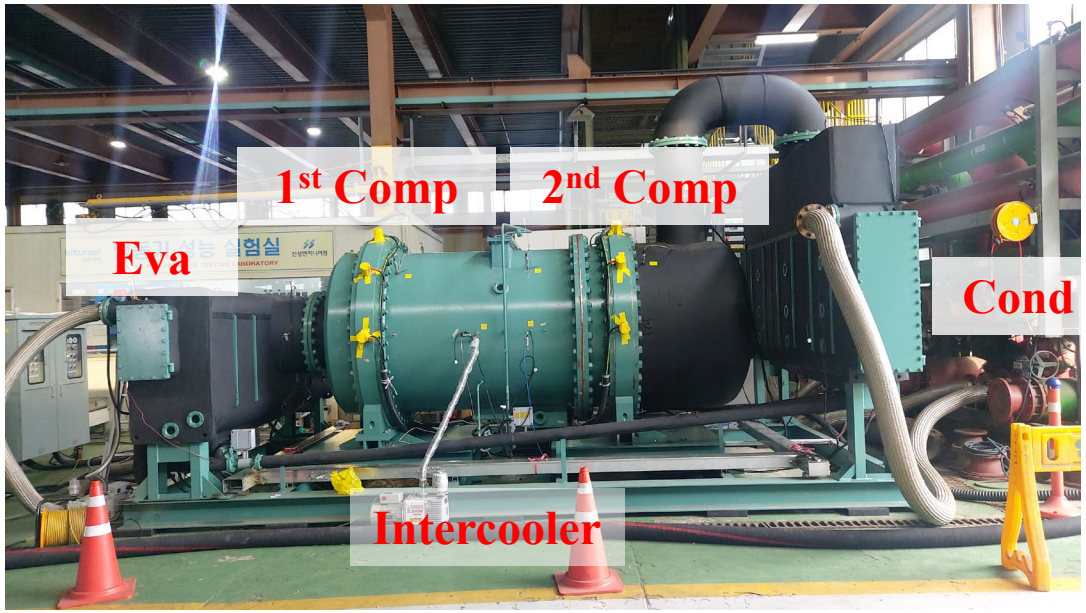



COP = 5.372
Pressure
Enthalpy
T5 = 36.43°C
P5 = 6.093 kPa
ΔTsc = 0.01°C
Qcond = 415.154kW
Tcond = 36.5°C
ṁ = 0.1598 kg/s
T4 = 133.1°C
P4 = 6.113 kPa
Wcomp,2 = 32.87 kW
Pr2 = 2.547
T6 = 21.08°C
P6 = 2.5 kPa
q6 = 0.02619
Qcooler = 27.12kW
ΔTsh,2 = 3°C
ṁ2 = 0.01134 kg/s
T2 = 120.8°C
P2 = 2.5 kPa
Wcomp,1 = 32.28 kW
Pr1 = 2.83
T7 = 5.5°C
P7 = 0.9035 kPa
q7 = 0.05205
Qevap = 350kW
Tevap = 5.5°C
ṁ1 = 0.1484 kg/s
T1 = 5.188°C
P1 = 0.8835 kPa
ΔTsh,1 = 0.01°C

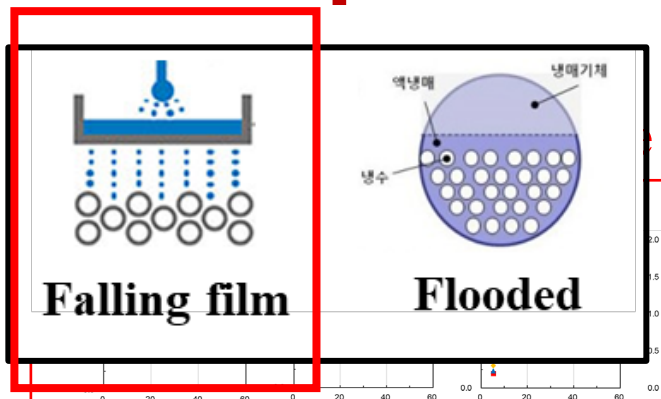

35°C
30°C
Cooling water
415 kW Cond
- Tsat = 36.5°C
- Psat = 6.1 kPa
M
U-trap
2nd Comp
Intermediate Cooler
M
U-trap
- Tsat = 5.4°C
- Psat = 0.9 kPa
1st Comp
Eva 350 kW
M
Cold water
7°C
12°C


COP = 5.372
EER = 5.265
- T_{sat} = 36.5℃
- P_{sat} = 6.1 kPa
Cond
M
U-trap
2nd Comp
Intermediate Cooler
M
U-trap
Eva
1st Comp
Cold water
M
- T_{sat} = 5.4℃
- P_{sat} = 0.9 kPa

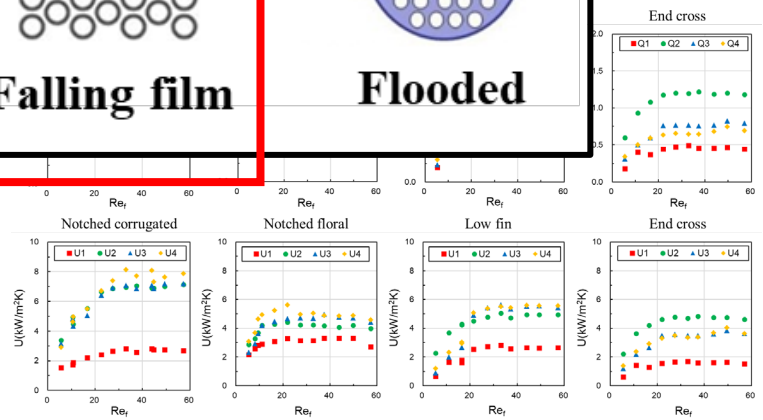

1st Comp
2nd Comp
Cond
Eva
Intercooler

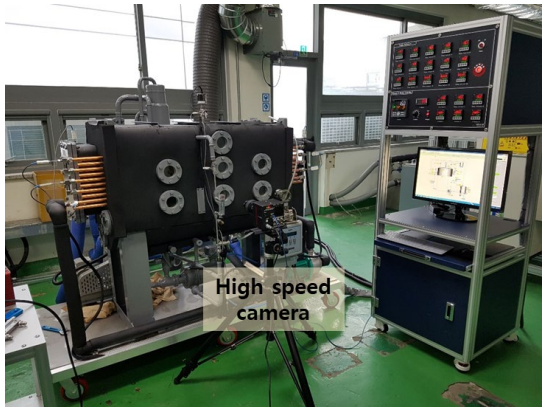

1st Comp
2nd Comp
Eva
Cond
Intercooler

Evaporator (falling film type)

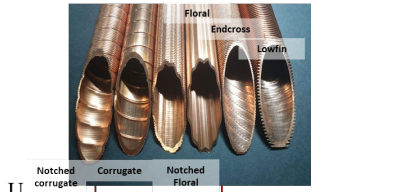


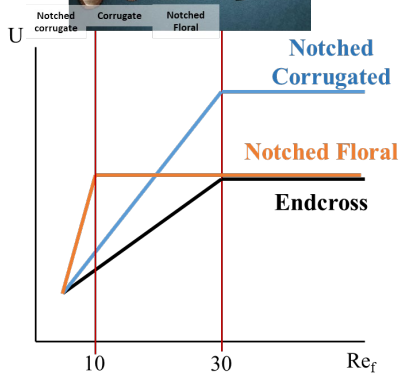
experiments





Performance test (tubes)





Heat transfer performance

NC (Notched corrugated)

