Thermodynamics and energetics 1

Prof. Sophia Haussener

Laboratory of Renewable Energy Sciences and Engineering

Summary last lecture

- Understand and demonstrate key concept of exergy and exergy analysis
- Evaluate exergy at a state and exergy changes between two states
- Apply exergy balances to closed and open systems
- Define and evaluate exergetic efficiencies

Learning outcomes of todays lecture

- Demonstrate and understand the basic principles of **vapor power systems**, i.e. power systems using a working fluid which is alternately vaporized and condensed

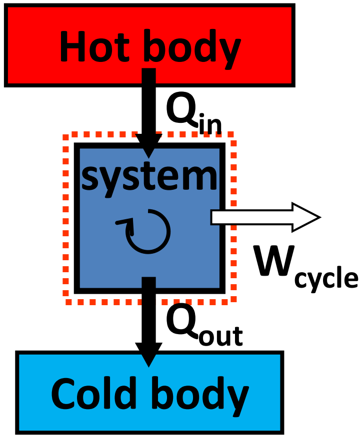
- Develop and analyze thermodynamic models of vapor power plants based on Rankine cycle and its modifications
  - Sketch *T*-*s*-, *p*-*v*-diagrams
  - Evaluate properties at states of cycle
  - Apply mass, energy and entropy balances to the processes
  - Determine performance

- Discuss and analyze the performance and optimization approaches

Moran book: chp. 8

Power systems

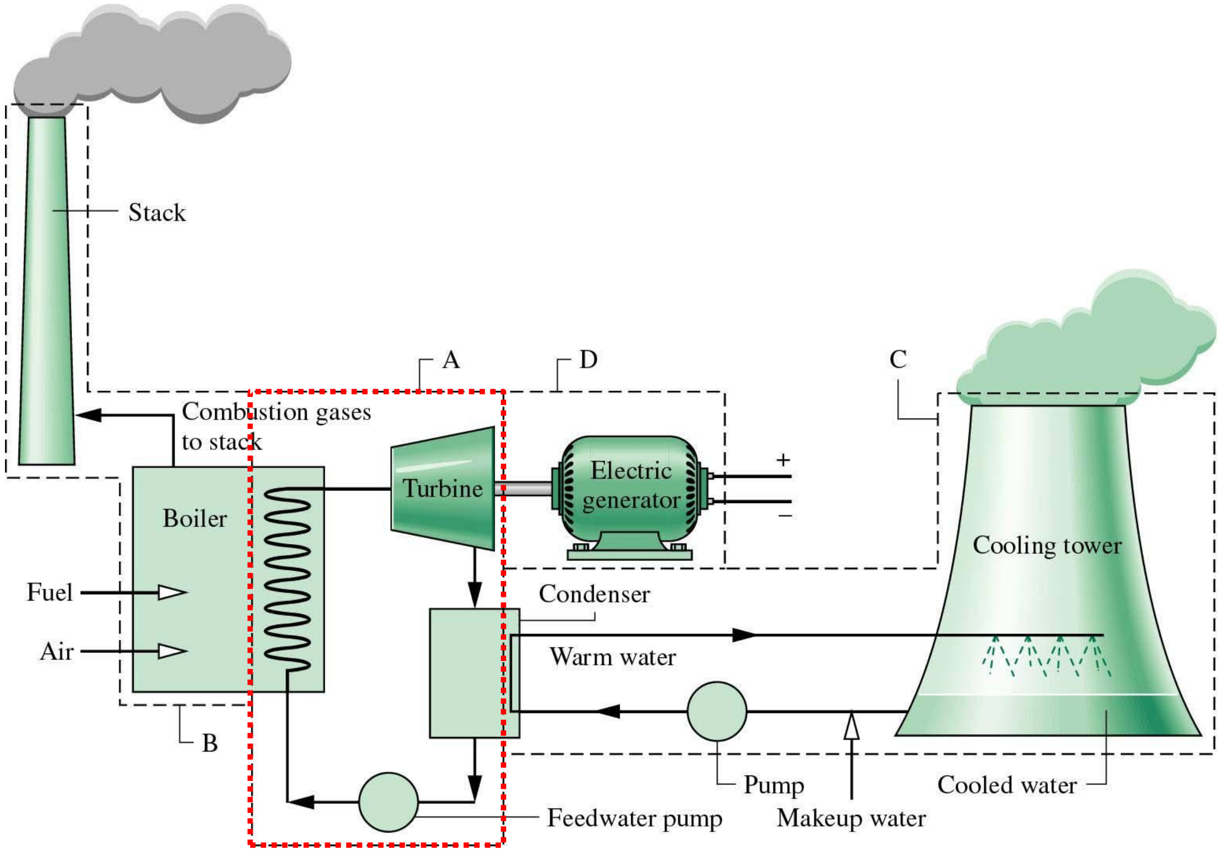
- Power generation systems:
  - Produce net power output from an energy source, such as fossil fuel, nuclear, or solar power



  - Three major types of systems:
    - Vapor power plants (working fluid alternately vaporizes and condenses)
    - Gas turbine power plants (working fluid gas, series of components)
    - Internal combustion engines (working fluid gas, reciprocating)

Vapor power systems

- Vapor power systems:
  - Water is the working fluid, which alternately vaporizes and condenses
  - Majority of electrical power generation done by these systems
  - Basic components in a simplified systems are:
    - Boiler
    - Turbine
    - Condenser
    - Pump

