Heat pump (열펌프)

Building HVAC System
(건축공기조화설비)

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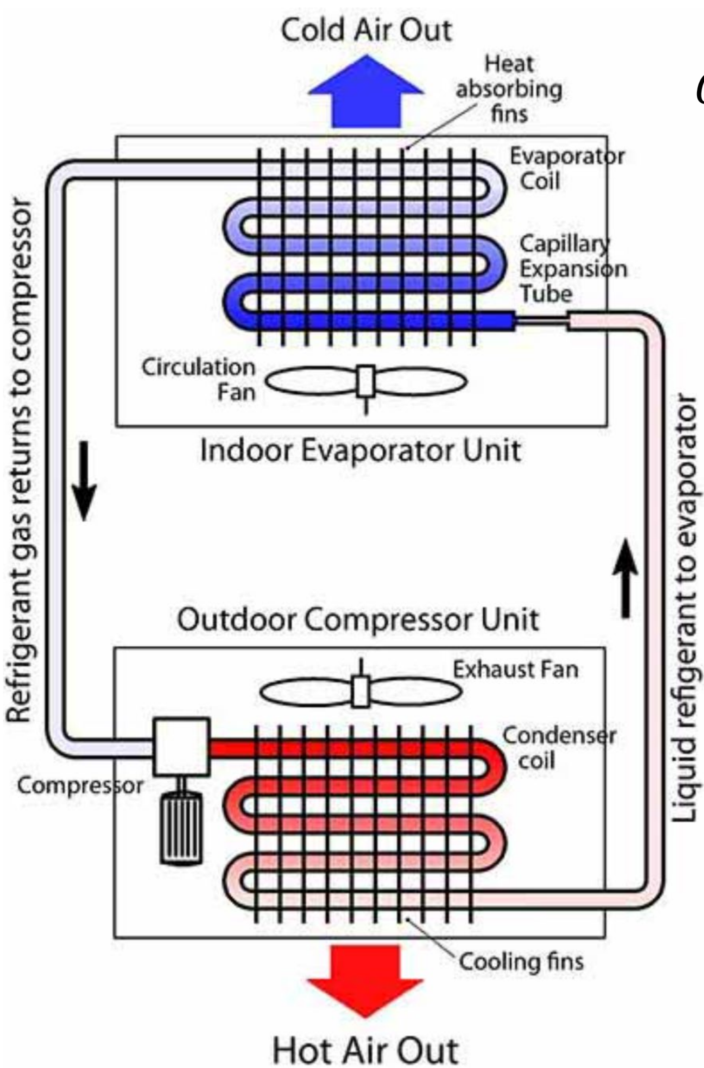
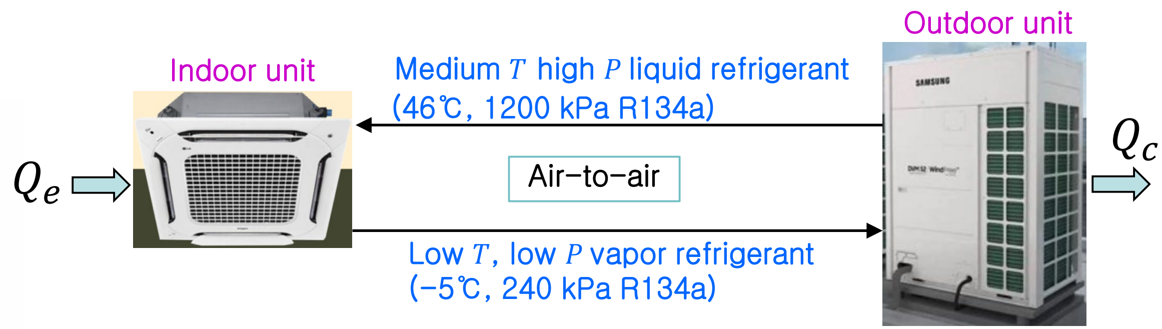
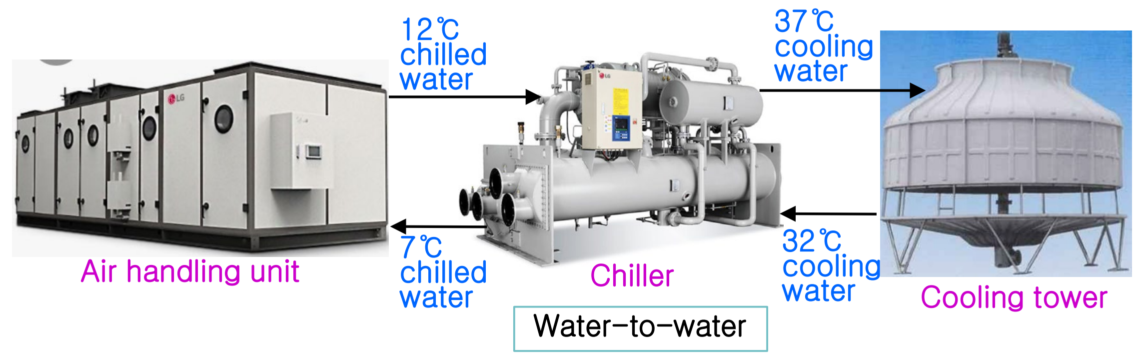
Young Il Kim (김영일)

Heat pump (Cooling & heating)

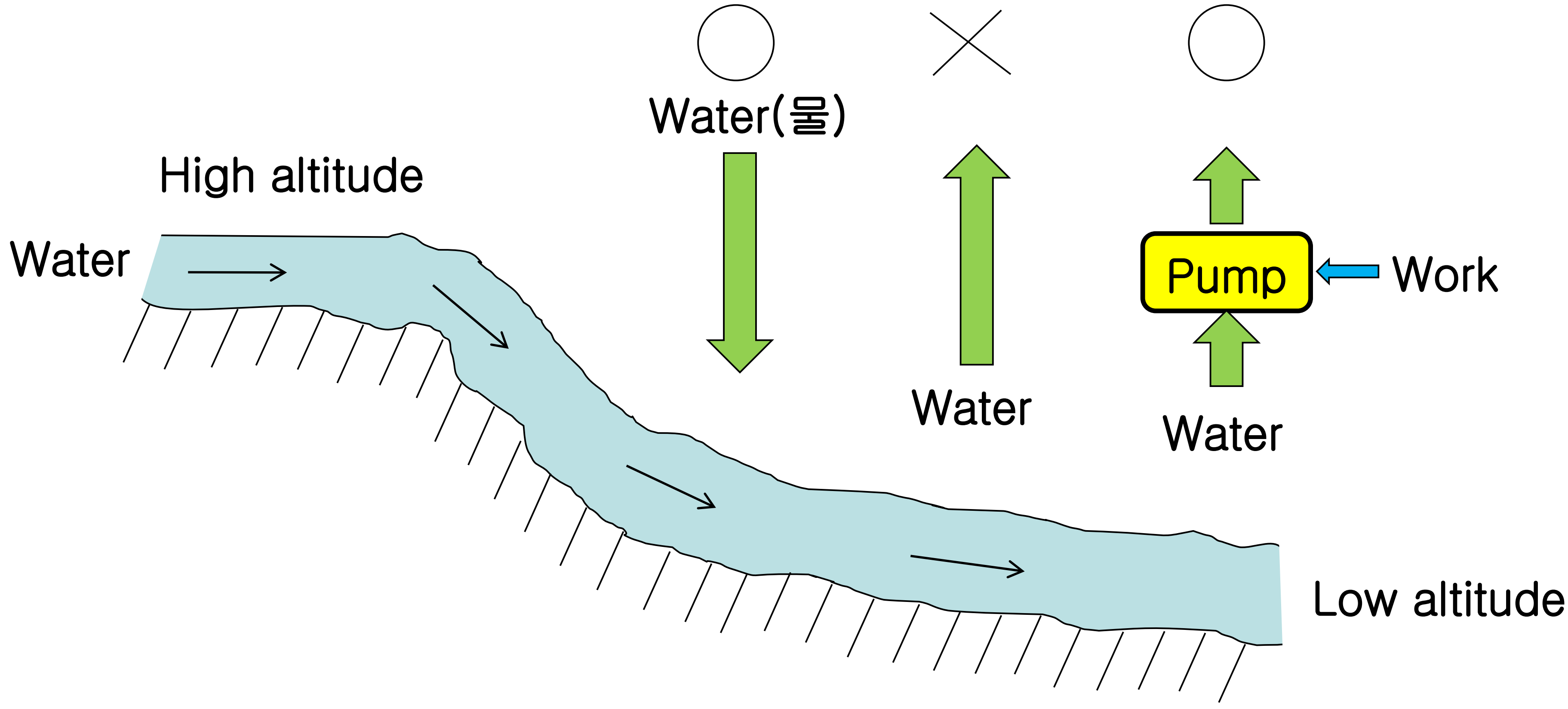






Refrigerants

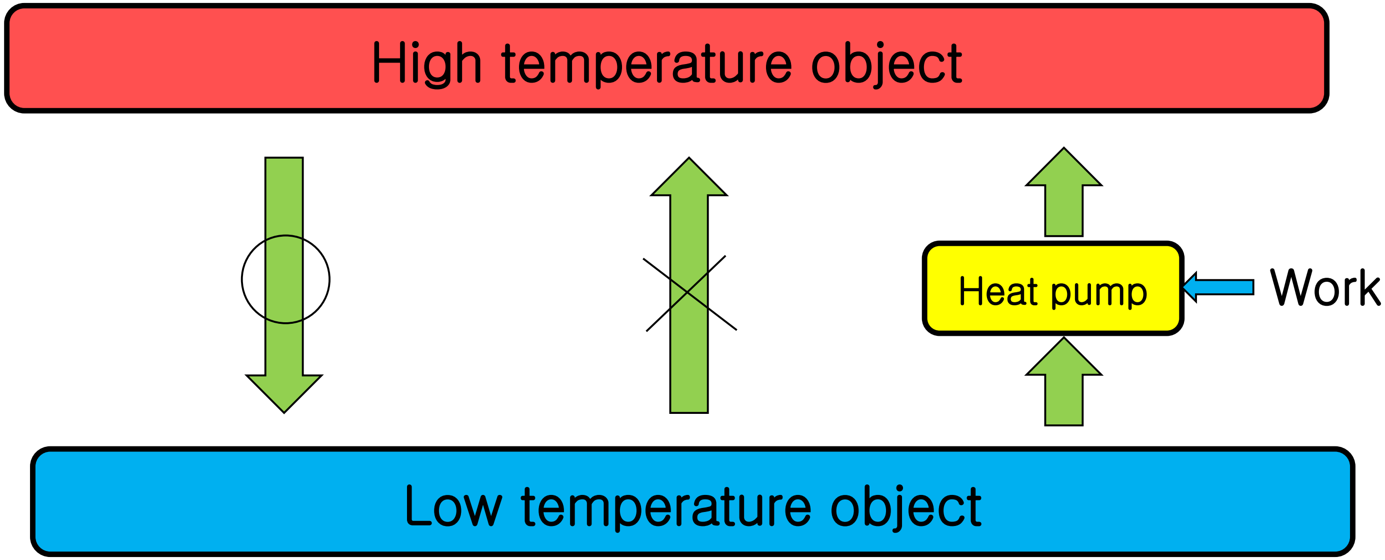
Pump



Water flows from high to low altitude (gravity effect).

