上海交通大學
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Research of water used as refrigerant in heat pump

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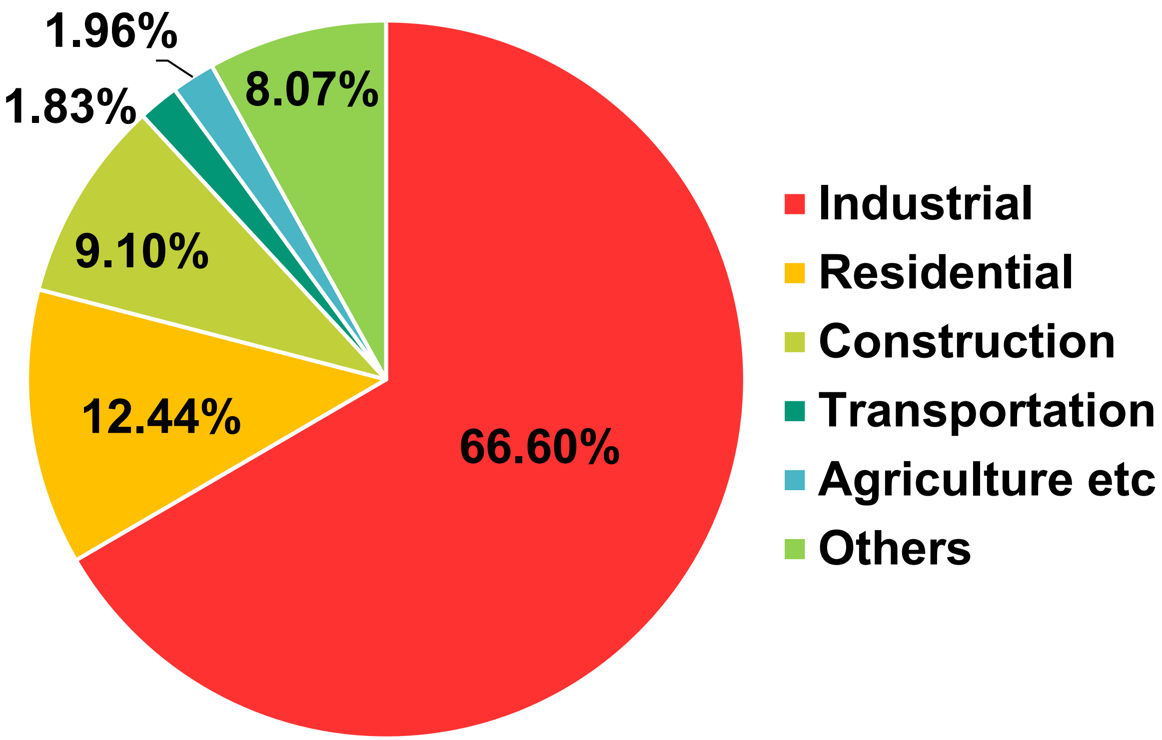
01

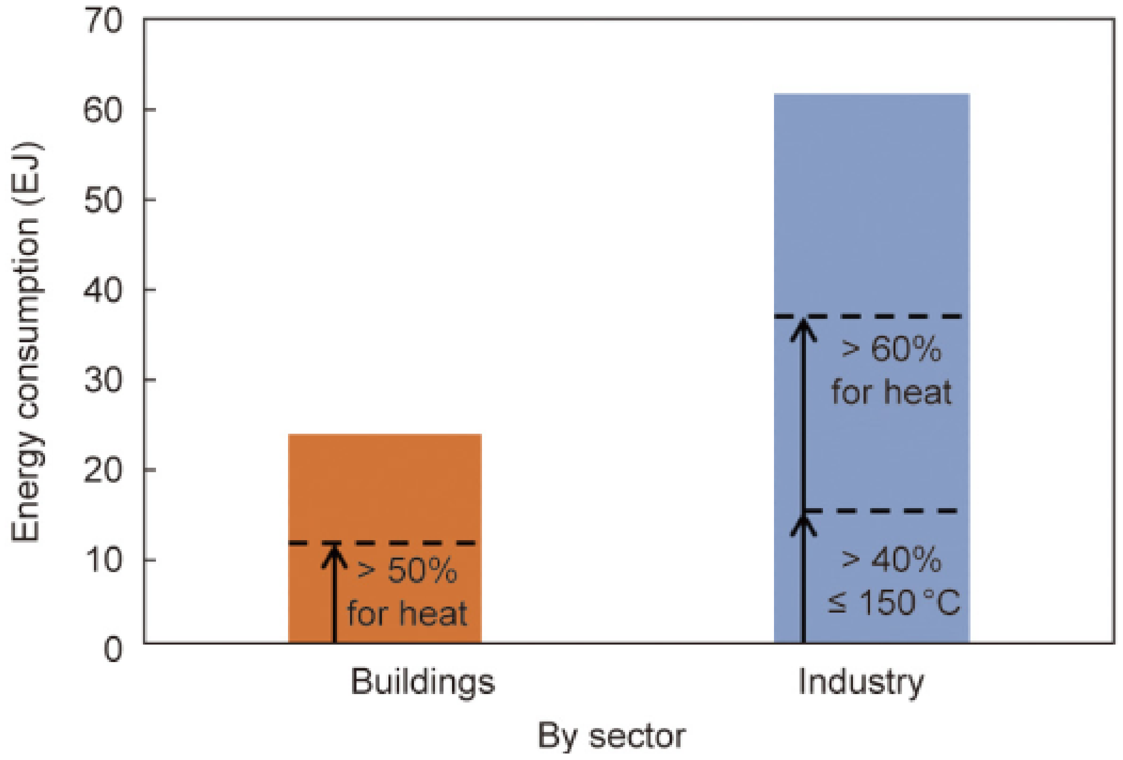
Introduction

HTHP is essential for industrial heating decarbonization

Industrial energy consumption



Industrial heat consumption

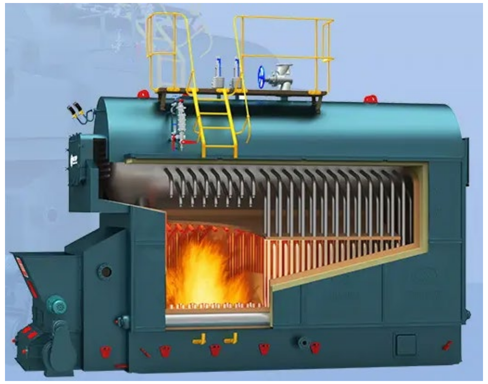


Industry accounts for 67% of total energy consumption in China, in which >60% is heat

HTHP is essential for industrial heating decarbonization

Conventional industrial heating technologies

Coal boiler



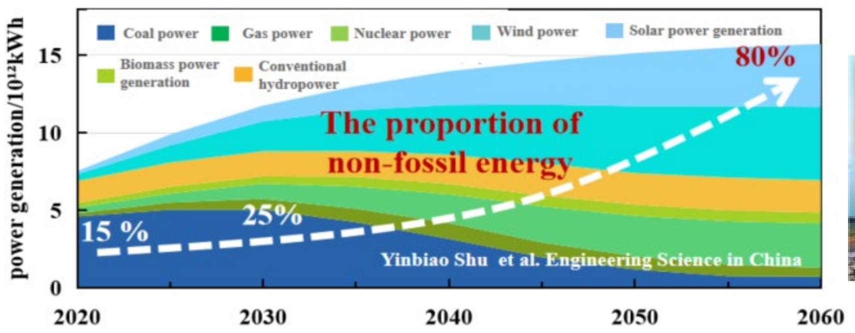
Oil boiler

Natural gas boiler

Electric boiler

Significant pollutant emissions such as SO_2, NO_x, PM, VOC

Efficiency limited to 1

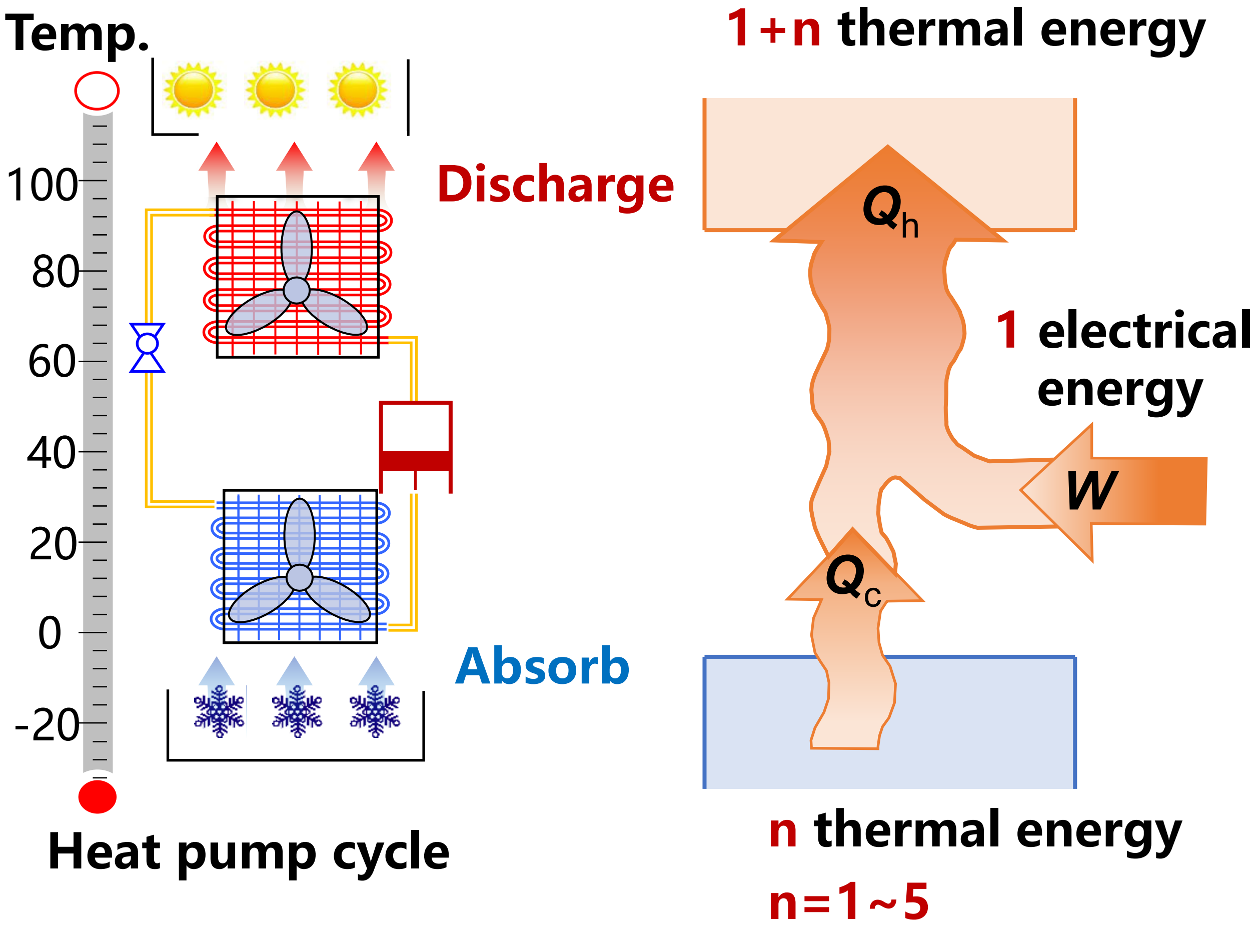


Clean electricity

Still have shortcomings:
High power consumption,
High operating cost,
Heavy load on power grid

