UNIVERSITÀ DEGLI STUDI DI TRIESTE

Vapor Compression Refrigeration Cycle

Course: INDUSTRIAL ENERGY MANAGEMENT [459MI]

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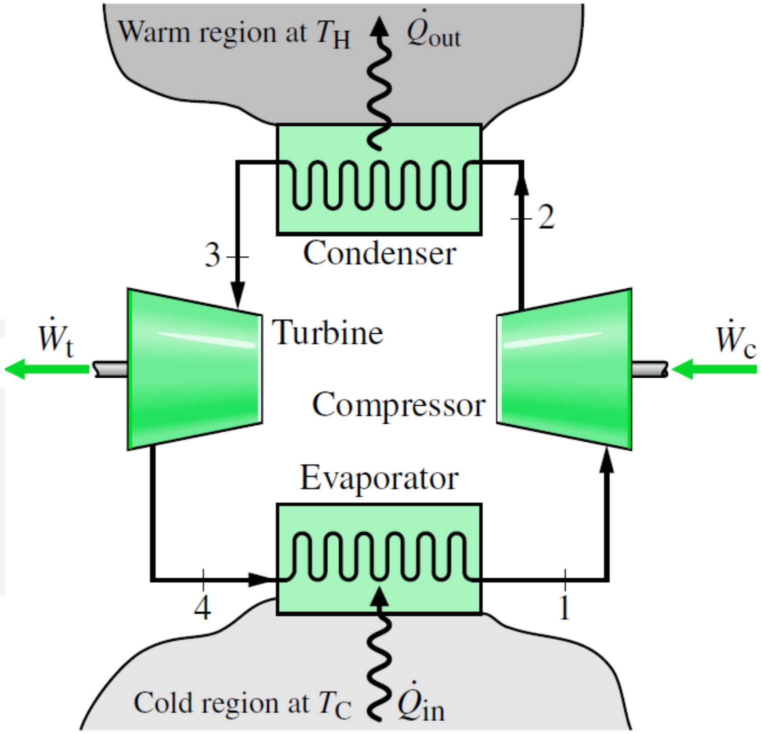
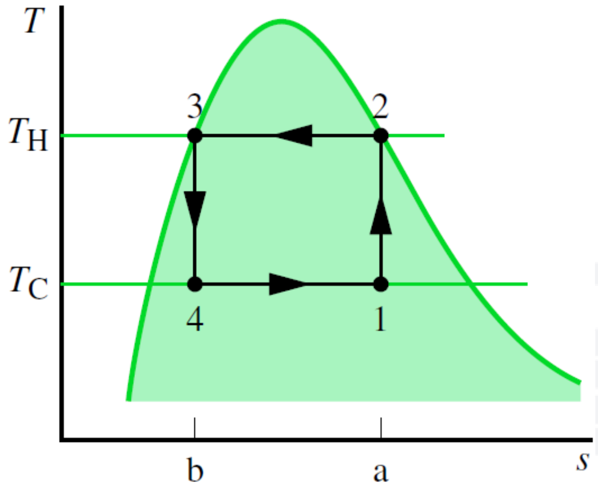
Objectives of the lesson:

- Make a recall on Vapor-Compression Refrigeration Cycle
- Modelling a Vapor-Compression Cycle in EES
- Work on two examples

Carnot Refrigeration Cycle





- Reversed version of the Carnot vapor power cycle
- Operates between two temperature: low temperature (TC) and high temperature (TH)

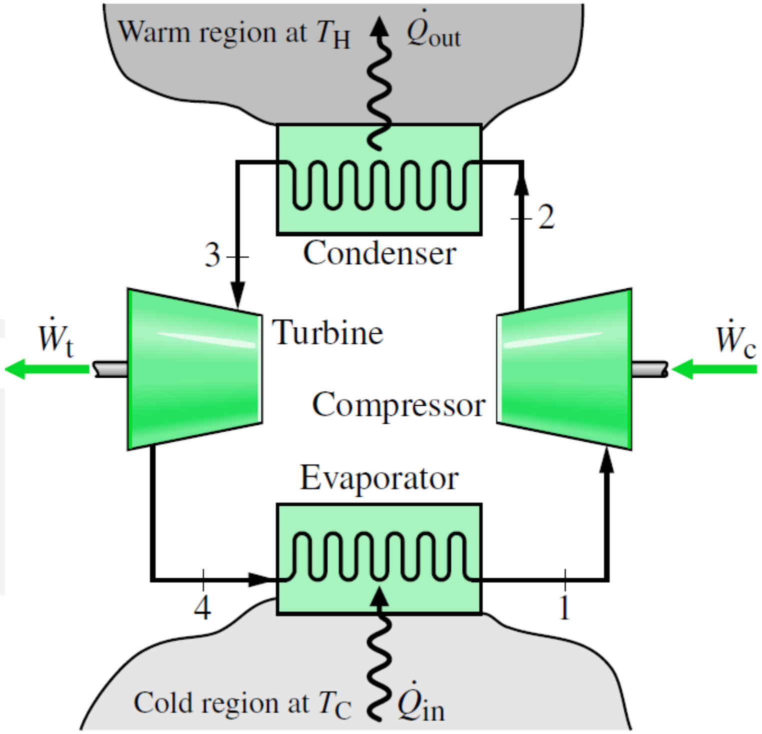
1 → 2: Adiabatic compression

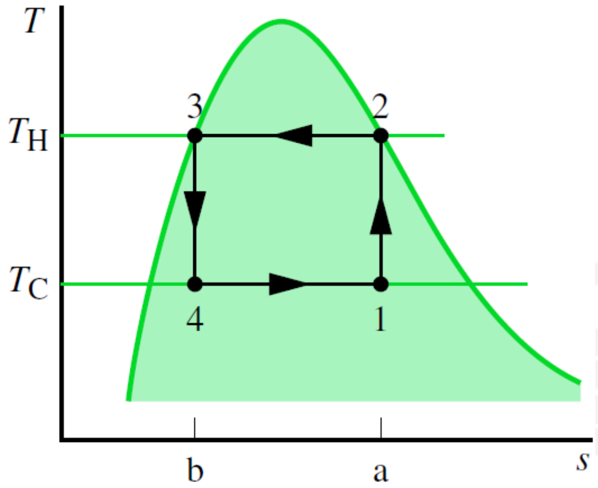
State 1: Two-phase liquid-vapor mixture.

State 2: Saturated vapor.

Temperature and pressure increase.

Carnot Refrigeration Cycle





2 → 3: Condensation

Refrigerant releases heat to the warm region, causing phase change from vapor to liquid.

Temperature and pressure constant.