- High performance
- No good spreading

→ High performance when fully wetted

NF (Notched floral)

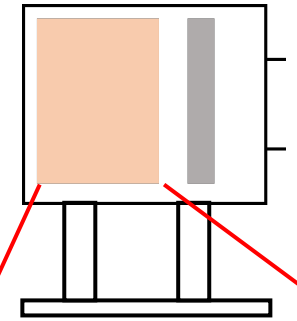
- Good spreading
- Normal performance

→ For increasing spreading

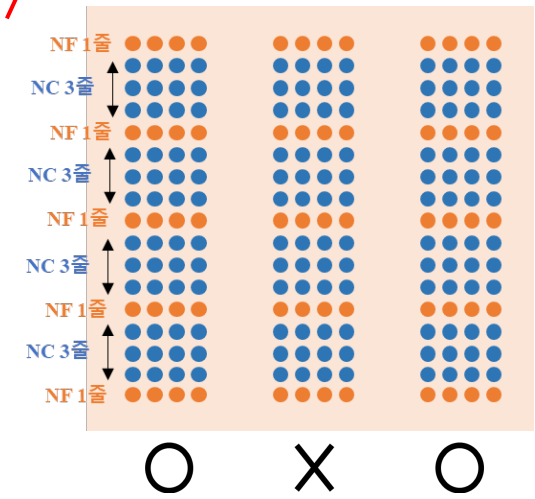
→ Combination of NC and NF

(NC : heat transfer↑, NF : spreading ↑)

Application to the prototype



Inside of the Eva (tubes)



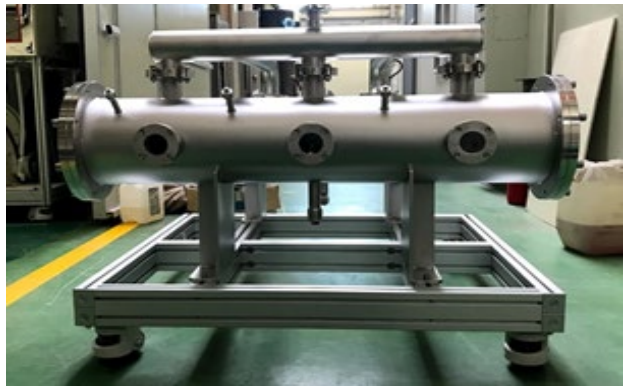
○ ✕ ○

→ Tubes : 204 (3m)

Evaporator (prototype)

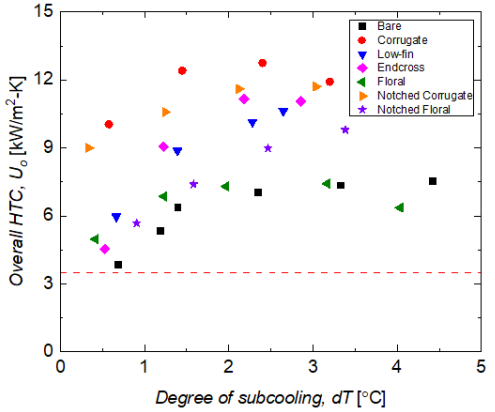
Condenser

- Experiments with Single tube and Multiple tubes system
- Derivation correlations



< Single tube >

< Multiple tubes >



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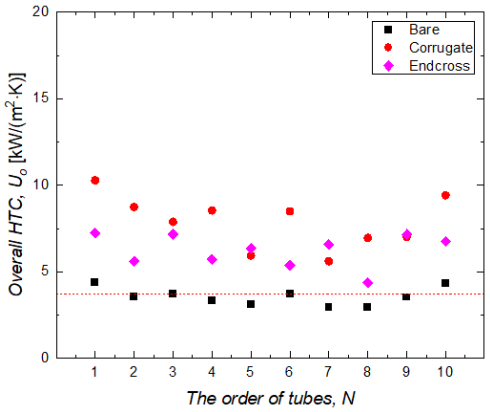

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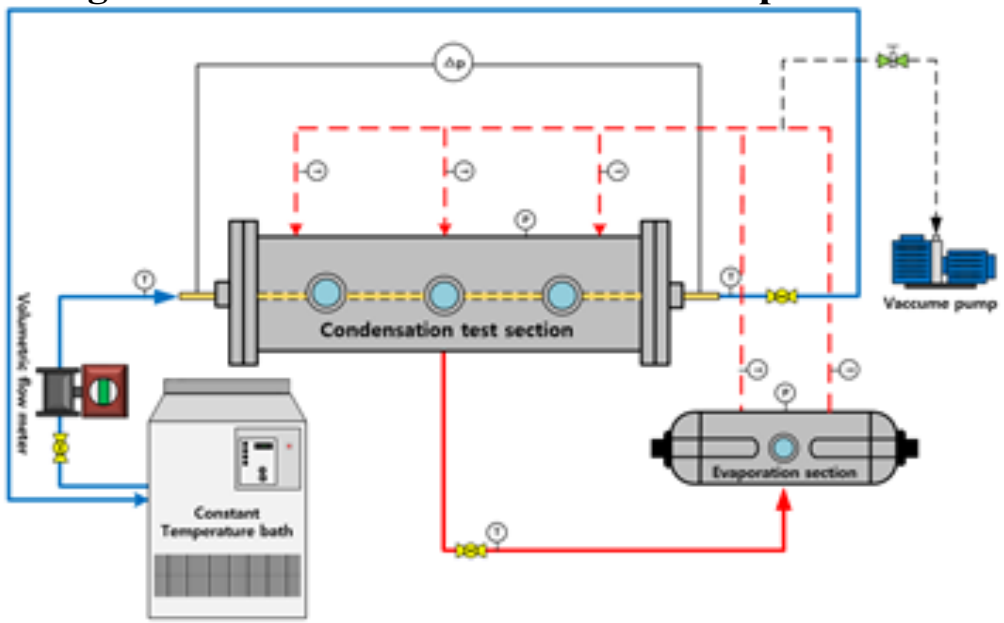
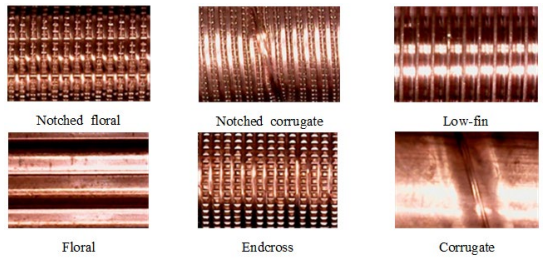
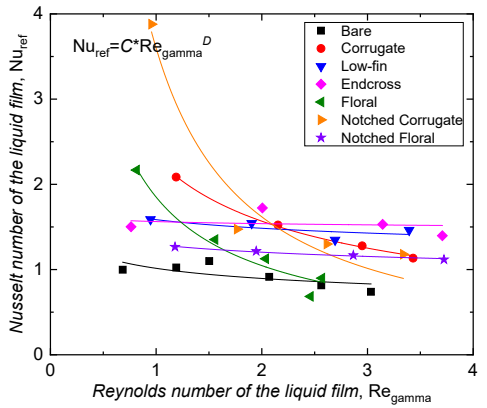


