Rankine Cycle

First Law of Thermodynamics Review

Steady - State First Law :

$$\dot{Q} - \dot{W} = \sum \dot{m}\left(h_e + \frac{V_e^2}{2} + gz_e \right) - \sum \dot{m}\left(h_i + \frac{V_i^2}{2} + gz_i \right)$$

if only 1 fluid stream exists &

kinetic and potential energy changes are negligible :

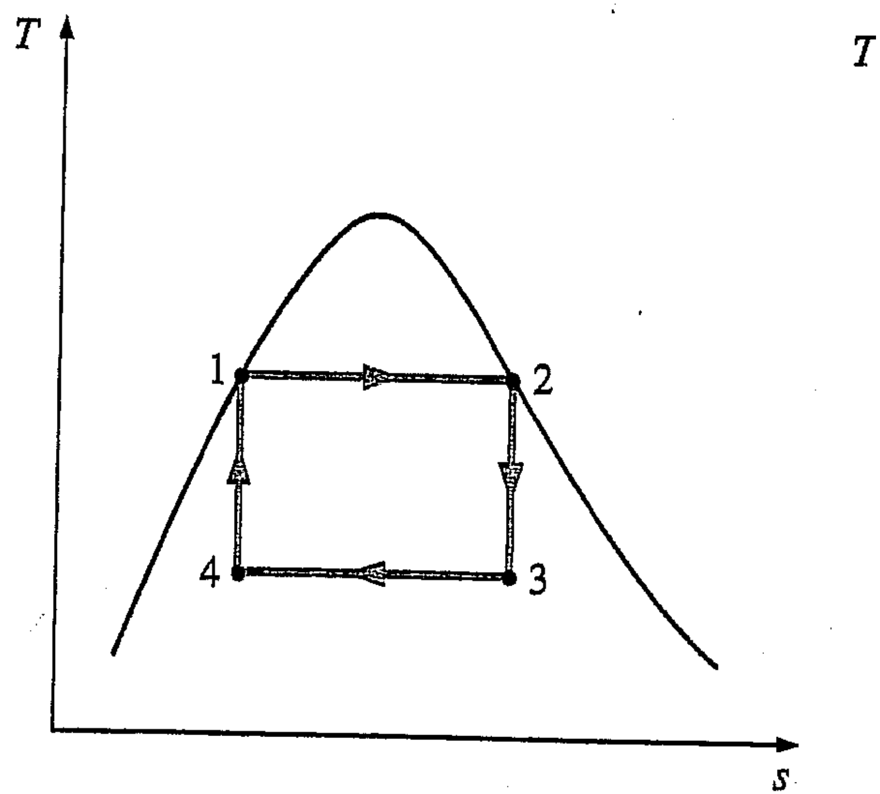
$$Q - W = h_e - h_i$$

rate of heat transfer $\dot{Q} = Q\dot{m}$ where Q has units of kJ/kg in SI

power $\dot{W} = W\dot{m}$ where W (work) has units of kJ/kg in SI

Vapor Power Cycles

- In these types of cycles, a fluid evaporates and condenses.
- Ideal cycle is the Carnot
- Which processes here would cause problems?



