# Week 8

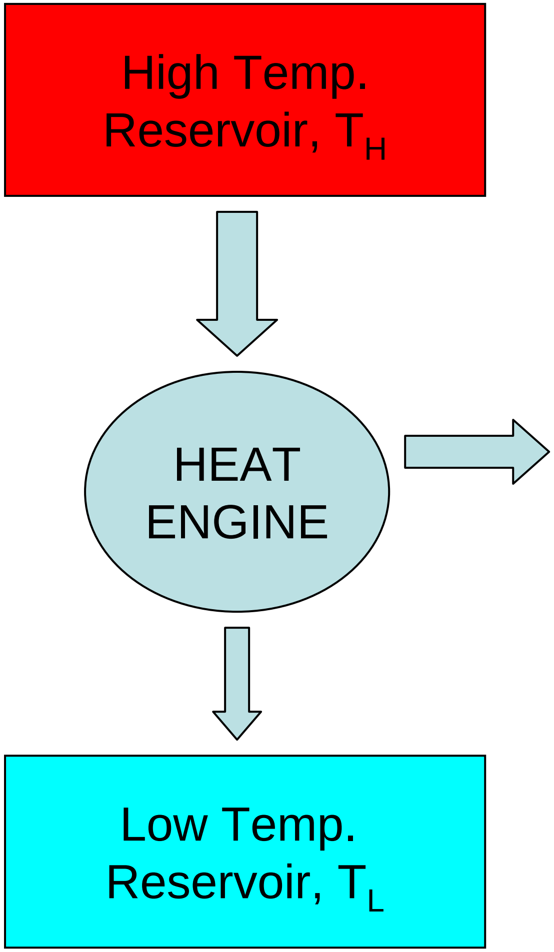
## Vapor Power Cycles

# Today's Outline

- Basics of Power Cycles
- Carnot cycle
- Vapor Power Cycles

# Power Cycle Basics

- Heat engines convert thermal energy into work
- Performance measured by thermal efficiency - determined by 1st law and limited by 2nd law



High Temp. Reservoir, $T_H$

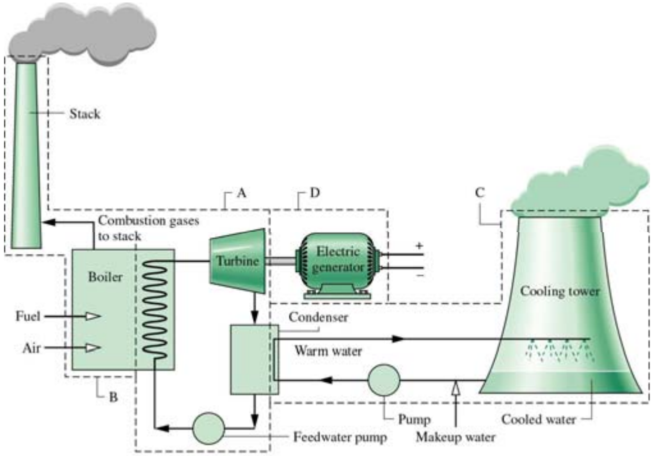
HEAT ENGINE

Low Temp. Reservoir, $T_L$

# Real Power Plants

- Power plants generate and then expand high enthalpy steam via a turbine to produce shaft work
- This mechanical energy gets converted into electrical energy by creating relative motion between a magnetic field and a conductor in a generator
- Heat source - nuclear, fossil-fueled, geothermal, renewable, etc.
- Prime mover e.g. steam-turbine, gas-turbine, combined, reciprocating, etc.

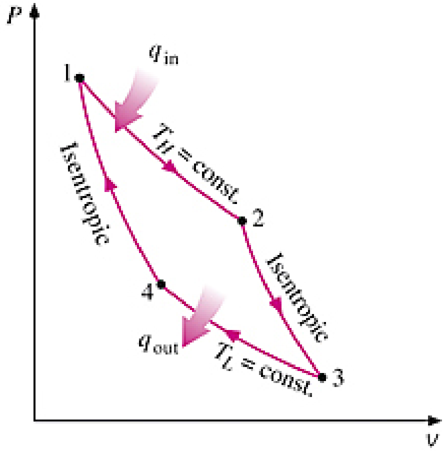
http://www.tva.gov/coalart.htm

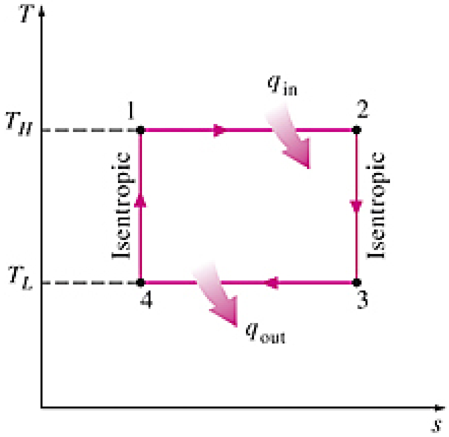


# Carnot Cycle

- Isothermal heat addition/rejection (*not practical*)
- Adiabatic (isentropic) compression/expansion
- Closed vs. open system
- Gas or vapor

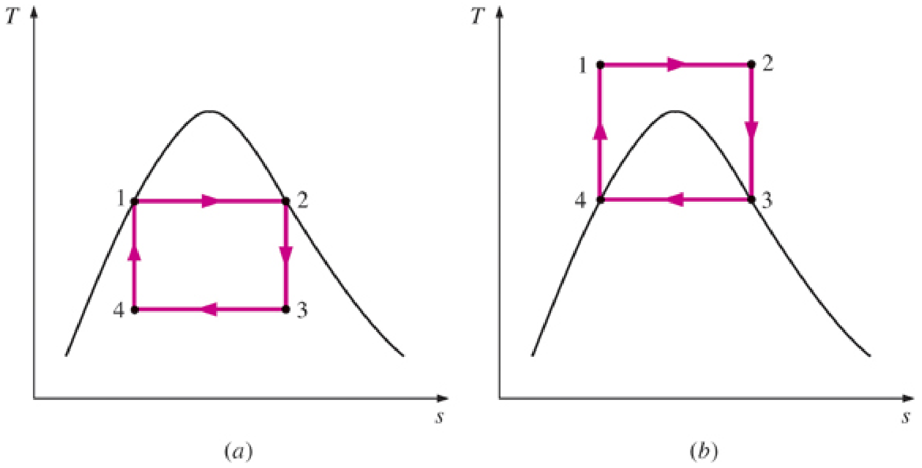
$$\eta_{th} = 1 - \frac{T_L}{T_H}$$





# Carnot Vapor Power Cycle

- Impracticalities of 2-phase cycle (left)
  - Isothermal heat transfer limits maximum temperature
  - Isentropic expansion brings moisture in turbine
  - Isentropic compression not practical
- At right, isentropic compression to high pressures and isothermal heat transfer at variable pressure