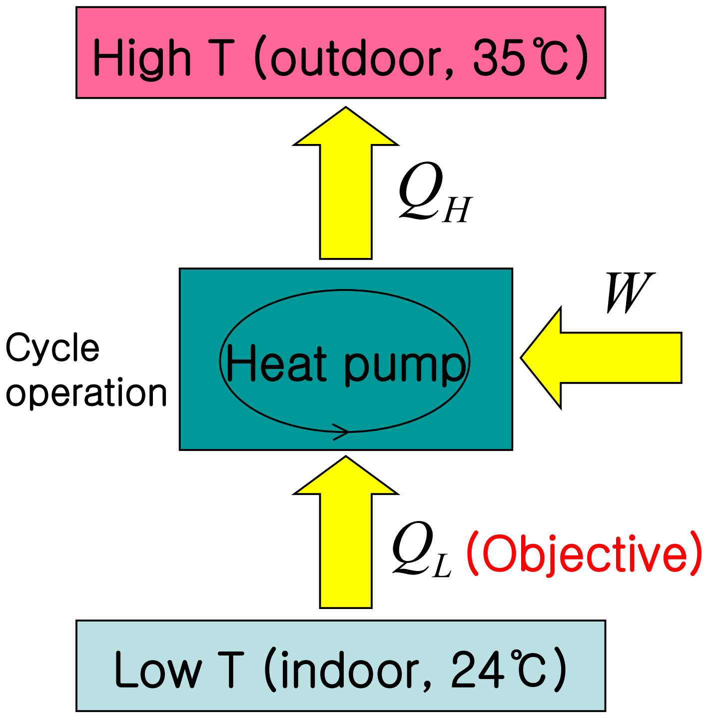
To transfer water from low to high altitude, external work is required.

Heat pump



- Naturally, heat flows from high to low temperature.
- To transfer heat from low to high temperature, heat pump which requires work input is required.
- 2nd law of thermodynamics : To transfer heat from low to high temperature, work input is required.

Heat pump (Cooling)

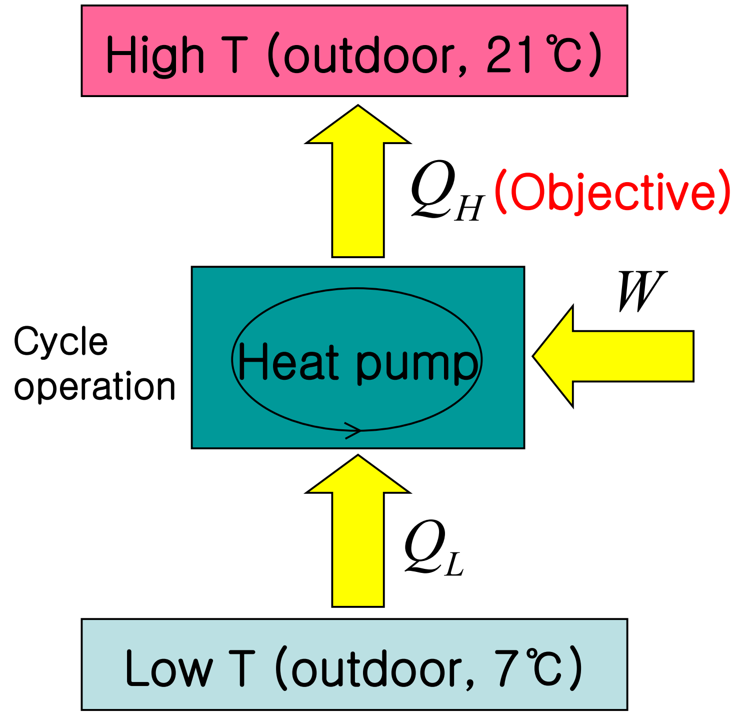


1st law of thermodynamics $Q_L + W = Q_H$

Coefficient of performance (COP)

$$\mathrm{COP_L} = \frac{Q_L}{W} \approx 3$$

Heat pump (Heating)



1st law of thermodynamics $Q_L + W = Q_H$

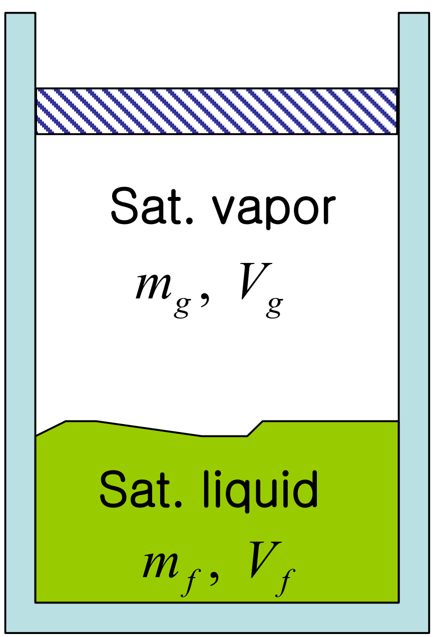
Coefficient of performance (COP)

$$\mathrm{COP_H} = \frac{Q_H}{W} \approx 2$$

Vapor–liquid equilibrium, Saturated state

Saturation temperature(포화온도) T_{sat}, saturation pressure(포화압력) P_{sat}

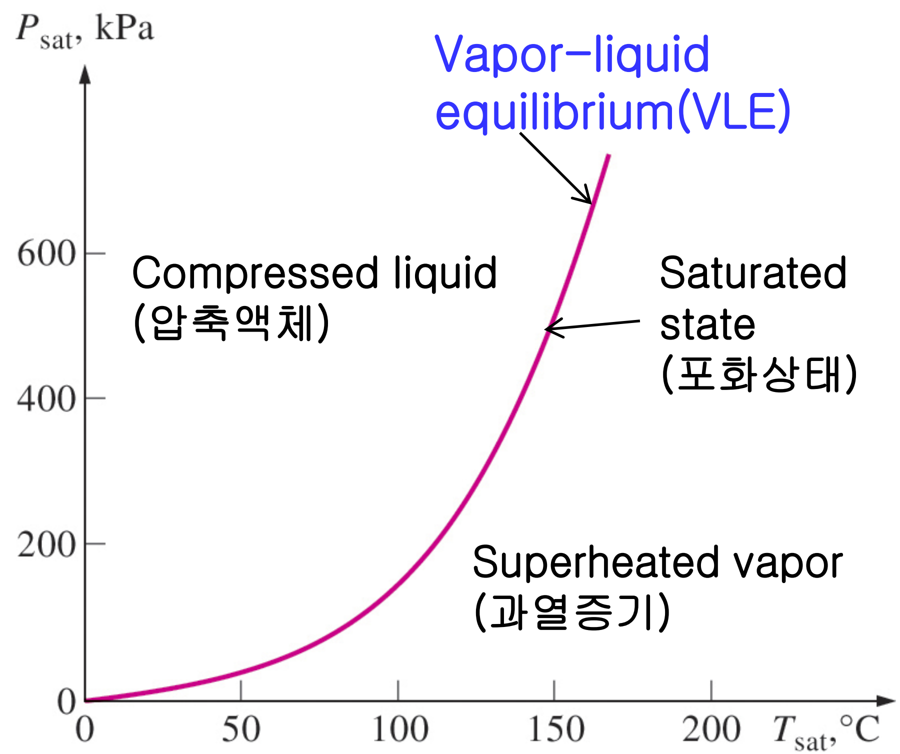
- Evaporation and condensation temperatures depend on pressure.
- If pressure is determined then evaporation or condensation T is known.
- At 1 atm (101.325 kPa) pressure, water boils at 100°C.
- Saturation T_{sat} : T at which 2 phases(liquid, vapor) exist under given P.
- Saturation P_{sat} : P at which 2 phases(liquid, vapor) exist under given T.



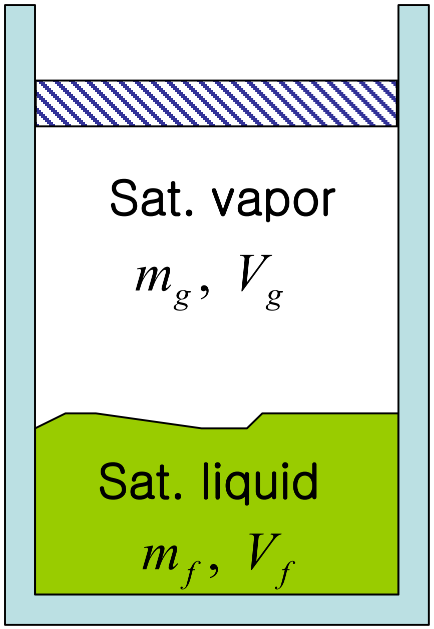
Quality(건도) x

$$x = \frac{\text{Sat. vapor mass}}{\text{Total mass}}$$

$$x = \frac{m_g}{m_f + m_g}$$



Vapor-liquid equilibrium, Saturated state



$$m = m_f + m_g$$

Quality(건도) x

$$x = \frac{m_g}{m} = \frac{m_g}{m_f + m_g}$$

If $x = 0$, then saturated liquid
If $x = 1$, then saturated vapor
$0 \leq x \leq 1$

