Lecture 17

Topic 4

Power & Refrigeration Cycles

Topic

– 4.2 Rankine Cycles (Steam Power Plant) pt 2

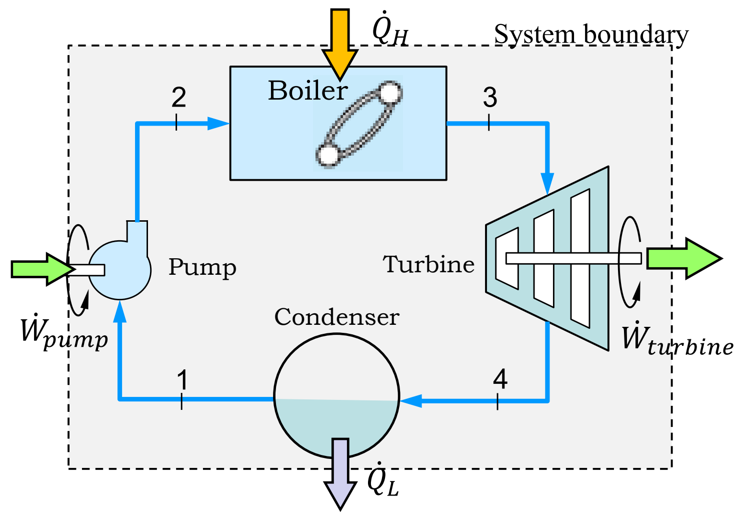
Reading:

Ch 9: 9.1 – 9.7 Borgnakke & Sonntag Ed. 8

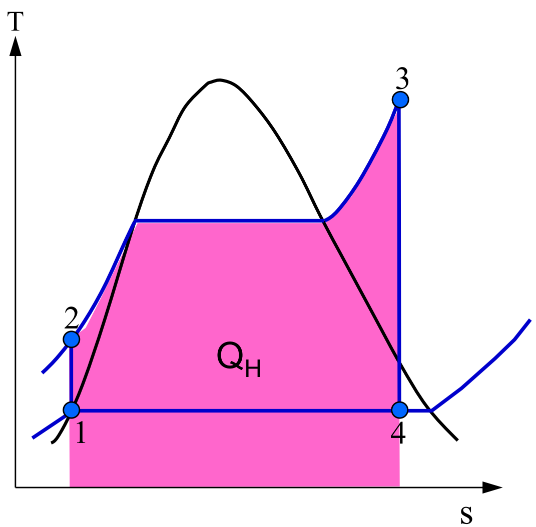
Ch 10: 10-1 – 10-7 Cengel and Boles Ed. 7

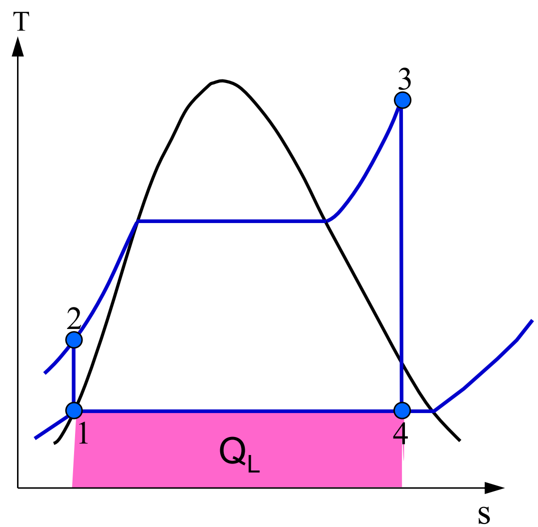
4.2.4 Rankine Cycle Efficiency

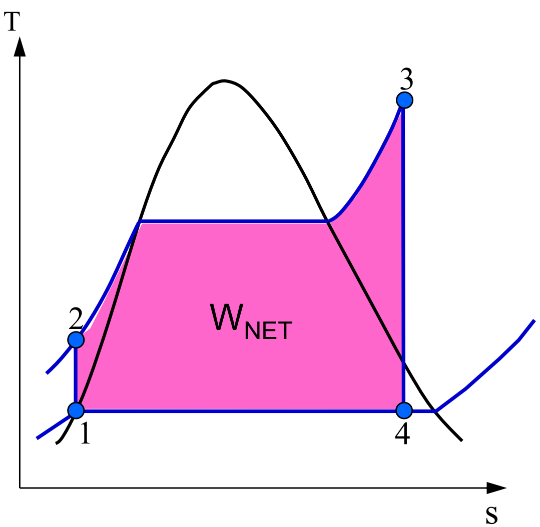
Increasing the Efficiency of the Rankine Cycle



- $\eta_{th} = \dfrac{desired\ output}{required\ input} = \dfrac{\dot{W}_{NET,out}}{\dot{Q}_H}$
- Want to maximize W_{NET} for a given Q_H
- $W_{NET} = Q_{NET} = Q_H - Q_L$
  - Q_H → area under T-s diagram (2-3)
  - Q_L → area under T-s diagram (4-1)
  - W_{NET} is area enclosed in T-s diagram



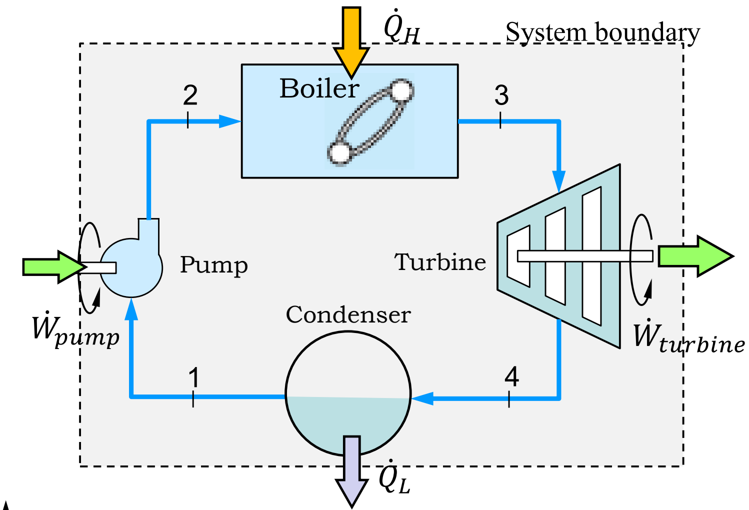




4.2.4 Rankine Cycle Efficiency

Increasing the Efficiency of the Rankine Cycle

- $\eta_{th} = \dfrac{desired\ output}{required\ input} = \dfrac{\dot{W}_{NET,out}}{\dot{Q}_H}$
- Want to maximize W_{NET} for a given Q_H