# More Basics of Power Cycles

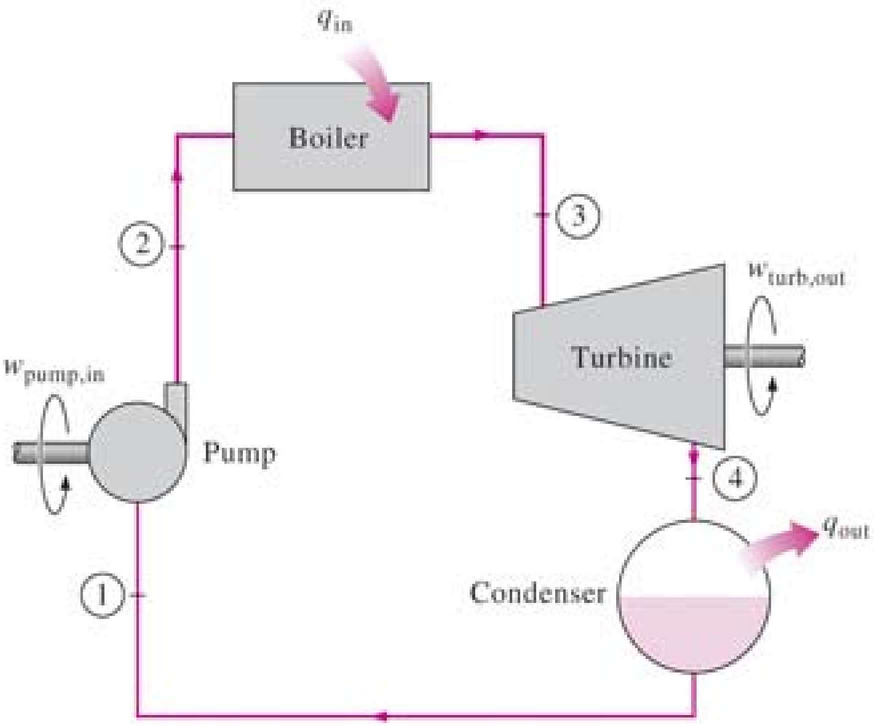
- Maximum performance achieved for a heat engine operating on totally reversible cycle e.g. Carnot heat engine
- Carnot not practical as ideal
- Ideal cycles will usually be internally reversible but not necessarily externally reversible

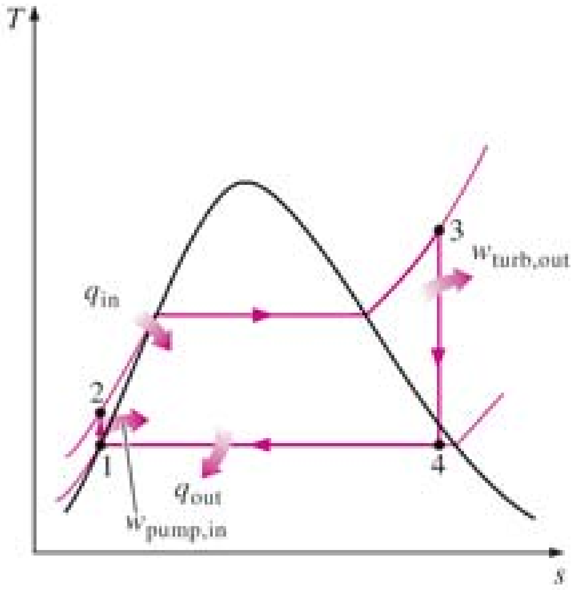
# Rankine Cycle

- Modify Carnot to
  - Superheat steam in boiler
  - Condense completely in condenser
- Ideal Rankine cycle – 4 internally reversible processes
  - 1-2: Isentropic compression in pump
  - 2-3: Constant pressure heat addition in boiler
  - 3-4: Isentropic expansion in turbine
  - 4-1: Constant pressure heat rejection in condenser

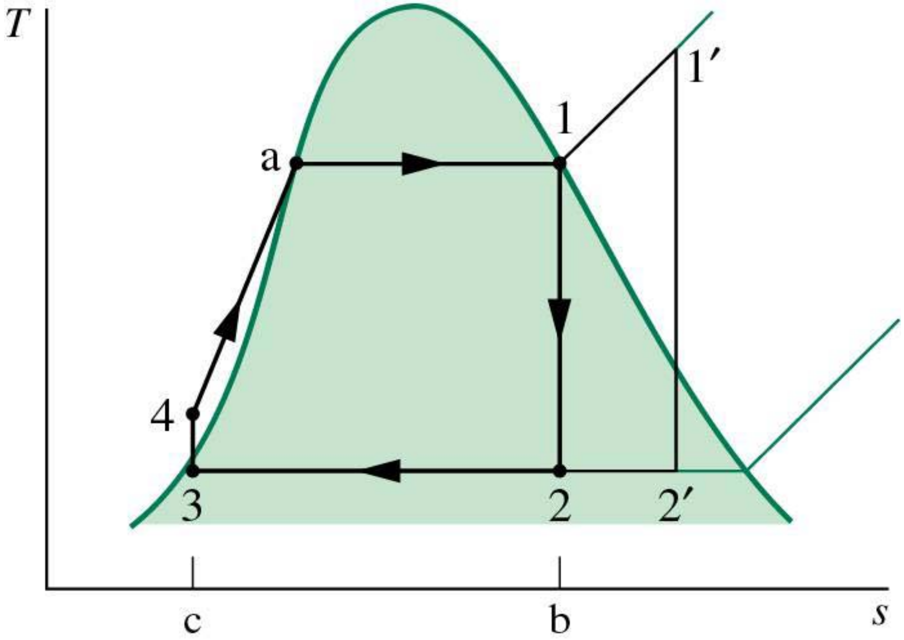
# Ideal Rankine Cycle (CB)

http://energy.sdsu.edu/testcenter/testhome/indexrankine.html





# Ideal Rankine Cycle (MS)



# Energy Analysis

$$(q_{in} - q_{out}) + (w_{in} - w_{out}) = h_e - h_i$$

$$w_{pump,in} = h_2 - h_1 = v(P_2 - P_1) \quad (h_1 = h_{f\,@T_1}, v = v_1 = v_{f\,@T_1})$$

$$q_{in} = h_3 - h_2$$

$$w_{turb,out} = h_3 - h_4$$

$$q_{out} = h_4 - h_1$$

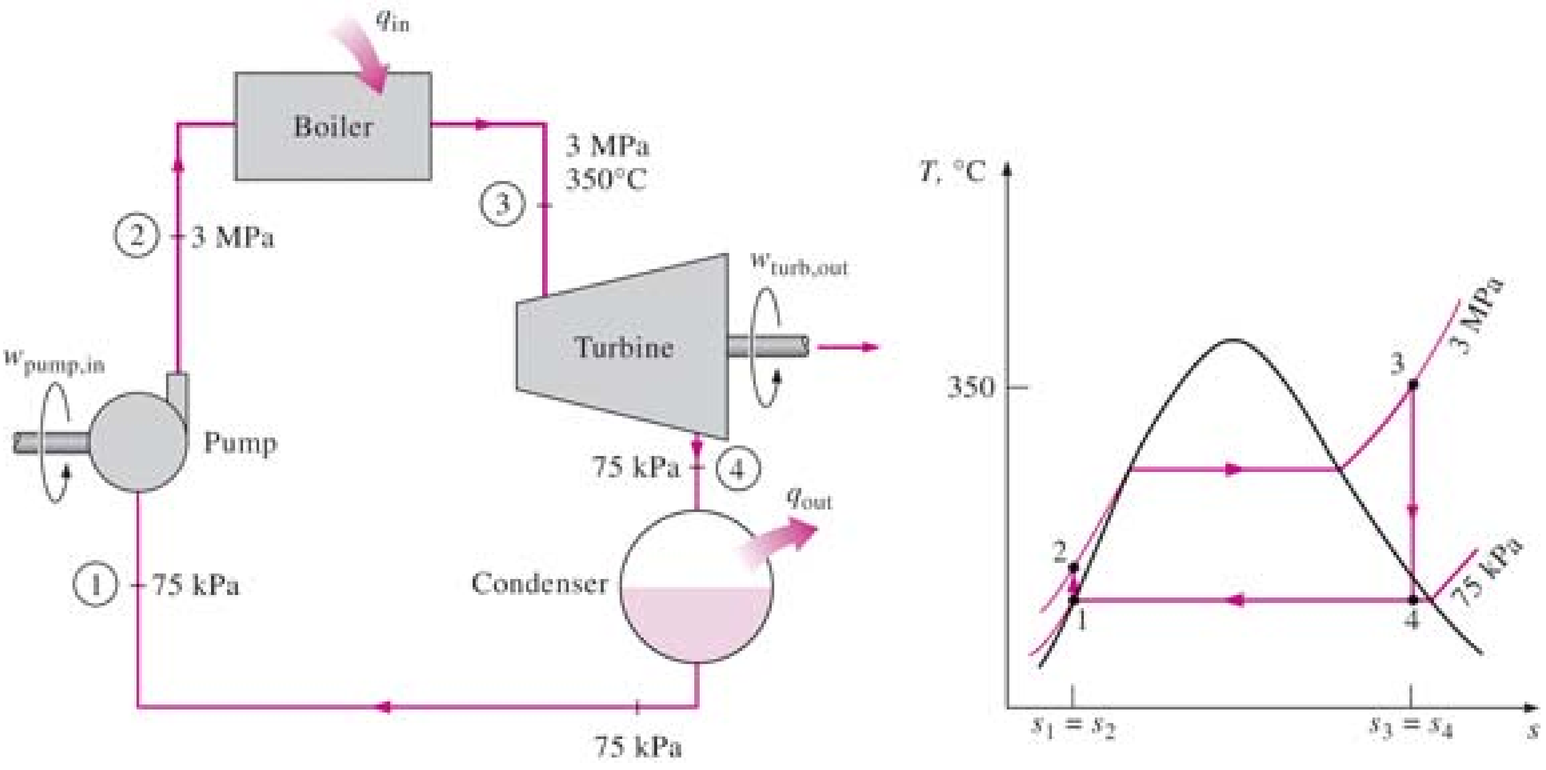
$$\eta_{th} = \frac{w_{net}}{q_{in}} = 1 - \frac{q_{out}}{q_{in}}$$

