Thermodynamic Analysis on High Temperature Heat Pump cycles using Low-GWP refrigerants for Heat recovery

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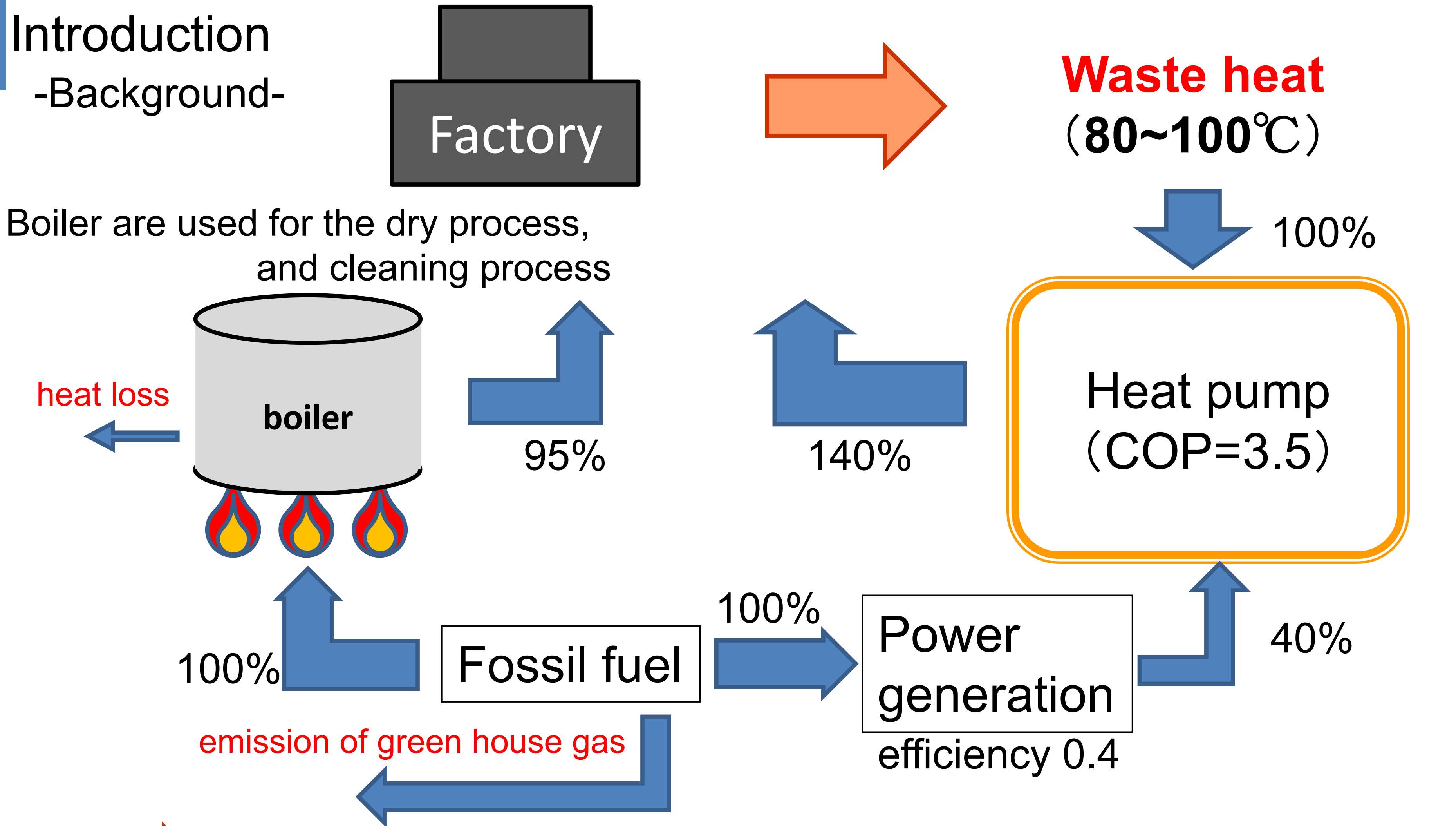
Introduction
-Background-



The development of high temperature heat pump systems for heat recovery from industrial waste heat below 100 °C is important.

Introduction

-Background-

・Refrigerants used in heat pump ⇨ **High global warming potential**

In the past few years

		GWP	
Currently	R245fa	858	similar thermodynamic properties
Alternative	R1234ze(Z), R1233zd(E)	< 1	

-Objective-

Candidate low-GWP refrigerants with different levels of critical temperature are selected, and two different cycle configurations are proposed for a case study.

Calculated refrigerants

The characteristics and properties of the selected refrigerants for industrial high-temperature heat pumps.

