An Optimisation of Very HTHP Systems for Industrial Applications with Low-GWP Refrigerants.

by: Adam Sulaiman

Prof. Neil Hewitt

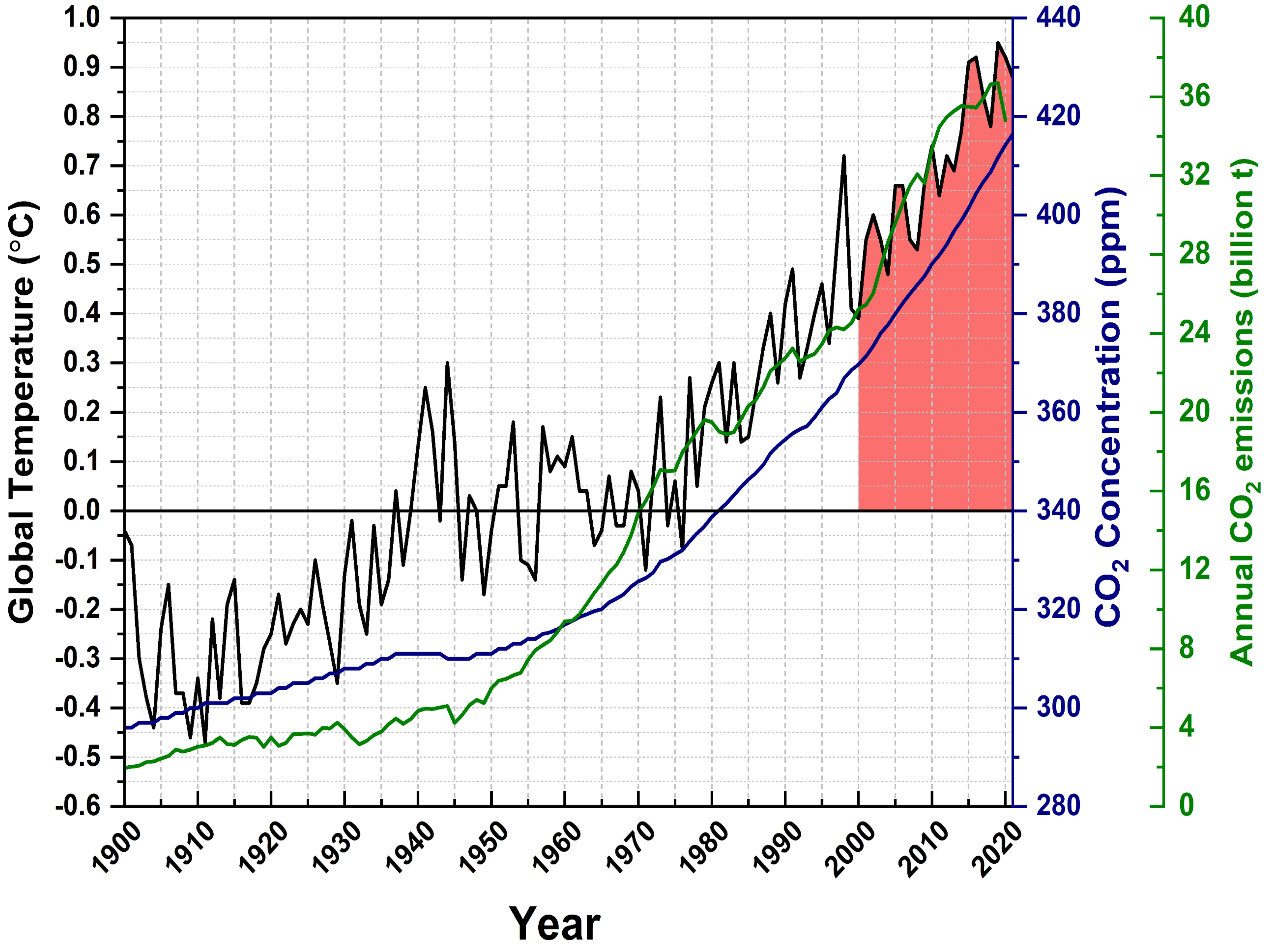
Center For Sustainable Technologies(CST),

School Of Build Environment,

Ulster University

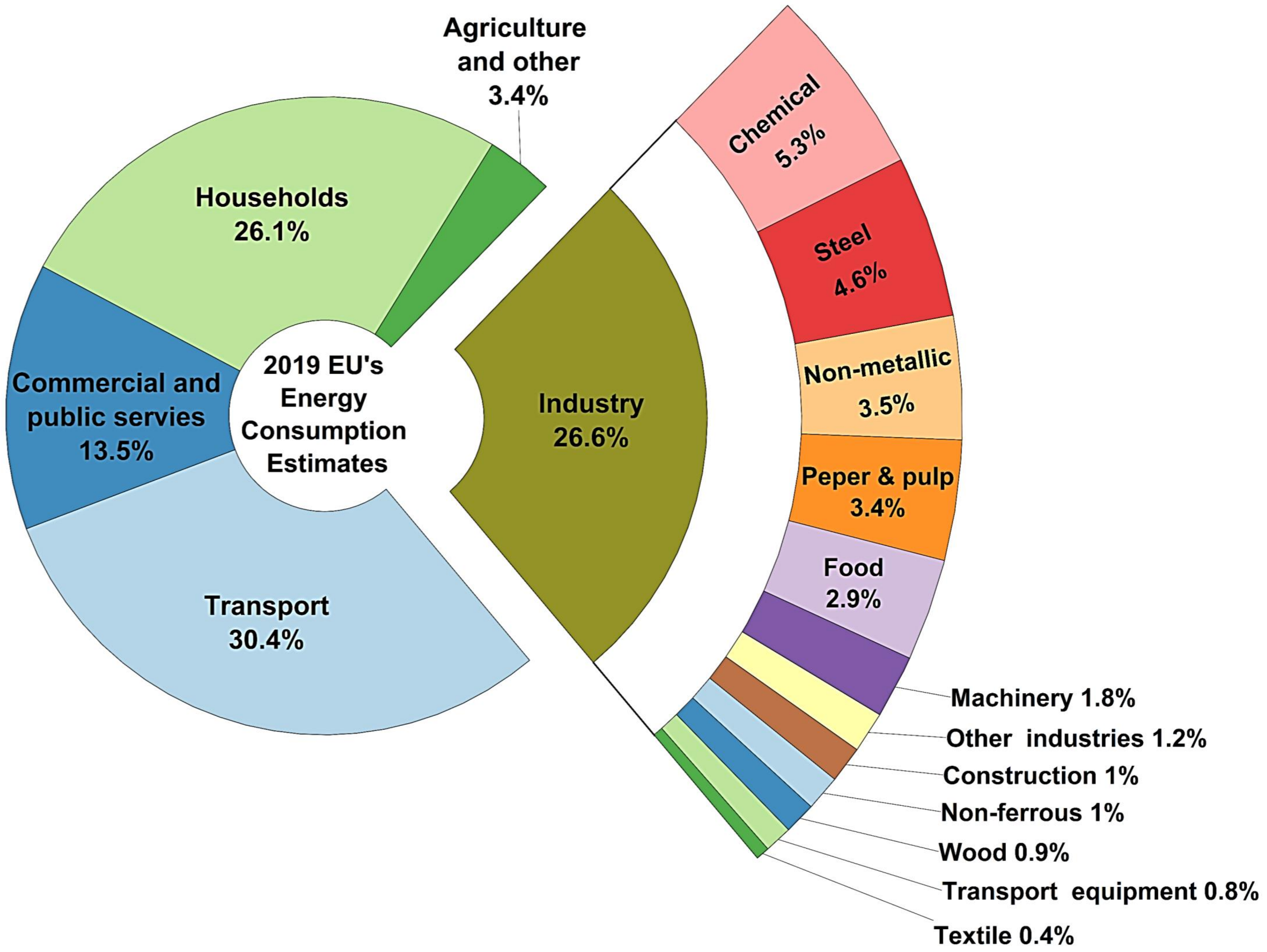
Global Environmental Situation

- Global temperature climbed by 0.5 °C
- CO_2 concentrations have risen by 45 ppm
- CO_2 emissions have surged by 10 billion tonnes
- The global temperature is projected to climb by 1.5 °C between 2030 and 2052
- UK and the EU have set a goal of reaching net zero emissions by 2050.



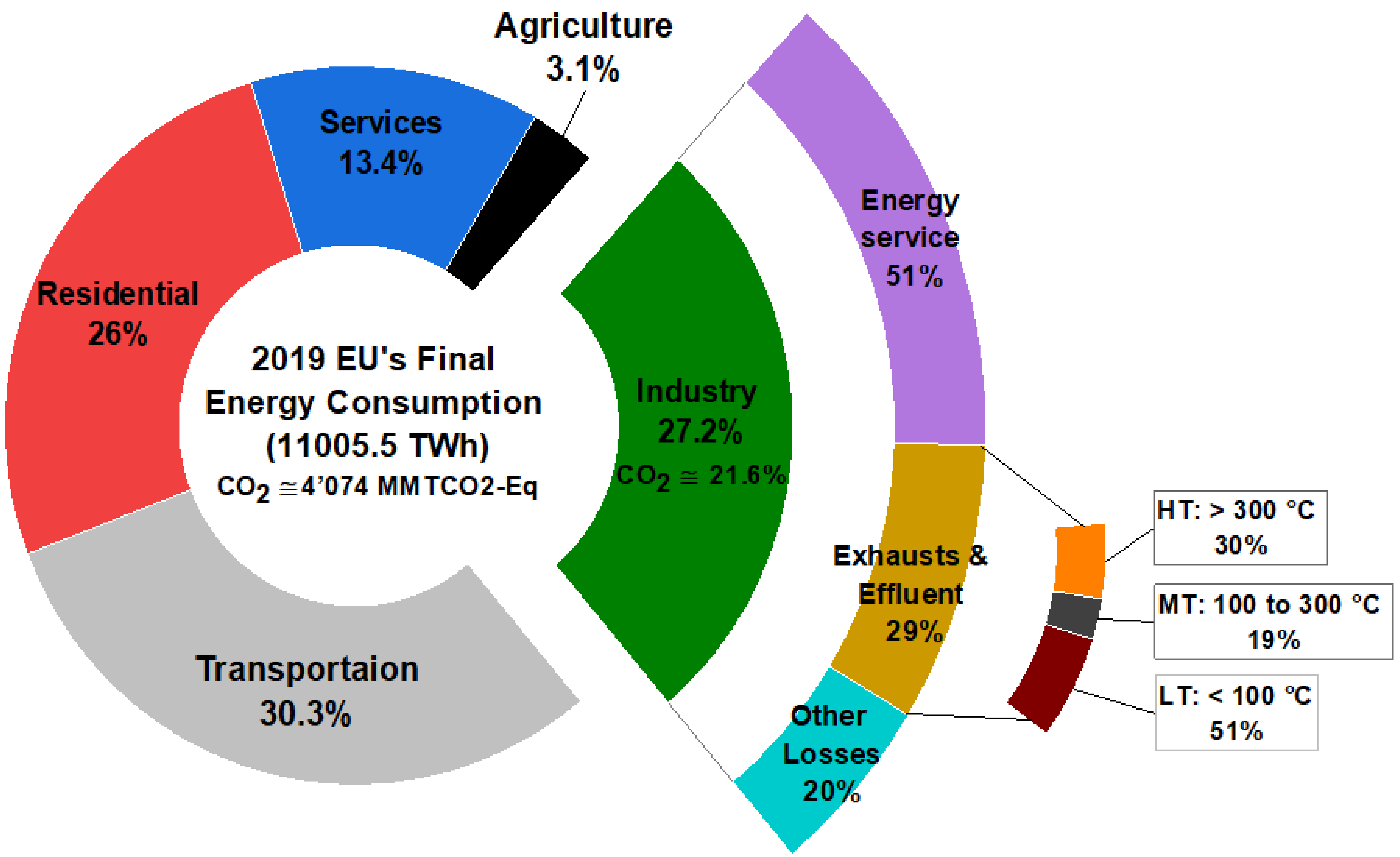
EU's Energy Consumption Per Sector

- The industrial sector consumes roughly 2784.4 Terawatt hours per year
- Five industrial sectors account for approximately 70%
- 15-20% of the industrial sector's overall heat consumption require steam between 100 and 200 °C.



Waste-heat Opportunity in Europe

- 72% of the world's primary energy supply is dissipated throughout the conversion process.
- 29.8% of industrial consumption was converted to anergy in the form of exhaust or effluents.
- Over 4.1% of the EU's total energy consumption is released to the atmosphere through LT waste heat.