Incompressible fluid!

# Example

- Consider steam power plant operating on ideal Rankine cycle.  Steam enters turbine at 3MPa, 350C and is condensed in condenser at 75kPa.  Find efficiency.

# Example

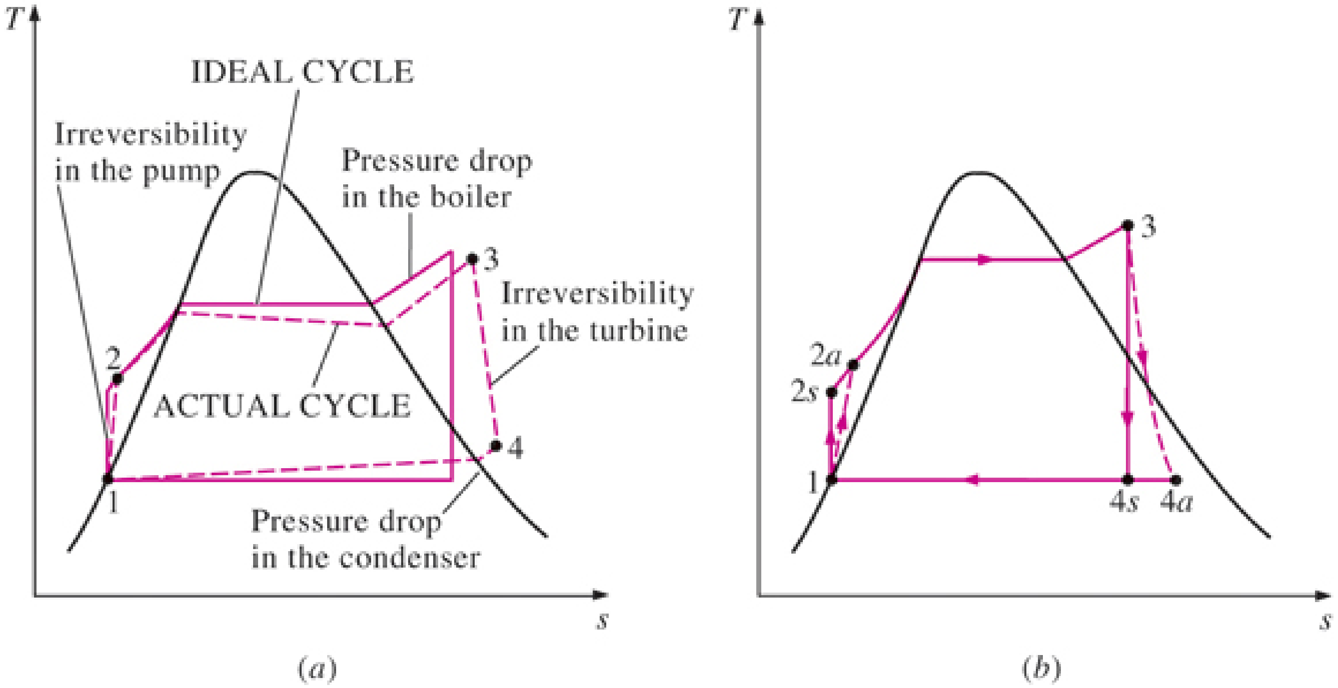

$q_{in}$
Boiler
3 MPa
350°C
③
② 3 MPa
$w_{turb,out}$
Turbine
$w_{pump,in}$
Pump
75 kPa ④
$q_{out}$
① 75 kPa
Condenser
75 kPa
T, °C
350
3 MPa
3
2
1
4
75 kPa
$s_1 = s_2$
$s_3 = s_4$
s