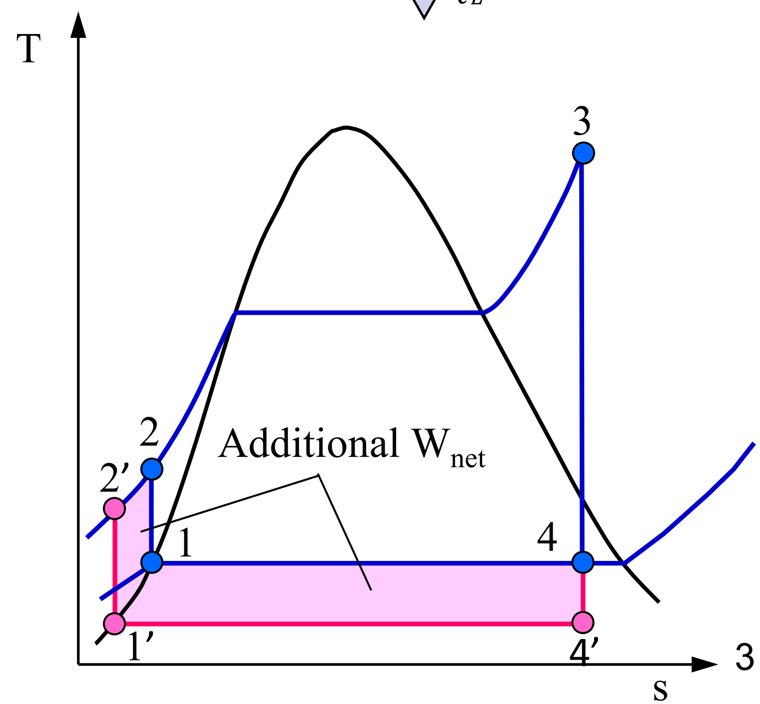
Effect of Pressure and Temperature

Method 1: Lower condenser pressure (P_1, P_4)

- Additional expansion of working fluid
- $W_{turbine}$ increases
- Q_L decreases
- η_{th} increases

Drawbacks

- W_{pump} increases (minor)
- Liquid in turbine increases
- Quality > 90% to avoid corrosion in turbine



4.2.4 Rankine Cycle Efficiency

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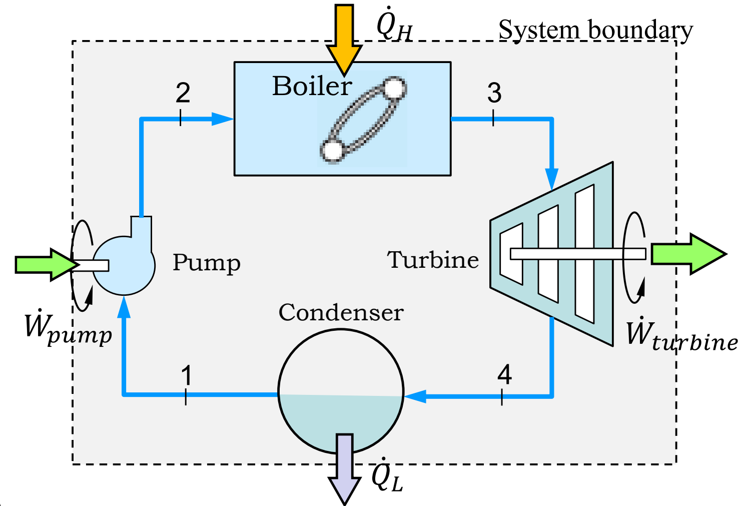
Increasing the Efficiency of the Rankine Cycle

- $\eta_{th} = \frac{desired\ output}{required\ input} = \frac{\dot{W}_{NET,out}}{\dot{Q}_H}$

- Want to maximize W_{NET} for a given Q_H



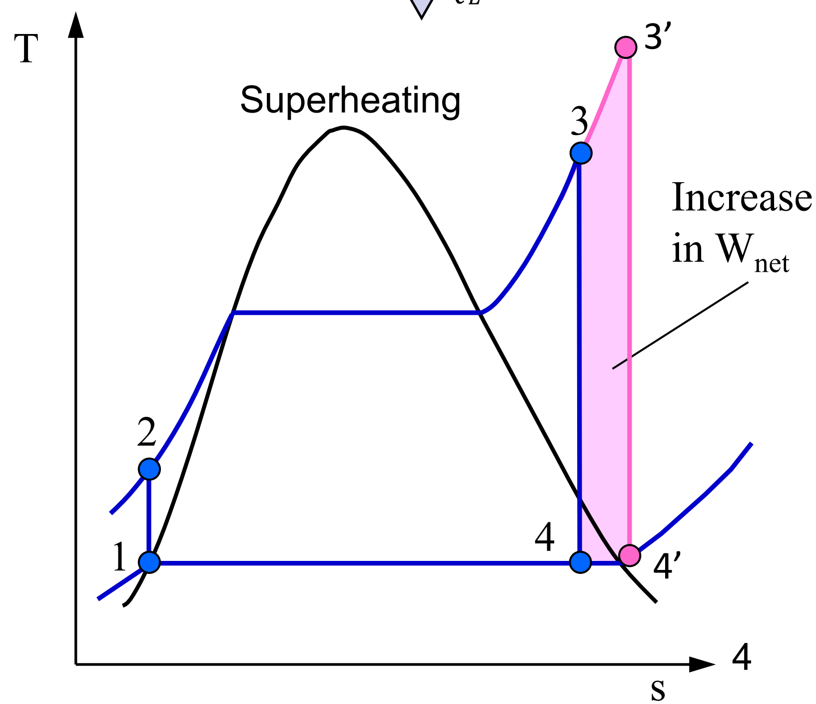
Effect of Pressure and Temperature

Method 2: Increase T_{max} ($T_3 \rightarrow T_{3'}$)

- η_{TH} increases (think Carnot: $\eta_{TH} = 1 - \frac{T_L}{T_H}$)
- Liquid content in turbine decreases
- $W_{turbine}$ increases