$$V = V_f + V_g$$

$$V = m_f v_f + m_g v_g$$

Dividing both sides by mass m

$$\frac{V}{m} = \frac{m_f}{m} v_f + \frac{m_g}{m} v_g = (1 - x)\ v_f + x v_g$$

$$\frac{V}{m} = v \qquad \frac{m_f}{m} = \frac{m - m_g}{m} = 1 - x$$

$$v = v_f + x(v_g - v_f)$$

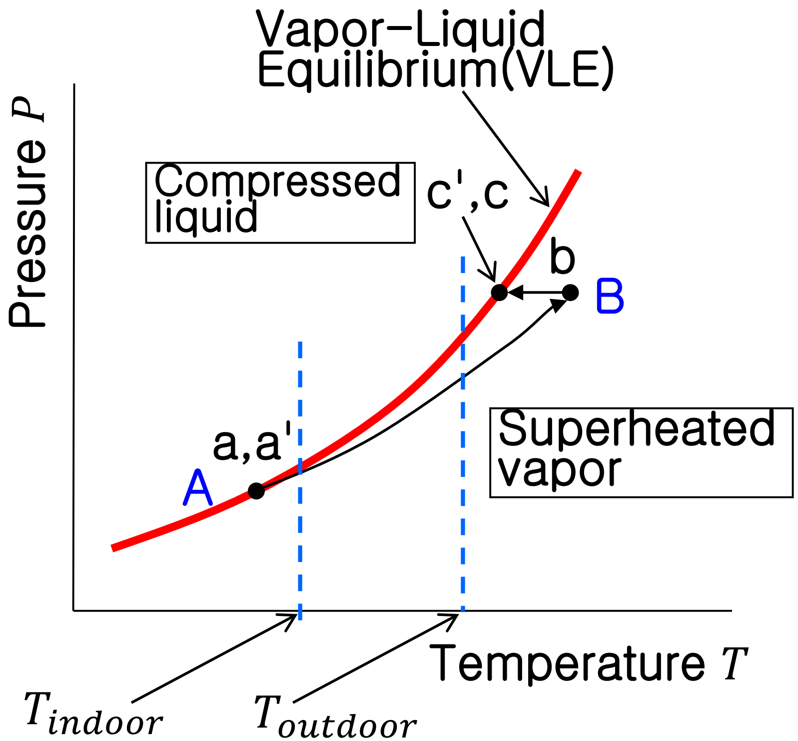
Average specific volume of saturated state

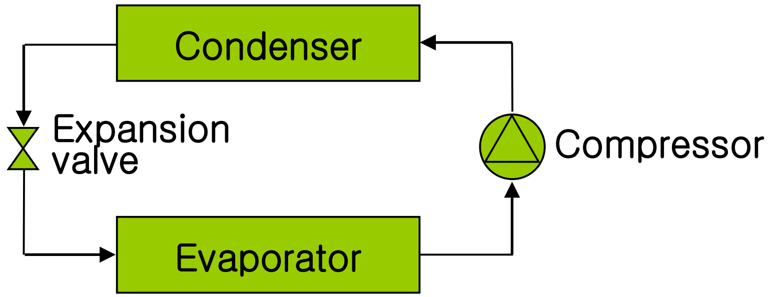
For saturated state

$$y = y_f + x(y_g - y_f)$$

y can be v(specific volume), u(internal energy), h(enthalpy) or s(entropy)

Ideal vapor compression heat pump cycle





◈ Evaporator(A) : P = C
a → a' Evaporation
Sat liquid → Sat. vapor, T = C

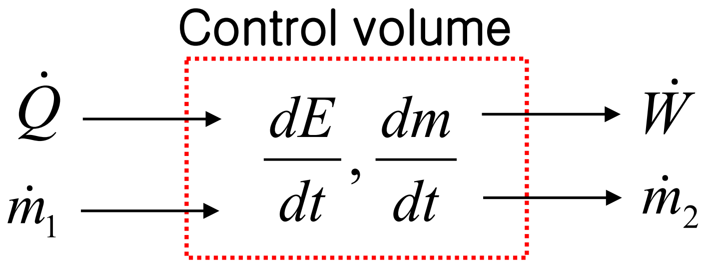
◈ Compressor : Adiabatic
a' → b Compression P ↑, T ↑,
Sat. vapor → Superheated vapor

◈ Condenser(B) : P = C
b → c' Cooling, T ↓
Superheated vapor → Sat. vapor
c' → c Condensation, T = C
Sat. vapor → Sat. liquid

◈ Expansion valve h = C
c → a Expansion, P ↓, T ↓, v ↑
Sat. liquid → Sat. vapor

에너지 보존의 법칙

1st Law of Thermodynamics or Conservation of Energy (Rate form)



g : gravitational acceleration, 9.807 m/s^2

h : enthalpy, kJ/kg $\quad$ $\dot{m}$: mass flow rate, kg/s

$\dot{Q}$: heat transfer rate, kJ/s = kW

$\dot{W}$: work rate, kJ/s = kW

t : time, s

Subscript: 1 : inlet 2 : exit

(1) Steady + kinetic and potential energy changes negligible

$$\dot{Q} + \dot{m}_1 h_1 = \dot{m}_2 h_2 + \dot{W} \qquad \dot{m}_1 = \dot{m}_2 = \dot{m} \qquad q + h_1 = h_2 + w$$

(2) Steady + kinetic and potential energy changes negligible + no work

$$\dot{Q} + \dot{m}_1 h_1 = \dot{m}_2 h_2 \qquad q = h_2 - h_1$$ {Heat exchanger(evaporator, condenser)}

(3) Steady + kinetic and potential energy changes negligible + no work + adiabatic

$$\dot{m}_1 h_1 = \dot{m}_2 h_2 \qquad h_1 = h_2$$ {Expansion valve}

(4) Steady + kinetic and potential energy changes negligible + adiabatic

$$\dot{m}_1 h_1 = \dot{m}_2 h_2 - \dot{W} \qquad w = h_1 - h_2$$ {Compressor}

Types of refrigerant compression

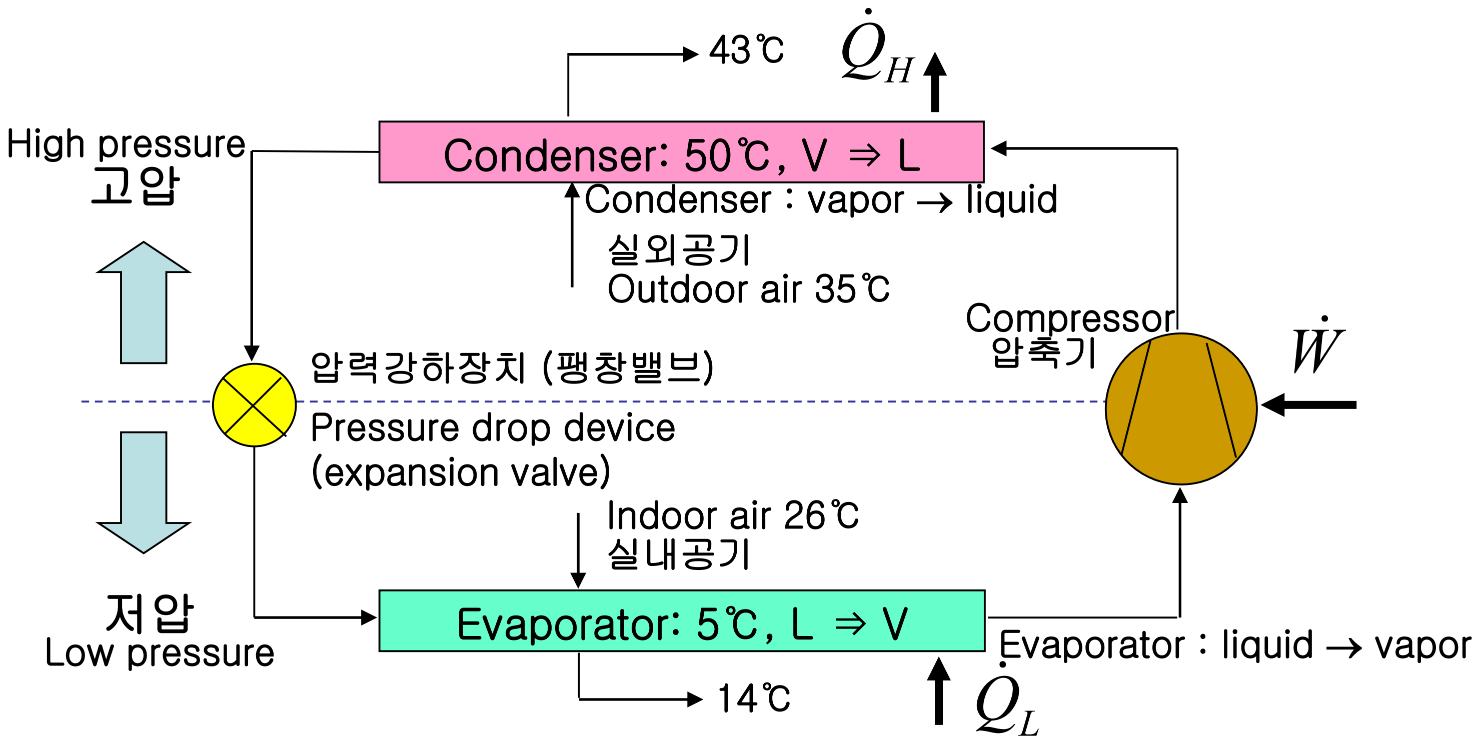
Pressure

- When in operation, refrigeration cycle operates between high P and low P.
- Types are classified based on pressure increasing methods.