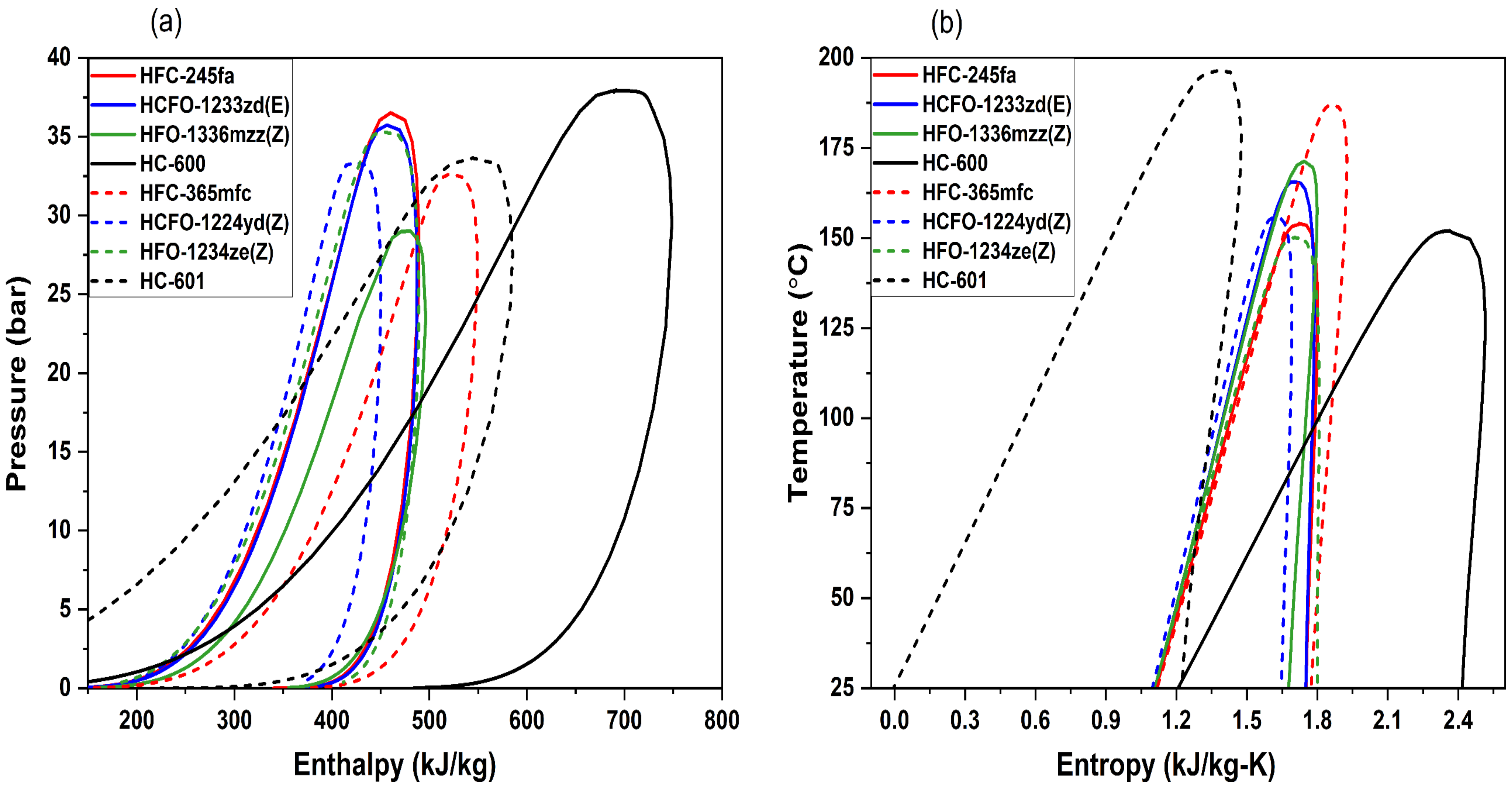


The Properties of Selected Refrigerants

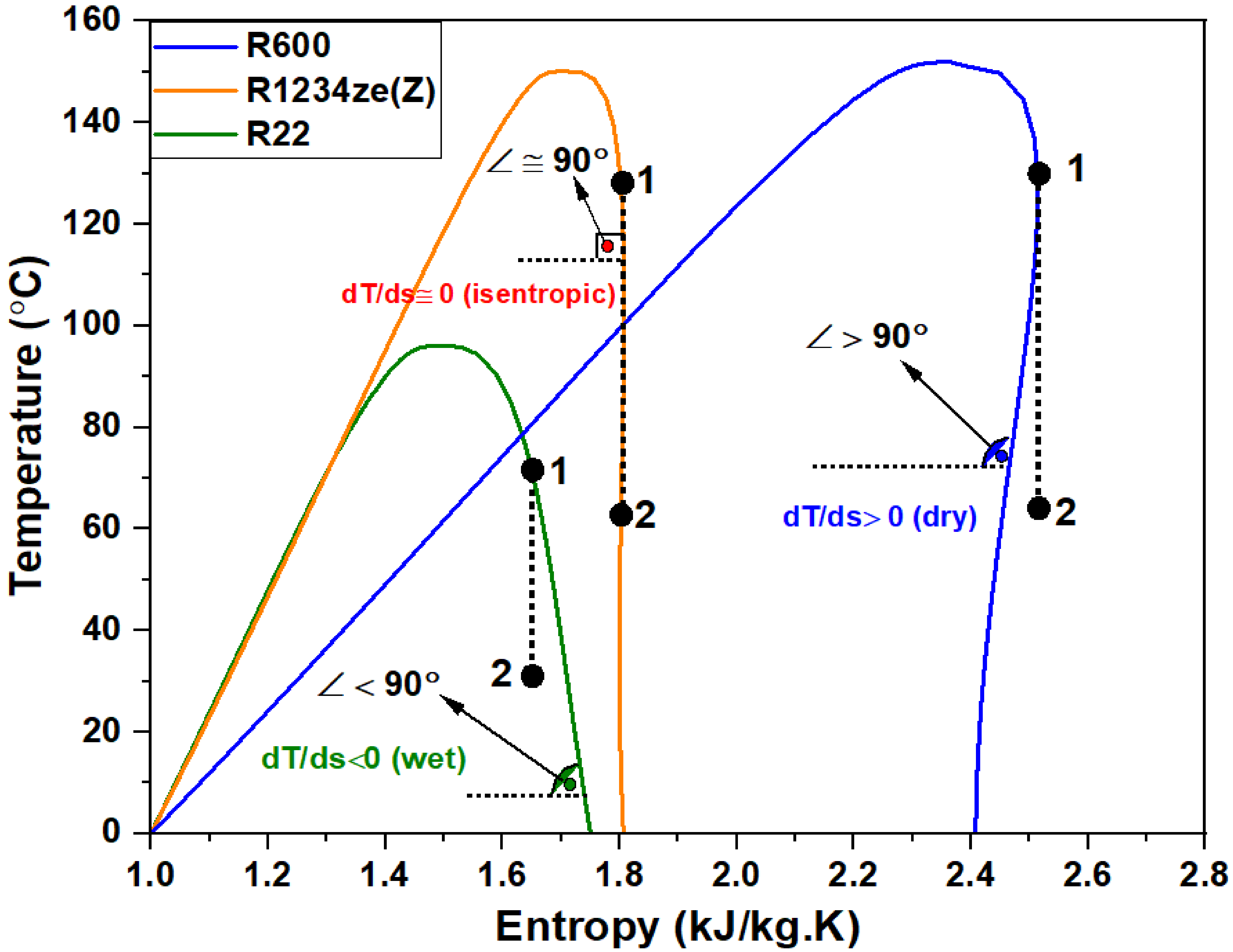
Type	Refrigerant (ASHRAE)	Composition	ODP	GWP_{100yrs}	T_{crit} [°C]	P_{crit} [bar]	Cp/Cv	NBP	SG
HC	R600	C_4H_{10}	0	4	152.01	37.96	1.105	0.0	A3
HC	R601	C_5H_{12}	0	5	196.56	33.58	1.336	36.1	A3
HCFO	R1224yd(Z)	C_3HF_4CI	0.00023	1	156.00	33.30	1.098	14.0	A1
HCFO	R1233zd(E)	$C_3H_2CIF_3$	0.00034	1	166.50	36.20	1.104	18.0	A1
HFC	R245fa	$C_3H_3F_5$	0	1030	154.05	36.40	1.101	15.0	B1
HFC	R365mfc	$C_4H_5F_5$	0	794	186.85	32.66	1.331	40.0	A2
HFO	R1234ze(Z)	$C_3F_4H_2$	0	<10	150.10	35.30	1.119	9.8	A2L
HFO	R1336mzz(Z)	$C_4H_2F_6$	0	2	171.30	29.00	1.001	33.4	A1

Refrigerants Under Consideration

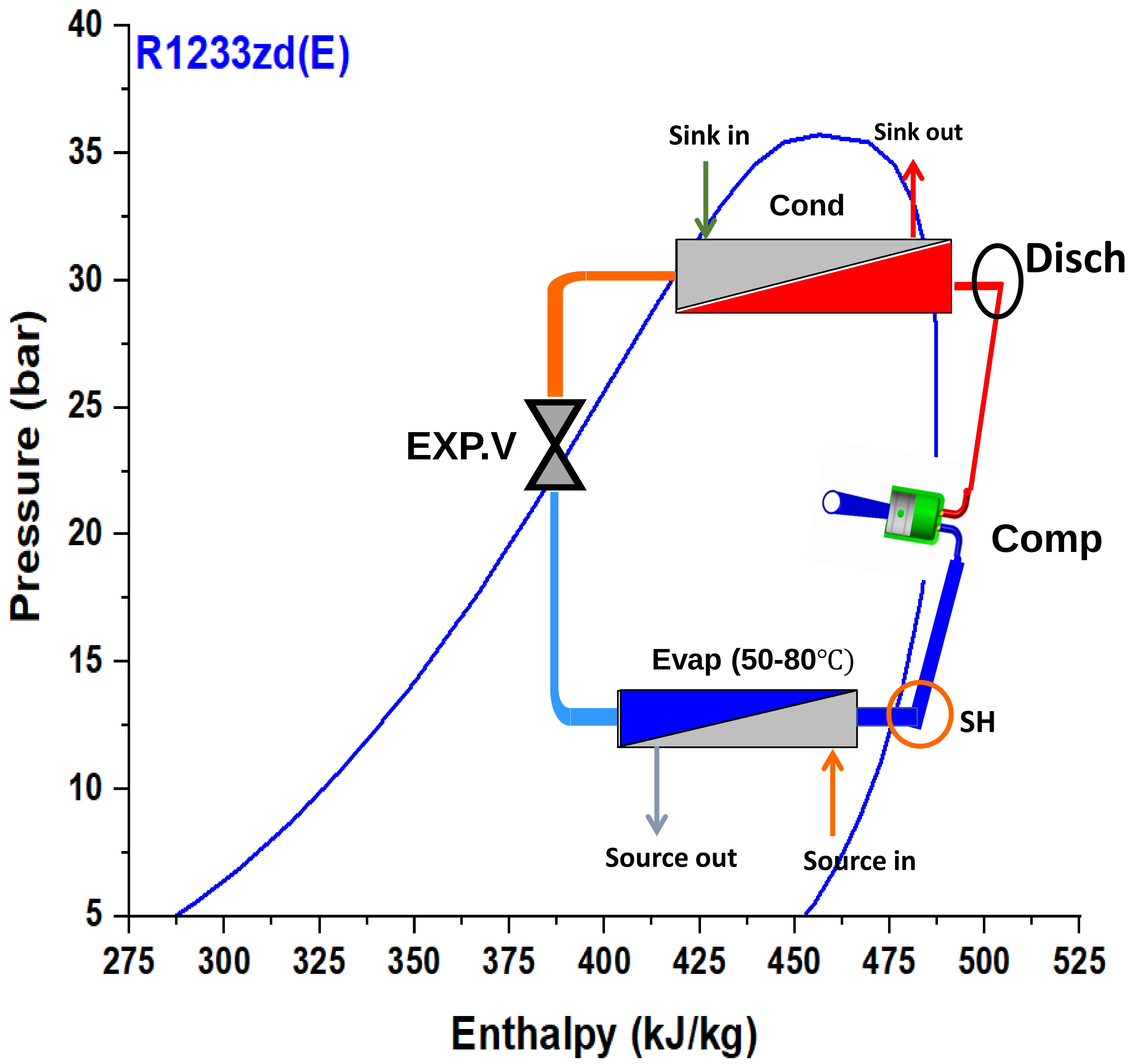
- R1233zd(E)
- R245fa
- R1336mzz(Z)
- R365mfc
- R1224yd(Z)
- R1234ze(Z)
- R600
- R601



HTHP Tech



R600
R1234ze(Z)
R22
∠≅ 90°
dT/ds≅ 0 (isentropic)
∠ > 90°
dT/ds> 0 (dry)
∠ < 90°
dT/ds<0 (wet)
1
2
Temperature (°C)
Entropy (kJ/kg.K)
160
140
120
100
80
60
40
20
0
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
2.6
2.8



R1233zd(E)
Sink in
Sink out
Cond
Disch
EXP.V
Comp
Evap (50-80℃)
SH
Source out
Source in
Pressure (bar)
Enthalpy (kJ/kg)
40
35
30
25
20
15
10
5
275
300
325
350
375
400
425
450
475
500
525

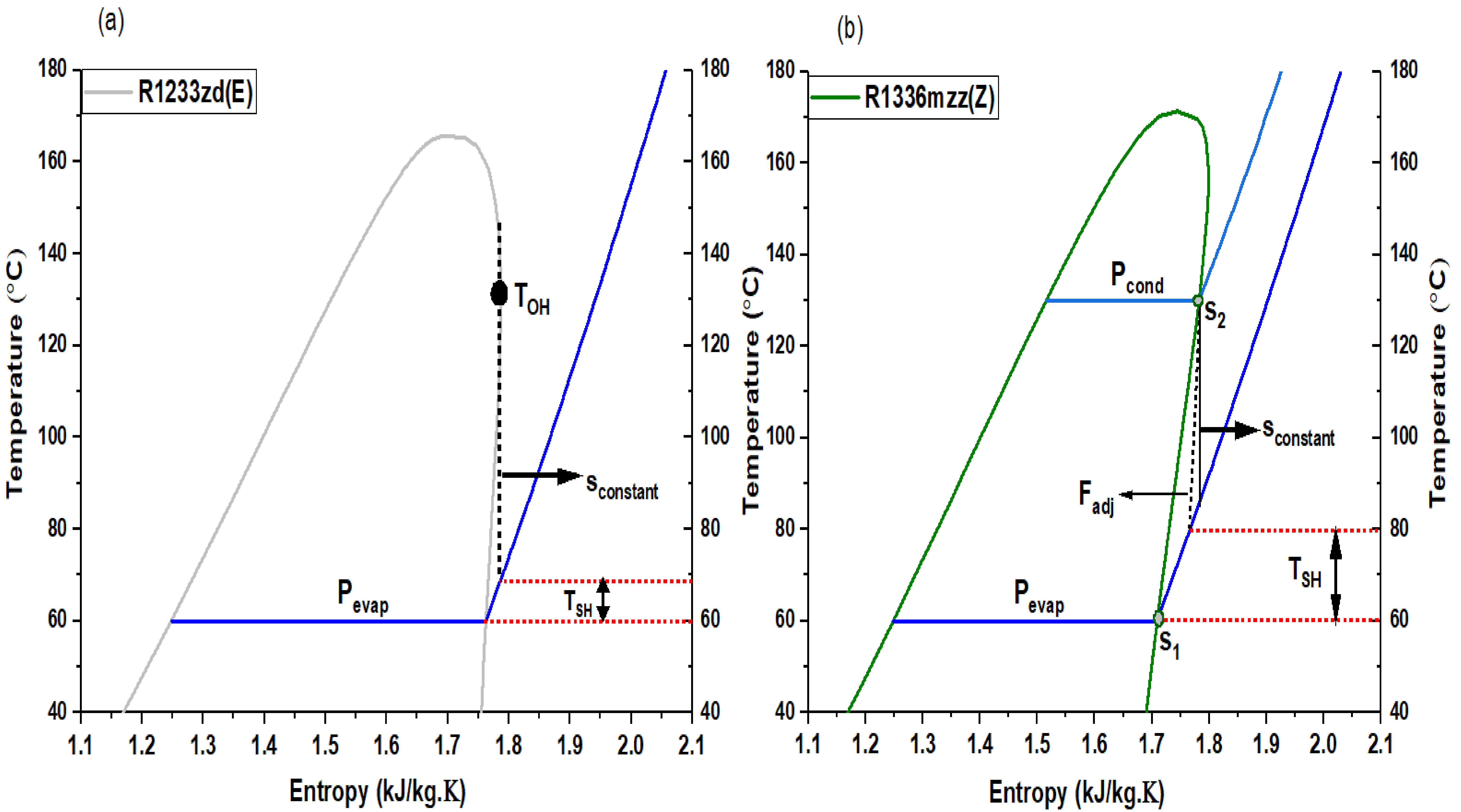
Computing the Minimum Degree of Superheat

R245fa & R1233zd(E)

- $s_1 = f(T = 400K, x = 1)$
- $T_1 = f(s_1, P_{evap})$

R1336mzz(Z) & R365mfc

- $s_{suc} = [(s_{sat,cond} - s_{sat,evap}) \times F_{adj}] + s_{sat,evap}$
- $T_{suc} = f(s_{suc}, P_{evap})$
- $T_{min,sup} = T_{suc} - T_{evap}$