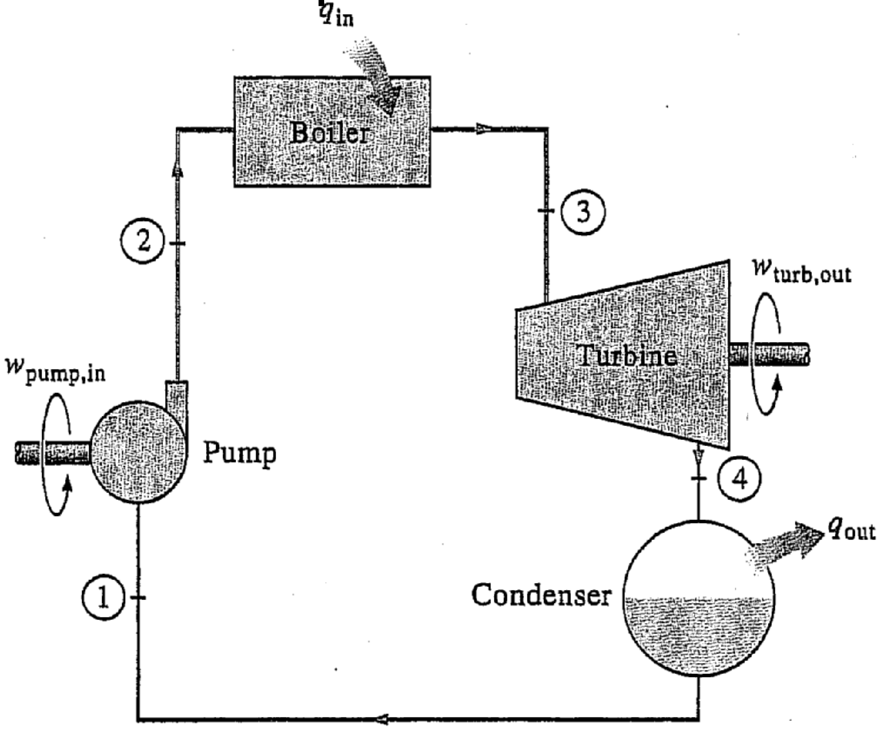
(a)

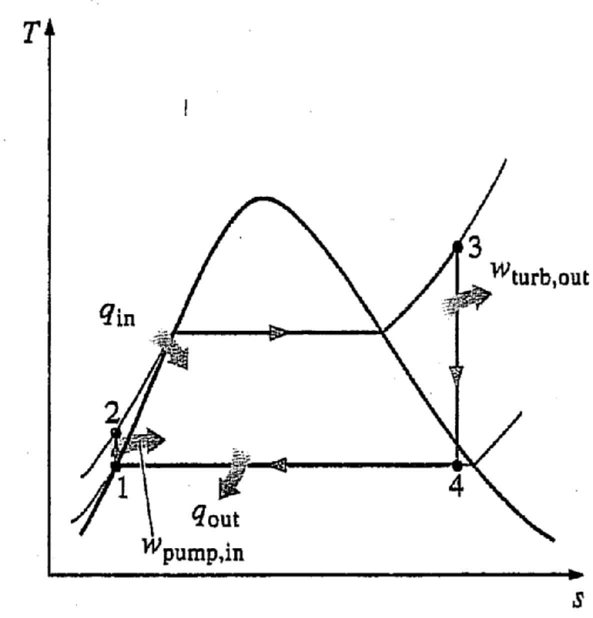
Ideal Rankine Cycle

- This cycle follows the idea of the Carnot cycle but can be practically implemented.

1-2 isentropic pump   2-3 constant pressure heat addition

3-4 isentropic turbine   4-1 constant pressure heat rejection





Ideal Cycle Analysis

- $h_1 = h_f$@ low pressure (saturated liquid)
- $W_{pump\ (ideal)} = h_2 - h_1 = v_f(P_{high} - P_{low})$
  - v_f=specific volume of saturated liquid at low pressure
- $Q_{in} = h_3 - h_2$ heat added in boiler (positive value)
  - Rate of heat transfer = Q*mass flow rate
  - Usually either Q_{in} will be specified or else the high temperature and pressure (so you can find h_3)

Ideal Cycle Analysis, cont.

- $Q_{out}=h_4-h_1$ heat removed from condenser (here h_4 and h_1 signs have been switched to keep this a positive value)
- $W_{turbine}=h_3-h_4$ turbine work
  - Power = work * mass flow rate
- h_4@ low pressure and $s_4=s_3$