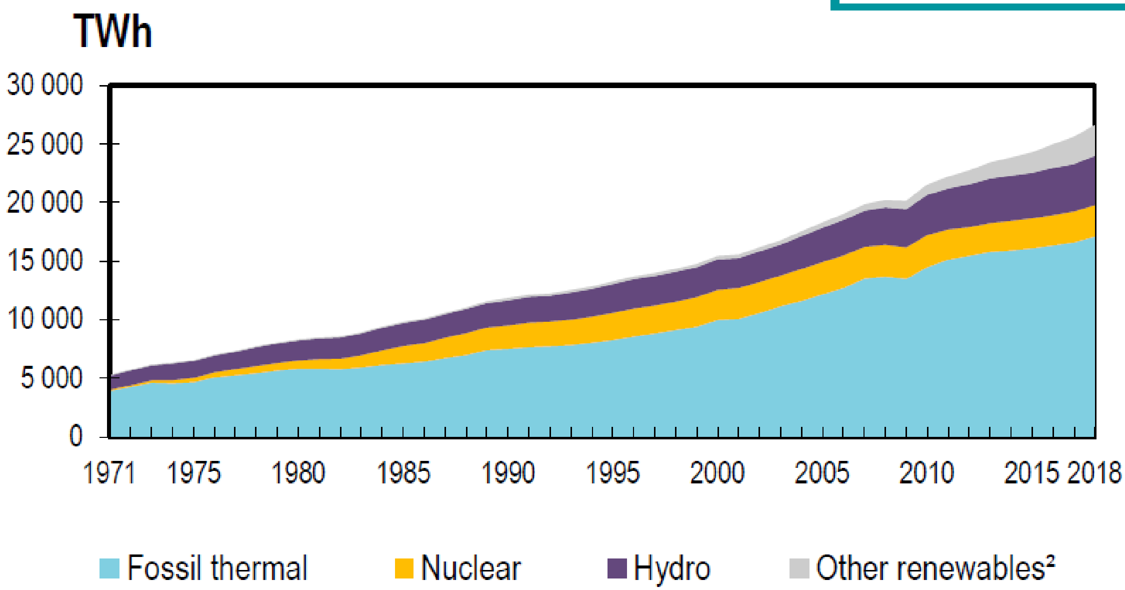


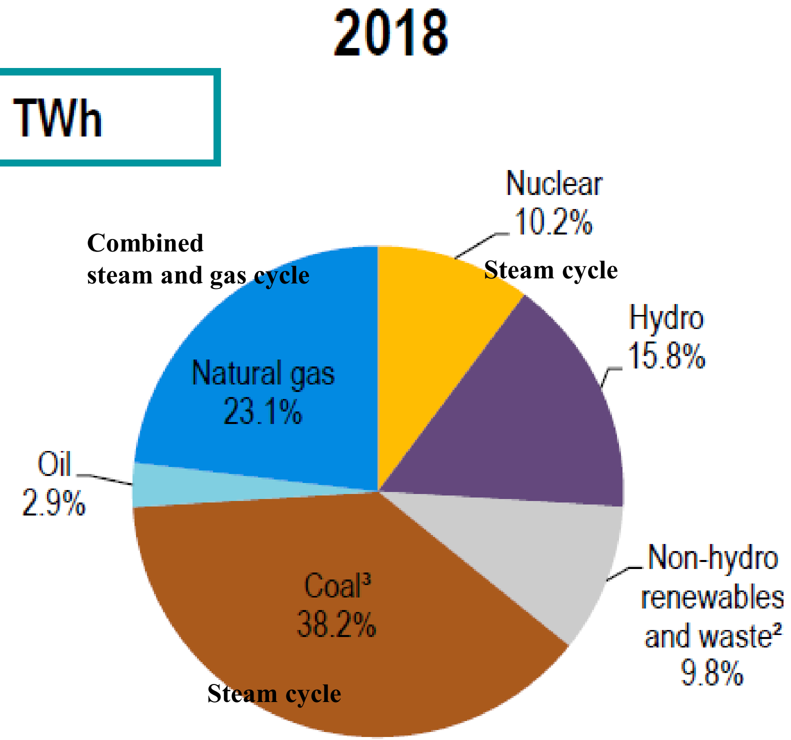
State of the art

- Current global power production[1]

IEA, World key energy statistics, 2020

26 619 TWh





[1] excl. electricity generation from pumped hydro
[2] incl. geothermal, solar, wind, heat, etc.
[3] incl. peat and oil shales

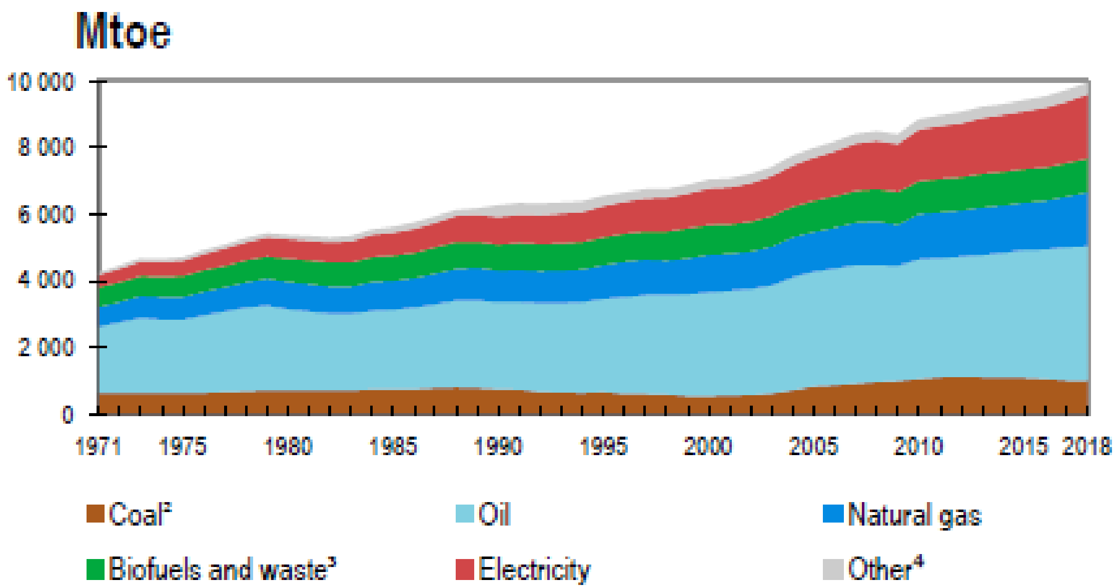
https://webstore.iea.org/download/direct/4093?fileName=Key_World_Energy_Statistics_2020.pdf

State of the art

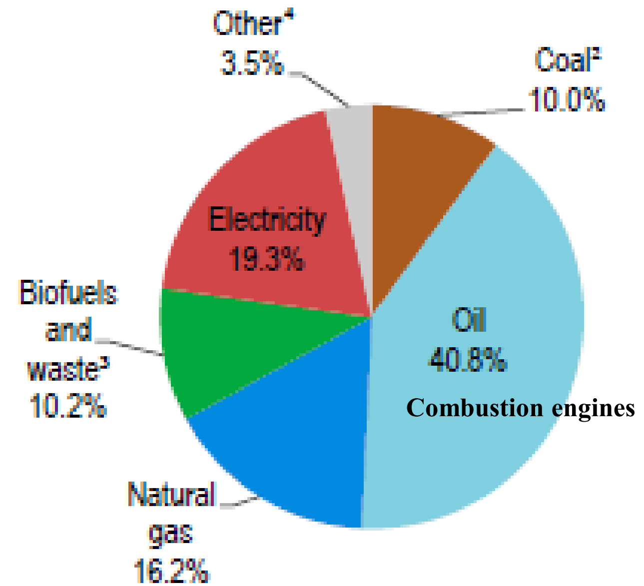
- Current global energy consumtion[1]

IEA, World key energy statistics, 2020

9 938 Mtoe



2018



[1]World includes international aviation and international marine bunkers.
[2]In these graphs, peat and oil shale are aggregated with coal.
[3]Data for biofuels and waste final consumption have been estimated for a number of countries.
[4]Includes heat, solar thermal and geothermal.

https://webstore.iea.org/download/direct/4093?fileName=Key_World_Energy_Statistics_2020.pdf