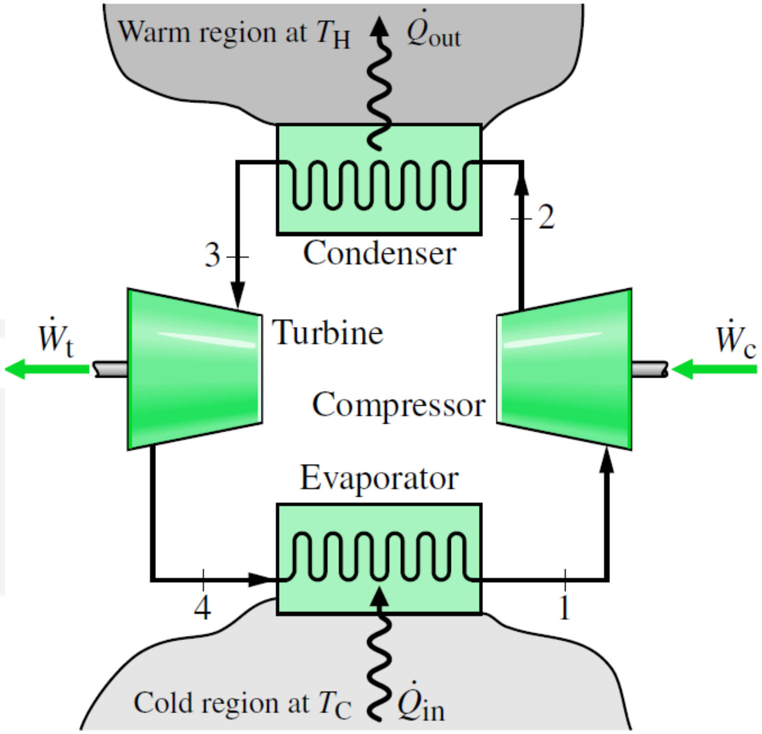
3 → 4: Adiabatic expansion

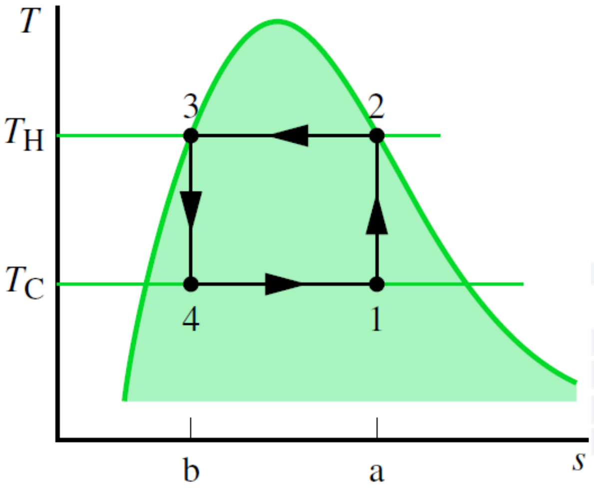
Temperature and pressure decrease.

The working fluid enters the evaporator

as a two-phase liquid–vapor mixture at state 4.

Carnot Refrigeration Cycle



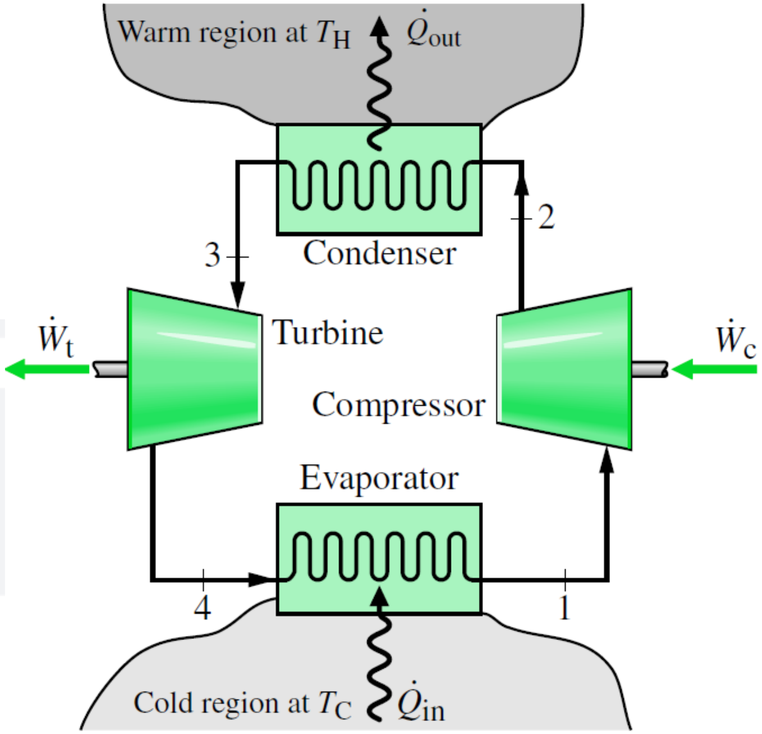


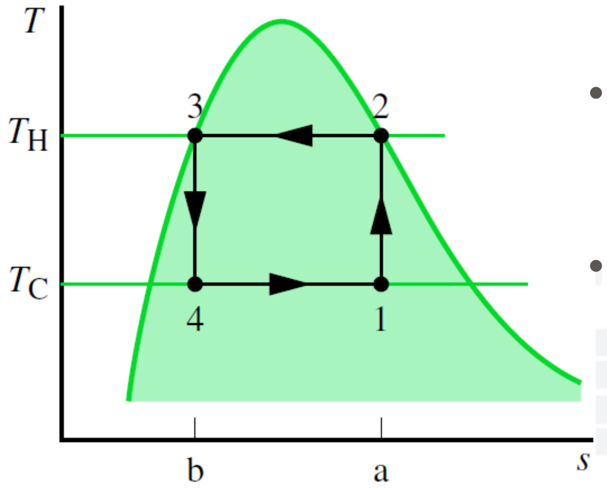
4 → 1: Evaporation

Some of the refrigerant changes phase from liquid to vapor as a result of heat transfer from the region at temperature TC to the refrigerant.

Temperature and pressure constant.

Carnot Refrigeration Cycle



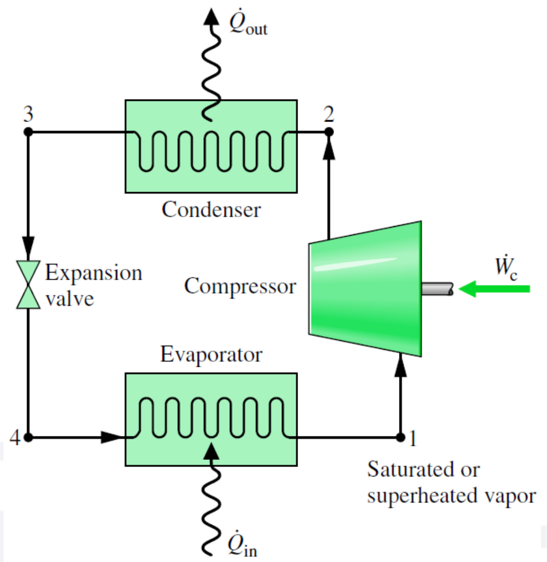


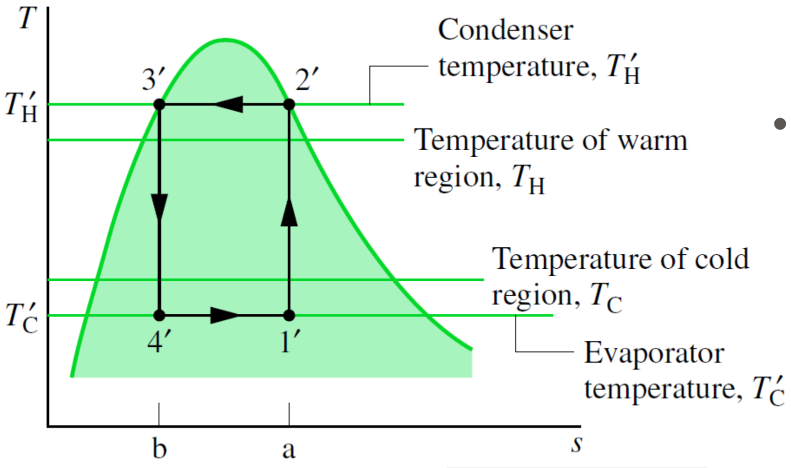
Heat Transfers (T–s Diagram Interpretation):

