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Rankine cycle

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

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Vapor power cycles

- To produce power a thermodynamic cycle is used
- Vapor power cycle is on 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

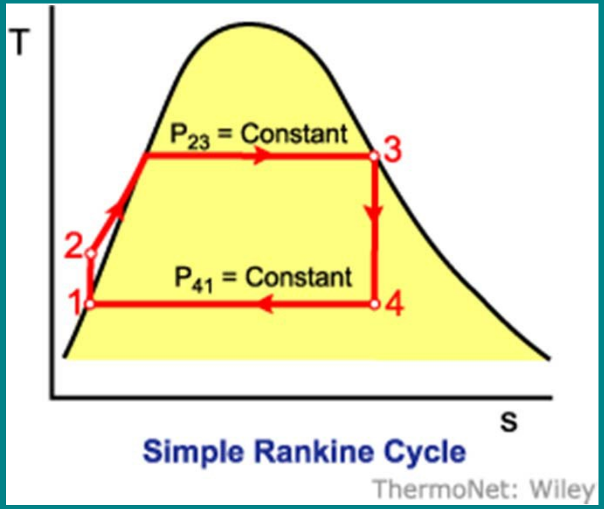
- Today the biggest application of vapor cycle is for power generation in the **steam turbine cycles** known also as **Rankine cycles**
- Nowadays, about 80% of world wide produced power comes from steam turbines in vapor power cycles
- **Water** is often a working liquid, however other liquids (especially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

Rotor of steam turbine

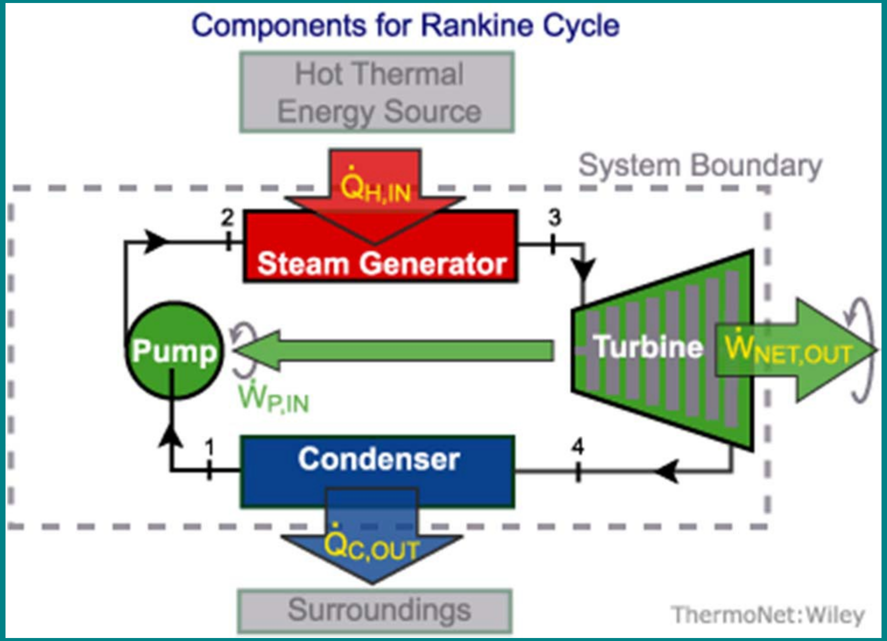
Simple Rankine cycle

- 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



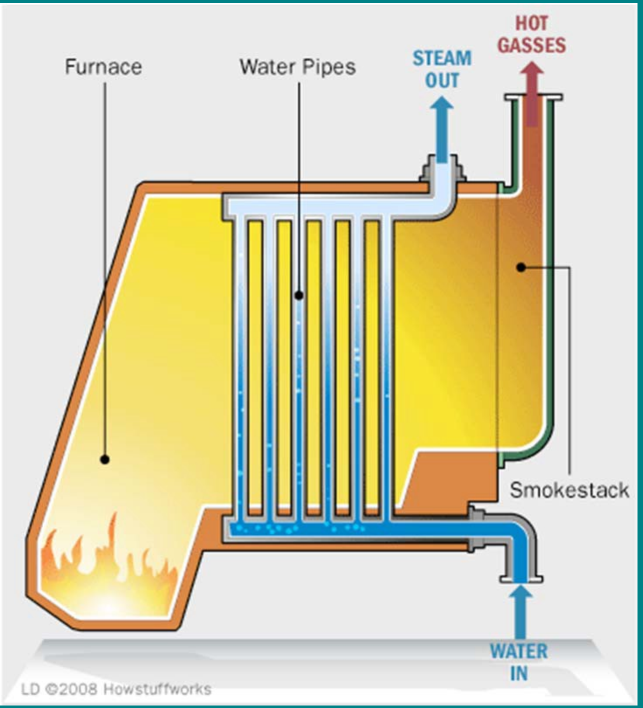
- Process 1→2 isentropic compression (w_{in})
- Process 2→3 isobaric heat addition (q_{in})
- Process 3→4 isentropic expansion (w_{out})
- Process 4→1 isobaric heat rejection (q_{out})



Simple, ideal Rankine Cycle

- As an external source of heat a renewable or fossil energy can be used (biomass, sun, waste heat, coal etc.)

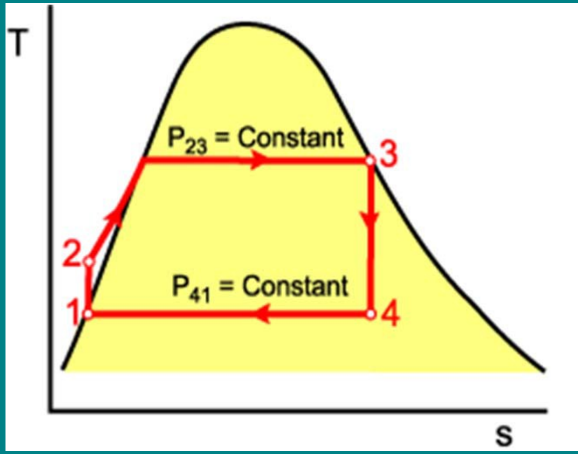
- The temperature of the source, thus the amount of heat transferred to the cycle, determines the efficiency and power output of the system
- Temperature of sustainable sources is usually low, but system is CO_2 neutral
- Mostly boiler is used to transfer heat to working medium