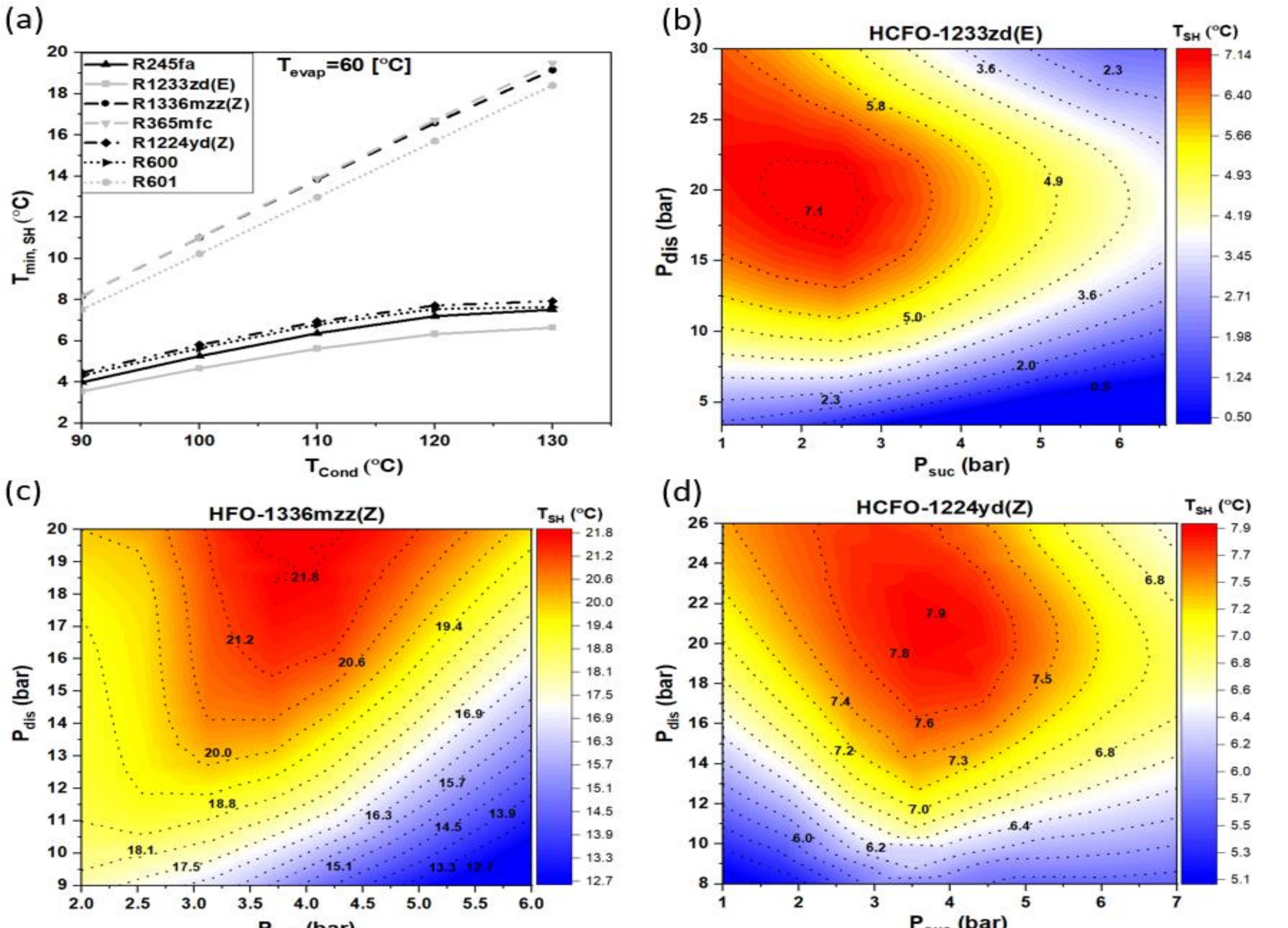


Mapping the Minimum Degree of Superheating

- ➢R1233zd(E), R1224yd(Z), R600, and R245fa are all examples of working fluids. With a superheat temperature requirement of less than 10 K.

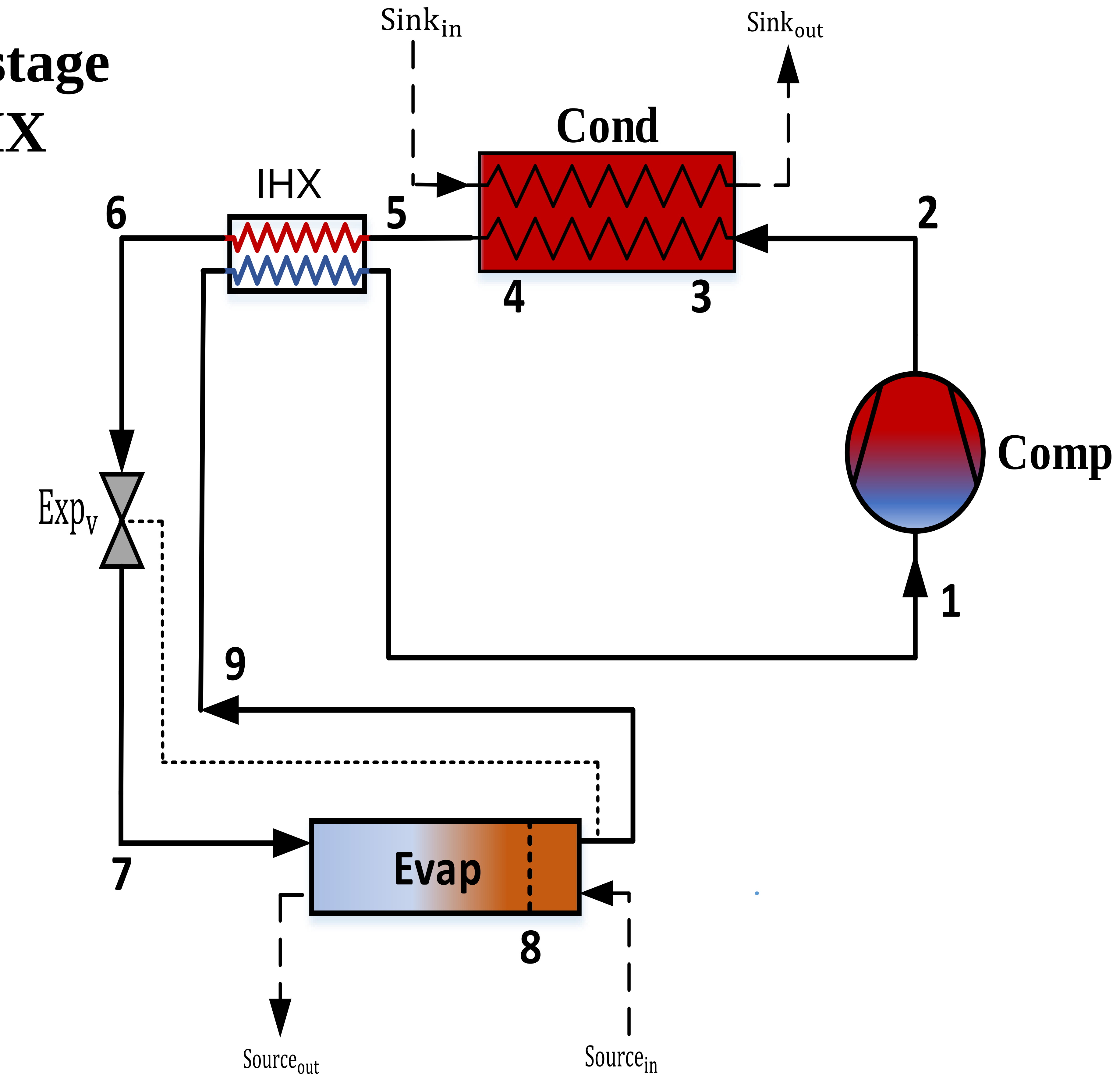
- ➢The working fluids R1336mzz(Z), R601, and R 365mfc require a high degree of superheat prior to the compressor.

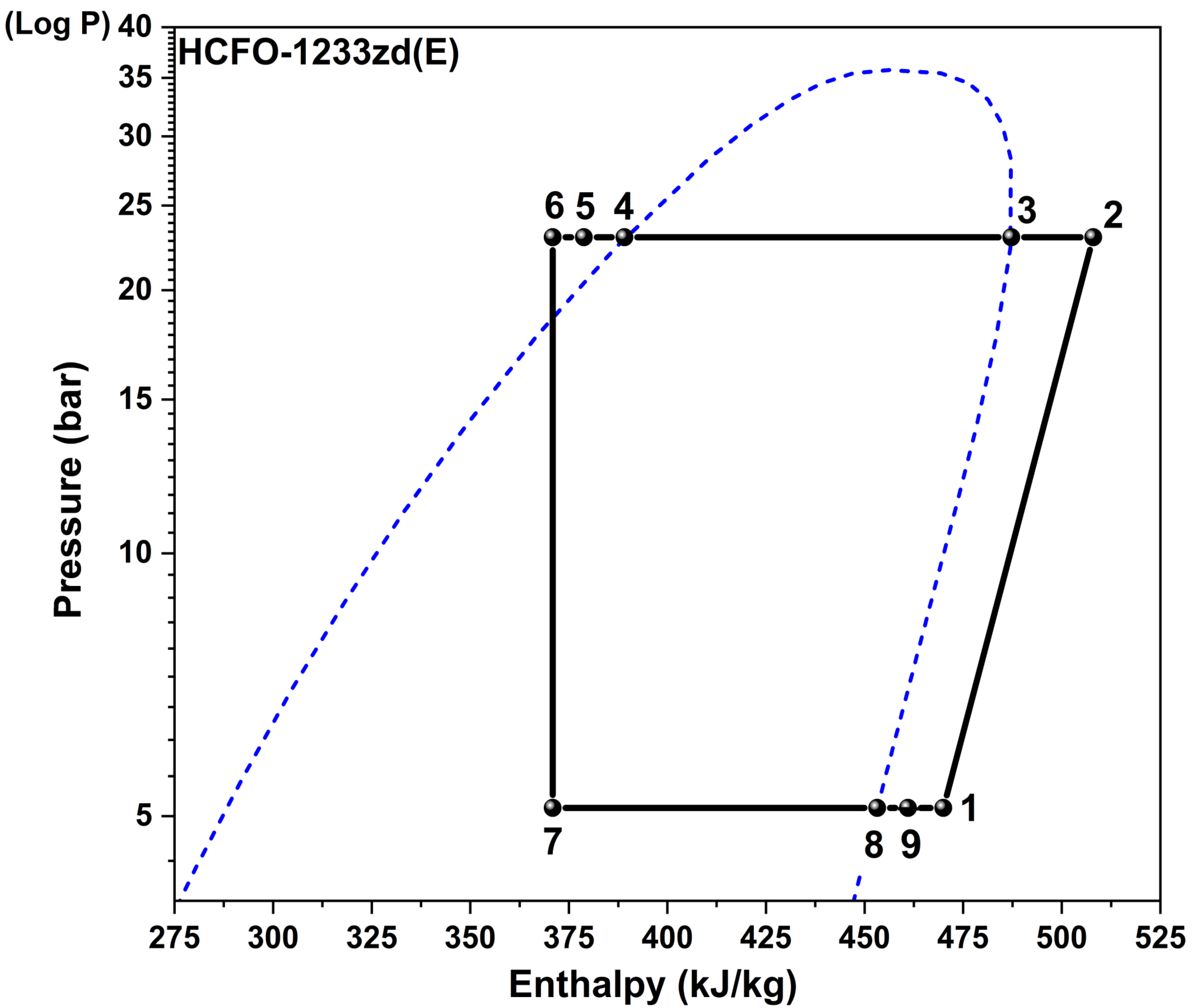
- ➢Due to the isentropic nature of R1234ze(Z), the required superheat degrees can form during the evaporation process.