Vapor power systems

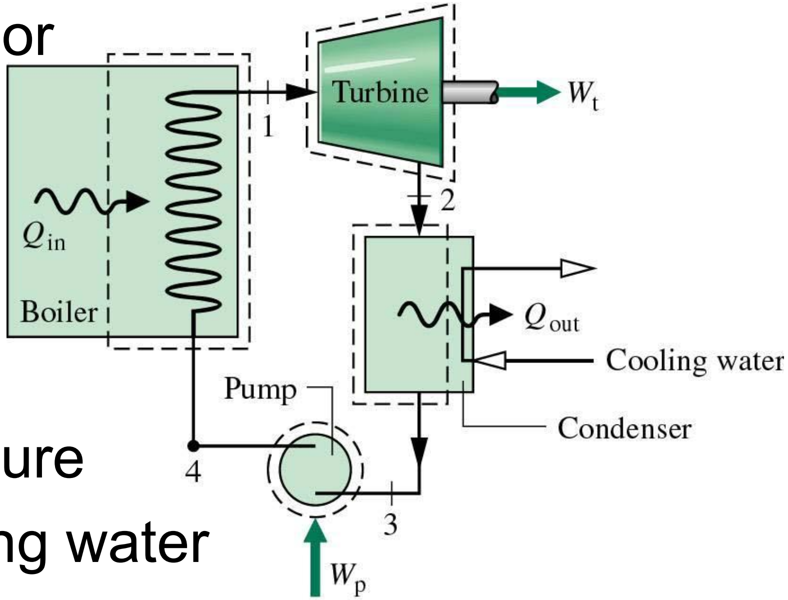
- Vapor power systems:
  - Nuclear powered:
    Leibstadt (CH)
    1200 MW

  - Fossil fuel powered:
    Arnot (South Africa)
    2100 MW (6 units)

  - Solar energy powered:
    SEGS (USA, CA)
    350 MW (9 units)

Vapor power systems

- Vapor power systems: fluid undergoes a thermodynamic cycle:
  - Turbine ($\dot{W}$>0): pressurized, hot vapor expands through the turbine and produces work, leaves turbine at relatively low pressure
  - Condenser ($\dot{Q}$<0): steam/vapor mixture is condensed, temperature of cooling water increases
  - Pump ($\dot{W}$<0): liquid water is pumped from the condenser into the higher pressure boiler
  - Boiler ($\dot{Q}$>0): the working fluid is heated to saturation and evaporated

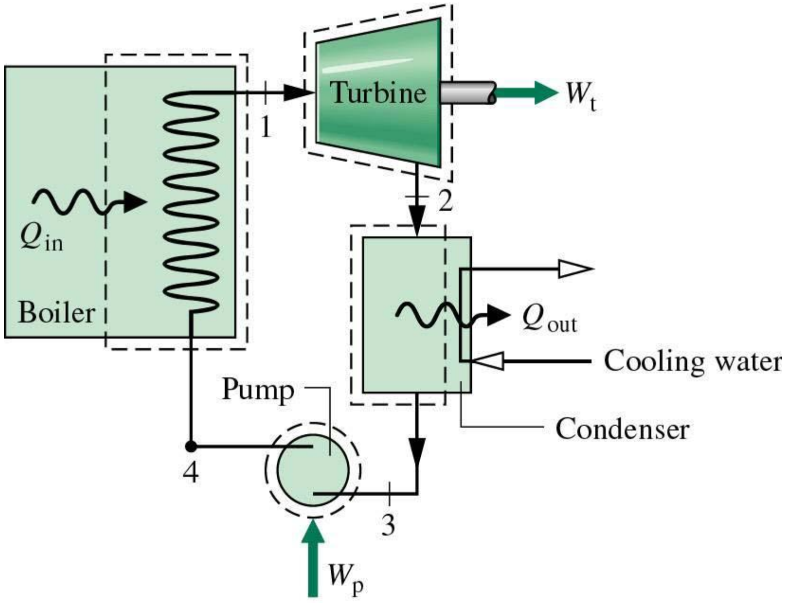


Vapor power systems

- Mass conservation and 1st law:
  - Turbine ($\dot{W}$>0): $\dot{W}_t / \dot{m} = (h_1 - h_2)$
  - Condenser ($\dot{Q}$<0):

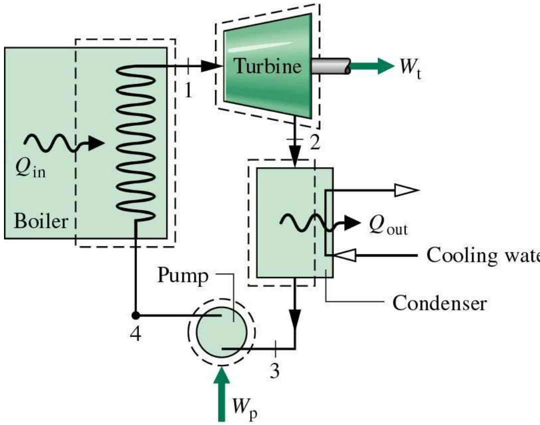
    $$\dot{Q}_{out} / \dot{m} = (h_3 - h_2)$$
  - Pump ($\dot{W}$<0): $\dot{W}_p / \dot{m} = (h_3 - h_4)$
  - Boiler ($\dot{Q}$>0): $\dot{Q}_{in} / \dot{m} = (h_1 - h_4)$
  - Thermal efficiency:

$$\eta = \frac{\dot{W}_t / \dot{m} + \dot{W}_p / \dot{m}}{\dot{Q}_{in} / \dot{m}} = \frac{(h_1 - h_2) + (h_3 - h_4)}{(h_1 - h_4)}$$

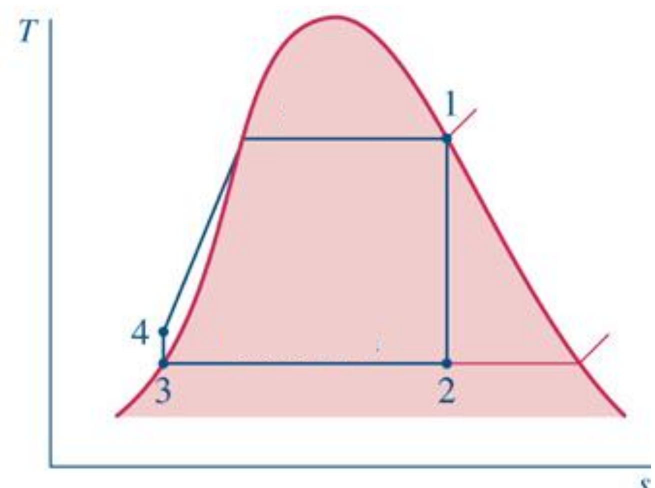


Vapor power systems

- Idealized *Rankine* cycle:
  - Turbine: *isentropic* expansion from saturated vapor state to condenser pressure