	GWP_{100}*	Critical Pressure	Critical temp.	NBP**	Latent heat***	Density***	
		[MPa]	[°C]	[°C]	[kJ·kg-1]	[kg·m-3]	
						Liquid	Vapor
R1234ze(Z)	<1	3.53	150.1	9.7	144.12	982.3	69.39
R1233zd(E)	<1	3.62	166.5	18.3	142.25	1049.7	56.26
R365mfc	794	3.27	186.9	40.2	154.04	1075.5	33.20

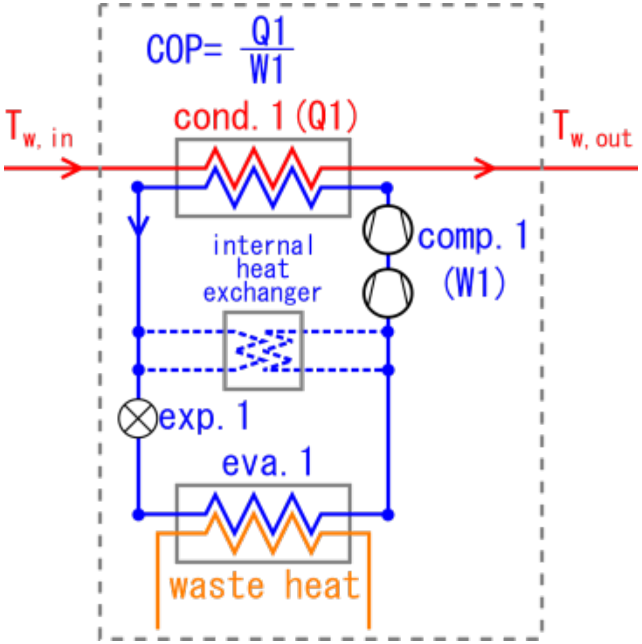
*IPCC 5th report **Normal boiling point ***at bulk temperature 100 ° C

