Refrigeration Cycles

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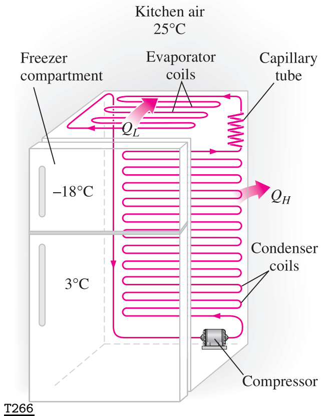
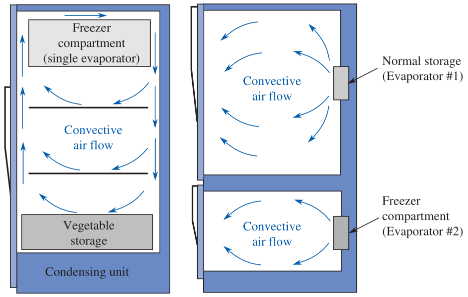
ME 203: Engineering Thermodynamics



T266

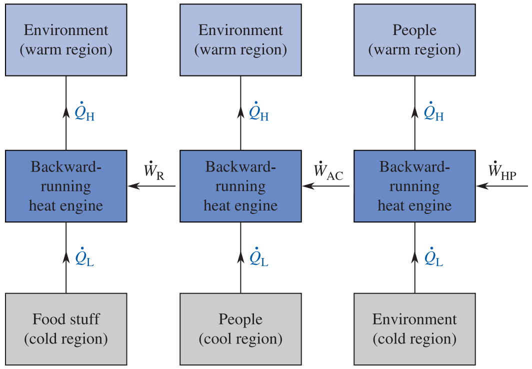


(a) Single-evaporator household refrigerator

(b) Dual-evaporator household refrigerator

T273

Refrigerators, Air-conditioners & Heat Pumps



(a) Refrigerator (b) Air conditioner (c) Heat pump

T270

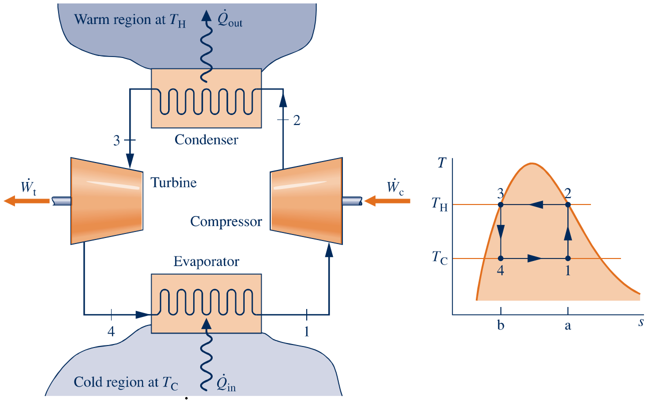
- $COP_R = \frac{\dot{Q}_L}{\dot{W}_R}$: $COP_{AC} = \frac{\dot{Q}_L}{\dot{W}_{AC}}$: $COP_{HP} = \frac{\dot{Q}_H}{\dot{W}_{HP}}$
- $COP_{HP} = COP_R + 1$

Refrigeration Capacity/Performance

- 1 ton refrigeration: heat absorbed by 1 ton (2000 lb) of ice melting at 0°C in 24 hours.
- 1 ton refrigeration (TR) = 3.516 kW = 12000 BTU/hr = 200 BTU/min
- Coefficient of Performance, $COP_R = \frac{Refrigeration\ Effect}{Net\ \ Work\ \ Required}$
- kW/ton ⇒ power required per ton of refrigeration

$$\boxed{kW/ton = \frac{3.516}{COP}}$$

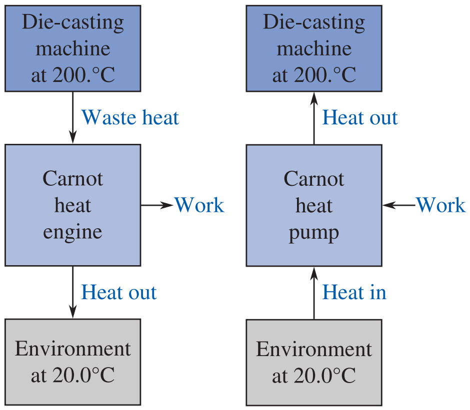
Reversed Carnot Cycle



T639

$$COP = \frac{\dot{Q}_{in}}{\dot{W}_c - \dot{W}_t} = \frac{T_C \Delta s}{(T_H - T_C)\Delta s} = \frac{T_C}{T_H - T_C}$$