# Example

# Example

# Example

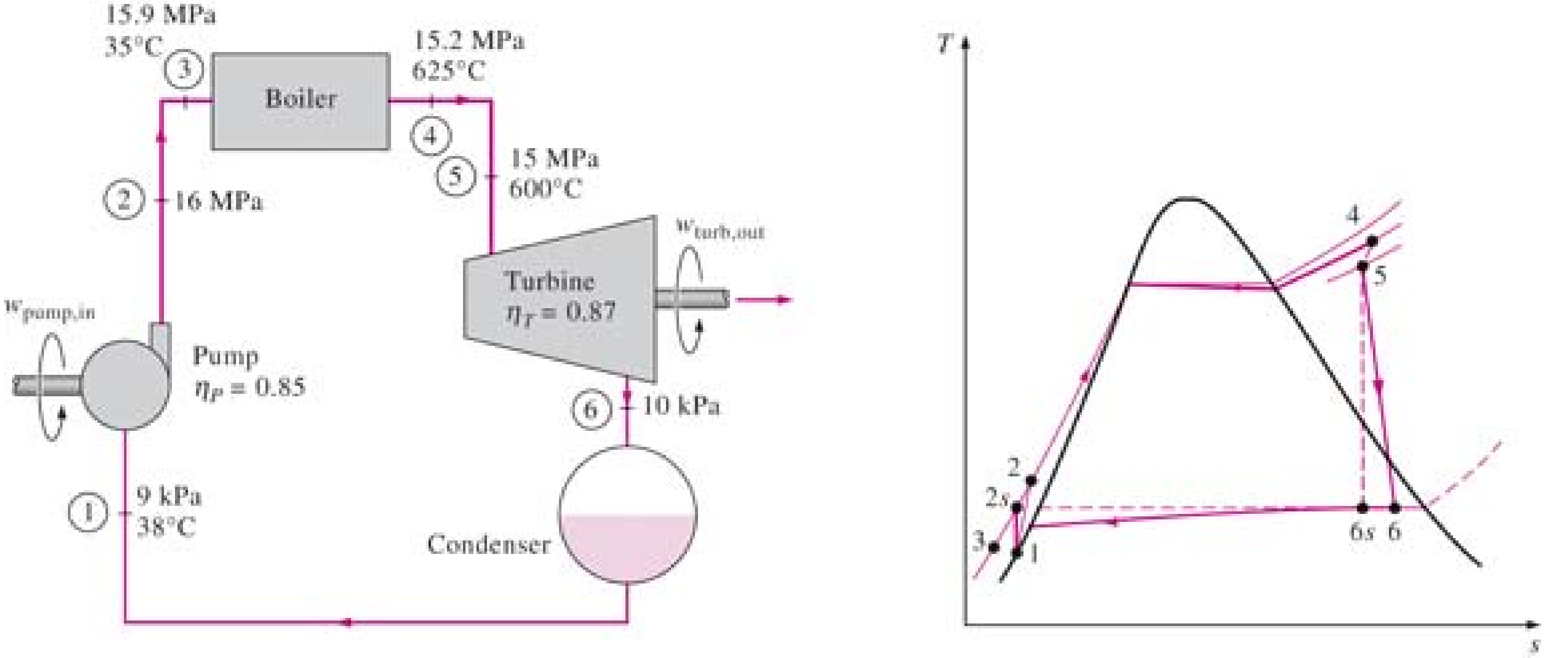
# Actual vs. Ideal



$$\eta_P = \frac{w_s}{w_a} = \frac{h_{2s} - h_1}{h_{2a} - h_1}$$

$$\eta_T = \frac{w_a}{w_s} = \frac{h_3 - h_{4a}}{h_3 - h_{4s}}$$

# Example


15.9 MPa
35°C
3
Boiler
15.2 MPa
625°C
4
5
15 MPa
600°C
2
16 MPa
$w_{turb,out}$
Turbine
$\eta_T = 0.87$
$w_{pump,in}$
Pump
$\eta_P = 0.85$
6
10 kPa
1
9 kPa
38°C
Condenser
T
4
5
2
2s
3
1
6s
6
s

# Example

# Example

# Example

# Summary

- Rankine cycle is ideal VPC involving 4 internally reversible processes:
  - heat addition/rejection is constant pressure;
  - compression/expansion is isentropic
- Actual cycles are less efficient due to:
  - Fluid friction
  - Heat loss
- Adiabatic efficiencies aid in analysis

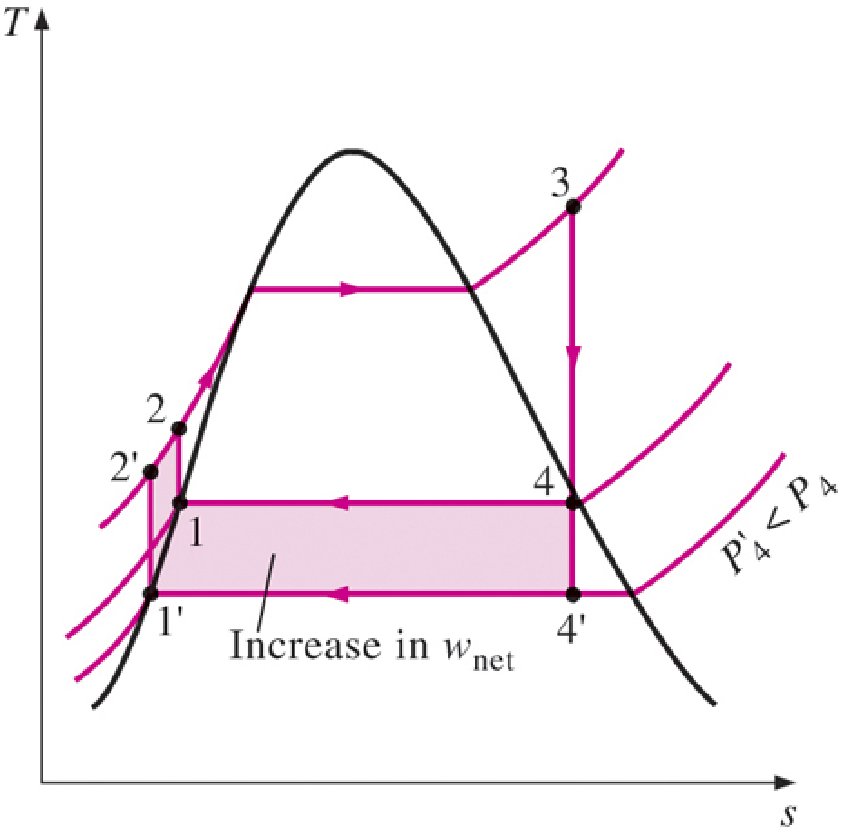
# Today’s Outline

- Increasing efficiency of Rankine cycle
- Main motivation provided by Carnot:

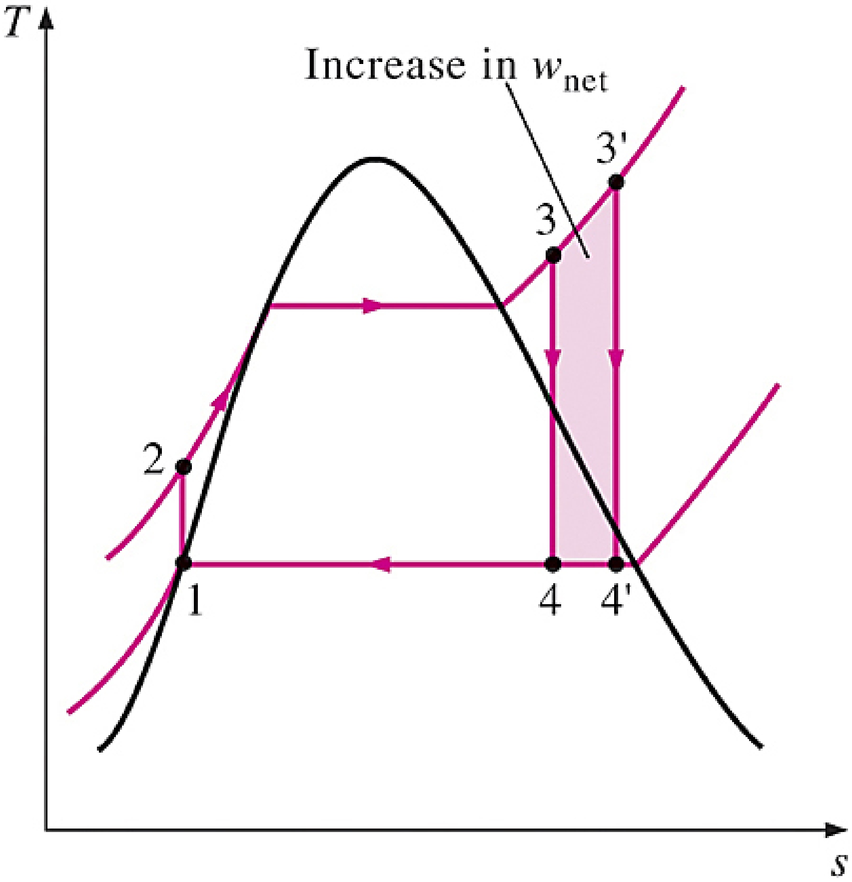
$$\eta_{th} = 1 - \frac{T_L}{T_H}$$

*Anything that raises the average temperature at which heat is added or lowers the average temperature at which heat is rejected will increase the efficiency operating temperature and pressure linked in two-phase region*

