

Rankine cycle

Workshop for inspectors – Method and Techniques in Geothermal Power Plant inspection

Theo van der Meer

Vapor power cycles

- To produce power a thermodynamic cycle is used
- Vapor power cycle is one of the examples of power systems
- In vapor cycle the working medium is fluid changing phase

Liquid → Vapor → Liquid

- This is external combustion engine, since heat is transferred via boiler to the system



Steam train with piston steam engine

Rankine cycle

- Today the biggest application of vapor cycle is for power generation in the **steam turbine cycles** known also as **Rankine cycles**
- Nowadays, about 80% of world wide produced power comes from steam turbines in vapor power cycles
- **Water** is often a working liquid, however other liquids (especially organic) are possible

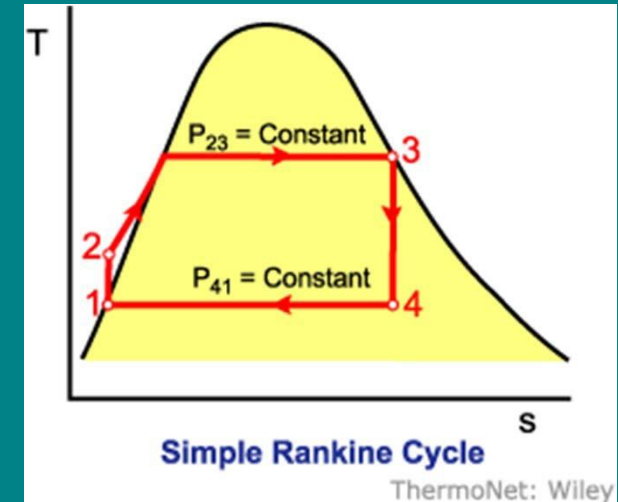


Rotor of steam turbine

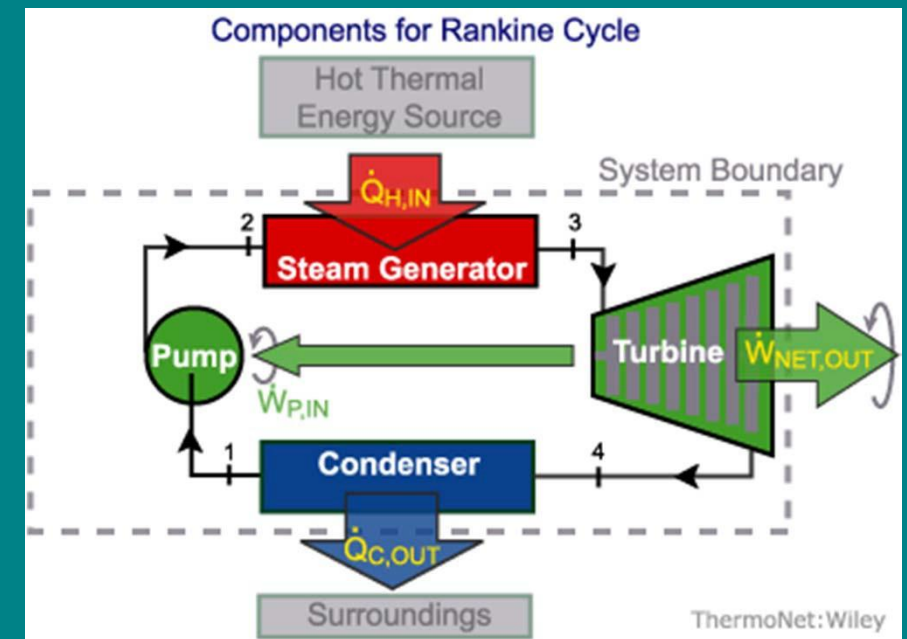
Simple Rankine cycle

- **Simple Rankine cycle** consist of **four** devices:
 - **Pump** – to increase pressure
 - **Steam generator/Boiler** – to add heat and change liquid's phase
 - **Steam turbine** – to decrease pressure and extract work
 - **Condenser** – for heat rejection

Simple, ideal Rankine Cycle

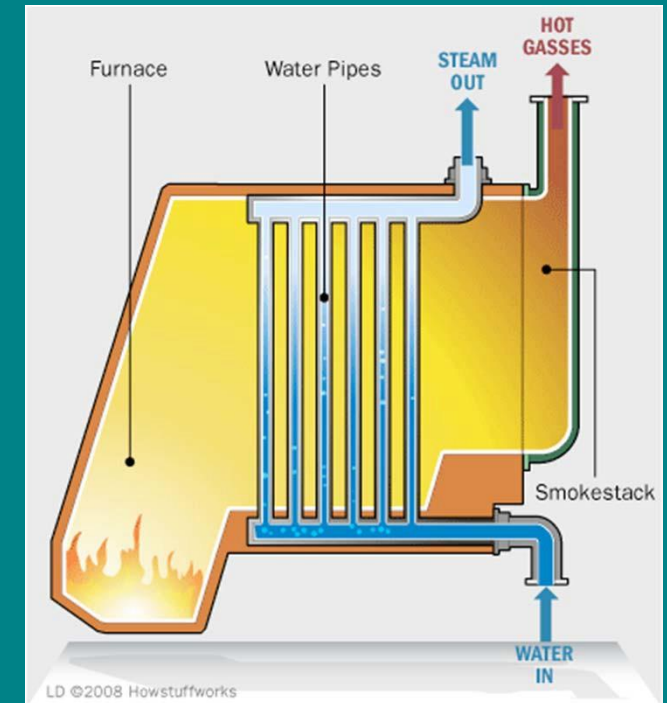


- Process 1→2 isentropic compression (w_{in})
- Process 2→3 isobaric heat addition (q_{in})
- Process 3→4 isentropic expansion (w_{out})
- Process 4→1 isobaric heat rejection (q_{out})



Simple, ideal Rankine Cycle

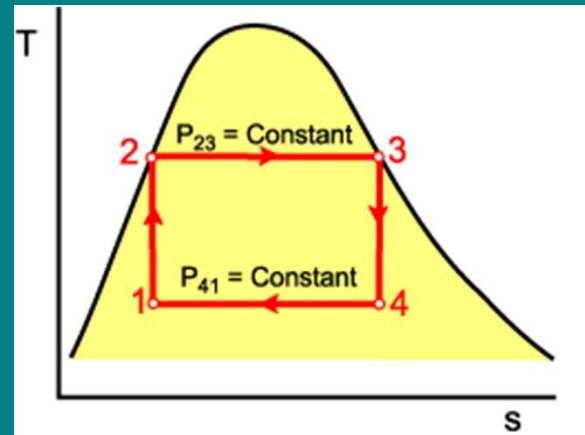
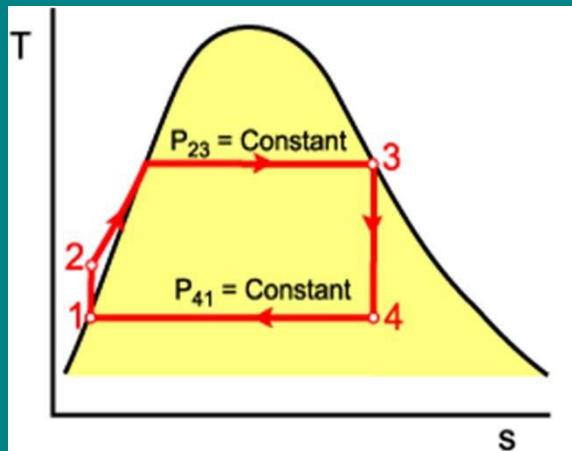
- As an external source of heat a renewable or fossil energy can be used (biomass, sun, waste heat, coal etc.)
- The temperature of the source, thus the amount of heat transferred to the cycle, determines the efficiency and power output of the system
- Temperature of sustainable sources is usually low, but system is CO₂ neutral
- Mostly boiler is used to transfer heat to working medium