▷ Example:



Die-casting machine at 200.°C

Waste heat

Carnot heat engine

Work

Heat out

Environment at 20.0°C

Die-casting machine at 200.°C

Heat out

Carnot heat pump

Work

Heat in

Environment at 20.0°C

T271

- $\eta_{Carnot} = 1 - \frac{T_L}{T_H} = 1 - \frac{293.15}{473.15} = 0.38 = 38\%$ ◀
- $COP_{R/AC} = \frac{T_L}{T_H - T_L} = \frac{293.15}{473.15 - 293.15} = 1.63$ ◀
- $COP_{HP} = \frac{T_H}{T_H - T_L} = \frac{473.15}{473.15 - 293.15} = 2.63$ ◀

Problems: Wet Compression in Carnot Cycle

- During compression, droplets in liquid are vaporised by the internal heat transfer process which requires finite time. High-speed compressors are susceptible to damage by liquid because of the short time available.
- In wet compression, the droplets of the liquids may wash the lubricating oil from the walls of the cylinder, accelerating wear. Dry compression takes place with no droplets and is preferable.
- Liquid refrigerants may be trapped in the head of reciprocating compressor by the rising piston, possibly damaging the valves or the cylinder head.

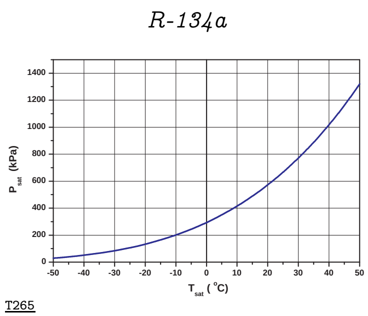
Problems: Expansion Process in Carnot Cycle

Carnot cycle demands that the expansion take place isentropically and that the resulting work be used to help drive the compressor. Practical difficulties, however, militate against the expansion engine:

- the possible work that can be derived from the engine is small fraction that must be supplied to the compressor.
- practical problems such as lubrication intrude when a fluid of two phases drives the engine.
- the economics of the power recovery have in past not justified the cost of the expansion engine.

⊗ A throttling device, such as a valve or other restriction, is almost universally used for this purpose.

Basic Refrigeration System using 2-Phase Refrigerant



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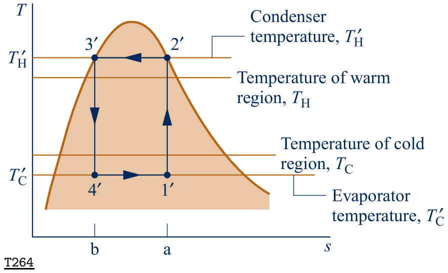
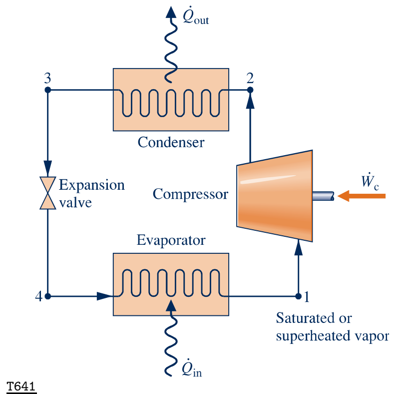


T264

Ideal Vapour Compression Refrigeration Cycle



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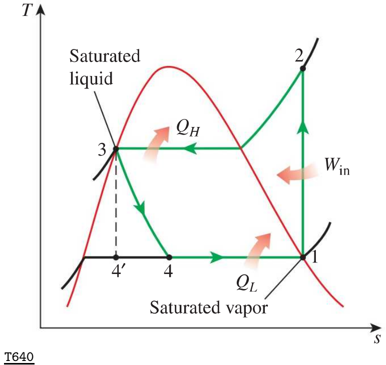
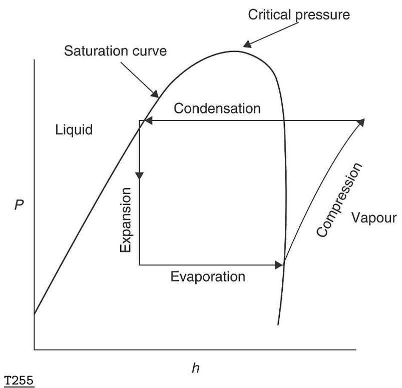