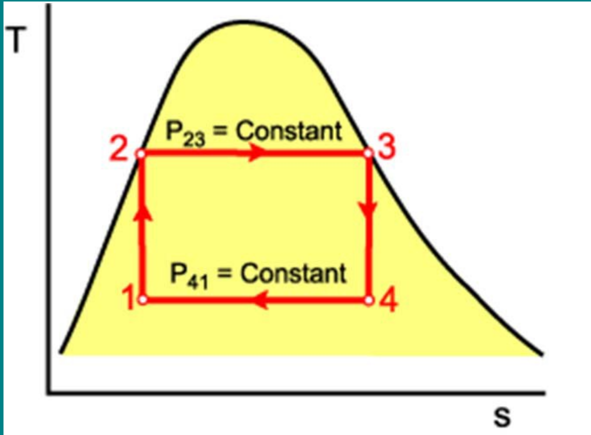


http://science.howstuffworks.com/transport/engines-equipment/steam2.htm

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

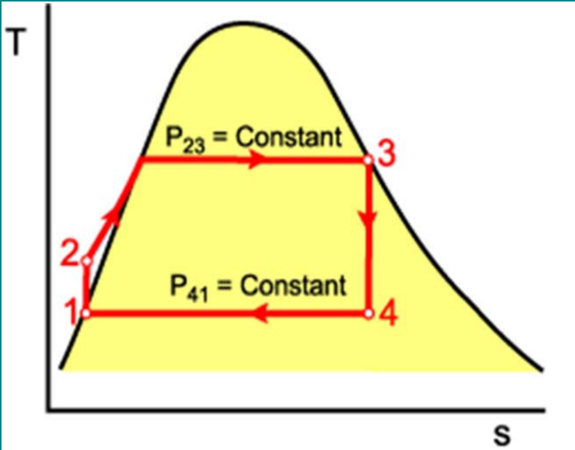


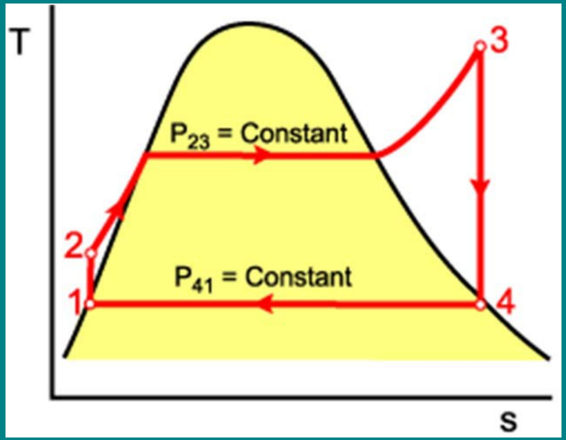


T-s diagram of Ideal Rankine cycle vs Carnot cycle

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=const.

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

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

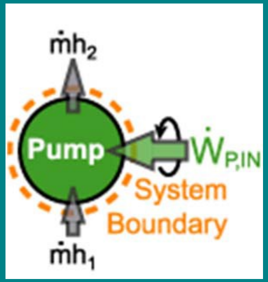
$$\dot{Q}_{net} + \dot{W}_{net} = \dot{m}(h_{out} - h_{in})$$

Ideal Rankine cycle – examples

- Process 1→2'

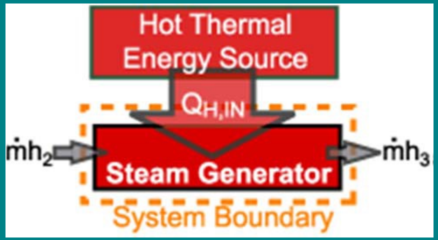
$$\cancel{\dot{Q}_{in}} + \dot{W}_{in} + \dot{m}h_{\ in} = \cancel{\dot{Q}_{out}} + \cancel{\dot{W}_{out}} + \dot{m}h_{\ out}$$

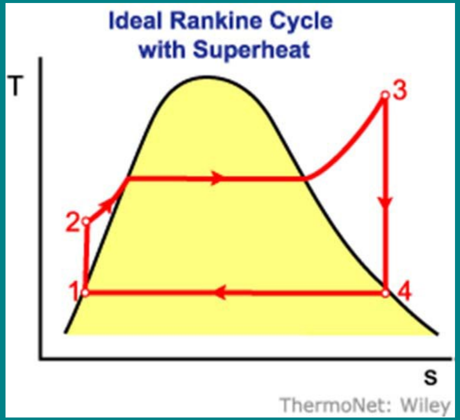
or alternatively: $dh = \dot{w}_{pump,in} = \cancel{Tds} + vdP$