- **Area 1–a–b–4–1:** Heat absorbed from the cold region.
- **Area 2–a–b–3–2:** Heat rejected to the warm region.
- **Enclosed area 1–2–3–4–1:** Net heat transfer, equal to net work done on refrigerant.

$$\beta_{max} = \frac{\dot{Q}_{in}/\dot{m}}{\dot{W}_c/\dot{m} - \dot{W}_t/\dot{m}} = \frac{\text{area 1–a–b–4–1}}{\text{area 1–2–3–4–1}} = \frac{T_C(s_a - s_b)}{(T_H - T_C)(s_a - s_b)} = \frac{T_C}{T_H - T_C}$$

Deviations from Carnot Refrigeration Cycle

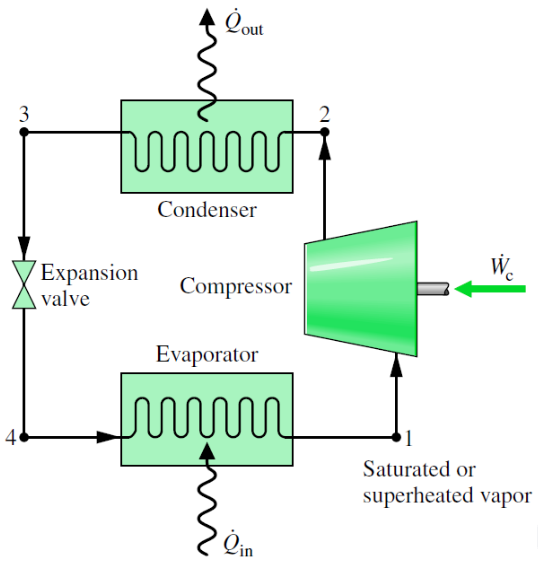


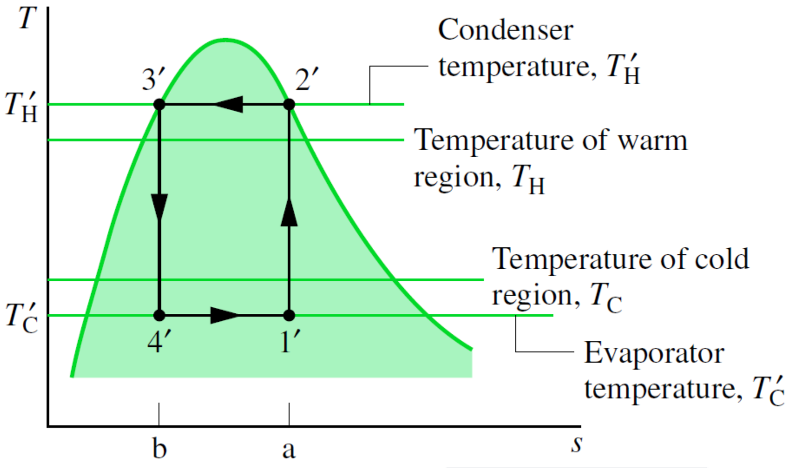


1. Irreversible Heat Transfer Between the Refrigerant and Surroundings

- In real systems, heat transfer does not occur reversibly as assumed in the Carnot cycle.
- To achieve practical heat transfer rates: the refrigerant temperature in the evaporator **(T'C) must be lower than the cold region temperature (TC).**The refrigerant temperature in the condenser **(T'H) must be higher than the warm region temperature (TH).**
- This temperature difference **reduces the COP of the cycle** compared to the ideal Carnot cycle.

Deviations from Carnot Refrigeration Cycle

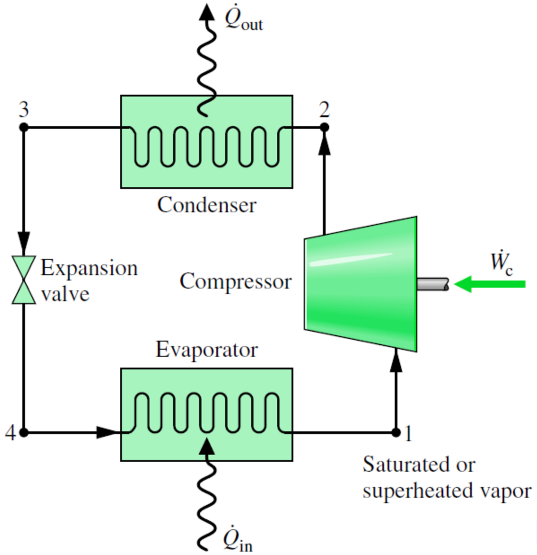




2. Avoidance of Wet Compression

- In actual systems, **wet compression is avoided** because liquid droplets can damage the compressor.
- Instead, real compressors should operate under **dry compression**, meaning they compress only **vapor** to improve reliability and efficiency.