Cycle Configurations

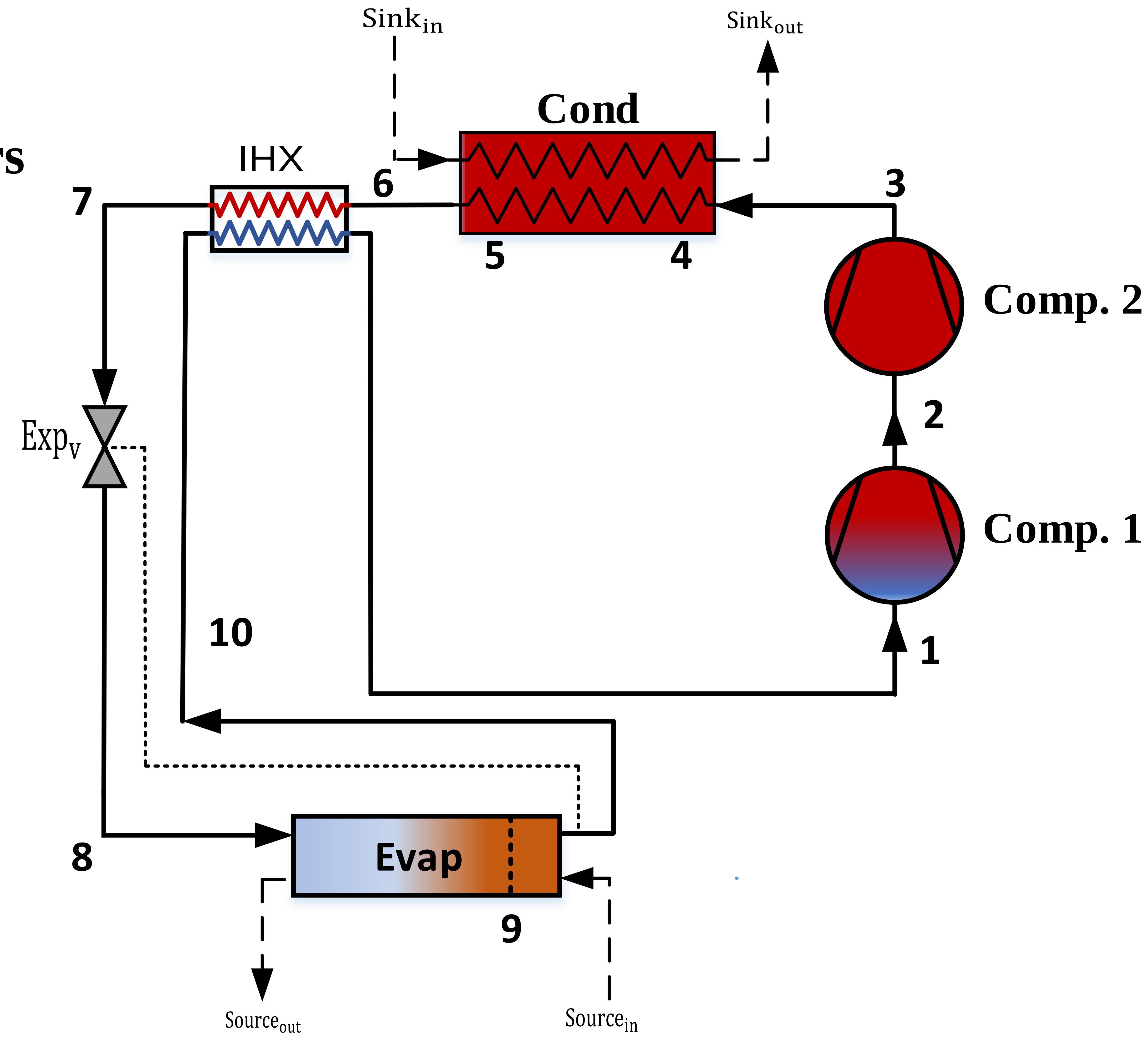
Single-stage with IHX

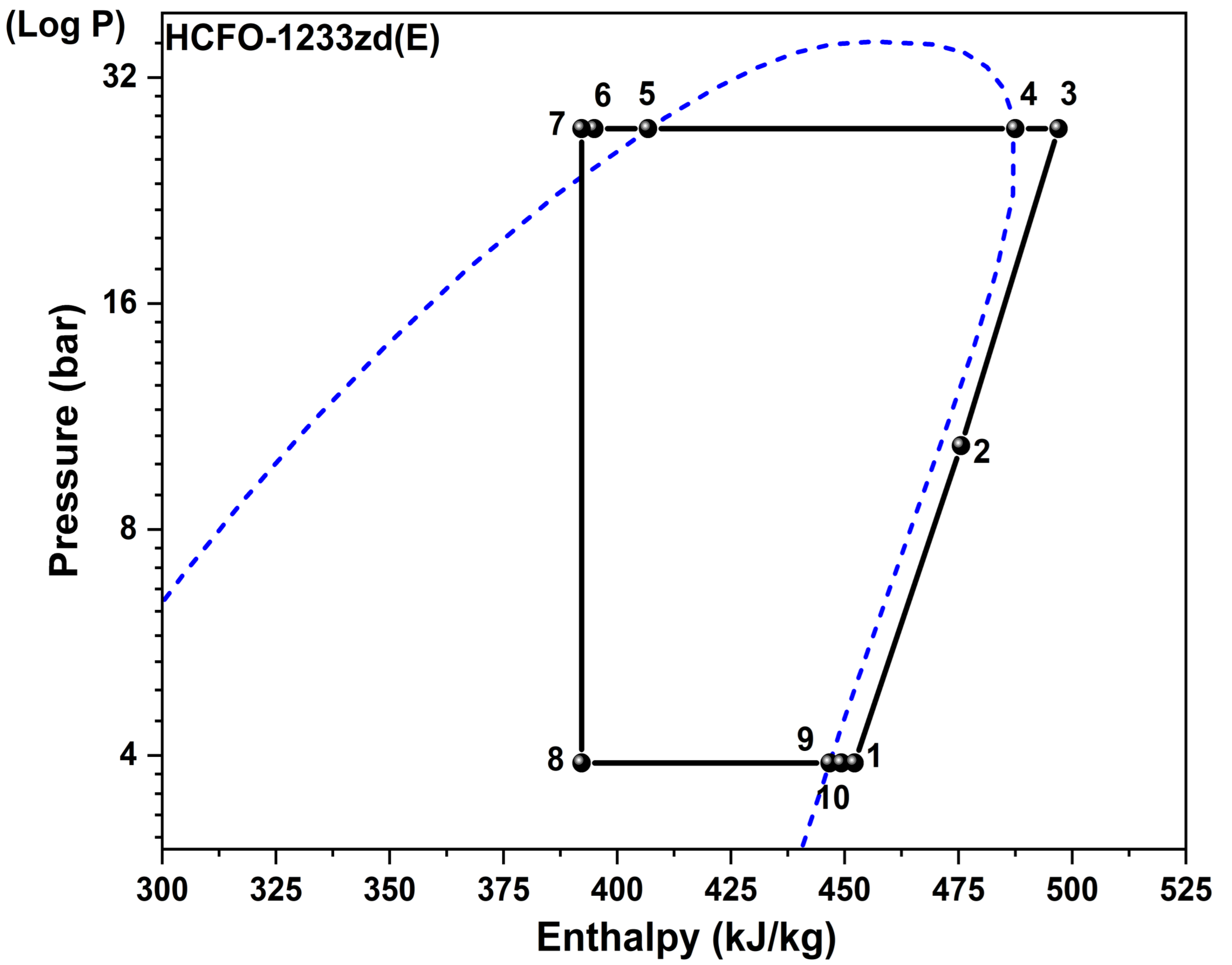




Configs Continues

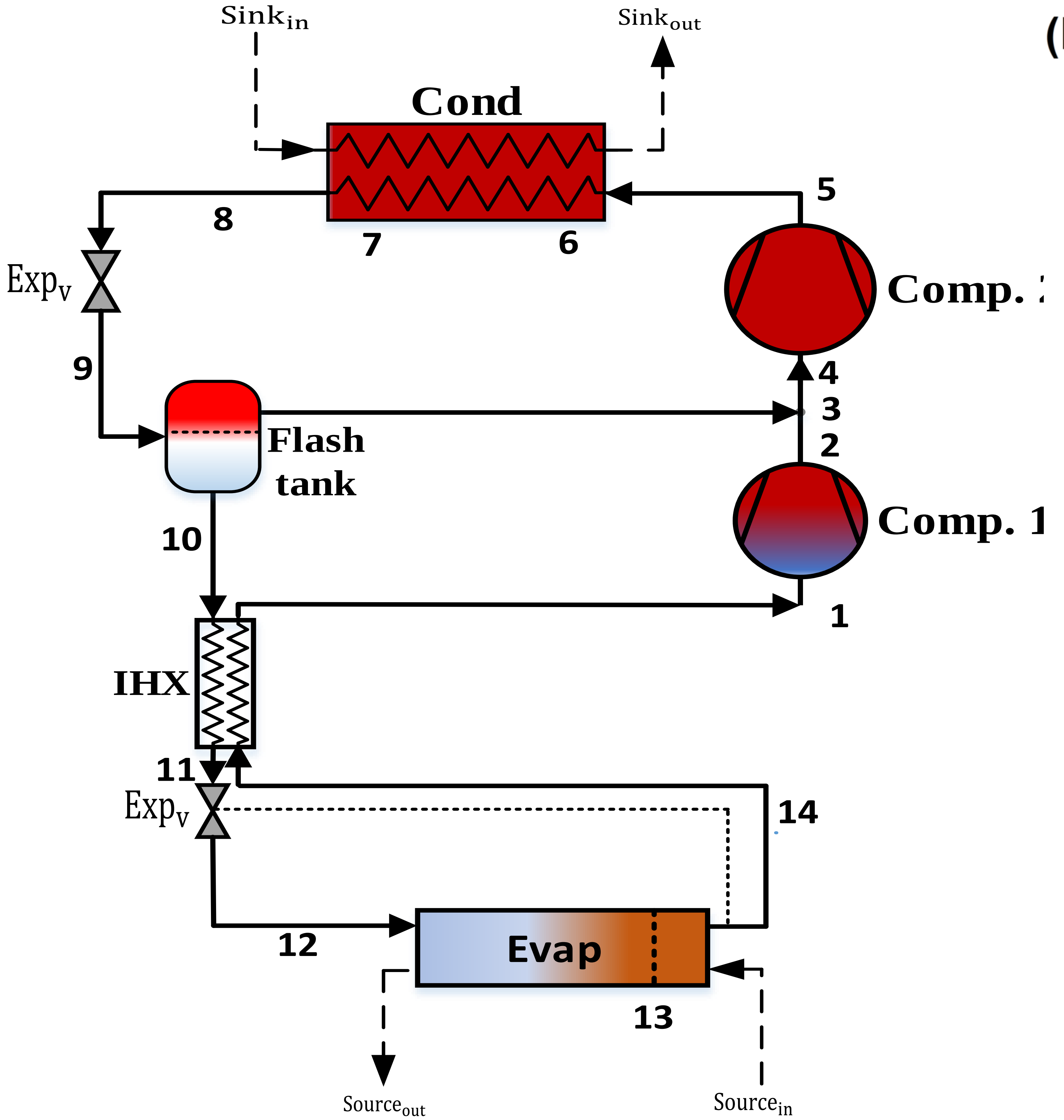
Basic cycle with dual compressors and IHX

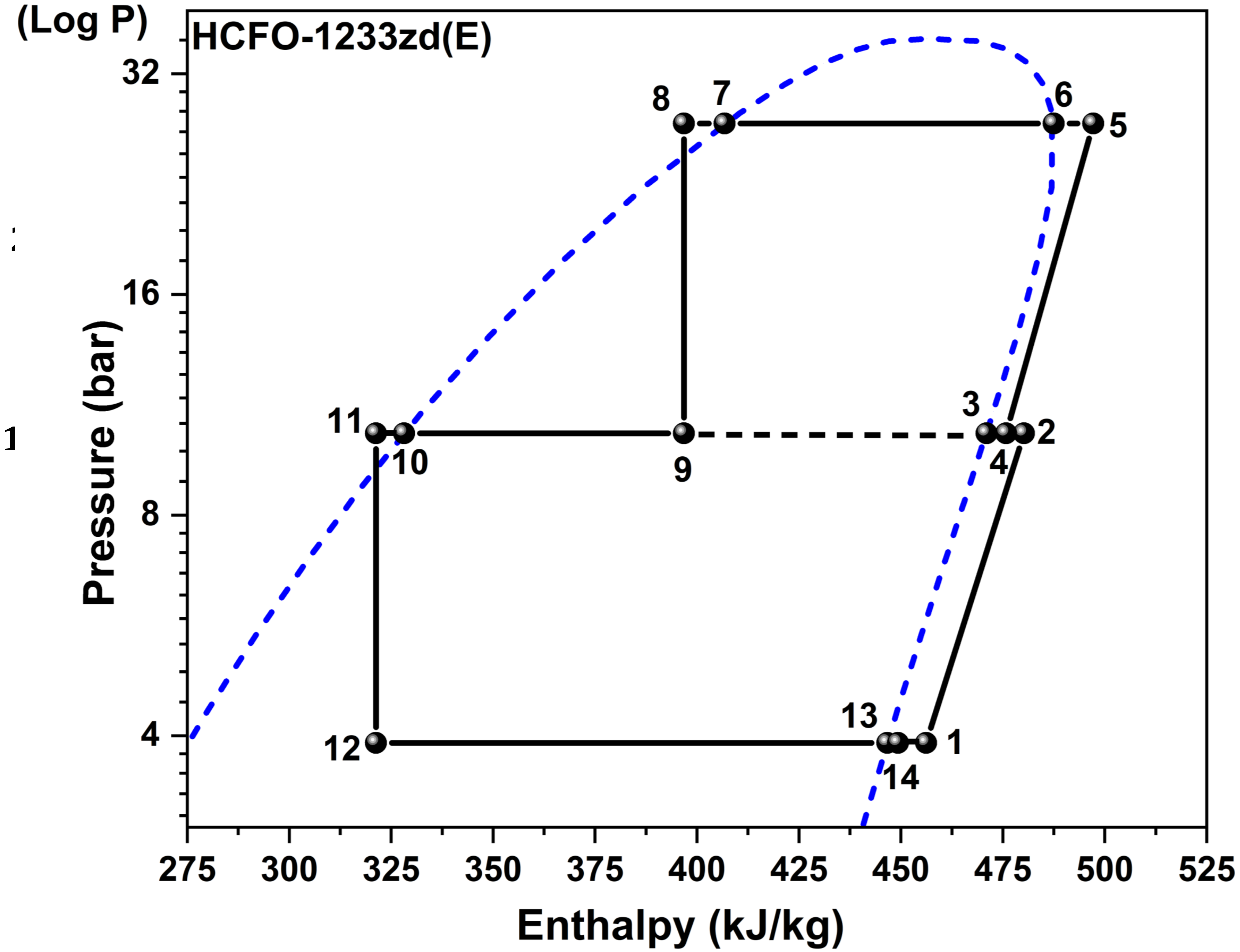




Configs Continues

Double stage Cycle with flash tank and IHX





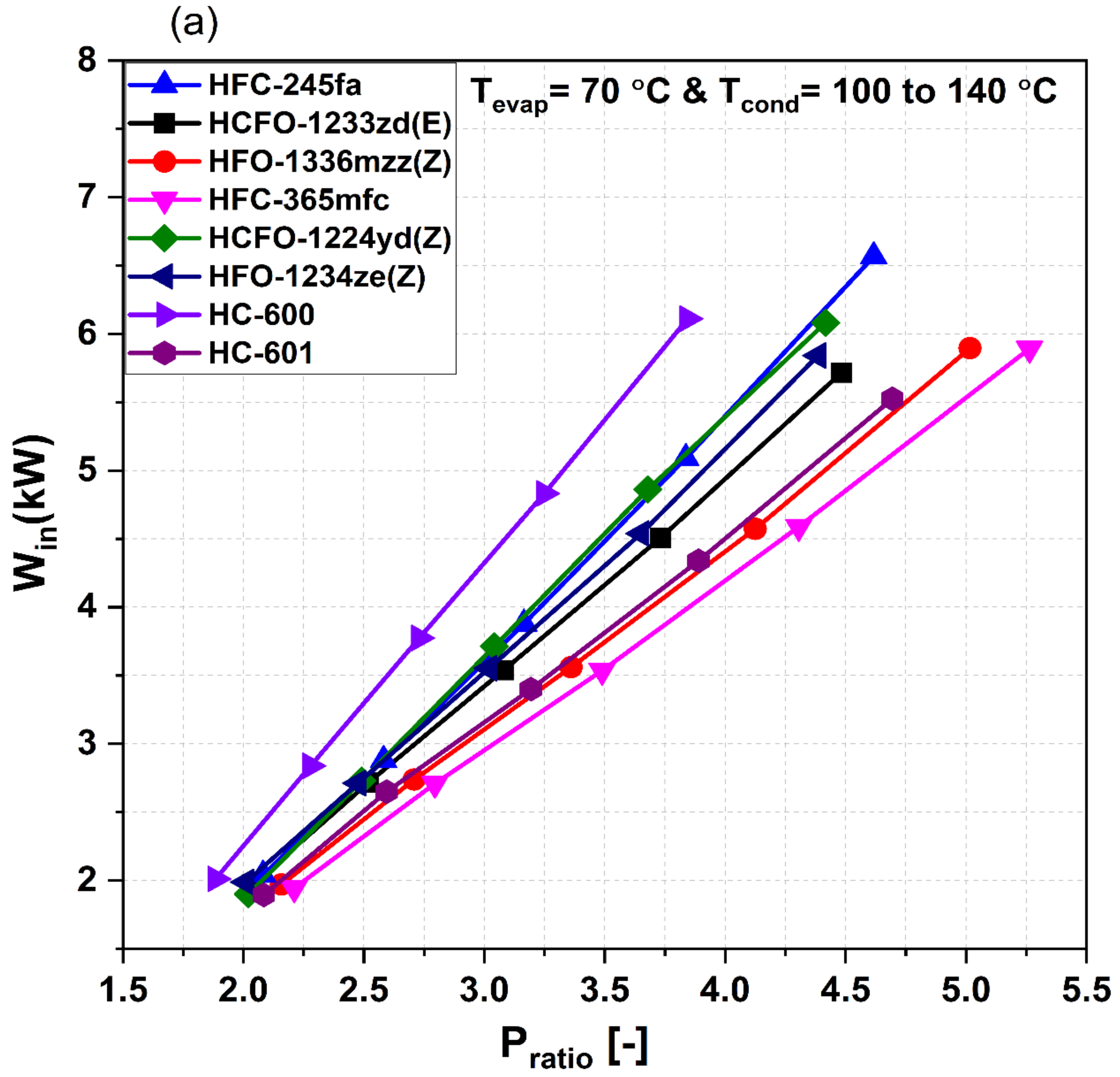
Simulation Model of Sub-critical HTHP Cycle