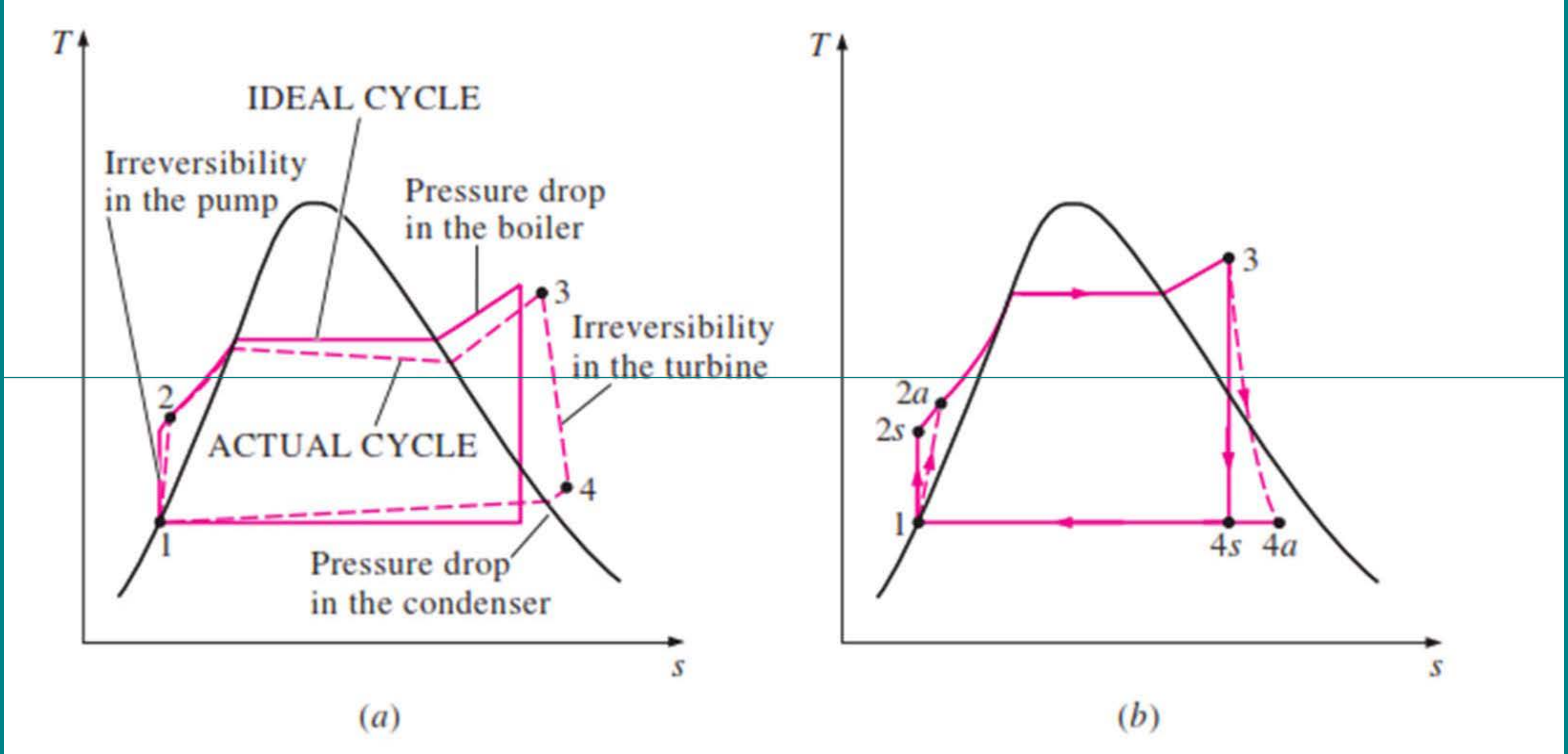
- Process 2→3

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





Ideal Rankine cycle vs non-ideal

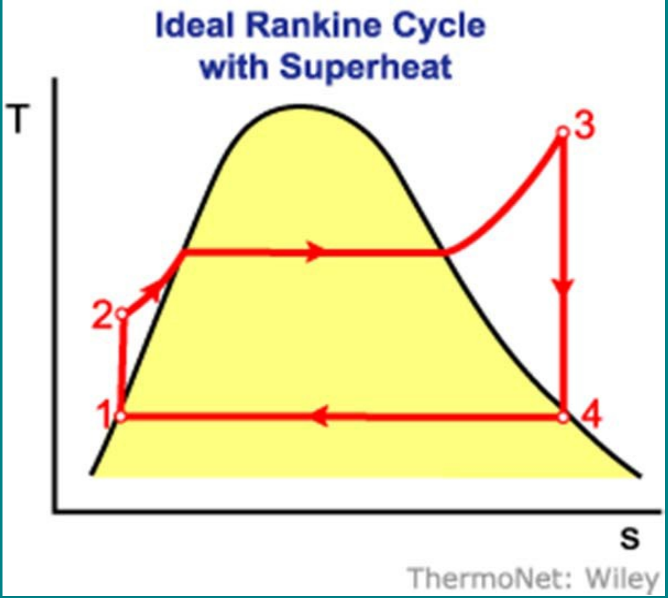


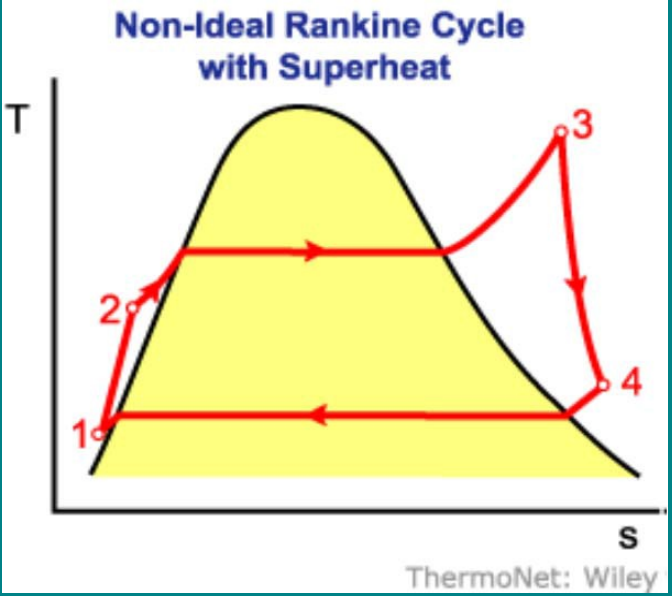
Ideal Rankine cycle vs non-ideal

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

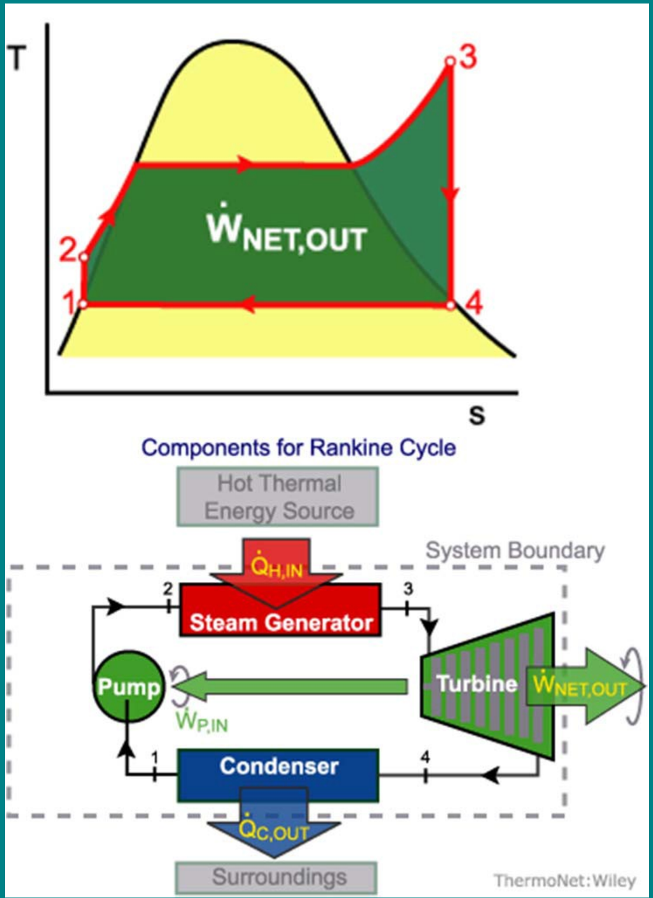
$$\eta_{S,Pump} = \frac{work_S}{work_A} = \frac{h_{S,OUT} - h_{IN}}{h_{A,OUT} - h_{IN}}$$