			Capacity	Usage (용도)
Vapor Compression (증기 압축식)	Volume (용적식)	Reciprocating	Small Medium	Refrigerator, air-conditioner, car air-conditioner
		Rotary	Small	Small capacity air-conditioner
		Scroll	S · M	Package air-conditioner
		Screw	M · L	Medium size building cooling
	Centrifugal (원심식)	Turbo	Large	Large size building cooling
Absorption (흡수식) Liquid compression (액체 압축식)	Single effect(1중효용)		Large	Hot water, LSB heating
	Double effect(2중효용)		Large	Steam, LSB heating
	Absorption chiller/heater (흡수식 냉온수기)		Large	Direct fired heat source, LSB cooling, heating, hot water

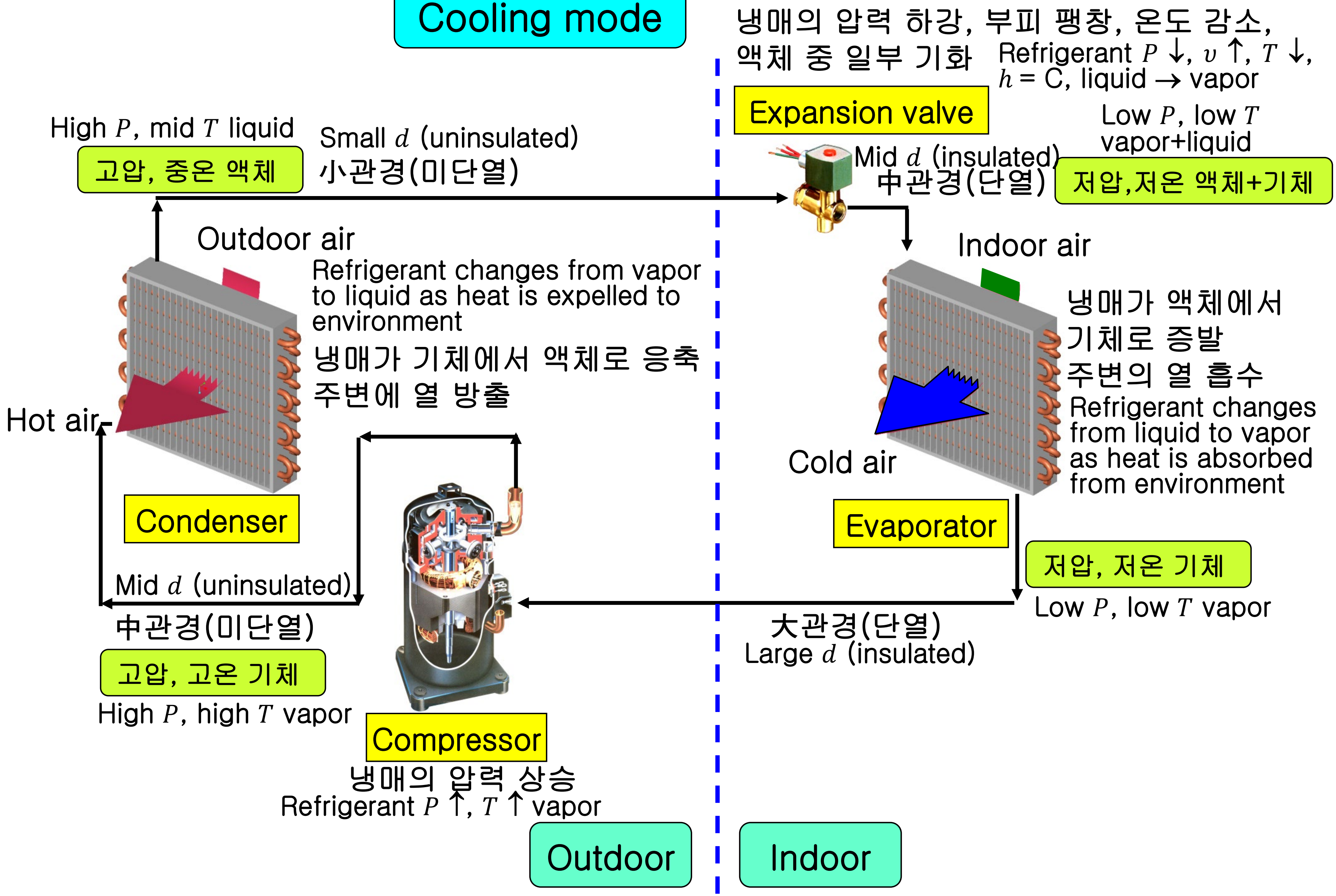
Vapor compression refrigeration cycle

- Most popular refrigeration type
- Consists of 4 major components
  - Compressor : increases refrigerant pressure (temperature ↑ as well)
  - Condenser : condenses vapor to liquid by discharging heat to outside
  - Pressure drop device (expansion valve) : P ↓, t ↓, part of liquid → vapor
  - Evaporator : evaporates liquid to vapor by absorbing heat from outside



냉방 운전

Cooling mode



Vapor compression – volume compression type

- Compressor affects 70% of heat pump performance
- For air cooled heat pump, heat exchanger affects 30% of performance, 50% of weight, 80% of volume.
- Compressor efficiency

entropy(s) = constant

1. Isentropic efficiency(등엔트로피 효율) : Related to power consumption

$$\eta_s = \frac{w_{ideal}}{w_{actual}} \approx 0.7$$

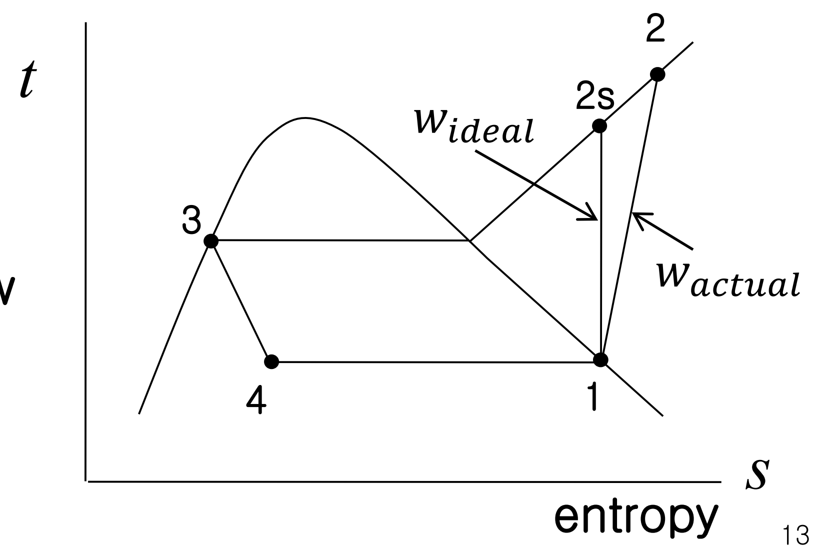
$$w_{ideal} = h_{2s} - h_1 \quad \text{(isentropic process)}$$

$$w_{actual} = h_2 - h_1$$

2. Volumetric efficiency(체적효율) : Related to capacity

$$\eta_v = \frac{\dot{m}_{actual}}{\dot{m}_{ideal}} \approx 0.9$$

- Type : Reciprocating, rotary, scroll, screw
  왕복동식, 로터리, 스크롤, 스크류



6 Assumptions of an ideal vapor compression refrigeration cycle

Rankine cycle : Steam turbine power cycle for generating electricity

Not an actual cycle, but simplified for theoretical analysis

◆ Ideal refrigeration cycle → Reverse Rankine cycle (역(逆)랭킨 사이클)

① Evaporator exit (state 1) : saturated vapor (x_1 = 1)

② Condenser exit (state 3) : saturated liquid (x_3 = 0) $x = \frac{m_g}{m}$ quality

③ 1→2 : adiabatic compression (P ↑, t ↑)

④ 2→3a→3 : P = C condensation

2→3a : vapor cooling (t ↓)

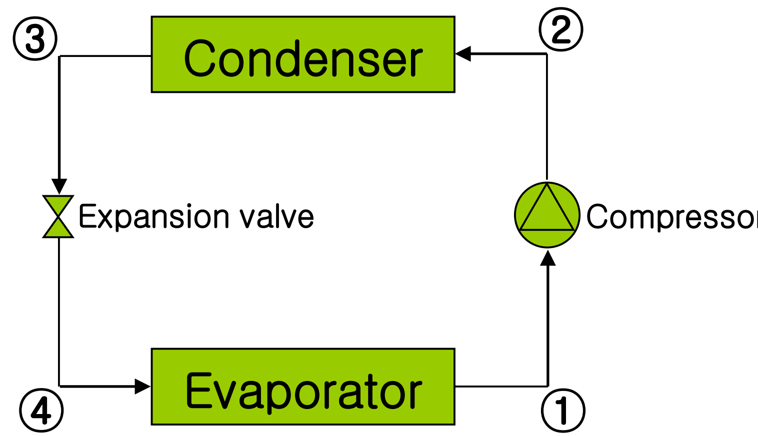
3a→3 : vapor → liquid (t = C)

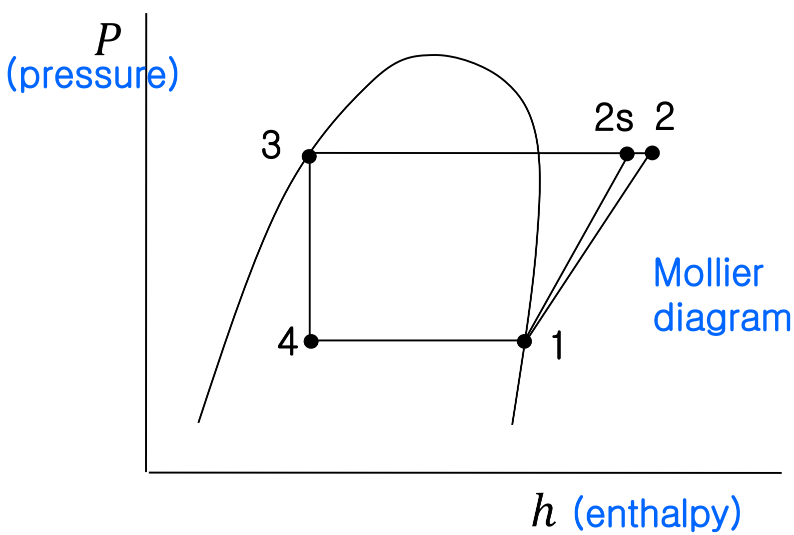
⑤ 3→4 : h = C expansion (t ↓, P ↓)