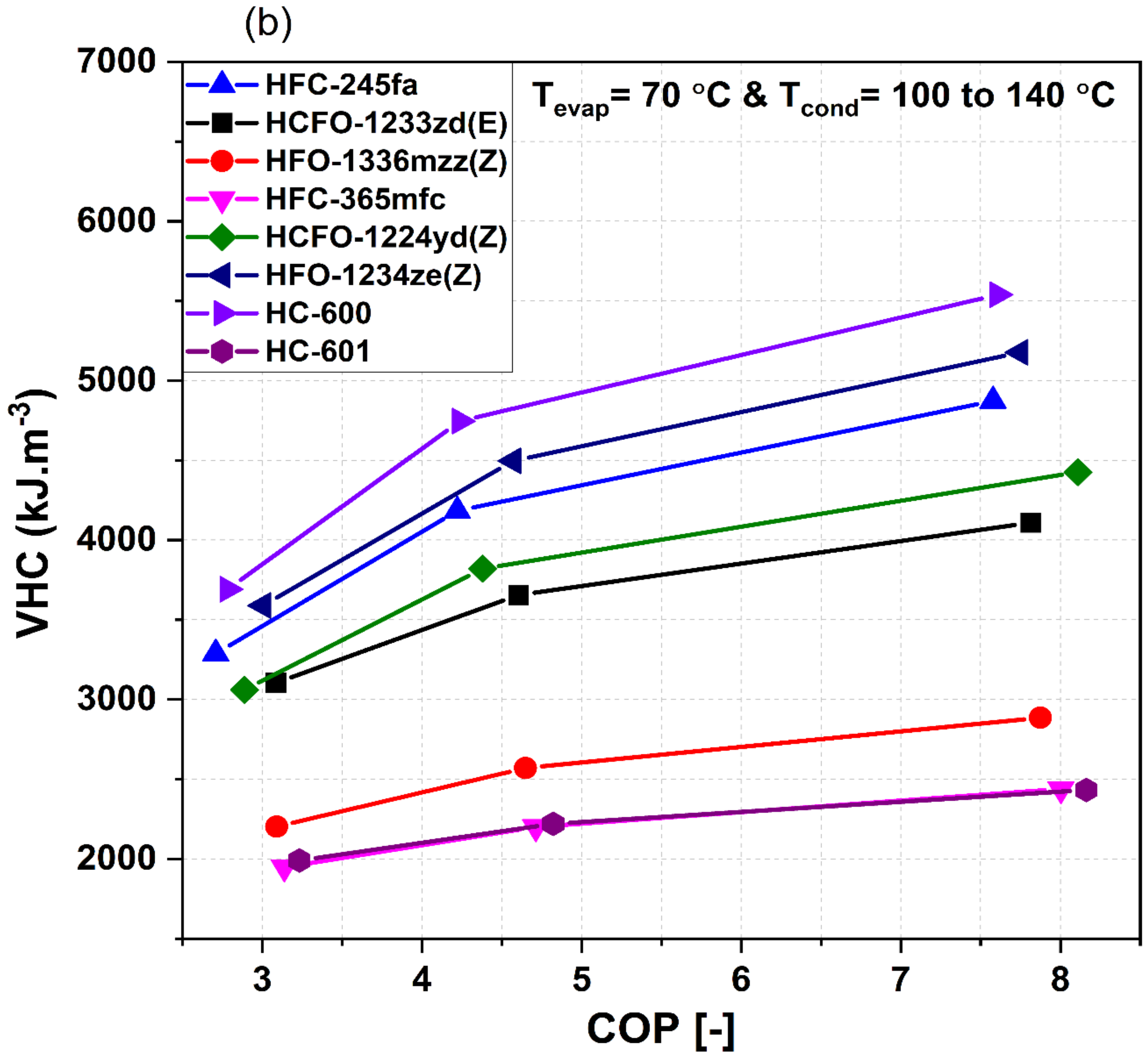
- Using EES Software
- Components Modelling
- Cycle Modelling
- Mapping of The Minimum Degree Of Superheat
- Energy Balance & Energy Efficiency
- Entropy Balance
- Exergy Destruction & Exergy Efficiency
- Heat Transfer Coefficient For Evaporator, Condenser And IHX (Double-tube &BPHE)
- Results

Numerical Results

Refrigerant	T_{dis} (°C)	COP [-]	VHC ($kJ.m^{-3}$)	W_{in} (kW)	Ex_{dest} (kW)	η_{ex} (%)	T_{dis} (°C)	COP [-]	VHC ($kJ.m^{-3}$)	W_{in} (kW)	Ex_{dest} (kW)	η_{ex} (%)
	(T_{evap} = 60 °C & T_{cond} = 90 °C, 130 °C)						(T_{evap} = 70 °C & T_{cond} = 100 °C, 140 °C)					
R1233zd(E)	95.97	7.93	3316	1.93	1.03	62.50	104.30	7.82	4110	1.89	1.03	61.81
	137.30	3.08	2633	5.87	3.80	49.59	145.90	3.04	3105	5.81	3.74	47.80
R245fa	95.52	7.76	3925	1.98	1.06	61.10	103.90	7.58	4873	1.95	1.03	60.17
	134.90	2.83	2876	6.47	4.33	45.54	144.00	2.71	3288	6.54	4.40	42.77
R1336mzz(Z)	93.41	7.99	2273	1.95	1.04	62.45	103.50	7.86	2886	1.89	1.01	62.18
	140.90	3.13	1854	6.07	3.91	49.91	148.60	3.09	2203	5.88	3.66	48.75
R365mfc	93.56	8.09	1899	1.95	1.06	62.63	103.10	8.00	2439	1.89	1.01	62.52
	141.70	3.18	1566	6.08	3.96	50.75	149.40	3.14	1948	5.78	3.61	50.37
R1224yd(Z)	95.52	8.14	3602	1.95	1.03	61.71	103.70	8.1	4426	1.92	1.00	60.68
	134.70	2.92	2678	6.23	4.10	46.50	144.00	2.89	3061	6.32	4.18	43.77
R600	95.20	7.62	4633	1.94	1.01	61.66	103.40	7.61	5540	1.92	0.99	60.37
	133.70	2.80	3378	6.00	3.86	46.38	143.50	2.78	3692	6.27	4.13	42.67
R601	93.71	8.28	1935	1.90	1.02	63.70	103.5	8.16	2433	1.85	0.98	63.30
	141.40	3.31	1623	5.54	3.46	53.30	154.01	3.23	1991	5.32	3.20	52.80
R1234ze(Z)	98.24	7.88	3221	1.94	1.08	61.91	107.80	7.75	5177	1.91	1.05	61.02
	142.90	3.02	3174	4.74	4.02	47.88	152.40	3.00	3589	6.12	4.09	45.07

