Thermodynamics and energetics 1

Prof. Sophia Haussener

Laboratory of Renewable Energy Sciences and Engineering

Summary last lecture

- Demonstrate and understand the basic principles of air-standard cycles of
  - Internal combustion engines (Otto, Diesel)
  - Gas turbine power plants

- This includes:
  - Sketch *T*-*s*-, *p*-*v*-diagrams
  - Evaluate properties at states of cycle
  - Apply mass, energy and entropy balances to the processes
  - Determine performance

- Discuss and analyze the performance and optimization approaches

Learning outcomes of todays lecture

- Demonstrate and understand the
  - Basic vapor-compression refrigeration and heat pump systems
  - Absorption refrigeration systems
  - Gas refrigeration systems

- Develop thermodynamic models, including:
  - Sketch *T*-*s*-, *p*-*v*-diagrams
  - Evaluate properties at states of cycle
  - Apply mass, energy and entropy balances to the processes
  - Determine performance

- Discuss and analyze the performance and optimization approaches

Moran book: chp. 10

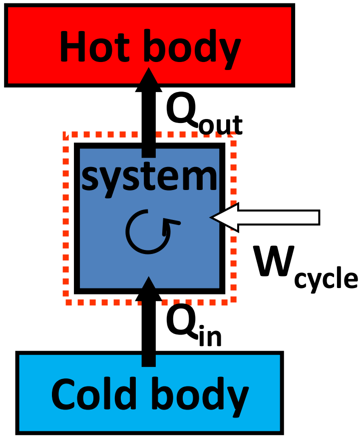
EPFL

Refrigeration and heat pump systems

- Daily life examples:
  - Refrigerator
  - Heat conditioner
  - Heating of buildings via heat pump using geothermal heat

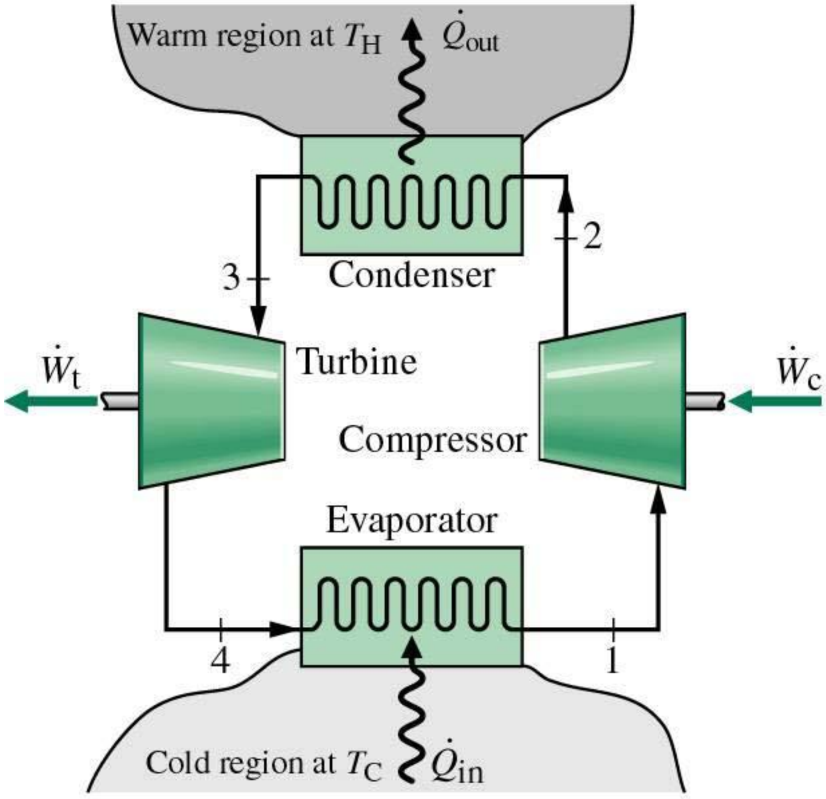
- As for power systems we consider also *vapor* refrigeration (heat transfer fluid evaporates and condenses) and *gas* refrigeration (heat transfer fluid stays in gas form)

- Difference between refrigeration and heat pump
  - Maintain cold temperature below temperature of surrounding
  - Maintain high temperature above temperature of surrounding



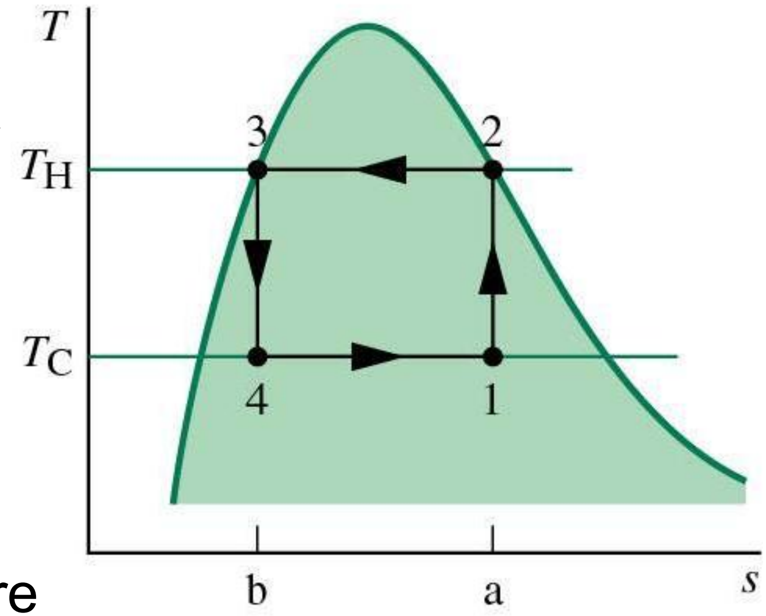
Vapor refrigeration system

- Carnot refrigeration cycle:
  - Reverse Carnot power cycle
  - Carnot refrigerant cycle between two regions with distinct temperatures
  - Refrigerant circulates steadily through a series of components (int. rev.):
    - Compressor, condenser, turbine, evaporator



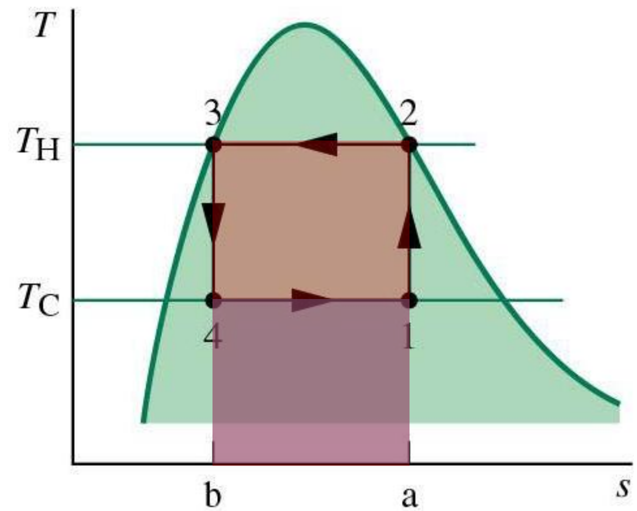
Vapor refrigeration system

- Carnot refrigeration cycle:
  1-2: Adiabatic compression from two-phase liquid-vapor mixture to saturated vapor
  2-3: Condensation (heat rejection) from saturated vapor to saturated liquid at constant pressure and temperature
  3-4: Adiabatic expansion through the turbine from saturated liquid to two-phase liquid-vapor mixture
  4-1: Evaporation (heat addition) of liquid-vapor mixture at constant temperature and pressure
- Four internally reversible processes



Vapor refrigeration system

- Carnot refrigeration cycle:
  - Net heat removed equals the net work done to the system
  - As composed of internally reversible cycles, *T*-*s*-diagram represents heat transfer to/from system