<http://science.howstuffworks.com/transport/engines-equipment/steam2.htm>

Ideal Rankine Cycle vs Carnot Cycle

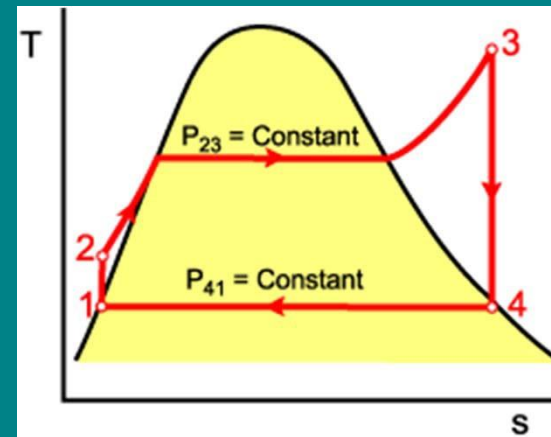
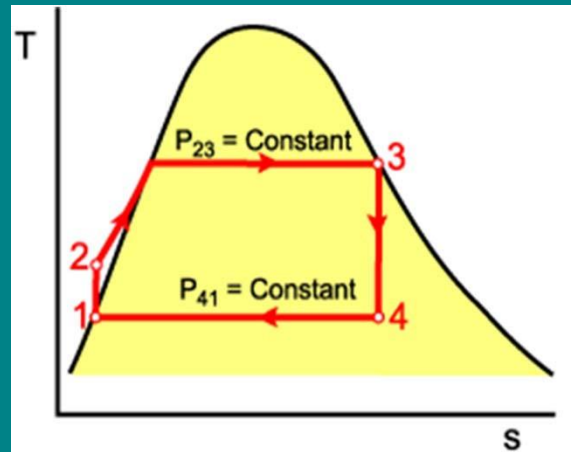
- Both cycles operate between the same pressures and water is working liquid
- **Process 1→2** of Carnot cycle is difficult to achieve in Rankine cycle, since increase pressure of mixture is mechanically difficult to perform reliably
- Effect → lower efficiency of ideal Rankine cycle



T-s diagram of Ideal Rankine cycle vs Carnot cycle

Ideal Rankine Cycle vs Superheated Cycle

- Both cycles operate between the same pressures and water is working liquid
- **Process 3→4** of Rankine cycle is restricted by quality of mixture, i.e. mixture with $x > 0.85$ can cause erosion and reliability problems
- Solution → superheat the saturated vapor
- Effect → temperature of heat source must be higher; higher power output



Ideal Rankine cycle - assumptions

- Pump – adiabatic, isentropic
- Turbine – adiabatic, isentropic
- No kinetic/potential energy change
- No pressure losses in pipes.
- For the total cycle each device is analyzed separately
- Boiler – no pressure change
- Condenser – no pressure change
- Incompressible liquid, i.e $v=\text{const.}$

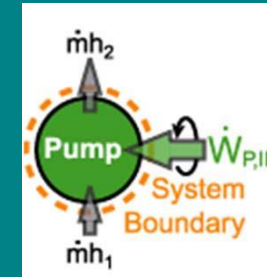
$$\dot{Q}_{in} + \dot{W}_{in} + \dot{m}(h + \cancel{ke} + \cancel{pe})_{in} = \dot{Q}_{out} + \dot{W}_{out} + \dot{m}(h + \cancel{ke} + \cancel{pe})_{out}$$
$$\dot{Q}_{in} + \dot{W}_{in} + \dot{m}h_{in} = \dot{Q}_{out} + \dot{W}_{out} + \dot{m}h_{out}$$
$$\dot{Q}_{net} + \dot{W}_{net} = \dot{m}(h_{out} - h_{in})$$

Ideal Rankine cycle – examples

- Process 1→2'

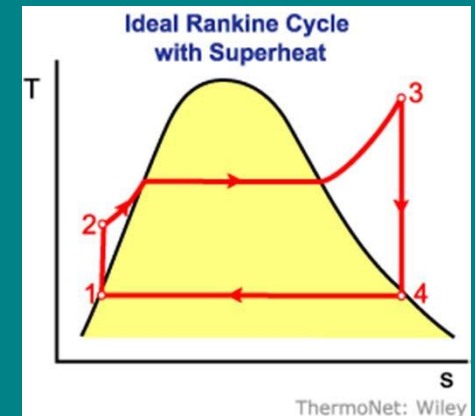
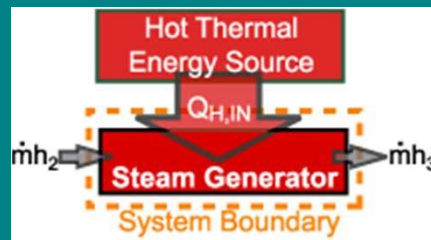
$$\cancel{\dot{Q}_{in}} + \dot{W}_{in} + \cancel{\dot{m}h_{in}} = \cancel{\dot{Q}_{out}} + \cancel{\dot{W}_{out}} + \dot{m}h_{out}$$