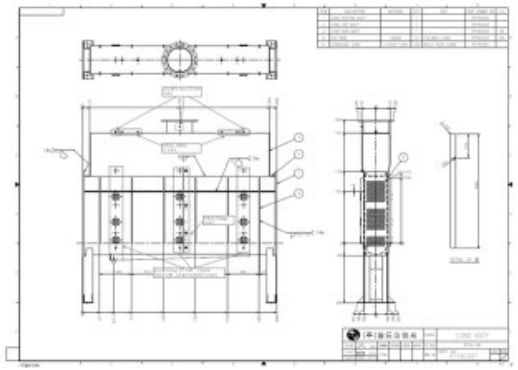




< Dimensionless correlation >

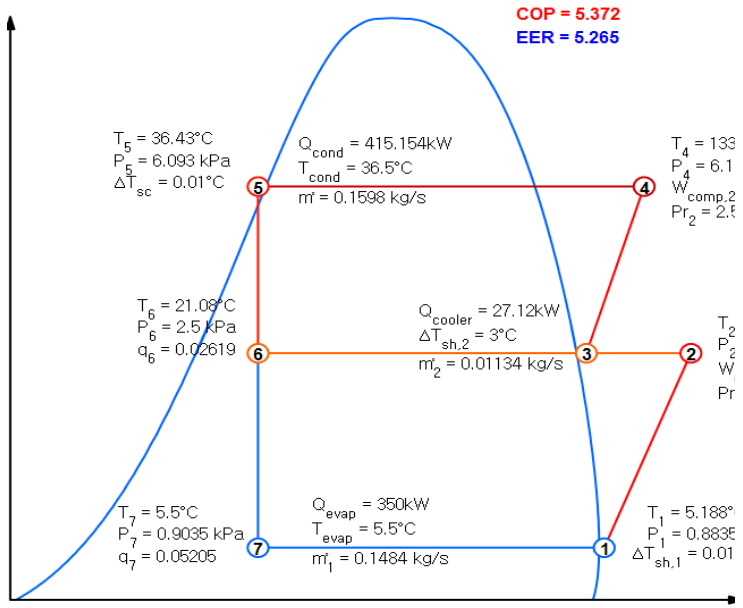
Condenser

❖350 kW prototype condenser



<350 kW condenser diagram >

< Condenser of the prototype >



T_in (cooling water)	T_out (cooling water)	Flow rate (cooling water)	Inner pressure	Inlet temp (refrig)	Satur temp	Oulet temp
℃	℃	LPM	kPa	℃	℃	℃
28.90	33.27	1207.29	5.83	73.00	35.64	31.82

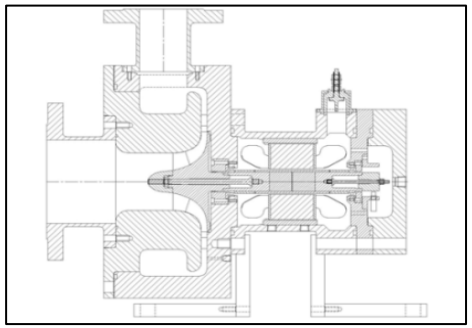
Heat rate (Cond)	Super-heated part	Sub-cooled part	Condensing part	LMTD (Condensation)	# (Condensation)	Area (Condensation)	Condensation coefficient
kW	kW	kW	kW	℃	ea	m^2	$kW(m^2 \cdot K)$
366.60	10.41	2.34	353.86	4.25	120	18.02	**4.60**

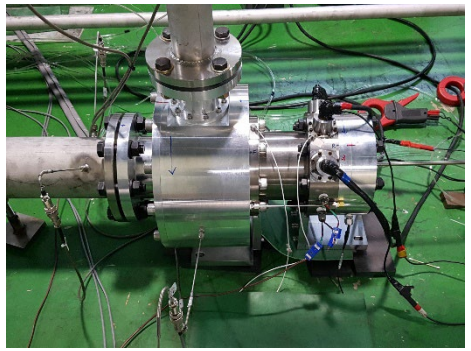
Compressor

- Design and manufacture of 1/5 scale compressors
- Perform experiments for the geometry similitude method

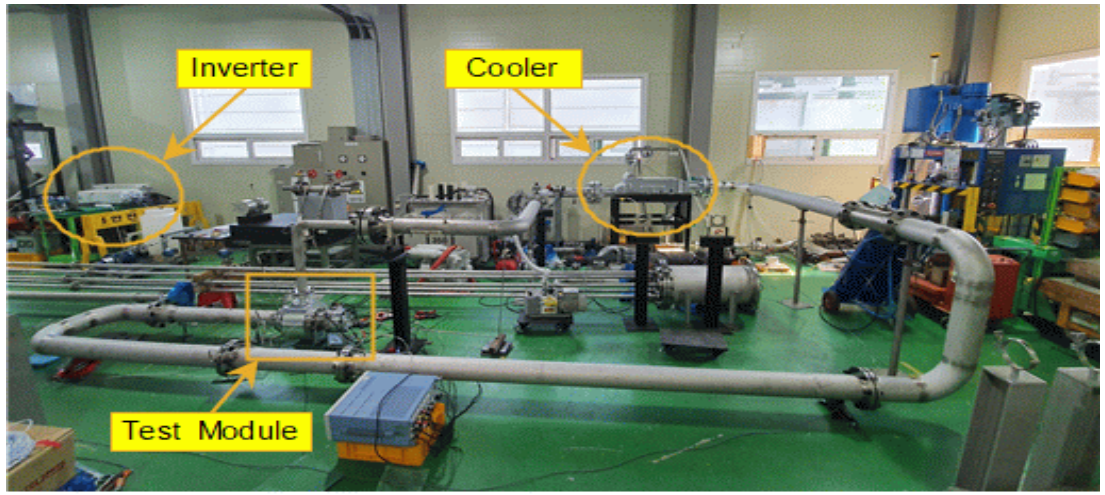
Compressor design → Geometry similitude method → Manufacture and assembly → Performance test

❖1/5 scale compressor





❖Experiments for the geometry similitude method

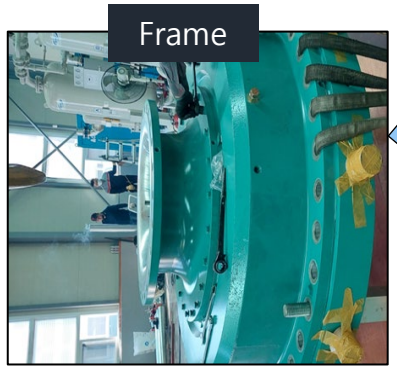


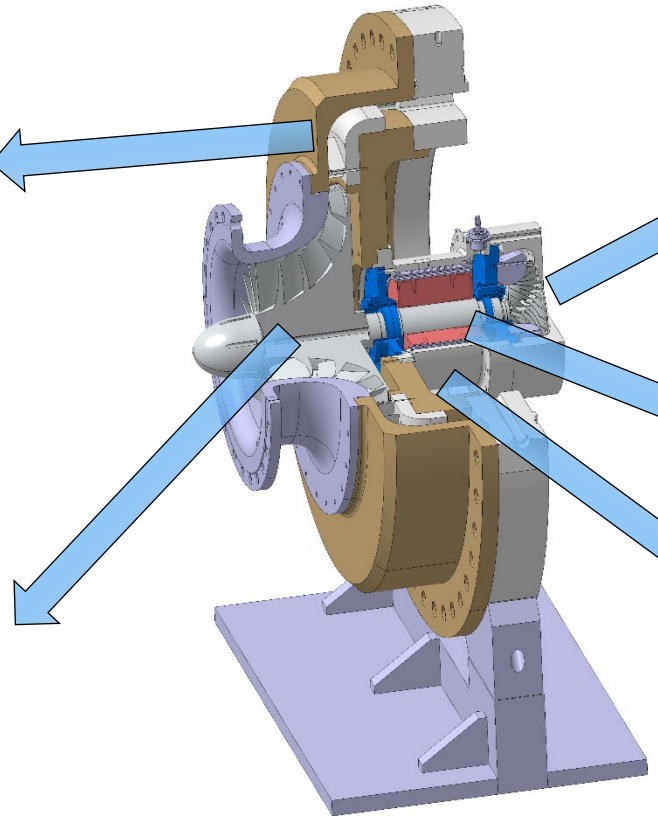
	Low pressure	High pressure
Working fluid	CO_2	CO_2+N_2
Revolutions	80,000 rpm	50,000 rpm
Isentropic efficiency	79 %	75.9 %