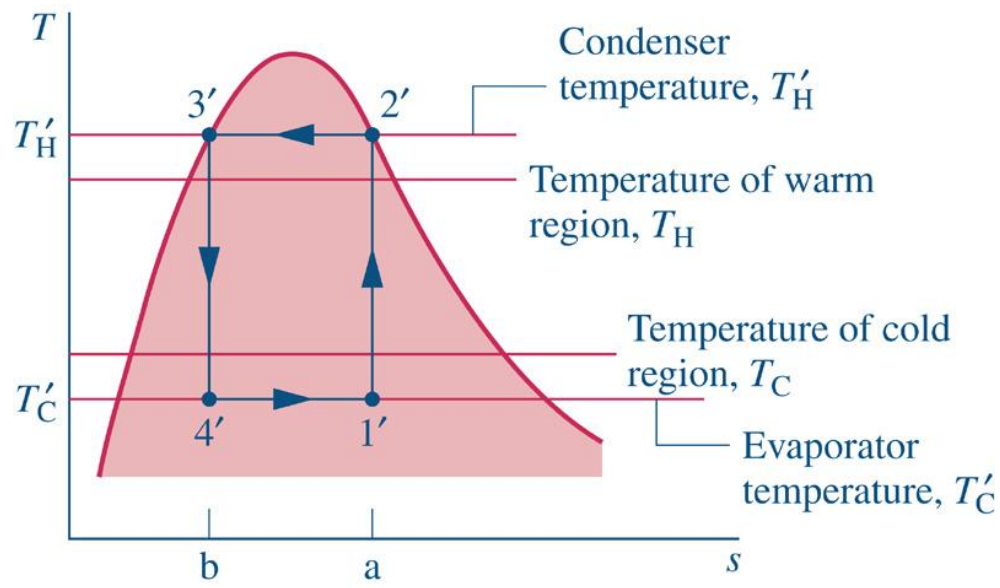
  - Coefficient of performance, maximum:

$$\mathrm{COP}_{\mathrm{cm,max}} = \frac{\dot{Q}_{\mathrm{in}} / \dot{m}}{\left| \dot{W}_{\mathrm{c}} / \dot{m} + \dot{W}_{\mathrm{t}} / \dot{m} \right|} = \frac{T_{\mathrm{C}}(s_a - s_b)}{(T_{\mathrm{H}} - T_{\mathrm{C}})(s_a - s_b)} = \frac{T_{\mathrm{C}}}{T_{\mathrm{H}} - T_{\mathrm{C}}}$$

Vapor refrigeration system

- Practical refrigeration cycle:
  - Heat transfer requires temperature gradient:

$$\mathrm{COP}_{\mathrm{cm}} = \frac{T_{\mathrm{C}}'}{T_{\mathrm{H}}' - T_{\mathrm{C}}'} < \mathrm{COP}_{\mathrm{cm,max}}$$



  - Compression (1-2) takes place in two-phase region (wet compression)

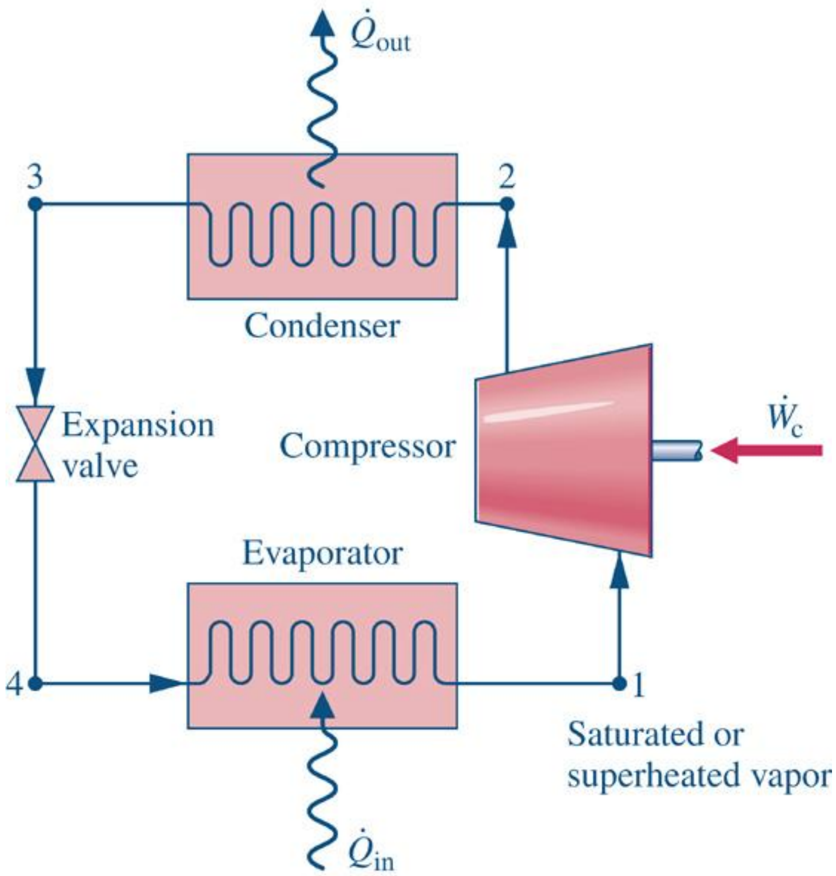
    → bad for compressor and unpractical, in actual system only dry compression

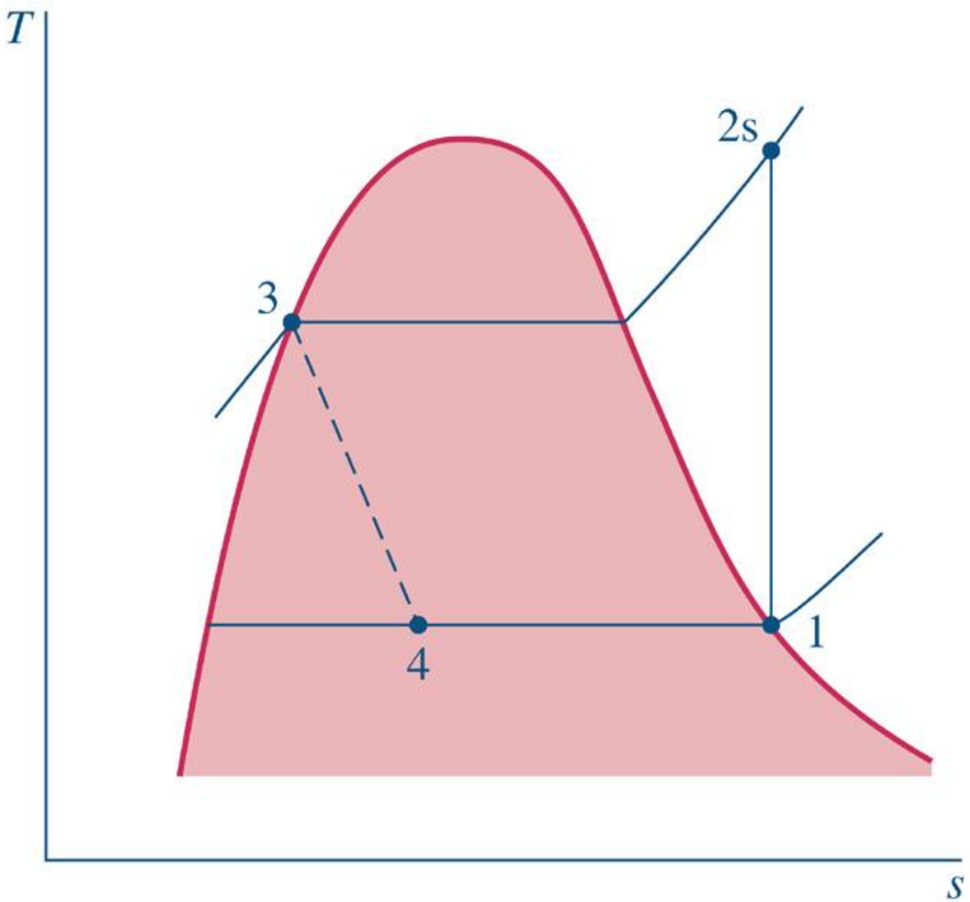
  - Work output via turbine expansion is low compared to work input for compression