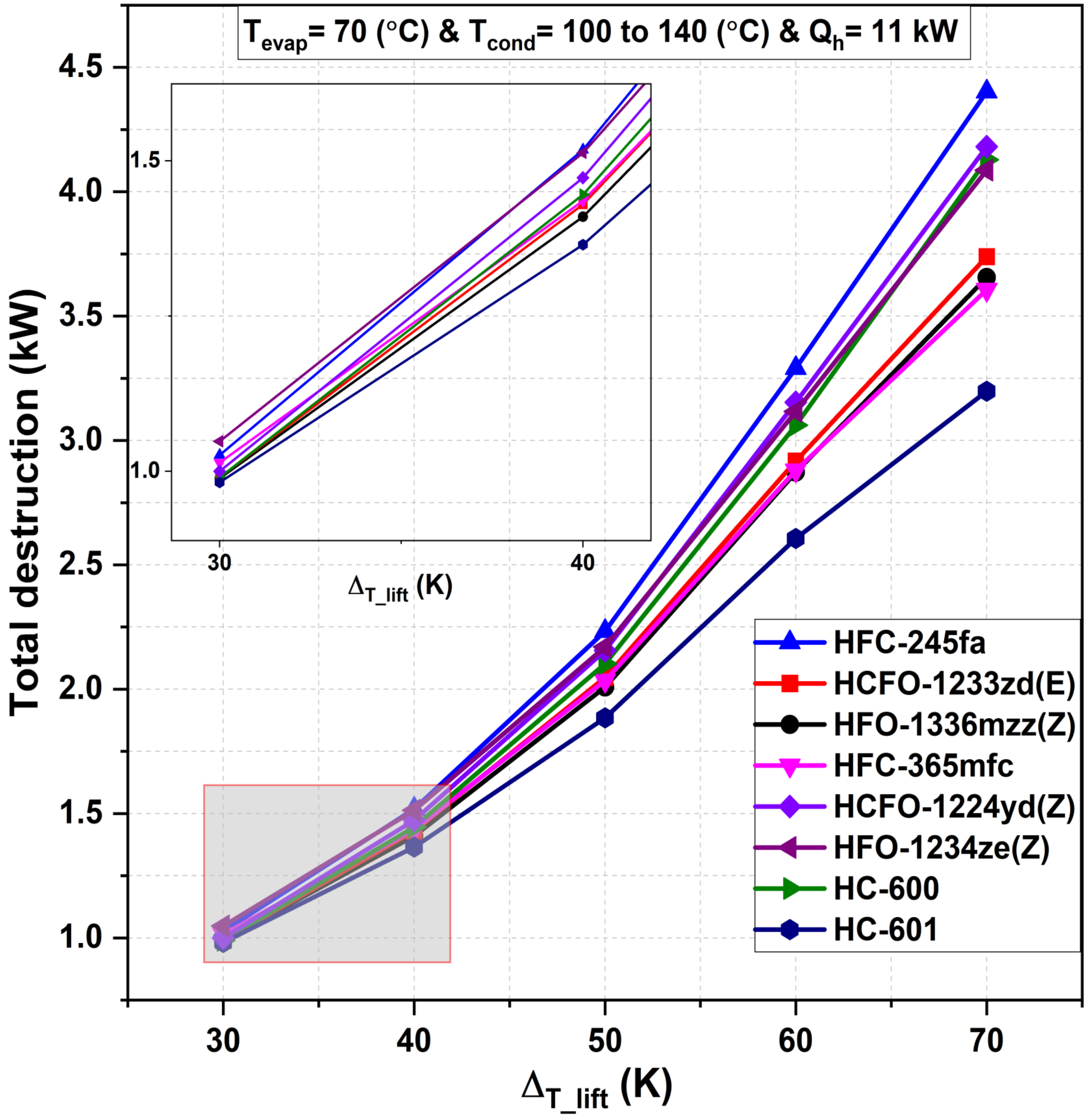
Energetic Graphs

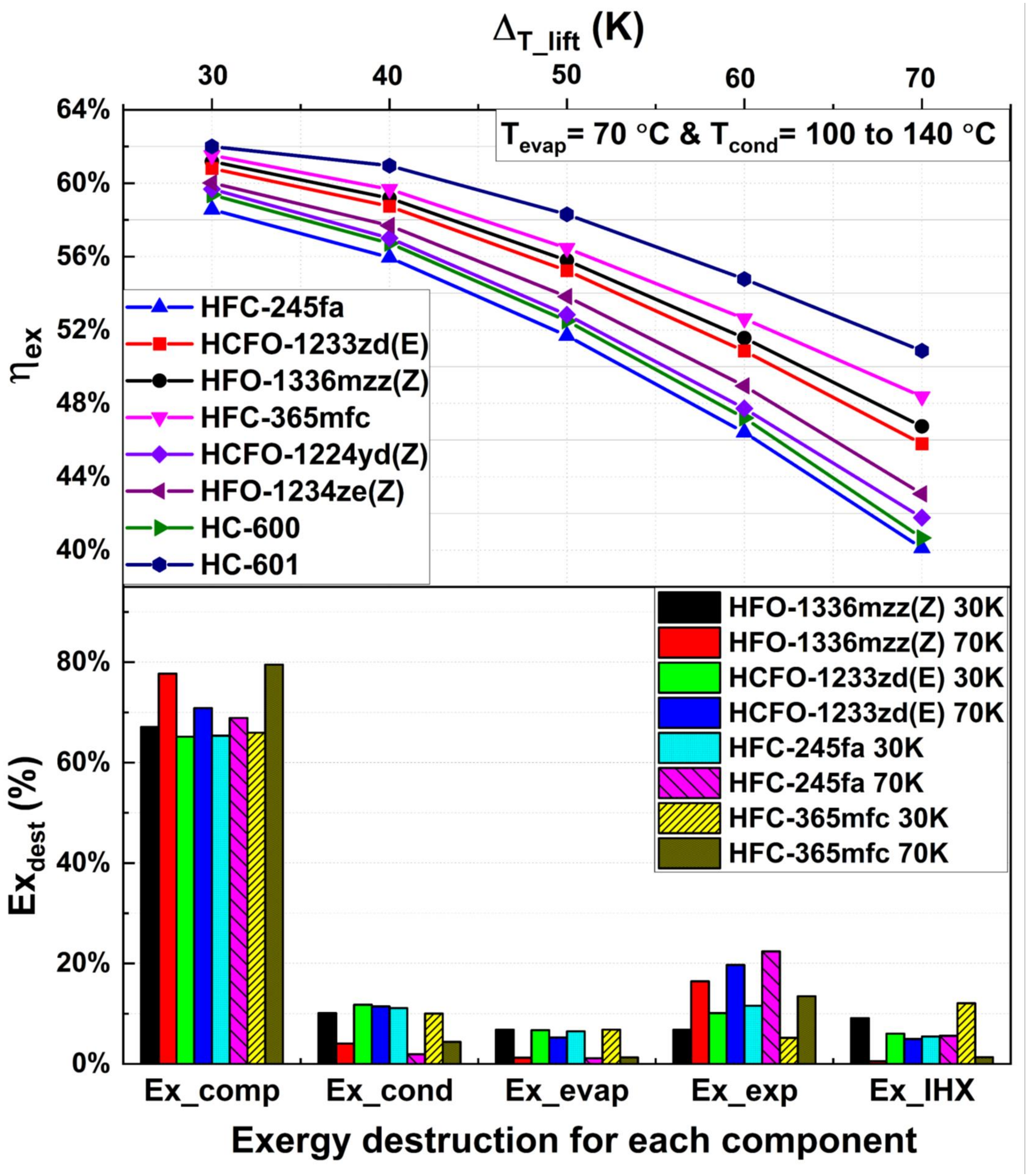




Exergy Destruction And Exergy Efficiency

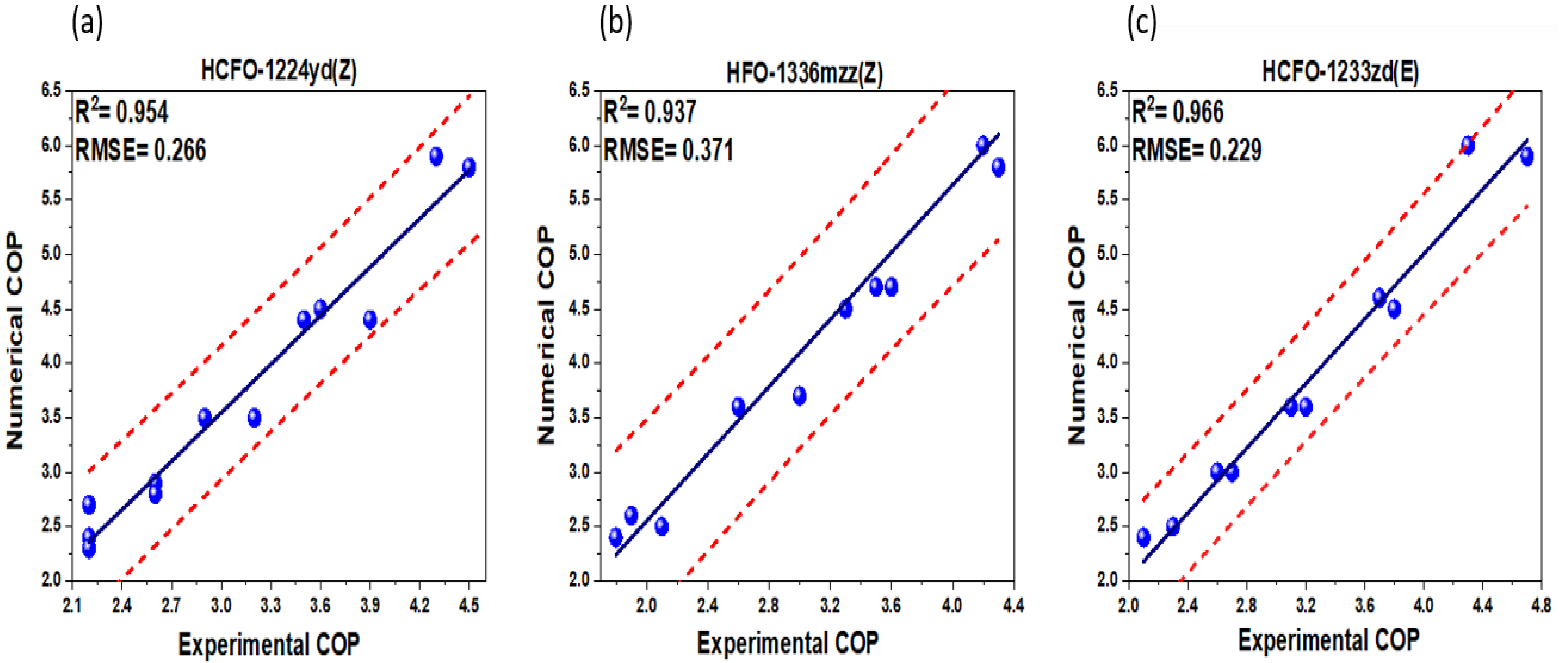
- **R601 followed by R1233zd(E) showed a higher exergetic efficiency**
- **The compressor, followed by the expansion valve, has the biggest loss.**
- **The losses in compression and expansion processes resulting from the dissipative forces.**
- **The losses in heat exchangers are a function of heat transfer temperature gradient**



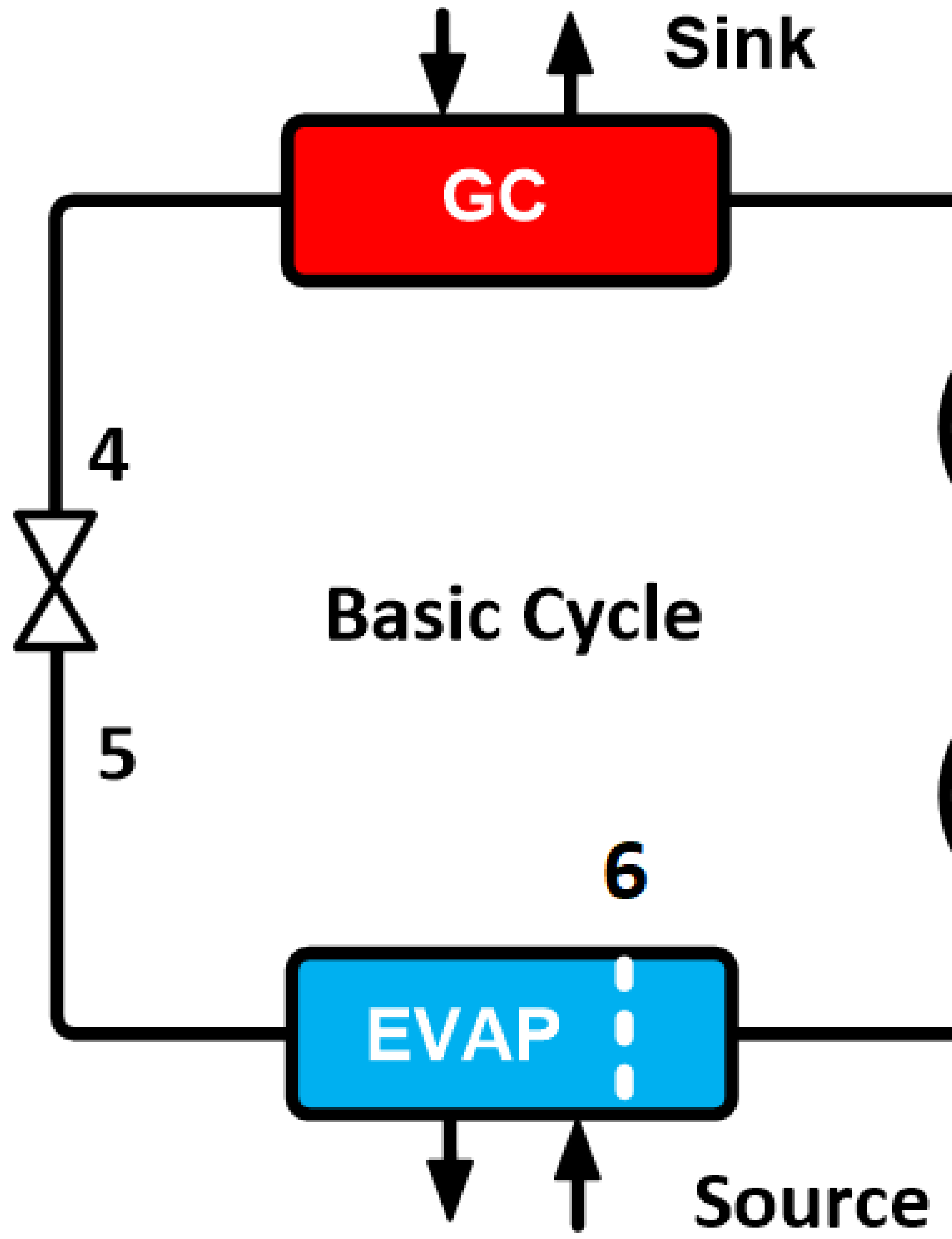


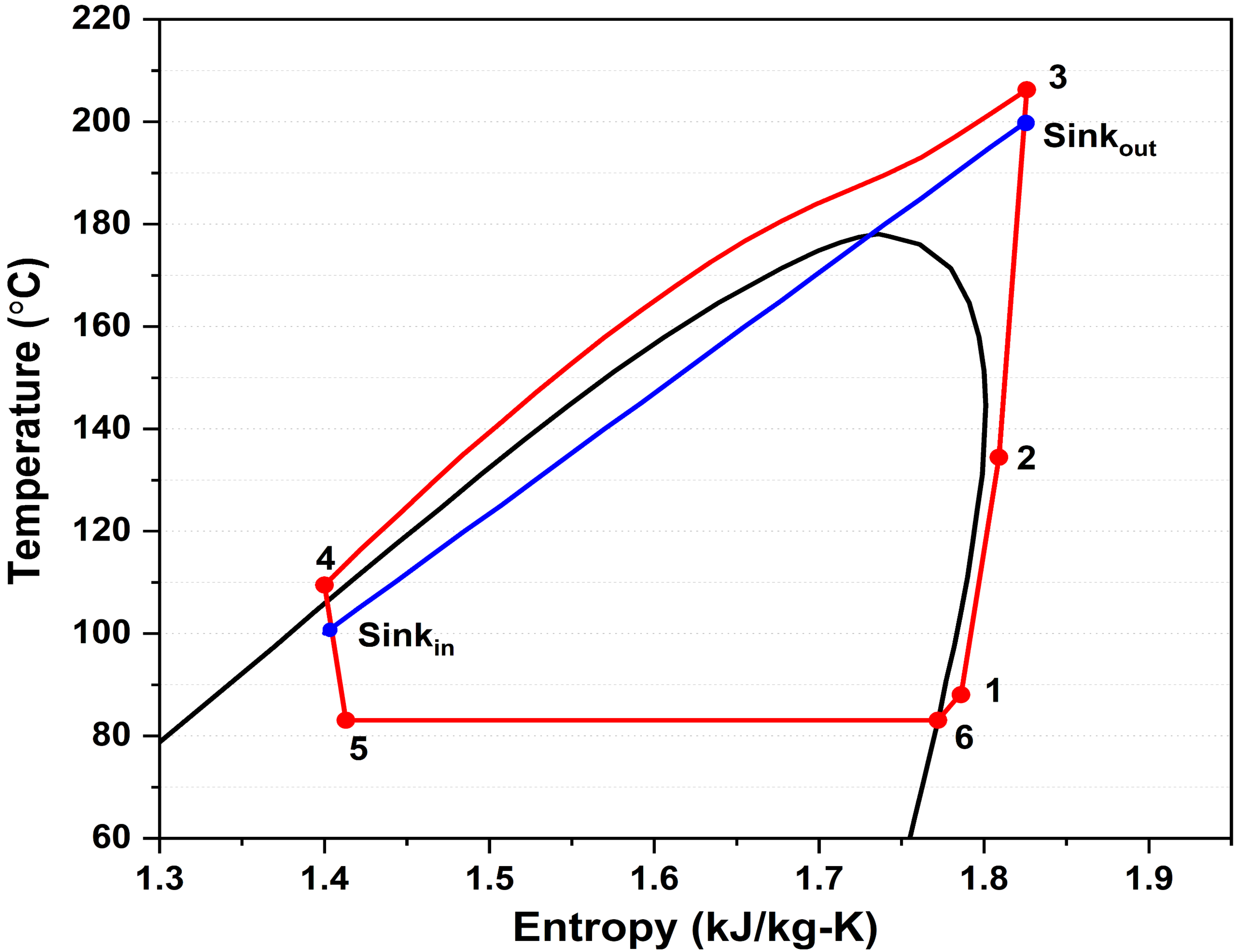
Model Validation

- ➢Experimental validation of the simulation model based on three statistical indices
- ➢A close regression line to the experimental points



Trans-critical HTHP Cycle





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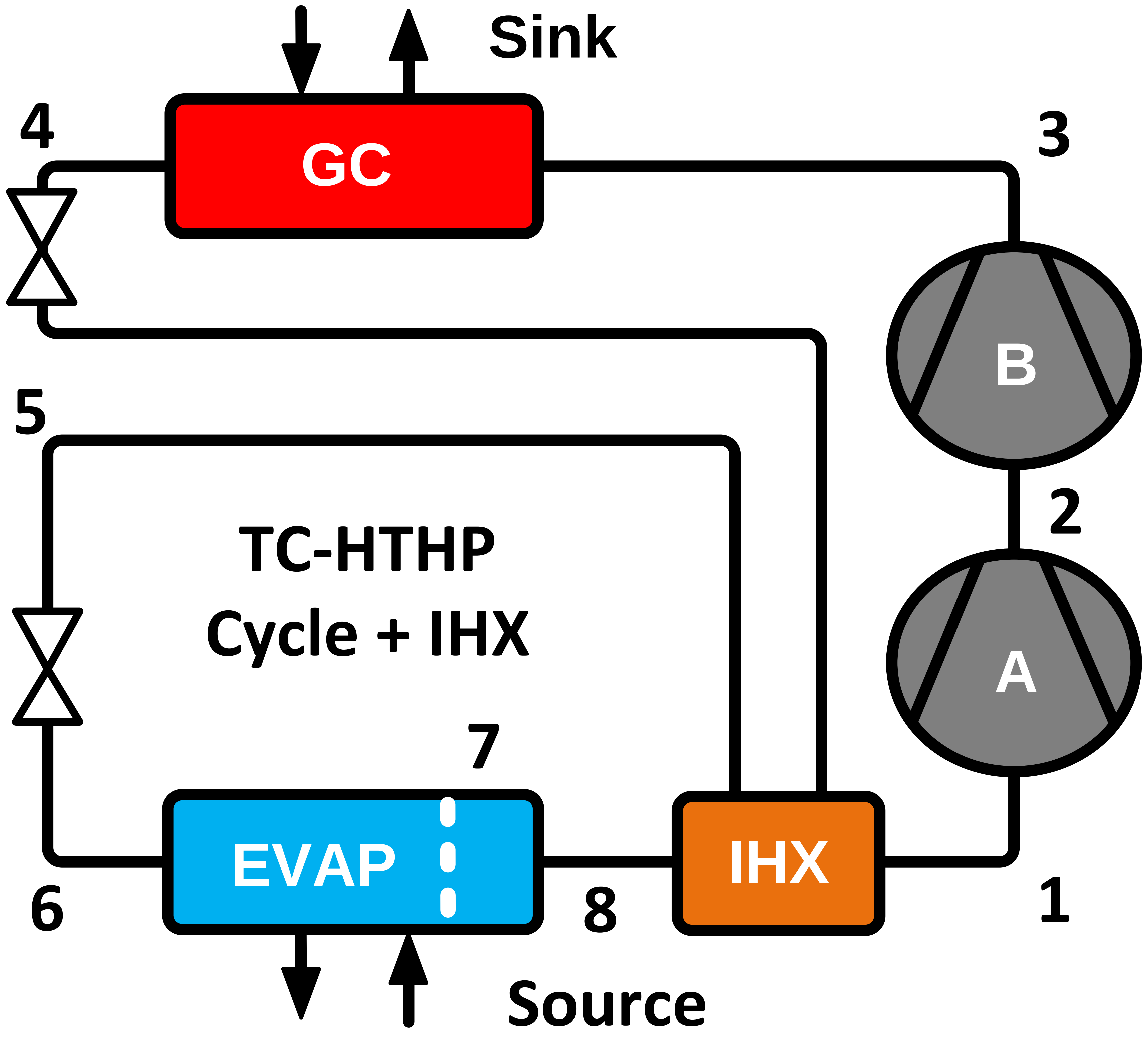