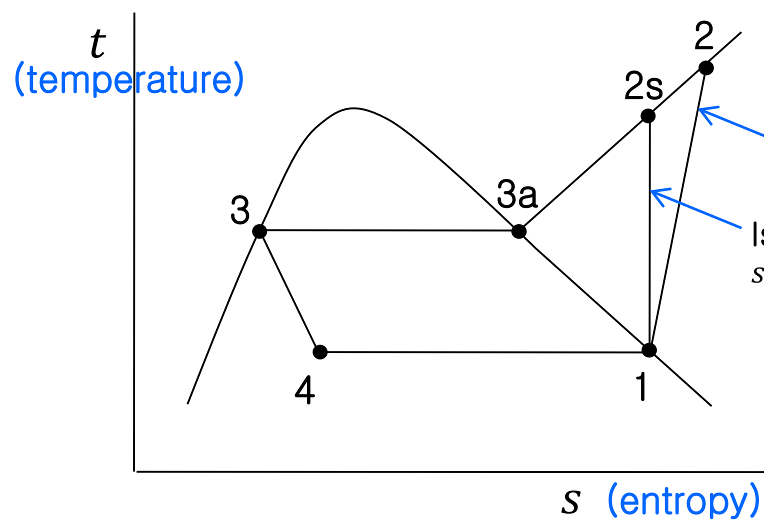
some liquid → vapor

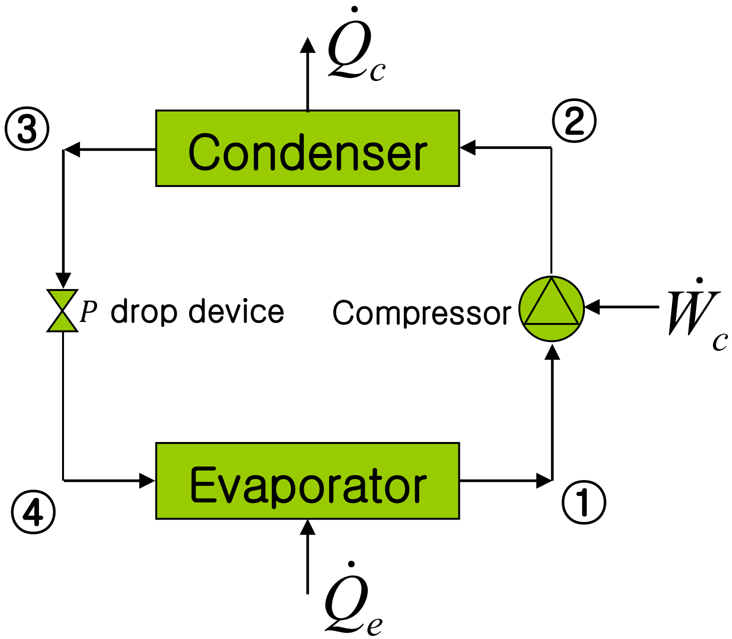
⑥ 4→1 : P = C evaporation (t = C)

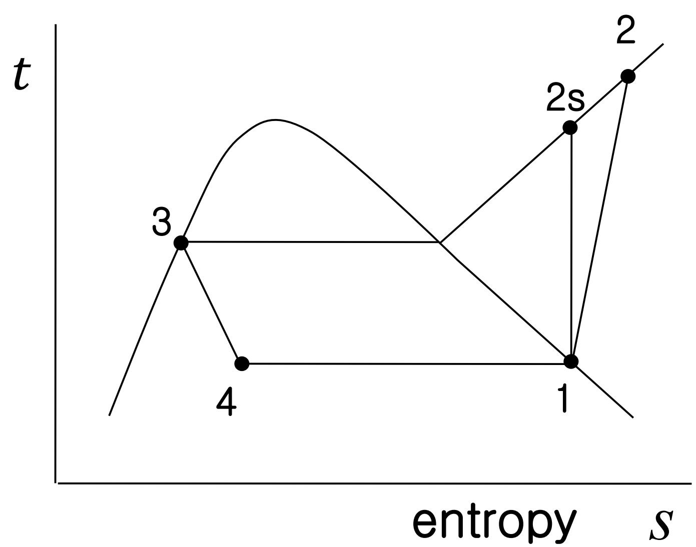
rest of the liquid → vapor











Evaporator : $\dot{m}h_4 + \dot{Q}_e = \dot{m}h_1$

$$\dot{Q}_e = \dot{m}(h_1 - h_4) \qquad q_e = \frac{\dot{Q}_e}{\dot{m}} = h_1 - h_4$$

Compressor : $\dot{m}h_1 + \dot{W}_c = \dot{m}h_2$

$$\dot{W}_c = \dot{m}(h_2 - h_1) \qquad w_c = \frac{\dot{W}_c}{\dot{m}} = h_2 - h_1$$

Condenser : $\dot{m}h_2 = \dot{Q}_c + \dot{m}h_3$

$$\dot{Q}_c = \dot{m}(h_2 - h_3) \qquad q_c = \frac{\dot{Q}_c}{\dot{m}} = h_2 - h_3$$

P drop device : $\dot{m}h_3 = \dot{m}h_4$
(Expansion valve)

$$h_3 = h_4$$

◈ Analysis of ideal refrigeration cycle

Given : $P_1, \; P_3, \; \eta_s$ (eta) or $t_1, \; t_3, \; \eta_s$ (η_s : Compressor isentropic efficiency)

State 1 = $f(P_1, x_1 = 1)$

State 3 = $f(P_3, x_3 = 0)$

$$P_{2s} = P_2 = P_3$$

$$s_{2s} = s_1$$

State 2s = $f(P_{2s}, s_{2s})$

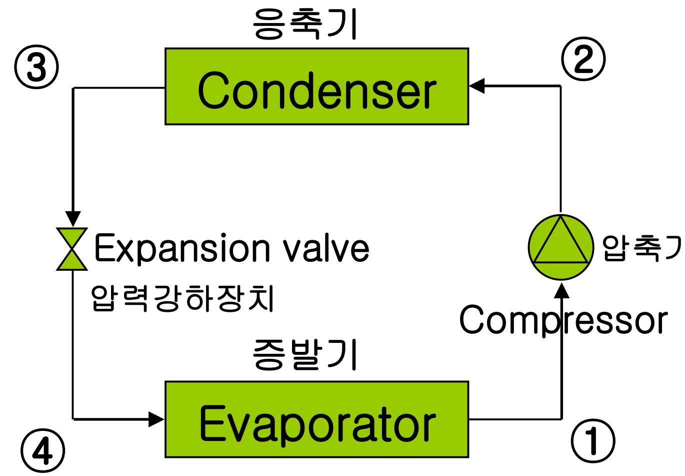
$$\eta_s = \frac{w_s}{w_a} = \frac{h_{2s} - h_1}{h_2 - h_1}$$

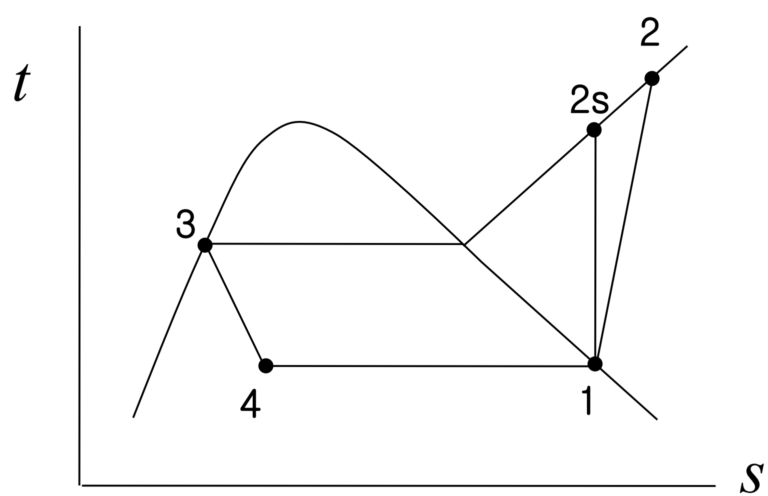
$$h_2 = h_1 + \frac{h_{2s} - h_1}{\eta_s}$$

State 2 = $f(P_2, h_2)$

$$P_4 = P_1, \quad h_4 = h_3$$

State 4 = $f(P_4, h_4)$





Cooling capacity per mass : $q_L = h_1 - h_4$

Heating capacity per mass : $q_H = h_2 - h_3$

Compressor work per mass: $w_c = h_2 - h_1$

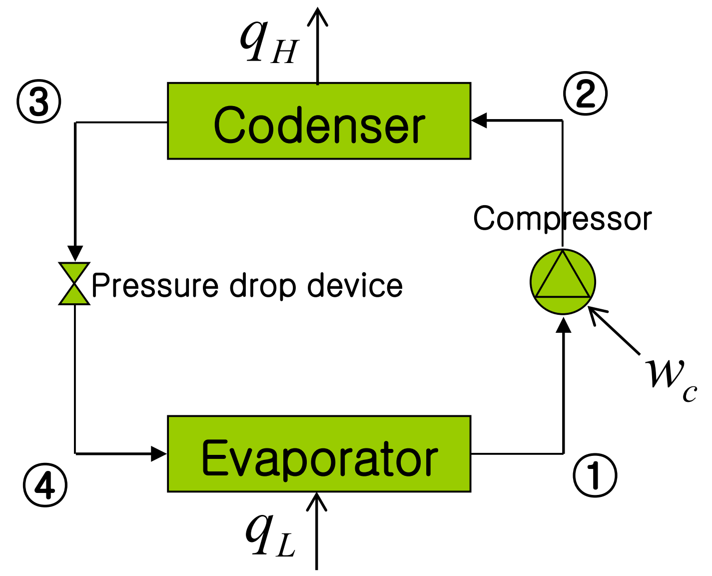
Coefficient of performance (COP, 성적계수) :

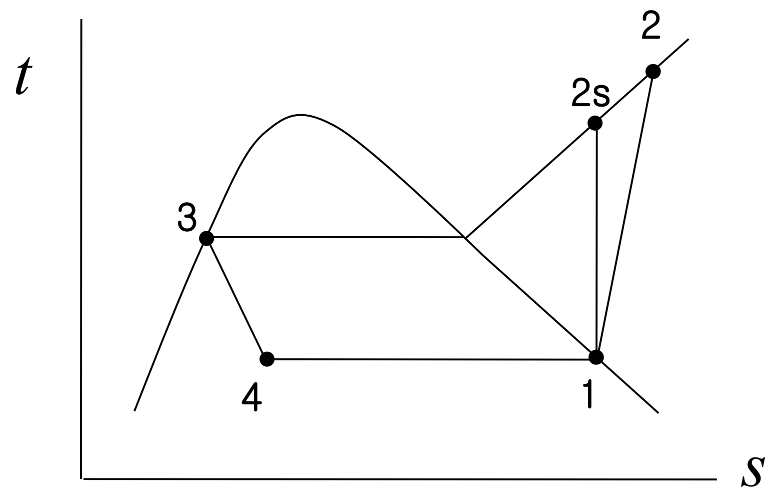
$$\mathrm{COP}_L = \frac{q_L}{w_c} = \frac{h_1 - h_4}{h_2 - h_1}$$

$$\mathrm{COP}_H = \frac{q_H}{w_c} = \frac{h_2 - h_3}{h_2 - h_1}$$

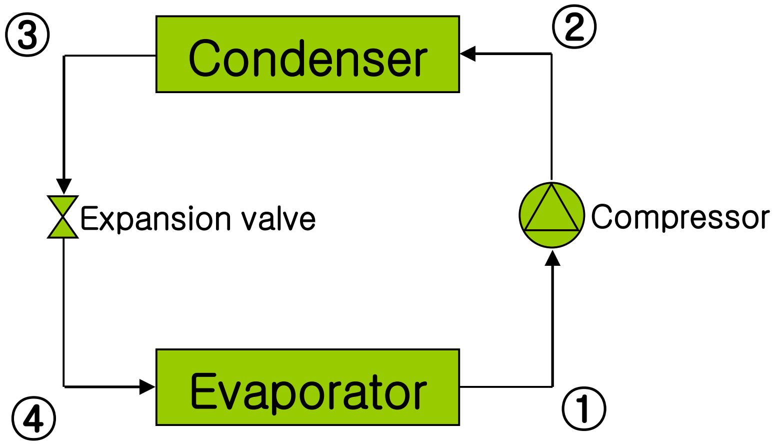
$$\mathrm{COP}_H = \frac{h_2 - h_3}{h_2 - h_1} = \frac{h_2 - h_1 + h_1 - h_3}{h_2 - h_1}$$

$$= \frac{h_2 - h_1}{h_2 - h_1} + \frac{h_1 - h_3}{h_2 - h_1} = 1 + \mathrm{COP}_L$$