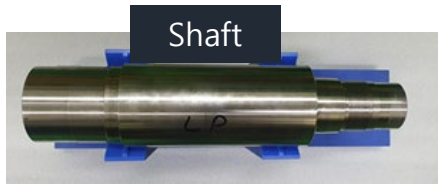
Compressor

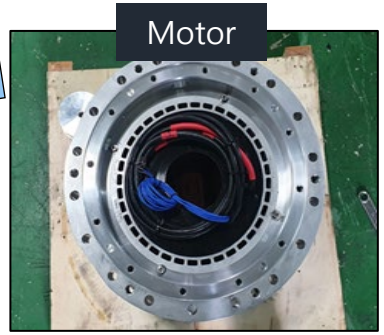
- Design and manufacture compressors for the prototype
- Design and manufacture motors, cooling fans, and frames

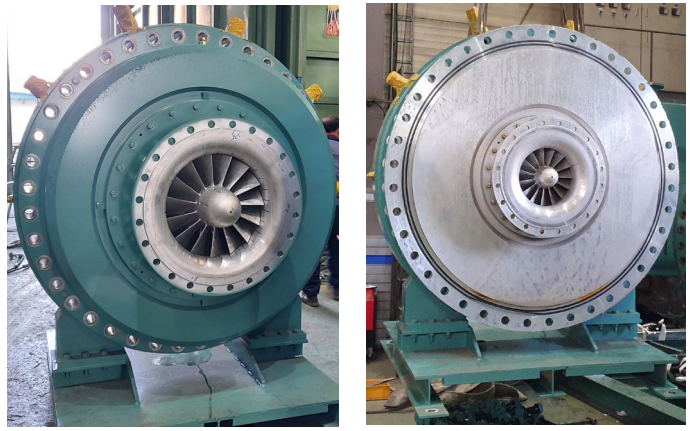
Compressor design → Geometry similitude method → Manufacture and assembly → Performance test



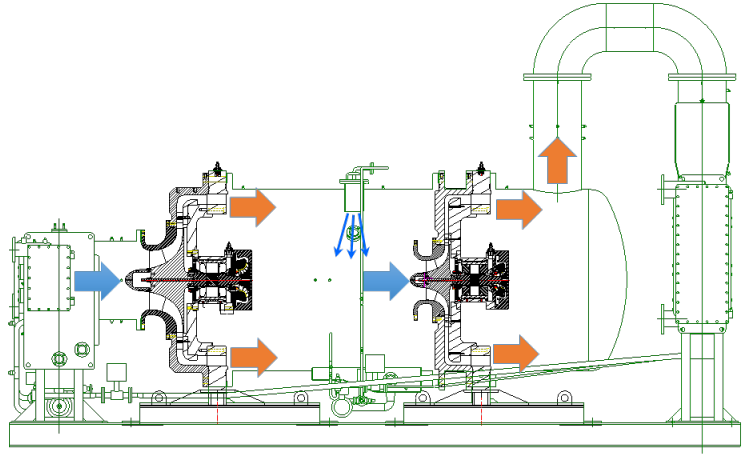








Comps (Left)LP, (right)HP



Prototype (Preparation)

- Manufacture by prototype part
- Manufacture and installation of the Electronic devices




Manufacture by prototype part
HP cover, U tube
Eva, Cond, Intercooler


Comps (Jinsol turbor(Co. Ltd.))
(Left)LP, (right)HP



Load bank, Inverter panel(control panel) and Data panel

Prototype (Preparation)

Test preparation

No	Contents
1	Prototype assembly
2	Moving and settling
3	Piping (Cold and cooling water)
4	Wire connection
5	Intercooler operation cooler
6	Compressor cooling line
7	Helium leakage test
8	Vacuum pump operation
9	No-load test
10	Injection Water(Refrigerant)

Assembly

Moving and settling

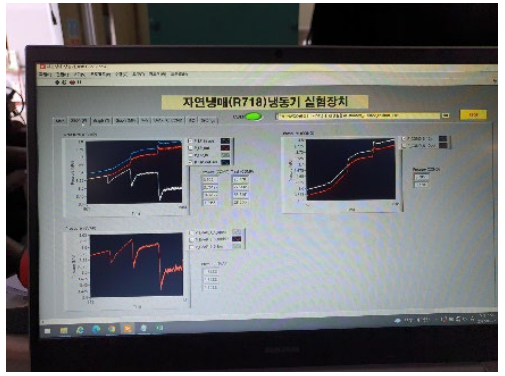
Piping and wire connection

Intercooler operation cooler

Compressor cooling line

Helium leakage test

Vacuum pump operation



No-load test

Injection Water(Refrigerant)

Prototype Performance Test

Test results

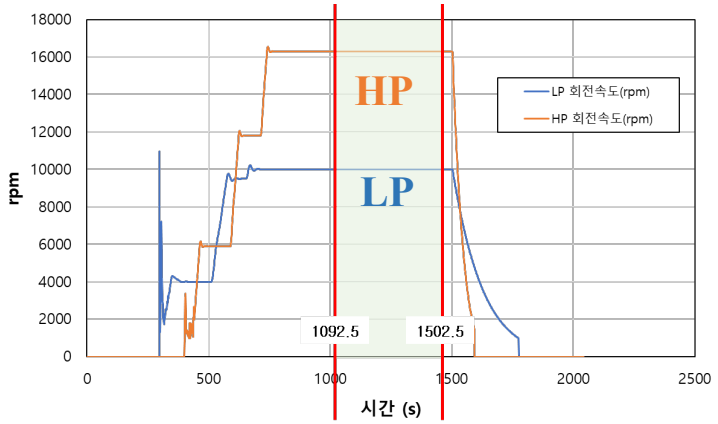
	Unit	Value	Design
Refrigeration capacity	kW	**359.9**	**350**
COP	-	**6.796**	**5.1**
U (Eva)	$kW/m^2°C$	**5.596**	**3,000**
U (Cond)	$kW/m^2°C$	**4.596**	**4,000**
Capacity variable range	%	**8.08 ~ 102.81**	**10 ~ 100**

Image of the test

	Unit	Value	Design
Saturation P (Evap) ($P_{sat,e}$)	kPa	1.302	0.9
Saturation T (Evap) ($T_{sat,e}$)	°C	10.88	5.4
Inlet T (Cold water) ($T_{in,e}$)	°C	16.48	12
Outlet T (Cold water) ($T_{o,e}$)	°C	11.36	7
Flow rate (Cold water)	m^3/h	60.52	60
Saturation P (Cond) ($P_{sat,c}$)	kPa	5.830	6.1
Saturation T (Cond) ($T_{sat,c}$)	°C	35.64	36.5
Inlet T (Cold water) ($T_{in,c}$)	°C	28.90	30
Outlet T (Cold water) ($T_{o,c}$)	°C	33.27	35
Flow rate (Cooling water)	m^3/h	72.46	72