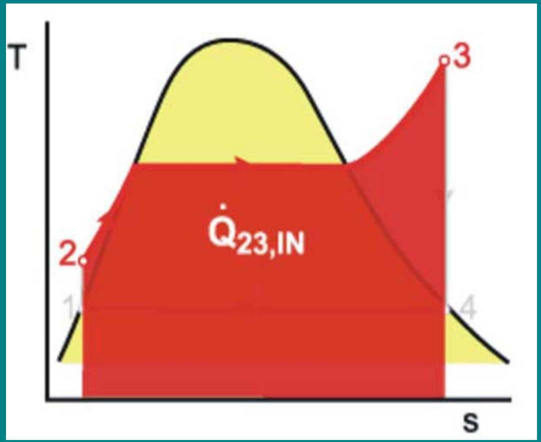
$$\eta_{S,Turb} = \frac{work_A}{work_S} = \frac{h_{IN} - h_{A,OUT}}{h_{IN} - h_{S,OUT}}$$





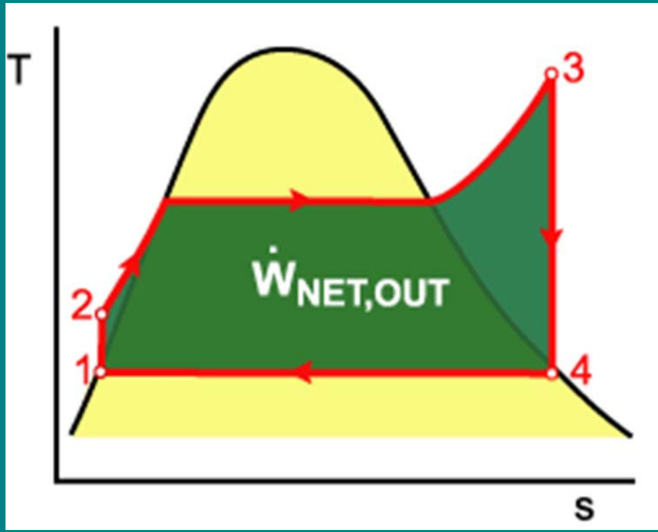
Rankine Cycle Efficiency





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

Rankine Cycle Efficiency



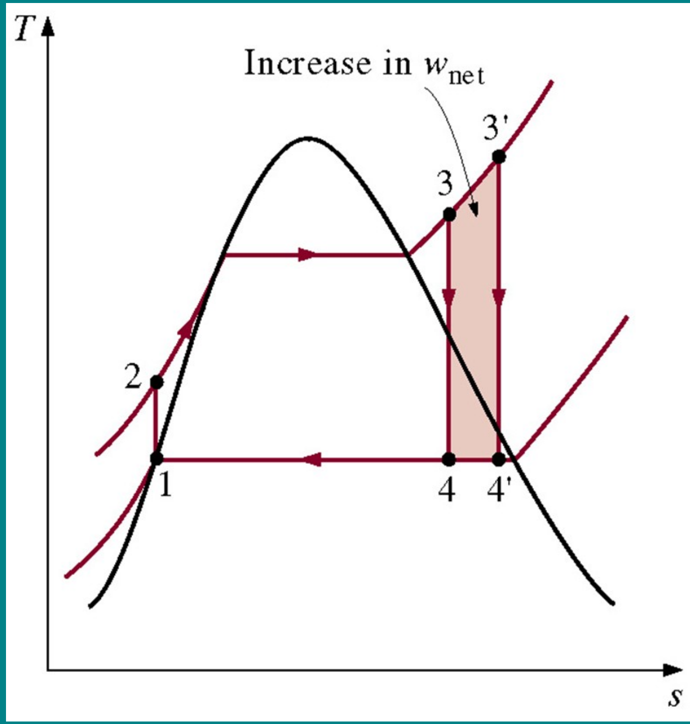
$$\eta_{Rankine} = \frac{\dot{W}_{net}}{\dot{Q}_{in}}$$

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

Rankine efficiency

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

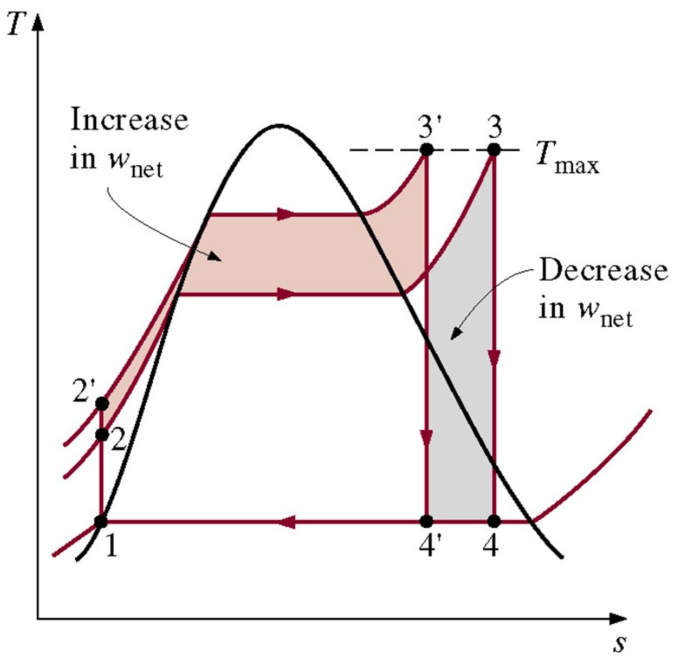
- Superheating
  - Power output – increases
  - Heat input – increases
  - Efficiency – increases (due to heat added at higher average T)
  - Decreases the moisture content of the steam at turbine exit
  - Maximum temperature of steam is restricted by material properties of boiler and turbine to approx.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



Rankine Cycle Efficiency

- Increasing boiling pressure

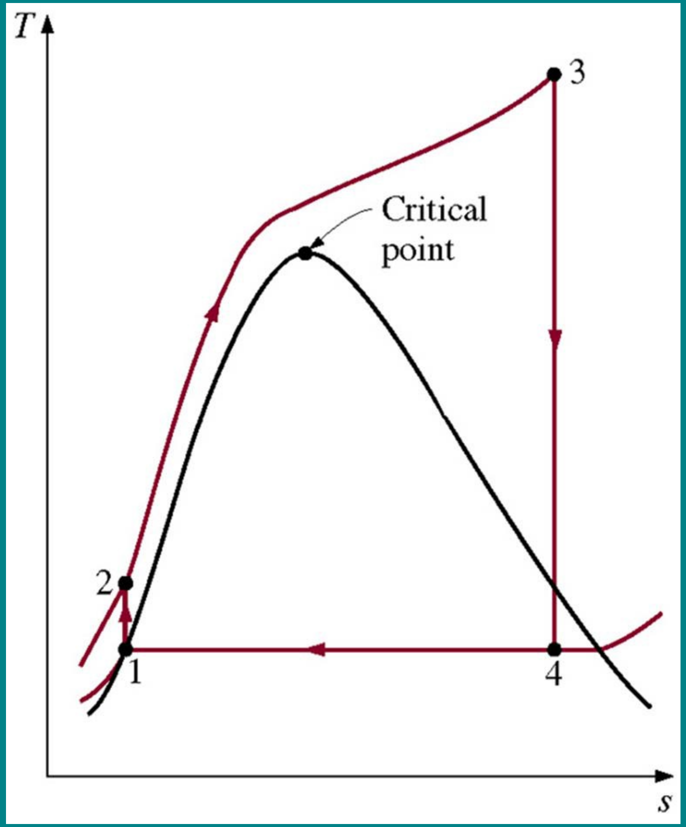
- Power output – similar
- Heat input – similar
- Efficiency – increases (due to heat added at higher average T)
- Decreases the quality of steam at turbine exit