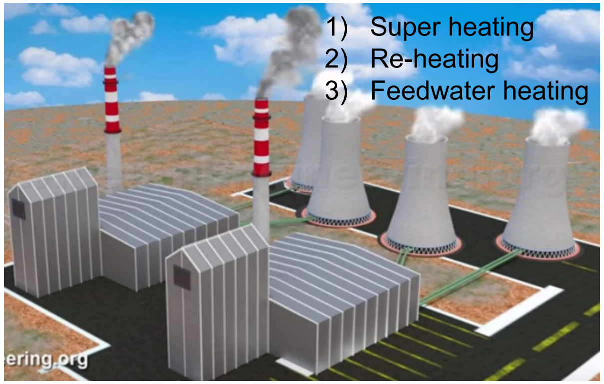
Drawbacks

- Q_H increases
- Turbine components can be damaged above 600°C

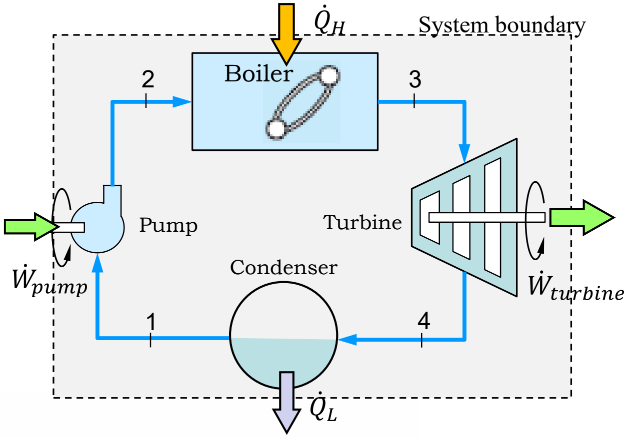


4.2.4 Rankine Cycle

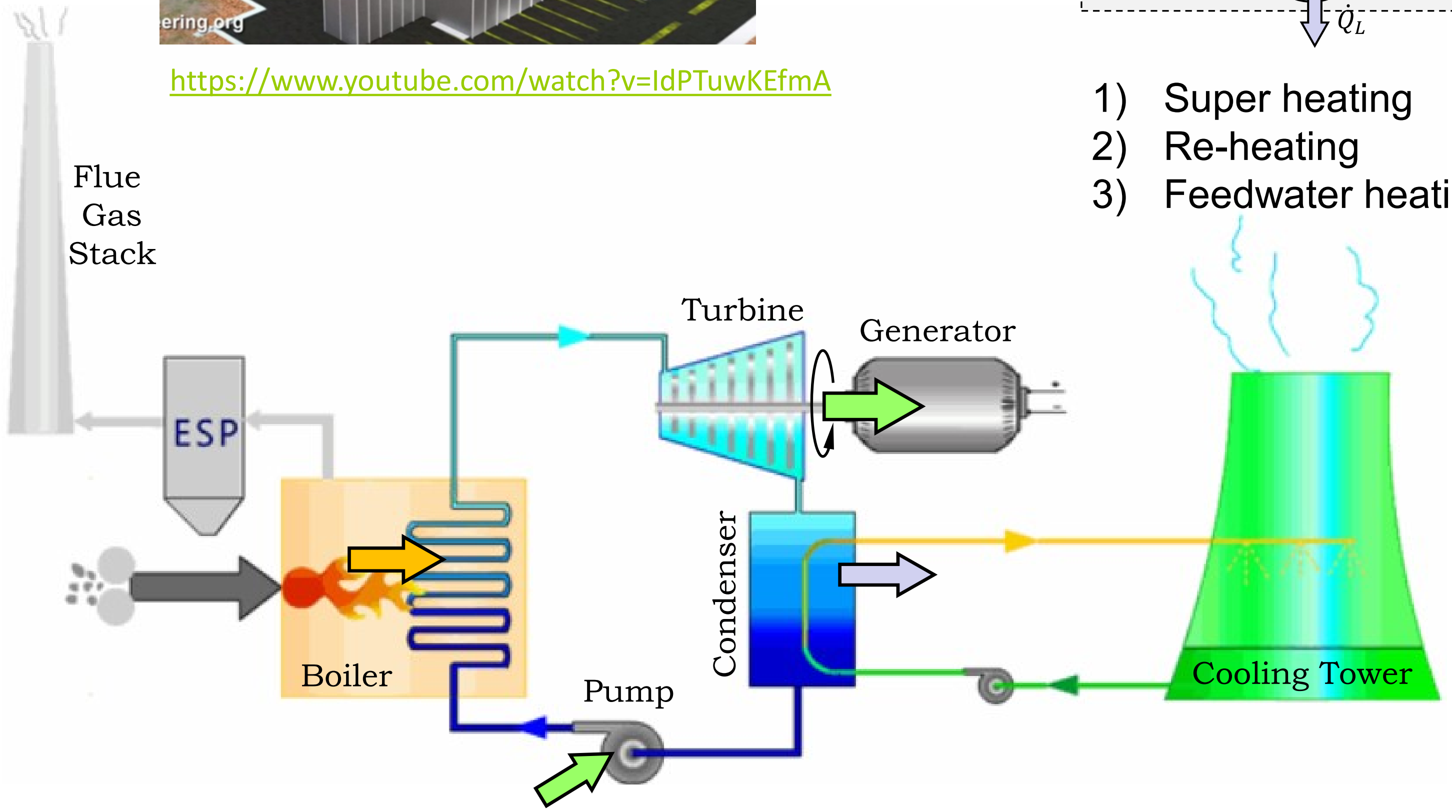
Video content – other methods to increase efficiency



https://www.youtube.com/watch?v=IdPTuwKEfmA



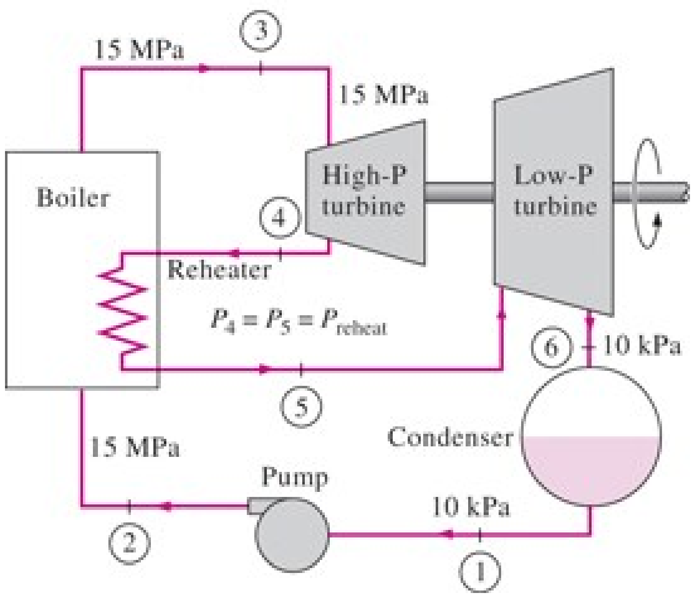
1) Super heating
2) Re-heating
3) Feedwater heating