  - Condenser: *isobaric* heat transfer from working fluid as it flow through condenser to saturated liquid conditions
  - Pump: *isentropic* compression in pump, reminder: $\left(\frac{\dot{W}}{\dot{m}}\right)_{\substack{\text{int}\\\text{rev}}} = \int_3^4 -vdp \approx -v(p_4 - p_3)$ (incompressible fluid)



  - Boiler: *isobaric* heat transfer to fluid as it flows through boiler

Vapor power systems

- Example (8.0): Steam is the working fluid of an ideal Rankine cycle. Saturated vapor enters the turbine at 8 MPa and saturated liquid exits the condenser at a pressure of 0.008 MPa. Determine the cycle's:
  - Thermal efficiency
  - Back-work-ratio

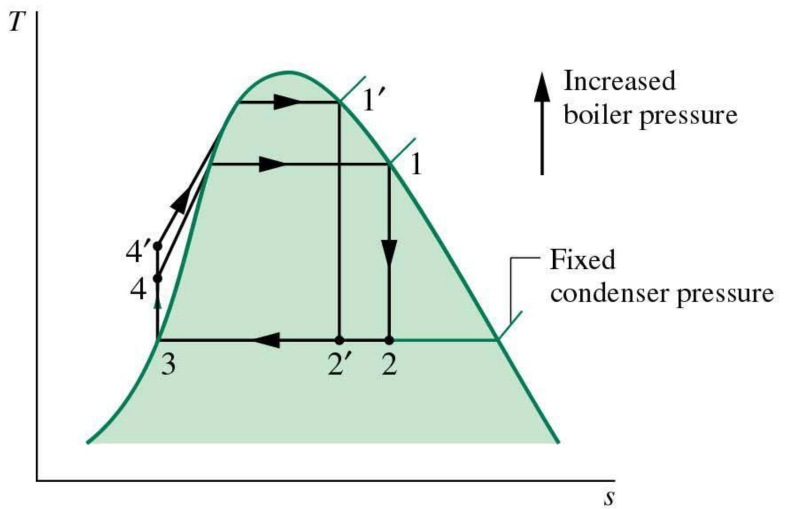
η_{th}=37%
bwr=0.84%

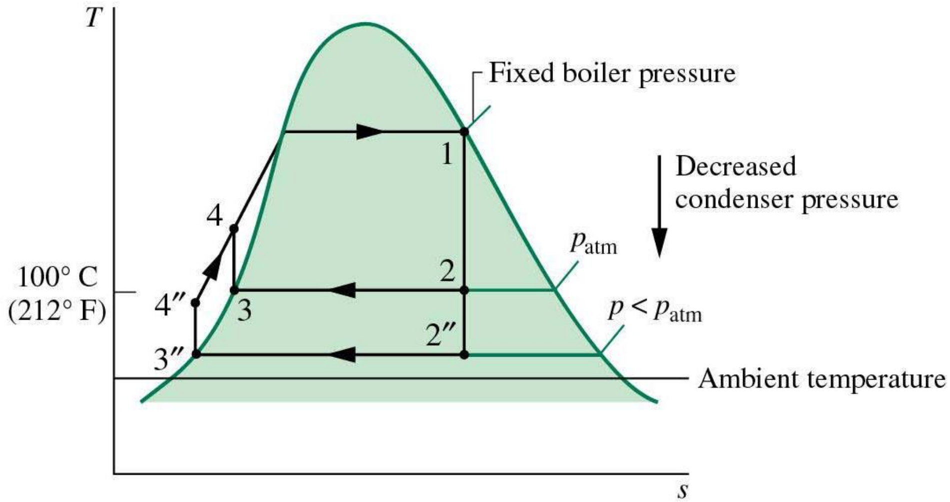
Vapor power systems

- Idealized Rankine cycle: effects of components on performance:
  - Increase of average temperature at which energy is added and decrease of average temperature at which energy is rejected leads to increased efficiency (Carnot):

$$\eta_{\text{ideal}} = \frac{(\dot{Q}_{\text{in}} / \dot{m})_{\text{int,rev}} - (\dot{Q}_{\text{out}} / \dot{m})_{\text{int,rev}}}{(\dot{Q}_{\text{in}} / \dot{m})_{\text{int,rev}}} = 1 - \frac{T_{\text{out}}}{\overline{T}_{\text{in}}}$$

  - Increase in boiler pressure and decrease in condenser pressures:





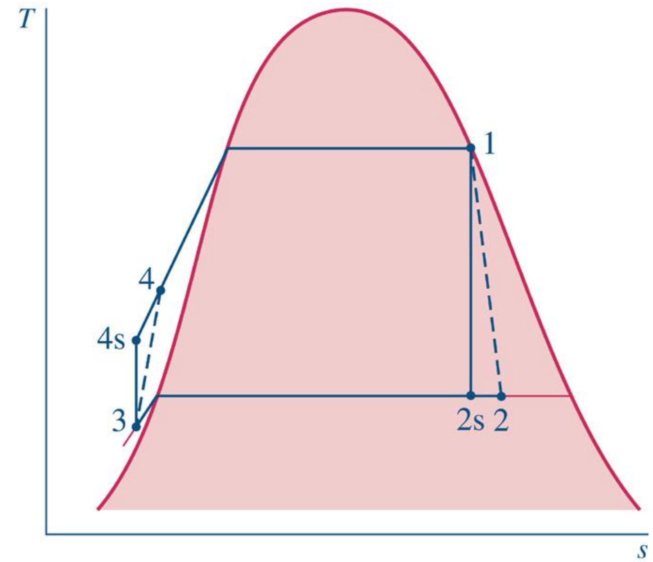
Vapor power systems

- Real Rankine cycle: irreversibilities (2nd law):
  - Turbine (friction):

$$\eta_{t,s} = \frac{\dot{W}/\dot{m}}{\left(\dot{W}/\dot{m}\right)_s} = \frac{h_1 - h_2}{h_1 - h_{2,s}}$$

  - Pump (friction):

$$\eta_{p,s} = \frac{\left(-\dot{W}/\dot{m}\right)_s}{-\dot{W}/\dot{m}} = \frac{h_{2,s} - h_1}{h_2 - h_1}$$