or alternatively: $dh = \dot{w}_{pump,in} = \cancel{Tds} + v dP$

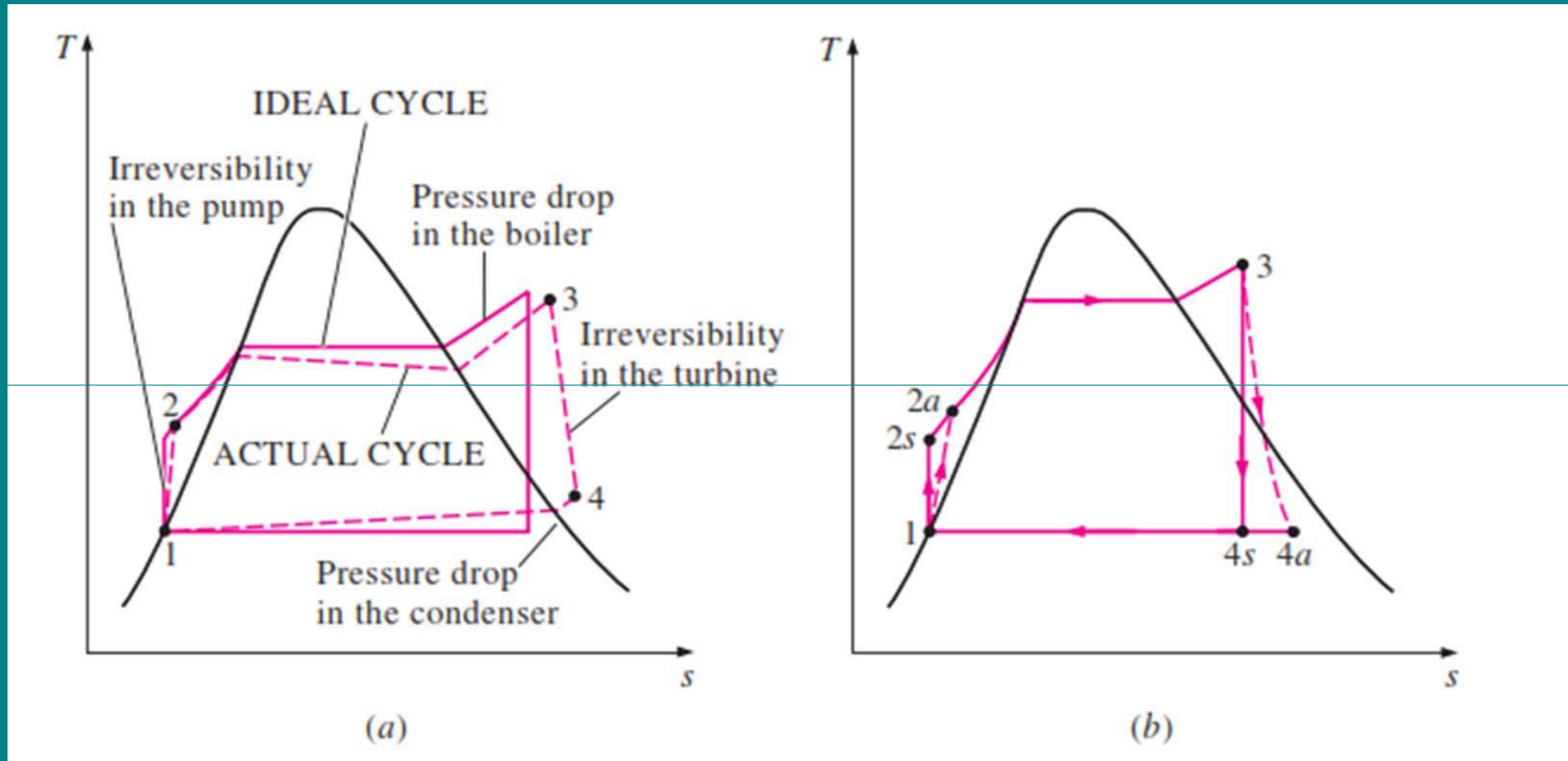


- Process 2→3

$$\dot{Q}_{in} + \cancel{\dot{W}_{in}} + \dot{m}h_{in} = \cancel{\dot{Q}_{out}} + \cancel{\dot{W}_{out}} + \dot{m}h_{out}$$



Ideal Rankine cycle vs non-ideal

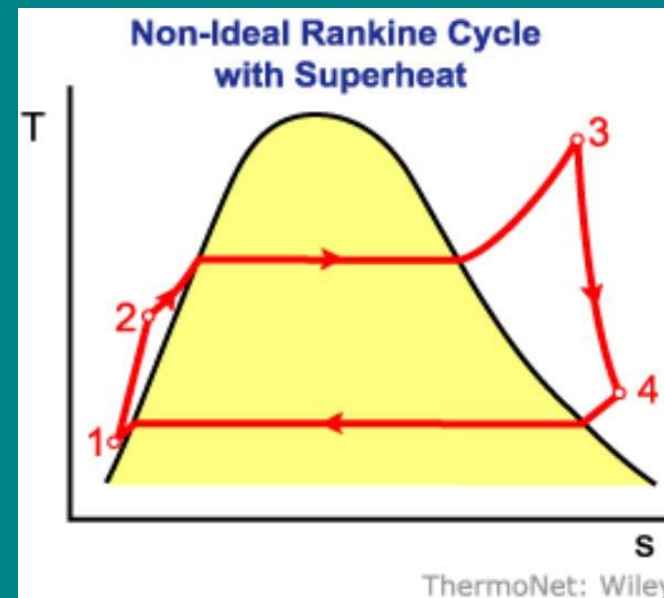
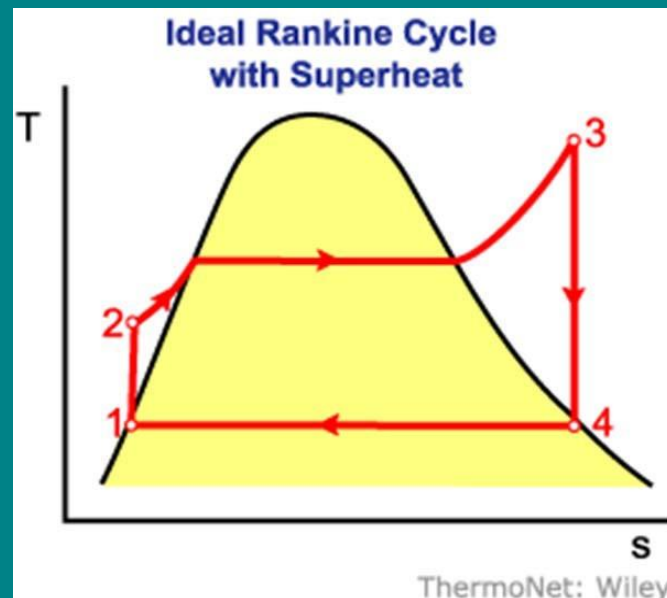


Ideal Rankine cycle vs non-ideal

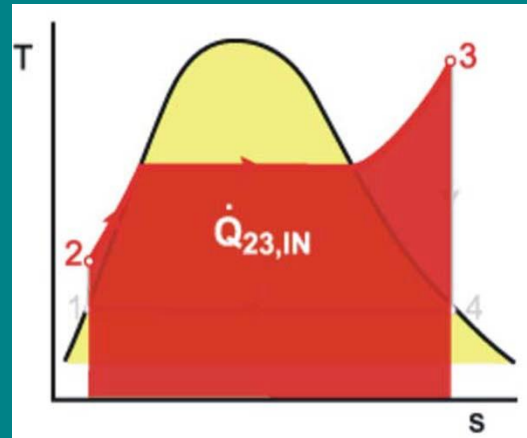
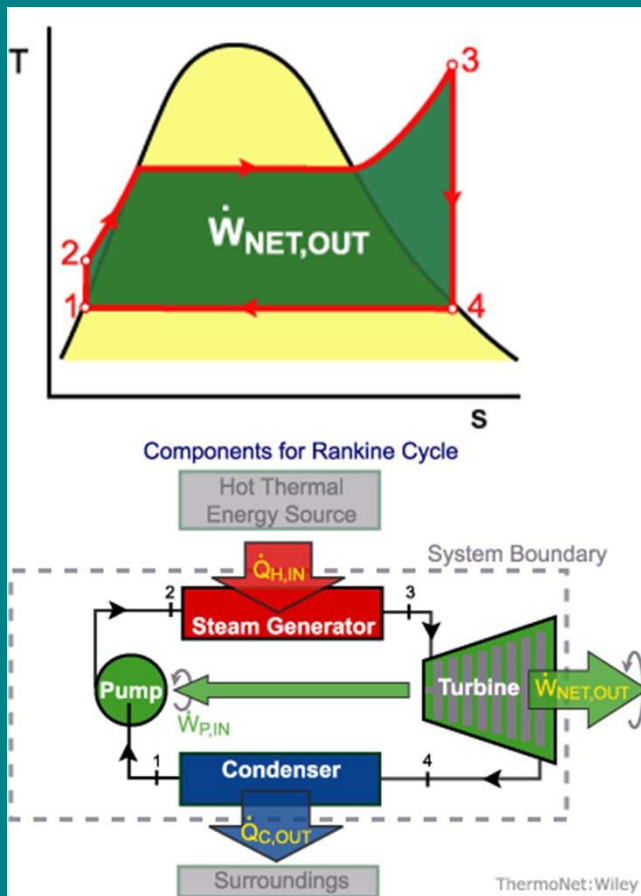
- For a non-ideal (real/actual) Rankine cycle, isentropic efficiencies of pump and turbine have to be included, since entropy increases

$$\eta_{S,Pump} = \frac{work_S}{work_A} = \frac{h_{S,OUT} - h_{IN}}{h_{A,OUT} - h_{IN}}$$

$$\eta_{S,Turb} = \frac{work_A}{work_S} = \frac{h_{IN} - h_{A,OUT}}{h_{IN} - h_{S,OUT}}$$