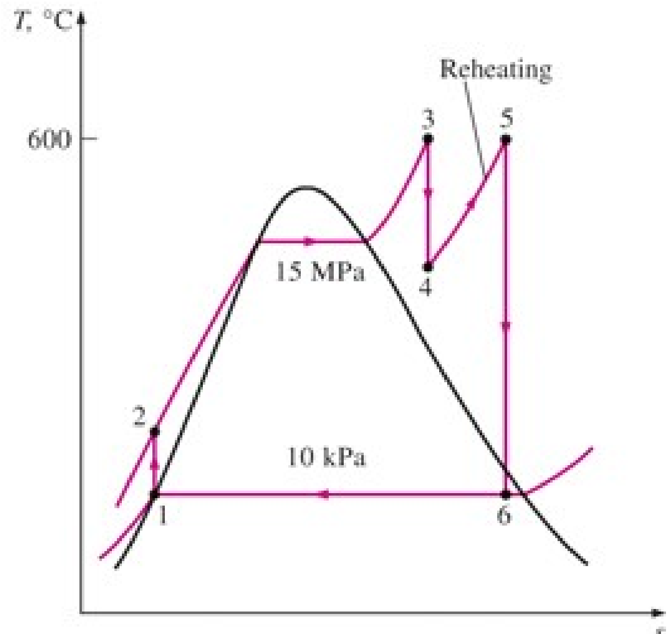


4.2.4 Efficiency Improvements (Rankine)

<u>REHEAT Rankine Cycle</u> –

- Two stage turbine
  - Fluid from high-P turbine is reheated in the boiler
  - Reheated vapour sent to low pressure turbine
- Achieve two expansion processes
  - Increase W_{NET}
  - η_{TH} increases (but so does $\dot{Q}_H$)
  - Increase mixture quality exiting turbine

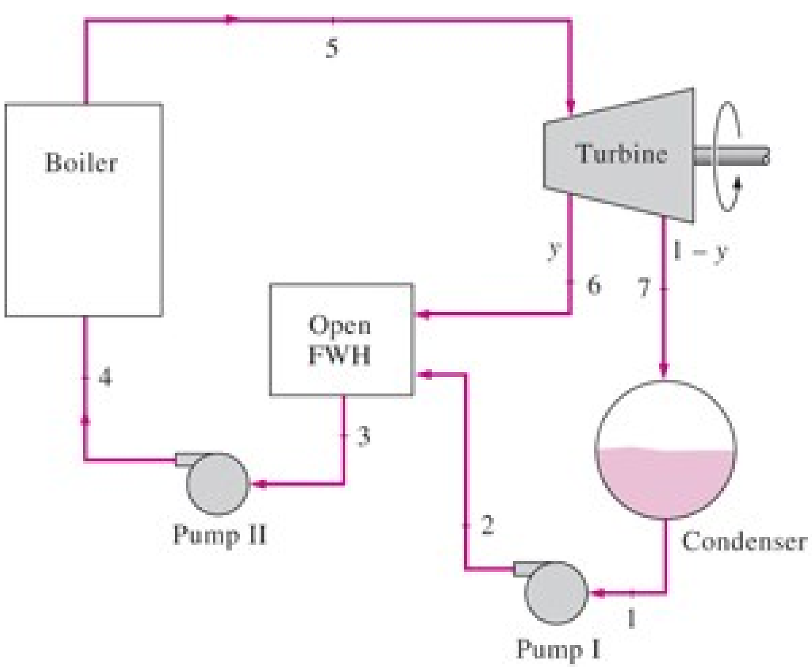


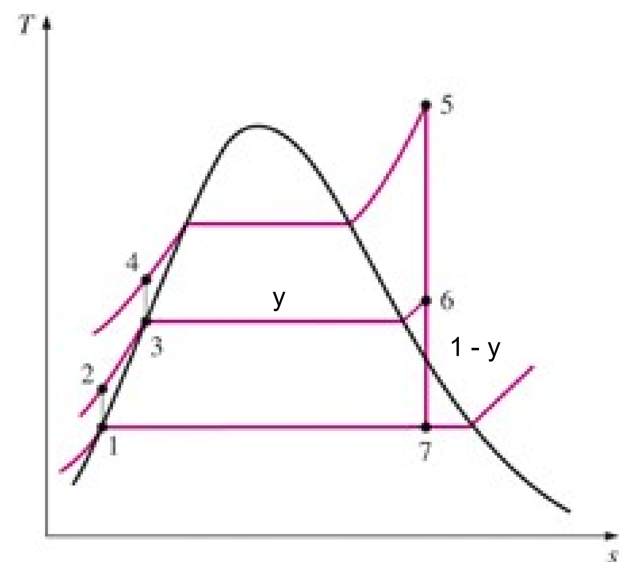


4.2.4 Efficiency Improvements (Rankine)

***Regenerative* Rankine Cycle with *OPEN* Feed Water Heater** –

- Preheat & require less energy from boiler
- Steam from the turbine extracted to heat (& mix) liquid before boiler.
- Open FWH: constant pressure mixing process
- Fluid leaving FWH (sat. liquid) enters Pump II to achieve higher press.
- 2 stage pumping process





4.2.4 Efficiency Improvements (Rankine)

Open Feed Water Heater – Control Volume analysis

Conservation of mass: $\dot{m}_6 + \dot{m}_2 = \dot{m}_3$, where $\dot{m}_6 = (y)\dot{m}_5$ and $\dot{m}_7 = (1-y)\dot{m}_5 = \dot{m}_2$