    → spare the money for turbine and add simple throttling valve

Vapor-compression refrigeration system

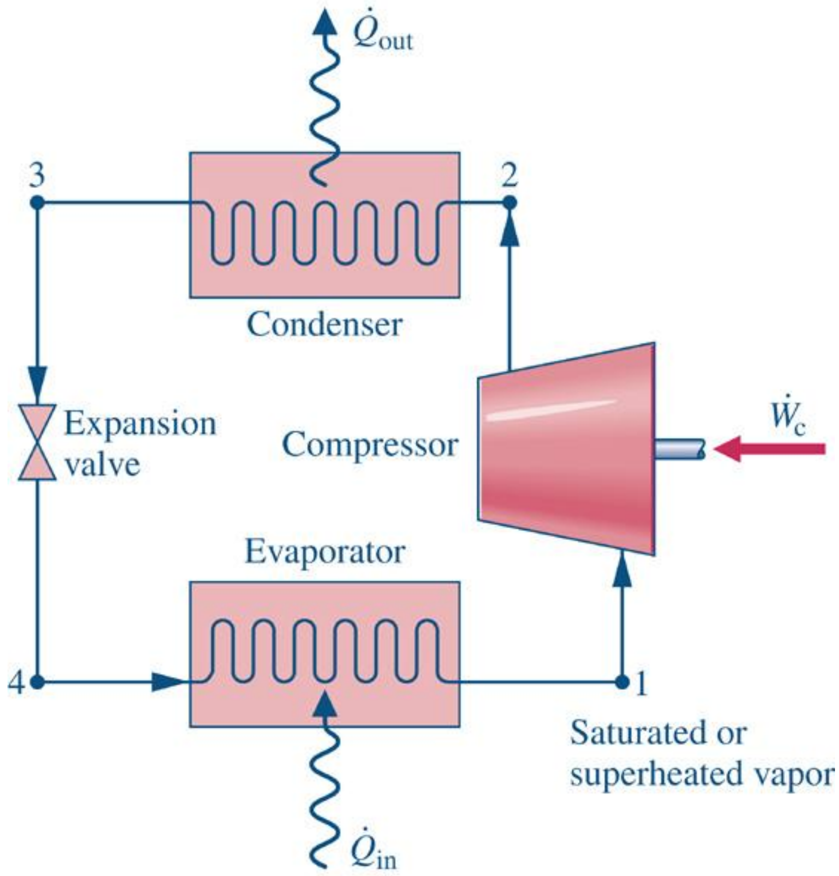
- Practical refrigeration cycle:





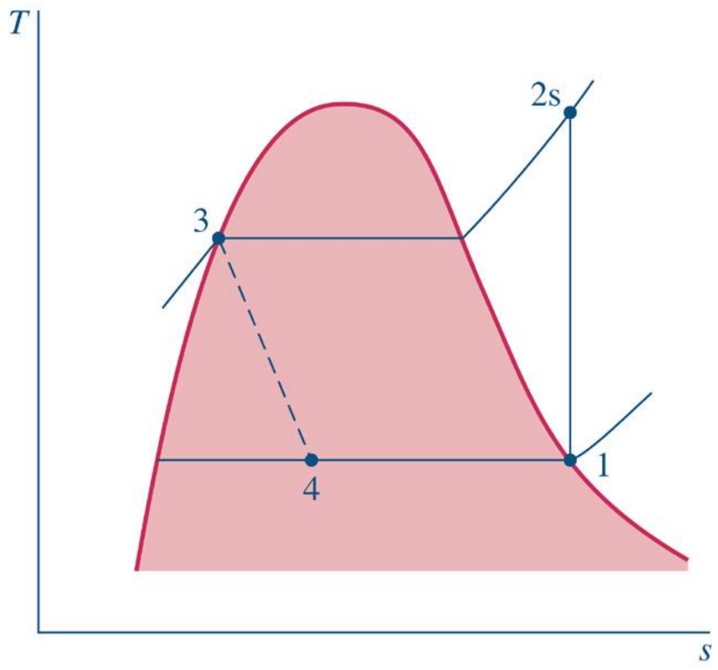
Vapor-compression refrigeration system

- Practical refrigeration cycle:
  - 1-2: $\frac{\dot{W}_c}{\dot{m}} = h_1 - h_2$
  - 2-3: $\frac{\dot{Q}_{out}}{\dot{m}} = h_3 - h_2$
  - 3-4: $h_3 = h_4$
  - 4-1: $\frac{\dot{Q}_{in}}{\dot{m}} = h_1 - h_4$ — Refrigeration capacity
  - Performance: $COP_{cm} = \frac{h_1 - h_4}{h_2 - h_1}$



Vapor-compression refrigeration system

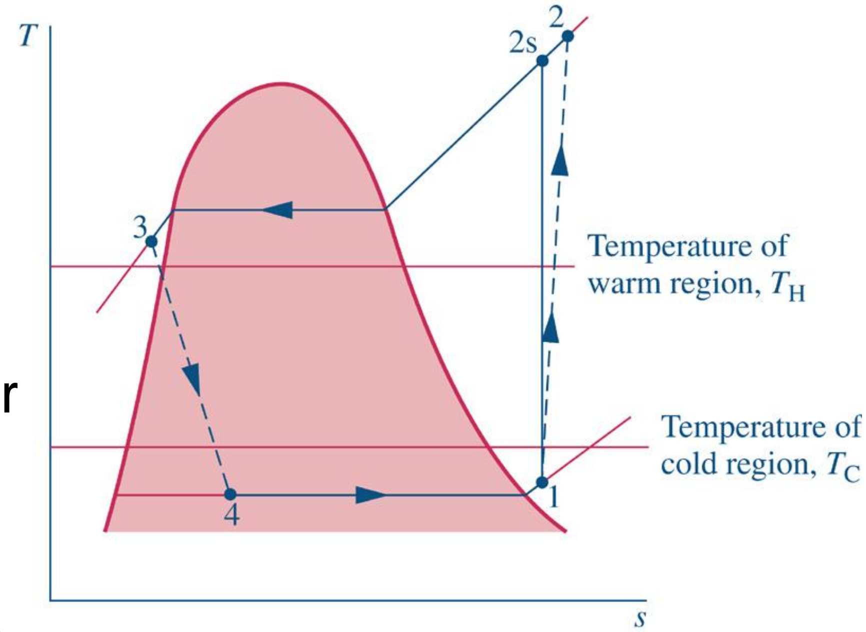
- Practical refrigeration cycle, ideal:
  - 1-2: Isentropic compression
    to condenser pressure
  - 2-3: Isobaric heat rejection
    to saturated liquid
  - 3-4: Throttling process to a
    two-phase liquid-vapor mixture
  - 4-1: Isobaric heat addition to
    saturated vapor



  - All of the processes, except the throttling, are reversible processes
  - The cycle is called the **ideal vapor-compression cycle**

Vapor-compression refrigeration system

- Practical refrigeration cycle, real:
  - Temperature in evaporator is less than cold region temperature
  - Temperature in condenser is higher than hot region temperature
  - Irreversibilities during compression
    - Use isentropic compressor efficiency
    - Cycle with non/isentropic compr. have same refrigeration capacity
    - Cycle with non-isentropic compression requires more work input
  - Superheating in evaporator and subcooling in condenser
  - Pressure losses during heat transfer and other piping



Vapor-compression refrigeration system

- Example (8.4): Refrigerant 134a is the working fluid in an actual vapor-compression refrigeration cycle.
  - saturated vapor enters the compressor at -10°C
  - the compressor works with 80% isentropic efficiency
  - the liquid leaves the condenser at 30°C and 9 bar
  - Refrigerant mass flow rate of 0.08 kg/s

  Determine:
  - Compressor power
  - Refrigeration capacity
  - Coefficient of performance
  - Exergy destruction in valve (T_0=299K)

$\dot{W}_c$=3.1 kW
$\dot{Q}_{in}$=12.0 kW
COP_{cm}=3.86
$\dot{Ex}_d$=0.39 kW

Refrigerants

- Early refrigerants based on chlorofluorcarbons, e.g.:
  - Refrigerant 12 (CCl_2F_2)