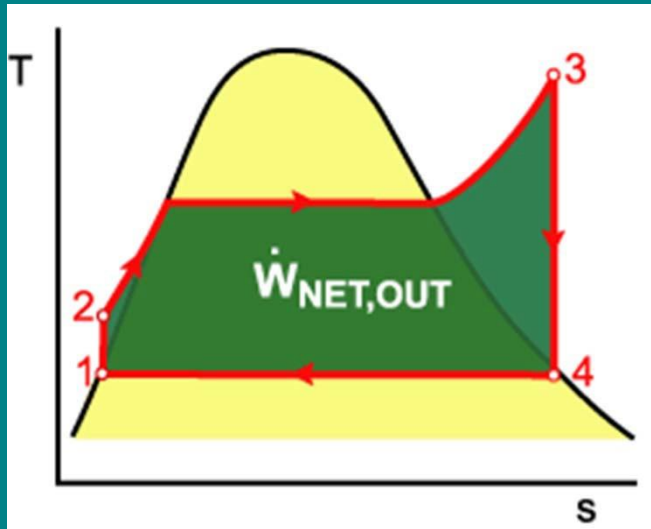


Rankine Cycle Efficiency



$$\begin{aligned}\eta_{Rankine} &= \frac{\text{get}}{\text{pay}} \\ &= \frac{\text{net work output}}{\text{heat added}} \\ &= \frac{\dot{W}_{turb} - \dot{W}_{pump}}{\dot{Q}_{in}} = \frac{\dot{W}_{net}}{\dot{Q}_{in}} \\ &= \frac{\dot{m}(h_3 - h_4) - \dot{m}(h_2 - h_1)}{\dot{m}(h_3 - h_2)}\end{aligned}$$

Rankine Cycle Efficiency



$$\eta_{Rankine} = \frac{\dot{W}_{net}}{\dot{Q}_{in}}$$

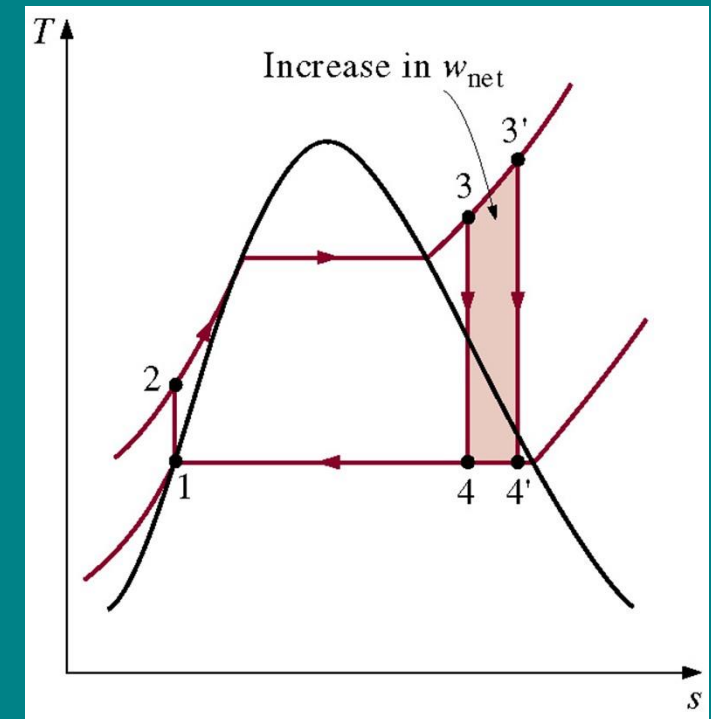
- Cycle efficiency can be changed by:
 - Changing pressure at turbine or/and condenser
 - Changing temperature at turbine or/and condenser

Rankine efficiency

$$\eta_{Rankine} = \frac{\dot{W}_{net}}{\dot{Q}_{in}}$$

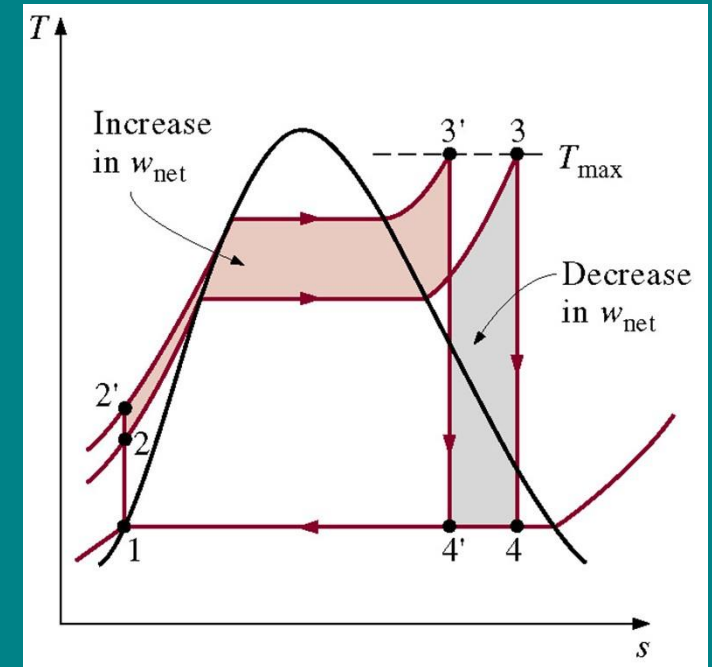
- **Superheating**

- Power output – increases
- Heat input – increases
- Efficiency – increases (due to heat added at higher average T)
- Decreases the moisture content of the steam at turbine exit
- Maximum temperature of steam is restricted by material properties of boiler and turbine to approx. 650°C



Rankine Cycle Efficiency

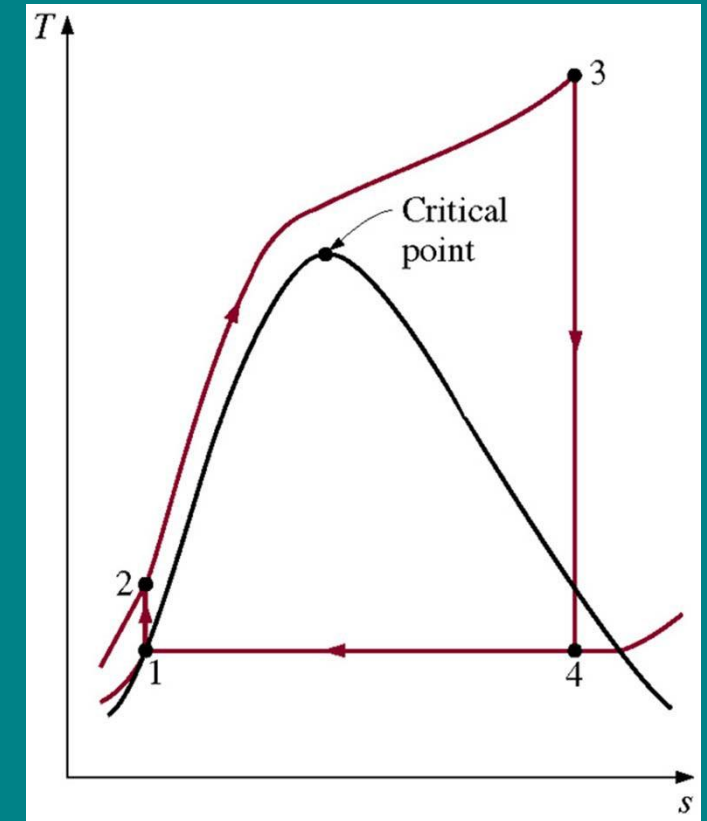
- Increasing boiling pressure
 - Power output – similar
 - Heat input – similar
 - Efficiency – increases (due to heat added at higher average T)
 - Decreases the quality of steam at turbine exit