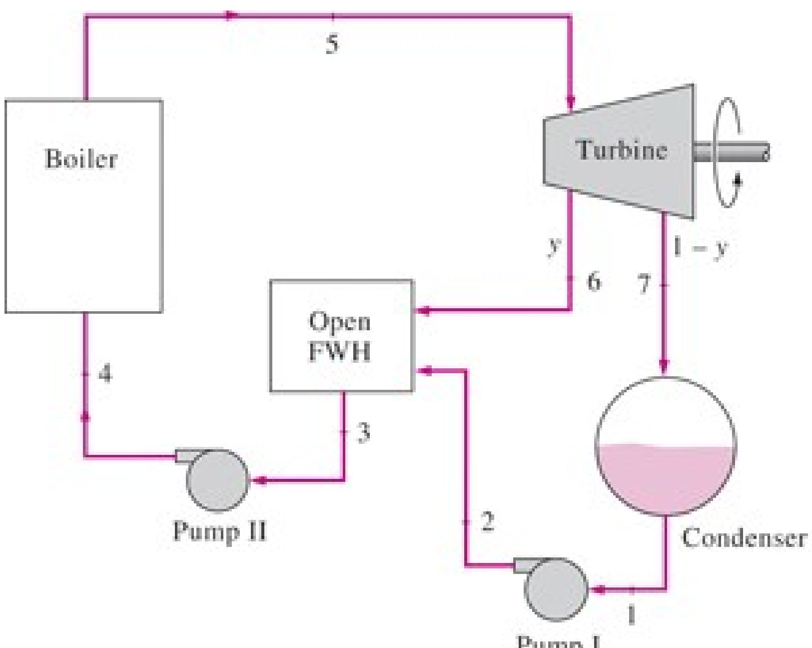
Conservation of energy: $\dot{m}_6 h_6 + \dot{m}_2 h_2 = \dot{m}_3 h_3 \rightarrow (y)\dot{m}_5 h_6 + (1-y)\dot{m}_5 h_2 = \dot{m}_5 h_3$

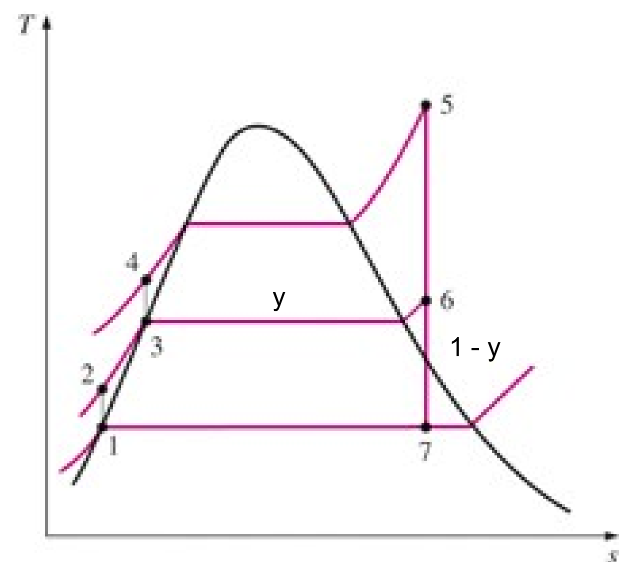
Turbine – Control Volume analysis

Conservation of mass: $\dot{m}_5 = \dot{m}_6 + \dot{m}_7$, where $\dot{m}_6 = (y)\dot{m}_5$ and $\dot{m}_7 = (1-y)\dot{m}_5$

Conservation of energy:

$$\dot{W}_{Turbine} = \dot{m}_5 h_5 - \dot{m}_6 h_6 - \dot{m}_7 h_7 = \dot{m}_5 (h_5 - y h_6 - (1-y) h_7)$$