・R1234ze(Z) ≒ R245fa ・R365mfc ≒ HFE refrigerants

NOT correct physical property

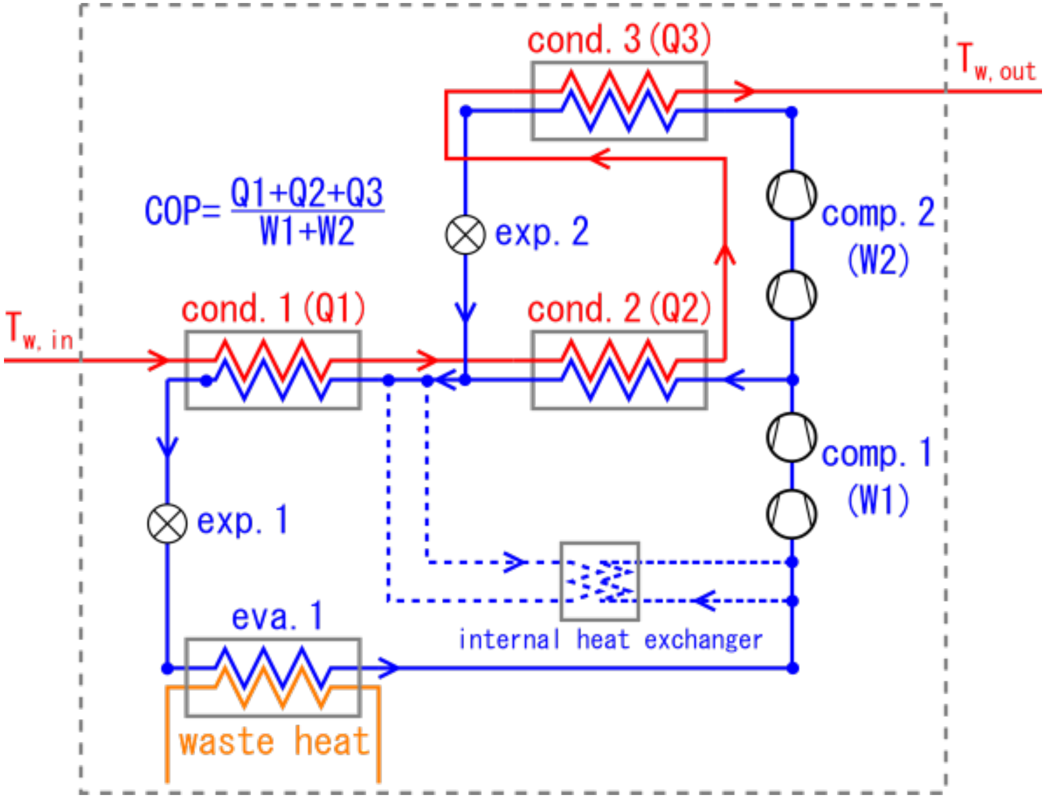
Calculated heat pump cycle

Single-stage compressed cycle



Base cycle

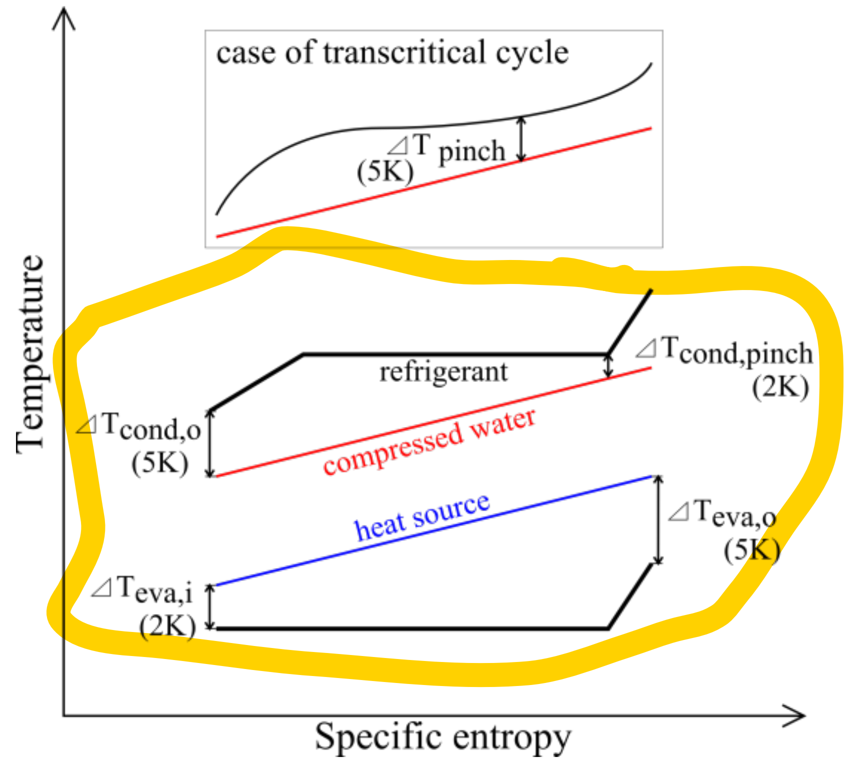
Two-stage compressed extraction cycle



extraction process to extract the vapor from the compressor.

Calculation condition

Temperature of waste heat		80	°C
Compressed water	inlet temperature (after pre-heating)	70	°C
	outlet temperature	160	°C
Heat source fluid (waste heat)	inlet temperature	80	°C
	outlet temperature	70	°C
Compressed water mass flow rate		0.2	kg/s