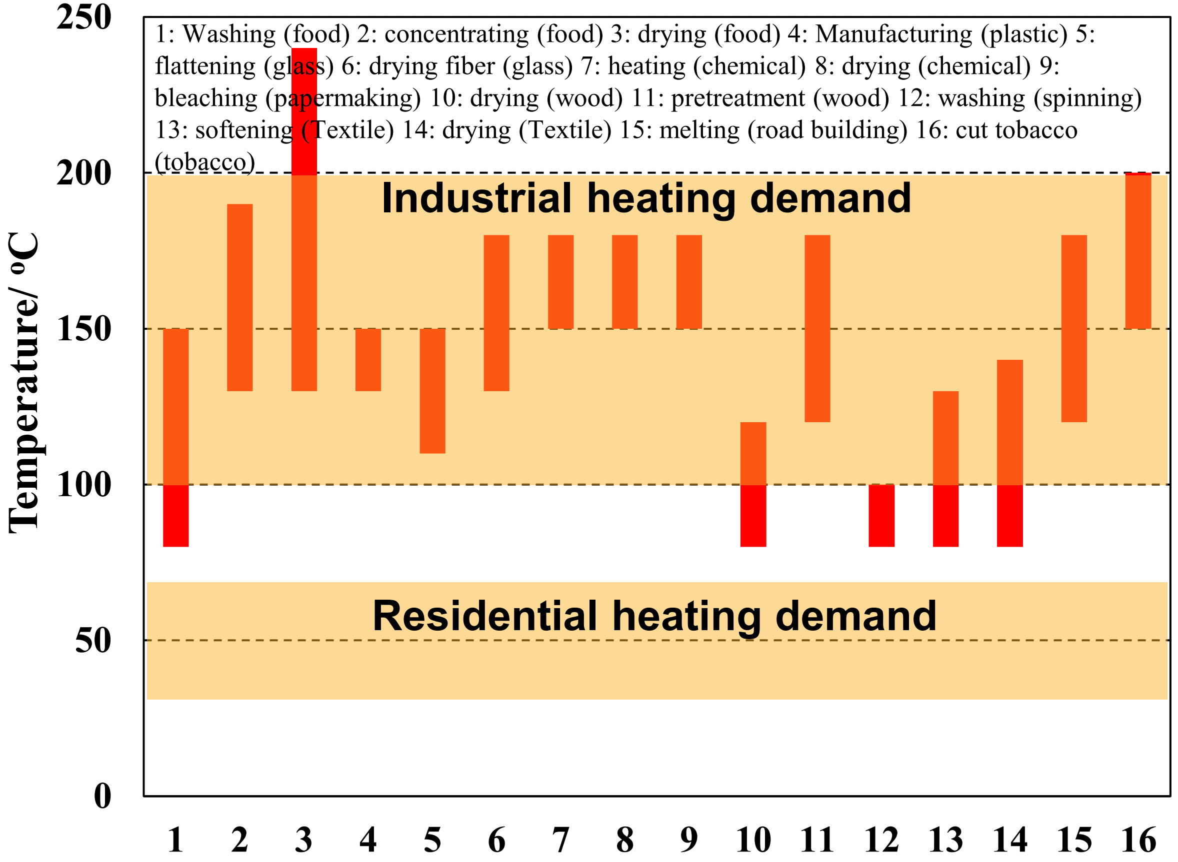
Clean and Efficient high temperature heating equipment is required

HTHP is essential for industrial heating decarbonization



Heat pump is an efficient equipment for Clean and Efficient heating.

High temperature heating in industry



Heat pump in industrial sector usually refers to high temperature heat pump (HTHP)

Water as refrigerant / Steam as heating medium

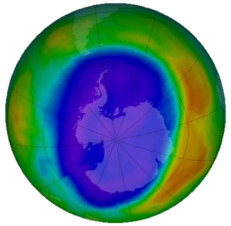
Advantages of water as refrigerant

- **Environmentally-friendly**

Safer — Greener — More efficient

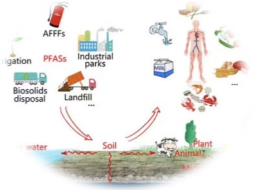
First stage	Second stage	Third stage	Fourth stage
Whatever worked	*Safety and durability*	*Ozone protection*	*Reducing global warming*
ethers, CO_2, NH_3, SO_2, $HCOOCH_3$, HCs, H_2O, CCl_4, CHCs, …	CFCs, HCFCs, HFCs, NH_3, H_2O, …	HCs, HCFCs, NH_3, HFCs, H_2O, CO_2, …	HFOs, HCFOs, HCs, NH_3, H_2O, CO_2, Air …

1830 — *1930s* — *1990s* — *2010s*



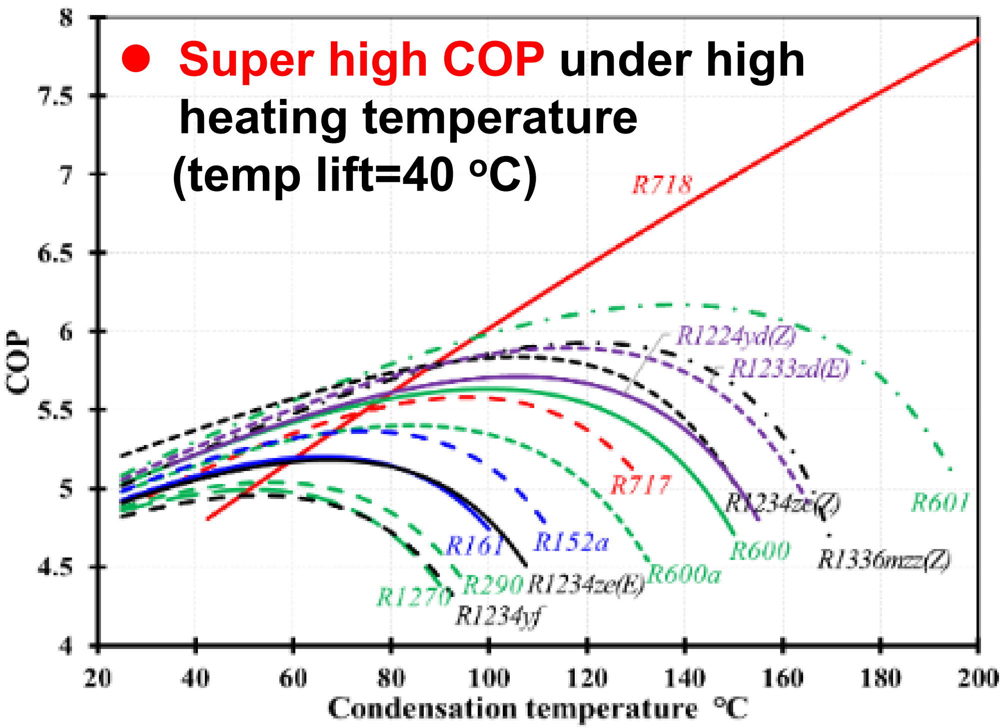
0 ozone depletion potential

0 global warming potential



0 other impact on environment

- **Super high COP** under high heating temperature (temp lift=40 °C)



- **Good security**
  non-toxic and non-flammable

- **Good economy**
  Low price and easily available

Water as refrigerant / Steam as heating medium

Steam as heating medium

A better carrier in many industrial processes

Brewing

Dyeing

Paper-making

Rectification

Metal processing

Pharma sterilization

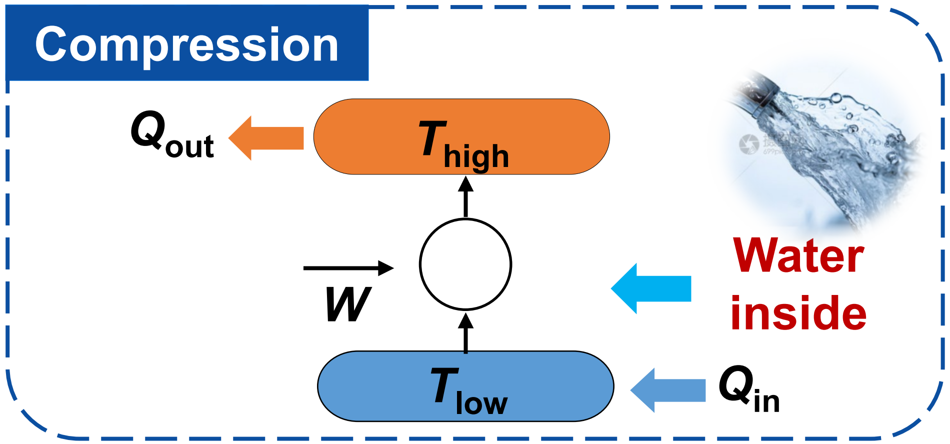
Steam VS water as heating medium

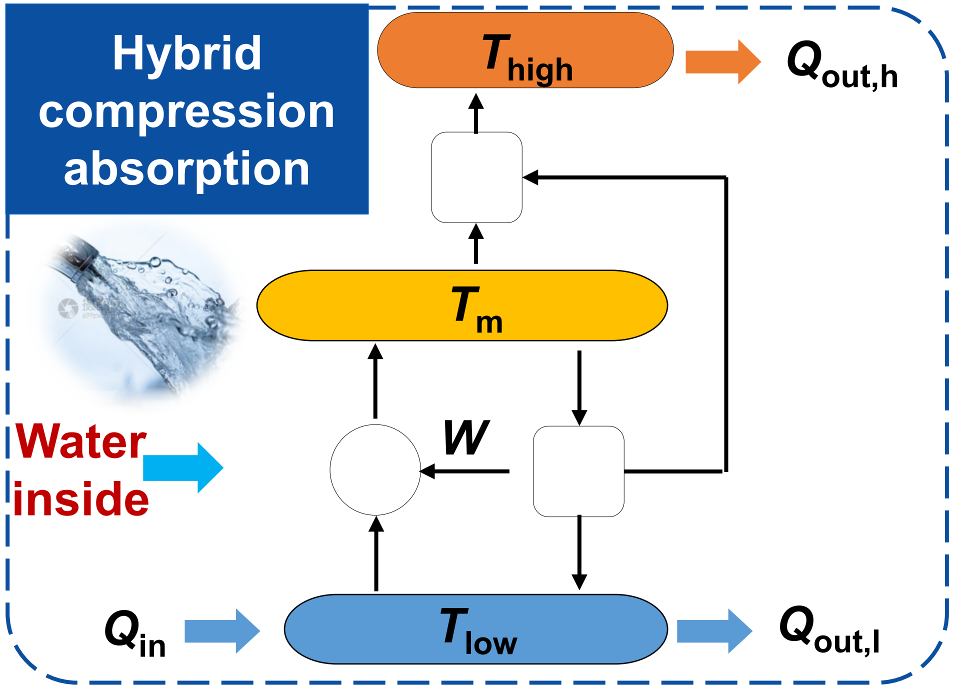
Heating medium	Steam	Water
Principle	Latent heat	Sensible heat
Temp. control	Easy	Difficult
Heat capacity	≈2000 kJ/kg	≈3.7 kJ/kg
Heat flux	High	Low
Temp. distribution	Even	Gradient
Heating temp.	100-200℃	80-150℃
Mass flow rate	Less	More

Steam has higher heating capacity, higher heating temperature, less mass flow rate. Its heating process is relatively even and easy to be controlled.