Rankine Cycle Efficiency

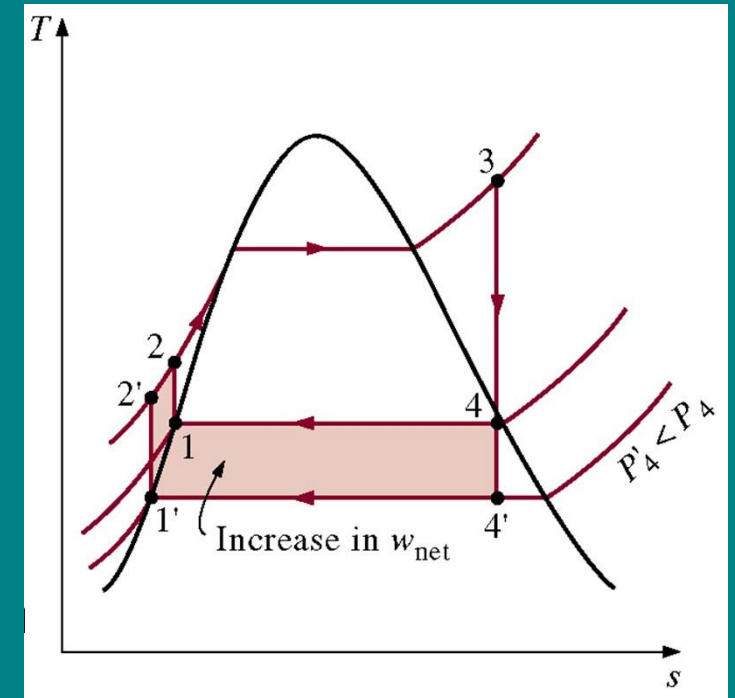
- **Supercritical Rankine cycle**

- Power output – increases
- Heat input – increases
- Efficiency – increases (due to heat added at higher average T)
- In supercritical configurations of Rankine cycle, maximum pressure can reach 30 MPa



Rankine Cycle Efficiency

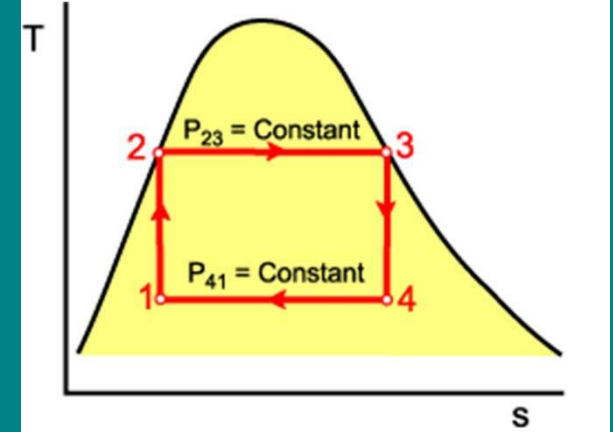
- Lowering condenser pressure/temperature
 - Power output – increases
 - Heat input – increases slightly
 - Efficiency – increases
 - Quality of the mixture at turbine exit decreases
 - Pressure/temperature are restricted by temperature of cooling medium condenser (usually to 20-25°C) in
 - Condenser may work at below atmospheric pressure



Improved Rankine cycle

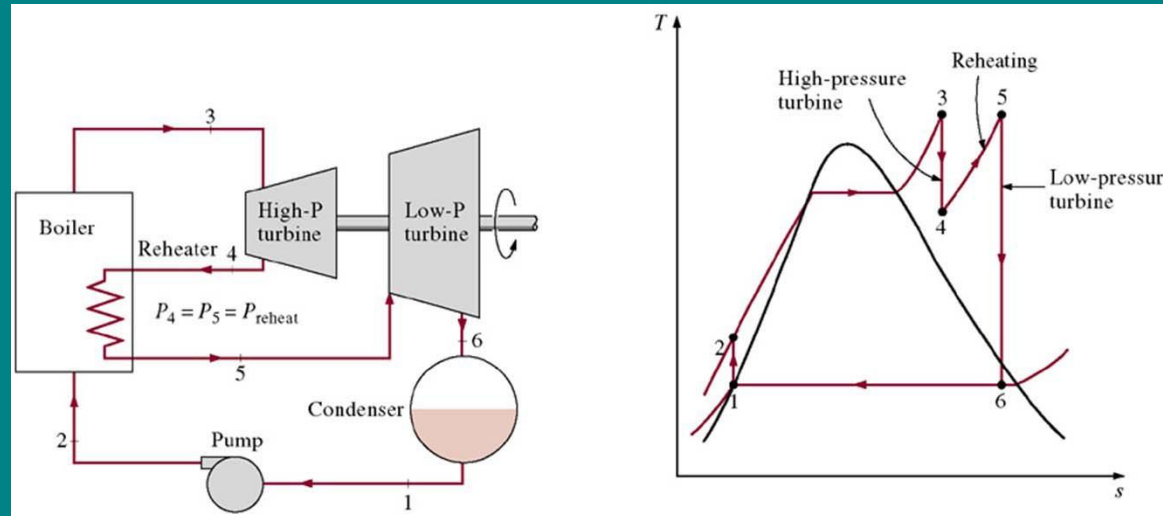
- Improvement with respect to increased efficiency and/or power output by adding extra devices. Two main processes which increase the mean temperature of heat addition are:
 - Reheating
 - Regeneration
- From Carnot engine (with isothermal heat addition)

$$\eta_{Carnot} = 1 - \frac{T_{Cold}}{T_{Hot}}$$

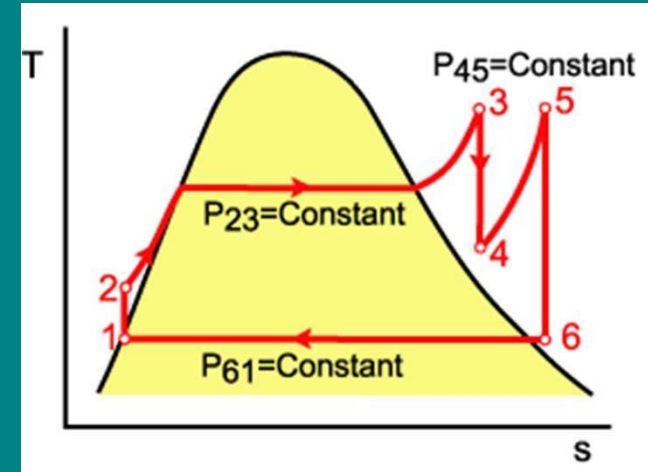
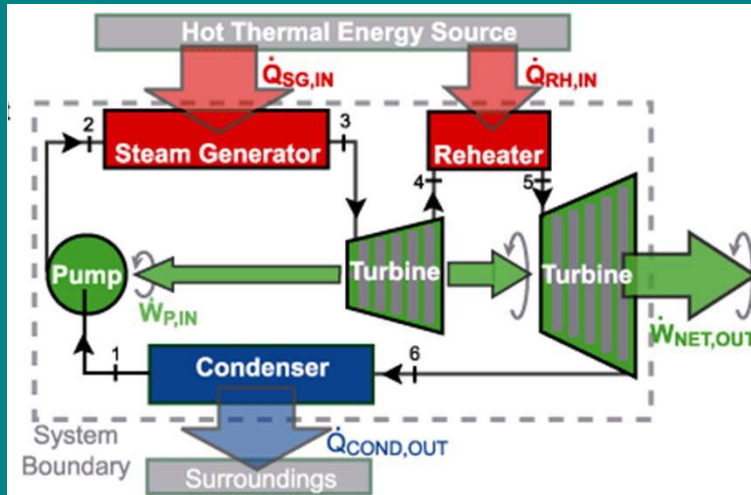