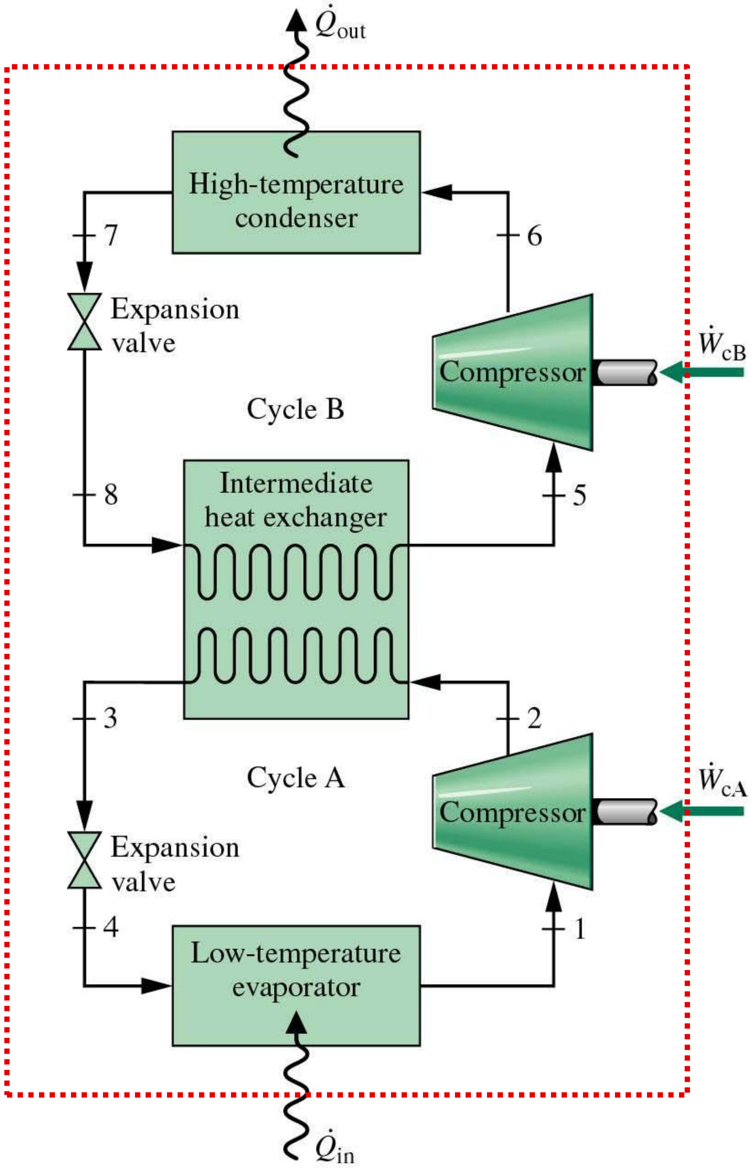
    Shows good performance but environmental concerns (destruction of ozon layer, global warming potential)
- Replacing the chlorine:
  - Refrigerant 134a (CF_3CH_2F)
- Alternatives: Ammonia, propane, carbon dioxide
- Choice of refrigerant based on
  - Operating conditions (pressures, temperatures)
  - Stability
  - Toxicity, falmmability
  - Corrosiveness
  - Cost

Vapor-compression system

- Ways to improve performance:
  - Cascade cycles:
    - Cycle performance:

$$\mathrm{COP}_{\mathrm{cm}} = \frac{\dot{Q}_{\mathrm{in}}}{\dot{W}_{\mathrm{cA}} + \dot{W}_{\mathrm{cB}}}$$

    - Cycles have different refrigerant
      A: allow for low evaporator temperature at moderate pressure
      B: allow for condensation at not to high pressure



Vapor-compression refrigeration system

- Example (8.5): Consider a single and two-stage refrigeration system operating between the pressure limits of 0.8 and 0.14 MPa.

  For the single stage system: it operates on an ideal vapor compression cycle with refrigerant-134a as working fluid. The mass flow rate of the cycle is 0.05 kg/s.

  For the two-stage system: Each stage operates on an ideal vapor compression cycle with refrigerant-134a as working fluid. Heat rejection from the lower to the upper cycle takes place in an adiabatic counterflow heat exchanger where both streams enter at 0.32 MPa. The mass flow rate of the topping cycle is 0.05 kg/s.

  Determine

  – The COP of the single stage system.

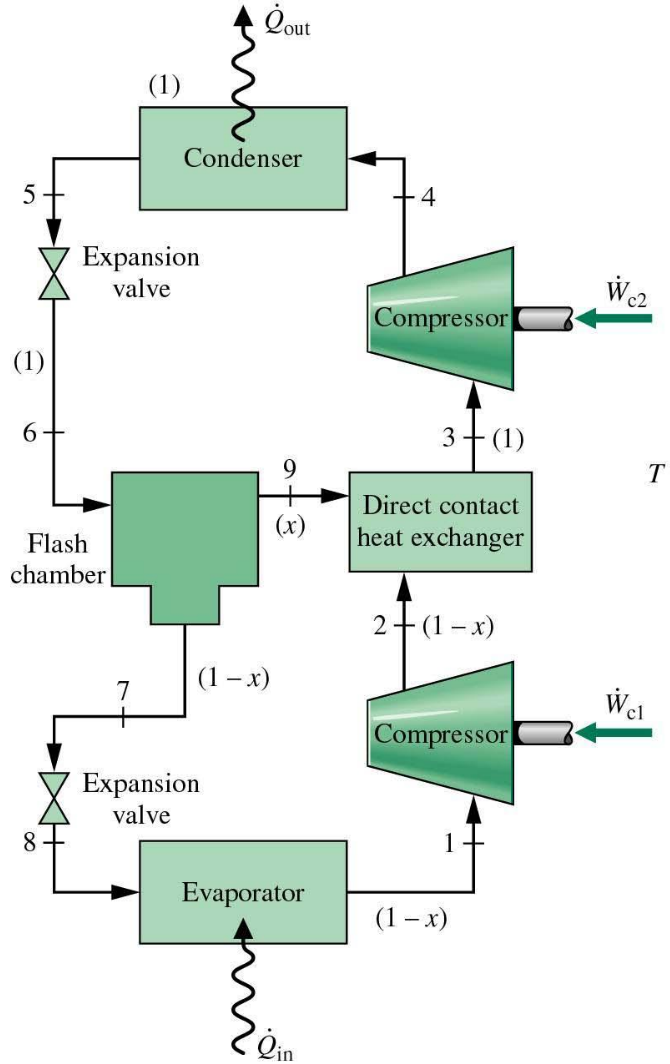
  – The COP of the two-stage system and the mass flow rate of the bottoming cycle

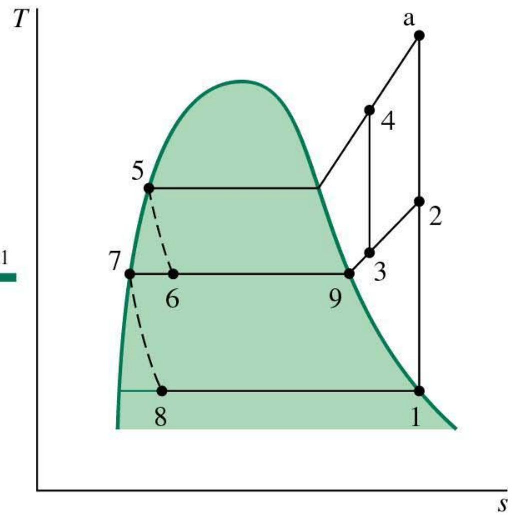
$COP_{single}=3.97$
$\dot{m}_{bottom}=0.039\text{kg/s}$
$COP_{double}=4.46$

Vapor-compression system

- Ways to improve performance:
  - Multistage compression with intercooling:

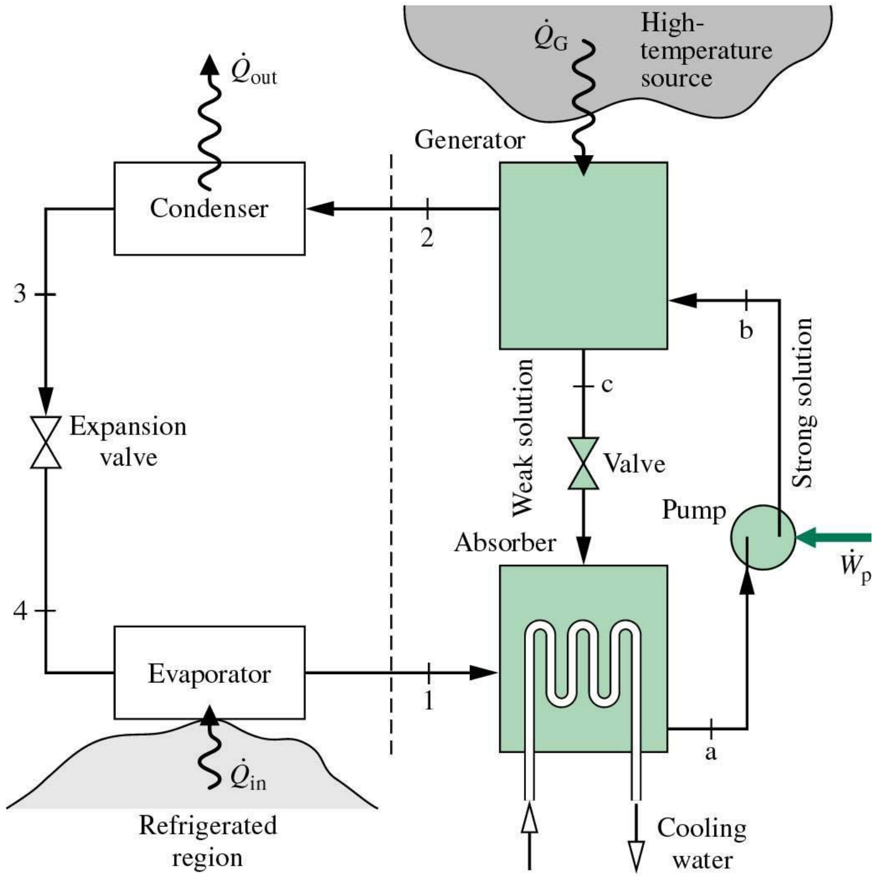
    - Cooling via refrigerant itself
    - Reduction in required work
    - Reduces condenser inlet temperature (external irreversibilities)





Absorption refrigeration

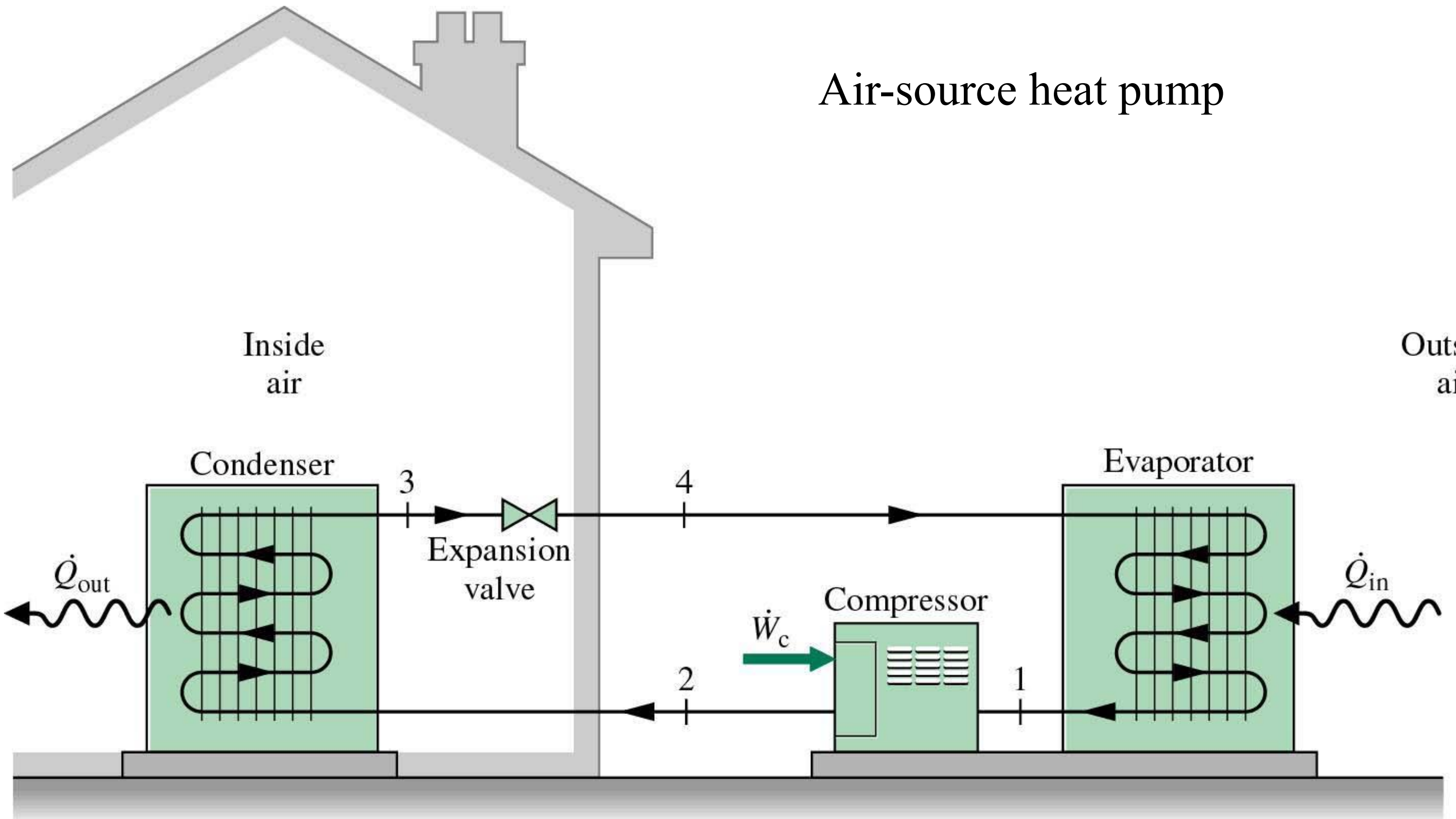
- Absorption refrigeration:
  - No compressor is used
  - Instead vapor is absorbed by absorbent forming liquid solution, which is pumped to higher pressure
  - As liquid is pumped (with lower spec. vol. than gas) less work input is required
  - Refrigerant recovered via high temperature source (e.g. solar, geothermal)
  - More components, more expensive



e.g. using ammonia as refrigerant and water as absorbent
Or water as refrigerant and lithium bromide as absorbent

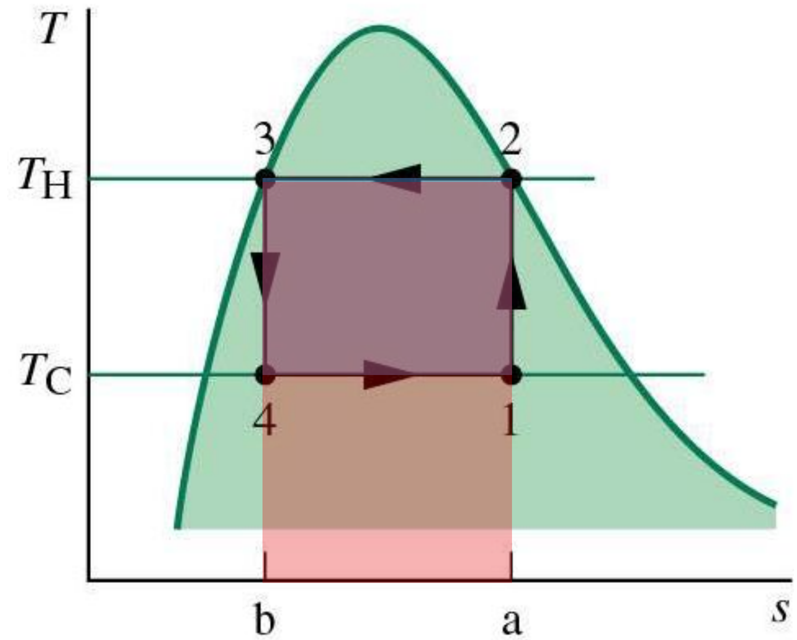
Heat pump systems

- Heat pump system:
  - Common application: space heating
  - Vapor-compression as well as absorption heat pumps