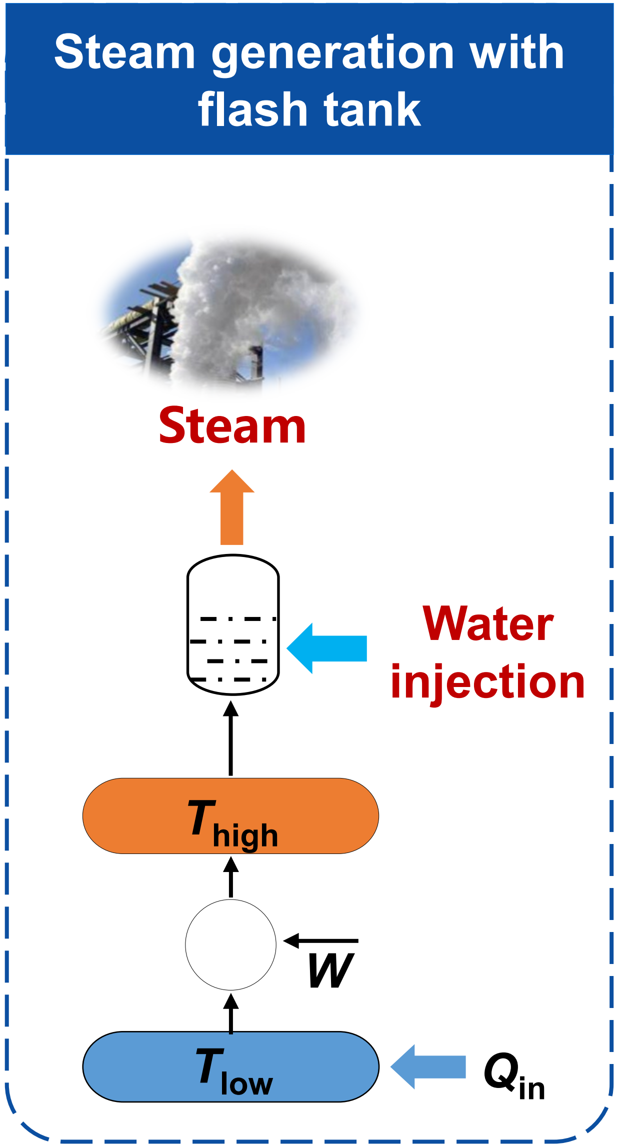
Water in HTHP

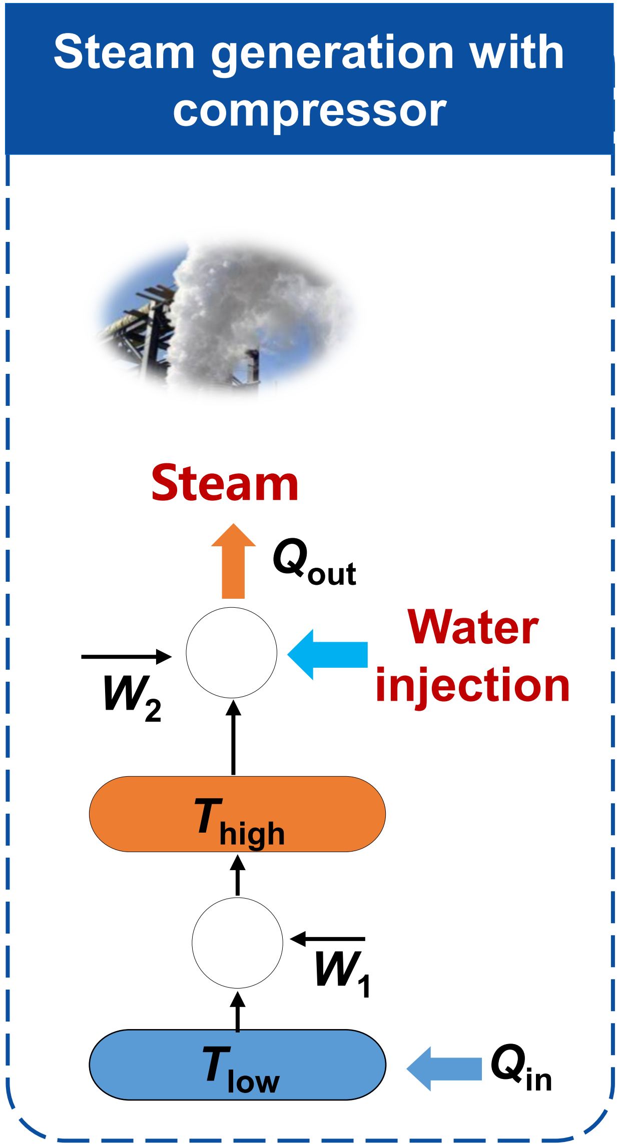
- Water as refrigerant





- Steam as heating medium



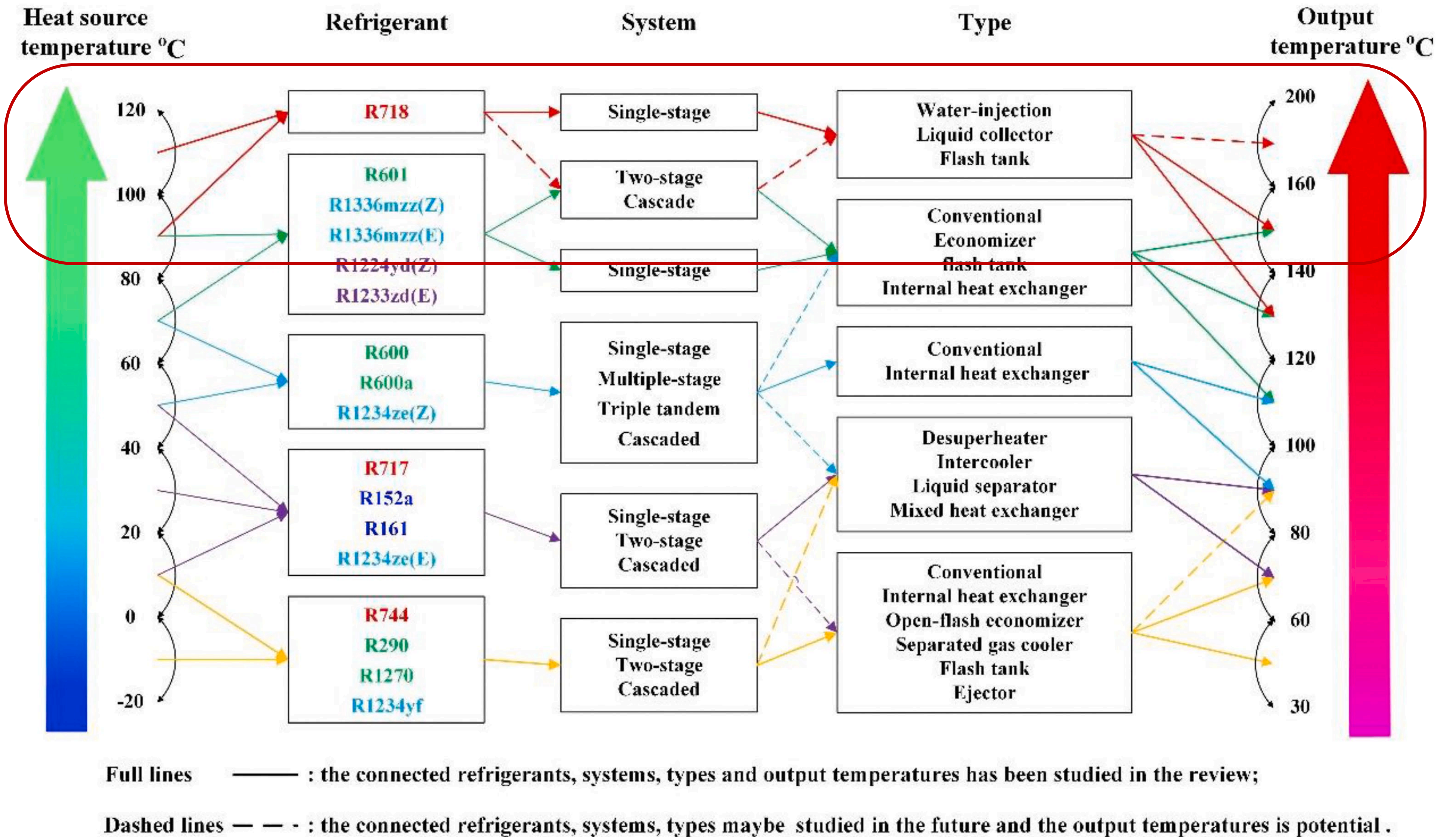


02

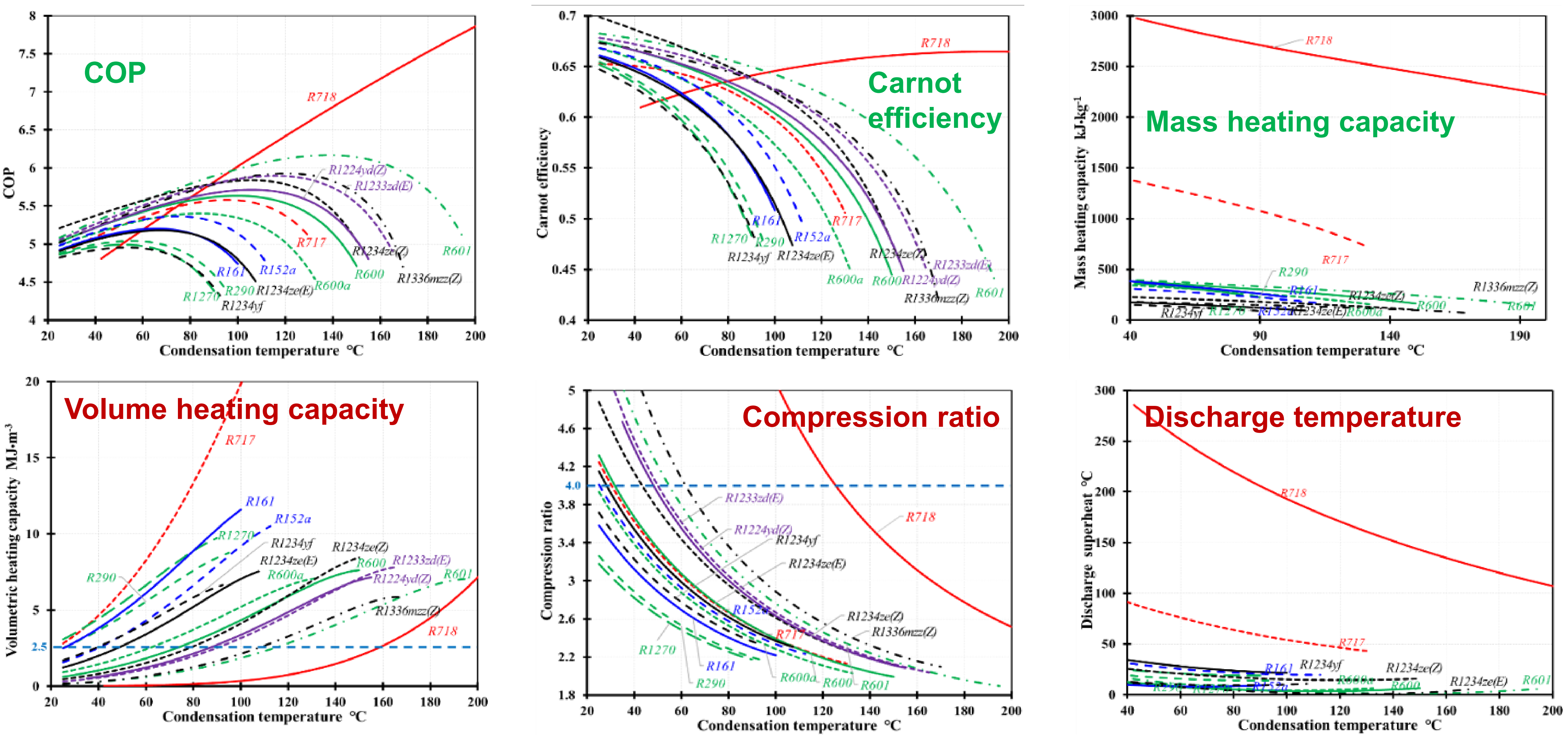
Water-based closed-cycle HTHP

Water-based closed-cycle HTHP (water as refrigerant)

Ideal for high temperature heat source and output t_{cr}=374°C and $t_{boil,atm}$=100°C



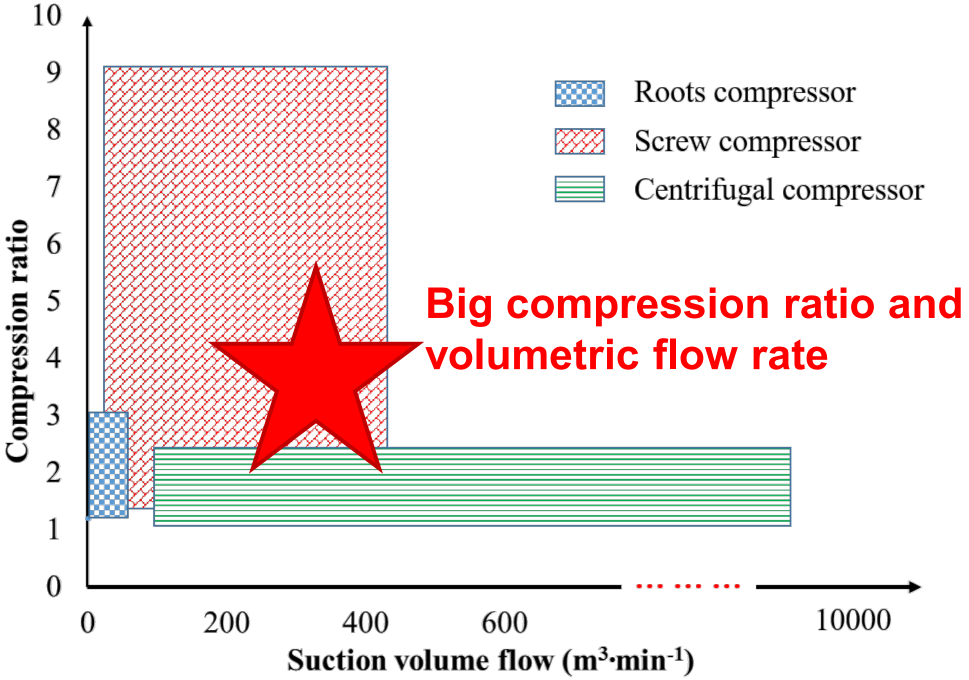
Water-based closed-cycle HTHP (water as refrigerant)



Advantages: high heating capacity and efficiency; **Disadvantages**: high requirement for compressor

Water-based closed-cycle HTHP (water as refrigerant)

Challenge of water refrigerant on compressor: big pressure ratio and volume flow rate