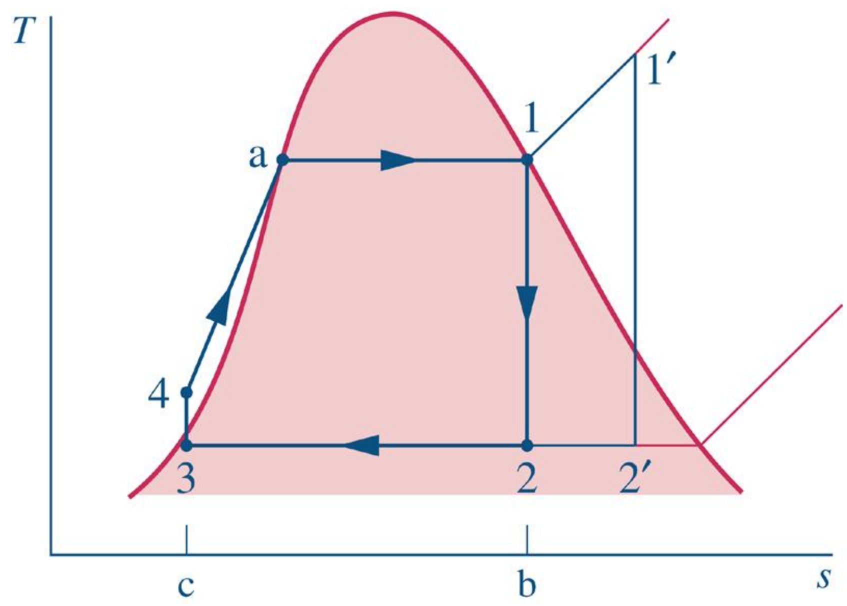
  - Irreversibilities in pump less significant as pump work much smaller than work extracted from turbine

Vapor power systems

- Rankine cycle: improving performance:

  Steam quality becomes low when increasing boiler pressure or decreasing condenser pressure → evolving droplets can damage turbine and decrease efficiency

  – *Superheating* (using additional heat exchanger, combination of boiler and heat exchanger is called steam generator):
    - Higher steam quality at turbine exit
    - Higher average temperature at which heat is added



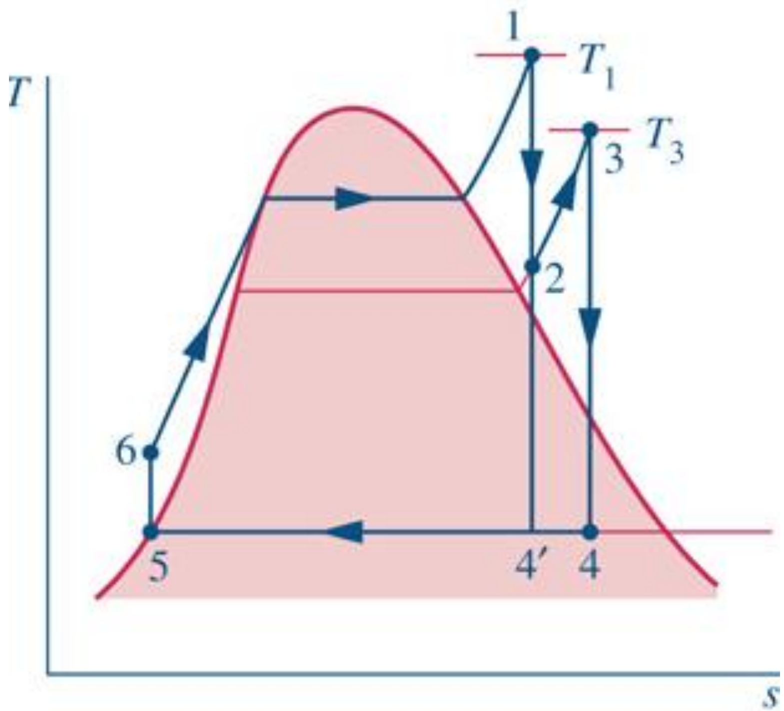
Vapor power systems

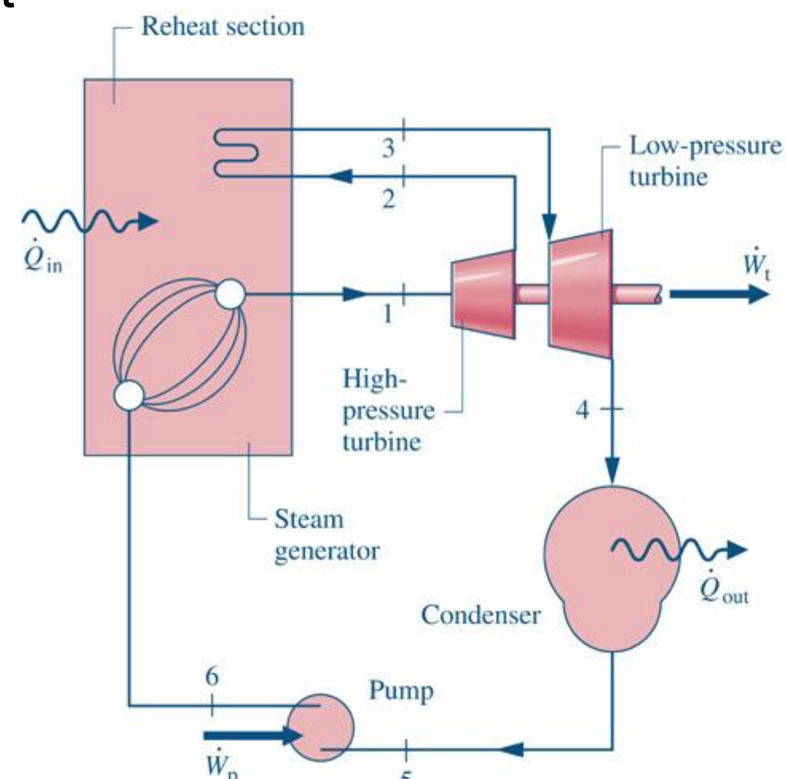
- Rankine cycle: improving performance:

  Steam quality becomes low when increasing boiler pressure or decreasing condenser pressure → evolving droplets can damage turbine and decrease efficiency

  – *Reheating*:

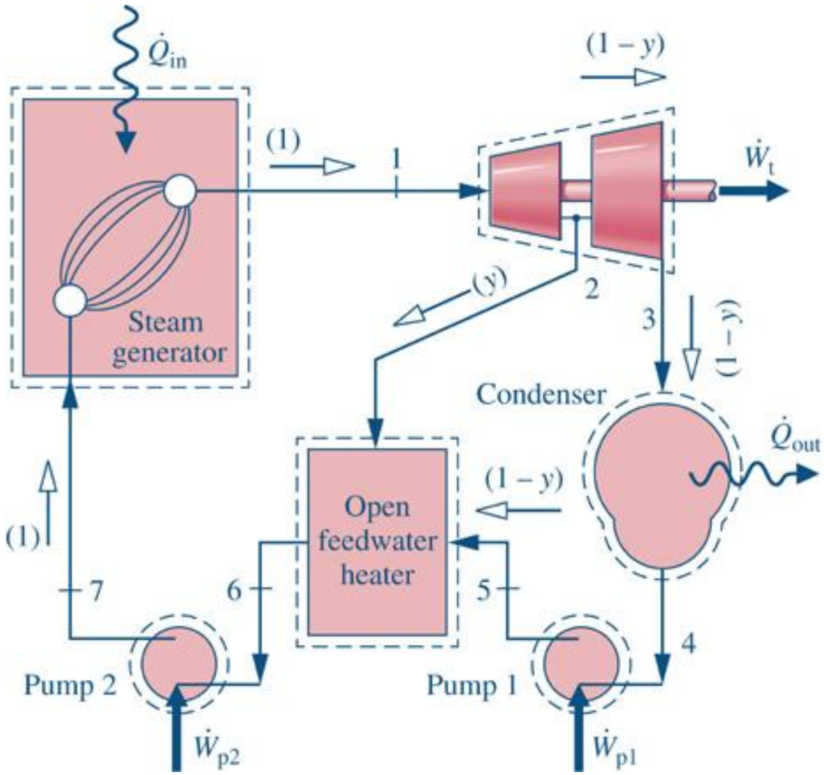
    - Higher steam quality at turbine exit