Improved Rankine cycle - Reheating

- In order to get benefit of improved efficiency due to increased boiler pressure and to overcome problems related to maximum temperature allowed in the cycle (about 650°C) and moisture content (should not be $x < 0.85$) a reheating was introduced
- In reheating a second turbine is added, thus expansion takes place in two steps



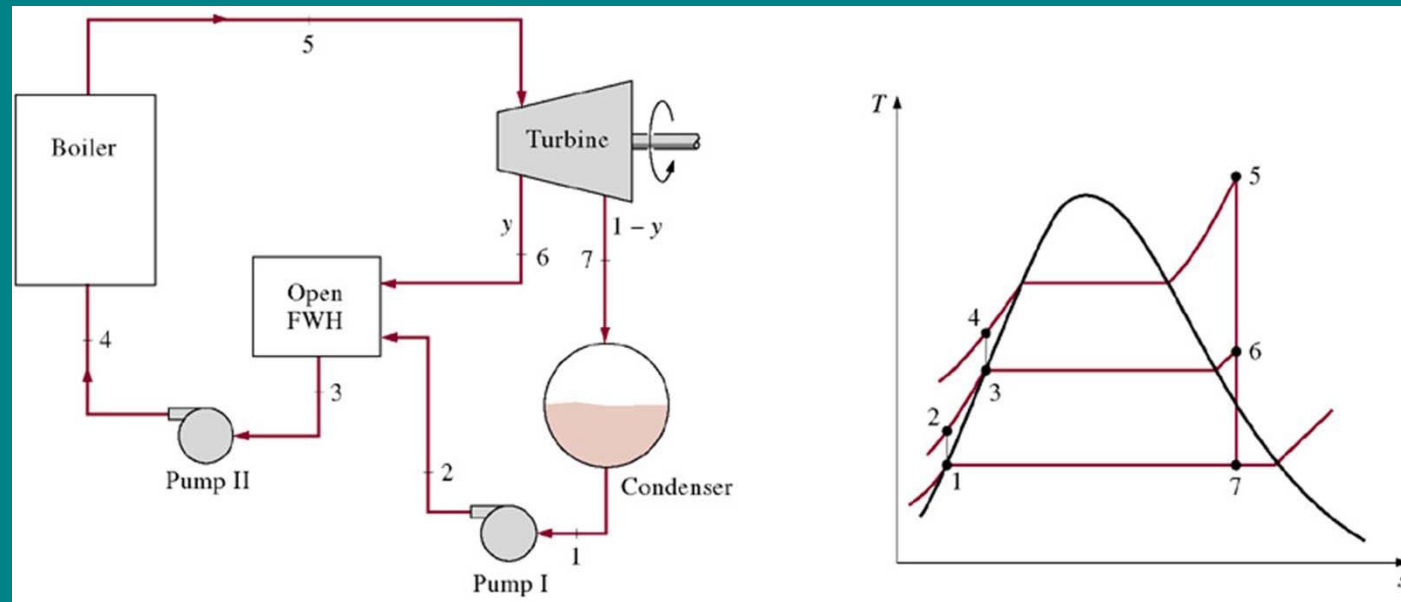
Improved Rankine cycle - Reheating



$$\begin{aligned}
 \eta_{\text{Rankine}} &= \frac{\text{get}}{\text{pay}} = \frac{\text{net work output}}{\text{heat added}} = \frac{\dot{W}_{\text{net}}}{\dot{Q}_{\text{in}}} \\
 &= \frac{\dot{W}_{\text{turb},1} + \dot{W}_{\text{turb},2} - \dot{W}_{\text{pump}}}{\dot{Q}_{\text{in},1} + \dot{Q}_{\text{in},2}} = \\
 &= \frac{\dot{m}(h_3 - h_4) + \dot{m}(h_5 - h_6) - \dot{m}(h_2 - h_1)}{\dot{m}(h_3 - h_2) + \dot{m}(h_5 - h_4)}
 \end{aligned}$$

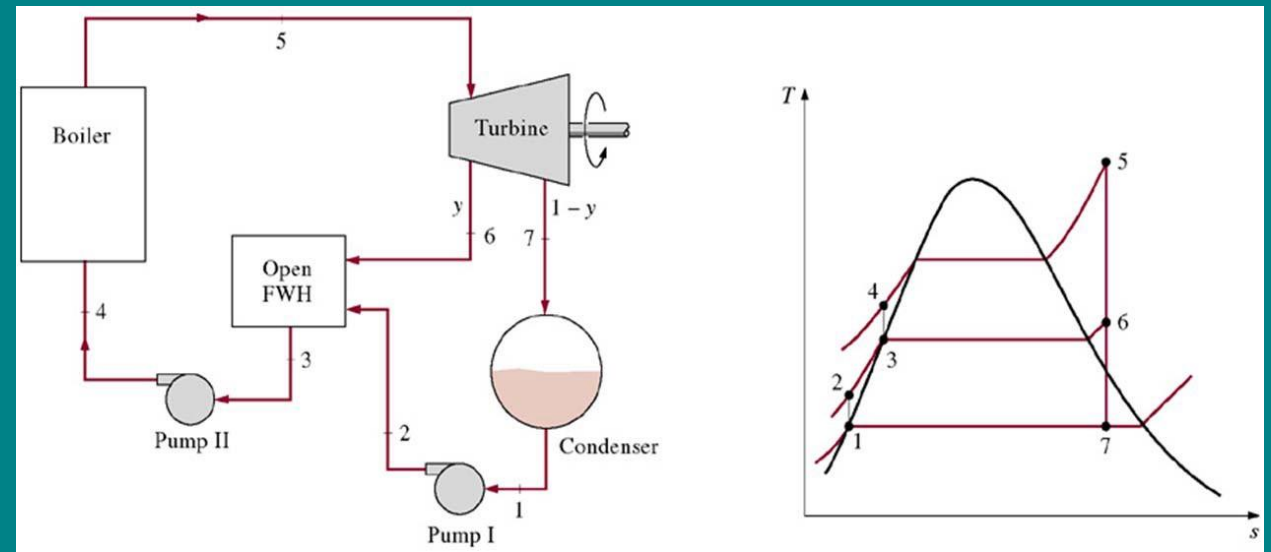
Improved Rankine cycle - Regeneration

- To increase the average temperature of heat addition, a part of steam is used to preheat the feedwater, after the pump
- The device where this process is performed is called a feedwater preheater



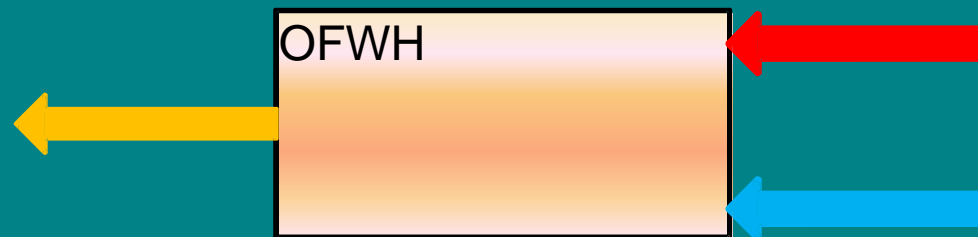
Improved Rankine cycle - Regeneration

- Extracting steam from turbine results in:
 - Reduced work output (lower mass flow rate at second stage turbine)
 - Reduced heat output (lower mfr)
 - Reduced heat input
 - Increased thermal efficiency