Heat pump systems

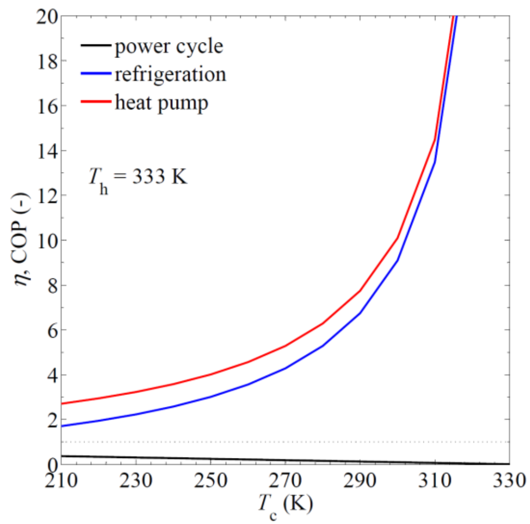
- Carnot heat pump cycle:
  - Same processes
  - Different purpose



  - Performance:

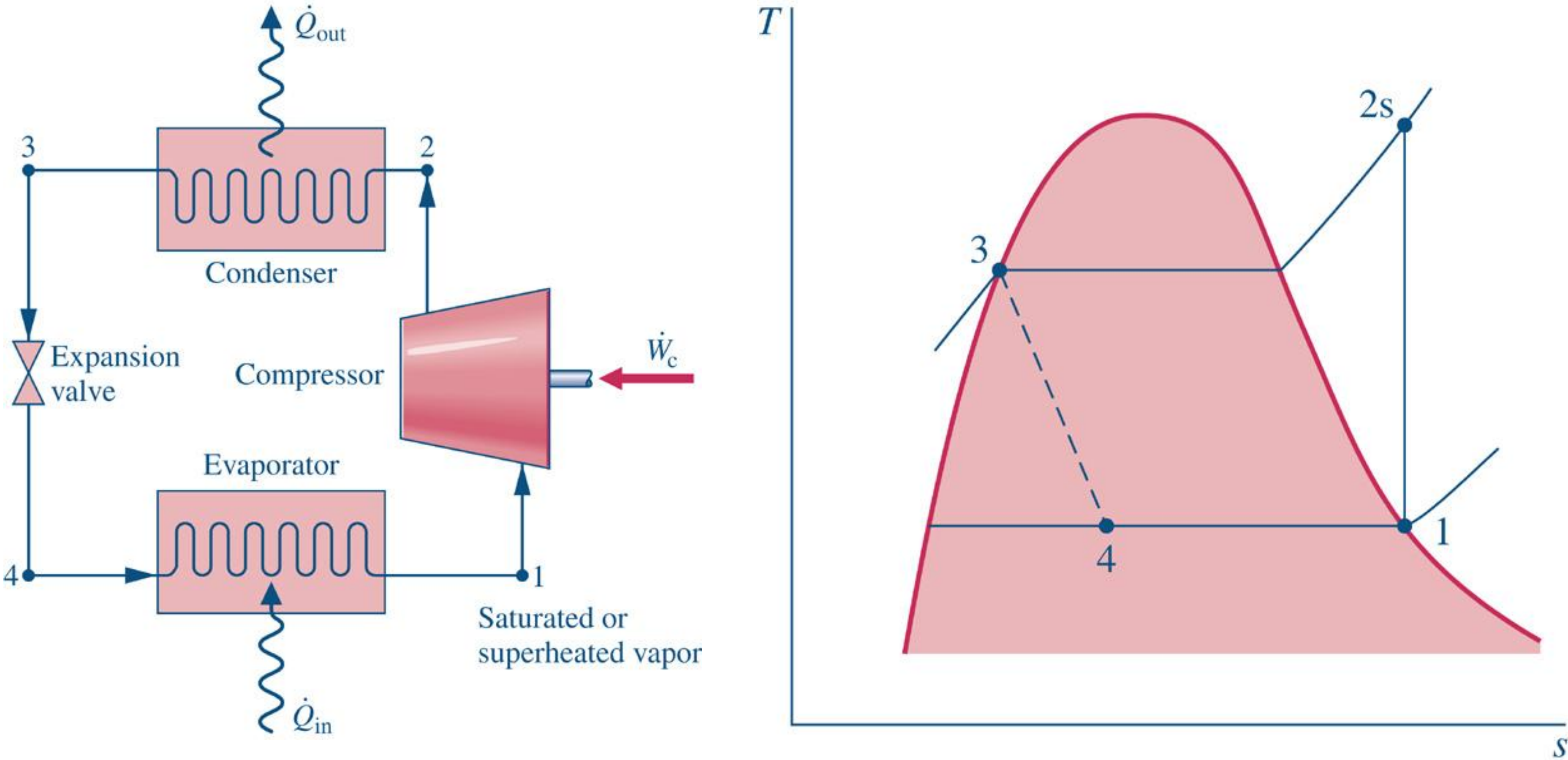
$$\text{COP}_{\text{hm,max}} = \frac{\dot{Q}_{\text{out}} / \dot{m}}{\left|\dot{W}_{\text{c}} / \dot{m} + \dot{W}_{\text{t}} / \dot{m}\right|} = \frac{T_{\text{H}}(s_a - s_b)}{(T_{\text{H}} - T_{\text{C}})(s_a - s_b)}$$

$$= \frac{T_{\text{H}}}{T_{\text{H}} - T_{\text{C}}}$$



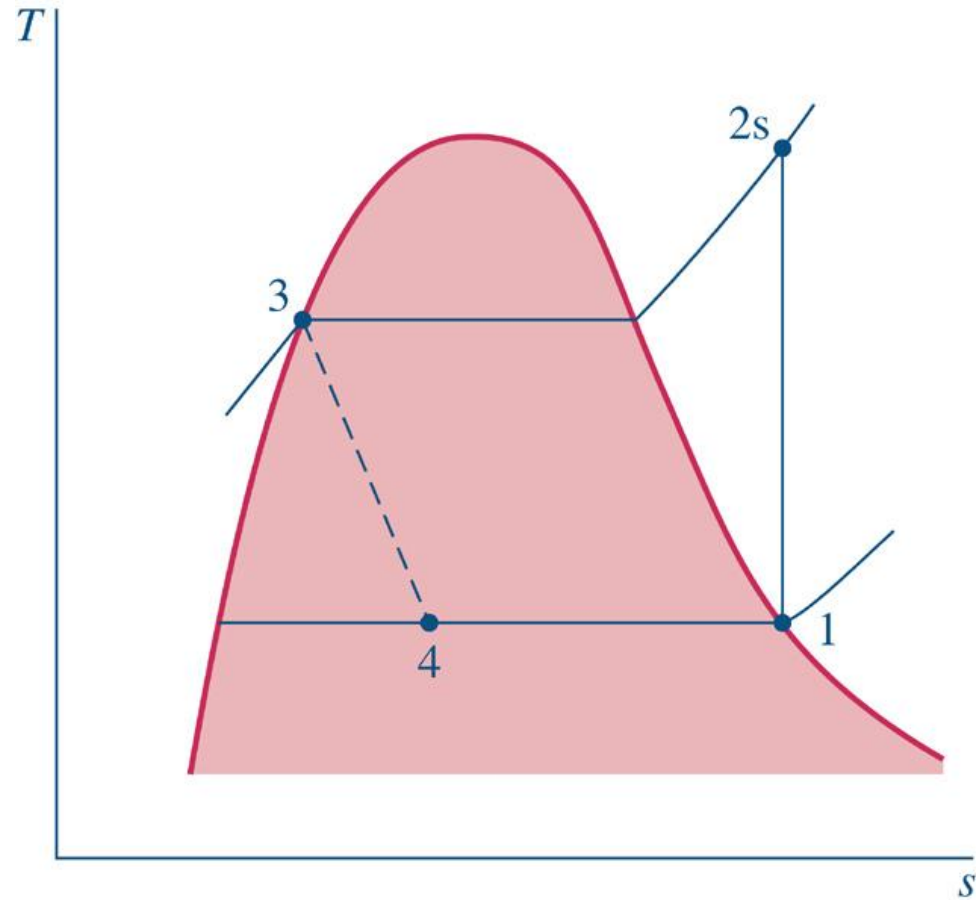
Heat pump systems

- Vapor-compression heat pumps:



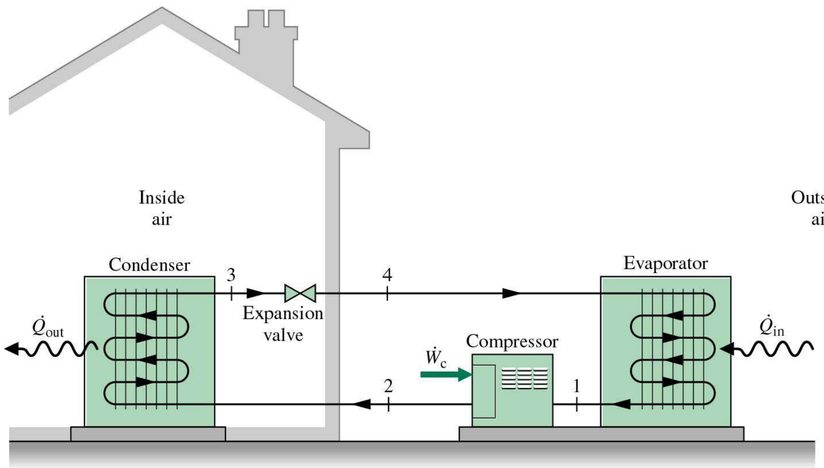
Heat pump systems

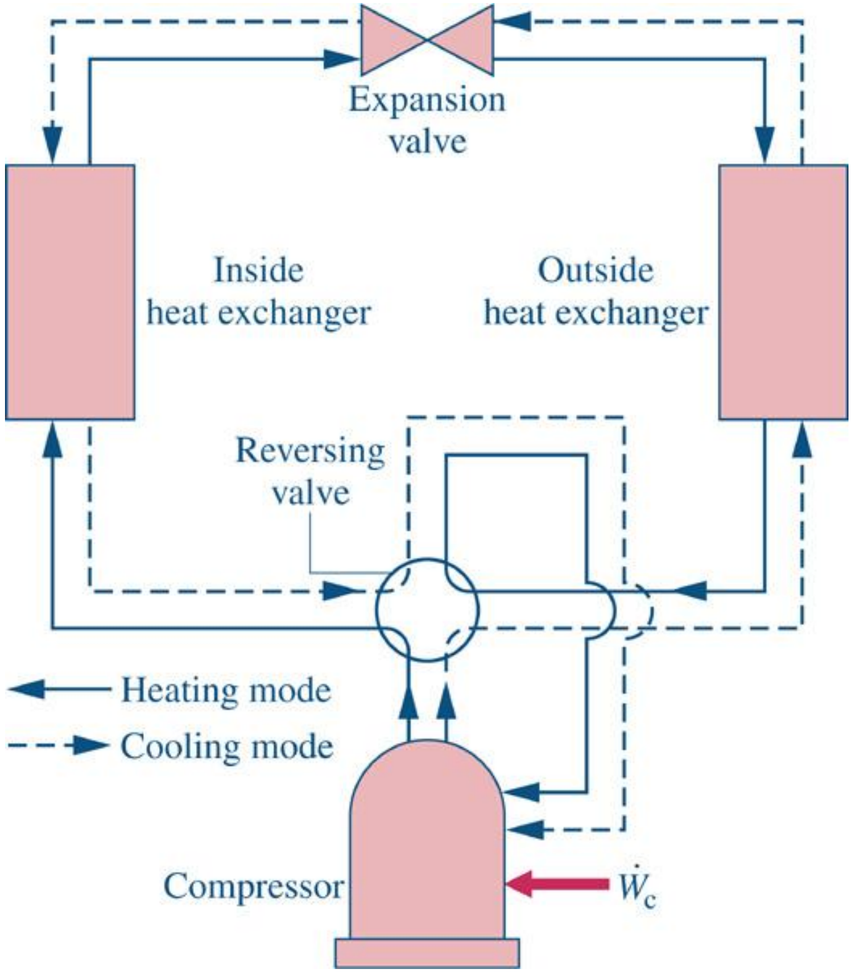
- Vapor-compression heat pumps:
  - 1-2: $\frac{\dot{W}_c}{\dot{m}} = h_1 - h_2$
  - 2-3: $\frac{\dot{Q}_{out}}{\dot{m}} = h_3 - h_2$
  - 3-4: $h_3 = h_4$
  - 4-1: $\frac{\dot{Q}_{in}}{\dot{m}} = h_1 - h_4$
  - Performance: $COP_{hm} = \frac{\dot{Q}_{out} / \dot{m}}{\dot{W}_c / \dot{m}} = \frac{h_2 - h_3}{h_2 - h_1}$



Heat pump systems

- Vapor-compression heat pumps:
  – Reverse operation possible e.g. during summer via reversing valve