[1a] Ideal refrigerant cycle. R134a, evaporator pressure P_{evap} = 240 kPa, condenser pressure P_{cond} = 1200 kPa, compressor isentropic efficiency η_s = 0.7, mass flow rate $\dot{m}$ = 0.1 kg/s. Find evaporator capacity per mass q_e (kJ/kg), condenser capacity per mass q_c(kJ/kg), compressor work per mass w_c(kJ/kg), cooling COP_L, heating COP_H, compressor exit temperature t_2(℃), evaporator inlet quality x_4, evaporator capacity $\dot{Q}_e$, condenser capacity $\dot{Q}_c$, compressor power $\dot{W}_c$ in kW. Use thermodynamic property table.



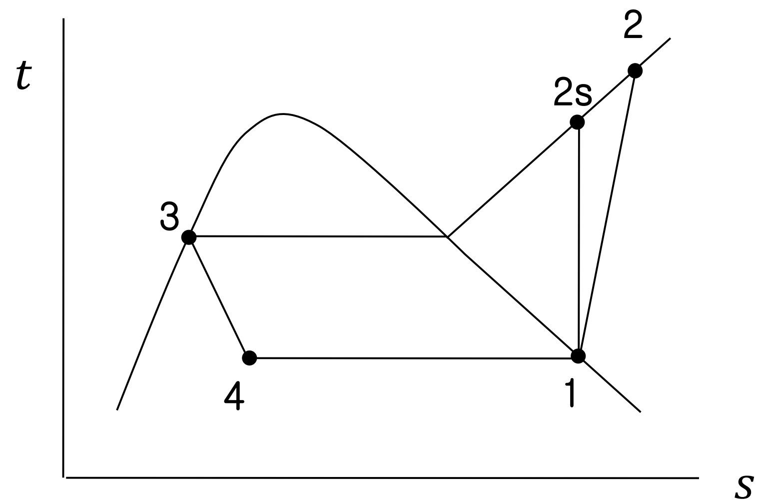


TABLE A–12

Saturated refrigerant-134a—Pressure table

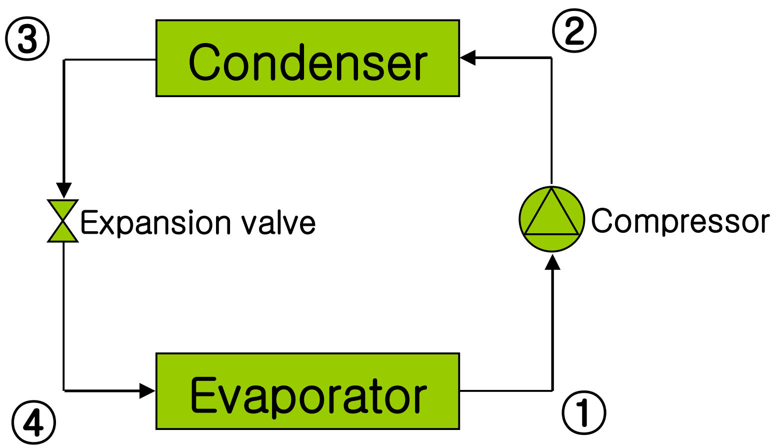
		Specific volume, m³/kg		Internal energy, kJ/kg			Enthalpy, kJ/kg			Entropy, kJ/kg·K		
Press., P kPa	Sat. temp., T_{sat} °C	Sat. liquid, v_f	Sat. vapor, v_g	Sat. liquid, u_f	Evap., u_{fg}	Sat. vapor, u_g	Sat. liquid, h_f	Evap., h_{fg}	Sat. vapor, h_g	Sat. liquid, s_f	Evap., s_{fg}	Sat. vapor, s_g
60	−36.95	0.0007097	0.31108	3.795	205.34	209.13	3.837	223.96	227.80	0.01633	0.94812	0.96445
70	−33.87	0.0007143	0.26921	7.672	203.23	210.90	7.722	222.02	229.74	0.03264	0.92783	0.96047
80	−31.13	0.0007184	0.23749	11.14	201.33	212.48	11.20	220.27	231.47	0.04707	0.91009	0.95716
90	−28.65	0.0007222	0.21261	14.30	199.60	213.90	14.36	218.67	233.04	0.06003	0.89431	0.95434
100	−26.37	0.0007258	0.19255	17.19	198.01	215.21	17.27	217.19	234.46	0.07182	0.88008	0.95191
120	−22.32	0.0007323	0.16216	22.38	195.15	217.53	22.47	214.52	236.99	0.09269	0.85520	0.94789
140	−18.77	0.0007381	0.14020	26.96	192.60	219.56	27.06	212.13	239.19	0.11080	0.83387	0.94467
160	−15.60	0.0007435	0.12355	31.06	190.31	221.37	31.18	209.96	241.14	0.12686	0.81517	0.94202
180	−12.73	0.0007485	0.11049	34.81	188.20	223.01	34.94	207.95	242.90	0.14131	0.79848	0.93979
200	−10.09	0.0007532	0.099951	38.26	186.25	224.51	38.41	206.09	244.50	0.15449	0.78339	0.93788
240	−5.38	0.0007618	0.083983	44.46	182.71	227.17	44.64	202.68	247.32	0.17786	0.75689	0.93475
280	−1.25	0.0007697	0.072434	49.95	179.54	229.49	50.16	199.61	249.77	0.19822	0.73406	0.93228
320	2.46	0.0007771	0.063681	54.90	176.65	231.55	55.14	196.78	251.93	0.21631	0.71395	0.93026
360	5.82	0.0007840	0.056809	59.42	173.99	233.41	59.70	194.15	253.86	0.23265	0.69591	0.92856
400	8.91	0.0007905	0.051266	63.61	171.49	235.10	63.92	191.68	255.61	0.24757	0.67954	0.92711
450	12.46	0.0007983	0.045677	68.44	168.58	237.03	68.80	188.78	257.58	0.26462	0.66093	0.92555
500	15.71	0.0008058	0.041168	72.92	165.86	238.77	73.32	186.04	259.36	0.28021	0.64399	0.92420
550	18.73	0.0008129	0.037452	77.09	163.29	240.38	77.54	183.44	260.98	0.29460	0.62842	0.92302
600	21.55	0.0008198	0.034335	81.01	160.84	241.86	81.50	180.95	262.46	0.30799	0.61398	0.92196
650	24.20	0.0008265	0.031680	84.72	158.51	243.23	85.26	178.56	263.82	0.32052	0.60048	0.92100
700	26.69	0.0008331	0.029392	88.24	156.27	244.51	88.82	176.26	265.08	0.33232	0.58780	0.92012
750	29.06	0.0008395	0.027398	91.59	154.11	245.70	92.22	174.03	266.25	0.34348	0.57582	0.91930
800	31.31	0.0008457	0.025645	94.80	152.02	246.82	95.48	171.86	267.34	0.35408	0.56445	0.91853
850	33.45	0.0008519	0.024091	97.88	150.00	247.88	98.61	169.75	268.36	0.36417	0.55362	0.91779
900	35.51	0.0008580	0.022703	100.84	148.03	248.88	101.62	167.69	269.31	0.37383	0.54326	0.91709
950	37.48	0.0008640	0.021456	103.70	146.11	249.82	104.52	165.68	270.20	0.38307	0.53333	0.91641
1000	39.37	0.0008700	0.020329	106.47	144.24	250.71	107.34	163.70	271.04	0.39196	0.52378	0.91574
1200	46.29	0.0008935	0.016728	116.72	137.12	253.84	117.79	156.12	273.92	0.42449	0.48870	0.91320
1400	52.40	0.0009167	0.014119	125.96	130.44	256.40	127.25	148.92	276.17	0.45325	0.45742	0.91067
1600	57.88	0.0009400	0.012134	134.45	124.05	258.50	135.96	141.96	277.92	0.47921	0.42881	0.90802
1800	62.87	0.0009639	0.010568	142.36	117.85	260.21	144.09	135.14	279.23	0.50304	0.40213	0.90517
2000	67.45	0.0009887	0.009297	149.81	111.75	261.56	151.78	128.36	280.15	0.52519	0.37684	0.90204
2500	77.54	0.0010567	0.006941	167.02	96.47	263.49	169.66	111.18	280.84	0.57542	0.31701	0.89243
3000	86.16	0.0011410	0.005272	183.09	80.17	263.26	186.51	92.57	279.08	0.62133	0.25759	0.87893