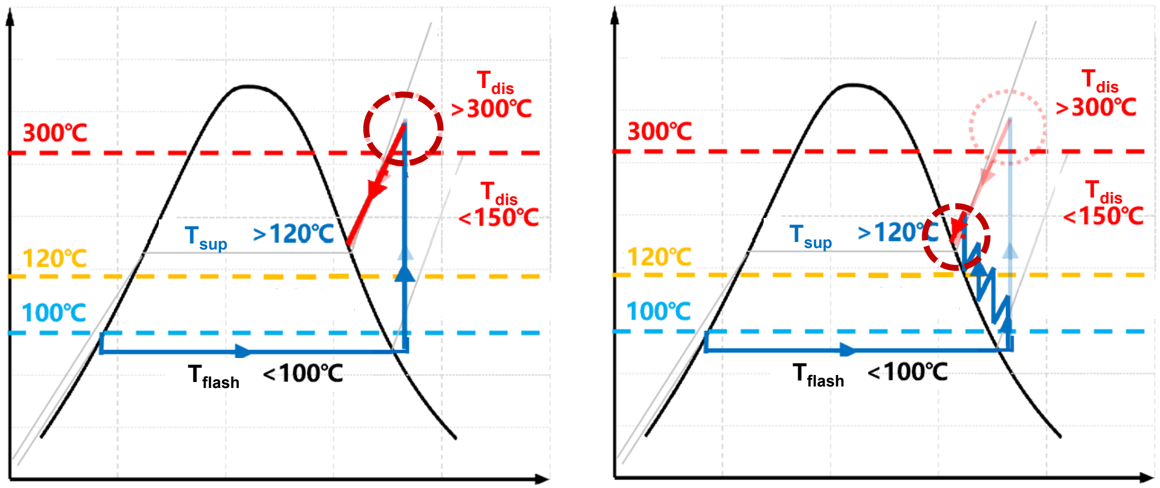


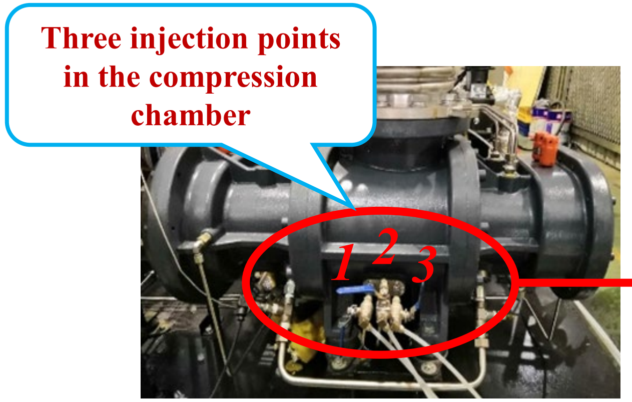
Compressor selection

- Twin-screw compressor
- Flexibility and stability

Challenge of water refrigerant on compressor: high discharge temperature

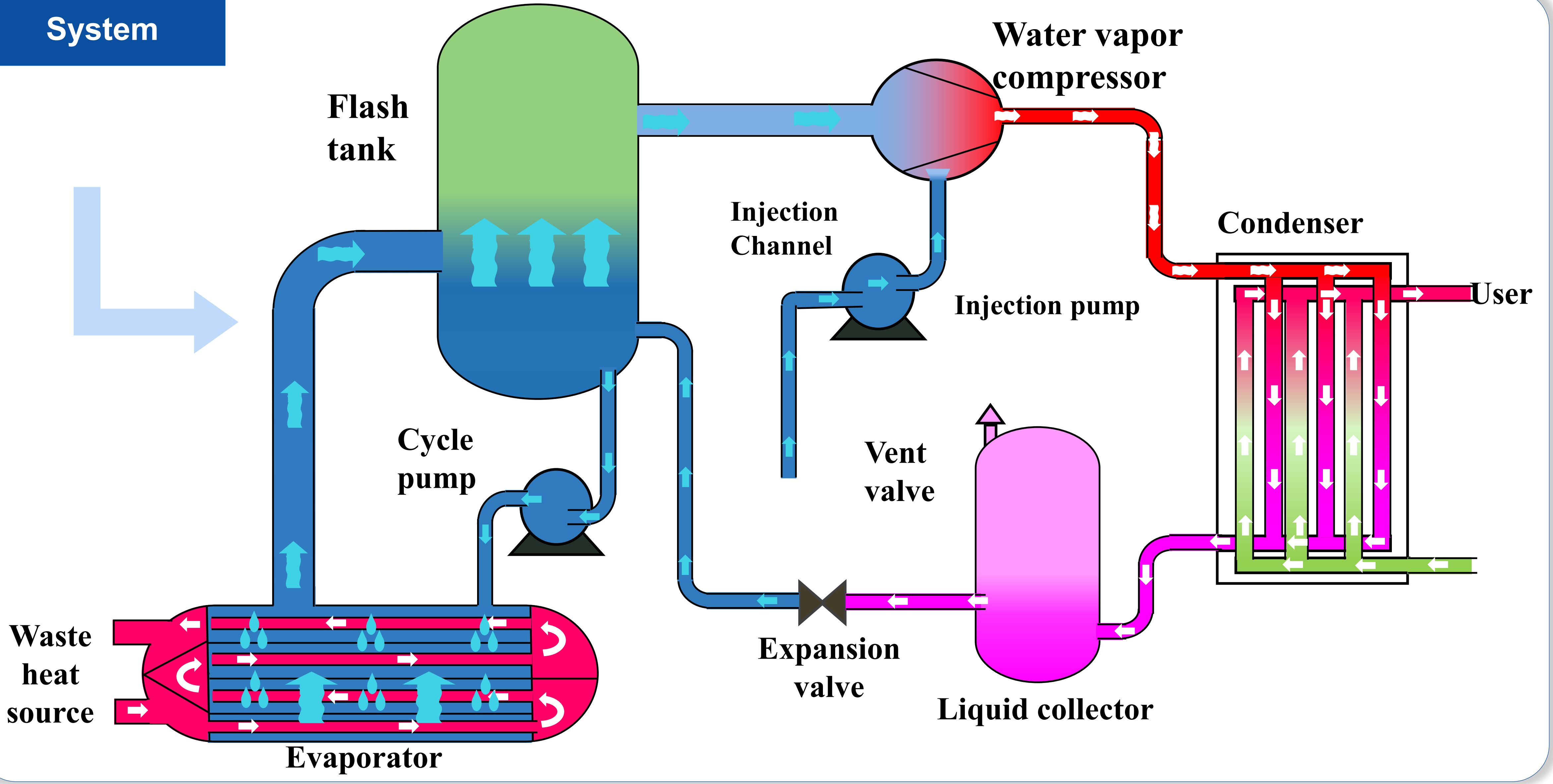
Water injection technology for multistage cooling





Water-based closed-cycle HTHP (water as refrigerant)

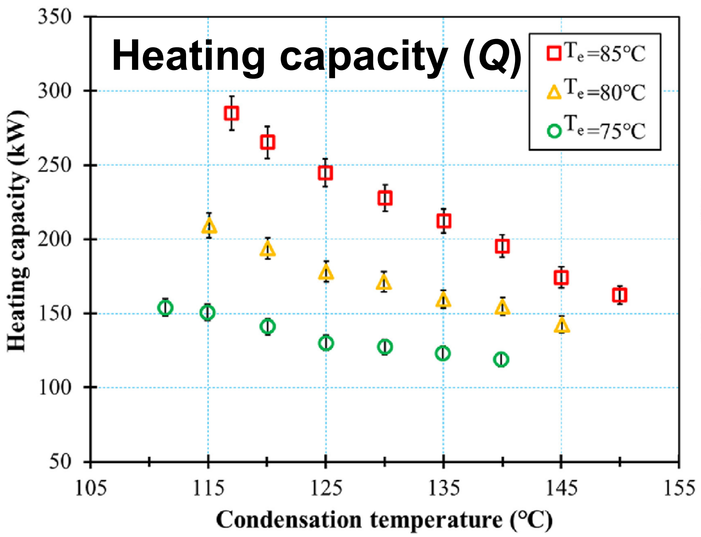
System

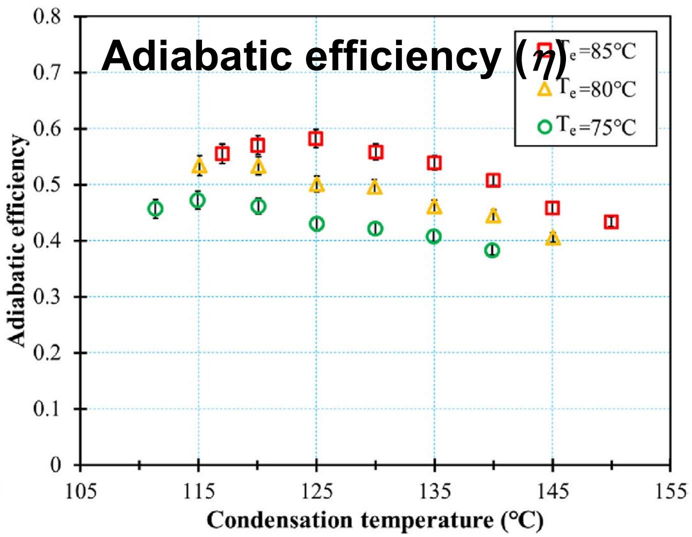


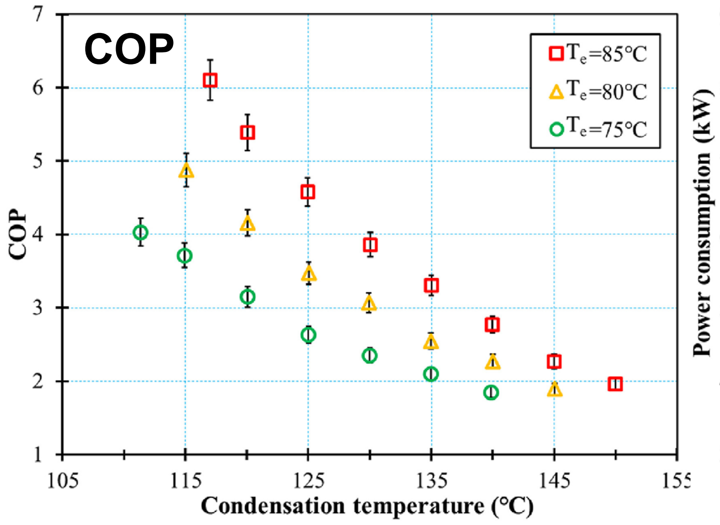
Water-based closed-cycle HTHP (water as refrigerant)

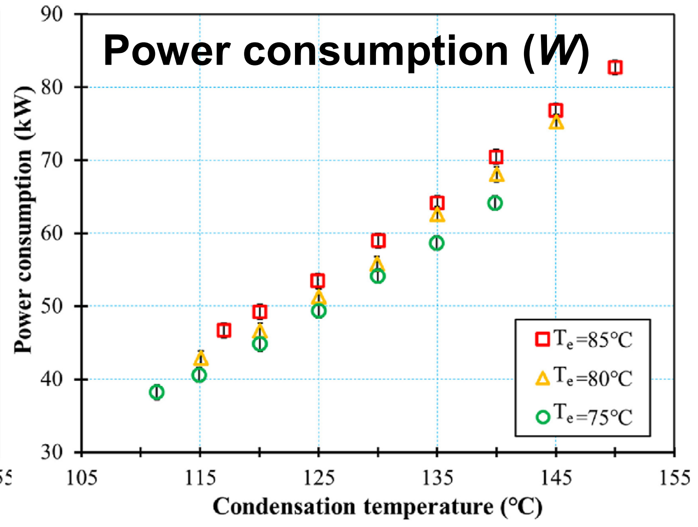
Prototype and performance test

	Q (kW)	W (kW)	COP
Evaporation : 82.9°C Condensation : 115.0°C	260.12	45.61	5.70
Evaporation : 80.4°C Condensation : 120.5°C	211.07	46.84	4.51
Evaporation : 81.4°C Condensation : 130.5°C	199.58	57.10	3.49