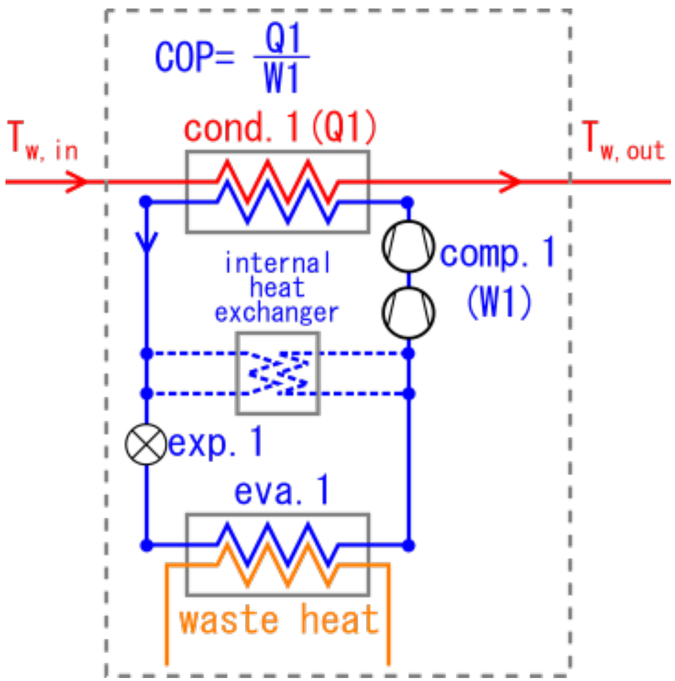


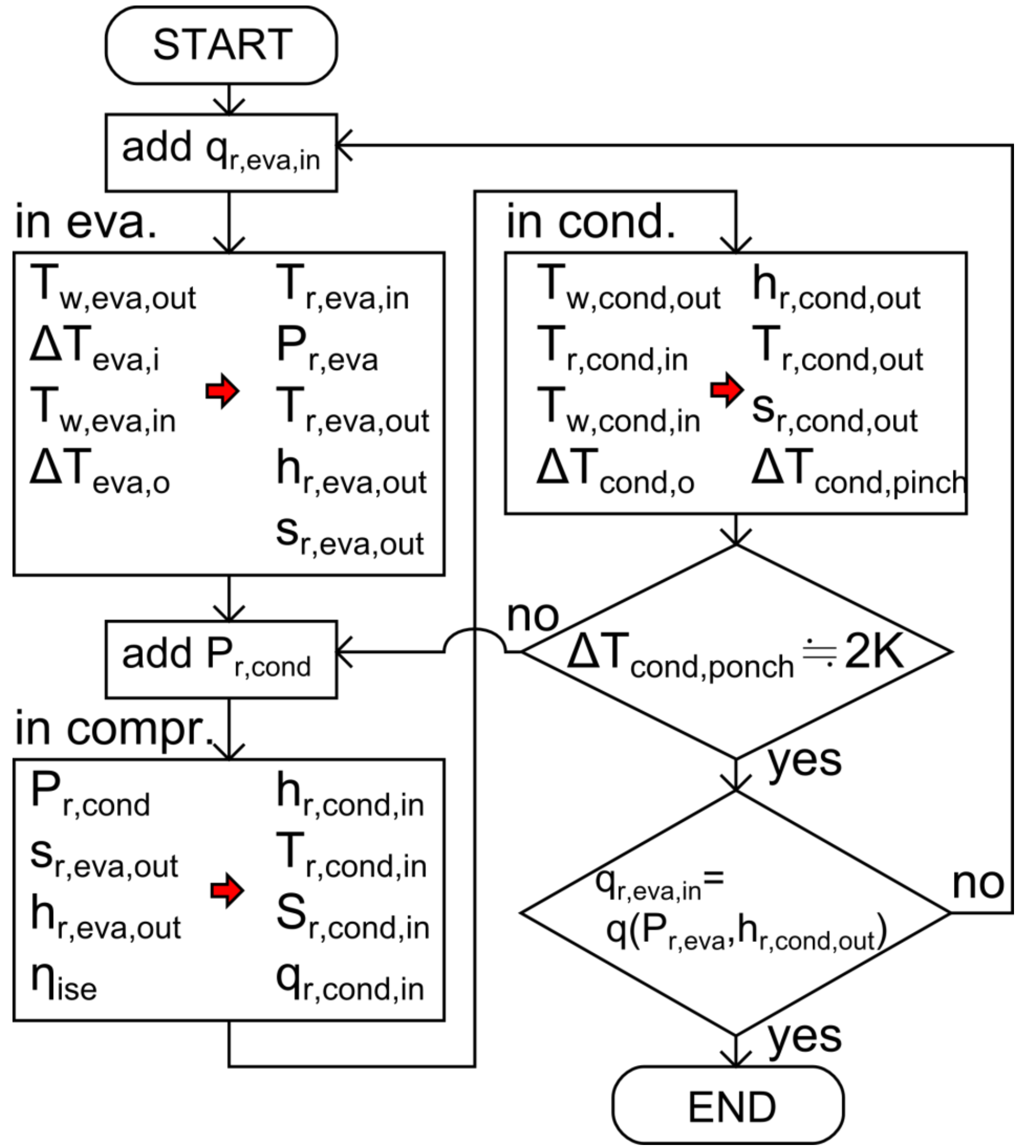
Model of the temperature distribution on the T-s diagram