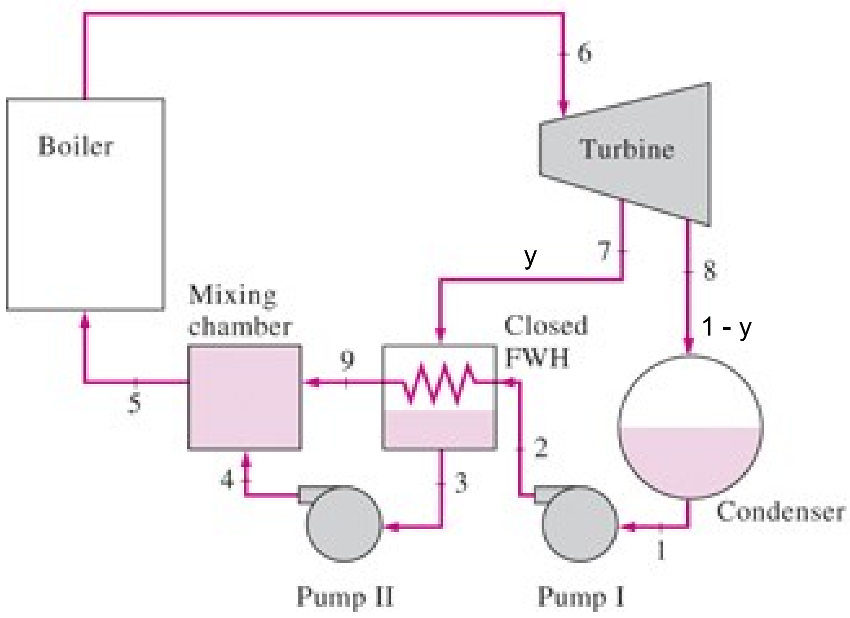


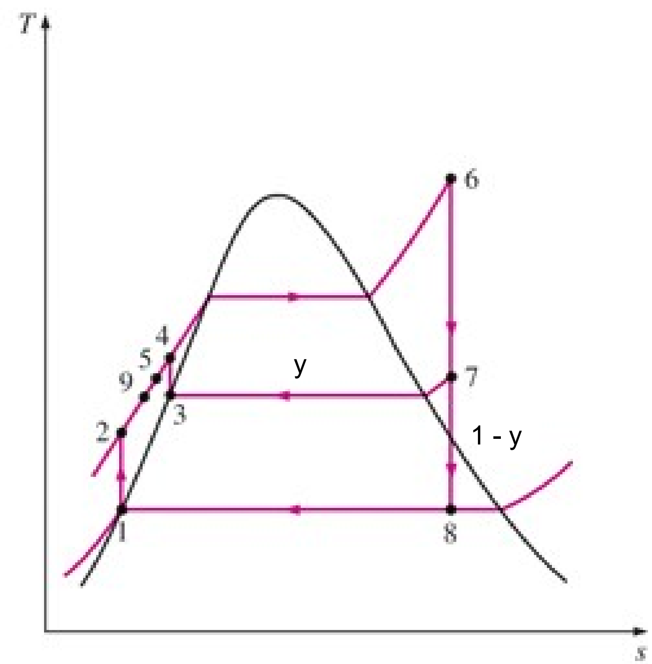


4.2.4 Efficiency Improvements (Rankine)

Regenerative **Rankine Cycle with *CLOSED* Feed Water Heater**

- Preheat, but no mixing in FWH
- Each fluid can be at different pressures.
- Fluid ($\dot{m}_7$) exits FWH as a saturated liquid.
- Compressed liquids mix in a mixing chamber
- Mixing chamber: compressed liquid at two different temperatures.





4.2.4 Efficiency Improvements (Rankine)

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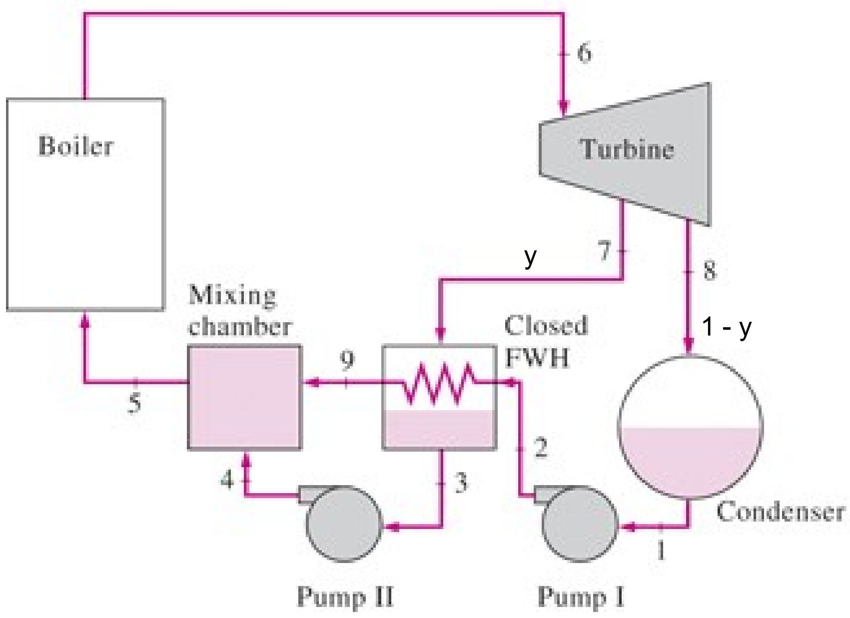
Closed Feed Water Heater – Control Volume Analysis

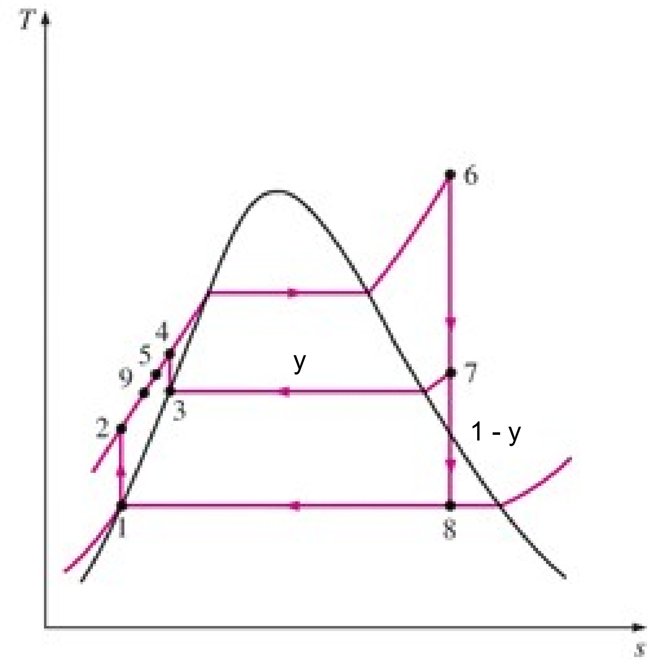
Conservation of energy: $\dot{m}_7 h_7 + \dot{m}_2 h_2 = \dot{m}_3 h_3 + \dot{m}_9 h_9$

Mixing Chamber – Control Volume Analysis

Conservation of mass: $\dot{m}_9 + \dot{m}_4 = \dot{m}_5$, where $\dot{m}_9 = (y)\dot{m}_6$ and $\dot{m}_4 = (1-y)\dot{m}_6$ and $\dot{m}_5 = \dot{m}_6$

Conservation of energy: $\dot{m}_9 h_9 + \dot{m}_4 h_4 = \dot{m}_5 h_5 \rightarrow (y)\dot{m}_6 h_9 + (1-y)\dot{m}_6 h_4 = \dot{m}_6 h_5$