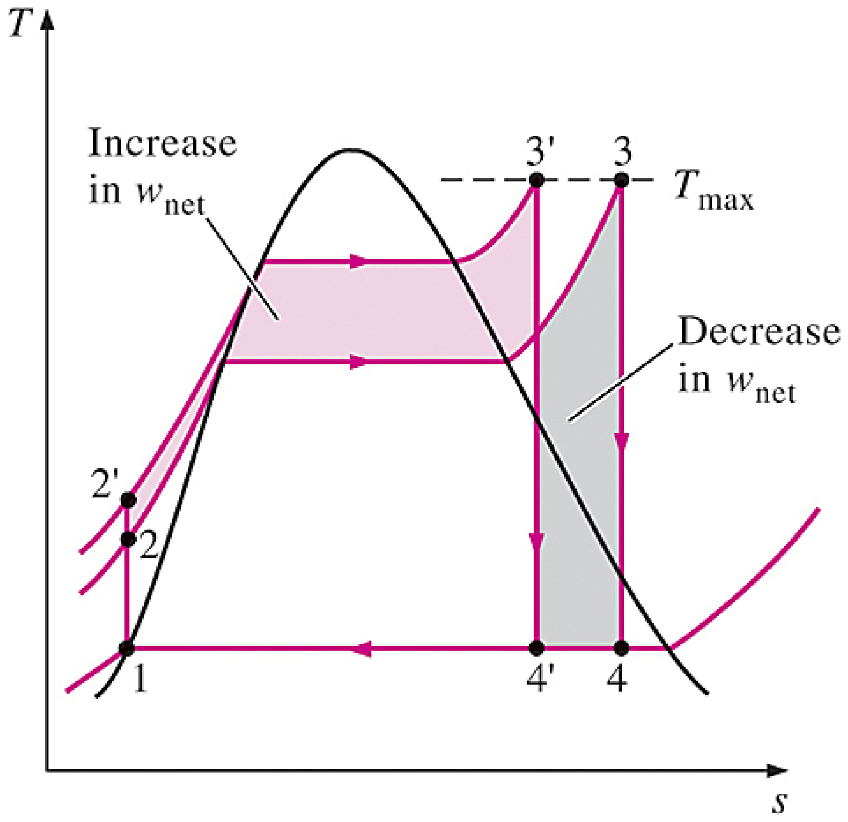
# Increasing Rankine Cycle Efficiency – Lower condenser pressure



# Increasing Rankine Cycle Efficiency – Superheating stream to higher temperatures

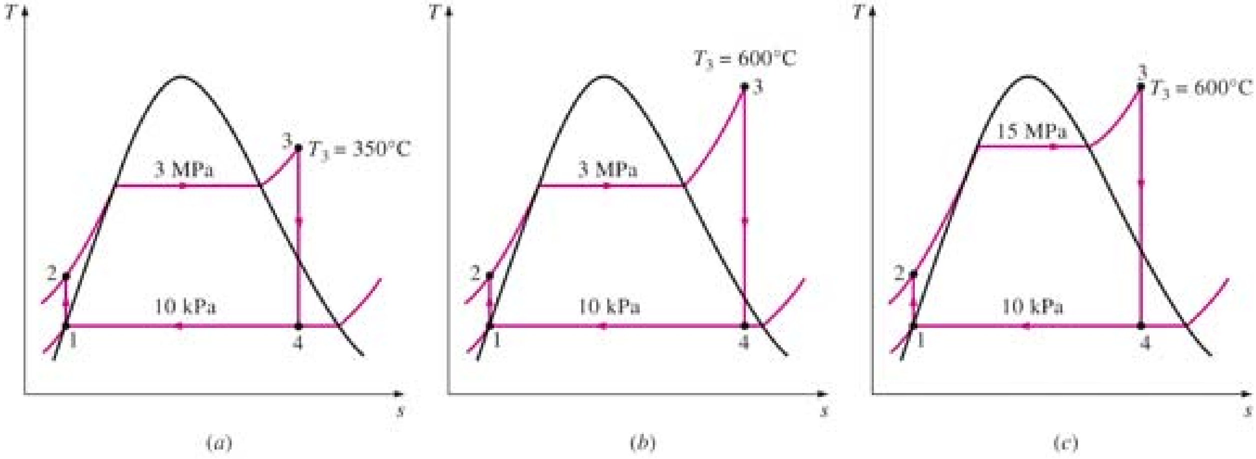


# Increasing Rankine Cycle Efficiency – Increasing boiler pressure



# Example 10-3

- Consider ideal Rankine cycle with steam entering turbine at 3MPa and 350C and condensed at 10kPa. Find (a) efficiency, (b) efficiency if steam is superheated to 600C, and efficiency if boiler pressure is 15MPa keeping turbine inlet temp. fixed at 600C.



(a) (b) (c)