Revolutions
- LP : 10,000
- HP : 6,300

- Step by step increase
- Vibration↑, Bearing temperature↑ → Stop operation

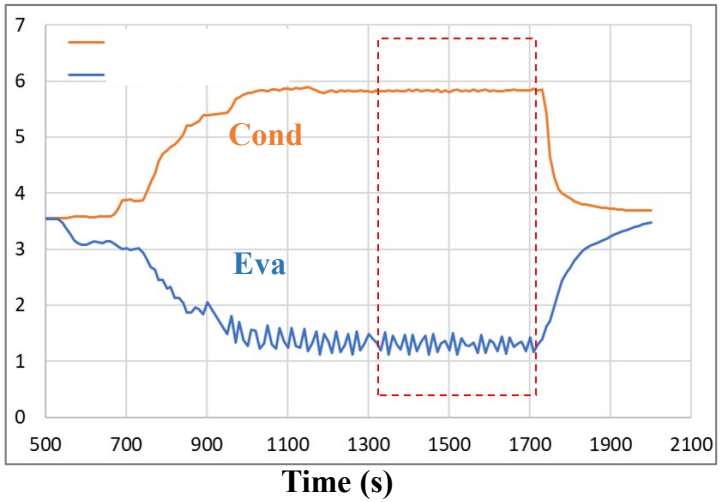


Revolution of Comps

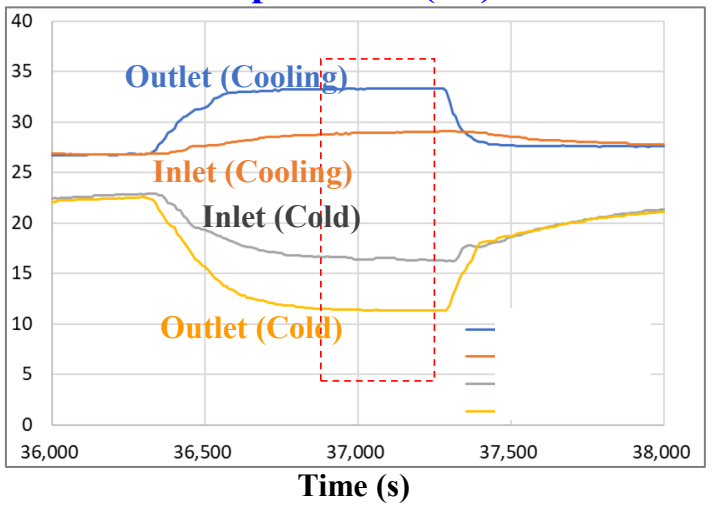
Prototype Performance Test

- Refrigeration capacity and COP
- Overall heat transfer coefficient of the Heat exchangers(Eva and Cond)

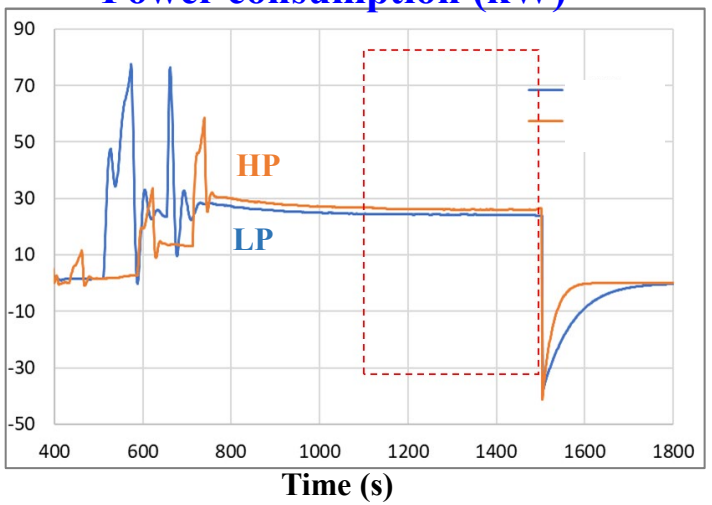
Pressure (kPa)



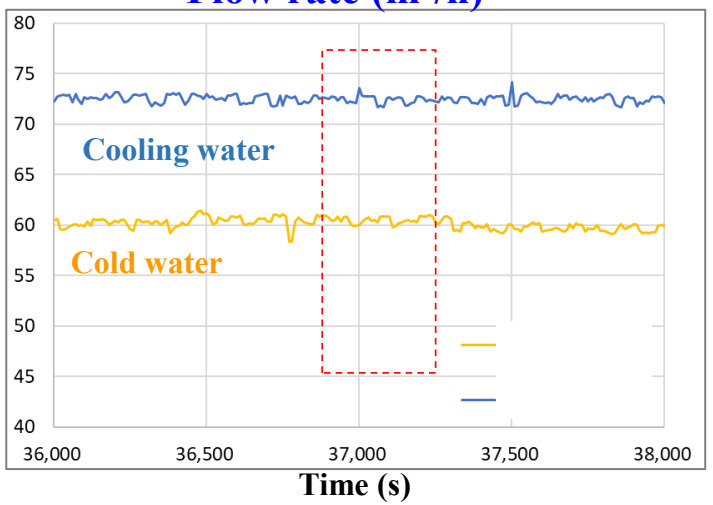
Temperature (℃)



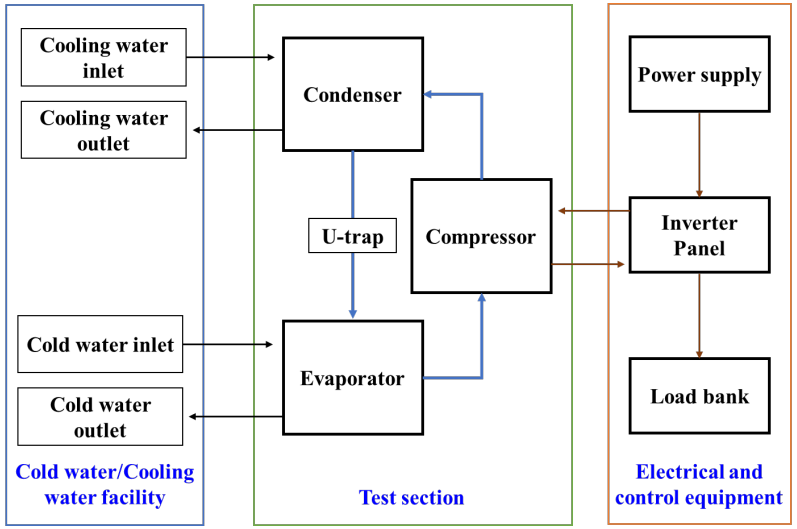
Power consumption (kW)



Flow rate (m^3/h)



Condensation



Schematic diagram of the entire facility

Prototype Performance Test

1st test 22.2~3 (2months)

2nd test 22.6 (About 3 weeks)

3rd test 22.8 (About 10 days)

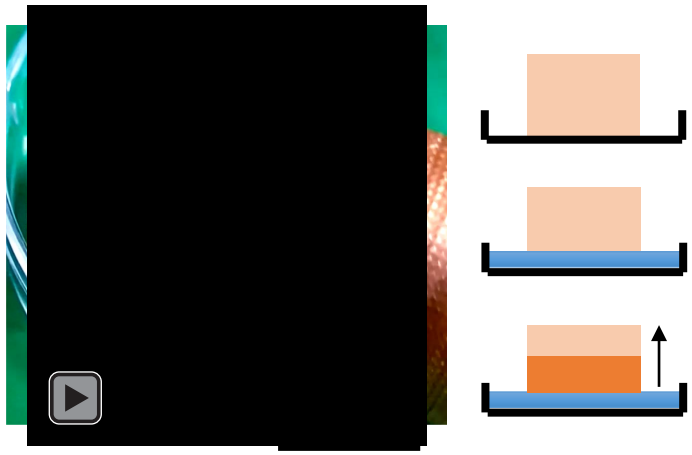
Requirements
- **Size**
- **Noise**
- **Leakage (Non-condensable gas problem)**
- **Condensation location**

4th ???