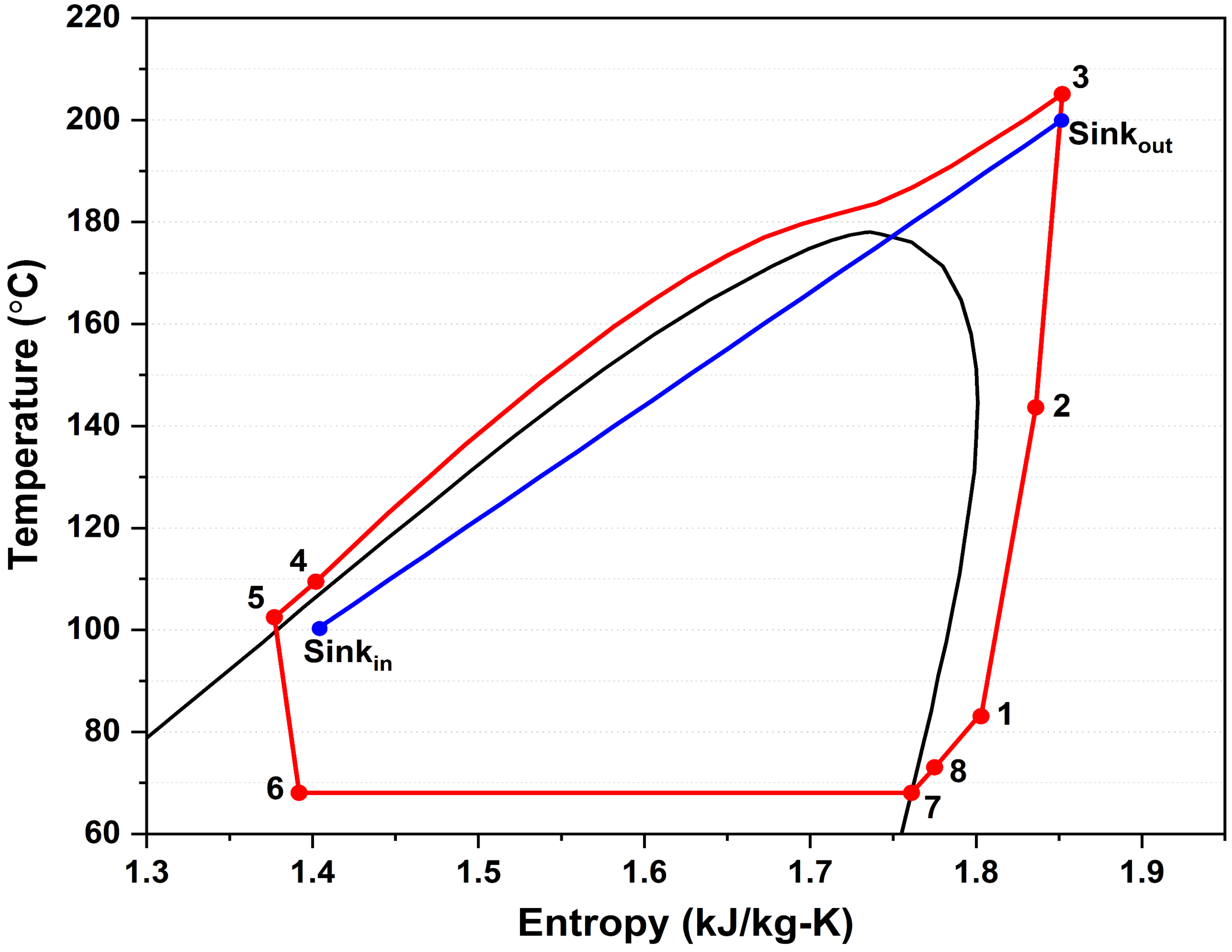

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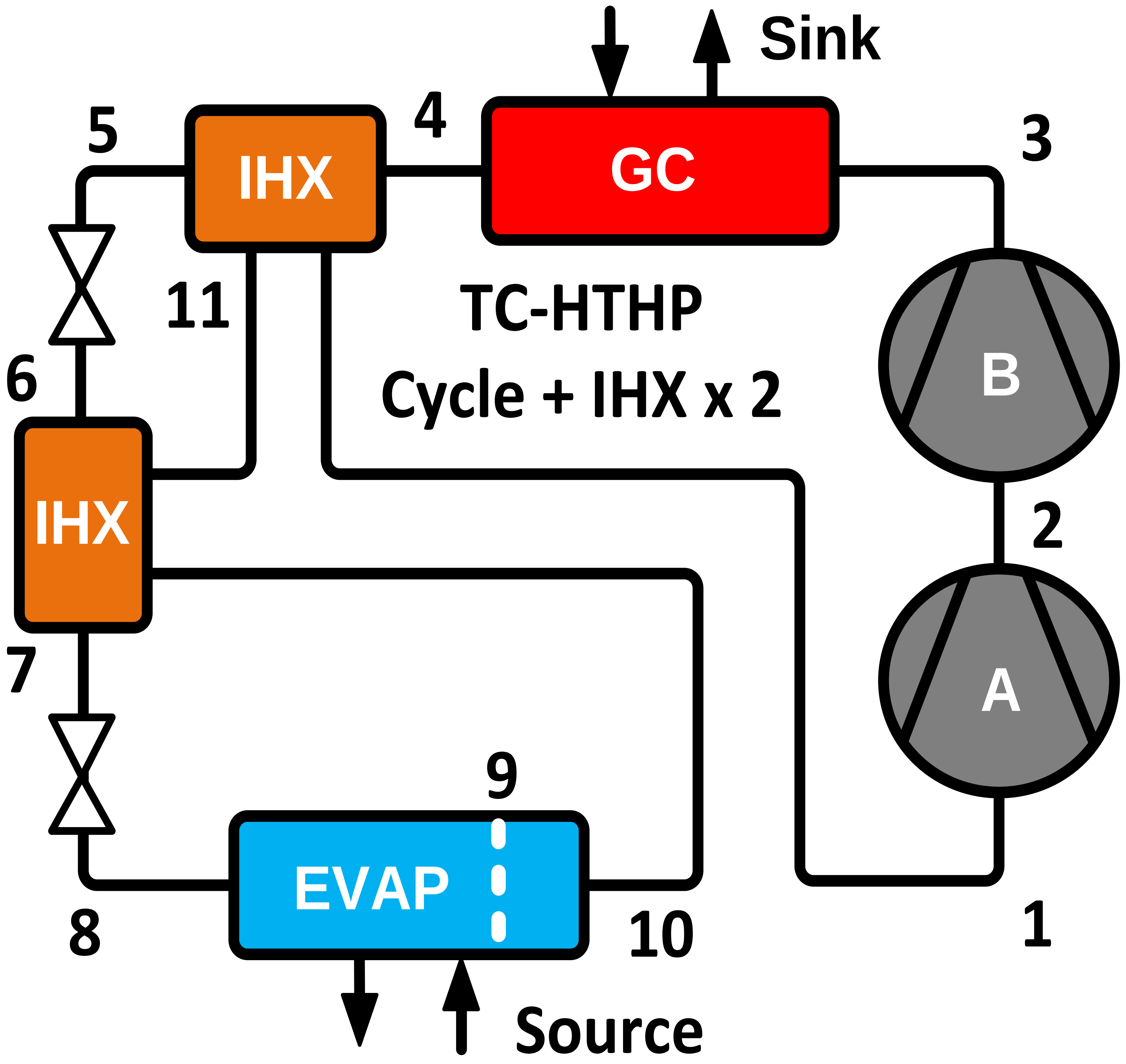
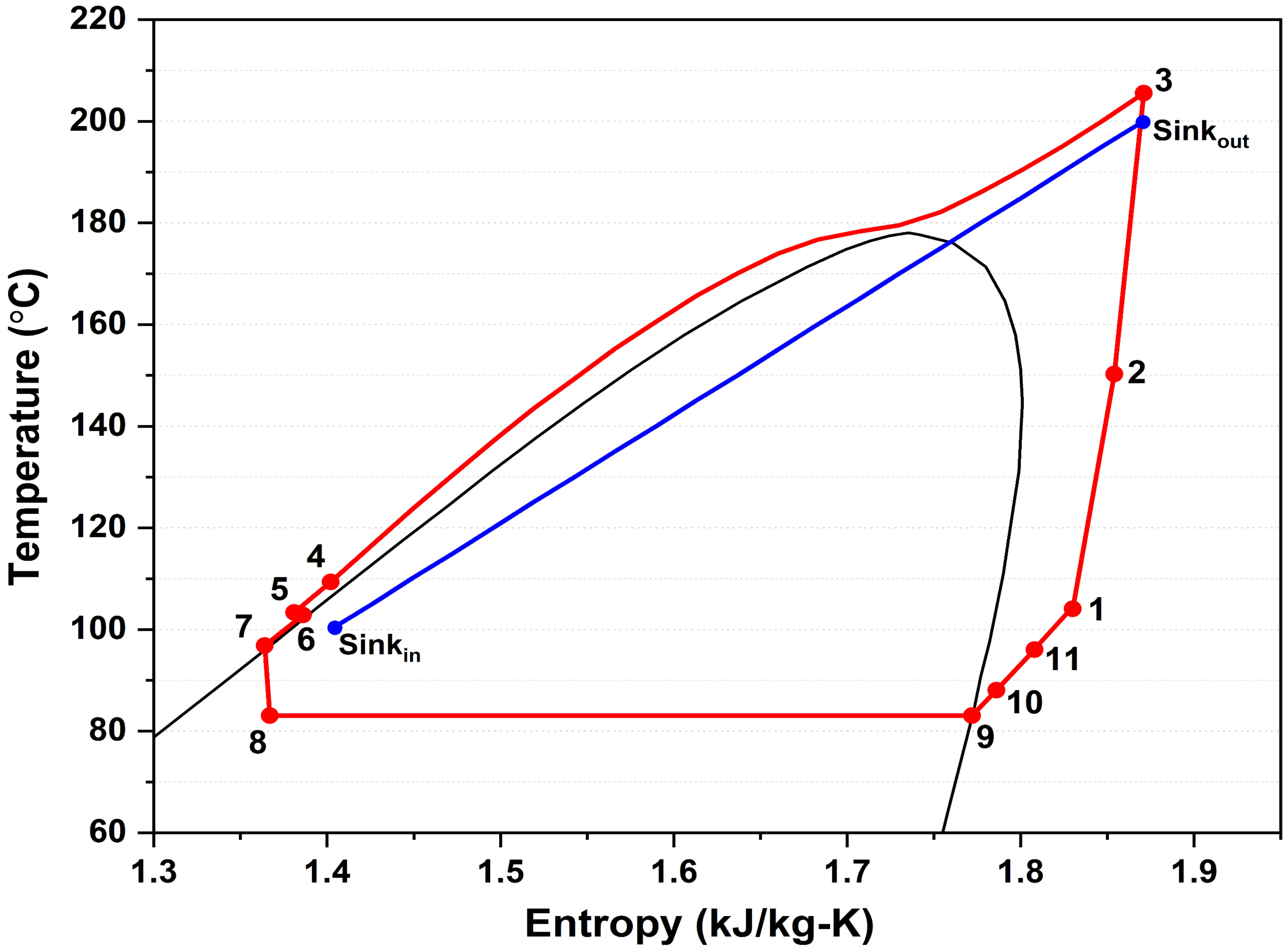
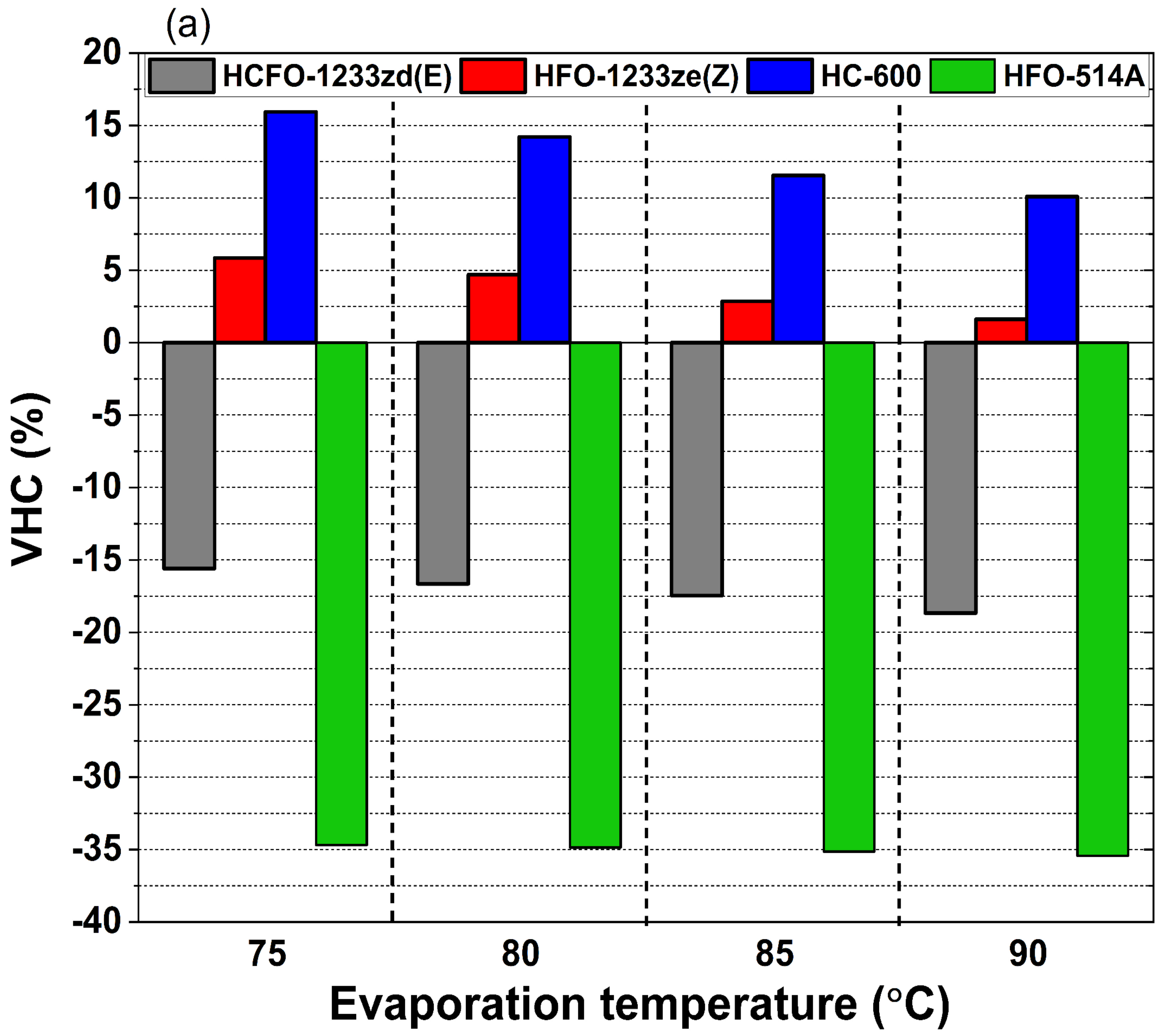
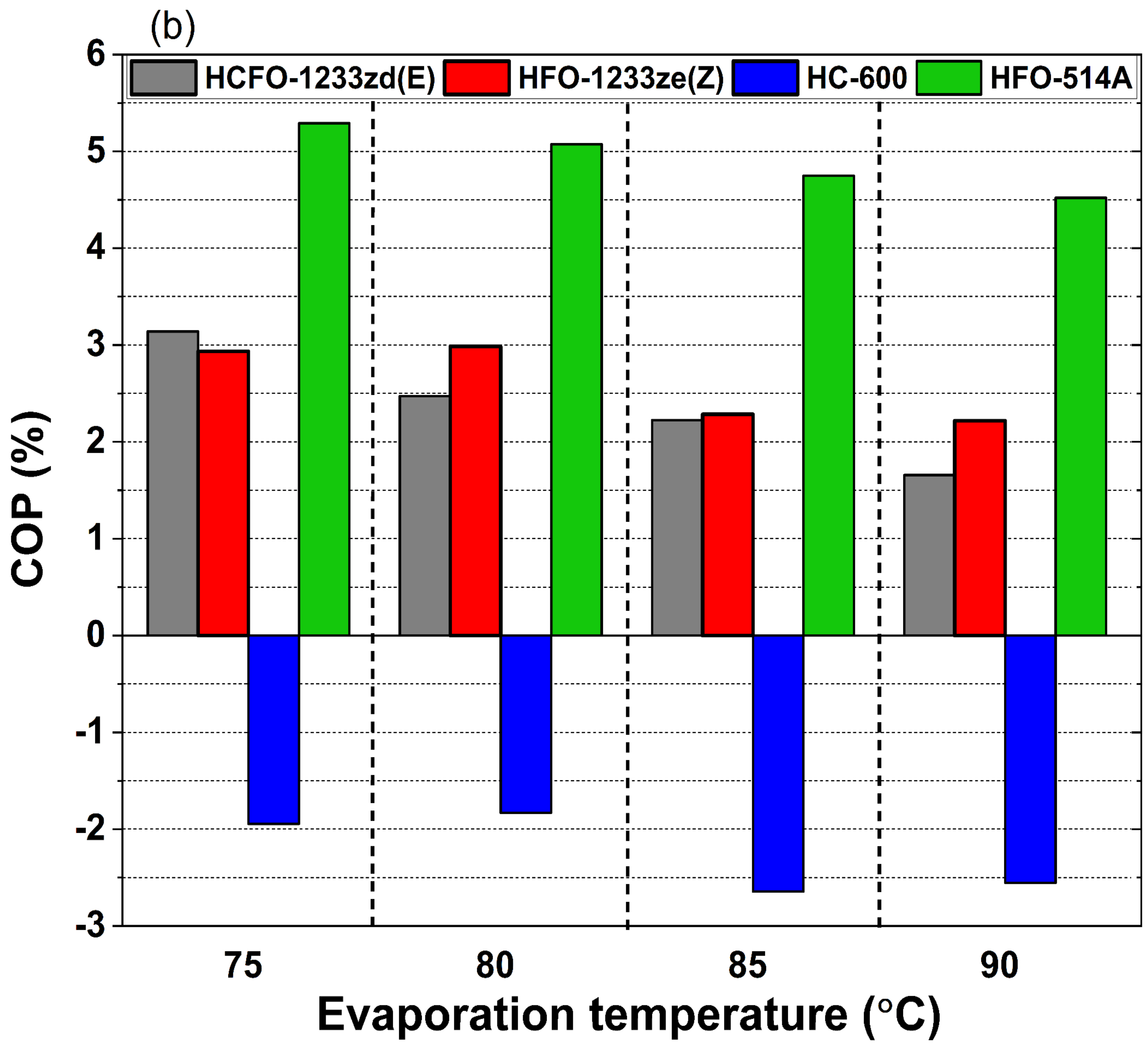