# Example 10-3

# Example 10-3

# Example 10-3

# Example 10-3

# Example 10-3

# Summary

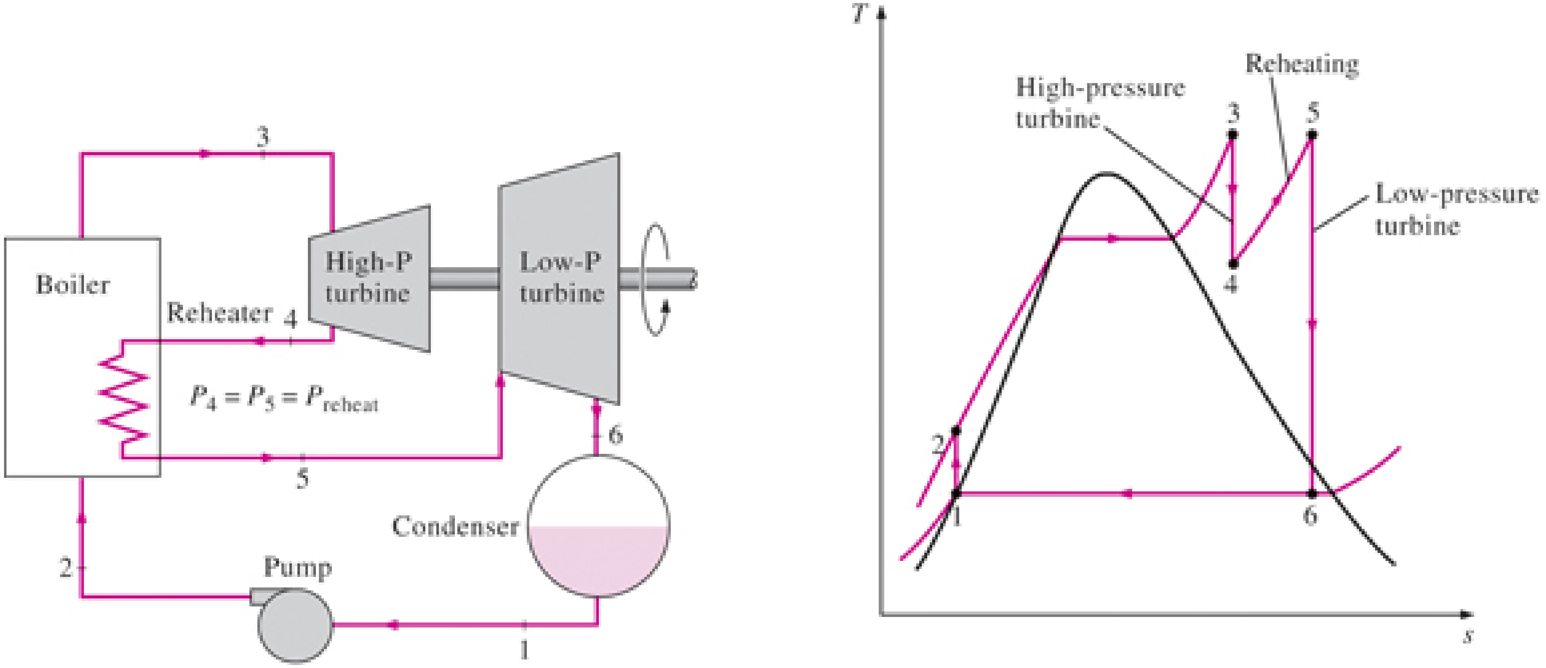
# Today’s Outline

- Reheat

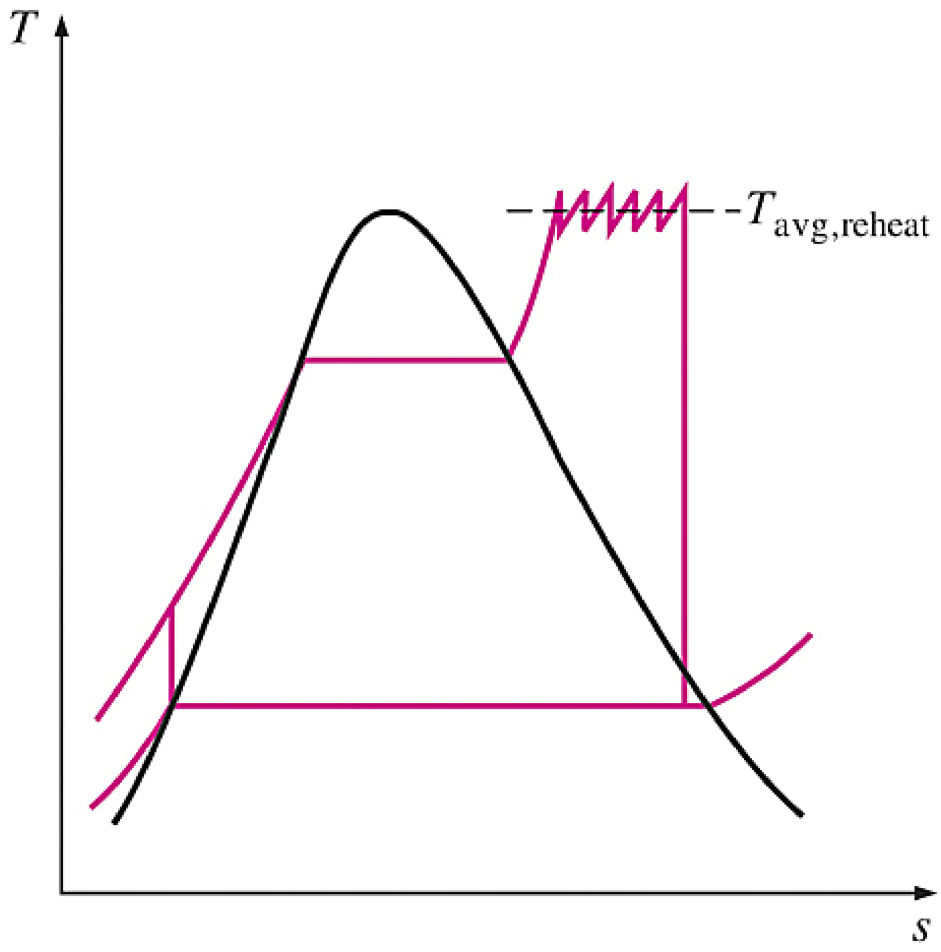
# Reheat

- *How can we take advantage of increased efficiencies at higher boiler pressure without facing problem of excessive moisture in final turbine stages?*
  - Superheat steam to very high temperatures
  - Expand steam in turbine in two stages, and reheat it in between

# Reheat


3
Boiler
Reheater
4
High-P turbine
Low-P turbine
$P_4 = P_5 = P_{\text{reheat}}$
5
6
Condenser
2
Pump
1
T
s
High-pressure turbine
Reheating
Low-pressure turbine
3
5
4
2
1
6

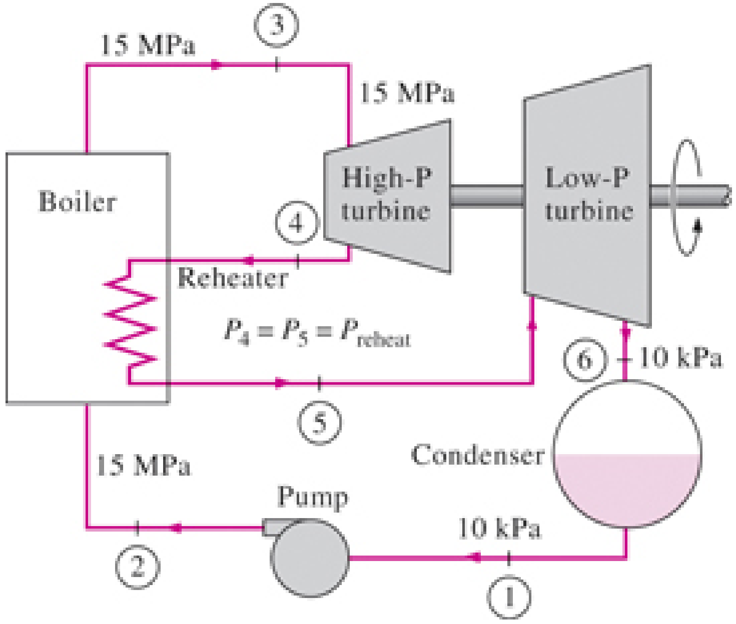
# Increasing Reheat Stages

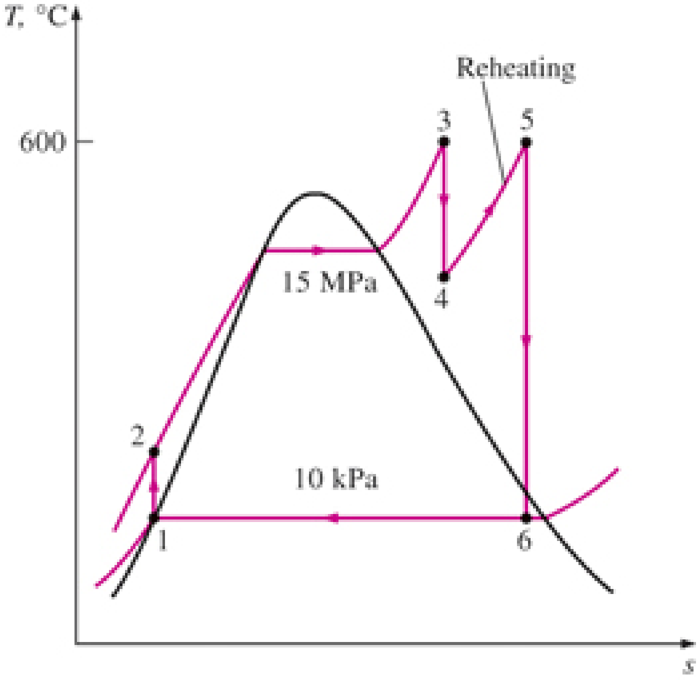


# Example 10-4

- Consider steam power plant based on ideal reheat Rankine cycle. Steam enters high-pressure turbine at 15MPa and 600C and is condensed in condenser at 10kPa. If moisture content of steam at exit of low-pressure turbine is not to exceed 10.4%, determine (a) pressure at which steam should be reheated and (b) efficiency. Assume steam is reheated to inlet temperature of high-pressure turbine.

# Example 10-4


15 MPa
③
15 MPa
Boiler
High-P turbine
Low-P turbine
④
Reheater
$P_4 = P_5 = P_{reheat}$
⑥
10 kPa
⑤
Condenser
15 MPa
Pump
10 kPa
②
①