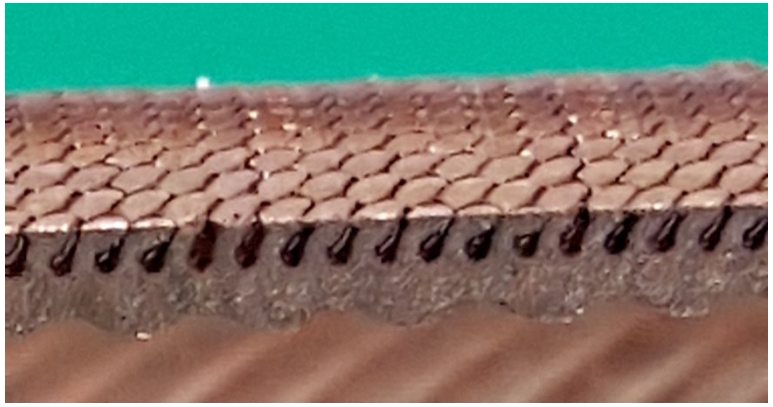
Thank you

Appendix

Ethanol
σ = 20
(mN/m)

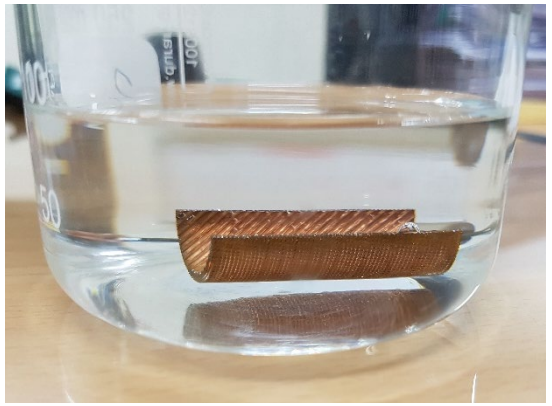


1 cm



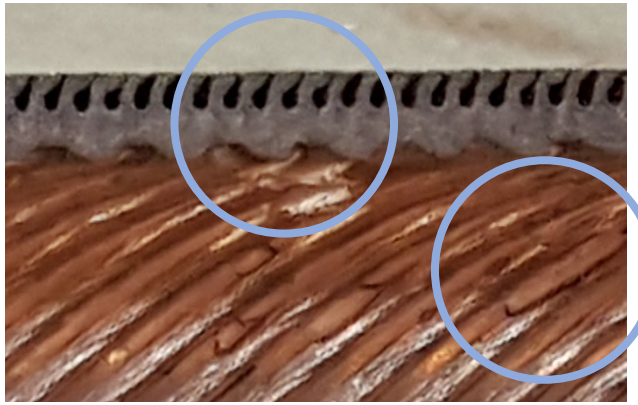
1 mm

Water
σ = 72
(mN/m)