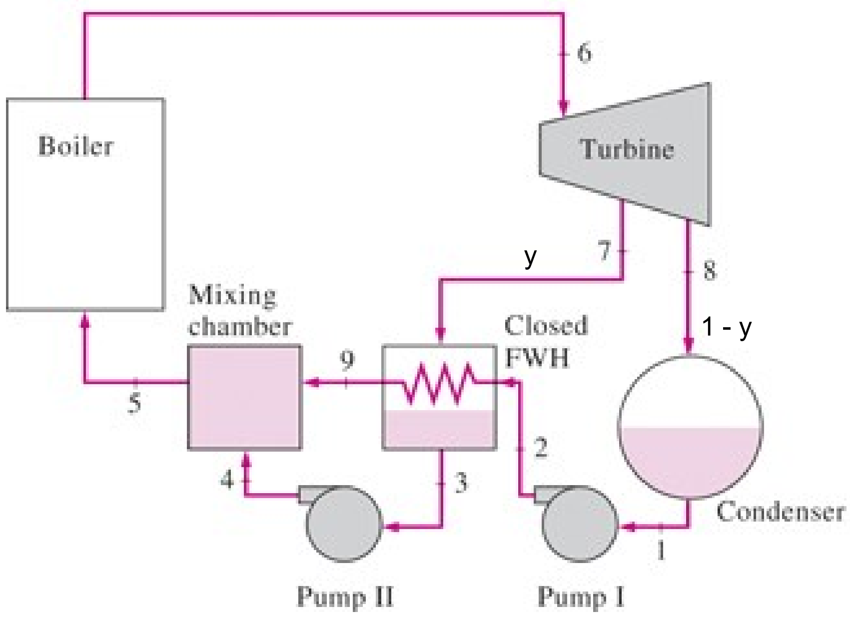


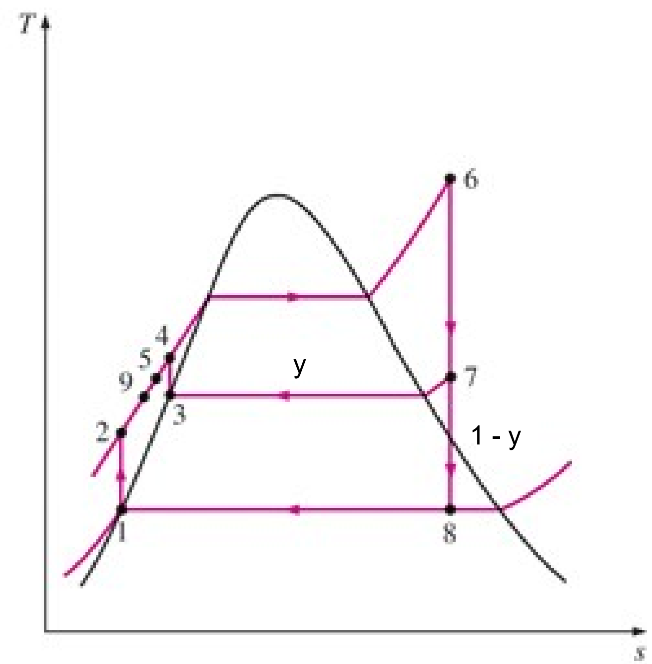
4.2.4 Efficiency Improvements (Rankine)

Turbine – Control Volume Analysis

Conservation of mass: $\dot{m}_6 = \dot{m}_7 + \dot{m}_8$, where $\dot{m}_7 = (y)\dot{m}_6$ & $\dot{m}_8 = (1-y)\dot{m}_6$

Conservation of energy: $\dot{W}_T = \dot{m}_6 h_6 - \dot{m}_7 h_7 - \dot{m}_8 h_8 \rightarrow \dot{m}_6(h_5 - yh_7 - (1-y)h_8)$





4.2.4 Efficiency Improvements (Rankine)

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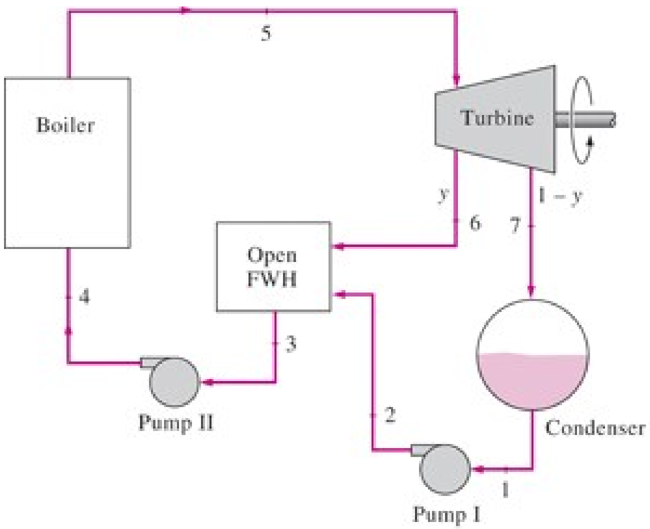
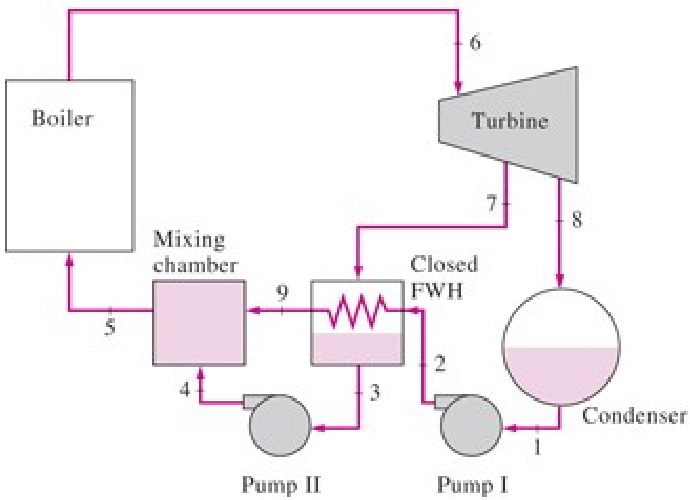
Ideal Feedwater Heater cycles

- Goal: preheat liquid before boiler
- Pumps: adiabatic & reversible
  - Saturated liquid entering pumps: h_f, s_f, v_f
- Turbine: adiabatic, reversible
  - Fraction of steam $(y\, \dot{m}_{total})$ sent to FWH
- FWH: adiabatic & const. pressure
  - Open:
    - Mixing & internal heat transfer
    - Two-stage pumping in series
  - Closed:
    - Internal heat transfer
    - Two pumps in parallel
- Mixing chamber (closed FWH)
  - Constant pressure
  - Compressed liquid