Deviations from Ideal in Real Cycles

- Pump is not ideal

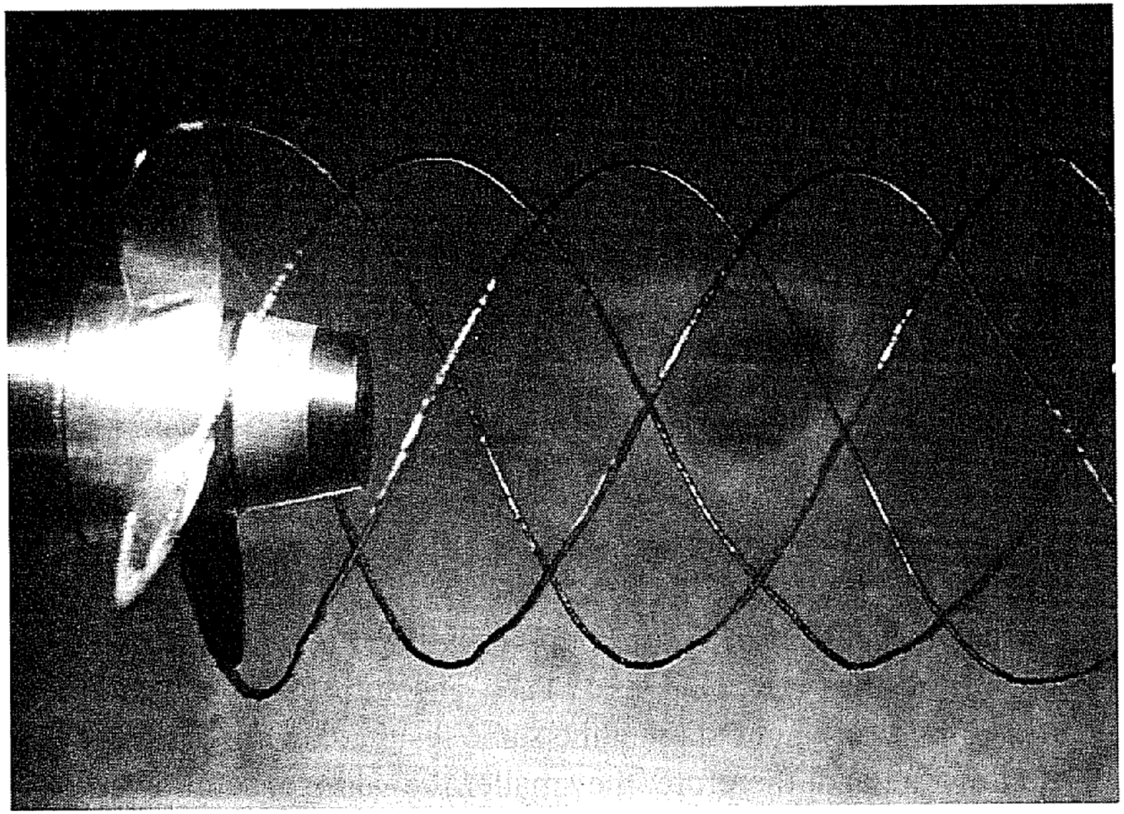
$$\eta_{pump} = {W_{ideal}}\Big/{W_{actual}} \qquad W_{actual} = {v_f\left(P_2 - P_1\right)}\Big/{\eta_{pump}}$$

- Turbine is not ideal

$$\eta_{turbine} = {W_{actual}}\Big/{W_{ideal}} \quad \text{note that this is an inverse of the pump equation}$$

- There will be a pressure drop across the boiler and condenser
- Subcool the liquid in the condenser to prevent cavitation in the pump. For example, if you subcool it 5°C, that means that the temperauture entering the pump is 5°C below the saturation temperature.

Cavitation Photos



■ FIGURE 3.17 Tip cavitation from a propeller. (Photograph courtesy of Garfield Thomas Water Tunnel, Pennsylvania State University.)

Munson, Young, Okiishi, Fundamentals of Fluid Mechanics, 3rd ed., John Wiley and Sons, 1998.

T-s Diagrams

- Draw a T-s diagram for an ideal Rankine Cycle. Now show how that diagram will change if you keep the pressures the same but increase the superheating. What happens to
  - Pump work input?
  - Turbine work output?
  - Heat rejected?
  - Moisture content at turbine exit?