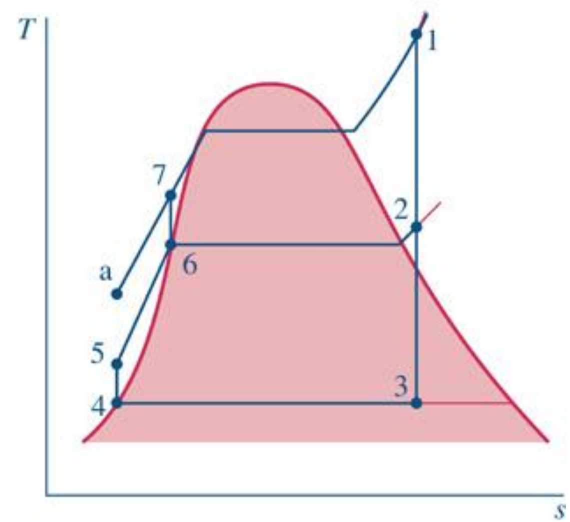




Vapor power systems

- Rankine cycle: improving performance:
  - *Regeneration* via **open** feedwater heater:
    - Higher average temperature at which heat is added (7-1)
    - Feedwater heater operates at p_2, and mass flow rates are chosen to make sure that feedwater exits at saturated liquid (state 6)





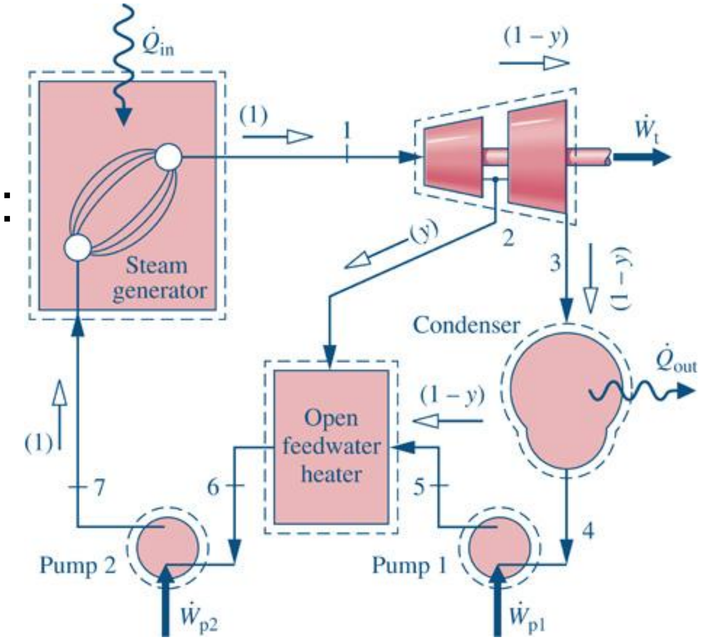
Vapor power systems

- Rankine cycle: improving performance:
  - *Regeneration* via open feedwater heater:
    - Mass conservation over both turbines:

$$\dot{m}_1 = \dot{m}_2 + \dot{m}_3 \;\rightarrow\; \dot{m}_3 / \dot{m}_1 = 1 - y$$

    - Mass conservation feedwater heater:

$$\dot{m}_1 = \dot{m}_6 = \dot{m}_2 + \dot{m}_5 = \dot{m}_2 + \dot{m}_3$$



    - Energy conservation feedwater heater:

$$0 = y h_2 + (1-y) h_5 - h_6 \;\rightarrow\; y = \frac{h_6 - h_5}{h_2 - h_5}$$

    - Energy conservation turbines and pumps:

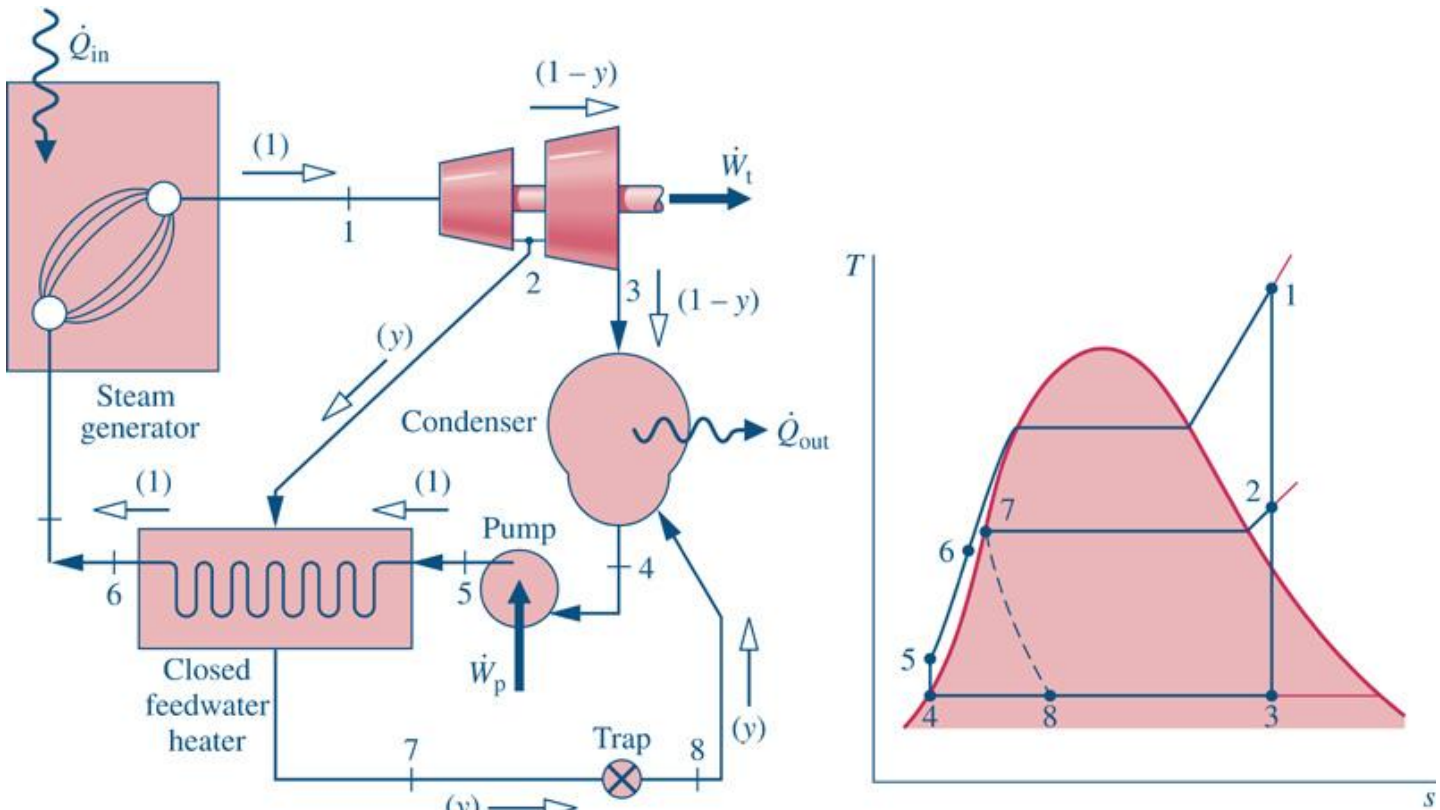
$$\dot{W}_t / \dot{m}_1 = (h_1 - h_2) + (1-y)(h_2 - h_3) \qquad \dot{W}_p / \dot{m}_1 = (h_6 - h_7) + (1-y)(h_4 - h_5)$$