Single phase = 5 K
Two phase = 2 K

Calculation method

-Single-stage compressed cycle-



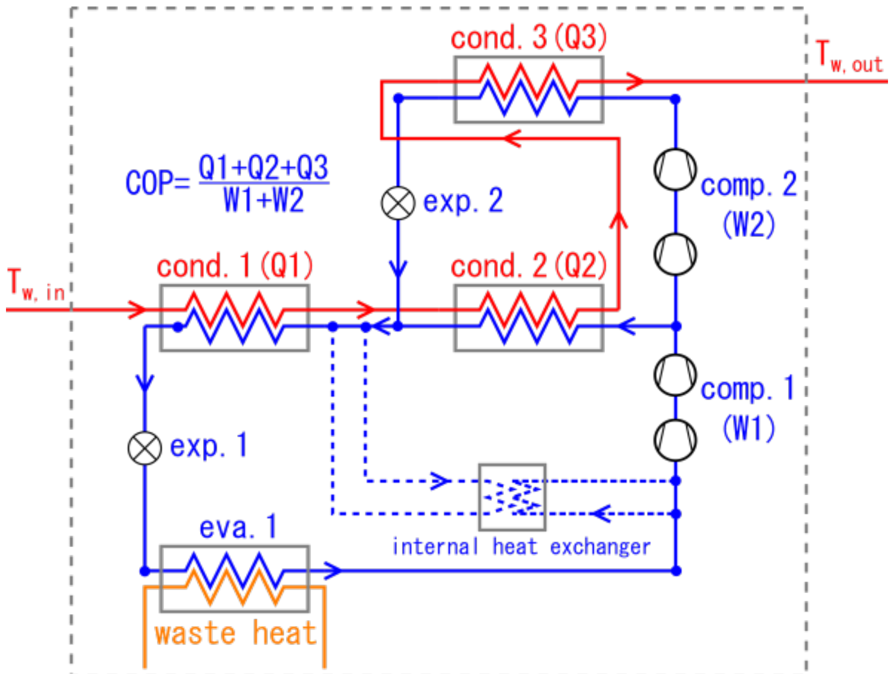


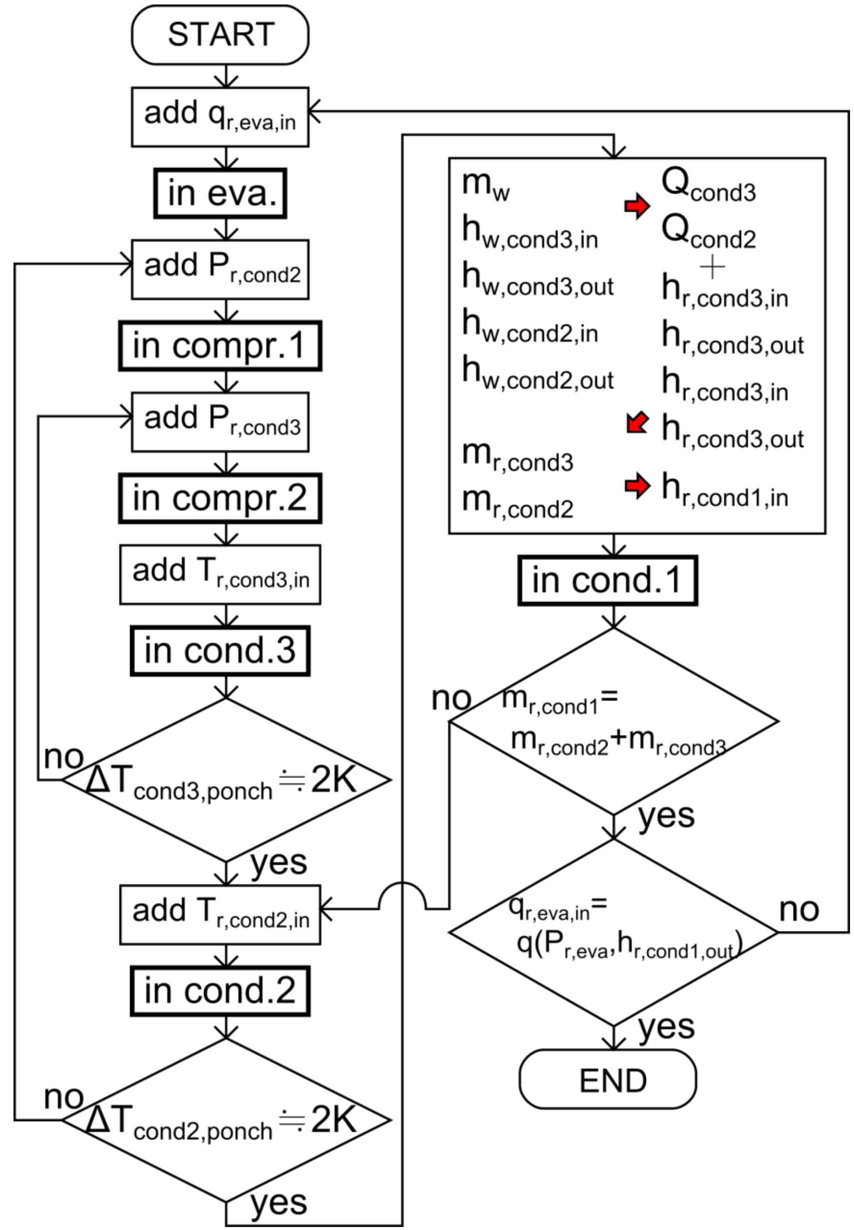
Compressor efficiency

Isentropic(η_{ise})	0.85
Mechanical	0.90
Motor	0.90

Calculation method

-Two-stage compressed extraction cycle-





Compressor efficiency

Isentropic(η_{ise})	0.85
Mechanical	0.90
Motor	0.90

Data reduction

The COPs are defined as,

$$COP = \frac{Q_1}{W_1}$$ -Single-stage compressed cycle-

$$COP = \frac{Q_1 + Q_2 + Q_3}{W_1 + W_2}$$ -Two-stage compressed extraction cycle-

Total irreversible loss in W is,

$$L_{\text{total}} = L_{\text{COND}} + L_{\text{EVA}} + L_{\text{EXP}} + L_{\text{COMPR}}$$