T-s Diagrams

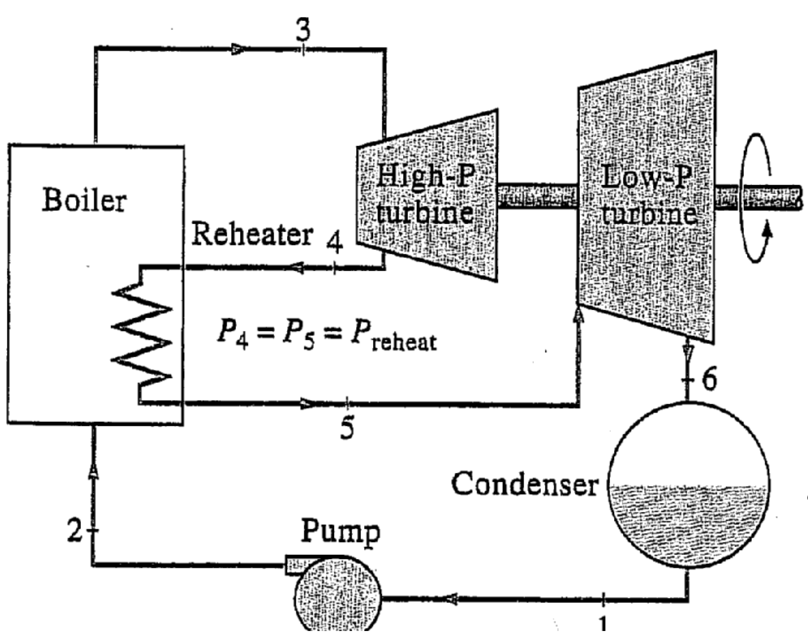
- Draw a T-s diagram for an ideal Rankine Cycle. Now show how that diagram will change if you bix the turbine inlet temperature and condenser pressure but increase the boiler pressure. What happens to
  - Pump work input?
  - Heat rejected?
  - Moisture content at exit of turbine?

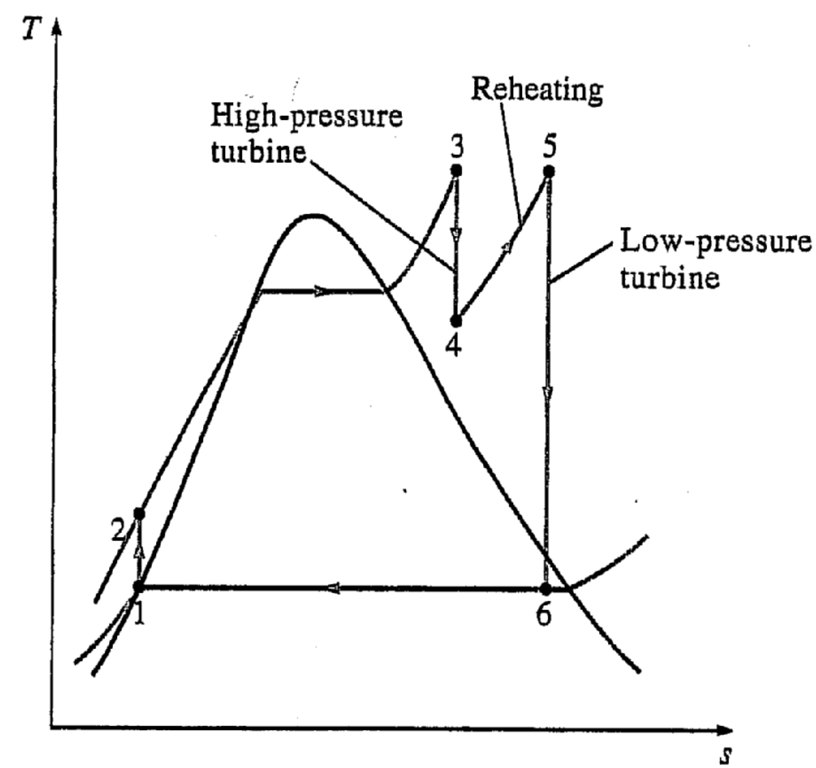
To increase system efficiency

- Lower condenser pressure
  - Must have at least 10°C ΔT between condenser and cooling water or air temperature for effective heat transfer
  - Watch quality at exit to prevent turbine problems (shouldn't go less than about 88%)
- Superheat the steam more
  - T_{max} ~ 620° due to metallurgical considerations
- Increase boiler pressure (with same T_{max})
  - P_{max} ~ 30 MPa
  - Watch quality at exit