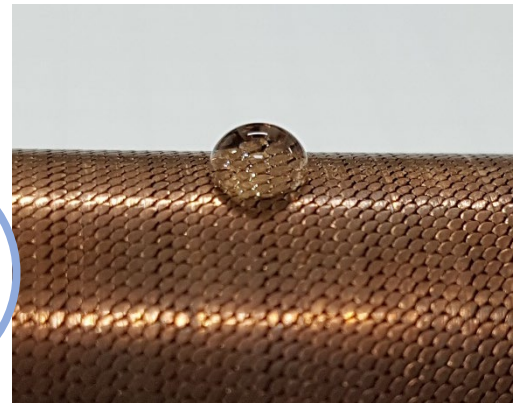


About 30 s

1 cm

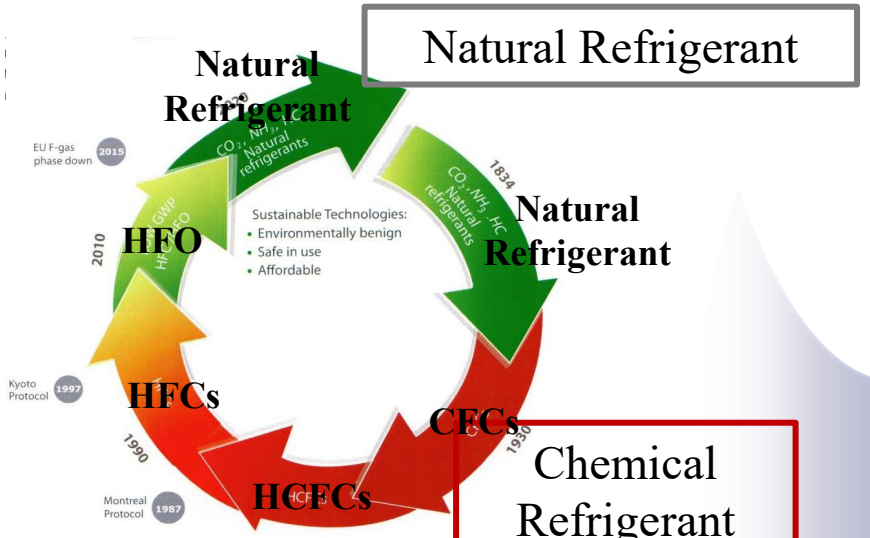


1 mm



2 mm

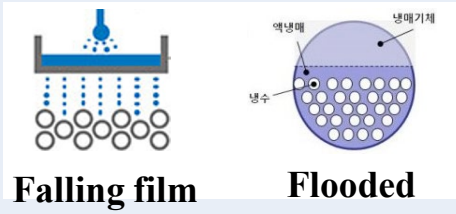
Introduction

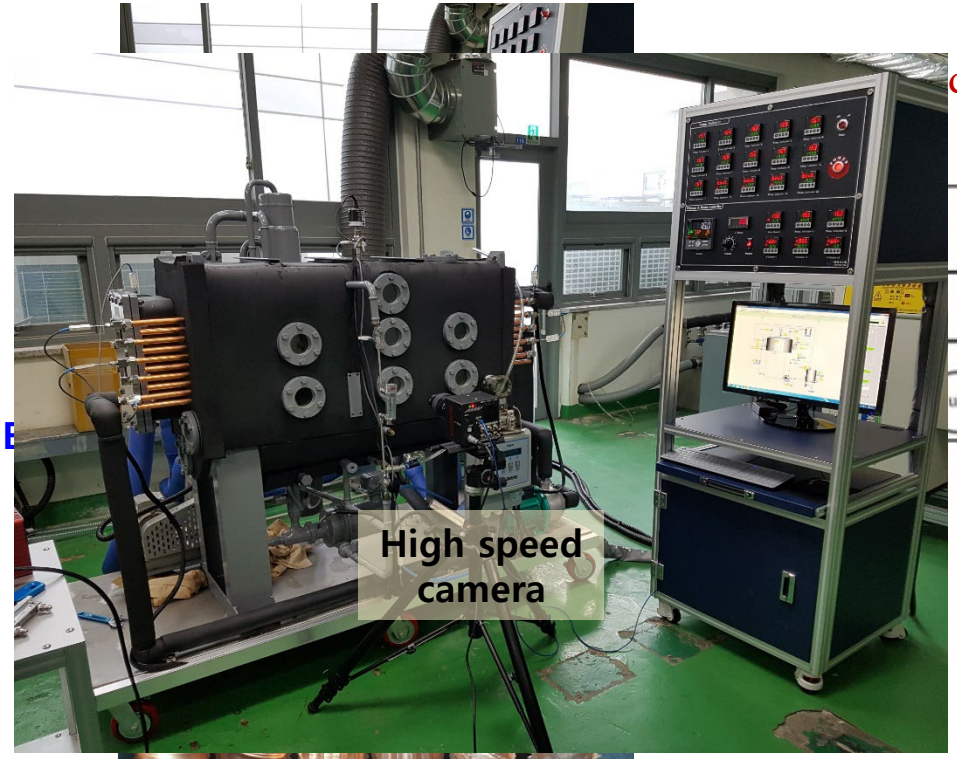


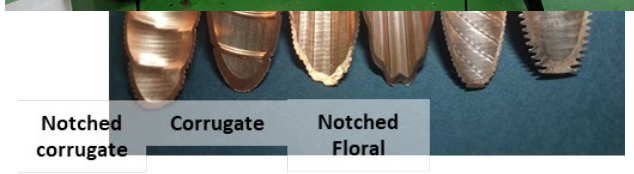
R-718 chiller

Evaporator

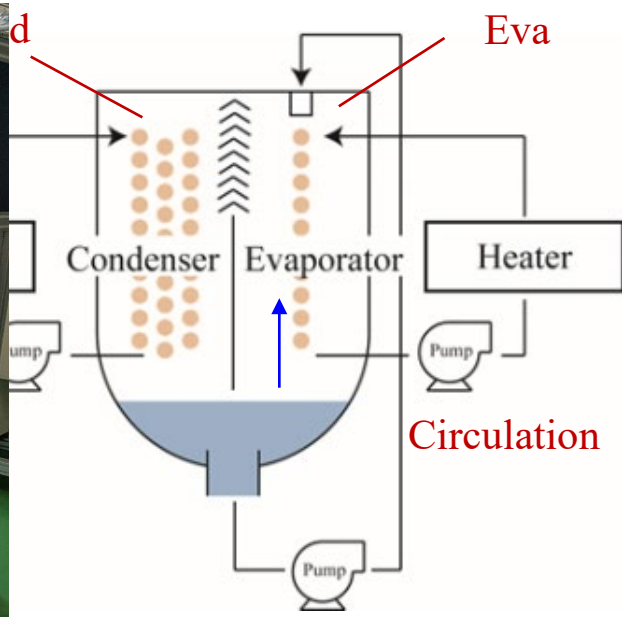
- Vacuum condition
- Falling film type
- Various heat transfer tubes







Heat transfer tubes



Schematic diagram

Chiller	0 ~ 1℃
Pressure (Shell)	0.8 ~ 1.3 kPa
Inlet T	12℃
Saturation T	5.4℃
Refrig flow rate	0.25 ~ 2.6 *l*/min
Cold water flow rate	7 ~ 22 *l*/min
Re_f	0 ~ 70
Re_{tube}	0 ~ 35000

- Eva and Cond integrated system (Absorption refrigerator type)
- Eliminator
- Distributor (tray)
- Visualization

Evaporator

- Derivation of Correlation
- 10 kW experiments

- Visualization of the evaporation
- Derivation of the theory (distribution)

- **Friction coeff**

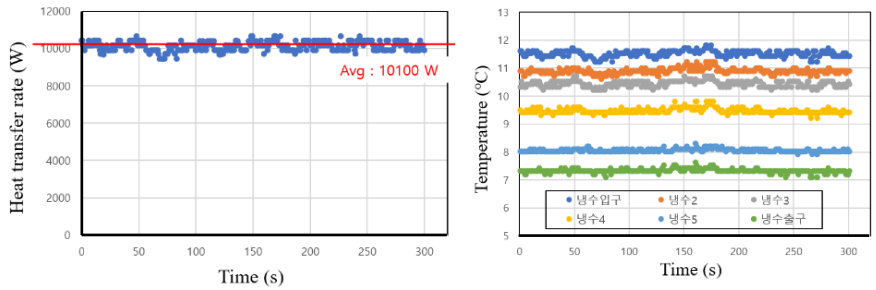
$$f = a\,\mathrm{Re}_f^b$$

	Do (mm)	Din (mm)	a	b
Smooth	16.01	13.78	0.000734	0.0808
Endcross	15.94	13.79	0.00472	-0.0804
Low fin	15.85	11.97	0.0108	-0.109

- **Heat transfer coeff**

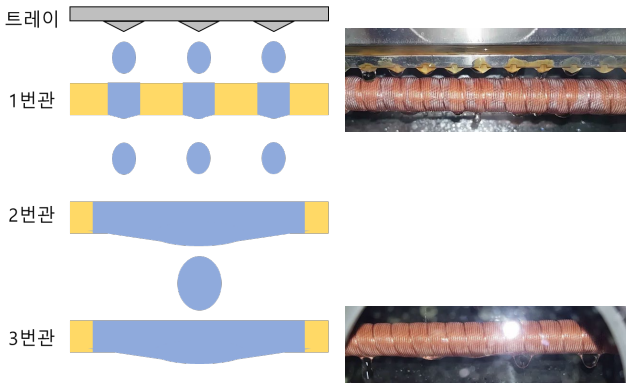
$$h_0\left(\frac{\nu^2}{gk^3}\right)^{1/3} = a\,\mathrm{Re}_f^b\,\mathrm{Pr}^c$$

	a	b	c
Smooth	0.0136	0.21	0.53
Endcross	0.134	0.14	0.53
Low fin	0.0268	0.395	0.53

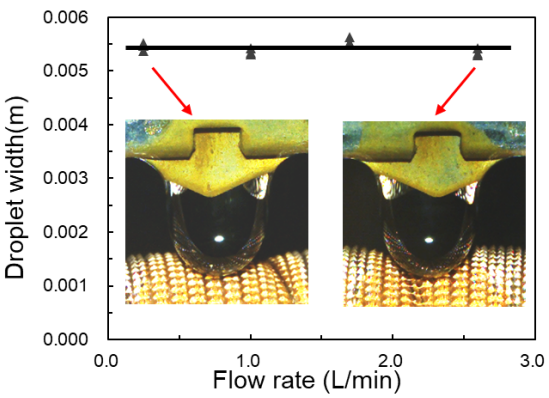


10 kW Eva performance test

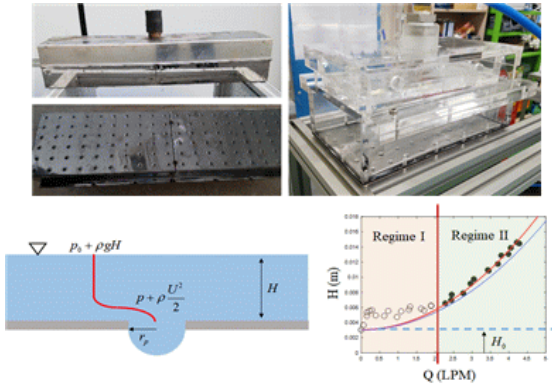
- Q : 10.1 kW
- U : 5,957 kW/m^{2}K



Wetting on 1st and lower tubes



Droplet size difference (flow rate)



$$H = H_0 + \frac{\dot{V}}{2gA_p^2},$$

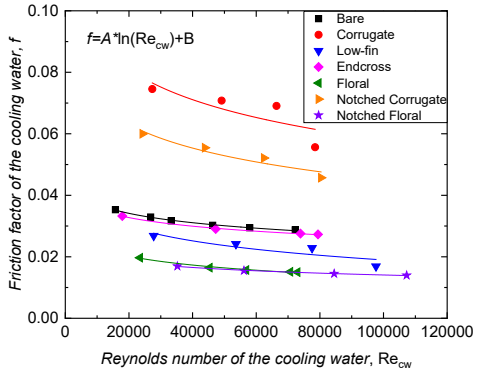
$$H_0 \propto \frac{\sigma}{r_p}$$

Investigation of the mechanism (Distributing tray)