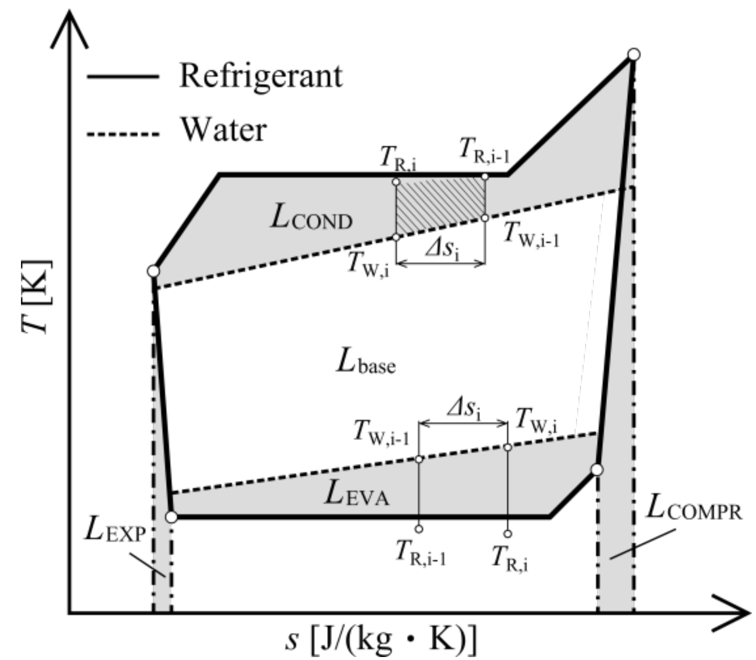
Specific irreversible losses in J・kg^{-1} are expressed as,

$$L_{\text{COND}} = m_{\text{ref}} \times \sum_{n} \left[\left(T_{\text{R,i}} - T_{\text{W,i}} \right) + \left(T_{\text{R,i-1}} - T_{\text{W,i-1}} \right) \right] \Delta s_{\text{i}} \Big/ 2$$

$$L_{\text{EVA}} = m_{\text{ref}} \times \sum_{n} \left[\left(T_{\text{W,i}} - T_{\text{R,i}} \right) + \left(T_{\text{W,i-1}} - T_{\text{R,i-1}} \right) \right] \Delta s_{\text{i}} \Big/ 2$$

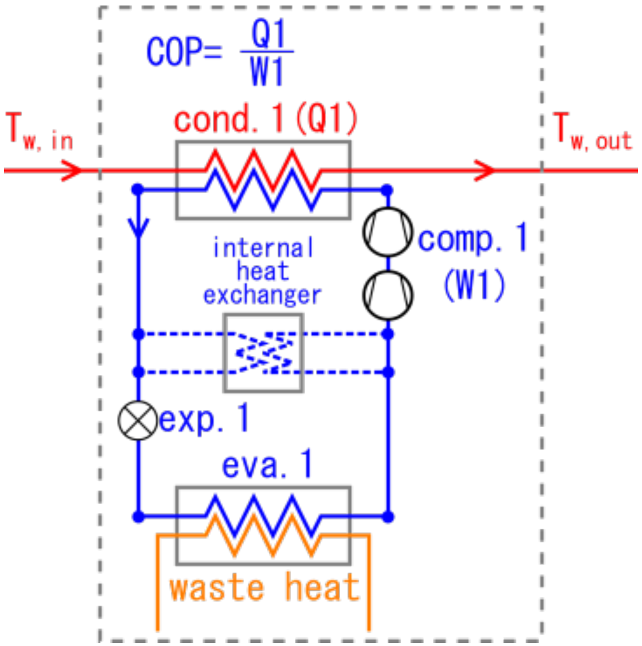
$$L_{\text{EXP}} = \int_{s_{\text{EXP,in}}}^{s_{\text{EXP,out}}} T_{\text{R}} \, ds$$

$$L_{\text{COMPR}} = \int_{s_{\text{COMPR,in}}}^{s_{\text{COMPR,out}}} T_{\text{R}} \, ds$$