Energetic Results





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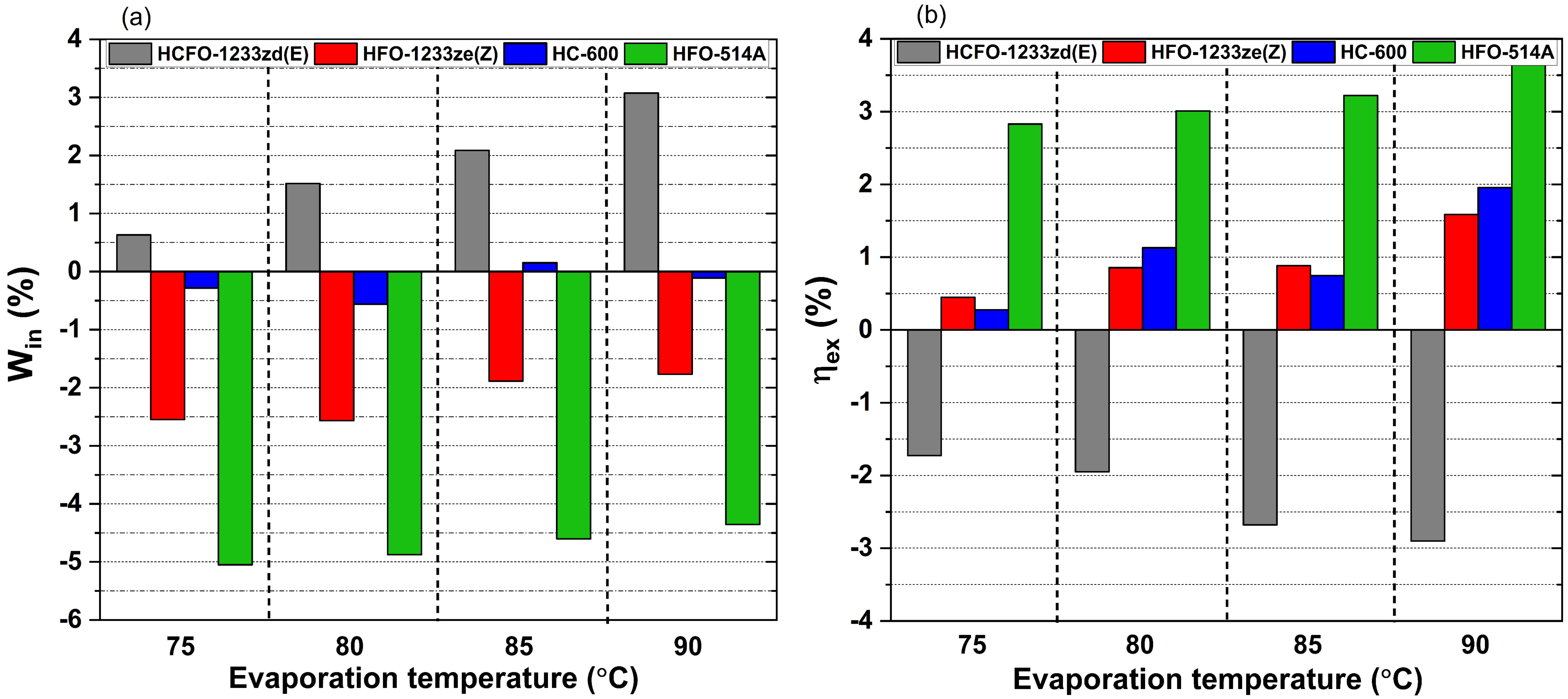
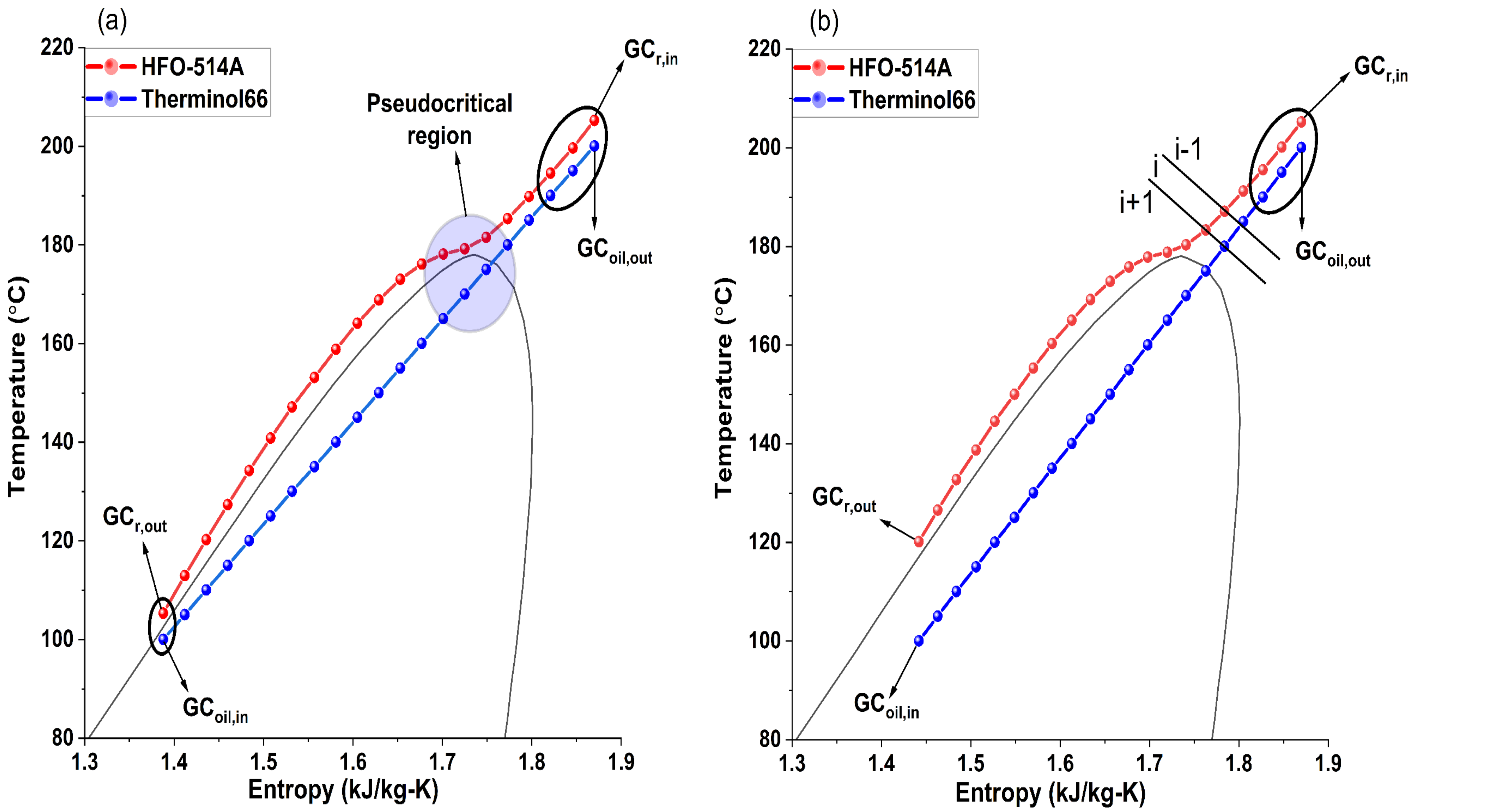


Technical Challenges and Solution

- **The design approach**
- **High glide temperature**
- **Compression process and lubrication**



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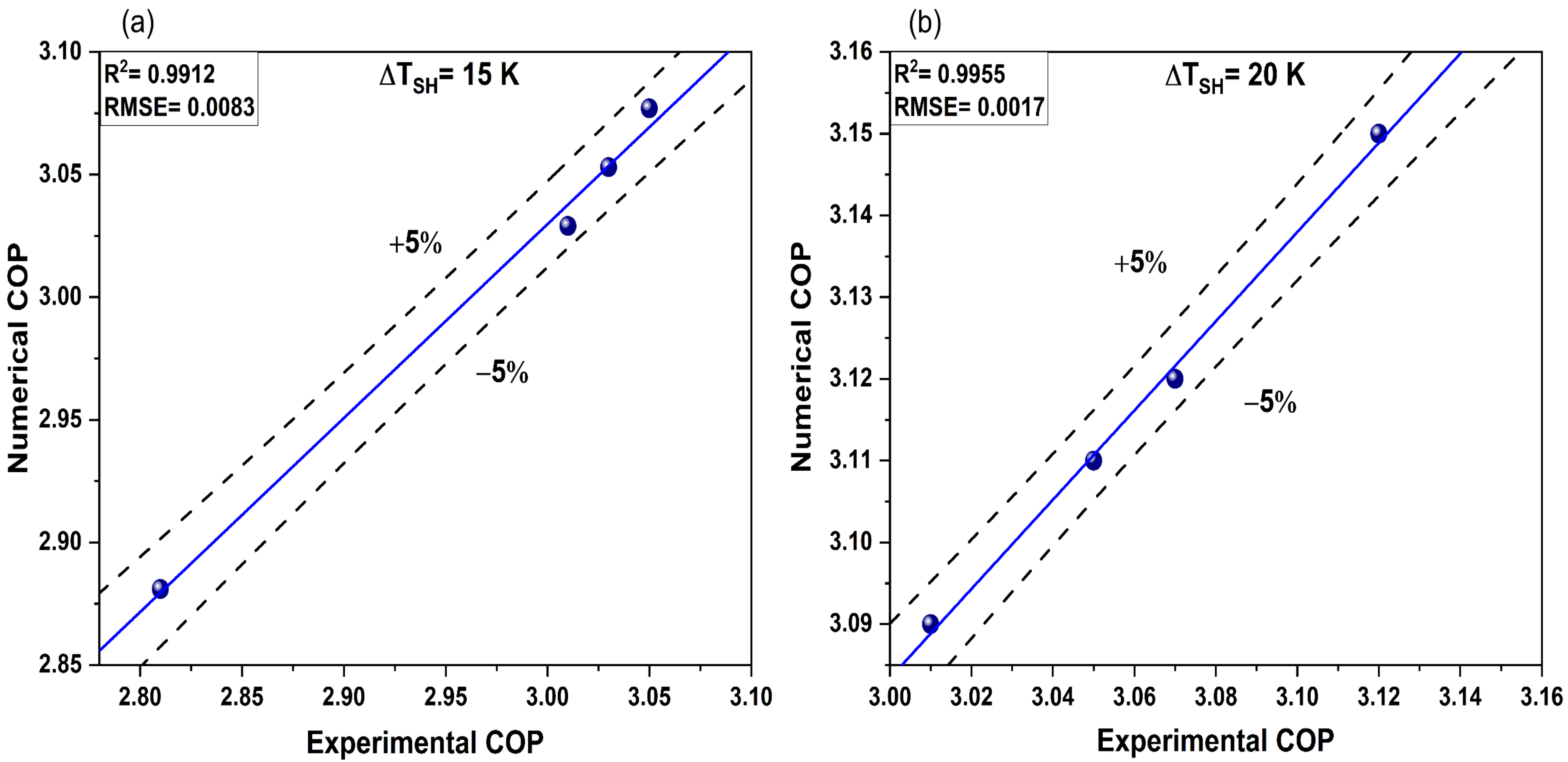

Publications

1. **Thermodynamic analysis of subcritical High-Temperature heat pump using low GWP Refrigerants: A theoretical evaluation (ECM) https://doi.org/10.1016/j.enconman.2022.116034**

2. **Theoretical Evaluation of Energy, Exergy, and Minimum Superheat in a High-Temperature Heat Pump with Low GWP Refrigerants (IJR) https://doi.org/10.1016/j.ijrefrig.2023.06.001**

3. **A solar powered off-grid air conditioning system with natural refrigerant for residential buildings: A theoretical and experimental evaluation (CES) https://doi.org/10.1016/j.cles.2023.100077**

4. **A Theoretical Evaluation of the Energy and Exergo-Environmental Analysis of the HTHP Transcritical Cycle Utilising Low GWP Refrigerants (IJR under review)**

Any Questions?