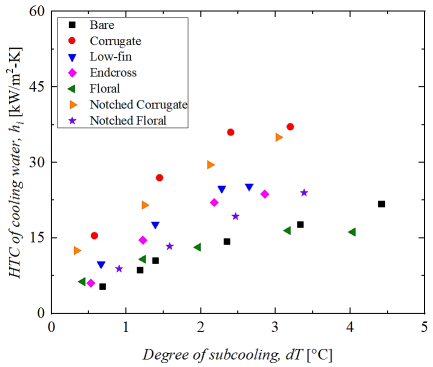
Condenser

- Experiments with Single tube and Multiple tubes system
- Derivation correlations

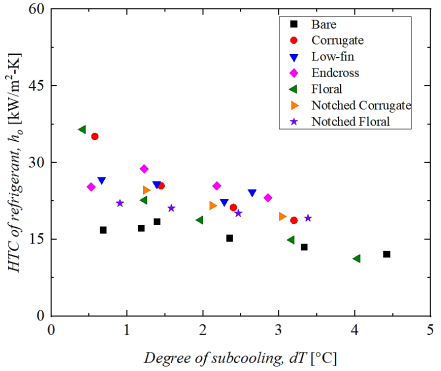
❖Friction factor, Inner heat transfer coefficient, condensation coefficient



< Re vs friction factor >

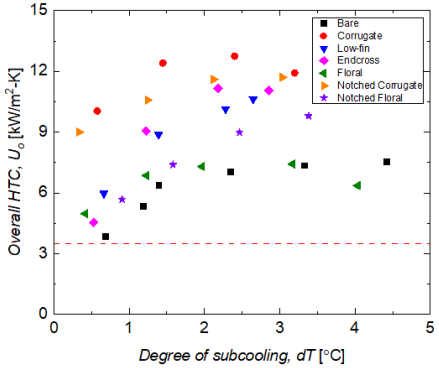


< Degree of sub-cooling vs Inner coefficient >

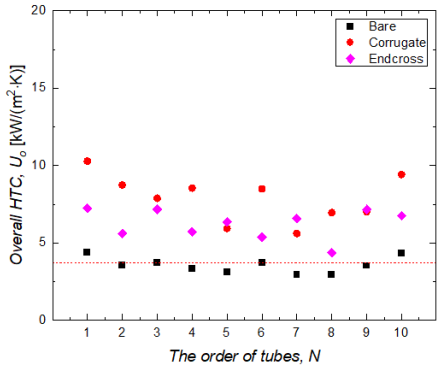


< Degree of sub-cooling vs Condensation coefficient >

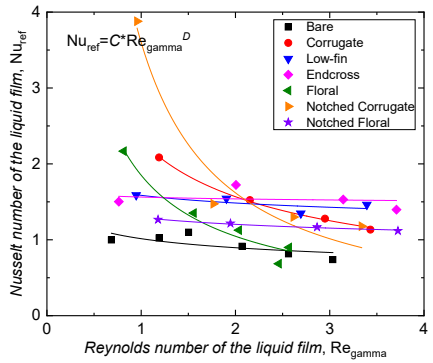
❖Overall heat transfer coefficient and correlations



< Overall heat transfer coefficient (single) >



< Overall heat transfer coefficient (multiple) >

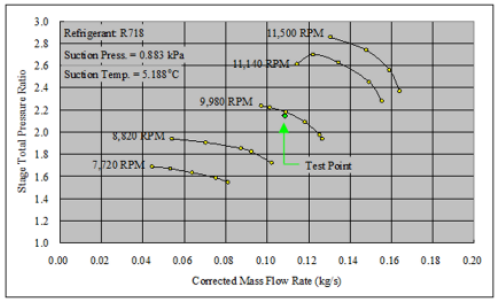


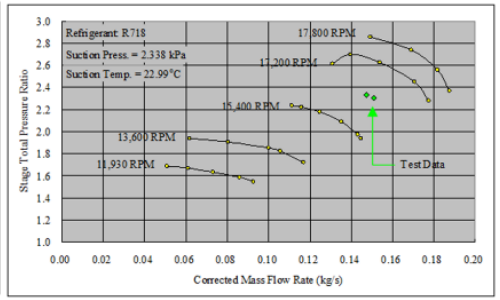
< Dimensionless correlation >

Compressor

- Electrical insulation and leak test prior to compressor installation
- Compression efficiency : 75.1 %

Compressor design → Geometry similitude method → Manufacture and assembly → Performance test



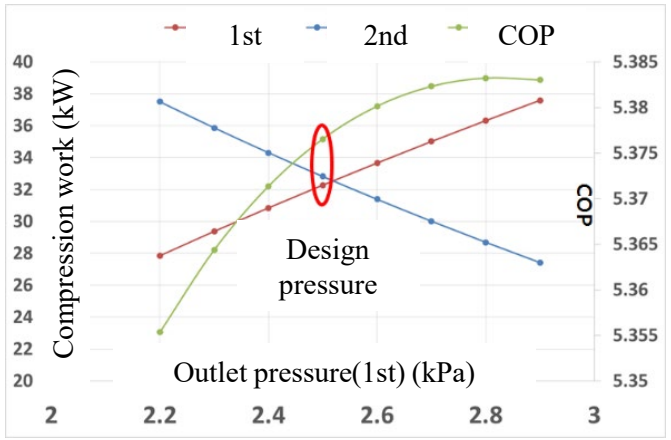


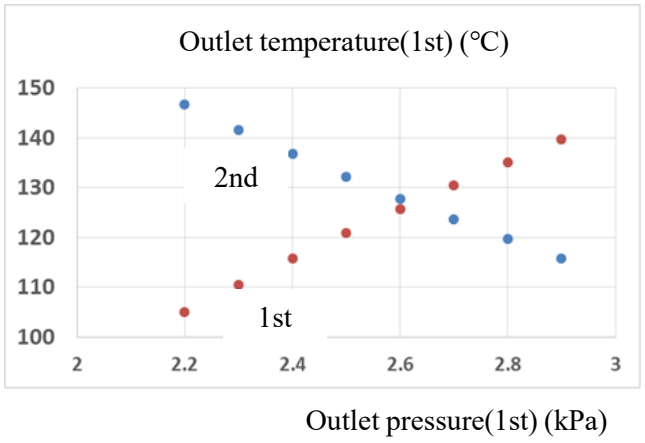
	1st	2nd
Revolutions (rpm)	10,000	16,300
Inlet pressure (kPa)	1.252	2.596
Inlet Temp (°C)	10.36	23.44
Power consumption(kW)	24.3	26.2

Convert to the designed Inlet condition

	1st	2nd
Revolutions (rpm)	9,911	16,292
Mass flow rate (kg/s)	0.1084	0.1473
Compression ratio	2.1486	2.3271
Power consumption (kW)	15.44	21.33
Efficiency(%)	***75.85***	***74.35***

System cycle





Comp efficiency : 70%