T640



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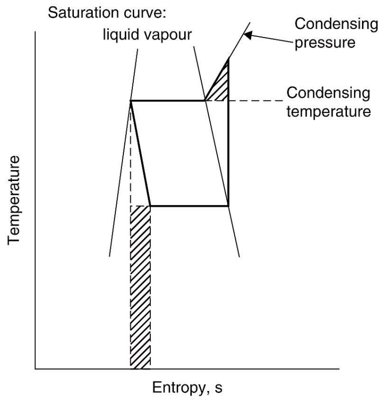

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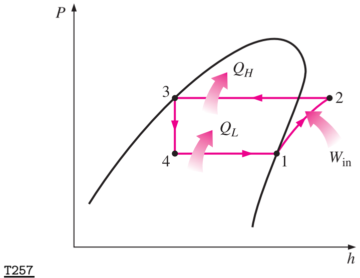
Processes of Vapour Compression Refrigeration System



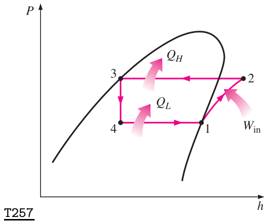
T257

$$
\begin{aligned}
Q_L &= Q_{41} = \dot{m}(h_1 - h_4)\\
Q_H &= Q_{23} = \dot{m}(h_2 - h_3)\\
W_{in} &= W_{12} = \dot{m}(h_2 - h_1)\\
COP &= Q_L / W_{in}
\end{aligned}
$$

- $1 \longrightarrow 2$: Isentropic compression, $P_{evap} \longrightarrow P_{cond}$
- $2 \longrightarrow 3$: Isobaric heat rejection, Q_H
- $3 \longrightarrow 4$: Isenthalpic expansion, $P_{cond} \longrightarrow P_{evap}$
- $4 \longrightarrow 1$: Isobaric heat extraction, Q_L

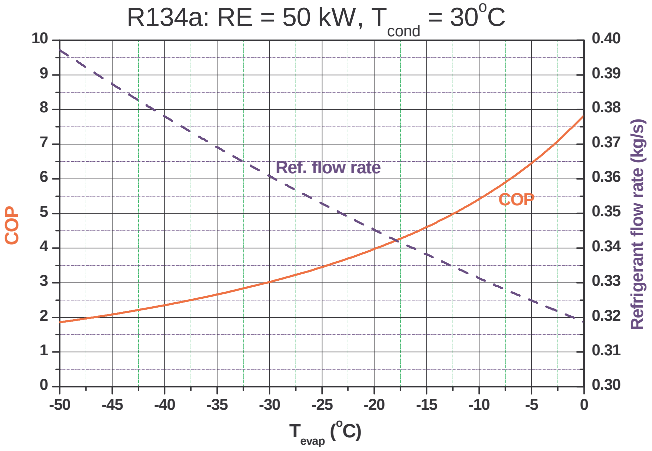
▷ Example: A theoretical single stage cycle using R134a as refrigerant operates with a condensing temperature of 30°C and an evaporator temperature of -20°C. The system produces 50 kW of refrigeration effect. Estimate:

1. Coefficient of performance, COP
2. Refrigerant mass flow rate, $\dot{m}$



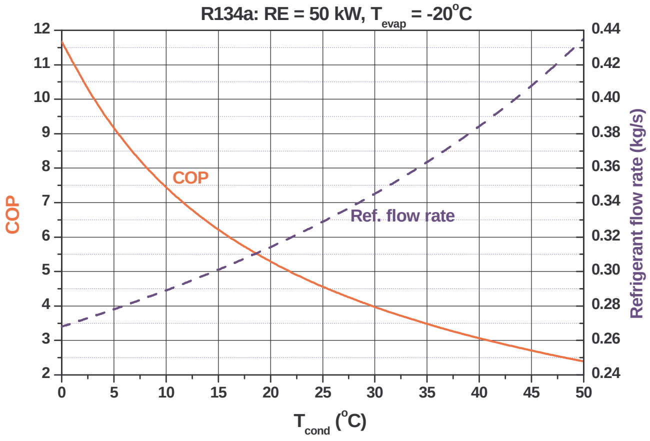
$$
\begin{aligned}
Q_L &= Q_{41} = \dot{m}(h_1 - h_4) = 50 \text{ kW}\\
&\rightsquigarrow \dot{m} = 0.345 \text{ Kg/s} \blacktriangleleft\\
W_{in} &= W_{12} = \dot{m}(h_2 - h_1) = 12.5 \text{ kW}\\
COP &= Q_L/W_{in} = 50.0/12.5 = 4.0 \blacktriangleleft
\end{aligned}
$$