T, °C
Reheating
600
3
5
15 MPa
4
2
10 kPa
1
6
s

# Example 10-4

# Example 10-4

# Example 10-4

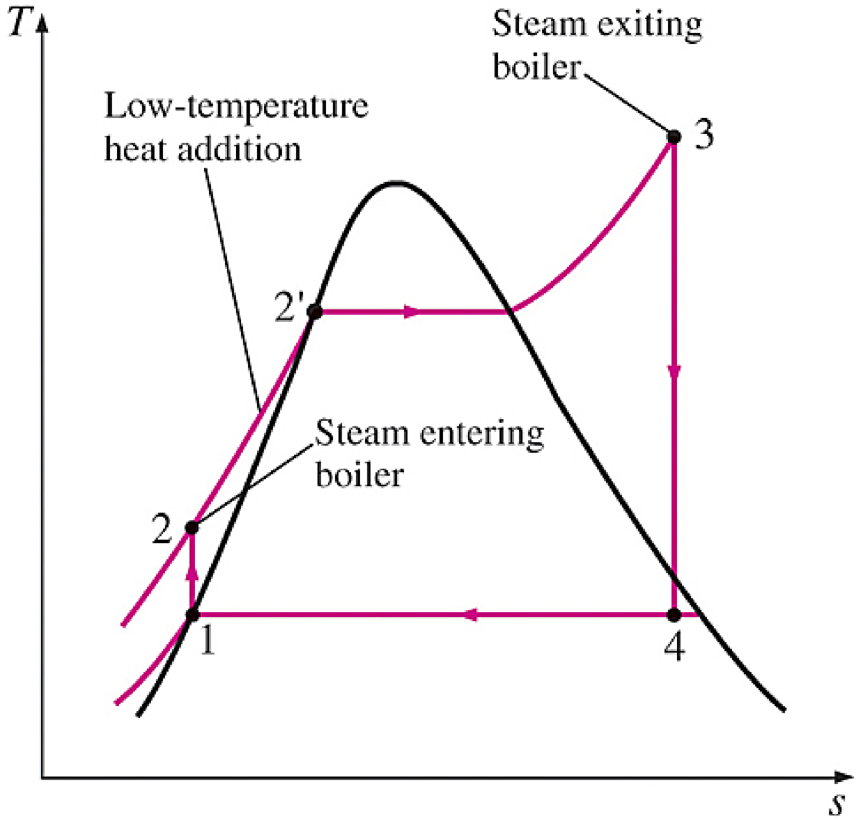
# Example 10-4

# Summary

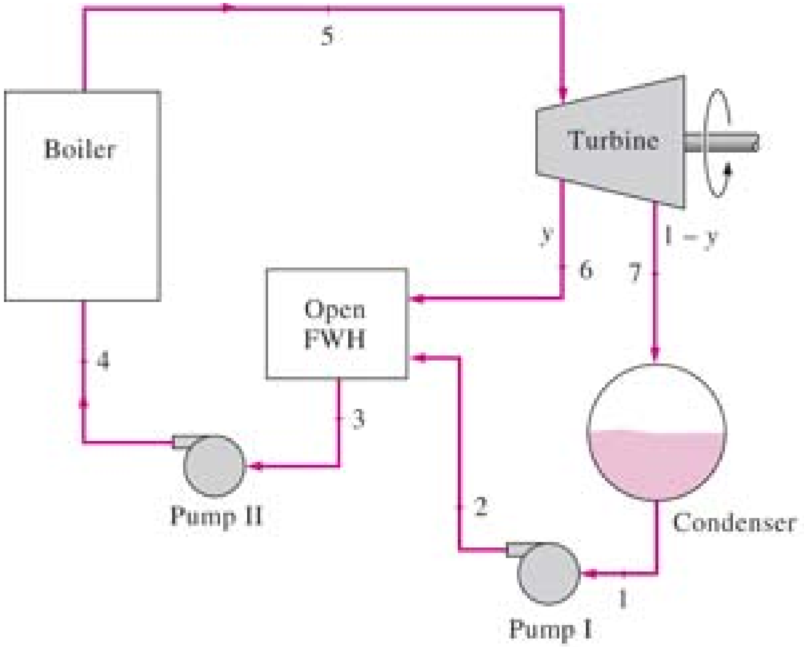
# Today’s Outline

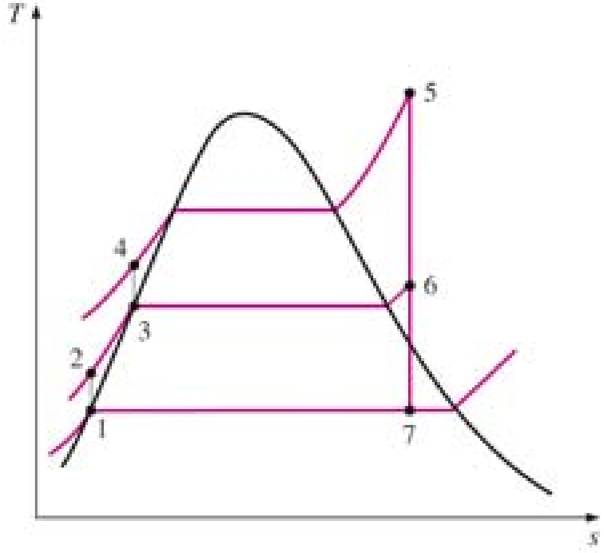
- Regeneration

# Regeneration



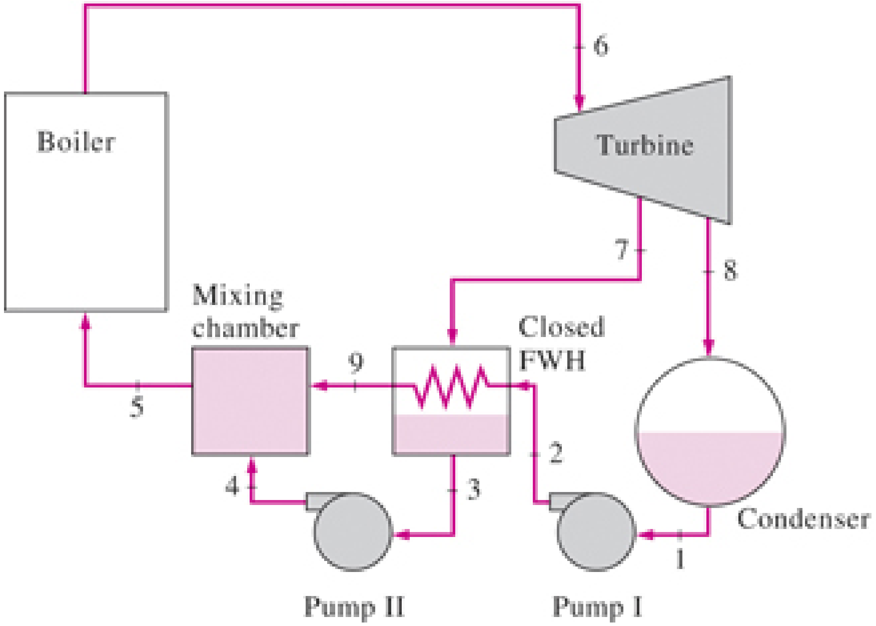
# Ideal regenerative Rankine cycle with open feedwater heater