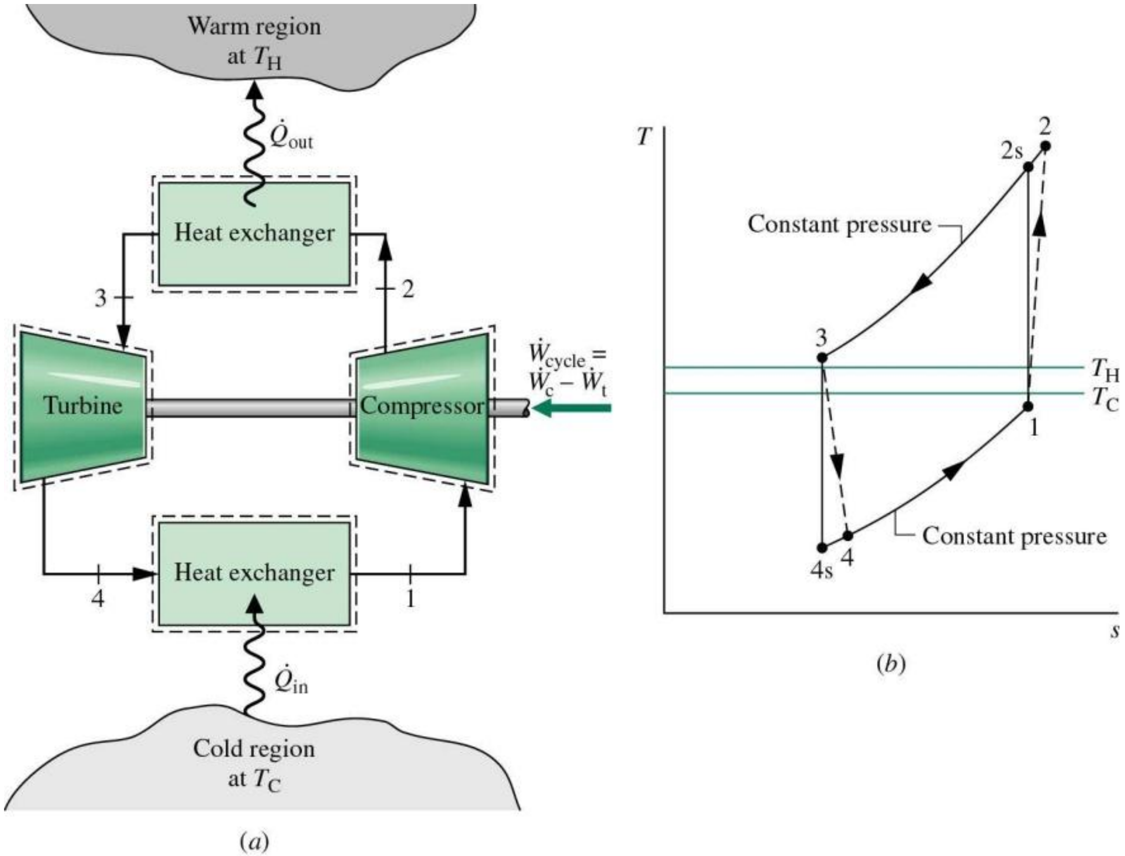




Gas refrigeration systems

- Gas refrigeration systems
  - Working fluid doesn’t change phase

- Brayton refrigeration cycle



Gas refrigeration systems

- Brayton refrigeration cycle

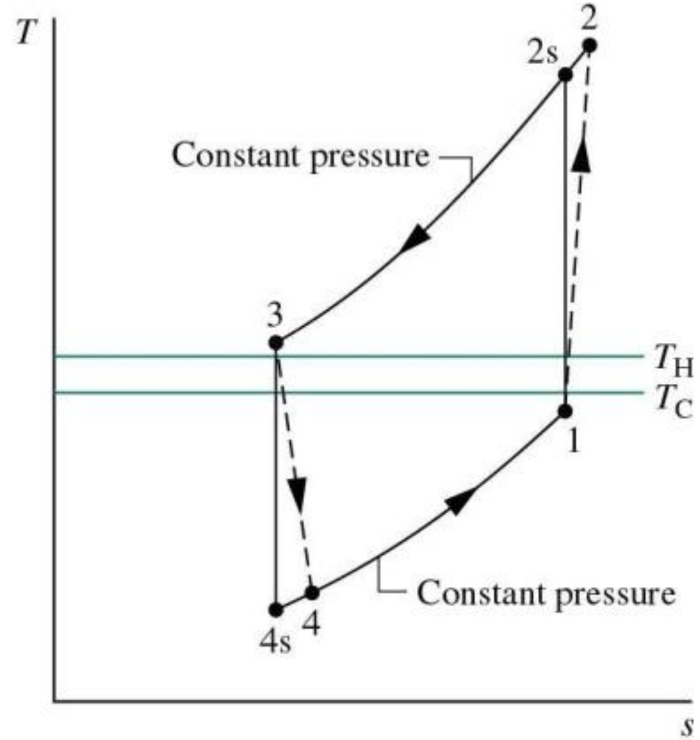
  1-2: Compression from temperature slightly lower than T_C

  2-3: Cooling (heat rejection) to temperature slightly above T_H

  3-4: Expansion through the turbine

  4-1: Evaporation (heat addition)

- Reversible vs. irreversible compression and expansion



(b)

Gas refrigeration systems

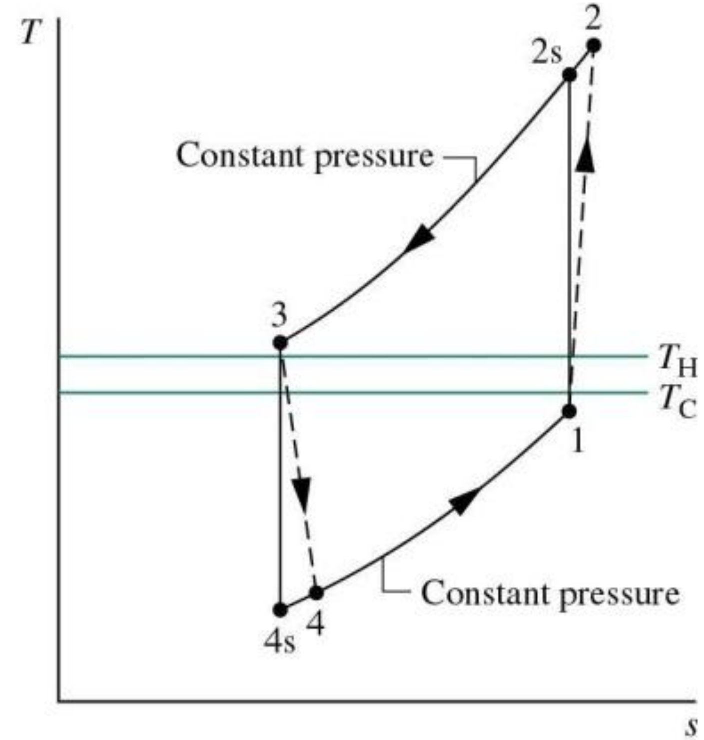
- Brayton refrigeration cycle

1-2: $$\frac{\dot{W}_c}{\dot{m}} = h_1 - h_2$$

2-3: $$\frac{\dot{Q}_{out}}{\dot{m}} = h_3 - h_2$$

3-4: $$\frac{\dot{W}_t}{\dot{m}} = h_3 - h_4$$

4-1: $$\frac{\dot{Q}_{in}}{\dot{m}} = h_1 - h_4$$



(b)

- Performance: $$\mathrm{COP}_{cm} = \frac{\dot{Q}_{in}/\dot{m}}{\left|\dot{W}_c/\dot{m} + \dot{W}_t/\dot{m}\right|} = \frac{h_1 - h_4}{\left|h_1 - h_2 + (h_3 - h_4)\right|}$$

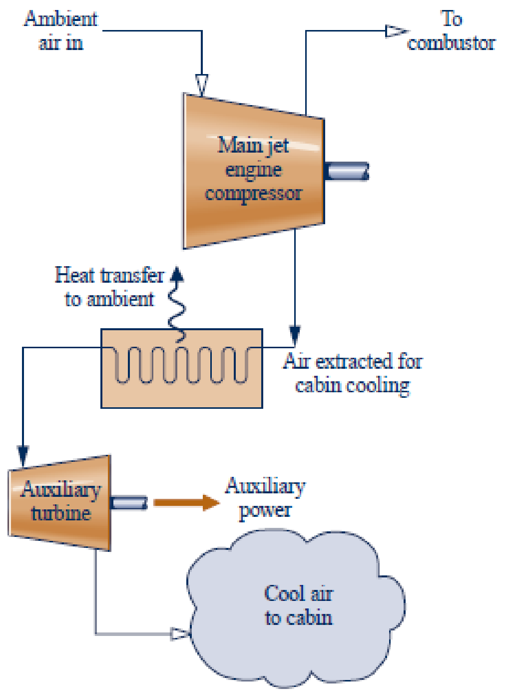
Gas refrigeration systems

- Example (8.6): Air enters the compressor an ideal Brayton cycle at 1 bar and 270 K, with volumetric flow rate of 1.4 m^3/s. The compressor ratio is 3 and the turbine inlet temperature is 300 K. Determine
  - Net power input
  - Refrigeration capacity
  - Coefficient of performance

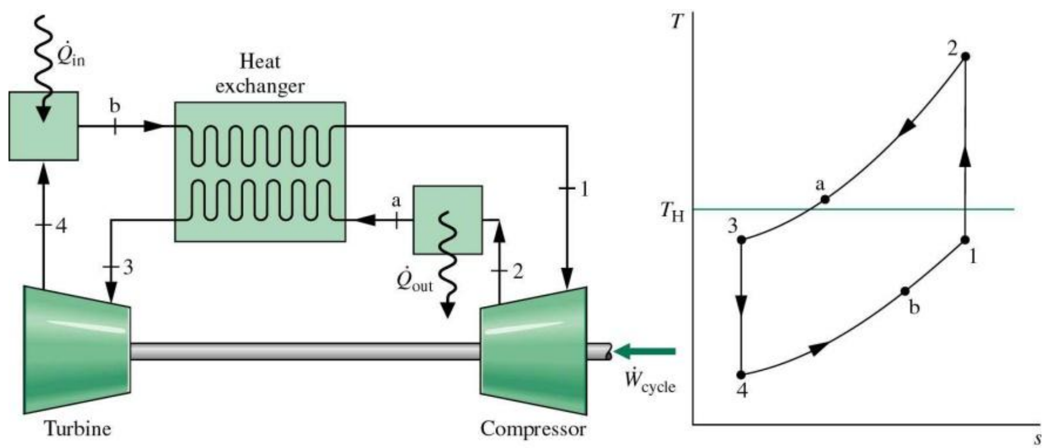
$$\dot{W}_c = 33.97 \text{ kW}$$
$$\dot{Q}_{in} = 92.36 \text{ kW}$$
$$COP_{cm} = 2.72$$

Gas refrigeration systems

- Often used in airplanes



- Can reach very low temperatures (using regenerative heat exchanger)



Learning outcomes of todays lecture

- Demonstrate and understand the
  - Basic vapor-compression refrigeration and heat pump systems
  - Absorption refrigeration systems
  - Gas refrigeration systems

- Develop thermodynamic models, including:
  - Sketch *T*-*s*-, *p*-*v*-diagrams
  - Evaluate properties at states of cycle
  - Apply mass, energy and entropy balances to the processes
  - Determine performance

- Discuss and analyze the performance and optimization approaches