Deviations from Carnot Refrigeration Cycle



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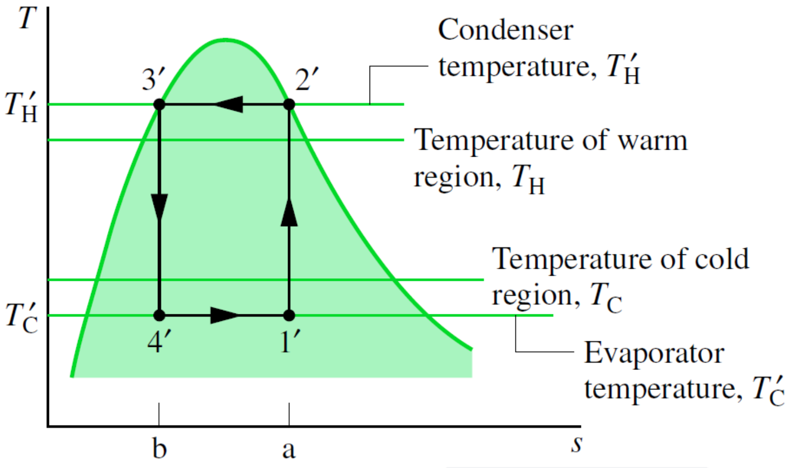
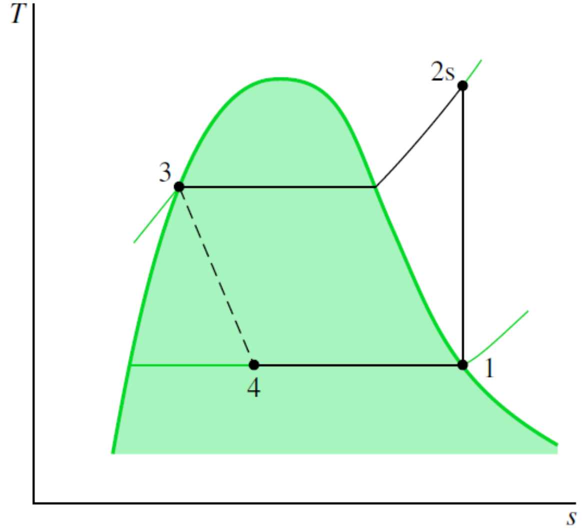
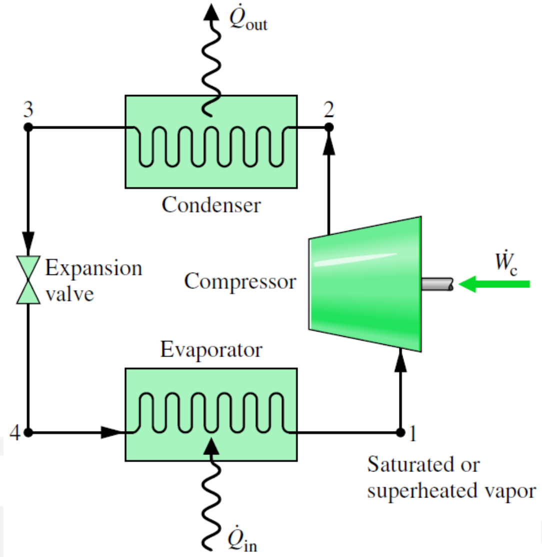
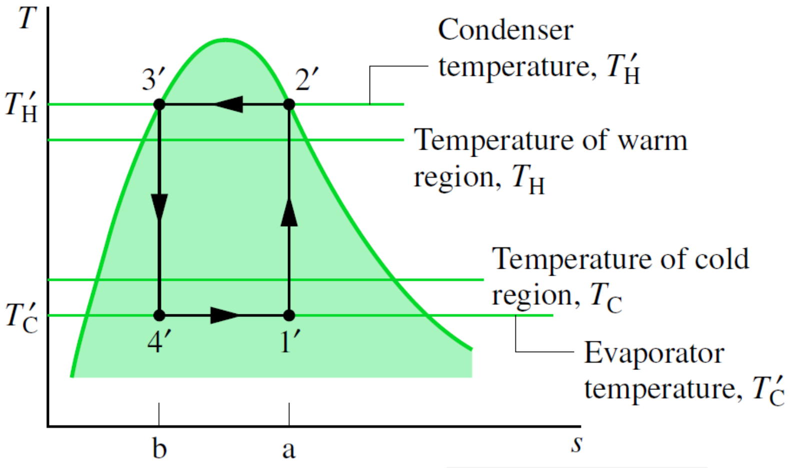




Deviations from Carnot Refrigeration Cycle

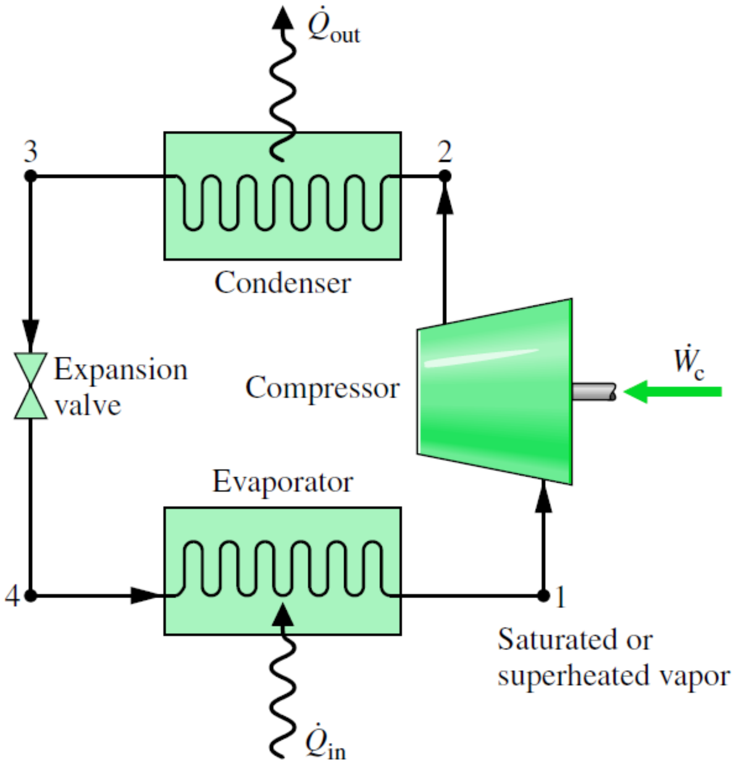




3. Replacement of the Expansion Turbine with a Throttling Valve

- In reality, the work output would be **small**, and turbines in such conditions have **low efficiency**.
- To reduce costs and simplify the system, **a throttling valve replaces the turbine.**
- This modification leads to the **vapor-compression refrigeration cycle**, which is commonly used in real-world applications.

Modelling a Vapor-Compression Refrigeration Cycle



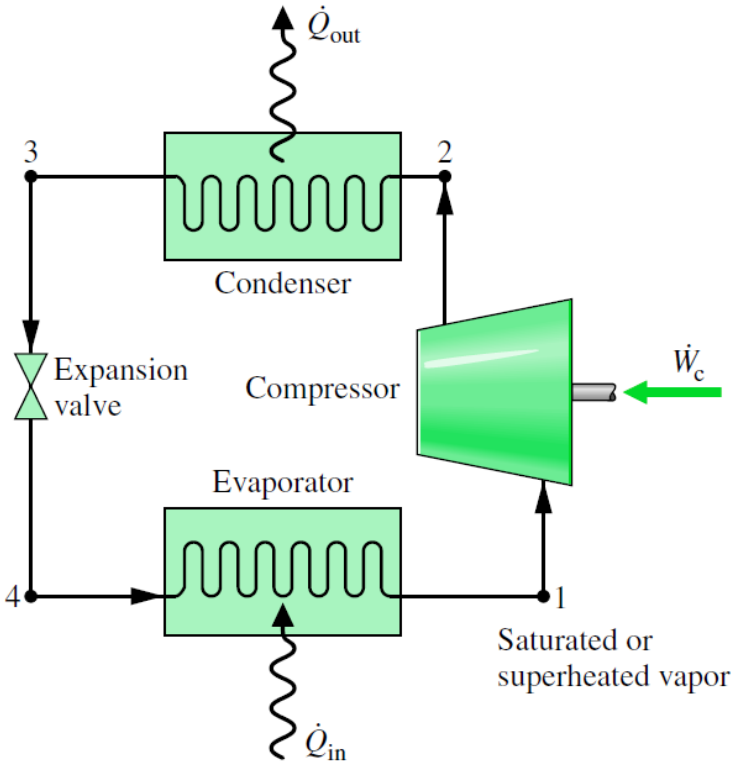
- Evaporation (Heat absorption)

$$\frac{\dot{Q}_{in}}{\dot{m}} = h_1 - h_4$$

Refrigeration capacity ($\dot{Q}_{in}$) generally in **kW**.