4.2.4 Efficiency Improvements (Rankine)

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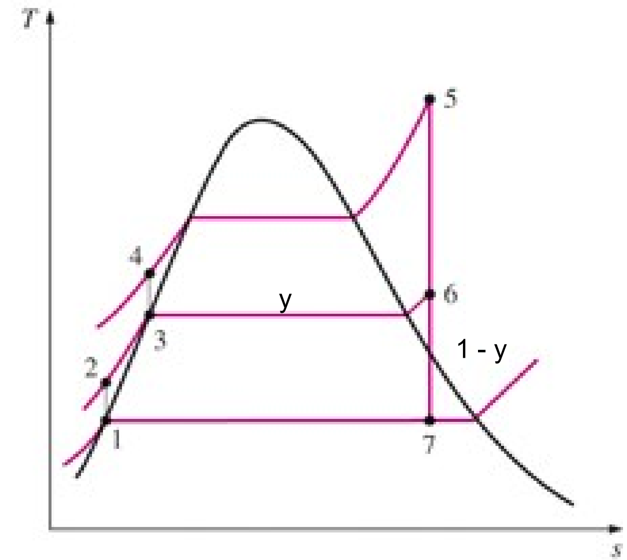
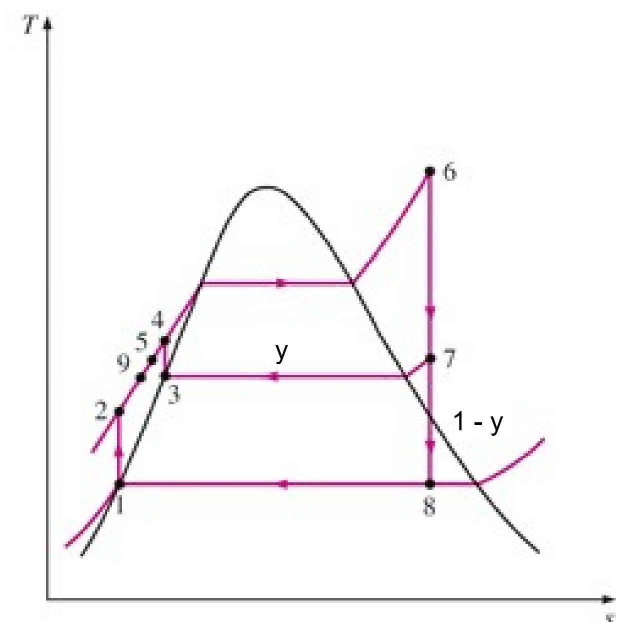
Ideal Feedwater Heater Processes

- Isentropic
  - Pumps & Turbine
  - $s_1 = s_2 = s_{f@P_1}$; $s_3 = s_4 = s_{f@P_3}$
  - OFWH: $s_5 = s_6 = s_7$
  - CFWH: $s_6 = s_7 = s_8$

- Constant pressure
  - Heat exchangers & mixing chambers
  - OFWH:
    - Condenser: $P_1 = P_7$
    - FWH: $P_2 = P_3 = P_6$
    - Boiler: $P_4 = P_5$
  - CFWH
    - Condenser: $P_1 = P_7$
    - FWH: $P_2 = P_3 = P_6$
    - Boiler & mix chamber: $P_4 = P_5 = P_9 = P_6$





4.2.5 Example

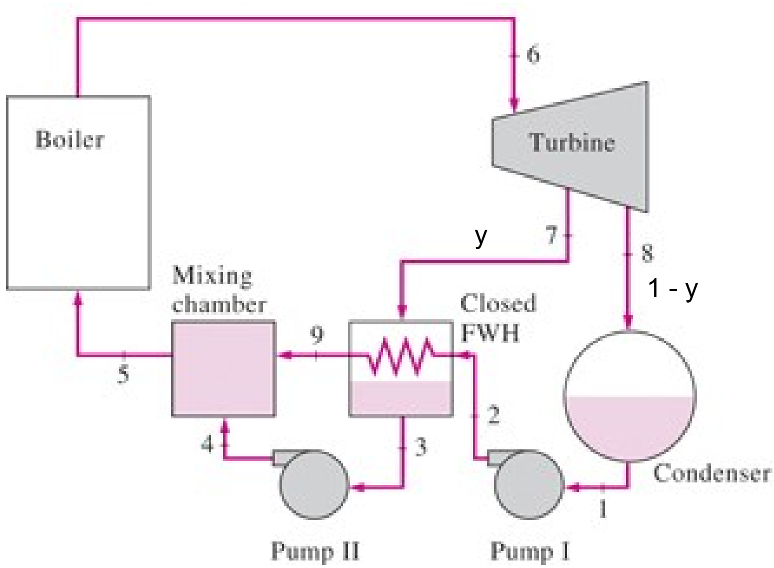
Example 4-5: An ideal closed feedwater heater is used in a steam power plant. 20 kg/s of liquid water is heated in the closed FWH from 100°C to 250°C at a constant pressure of 20 MPa. The extraction vapour from the turbine enters the FWH at 4 MPa and 300°C and leaves as a saturated liquid. The condenser pressure is 50 kPa.

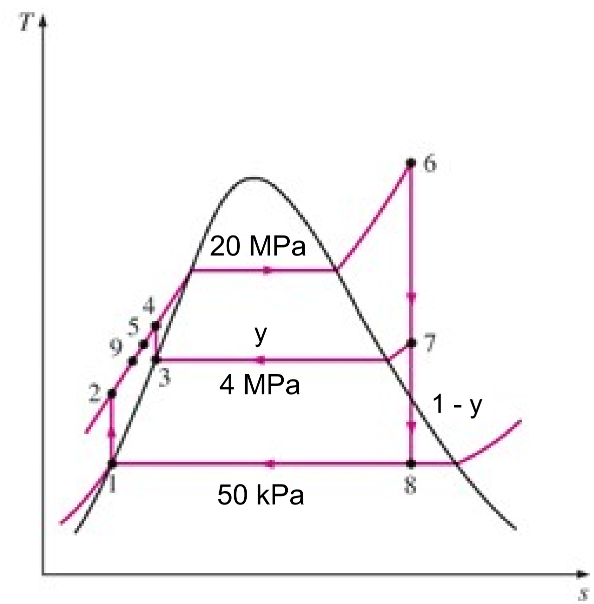
a) What is the mass flow rate of the extracted steam (i.e. $\dot{m}_7$)?.

b) What is the maximum working temperature of the cycle?

c) What is the power output from the turbine (in kW)?

d) Extra: What is the thermal efficiency of this Rankine Cycle?





4.2.6 Exercise (Rankine)

Exercise 4.2: .

a) Take Example 4.5. Find the processes (devices) where entropy is generated.

b) Assume that Q_H is delivered from a constant high temperature reservoir at 750°C and the heat is rejected to a lake at constant temperature of 20°C.

   i. Determine the rate of entropy generation for each process / device in which entropy is generated. What are the mechanisms for entropy generation?