Reheat Cycle

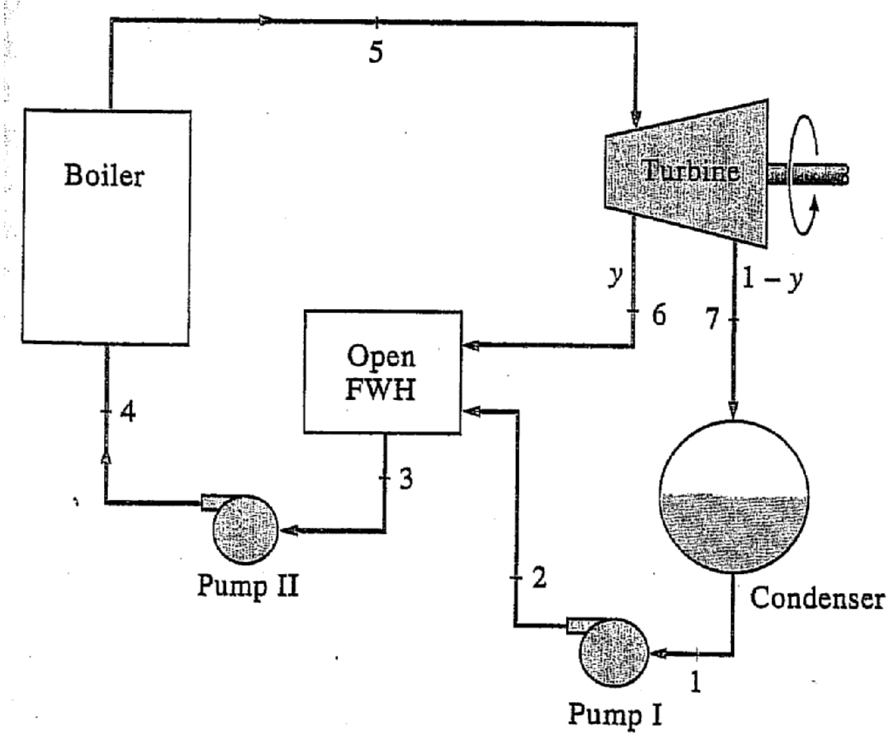
- Allows us to increase boiler pressure without problems of low quality at turbine exit