Refrigerant exits the evaporator as **saturated or superheated vapor**.

Modelling a Vapor-Compression Refrigeration Cycle



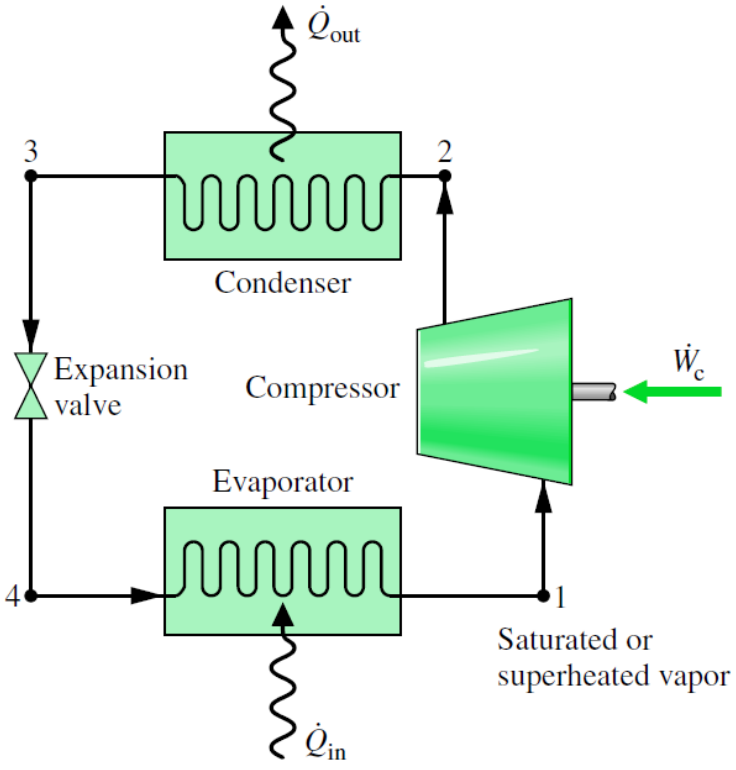
- Compression (Work input)

$$\frac{\dot{W}_c}{\dot{m}} = h_2 - h_1$$

Assumption: adiabatic compression.

Refrigerant exits the compressor as **high-pressure and high-temperature vapor**.

Modelling a Vapor-Compression Refrigeration Cycle



$$\beta = \frac{\dot{Q}_{in}/\dot{m}}{\dot{W}_c/\dot{m}} = \frac{h_1 - h_4}{h_2 - h_1}$$

- Condensation (Heat rejection)

$$\frac{\dot{Q}_{out}}{\dot{m}} = h_2 - h_3$$

Refrigerant exits the condenser as **saturated liquid**.

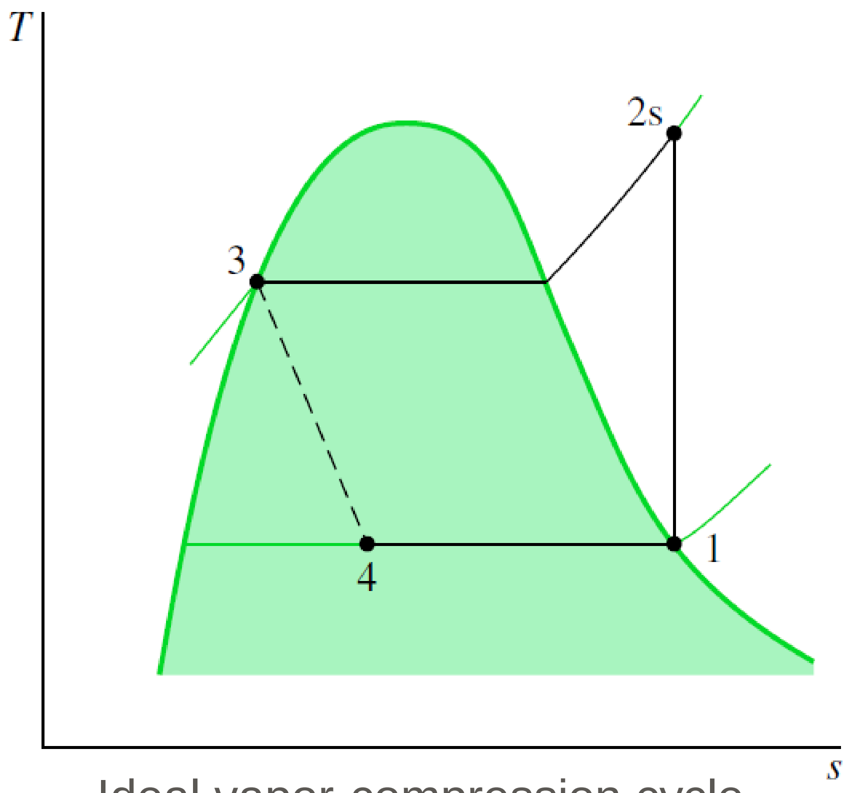
- Expansion valve (isenthalpic expansion)

$$h_4 = h_3$$

Pressure decreases **irreversibly**, and **entropy increases**.

Refrigerant exits as **two-phase liquid-vapor mixture**.

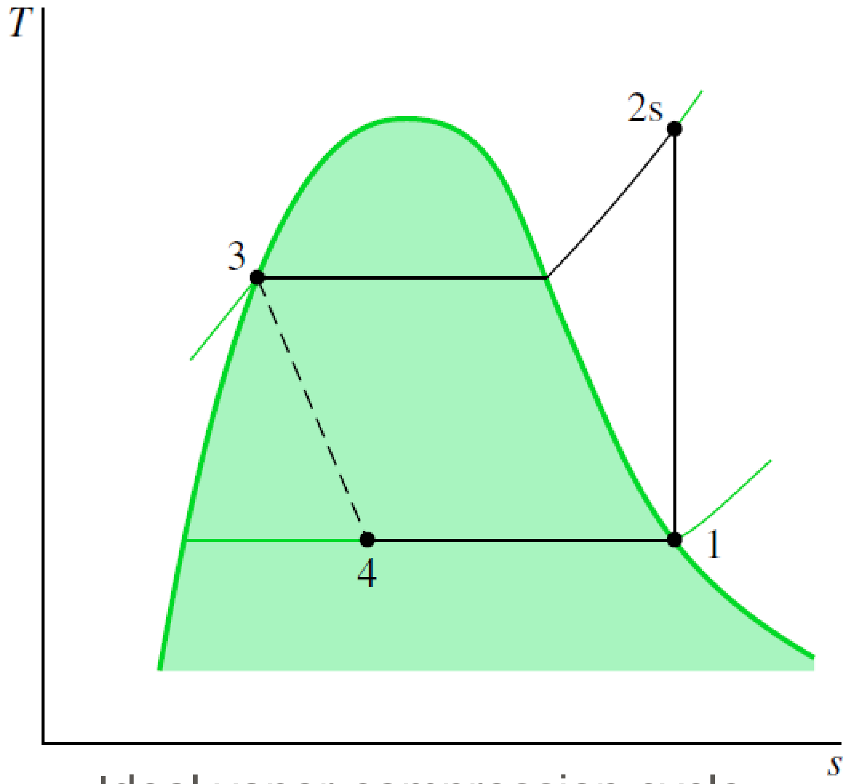
Ideal Vapor-Compression Refrigeration Cycle



Ideal vapor-compression cycle

- Assumes **no irreversibilities** in the evaporator, condenser, or compressor.
- **No frictional pressure drops** → refrigerant flows at constant pressure in heat exchangers.
- **Compression is isentropic** (no entropy change, no stray heat transfer).
- Despite the **irreversible throttling process**, the cycle is called "ideal."