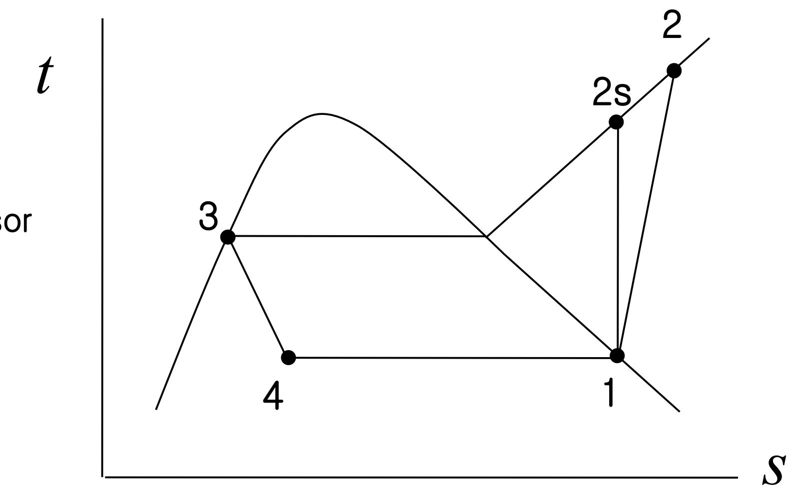
TABLE A–13

Superheated refrigerant-134a *(Concluded)*

T °C	v m^3/kg	u kJ/kg	h kJ/kg	s kJ/kg·K	v m^3/kg	u kJ/kg	h kJ/kg	s kJ/kg·K	v m^3/kg	u kJ/kg	h kJ/kg	s kJ/kg·K
	P = 0.50 MPa (T_{sat} = 15.71°C)				P = 0.60 MPa (T_{sat} = 21.55°C)				P = 0.70 MPa (T_{sat} = 26.69°C)			
Sat.	0.041168	238.77	259.36	0.9242	0.034335	241.86	262.46	0.9220	0.029392	244.51	265.08	0.9201
20	0.042115	242.42	263.48	0.9384								
30	0.044338	250.86	273.03	0.9704	0.035984	249.24	270.83	0.9500	0.029966	247.49	268.47	0.9314
40	0.046456	259.27	282.50	1.0011	0.037865	257.88	280.60	0.9817	0.031696	256.41	278.59	0.9642
50	0.048499	267.73	291.98	1.0309	0.039659	266.50	290.30	1.0122	0.033322	265.22	288.54	0.9955
60	0.050485	276.27	301.51	1.0600	0.041389	275.17	300.00	1.0417	0.034875	274.03	298.44	1.0257
70	0.052427	284.91	311.12	1.0884	0.043069	283.91	309.75	1.0706	0.036373	282.88	308.34	1.0550
80	0.054331	293.65	320.82	1.1163	0.044710	292.74	319.57	1.0988	0.037829	291.81	318.29	1.0835
90	0.056205	302.52	330.63	1.1436	0.046318	301.69	329.48	1.1265	0.039250	300.84	328.31	1.1115
100	0.058053	311.52	340.55	1.1706	0.047900	310.75	339.49	1.1536	0.040642	309.96	338.41	1.1389
110	0.059880	320.65	350.59	1.1971	0.049458	319.93	349.61	1.1804	0.042010	319.21	348.61	1.1659
120	0.061687	329.91	360.75	1.2233	0.050997	329.24	359.84	1.2068	0.043358	328.57	358.92	1.1925
130	0.063479	339.31	371.05	1.2492	0.052519	338.69	370.20	1.2328	0.044688	338.06	369.34	1.2186
140	0.065256	348.85	381.47	1.2747	0.054027	348.26	380.68	1.2585	0.046004	347.67	379.88	1.2445
150	0.067021	358.52	392.04	1.3000	0.055522	357.98	391.29	1.2838	0.047306	357.42	390.54	1.2700
160	0.068775	368.34	402.73	1.3250	0.057006	367.83	402.03	1.3089	0.048597	367.31	401.32	1.2952
	P = 0.80 MPa (T_{sat} = 31.31°C)				P = 0.90 MPa (T_{sat} = 35.51°C)				P = 1.00 MPa (T_{sat} = 39.37°C)			
Sat.	0.025645	246.82	267.34	0.9185	0.022686	248.82	269.25	0.9169	0.020319	250.71	271.04	0.9157
40	0.027035	254.84	276.46	0.9481	0.023375	253.15	274.19	0.9328	0.020406	251.32	271.73	0.9180
50	0.028547	263.87	286.71	0.9803	0.024809	262.46	284.79	0.9661	0.021796	260.96	282.76	0.9526
60	0.029973	272.85	296.82	1.0111	0.026146	271.62	295.15	0.9977	0.023068	270.33	293.40	0.9851
70	0.031340	281.83	306.90	1.0409	0.027413	280.74	305.41	1.0280	0.024261	279.61	303.87	1.0160
80	0.032659	290.86	316.99	1.0699	0.028630	289.88	315.65	1.0574	0.025398	288.87	314.27	1.0459
90	0.033941	299.97	327.12	1.0982	0.029806	299.08	325.90	1.0861	0.026492	298.17	324.66	1.0749
100	0.035193	309.17	337.32	1.1259	0.030951	308.35	336.21	1.1141	0.027552	307.52	335.08	1.1032
110	0.036420	318.47	347.61	1.1531	0.032068	317.72	346.58	1.1415	0.028584	316.96	345.54	1.1309
120	0.037625	327.89	357.99	1.1798	0.033164	327.19	357.04	1.1684	0.029592	326.49	356.08	1.1580
130	0.038813	337.42	368.47	1.2062	0.034241	336.78	367.59	1.1949	0.030581	336.12	366.70	1.1847
140	0.039985	347.08	379.07	1.2321	0.035302	346.48	378.25	1.2211	0.031554	345.87	377.42	1.2110
150	0.041143	356.86	389.78	1.2577	0.036349	356.30	389.01	1.2468	0.032512	355.73	388.24	1.2369
160	0.042290	366.78	400.61	1.2830	0.037384	366.25	399.89	1.2722	0.033457	365.71	399.17	1.2624
170	0.043427	376.83	411.57	1.3081	0.038408	376.33	410.89	1.2973	0.034392	375.82	410.22	1.2876
180	0.044554	387.01	422.65	1.3328	0.039423	386.54	422.02	1.3221	0.035317	386.06	421.38	1.3125
	P = 1.20 MPa (T_{sat} = 46.29°C)				P = 1.40 MPa (T_{sat} = 52.40°C)				P = 1.60 MPa (T_{sat} = 57.88°C)			
Sat.	0.016728	253.84	273.92	0.9132	0.014119	256.40	276.17	0.9107	0.012134	258.50	277.92	0.9080
50	0.017201	257.64	278.28	0.9268								
60	0.018404	267.57	289.66	0.9615	0.015005	264.46	285.47	0.9389	0.012372	260.91	280.71	0.9164
70	0.019502	277.23	300.63	0.9939	0.016060	274.62	297.10	0.9733	0.013430	271.78	293.27	0.9536
80	0.020529	286.77	311.40	1.0249	0.017023	284.51	308.34	1.0056	0.014362	282.11	305.09	0.9875
90	0.021506	296.28	322.09	1.0547	0.017923	294.28	319.37	1.0364	0.015215	292.19	316.53	1.0195
100	0.022442	305.81	332.74	1.0836	0.018778	304.01	330.30	1.0661	0.016014	302.16	327.78	1.0501
110	0.023348	315.40	343.41	1.1119	0.019597	313.76	341.19	1.0949	0.016773	312.09	338.93	1.0795
120	0.024228	325.05	354.12	1.1395	0.020388	323.55	352.09	1.1230	0.017500	322.03	350.03	1.1081
130	0.025086	334.79	364.90	1.1665	0.021155	333.41	363.02	1.1504	0.018201	332.02	361.14	1.1360
140	0.025927	344.63	375.74	1.1931	0.021904	343.34	374.01	1.1773	0.018882	342.06	372.27	1.1633
150	0.026753	354.57	386.68	1.2192	0.022636	353.37	385.07	1.2038	0.019545	352.19	383.46	1.1901
160	0.027566	364.63	397.71	1.2450	0.023355	363.51	396.20	1.2298	0.020194	362.40	394.71	1.2164
170	0.028367	374.80	408.84	1.2704	0.024061	373.75	407.43	1.2554	0.020830	372.71	406.04	1.2422
180	0.029158	385.10	420.09	1.2955	0.024757	384.12	418.78	1.2808	0.021456	383.13	417.46	1.2677

[1b] Ideal refrigerant cycle. R134a, evaporator pressure P_{evap} = 240 kPa, condenser pressure P_{cond} = 1200 kPa, compressor isentropic efficiency η_s = 0.7, mass flow rate $\dot{m}$ = 0.1 kg/s. Find evaporator capacity per mass q_e (kJ/kg), condenser capacity per mass q_c(kJ/kg), compressor work per mass w_c(kJ/kg), cooling COP_L, heating COP_H, compressor exit temperature t_2(℃), evaporator inlet quality x_4, evaporator capacity $\dot{Q}_e$, condenser capacity $\dot{Q}_c$, compressor power $\dot{W}_c$ in kW. Use EES software.



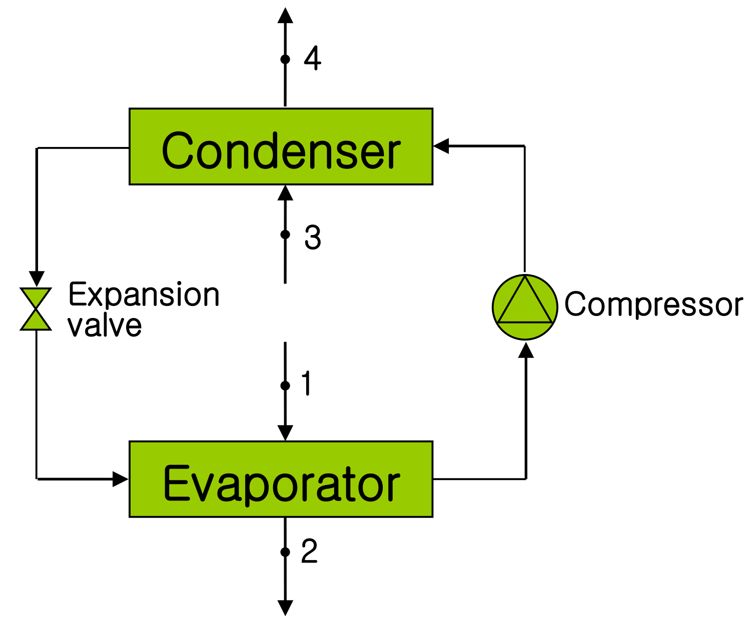


[2a] Heat pump(air–to–air). Evaporator air inlet temperature t_1 = 25.7℃, evaporator air inlet relative humidity ϕ_1 = 55%, Evaporator air outlet temperature t_2 = 12.7℃, evaporator air outlet relative humidity ϕ_2 = 95%, evaporator air inlet flow rate $\dot{V}_1$ =1325 cmh, condenser air inlet temperature t_3 = 30.7℃, condenser air inlet relative humidity ϕ_3 = 45%, condenser air outlet temperature t_4 = 39.4℃, condenser air outlet relative humidity ϕ_4 = 30.4%, condenser air inlet flow rate $\dot{V}_3$ = 4360 cmh, compressor power $\dot{W}_c$= 2.64 kW, indoor fan power $\dot{W}_{f,e}$= 0.12 kW, outdoor fan power $\dot{W}_{f,c}$= 0.22 kW.