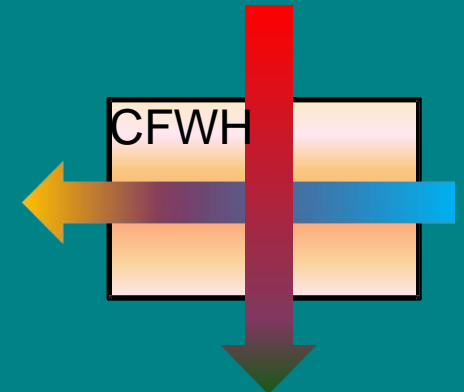
Improved Rankine cycle - Regeneration

- Two types of heat water heaters are in use: open and closed. Most steam power plants use a combination of both.
- Open feedwater heater (OFWH)
 - mixing chamber where hot and cold flows are mixed
 - ideally, the mixture leaves the OFWH as a saturated liquid at boiler pressure
 - OFWH is cheap, simple and has a good heat transfer characteristics, but additional pump is required



Improved Rankine cycle - Regeneration

- Closed feedwater heater (CFWH)
 - heat exchanger, in which heat is transferred from steam to cold liquid
 - since there is no mixing involved, both stream can be at different pressures
 - ideally, the mixture leaves the CFWH as a saturated liquid and temperature of feedwater equal to exit temperature of extracted steam
 - Condensed steam directed to feedwater line or routed to another heat water or to the condenser via a trap (throttle valve, $h=\text{const.}$)
 - CFWH is more complex, more expensive and heat transfer is less efficient than OFWH, however, it does not require separate pumps (flows at different pressures)

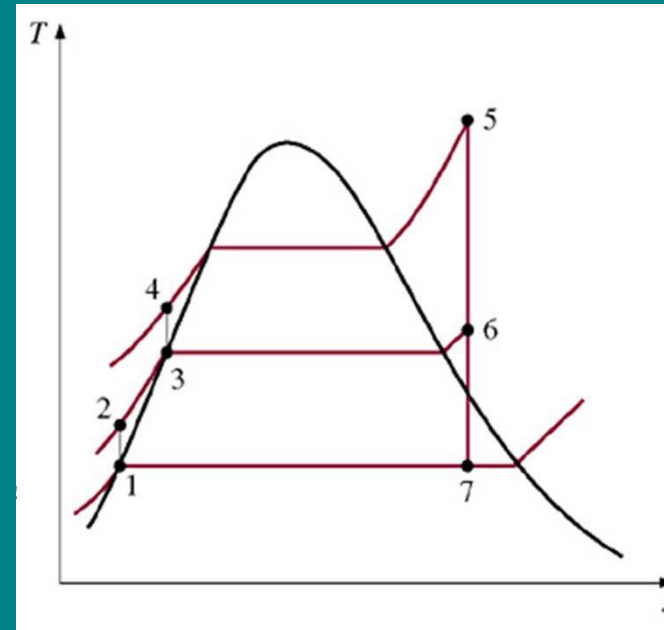
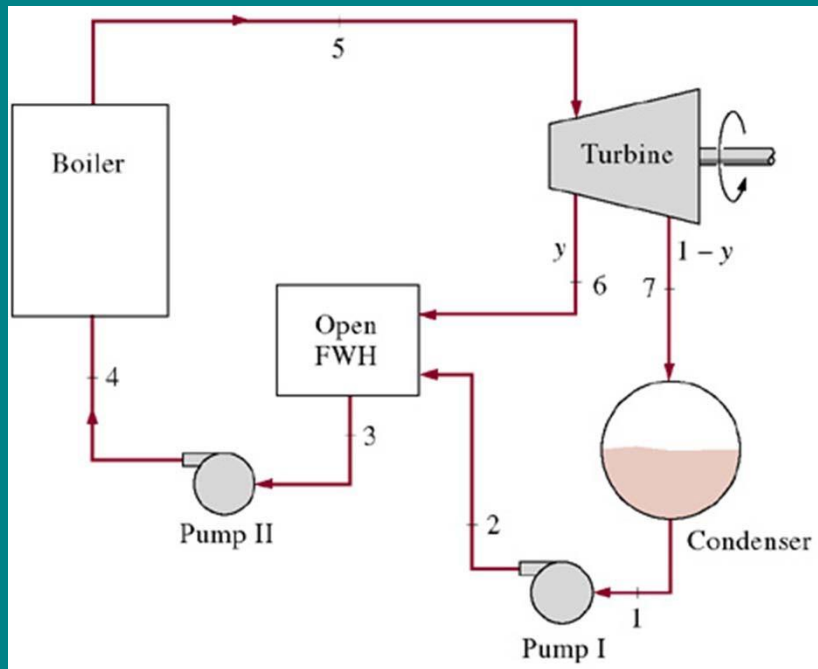


Improved Rankine cycle - Regeneration

- Rankine cycle with open feedwater heater
 - Mass balance (3 different flows)
 - Energy balance for OFWH (mixing chamber)

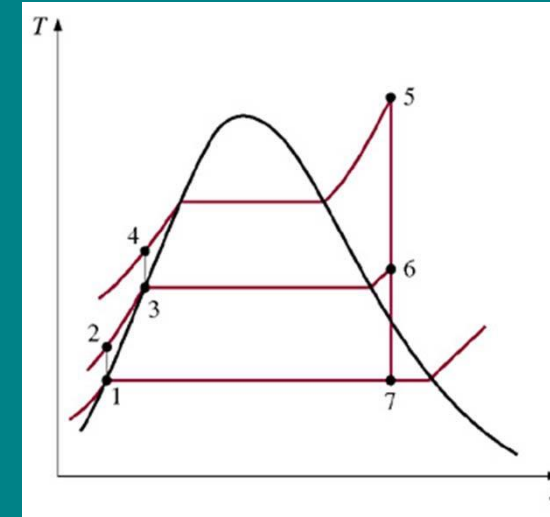
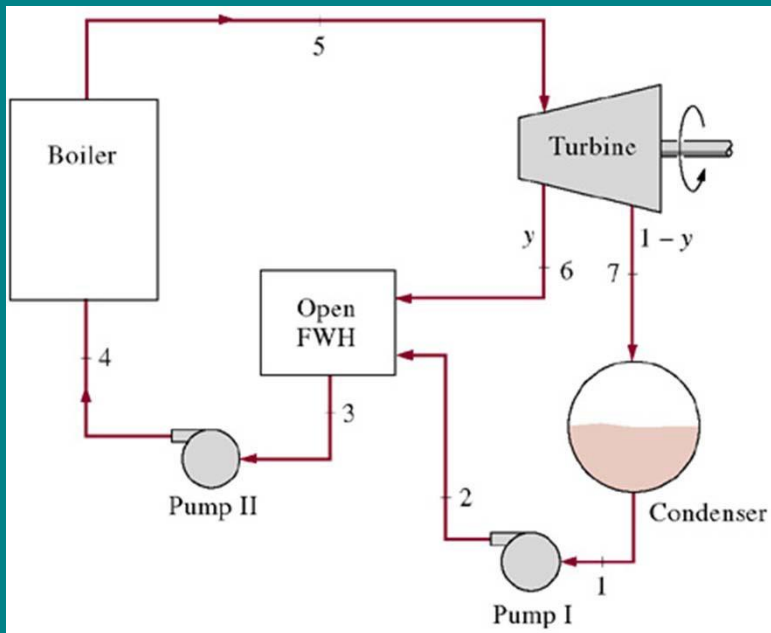
$$\dot{m}_3 = \dot{m}_2 + \dot{m}_6$$