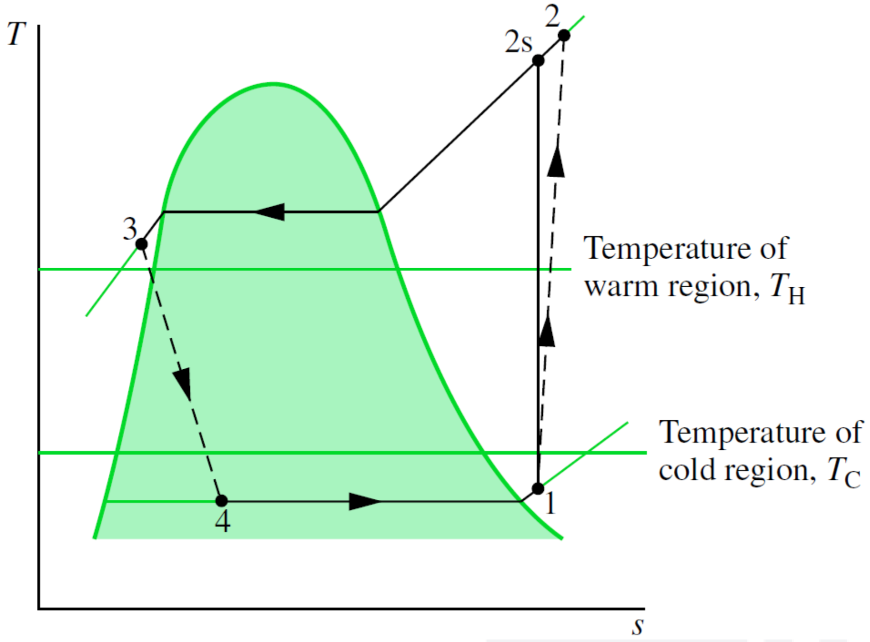
Ideal Vapor-Compression Refrigeration Cycle



Ideal vapor-compression cycle

- Process 1–2s: Isentropic Compression
- Process 2s–3: Heat Rejection in the Condenser
- Process 3–4: Throttling Expansion
- Process 4–1: Heat Absorption in the Evaporator

Actual Vapor-Compression Refrigeration Cycle

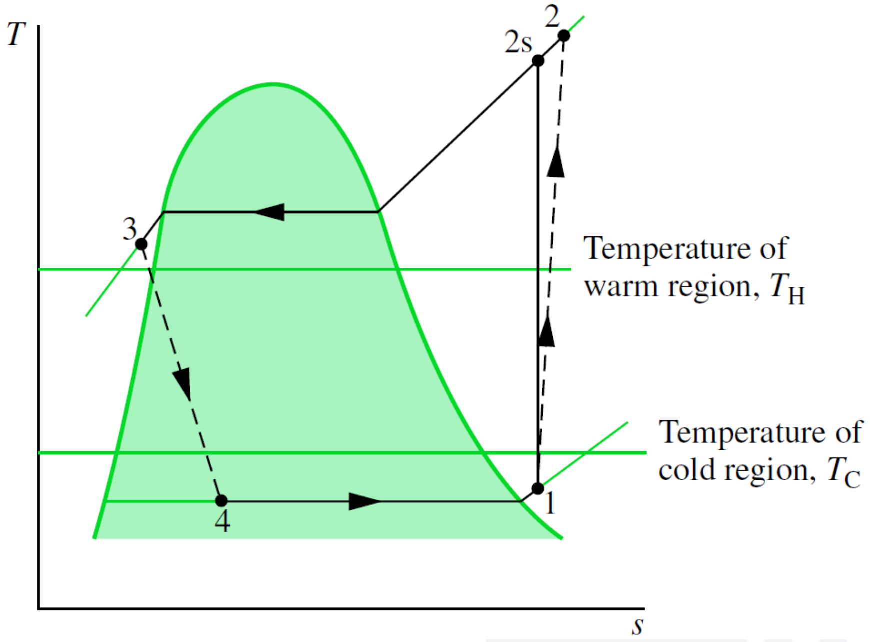


Actual vapor-compression cycle

Irreversible heat transfers

- Refrigerant temperature in the evaporator is lower than the cold region temperature (TC)
- Refrigerant temperature in the condenser is higher than the warm region temperature (TH)
- These irreversible heat transfers reduce the COP

Actual Vapor-Compression Refrigeration Cycle



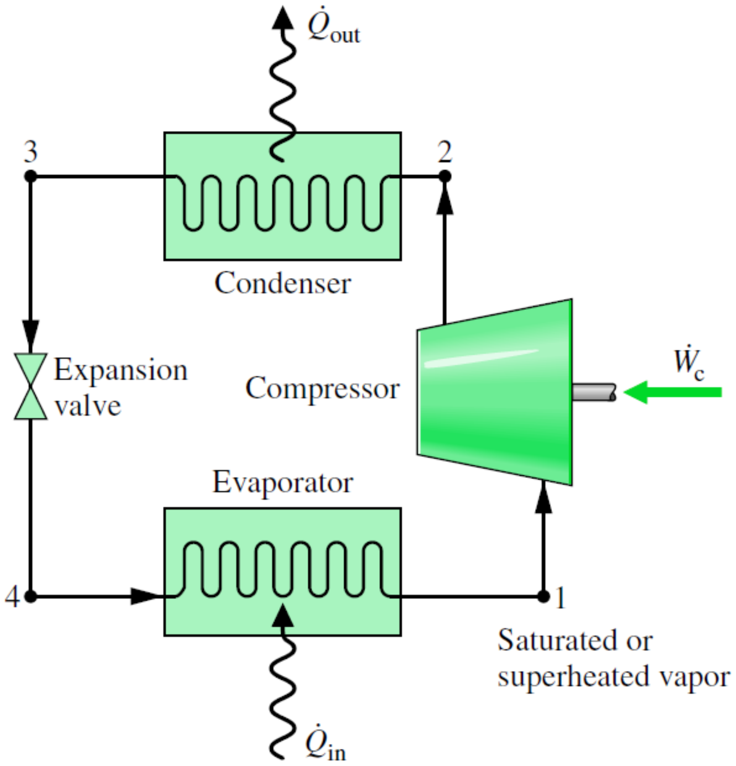
Actual vapor-compression cycle

Irreversibilities in compression

- Increased entropy
- Work input increases and COP decreases compared to the ideal cycle
- The isentropic compressor efficiency (η_c) accounts for this inefficiency:

$$\eta_c = \frac{(\dot{W}_c/\dot{m})_s}{(\dot{W}_c/\dot{m})} = \frac{h_{2s} - h_1}{h_2 - h_1}$$

Example 1



- Objective:

Calculate the COP of the cycle.