Rankine Cycle Efficiency

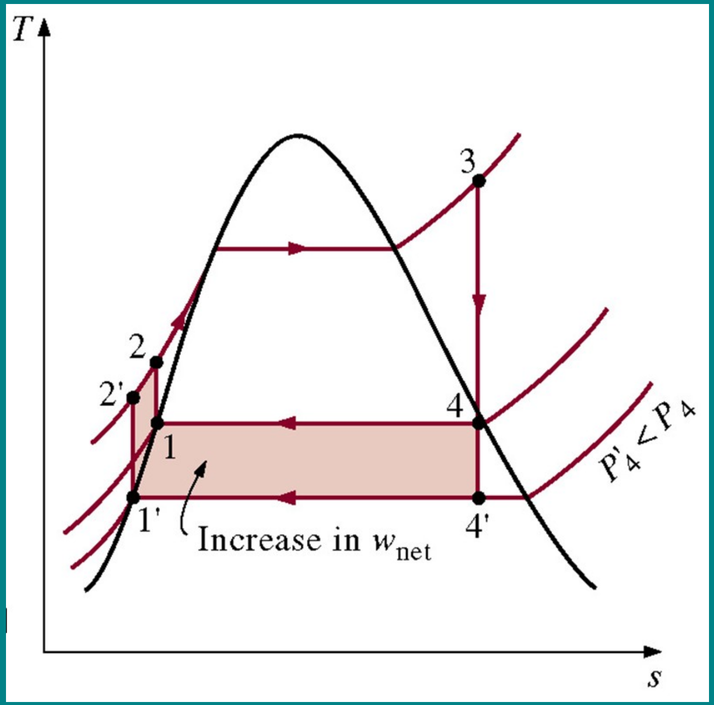
- Supercritical Rankine cycle

- 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

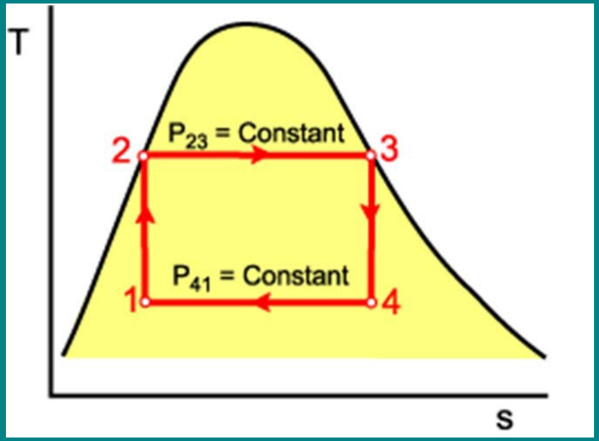
- Lowering condenser pressure/temperature
  - Power output – increases
  - Heat input – increases slightly
  - Efficiency – increases
  - Quality of the mixture at turbine exit decreases
  - Pressure/temperature are restricted by temperature of cooling medium condenser (usually to 20-25°C) in
  - Condenser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



Improved Rankine cycle

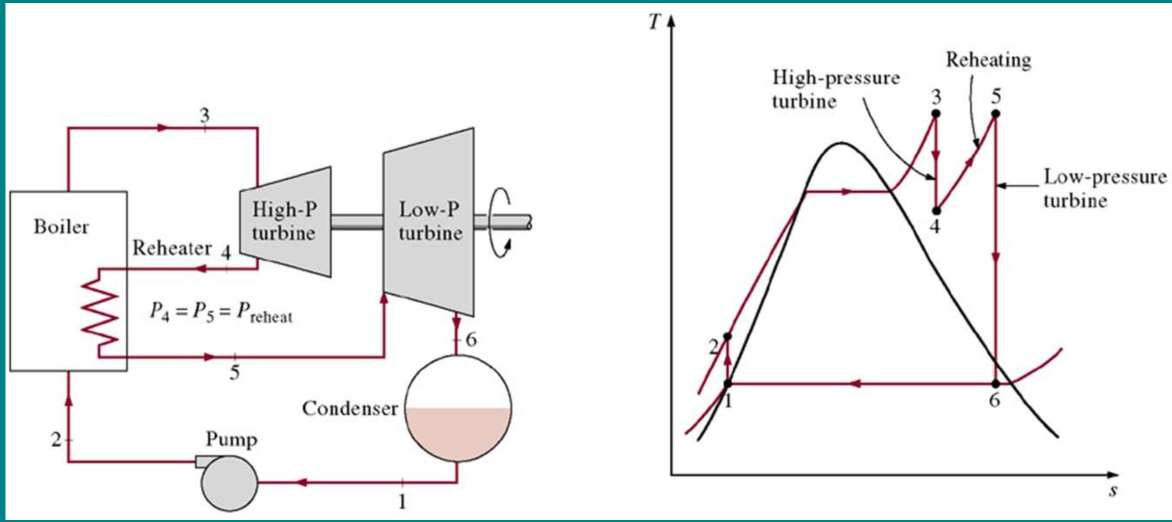
- Improvement with respect to increased efficiency and/or power output by adding extra devices. Two main processes which increase the mean temperature of heat addition are:
  - Reheating
  - Regeneration
- From Carnot engine (with isothermal heat addition)