$$\dot{m}_3 h_3 = \dot{m}_2 h_2 + \dot{m}_6 h_6$$



Improved Rankine cycle - Regeneration

- Rankine cycle with open feedwater heater

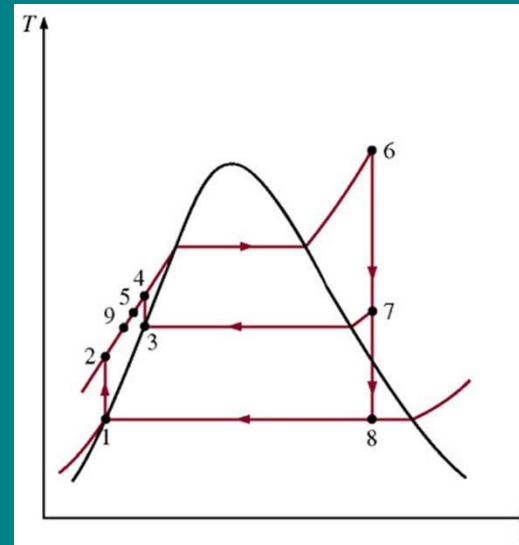
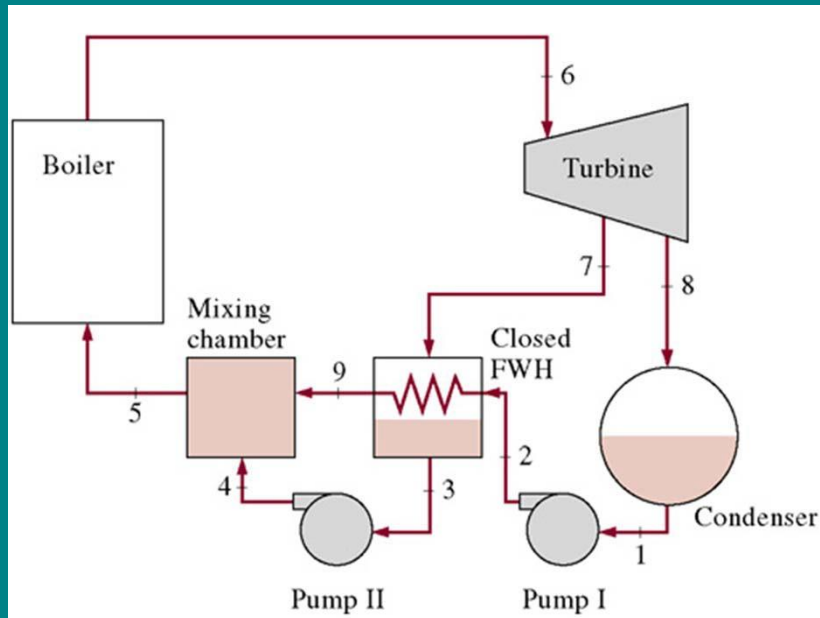


$$\eta_{Rankine} = \frac{\text{get}}{\text{pay}} = \frac{\dot{W}_{net}}{\dot{Q}_{in}} = \frac{\dot{W}_{turb,1} + \dot{W}_{turb,2} - \dot{W}_{pump,1} - \dot{W}_{pump,2}}{\dot{Q}_{in}} =$$

$$= \frac{\dot{m}_3(h_5 - h_6) + \dot{m}_2(h_6 - h_7) - \dot{m}_2(h_2 - h_1) - \dot{m}_3(h_4 - h_3)}{\dot{m}_3(h_5 - h_4)}$$

Improved Rankine cycle - Regeneration

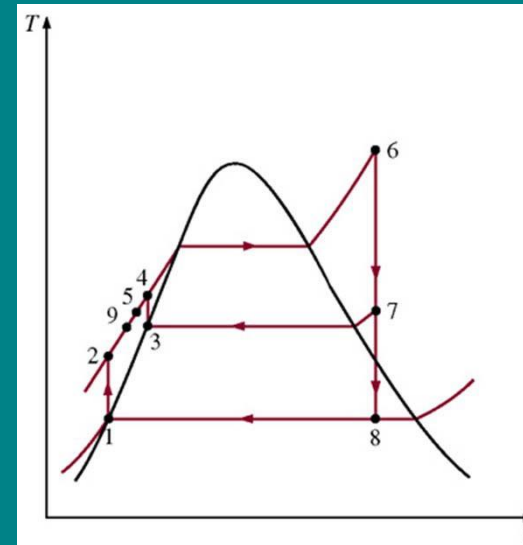
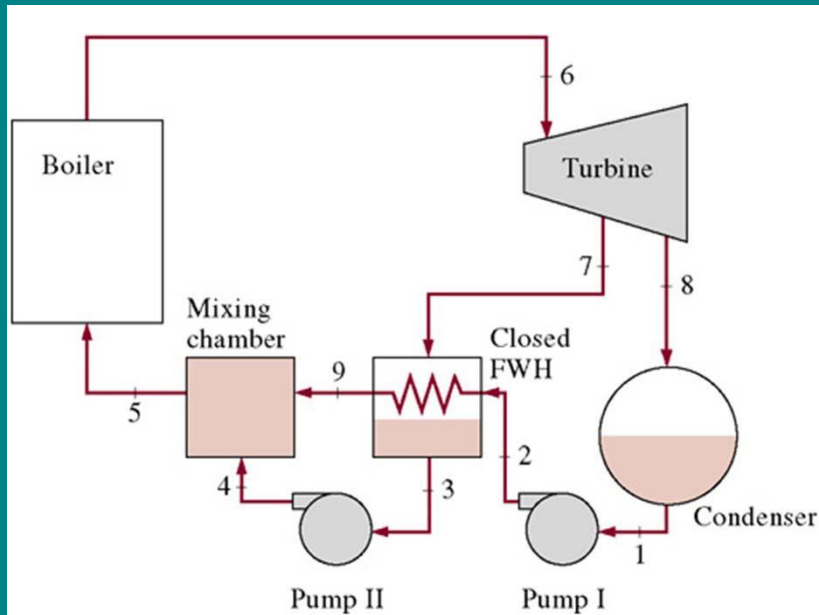
- Rankine cycle with closed feedwater heater
 - Mass balance (3 different flows)
 - Energy balance for mixing chamber and CFWH



$$\begin{aligned}\dot{m}_5 &= \dot{m}_4 + \dot{m}_9 \\ \dot{m}_5 h_5 &= \dot{m}_4 h_4 + \dot{m}_9 h_9 \\ \dot{m}_4 (h_7 - h_3) &= \dot{m}_9 (h_9 - h_2)\end{aligned}$$

Improved Rankine cycle - Regeneration

- Rankine cycle with closed feedwater heater



$$\eta_{Rankine} = \frac{\text{get}}{\text{pay}} = \frac{\dot{W}_{net}}{\dot{Q}_{in}} = \frac{\dot{W}_{turb,1} + \dot{W}_{turb,2} - \dot{W}_{pump,1} - \dot{W}_{pump,2}}{\dot{Q}_{in}} =$$

$$= \frac{\dot{m}_5(h_6 - h_7) + \dot{m}_9(h_7 - h_8) - \dot{m}_9(h_2 - h_1) - \dot{m}_4(h_4 - h_3)}{\dot{m}_5(h_6 - h_5)}$$

Calculate Rankine cycle