- Input data:

Evaporator temperature = 5°C

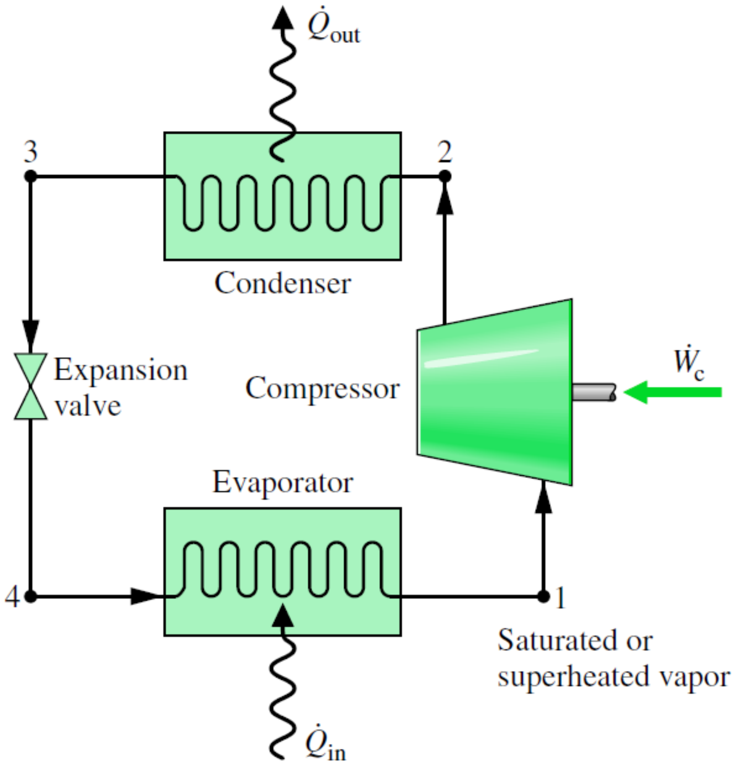
Condenser temperature = 40°C

Saturated vapor at evaporator outlet

Saturated liquid at condenser outlet

Isentropic compression

Example 2



- Objective:

Assume a compressor efficiency of 80%

Calculate the COP of the cycle and compare with example 1

- Input data:

Evaporator temperature = 5°C

Condenser temperature = 40°C

Saturated vapor at evaporator outlet

Saturated liquid at condenser outlet

Isentropic compression

Comparison between Example 1 and Example 2

Example 1:

Unit Settings: SI C bar kJ mass deg

COP = 7.181 Q_{evap} = 145.1 [kJ/kg] T_{cond} = 40 [C]

T_{evap} = 5 [C] W_{comp} = 20.2 [kJ/kg]

Sort	P_i [bar]	h_i [kJ/kg]	s_i [kJ/kg-K]	x_i	T_i [C]
[1]	3.499	253.3	0.9288	1	5
[2]	9.264	273.5	0.9288		40
[3]	9.264	108.3	0.3949	0	36.55
[4]	3.499	108.3	0.4072	0.255	5

Example 2:

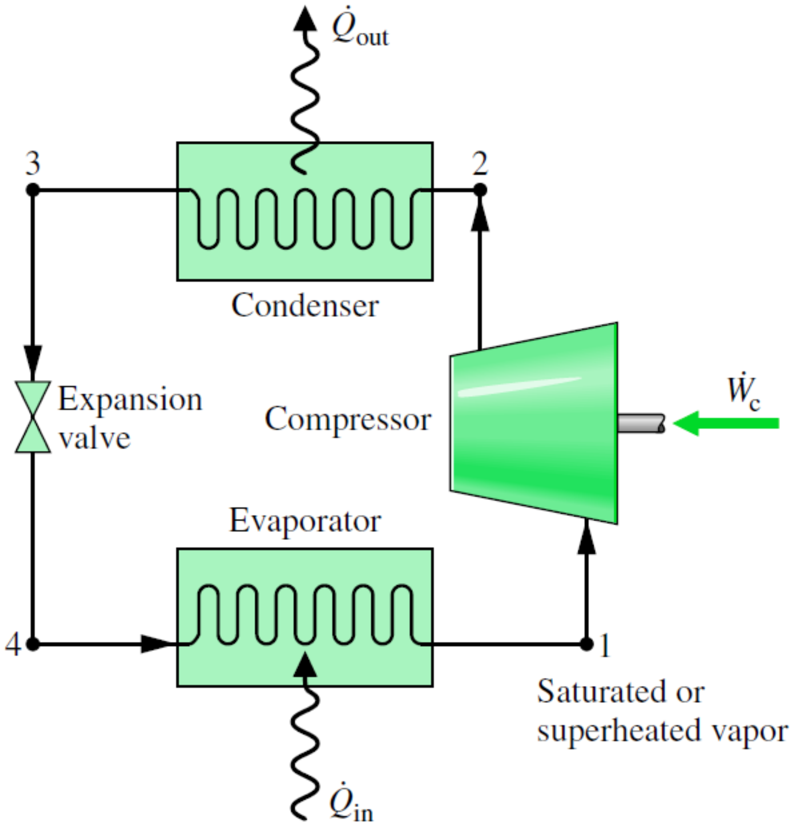
Unit Settings: SI C bar kJ mass deg

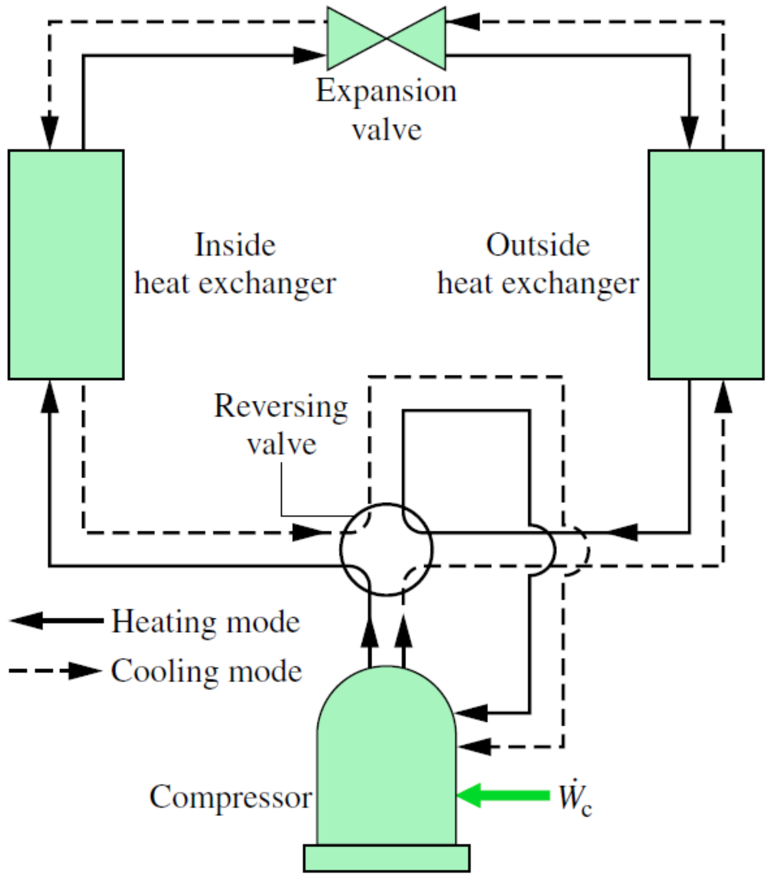
COP = 5.745 η_{comp} = 0.8 Q_{evap} = 145.1 [kJ/kg] T_{cond} = 40 [C]