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

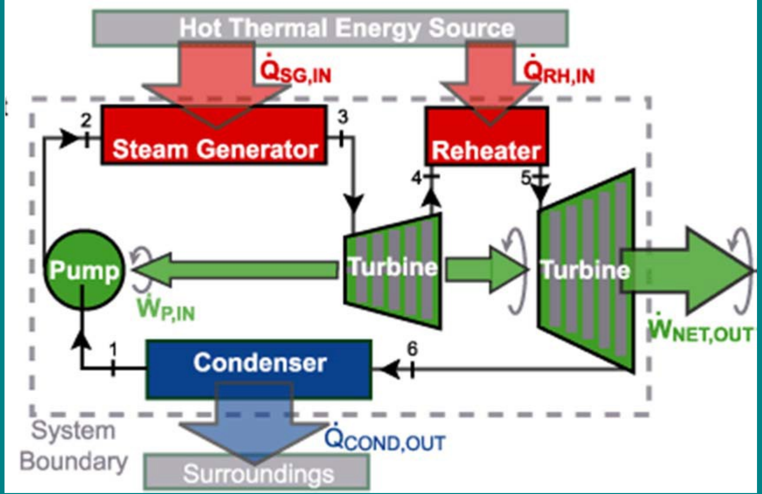


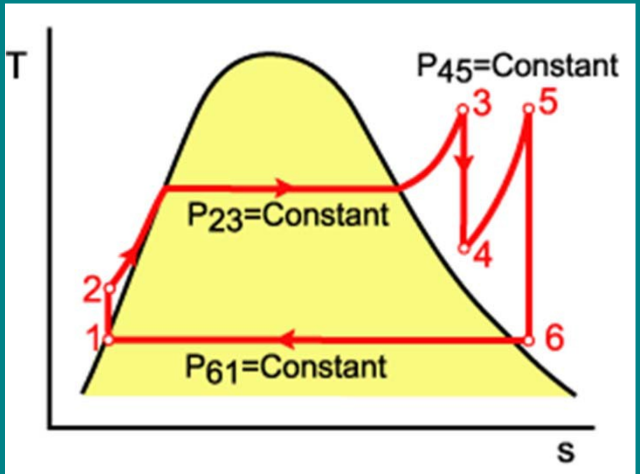
Improved Rankine cycle - Reheating

- 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 650ºC) 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





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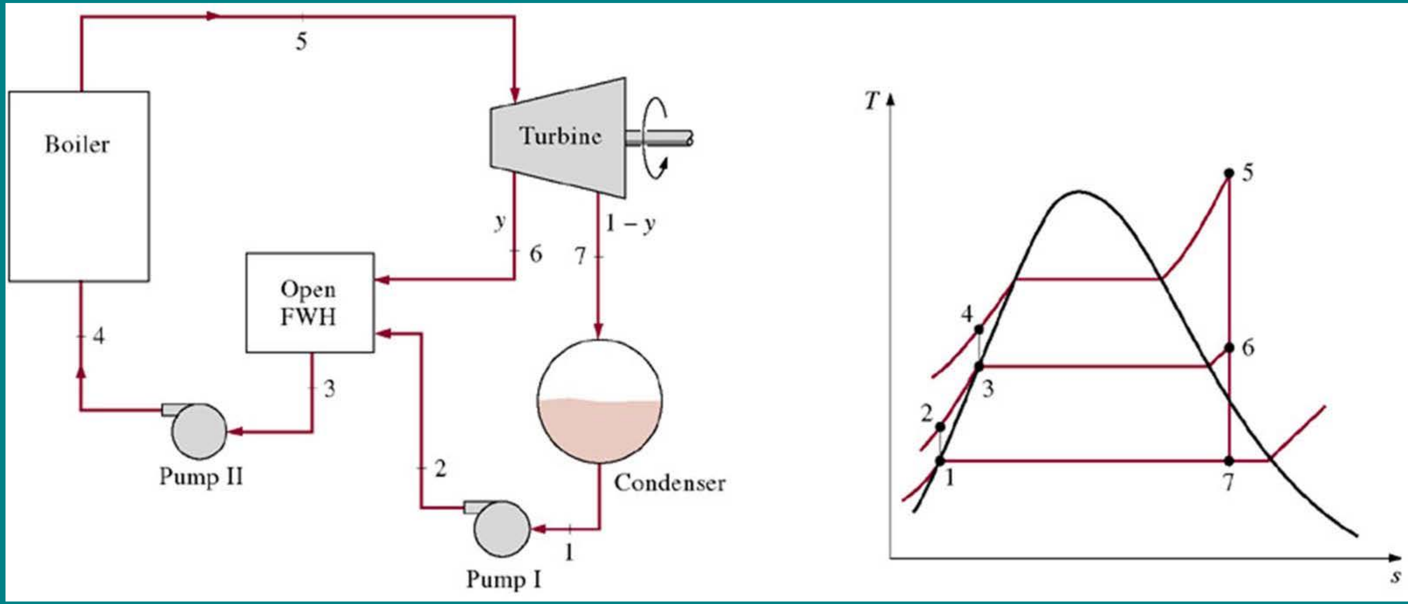
$$= \frac{\dot{W}_{turb,1} + \dot{W}_{turb,2} - \dot{W}_{pump}}{\dot{Q}_{in,1} + \dot{Q}_{in,2}} =$$
$$= \frac{\dot{m}(h_3 - h_4) + \dot{m}(h_5 - h_6) - \dot{m}(h_2 - h_1)}{\dot{m}(h_3 - h_2) + \dot{m}(h_5 - h_4)}$$