Effect of Evaporator Temperature



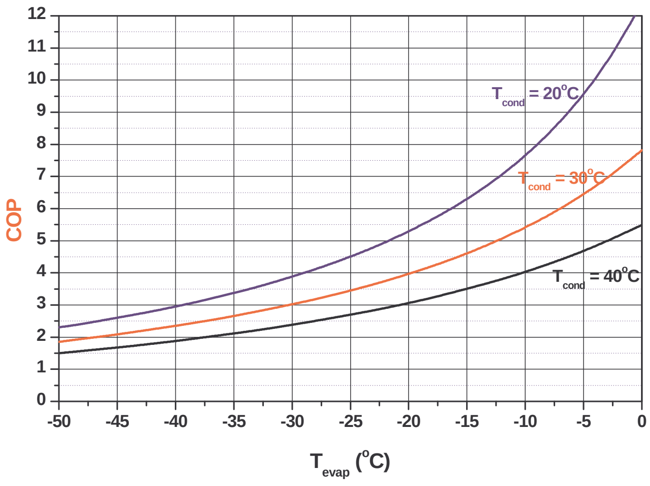
T259

Effect of Condenser Temperature



T261

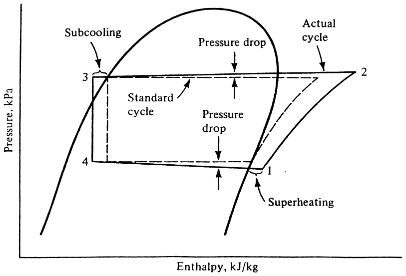
Effect of Evaporator & Condenser Temperatures



T260

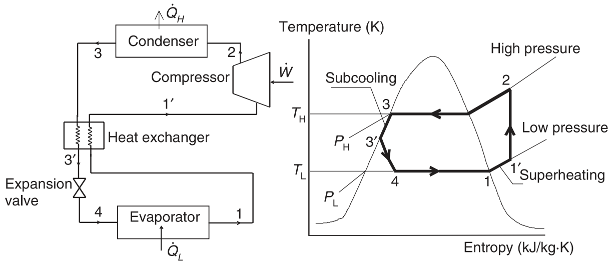
Deviations from Ideal Cycle

1. Refrigerant pressure drop in piping, evaporator, condenser, receiver tank, and through the valves and passages.
2. Sub-cooling of liquid leaving the condenser.
3. Super-heating of vapour leaving the evaporator.
4. Compression process is not isentropic.



T262

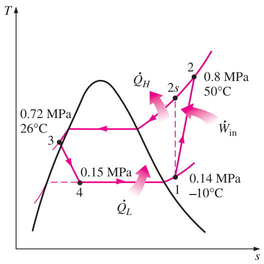
Super-heating & Sub-cooling



T263

- Sub-cooling of liquid serves a desirable function of ensuring that 100% liquid will enter the expansion device.
- Super-heating of vapour ensures no droplets of liquid being carried over into the compressor.
- Even through refrigeration effect is increased, compression work is greater & probably has negligible thermodynamic advantages.

▷ Example:

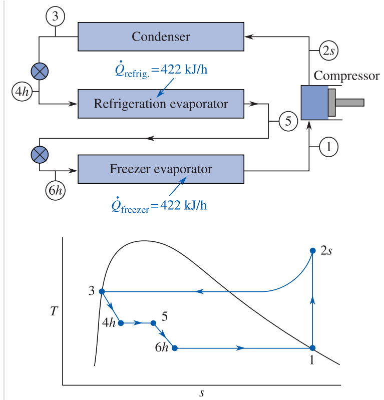


T258

- $h_1 = h(P = 0.14\text{ MPa}, T = -10^oC)$
- $h_2 = h(P = 0.80\text{ MPa}, T = 50^oC)$
- $h_3 \simeq h_{f,26^oC}$
- $h_4 = h_3$

- $Q_L = (h_1 - h_4) = 158.53\text{ kJ/kg}$
- $W_{in} = (h_2 - h_1) = 40.33\text{ kJ/kg}$
- $COP_R = \frac{Q_L}{W_{in}} = 3.93$ ◀
- $\eta_c = \frac{h_{2s} - h_1}{h_2 - h_1} = 93.6\%$ ◀

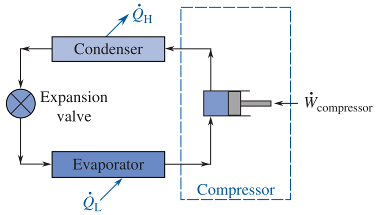
▷ Example: A dual-evaporator refrigeration system: T_F = -18.0°C, T_R = 4.0°C, T_c = 30.0°C & η_c = 80%.