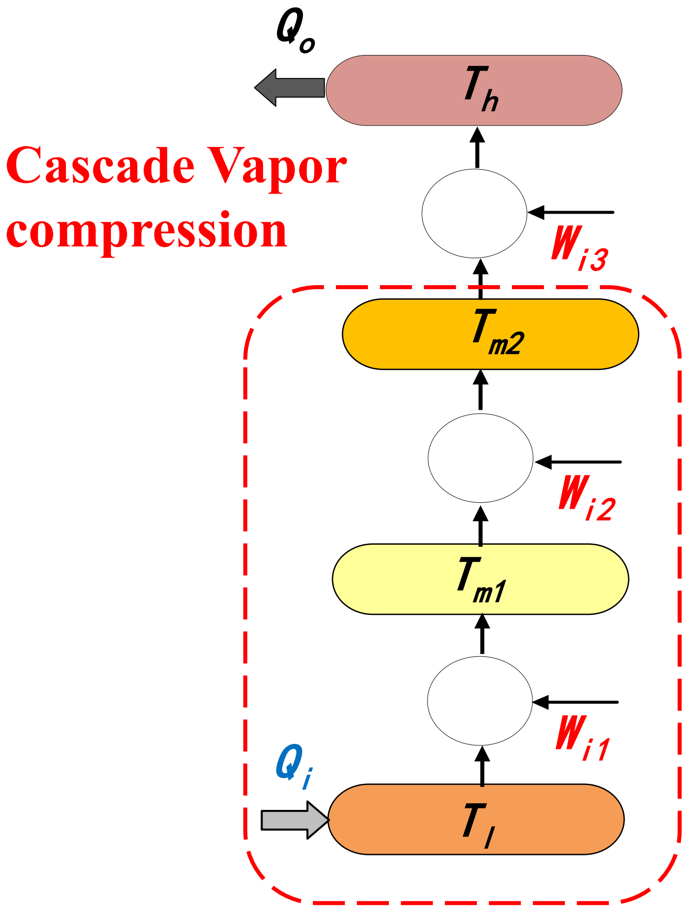
03

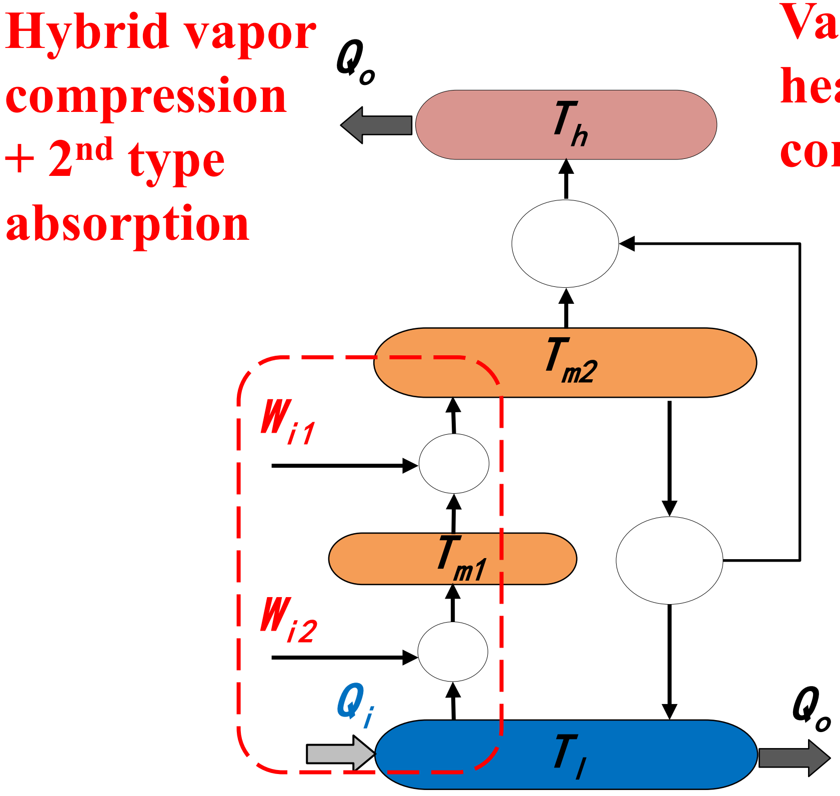
Steam generating HTHP

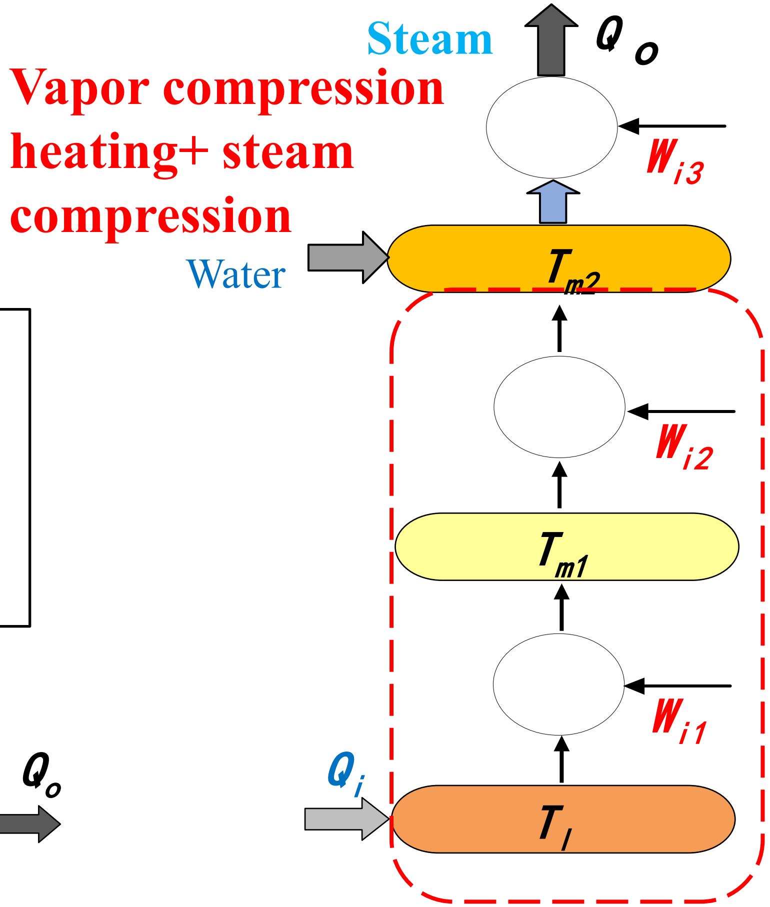
HTHP Thermodynamic Ways

Closed system to generate heat

Open system to generate steam



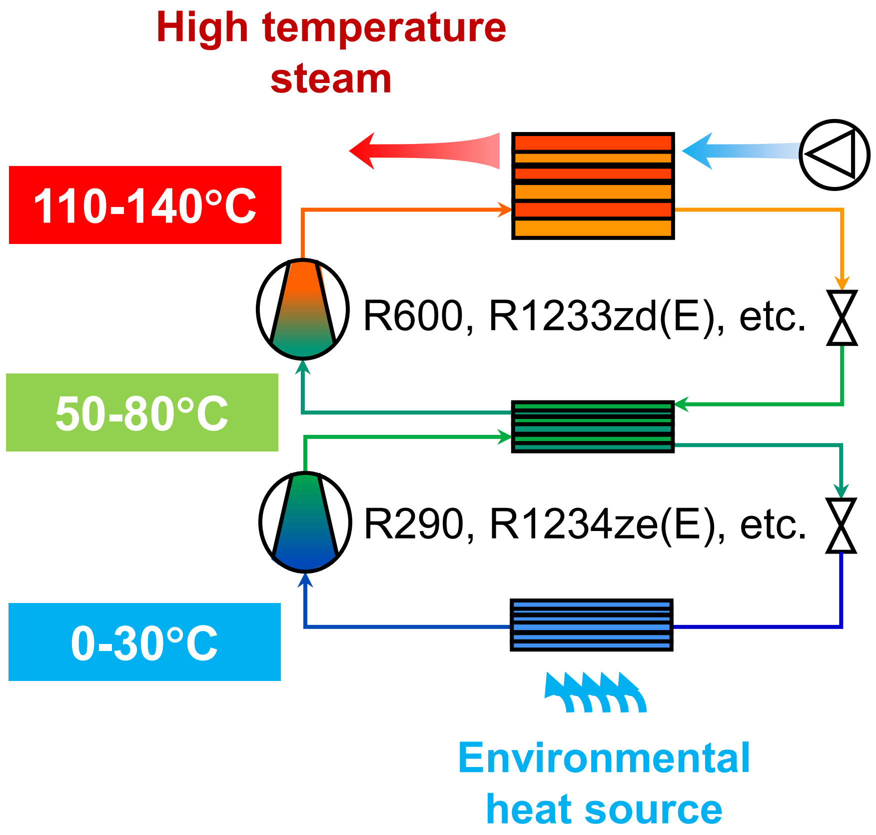


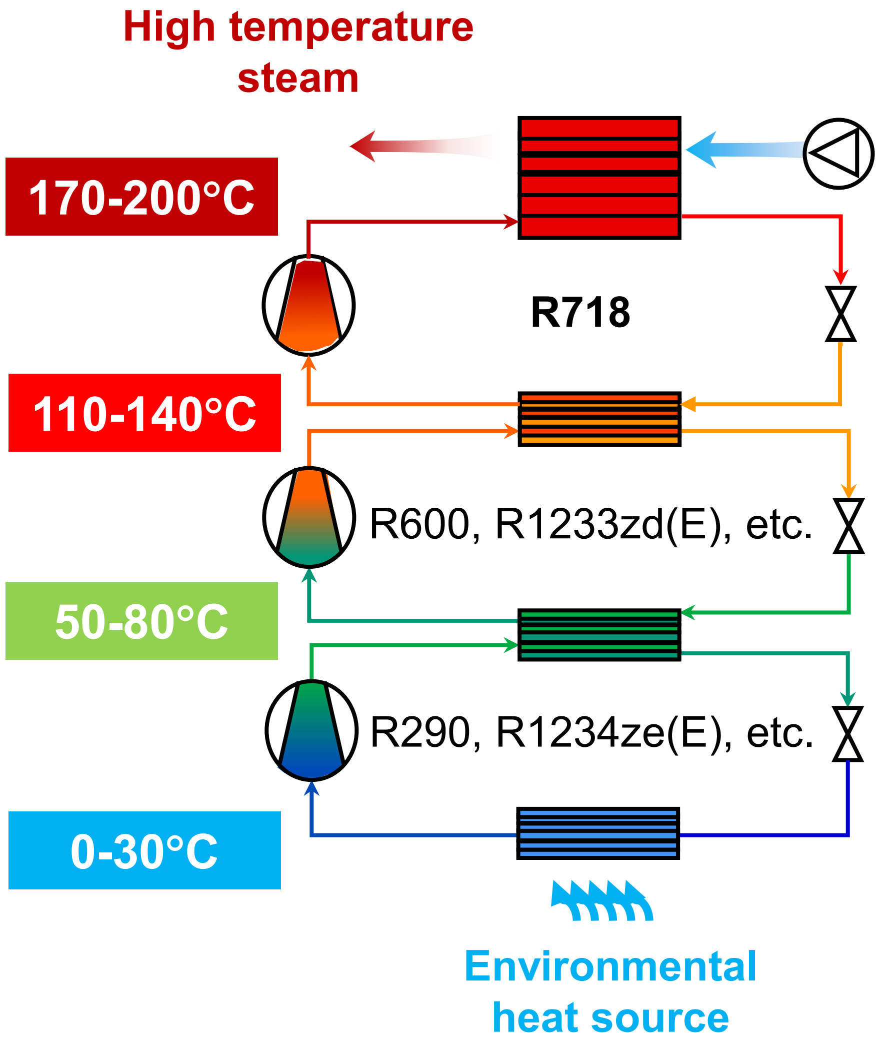


Steam generating HTHP

□ **From ambient air to high temperature steam**

① Closed-cycle compression + Water Evaporation

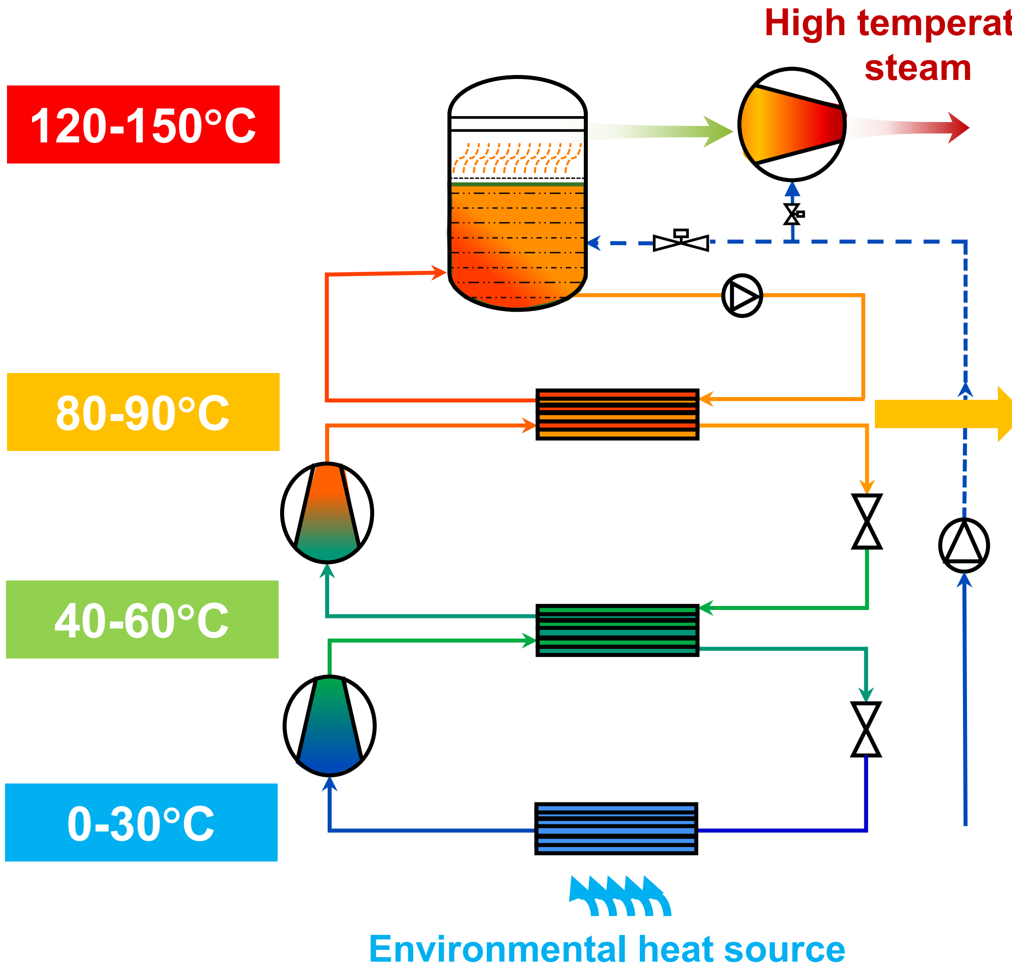


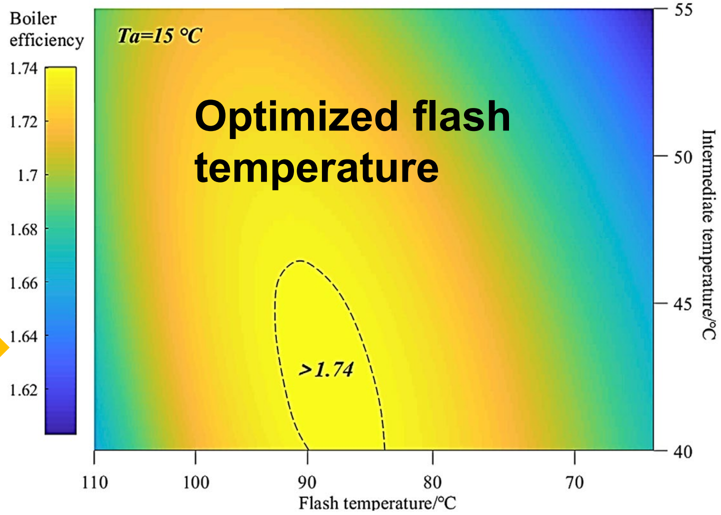


Steam generating HTHP

◻ From ambient air to high temperature steam

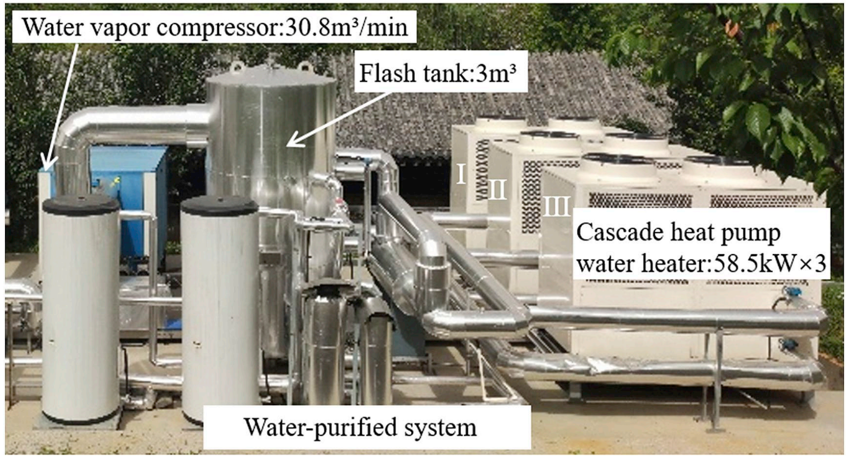
② Closed-cycle compression + Open-cycle compression

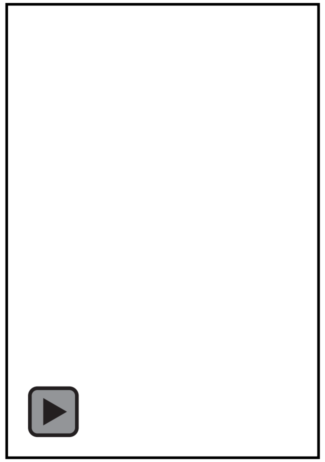