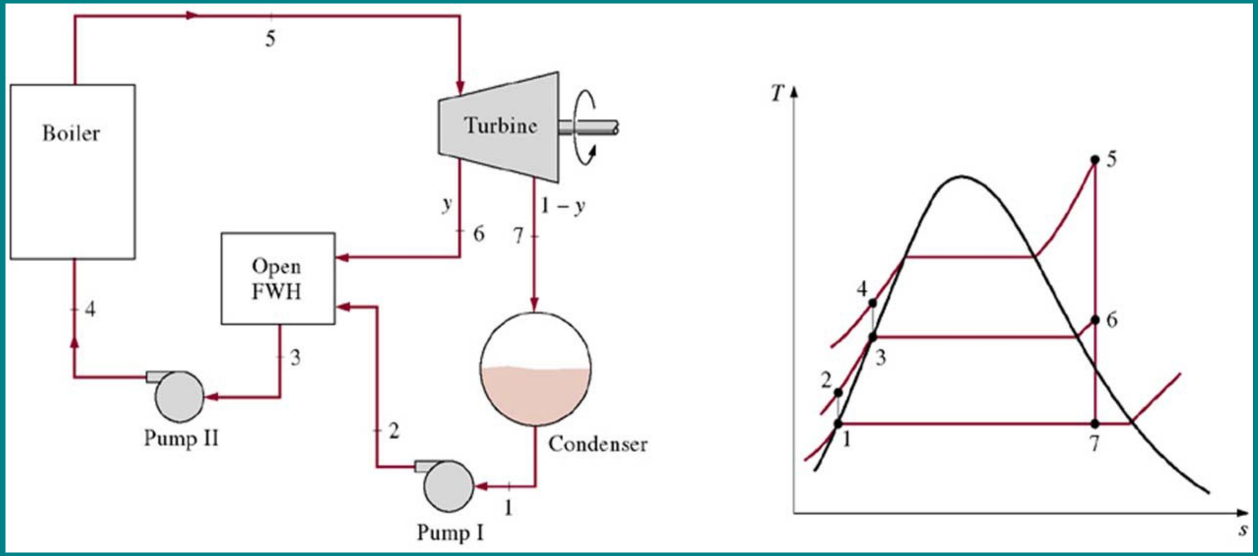
Improved Rankine cycle - Regeneration

- 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

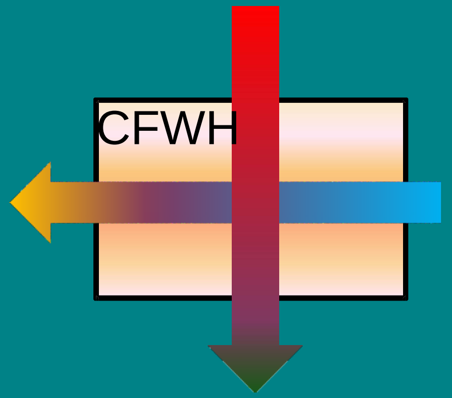


Improved Rankine cycle - Regeneration

- 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=const.)
  - CFWH is more complex, more expensive and heat transfer is less efficient then OFWH, however, it does not require separate pumps (flows at different pressures)

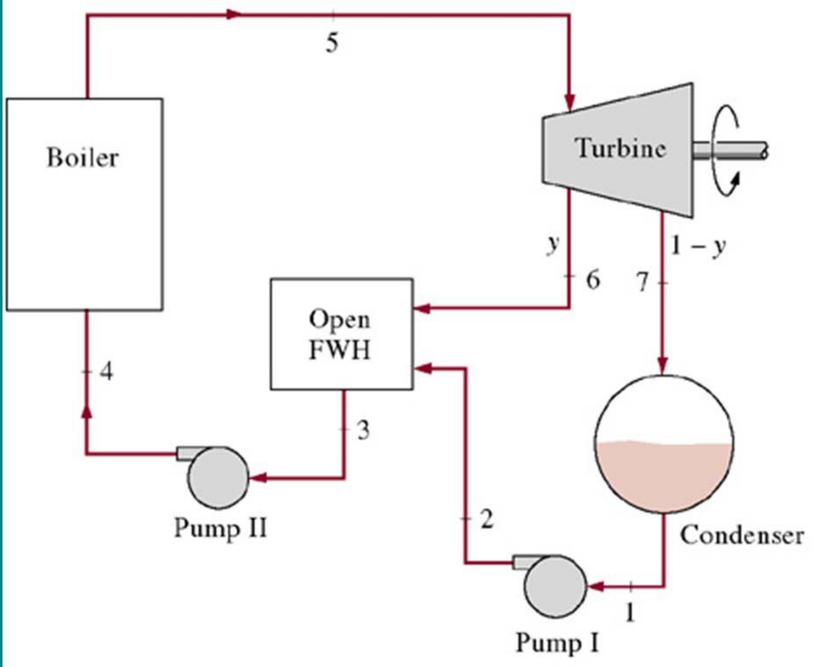


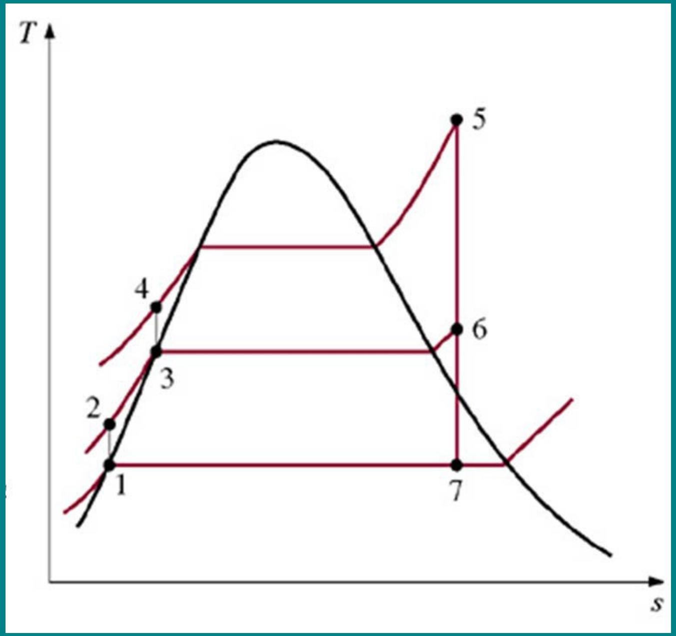
Improved Rankine cycle - Regeneration

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

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

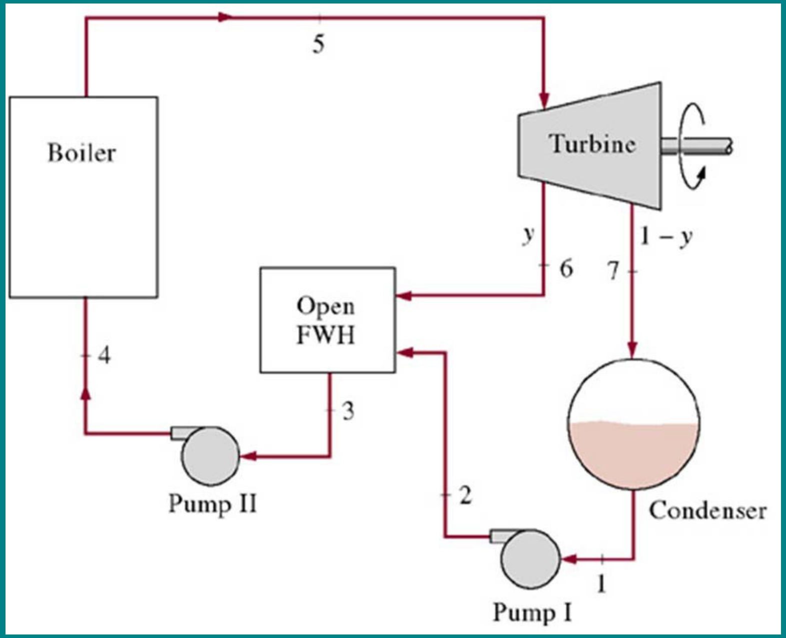
$$\dot{m}_3 h_3 = \dot{m}_2 h_2 + \dot{m}_6 h_6$$