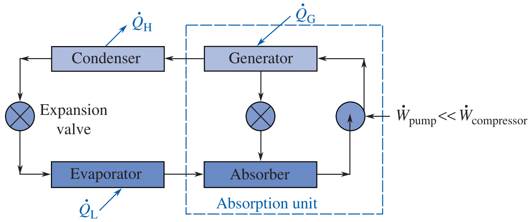
T274

- $COP_R = ?\ \ x_5 = ?$
- $\dot{m} = \frac{\dot{Q}_R + \dot{Q}_F}{h_1 - h_{4h}} = 1.62 \times 10^{-3}\text{ kg/s}$ ◀
- $\dot{W}_c = \frac{\dot{m}(h_{2s} - h_1)}{\eta_c}$
- $COP_R = \frac{\dot{Q}_R + \dot{Q}_F}{\dot{W}_c} = 3.37$ ◀
- $\dot{Q}_R = \dot{m}(h_5 - h_{4h}) \rightarrow h_5$
- $h_5 \Longrightarrow x_5 = 0.56$ ◀

Vapour Absorption Refrigeration System



(a) Standard vapor-compression refrigeration.



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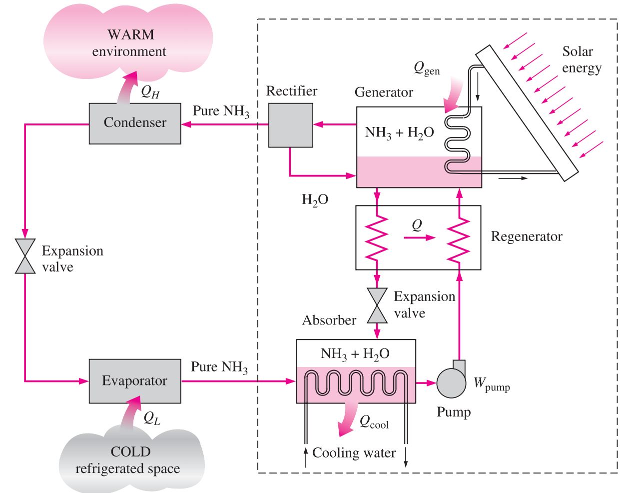
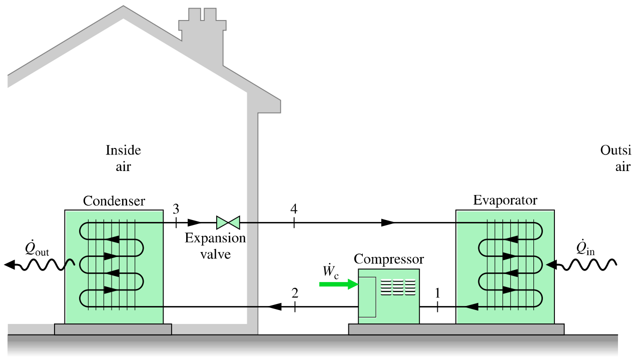
(b) Absorption vapor-compression refrigeration.



T267

Ammonia absorption refrigeration system

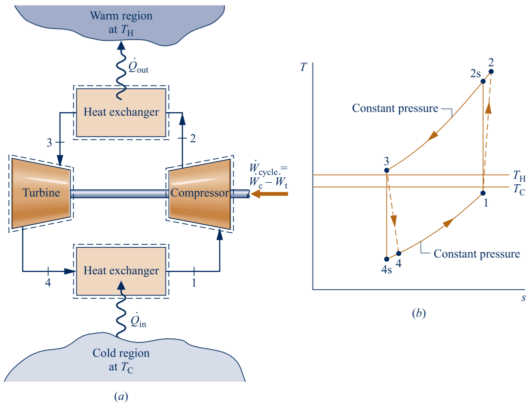
Vapour-Compression Heat Pump (HP) System



T268

- $\dot{Q}_{out} = \dot{W}_c + \dot{Q}_{in}$
- $COP|_{HP} = \frac{\dot{Q}_{out}}{\dot{W}_c} = 1 + COP|_{Ref}$

Gas Refrigeration System: Brayton Cycle



T269

$$COP = \frac{\dot{Q}_{in}}{\dot{W}_c - \dot{W}_t} = \frac{(h_1 - h_4)}{(h_2 - h_1) - (h_3 - h_4)}$$