On site performance test

	Cond.1	Cond.2
Ave. ambient temp. at 19°C		
Flow rate	0.3 t/h	1 t/h
Temp.	120°C	150°C
Pressure	0.2 MPa	0.4 MPa
COP	1.8	1.6





Steam generating HTHP

□ From ambient air to high temperature steam

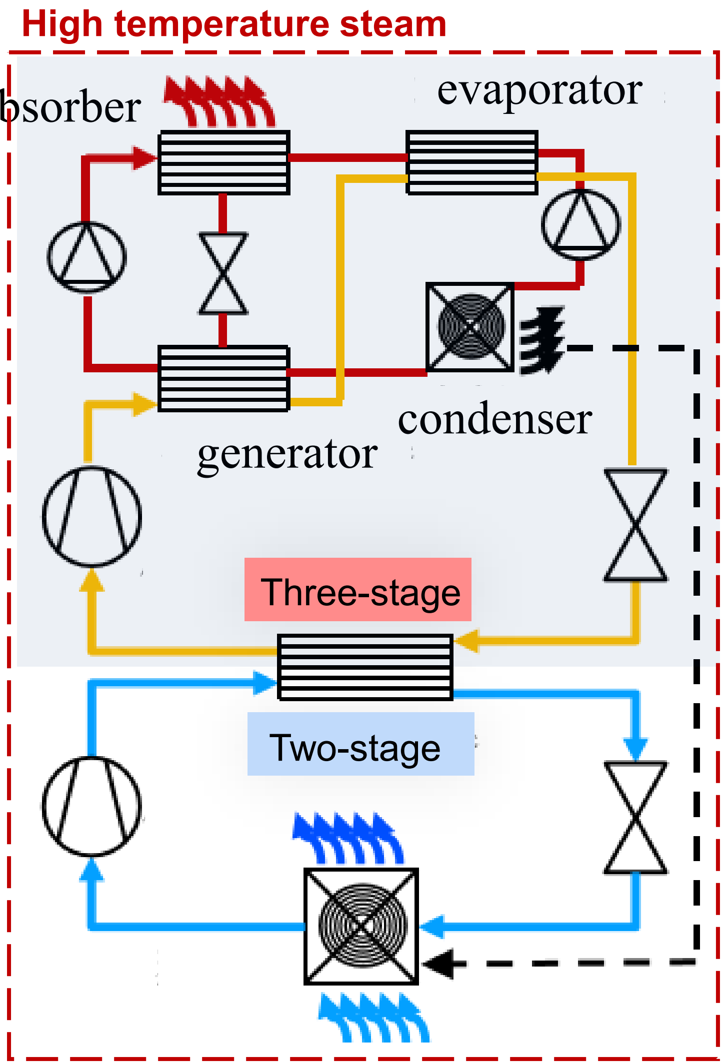
③ Closed-cycle compression + Absorption (Type Ⅱ)

100-160°C

65-85°C

30-50°C

10-30°C

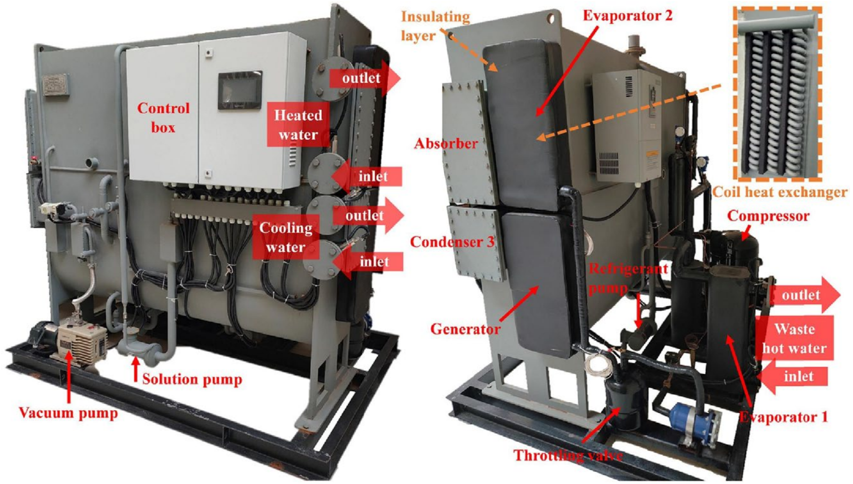


High temperature cycle—Absorption

Low temperature cycle—Compression

Cascade

Advantages:
- Large temperature lift
- High heating temp.
- Large heating capacity

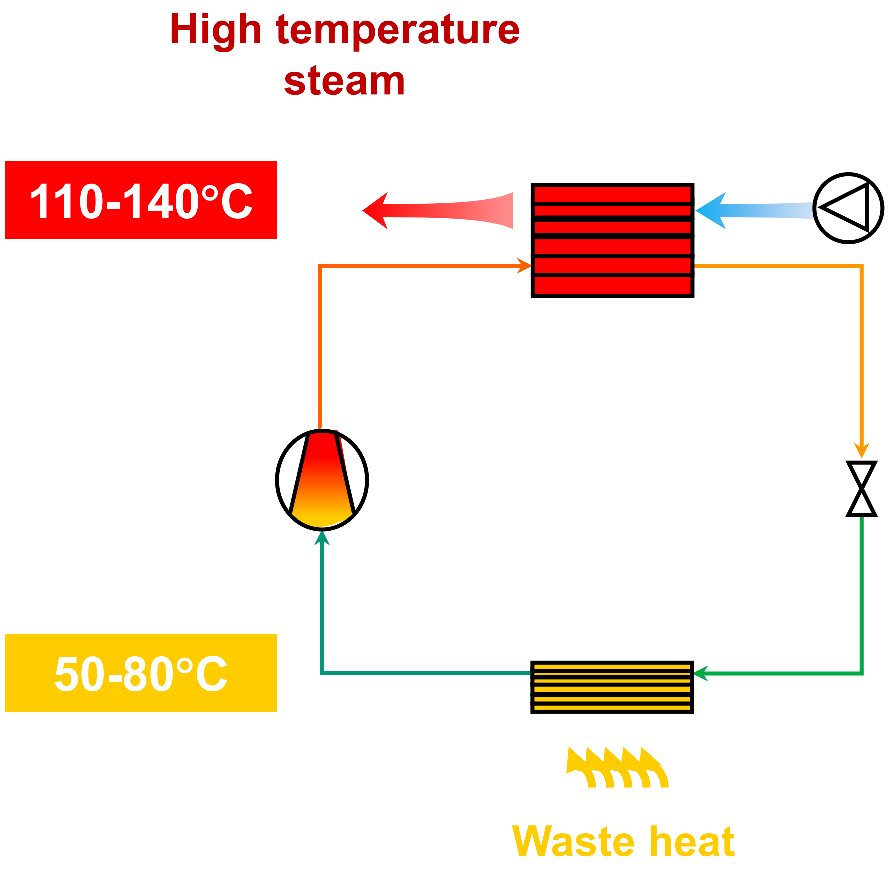


A two-stage prototype:
- Waste heat at 47-51°C
- Heat output at 99-102°C
- COP of 1.81
- 35 kW heating output