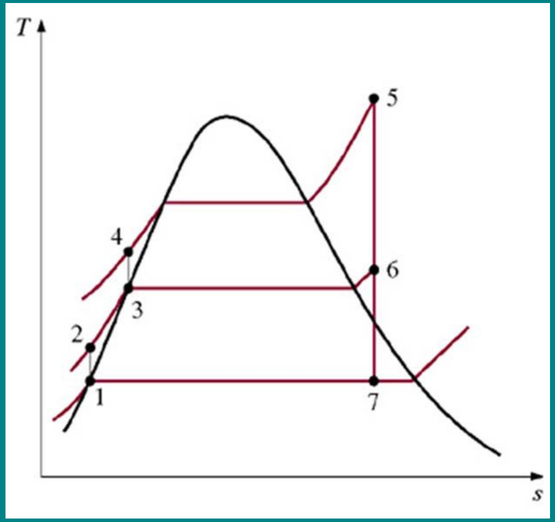




Improved Rankine cycle - Regeneration

- Rankine cycle with open feedwater heater



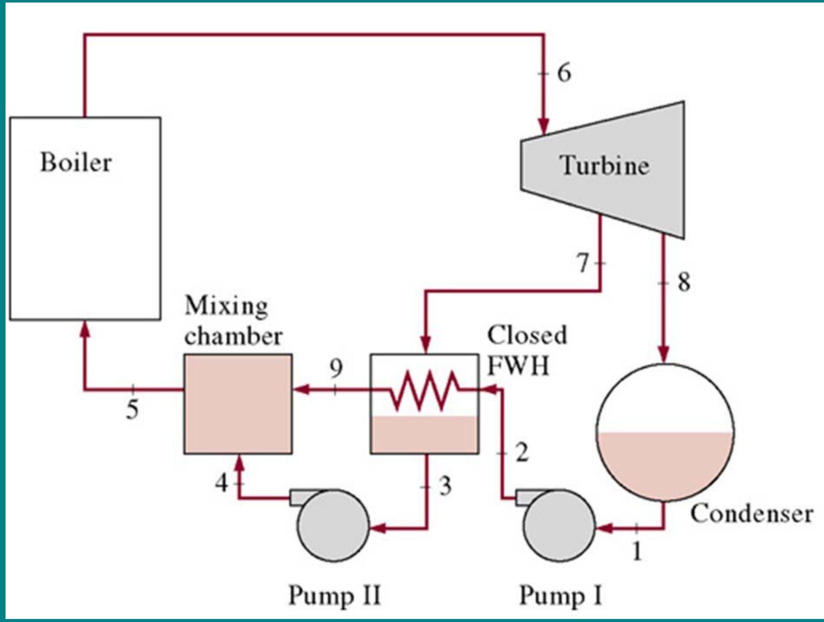


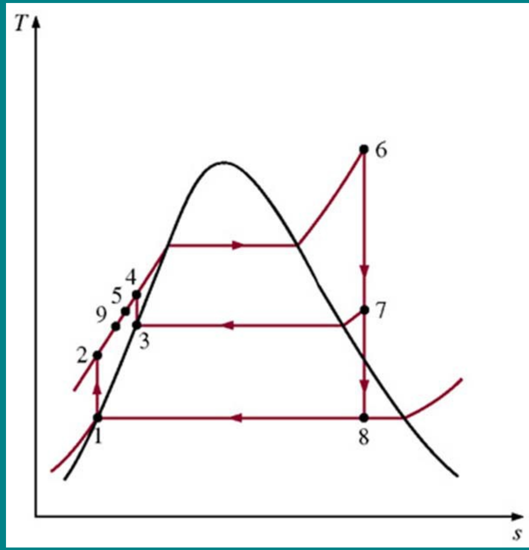
$$\eta_{Rankine} = \frac{get}{pay} = \frac{\dot{W}_{net}}{\dot{Q}_{in}} = \frac{\dot{W}_{turb,1} + \dot{W}_{turb,2} - \dot{W}_{pump,1} - \dot{W}_{pump,2}}{\dot{Q}_{in}} =$$

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

Improved Rankine cycle - Regeneration

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





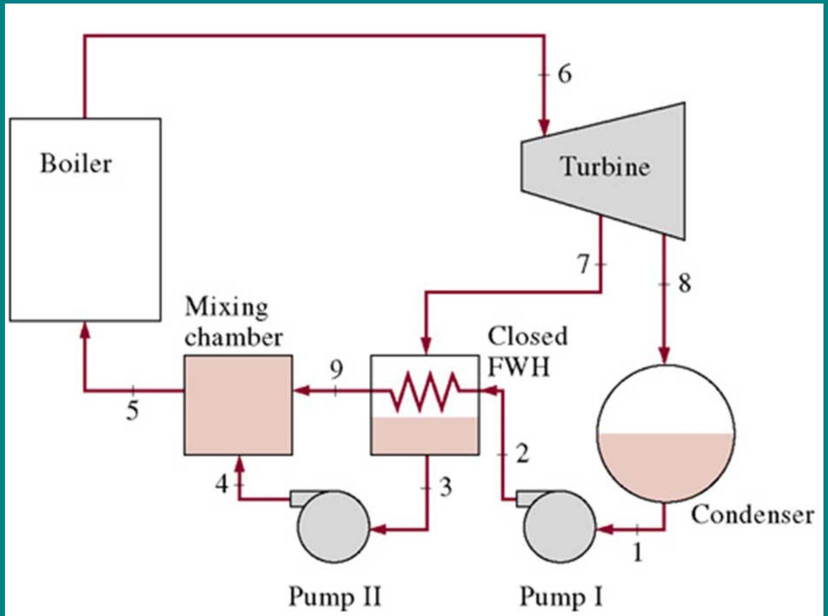
$$\dot{m}_5 = \dot{m}_4 + \dot{m}_9$$

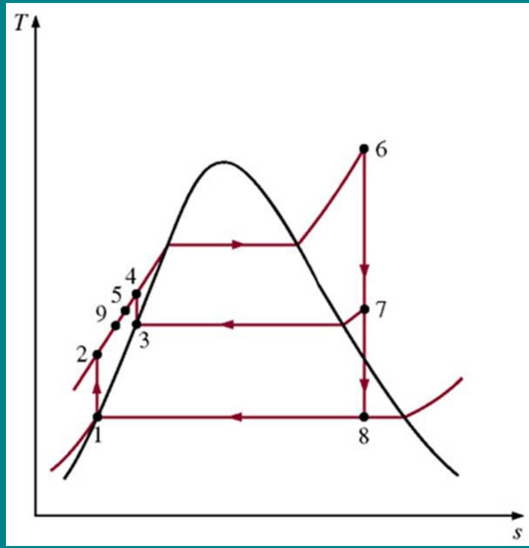
$$\dot{m}_5 h_5 = \dot{m}_4 h_4 + \dot{m}_9 h_9$$

$$\dot{m}_4 (h_7 - h_3) = \dot{m}_9 (h_9 - h_2)$$

Improved Rankine cycle - Regeneration

- Rankine cycle with closed feedwater heater





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

Calculate Rankine cycle