Use thermodynamic property table and equations.

(1) Find cooling heat pump COP_{HP}.

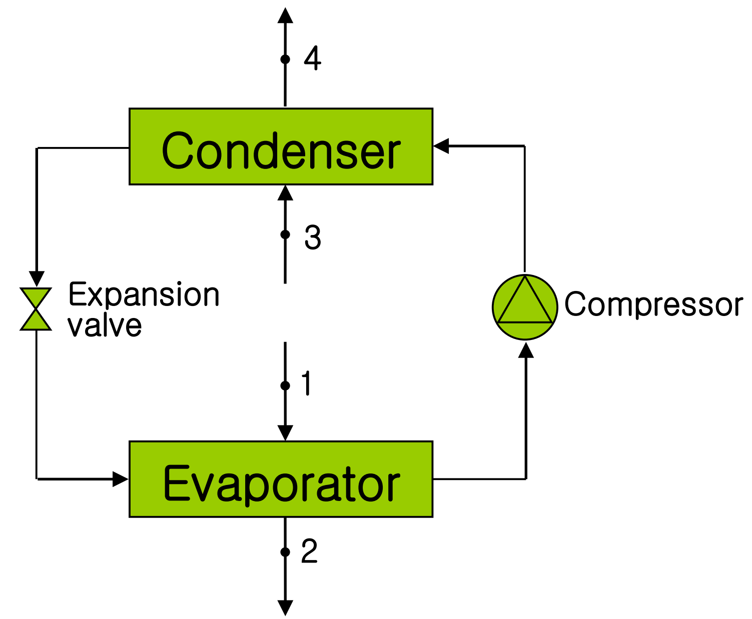
(2) Find cooling system COP_{system}.



[2b] Heat pump(air–to–air). Evaporator air inlet temperature t_1 = 25.7℃, evaporator air inlet relative humidity ϕ_1 = 55%, Evaporator air outlet temperature t_2 = 12.7℃, evaporator air outlet relative humidity ϕ_2 = 95%, evaporator air inlet flow rate $\dot{V}_1$ =1325 cmh, condenser air inlet temperature t_3 = 30.7℃, condenser air inlet relative humidity ϕ_3 = 45%, condenser air outlet temperature t_4 = 39.4℃, condenser air outlet relative humidity ϕ_4 = 30.4%, condenser air inlet flow rate $\dot{V}_3$ = 4360 cmh, compressor power $\dot{W}_c$= 2.64 kW, indoor fan power $\dot{W}_{f,e}$= 0.12 kW, outdoor fan power $\dot{W}_{f,c}$= 0.22 kW. Use psychrometric chart.

(1) Find cooling heat pump COP_{HP}.

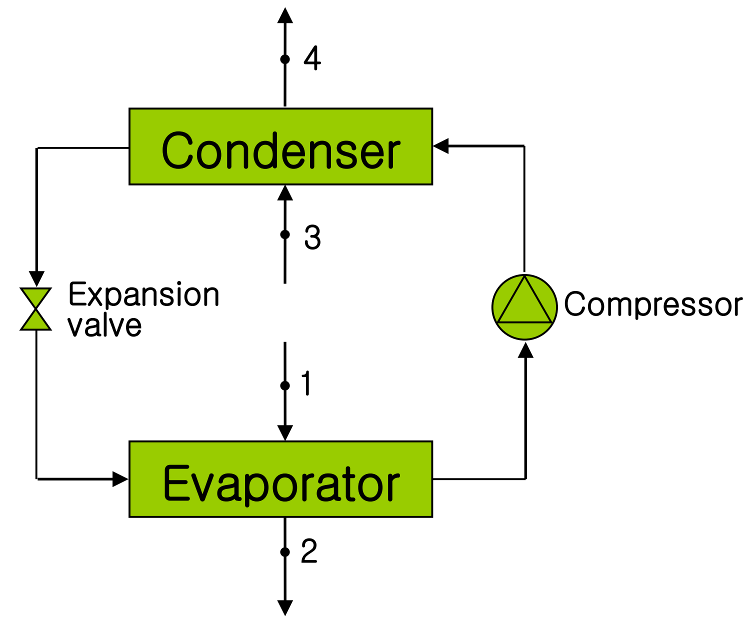
(2) Find cooling system COP_{system}.



[2c] Heat pump(air–to–air). Evaporator air inlet temperature t_1 = 25.7℃, evaporator air inlet relative humidity ϕ_1 = 55%, Evaporator air outlet temperature t_2 = 12.7℃, evaporator air outlet relative humidity ϕ_2 = 95%, evaporator air inlet flow rate $\dot{V}_1$ =1325 cmh, condenser air inlet temperature t_3 = 30.7℃, condenser air inlet relative humidity ϕ_3 = 45%, condenser air outlet temperature t_4 = 39.4℃, condenser air outlet relative humidity ϕ_4 = 30.4%, condenser air inlet flow rate $\dot{V}_3$ = 4360 cmh, compressor power $\dot{W}_c$= 2.64 kW, indoor fan power $\dot{W}_{f,e}$= 0.12 kW, outdoor fan power $\dot{W}_{f,c}$= 0.22 kW. Use EES software.

(1) Find cooling heat pump COP_{HP}.

(2) Find cooling system COP_{system}.



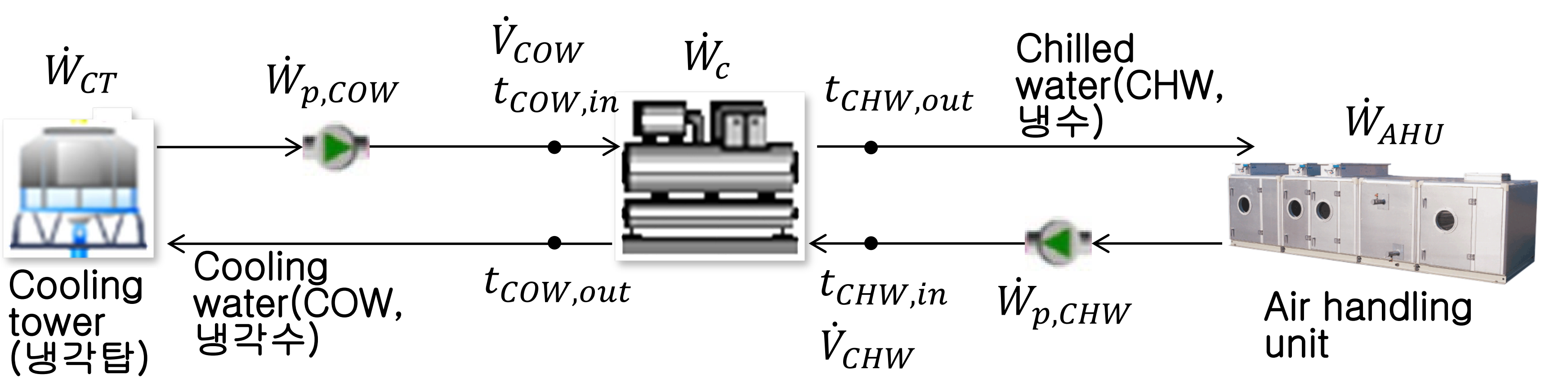
[3a] Chiller(water-to-water). Chilled water(CHW) flow rate $\dot{V}_{CHW}$ = 2000 lpm, CHW inlet temperature $t_{CHW,in}$ =12.6℃, CHW outlet temperature $t_{CHW,out}$ = 7.4℃, cooling water(COW) flow rate $\dot{V}_{COW}$ = 2630 lpm, COW inlet temperature $t_{COW,in}$ = 30.6℃, COW outlet temperature $t_{COW,out}$ = 35.8℃, compressor power $\dot{W}_c$ = 182.3 kW, CHW pump power $\dot{W}_{p,CHW}$ = 19.2 kW, COW pump power $\dot{W}_{p,COW}$ = 25.3 kW, cooling tower fan power $\dot{W}_{CT}$ = 7.5 kW, air handling unit power $\dot{W}_{AHU}$ = 29.5 kW. Water density ρ_w =1000 kg/m³, water specific heat c_w = 4.1868 kJ/(kg ℃). Use thermodynamic equations.

(1) Chiller COP. $\mathrm{COP}_{chiller} = \frac{\dot{Q}_e}{\dot{W}_c}$

(2) Chiller system COP. $\mathrm{COP}_{system} = \frac{\dot{Q}_e}{\dot{W}_{total}}$ $\quad \dot{W}_{total} = \dot{W}_c + \dot{W}_{p,CHW} + \dot{W}_{p,COW} + \dot{W}_{CT} + \dot{W}_{AHU}$

(3) Energy balance % error. $\mathrm{PE} = \frac{\dot{Q}_c - (\dot{Q}_e + \dot{W}_c)}{\dot{Q}_c} \times 100$

(4) Auxiliary power ratio. $R_{aux} = \frac{\dot{W}_{p,CHW} + \dot{W}_{p,COW} + \dot{W}_{CT} + \dot{W}_{AHU}}{\dot{W}_{total}}$



[3b] Chiller(water-to-water). $\dot{V}_{CHW}$ = 2000 lpm, $t_{CHW,in}$ =12.6℃, $t_{CHW,out}$ = 7.4℃, $\dot{V}_{COW}$ = 2630 lpm, $t_{COW,in}$ = 30.6℃, $t_{COW,out}$ = 35.8℃, $\dot{W}_c$ = 182.3 kW, $\dot{W}_{p,CHW}$ = 19.2 kW, $\dot{W}_{p,COW}$ = 25.3 kW, $\dot{W}_{CT}$ = 7.5 kW, $\dot{W}_{AHU}$ = 29.5 kW. Use EES software.

(1) Chiller COP. $\mathrm{COP}_{chiller} = \frac{\dot{Q}_e}{\dot{W}_c}$

(2) Chiller system COP. $\mathrm{COP}_{system} = \frac{\dot{Q}_e}{\dot{W}_{total}}$

$$\dot{W}_{total} = \dot{W}_c + \dot{W}_{p,CHW} + \dot{W}_{p,COW} + \dot{W}_{CT} + \dot{W}_{AHU}$$

(3) Energy balance % error. $\mathrm{PE} = \frac{\dot{Q}_c - (\dot{Q}_e + \dot{W}_c)}{\dot{Q}_c} \times 100$

(4) Auxiliary power ratio. $R_{aux} = \frac{\dot{W}_{p,CHW} + \dot{W}_{p,COW} + \dot{W}_{CT} + \dot{W}_{AHU}}{\dot{W}_{total}}$