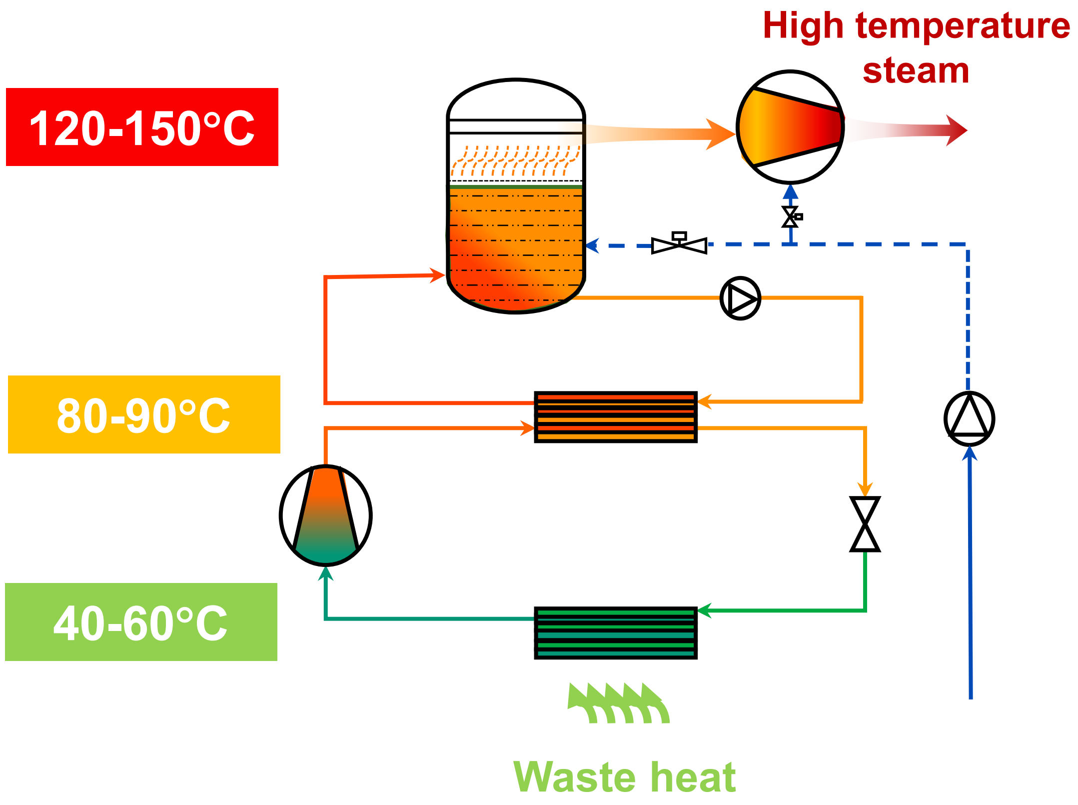
Steam generating HTHP

- From **waste heat to** high temperature **steam**

① Closed-cycle compression + Evaporation



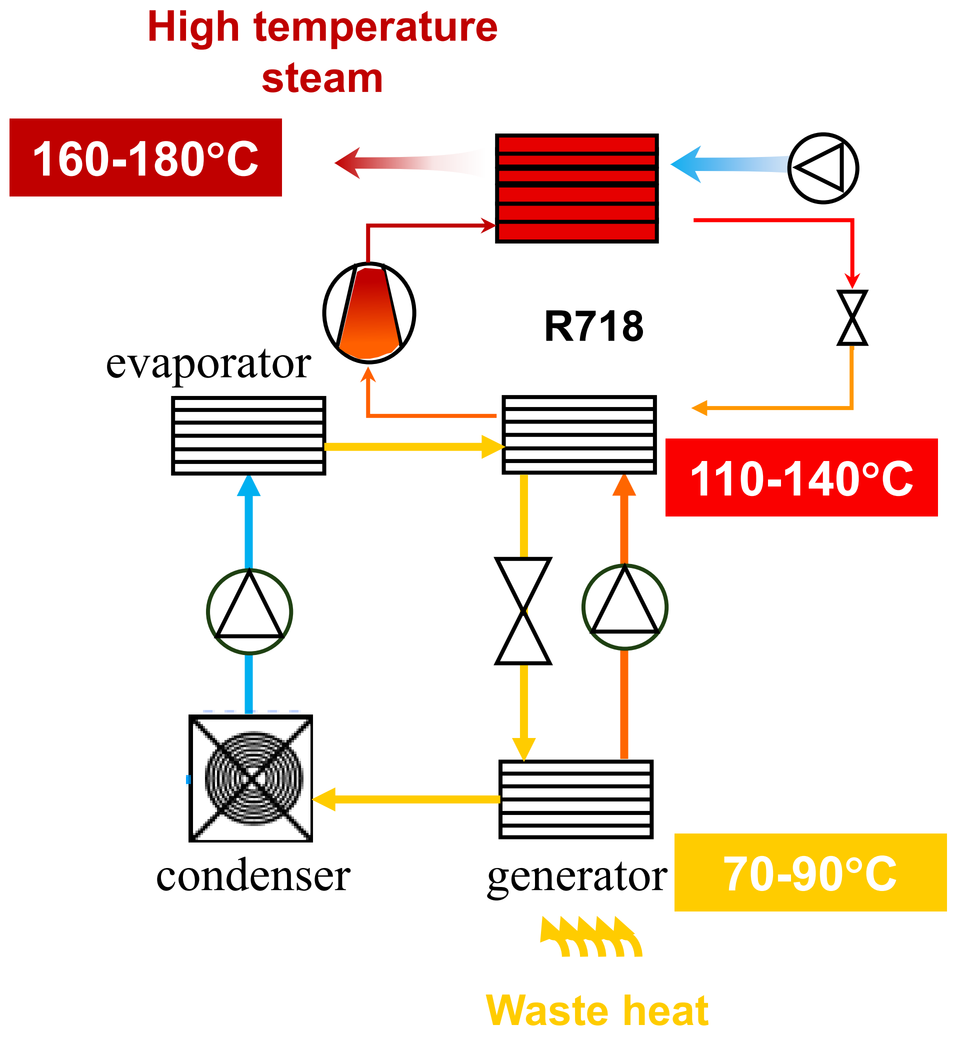
② Closed-cycle compression + Open-cycle compression

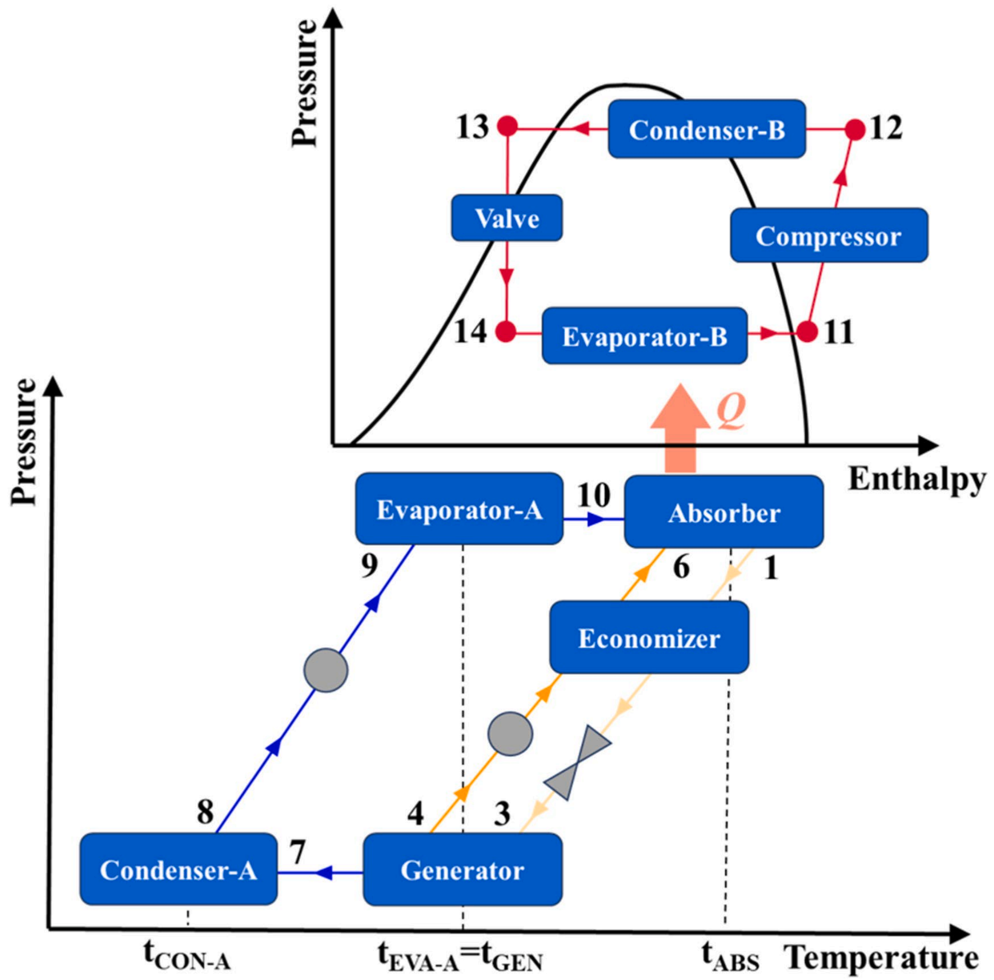


Steam generating HTHP

- ☐ From waste heat to high temperature steam

③ Absorption (Type Ⅱ) + Closed-cycle compression





Simulation results:
- Heat output up to 180°C
- Temperature lift up to 110°C
- COP from 2.5 to 3.0

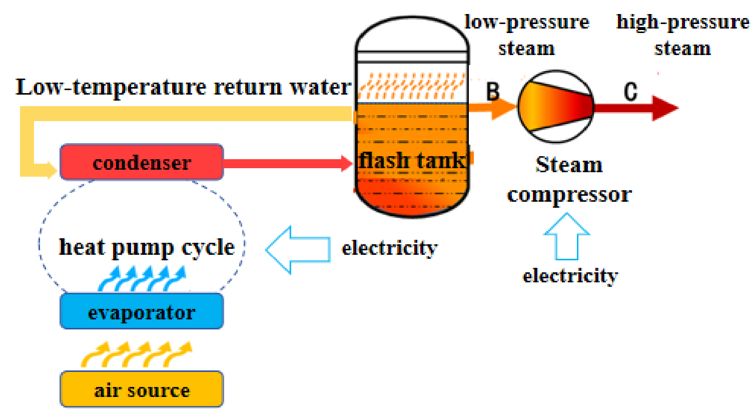
Application cases

Air source heat pump steam boiler in liquor processing

High-temperature steam heat pump

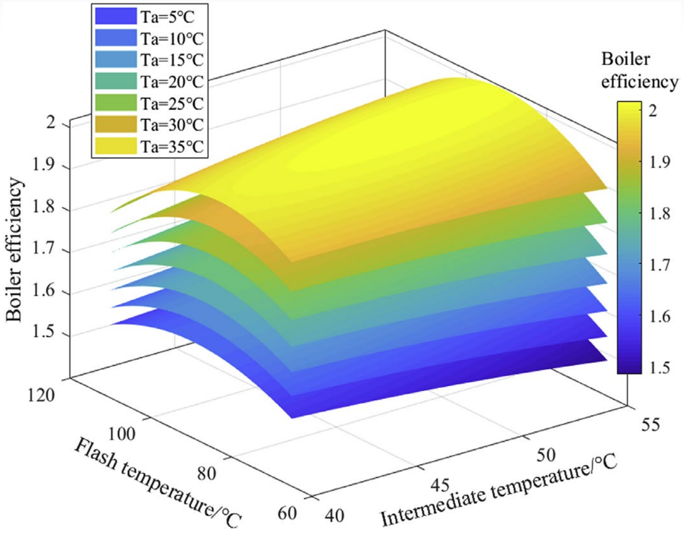
+

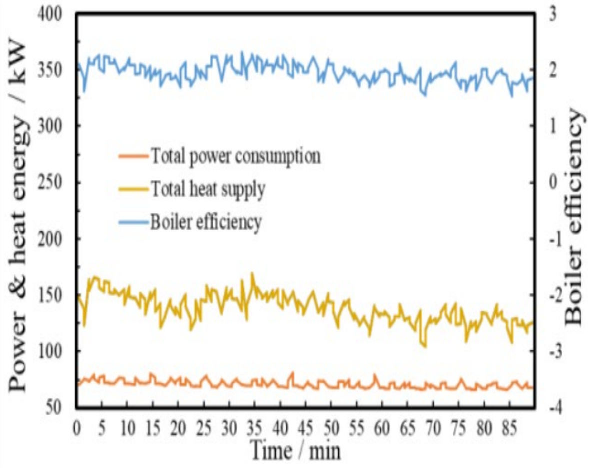
Air source heat pump



Steam open-cycle heat pump

Replacement coal boiler

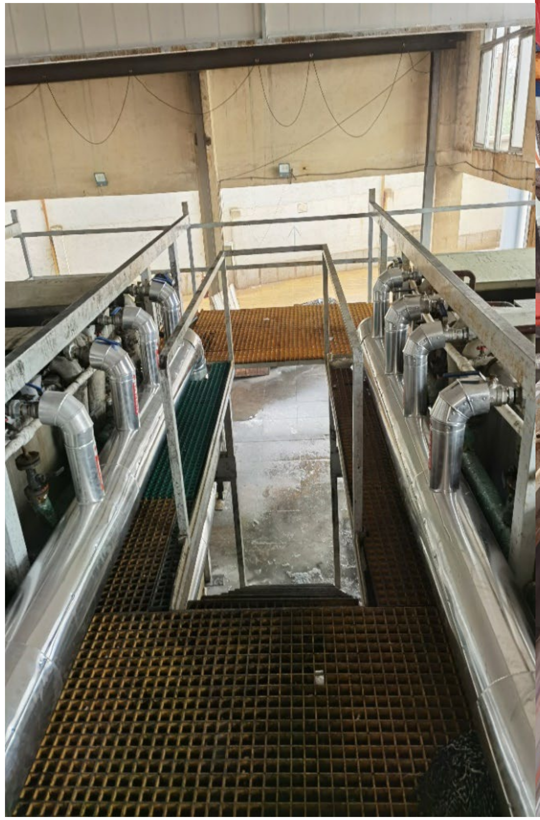


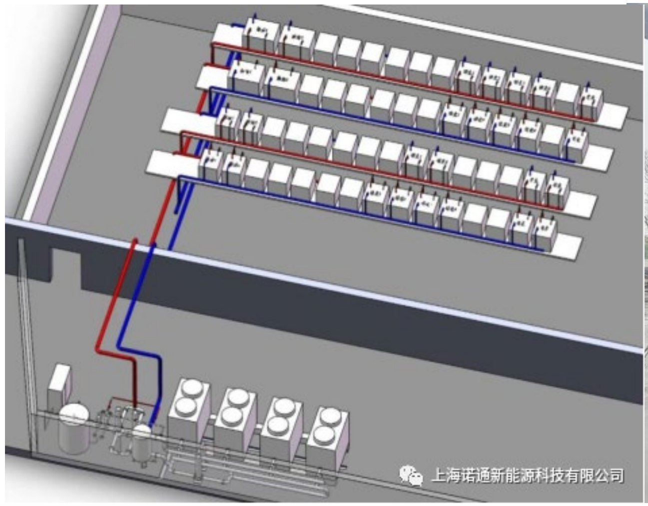


- Generate steadily **0.5 tons** of steam **per hour** (at **120°C** and **2 bar**).
- The **air** source temperature is **20°C**, the system's **COP** is **1.95**.