    - Energy conservation over steam generator and condenser:

$$\dot{Q}_{in} / \dot{m}_1 = h_1 - h_7 \qquad \dot{Q}_{out} / \dot{m}_1 = (1-y)(h_4 - h_3)$$

Vapor power systems

- Rankine cycle: improving performance:
  - *Regeneration* via **closed** feedwater heater:
    - Higher average temperature at which heat is added (6-1)
    - Both streams can operate at different pressures



Vapor power systems

- Rankine cycle: improving performance:
  - *Regeneration* via closed feedwater heater:
    - Energy conservation feedwater heater:

$$0 = y(h_2 - h_7) + h_5 - h_6 \;\rightarrow\; y = \frac{h_6 - h_5}{h_2 - h_7}$$

    - Energy conservation turbines and pumps:

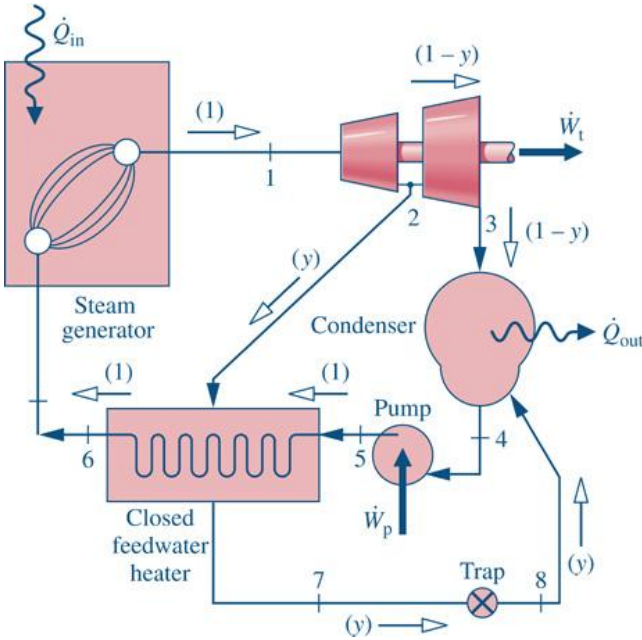
$$\dot{W}_t / \dot{m}_1 = (h_1 - h_2) + (1 - y)(h_2 - h_3)$$

$$\dot{W}_p / \dot{m}_1 = (h_4 - h_5)$$

    - Energy conservation over steam generator and condenser:

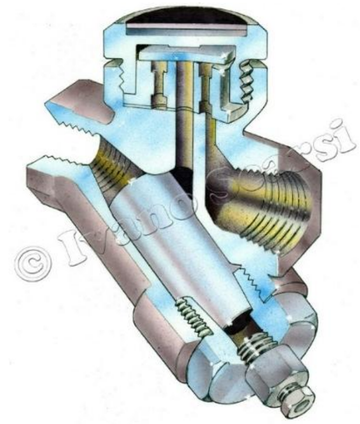
$$\dot{Q}_{in} / \dot{m}_1 = h_1 - h_6$$

$$\dot{Q}_{out} / \dot{m}_1 = h_4 - (1 - y)h_3 - yh_8$$



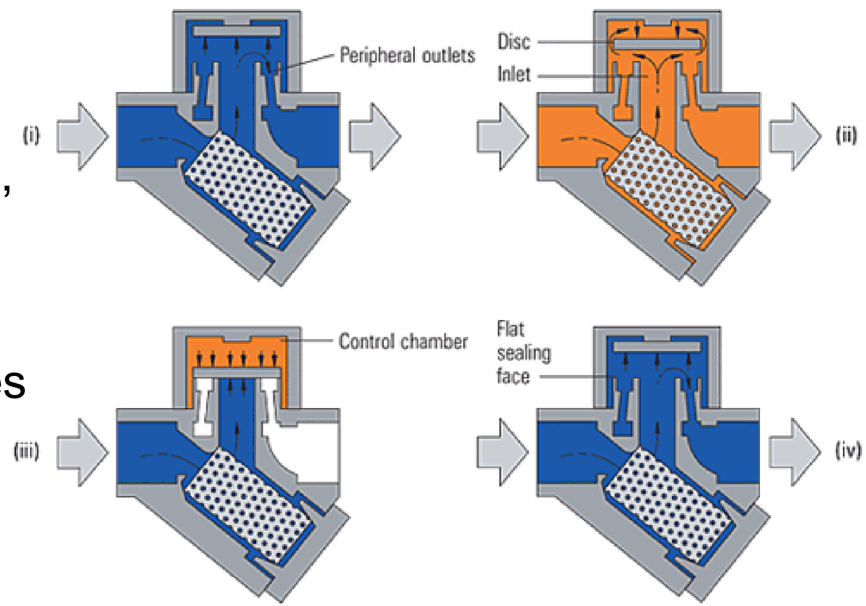
Vapor power systems

- Rankine cycle: improving performance:
  - Trap: A trap allows the liquid to be throttled to a lower pressure region but traps the vapor. The enthalpy of the streams remains constant during this throuttling process.