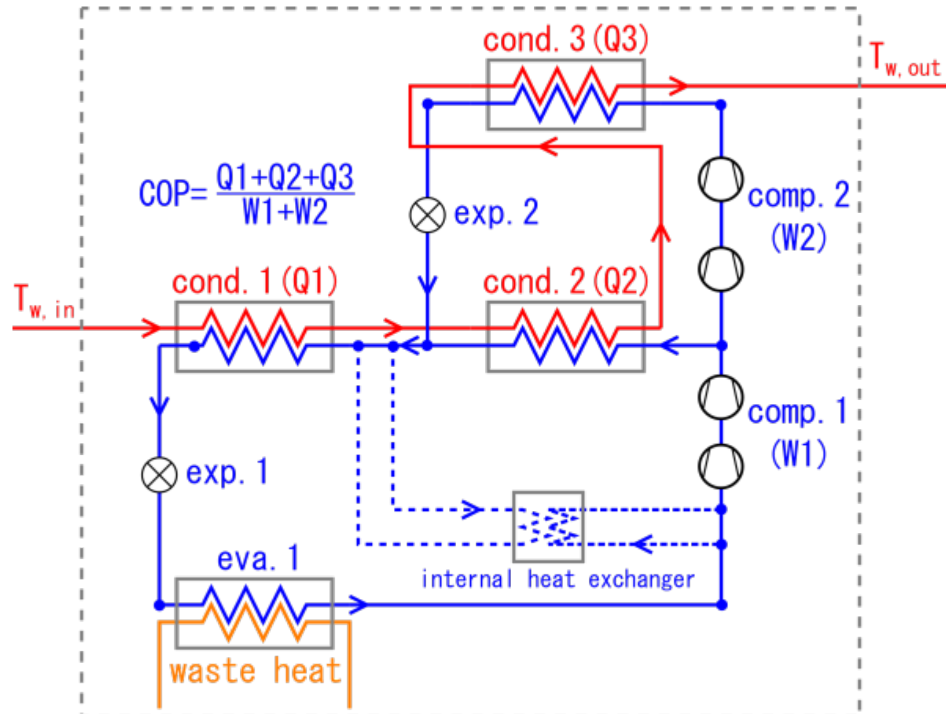
Results -COP-

-Single-stage compressed cycle-



Refrigerant	COP	*Pd/Ps*
R1234ze(Z)	4.24	5.94(2.44)
R1233zd(E)	4.18	6.36(2.52)
R365mfc	3.68	8.30(2.88)

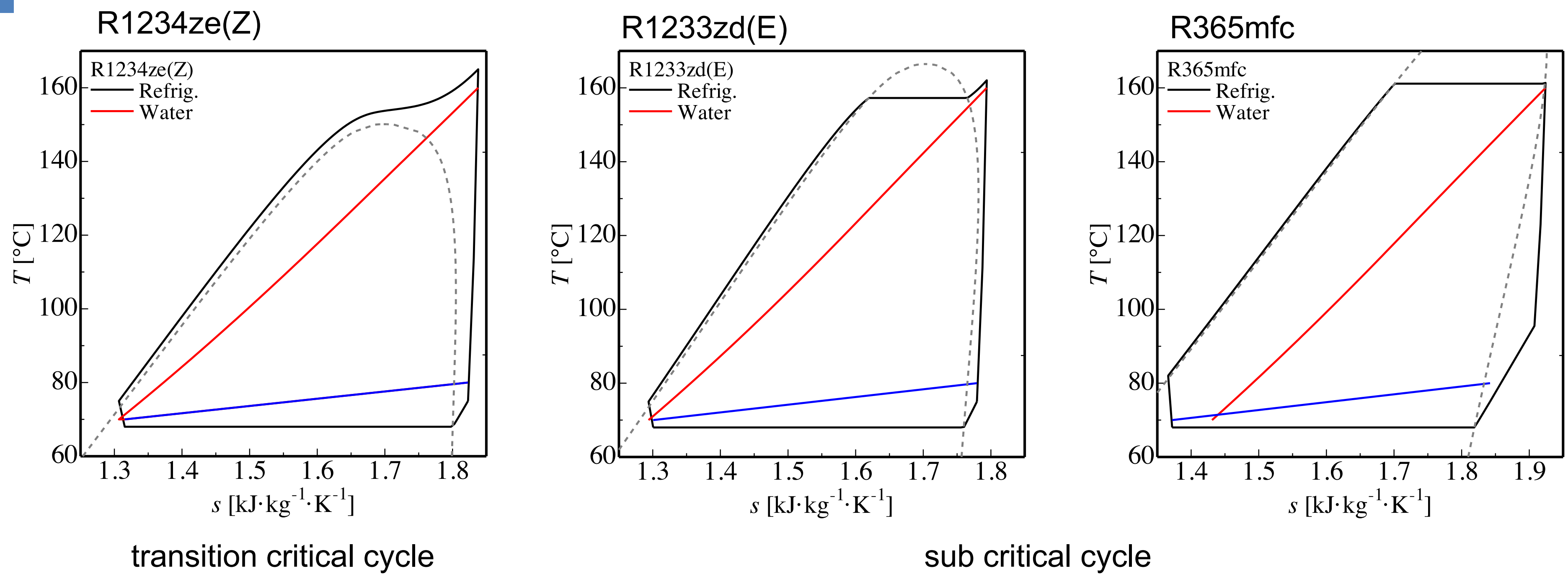
-Two-stage compressed extraction cycle-



COP	*Pd/Ps1*	*Pd/Ps2*
4.58	2.65(1.63)	2.26(1.50)
4.55	2.74(1.65)	2.35(1.53)
4.44	2.59(1.61)	3.21(1.79)