T_{evap} = 5 [C] W_{comp} = 25.25 [kJ/kg] $W_{comp,is}$ = 20.2 [kJ/kg]

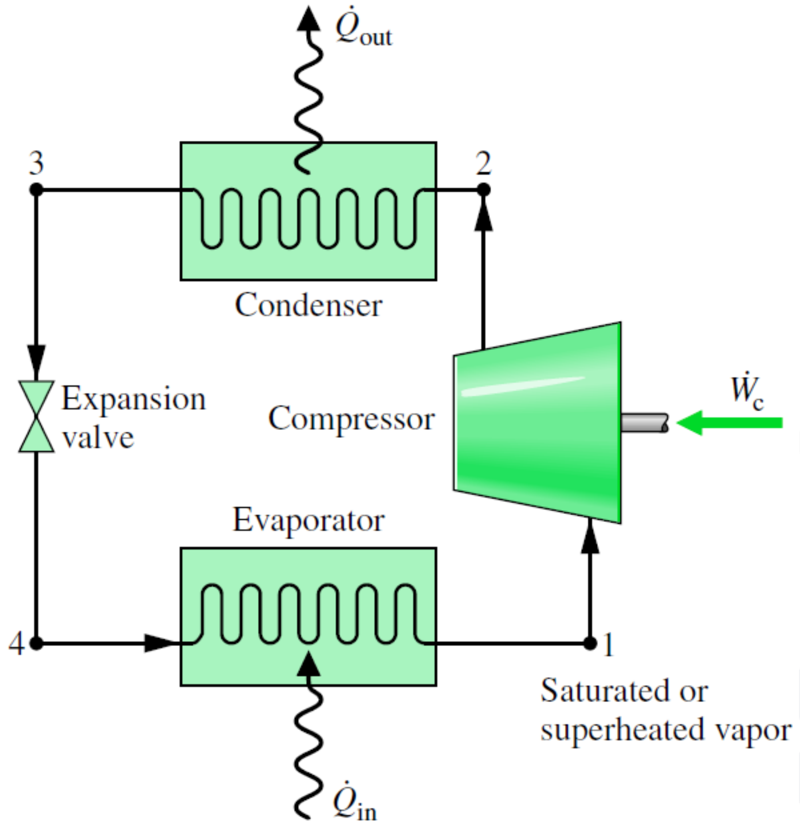
Sort	P_i [bar]	h_i [kJ/kg]	s_i [kJ/kg-K]	x_i	T_i [C]	$h_{is,i}$ [kJ/kg]	$s_{is,i}$ [kJ/kg-K]
[1]	3.499	253.3	0.9288	1	5		
[2]	9.264	278.6	0.9448		44.67	273.5	0.9288
[3]	9.264	108.3	0.3949	0	36.55		
[4]	3.499	108.3	0.4072	0.255	5		

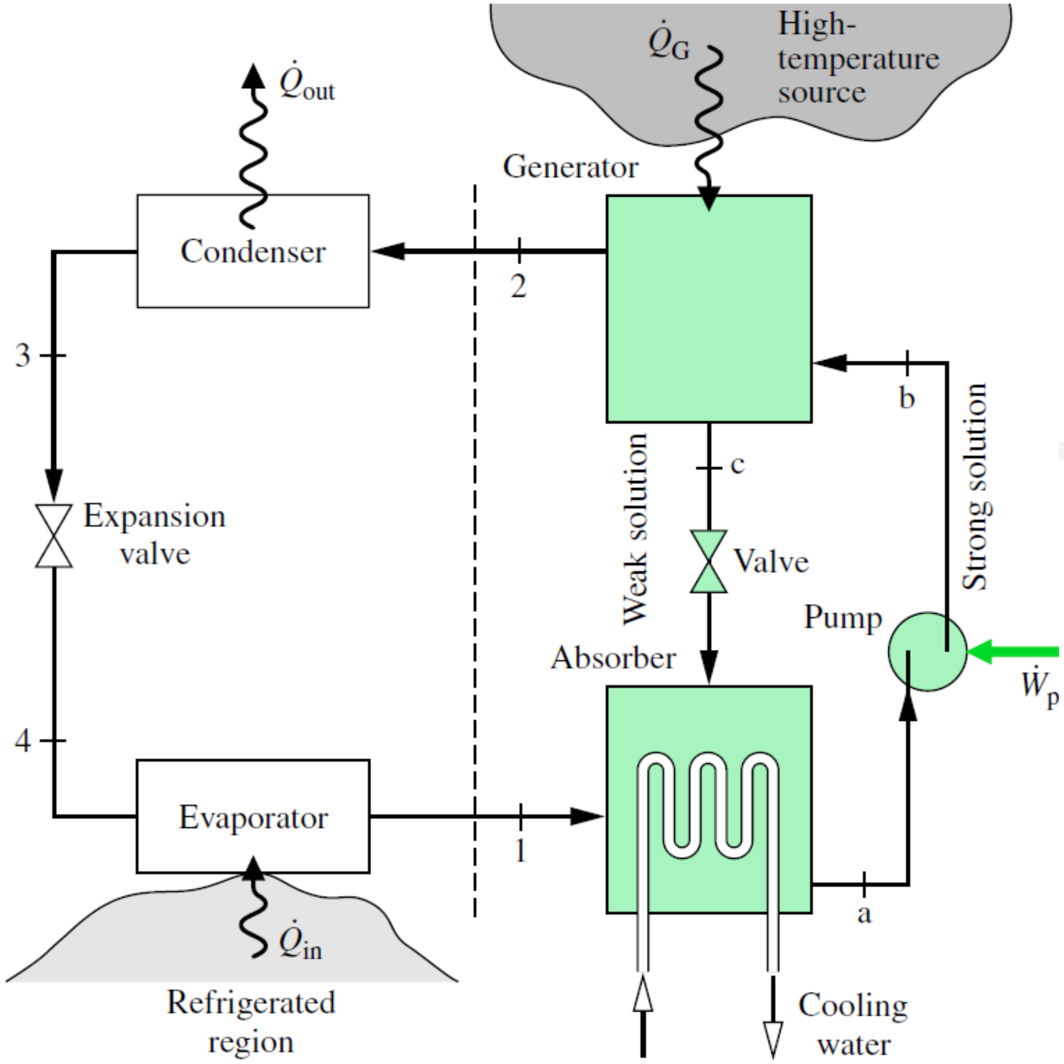
Similarities to a Vapor-Compression Heat Pump





Comparison with Absorption Refrigeration Cycle





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