Application cases

Air source heat pump steam boiler in electroplating





The required insulation temperature is 80-85°C, and each production line requires 0.3 tons of steam per hour.

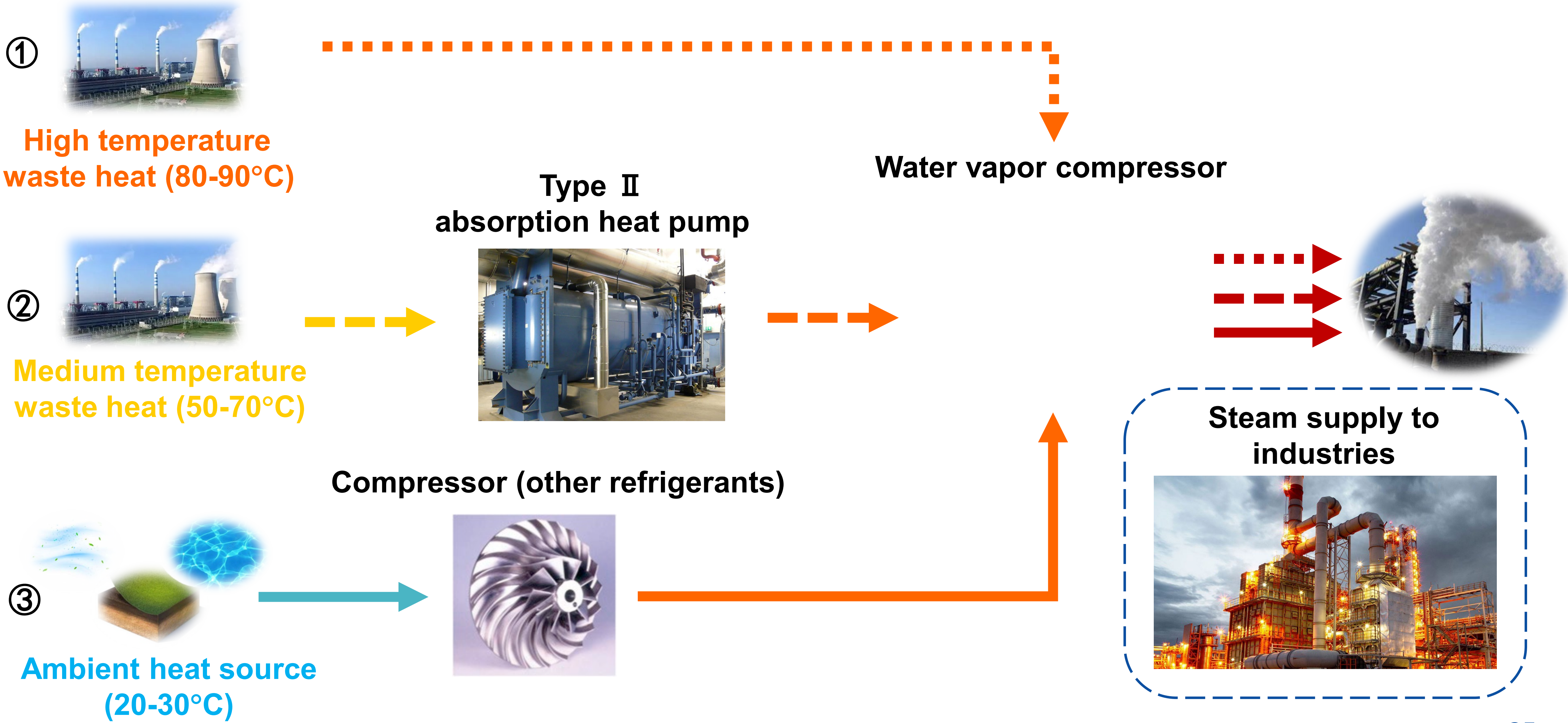
Original plan: 160°C gas steam boiler
Current plan: Air source heat pump
Operating effect:
- COP approximately at 1.8
- Daily energy consumption about 3050 kWh
- Daily cost is 2750 CNY
- Saving nearly 53% operating costs than original plan

04

Discussion

Water vapor compressor—Key to large scale and high temperature

Large scale steam generating heat pump



Water vapor compressor—Key to large scale and high temperature

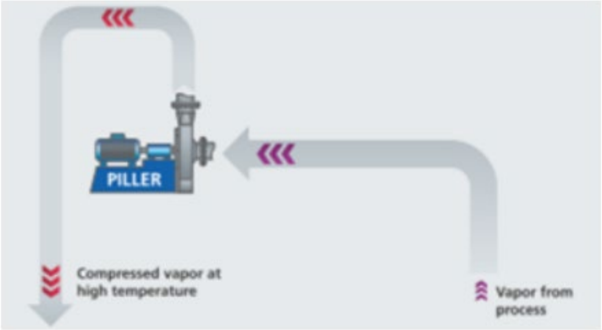
		Low-temperature	Mid-temperature	High-temperature		Very high-temperature
Heating temperature		<60 °C	60-100 °C	100-120 °C	120-160 °C	160-200 °C
Refrigerant		R290 R1270 R1234yf R717 R744	R717 R152a R161 R600a R1234ze(E)	R600 R1234ze(Z) R1224yd(Z)	R601 R1336mzz(Z) R1233zd(E) R718	R718
Compressor	<100 kW	Piston , Scroll				
	100 kW-1 MW	Piston , Screw , Centrifugal			Screw , Centrifugal	
	1-10 MW	Screw , Centrifugal			Centrifugal	

For high temperature output and large heating capacity ➡

Centrifugal water vapor compressor

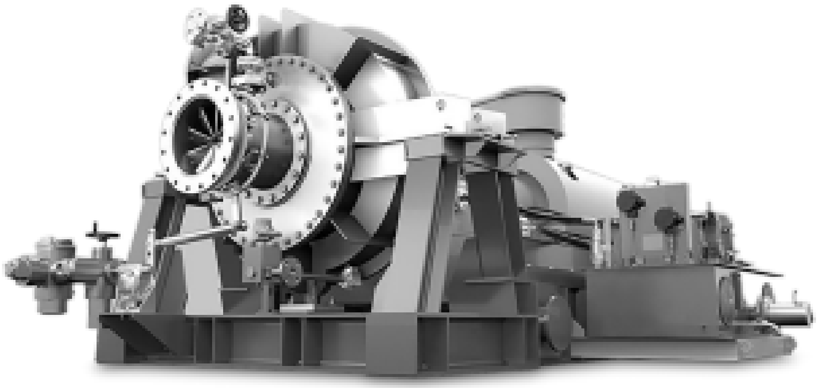
Water vapor compressor—Key to large scale and high temperature

Centrifugal water vapor compressor (mainly used for MVR)



$T_{source,in}$(°C)	$T_{source,out}$(°C)	$T_{sink,in}$(°C)	$T_{sink,out}$(°C)	$COP_{heating}$
92	64	80	130	4.38
95	-	95	131	7.27
100	86	80	159	3.50
53	-	100	100	4.56

Heat supply capacity: >1MW
Highest heating temperature: 212°C (20bar)



Skyven

$T_{source,in}$(°C)	$T_{source,out}$(°C)	$T_{sink,in}$(°C)	$T_{sink,out}$(°C)	$COP_{heating}$
30	20	99	148	2.64
65	45	99	148	3.51
75	55	99	207	2.67
75	55	99	148	3.83
90	65	99	190	6.58

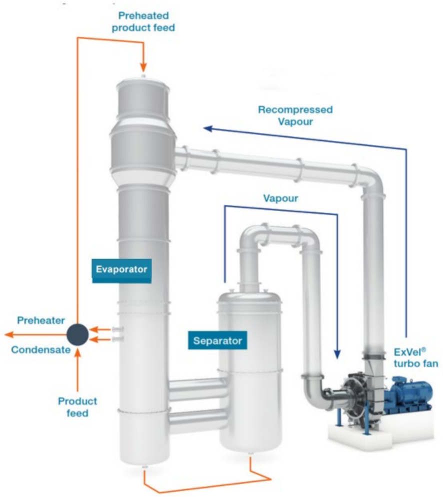
Heat supply capacity: <73MW
Highest heating temperature: 215°C

Water vapor compressor—Key to large scale and high temperature

Centrifugal water vapor compressor (mainly used for MVR)

Rotrex

Howden



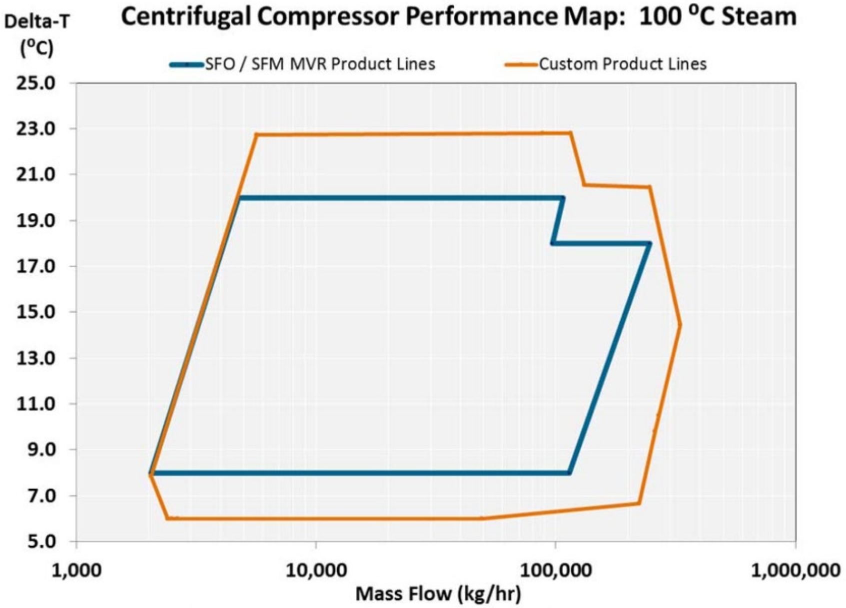


Chart depicts the potential performance from single stage equipment based on the properties of 100 °C (212 °F) saturated steam with 0.598 kg/m³ density (0.0373 lb/ft³).

In an industrial application:

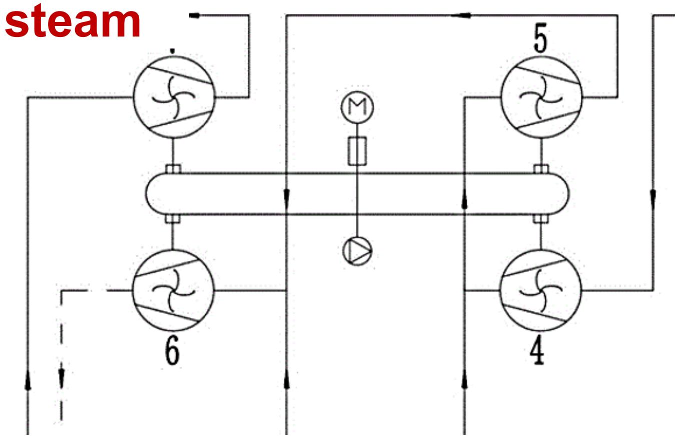
- Heat source: 100°C steam
- Heat sink: 125-146°C steam
- Heat supply capacity: 500 KW
- $COP_{heating:}$
  4.5 (T_{supply}=146°C, T_{source}=100°C)
  8.7 (T_{supply}: 125°C, T_{source}=100°C)

Water vapor compressor—Key to large scale and high temperature

Centrifugal water vapor compressor

Moon-Tech

steam



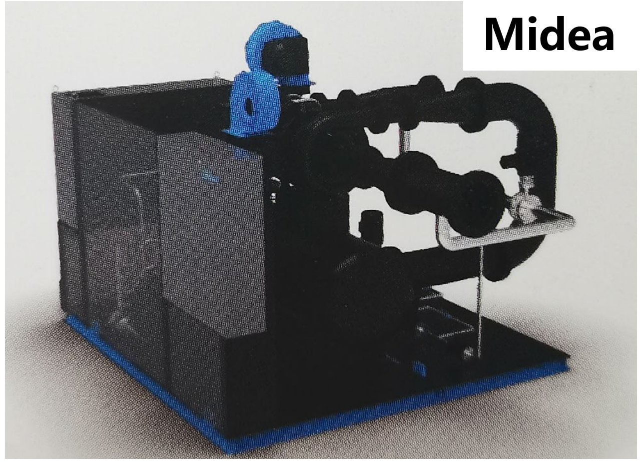
Technology:

- Four-stage compression and three-stage injection
- Constant pressure compensation and bidirectional multi-stage sealing

Effect:

- 60K and105K temperature lift for two- and four-stage compression
- 100-140°C steam output

Midea



Technology:

- Two-stage maglev compression
- Aviation grade pneumatic design
- Steam sealing

Effect:

- 30K-50K temperature lift
- Up to 200°C steam output
- Oil-free

References

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Thank you

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