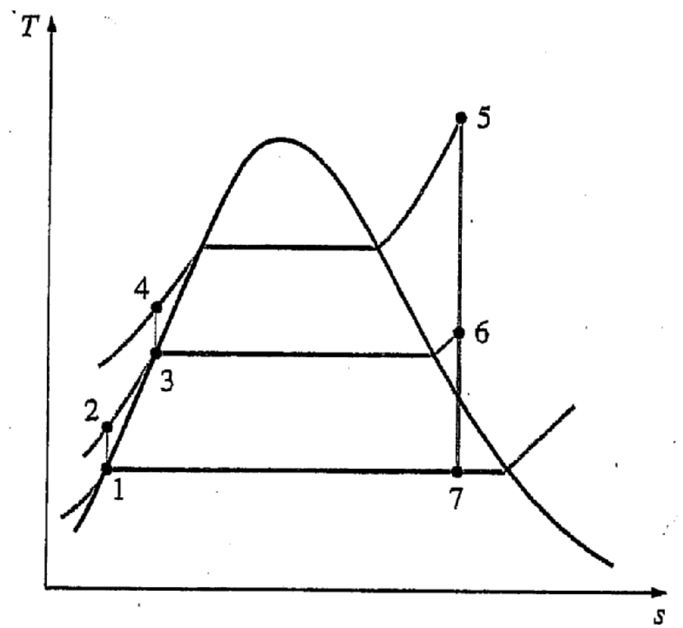




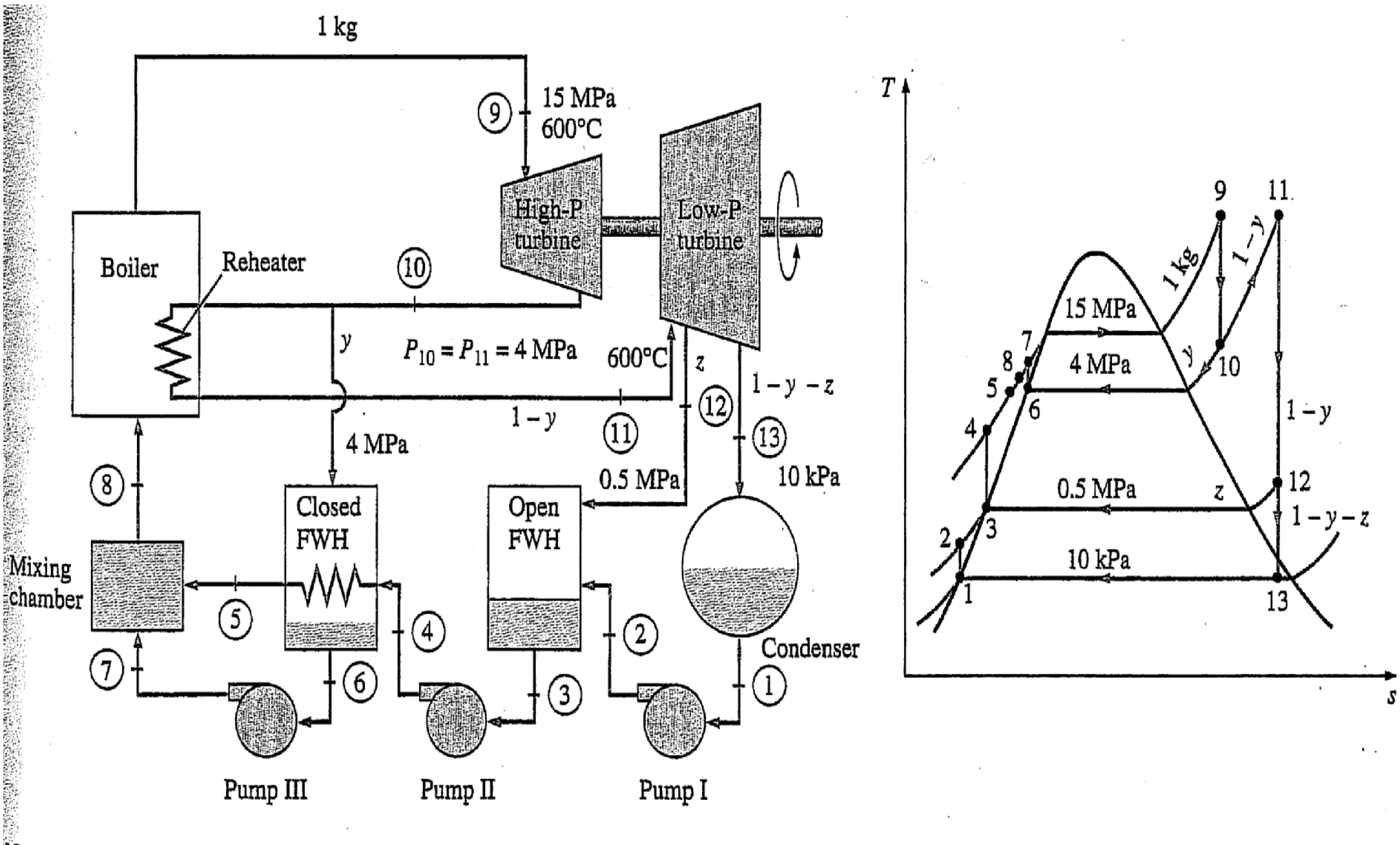
Regeneration

- Preheats steam entering boiler using a feedwater heater, improving efficiency
  - Also deaerates the fluid and reduces large volume flow rates at turbine exit.





A more complicated cycle…



Combined Cycle