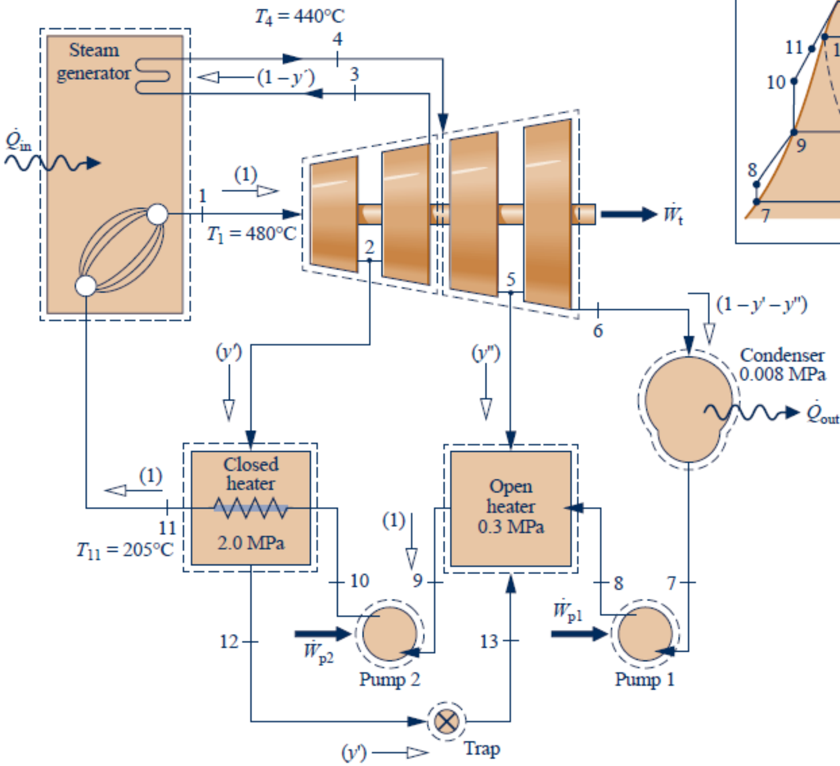
  - E.g. thermodynamic trap:

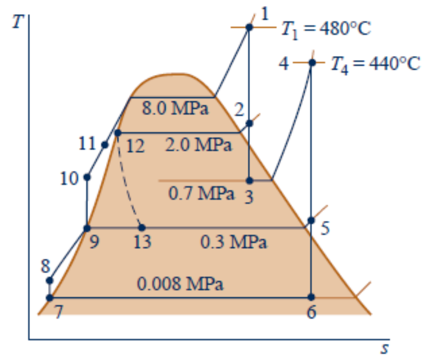
“Thermodynamic traps work on the difference in dynamic response to velocity change in flow of compressible and incompressible fluids. As steam enters, static pressure above the disk forces the disk against the valve seat. The static pressure over a large area overcomes the high inlet pressure of the steam. As the steam starts to condense, the pressure against the disk lessens.”

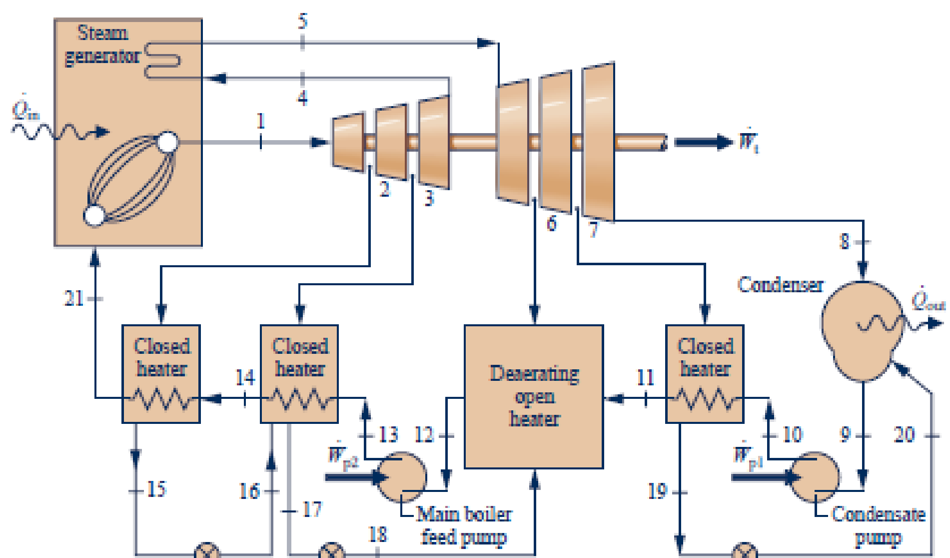


Vapor power systems

- In practice: even multiple feedwater heaters

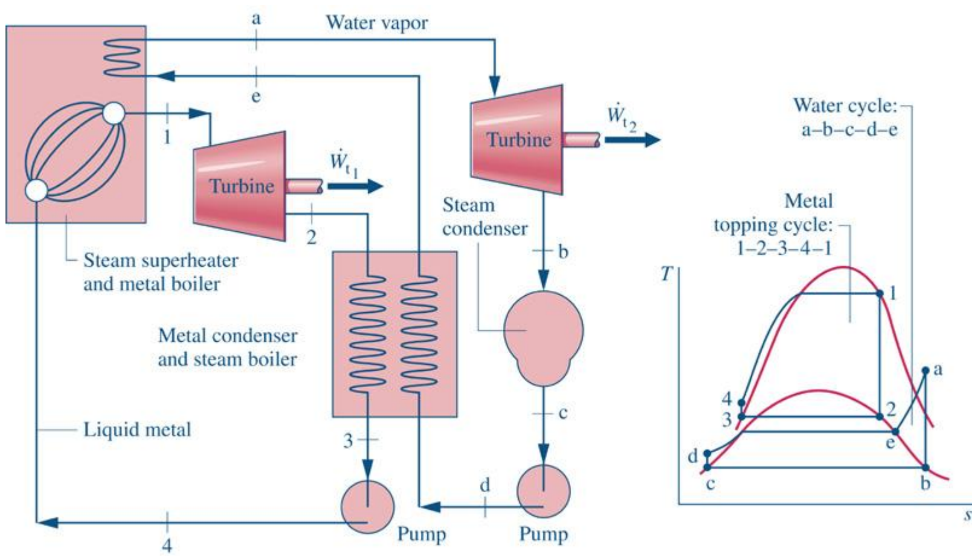






Vapor power systems

- Rankine cycle: improving performance:
  - Changing working fluid:
    - to allow for higher temperature, T_c of water is only 374 °C
    - Power cycles at lower temperatures might perform better with e.g. ammonia
  - Binary vapor cycles: using two working fluid
    - Temperature characteristics match high and low temperature parts



  - Cogeneration: generation of electricity and steam

Learning outcomes of todays lecture

- Demonstrate and understand the basic principles of vapor power systems, i.e. power systems using a working fluid which is alternately vaporized and condensed

- Develop and analyze thermodynamic models of vapor power plants based on Rankine cycle and its modifications
  - 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

EPFL