⇒ R1234ze(Z) is appropriate in this calculation condition

Results - irreversible loss (single-stage compressed cycle) -

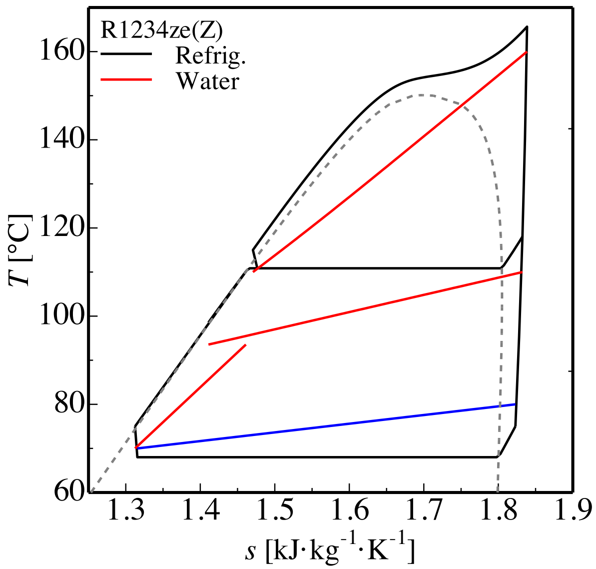


		L [kW]			
Refrigerant	**COND**	**EVA**	**EXP**	**COMPR**	**TOTAL**
R1234ze(Z)	3.10	1.24	1.06	2.07	7.48
R1233zd(E)	3.47	1.24	0.90	2.11	7.71
R365mfc	5.48	1.19	0.75	2.43	9.85

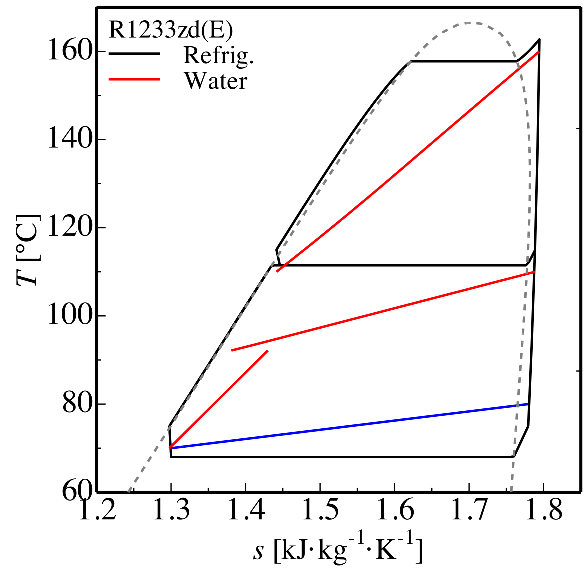
The value difference of irreversible loss in condenser between R1234ze(Z) and R365mfc are large.

Results - irreversible loss (two-stage compressed extraction cycle) -

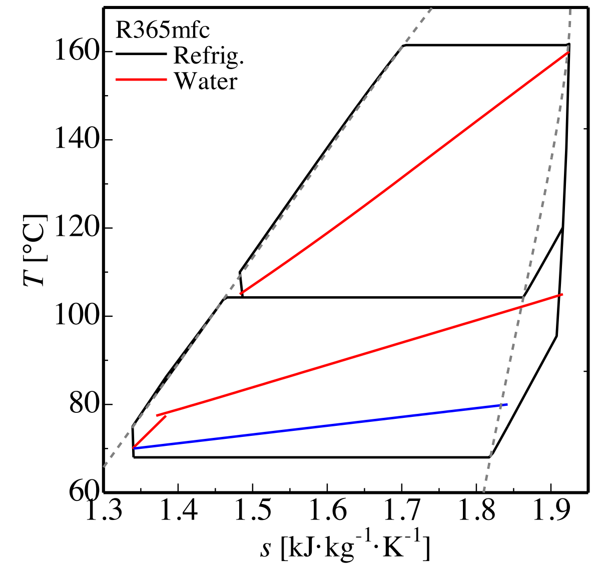
R1234ze(Z)



R1233zd(E)



R365mfc



transition critical cycle

Sub critical cycle

			L [kW]		
Refrigerant	**COND**	**EVA**	**EXP**	**COMPR**	**TOTAL**
R1234ze(Z)	2.03	1.26	1.02	1.97	6.28
R1233zd(E)	2.29	1.26	0.84	1.99	6.37
R365mfc	2.73	1.25	0.53	2.05	6.55

Refrigerant	**COND**	**EVA**	**EXP**	**COMPR**	**TOTAL**
R1234ze(Z)	3.10	1.24	1.06	2.07	7.48
R1233zd(E)	3.47	1.24	0.90	2.11	7.71
R365mfc	5.48	1.19	0.75	2.43	9.85

Conclusion

The cycle performances and irreversible loss of three refrigerants, R1234ze(Z), R1233zd(E) and R365mfc, were thermodynamically analyzed by using heat recovery systems. The following conclusions are drawn from the results:

(1) In both the single-stage compressed cycle and two-stage compressed extraction cycle,

COP : R1234ze(Z) > R1233zd(E) > R365mfc

(2) In single-stage compressed cycle,

All irreversible loss of R1234ze(Z) is lowest

⇒ irreversible loss in condenser is the lowest specifically.

(3) In two-stage compressed extraction cycle,

The tendency of each irreversible loss by the difference in refrigerant

two-stage = single-stage

Each irreversible loss expect for evaporator

two-stage < single-stage

Thank you for your attentions