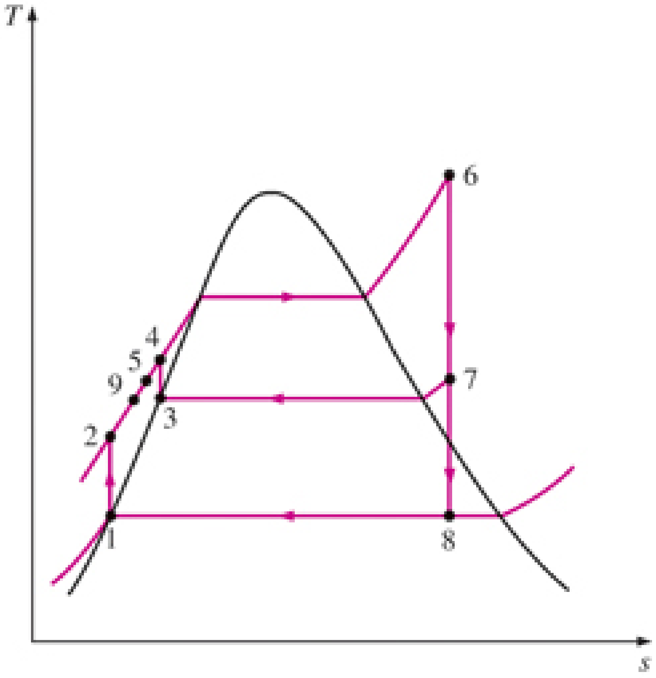




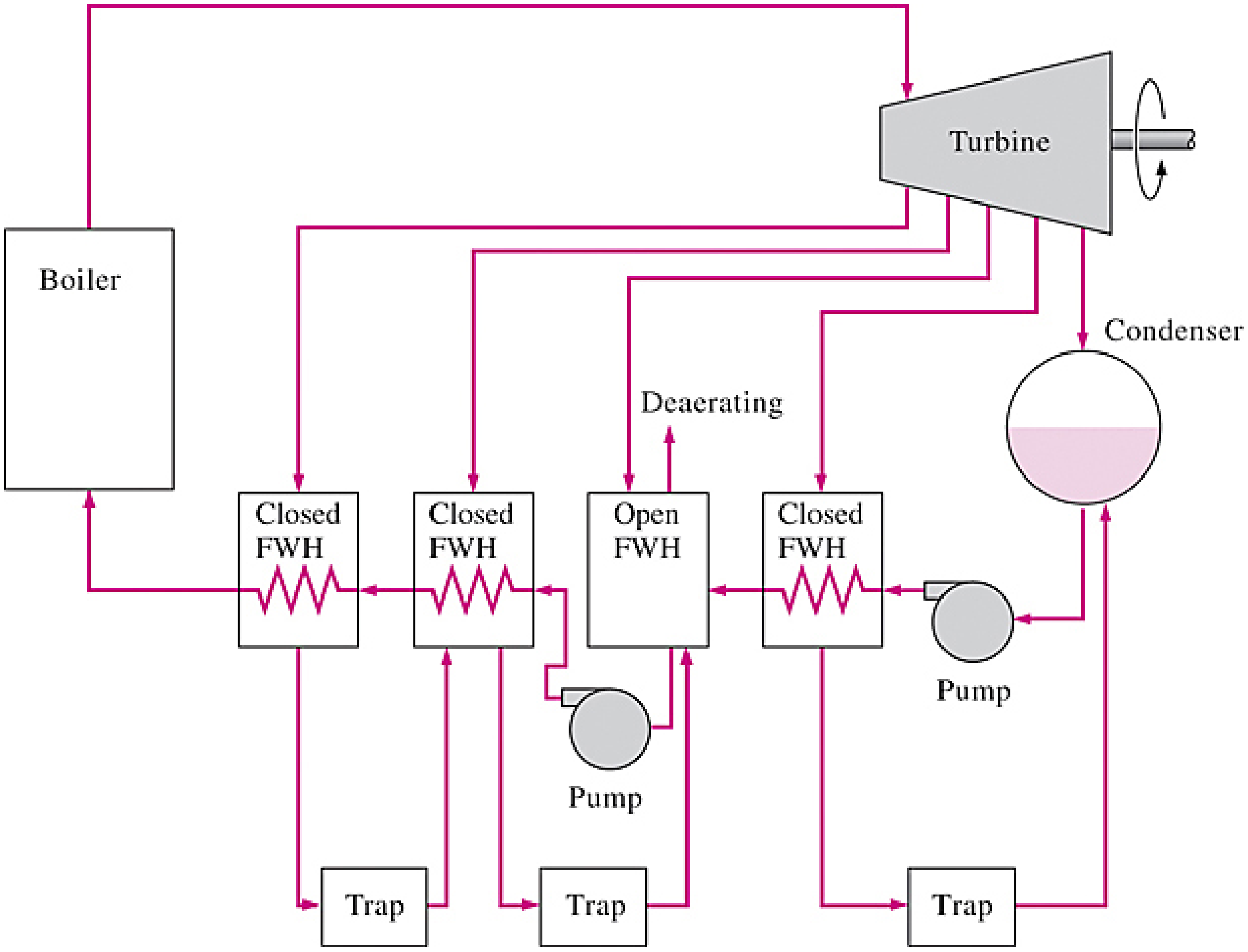
# Open Feedwater Heater - Analysis

# Ideal regenerative Rankine cycle with closed feedwater heater





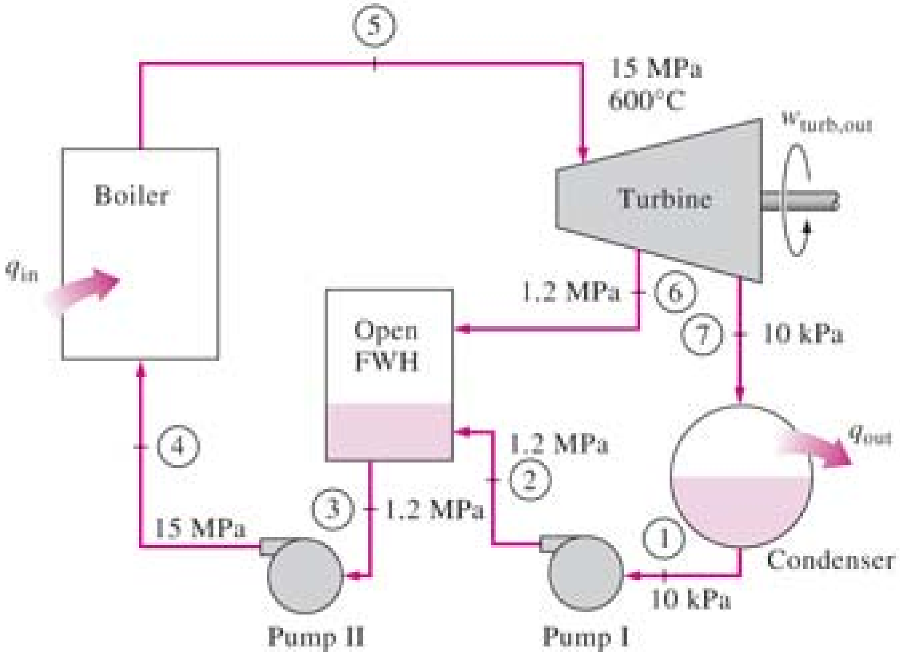
# One open and three closed feedwater heaters

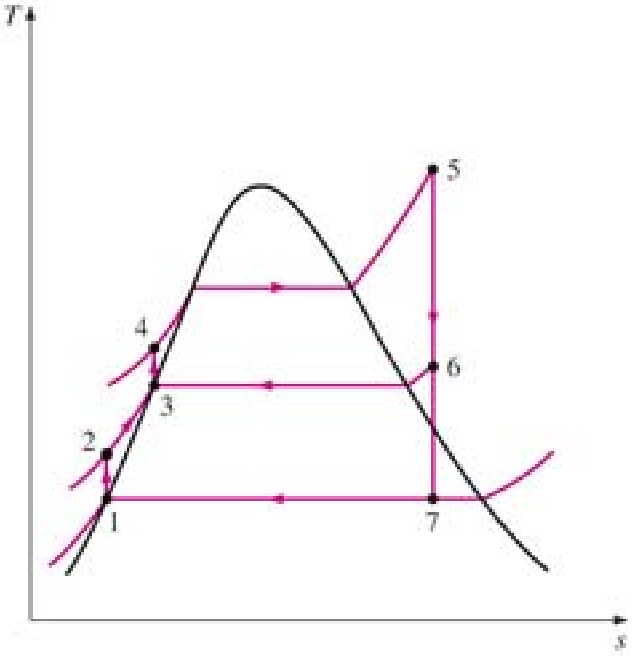


# Example 10-5

- Consider ideal regenerative Rankine cycle with one open feedwater heater.  Steam enters turbine at 15MPa and 600C and condensed at 10kPa.  Some steam leaves turbine at pressure of 1.2MPa and enters open feedwater heater.  Determine fraction of steam extracted from turbine and efficiency of cycle.

# Example 10-5


⑤
15 MPa
600°C
$w_{turb,out}$
Boiler
Turbine
$q_{in}$
1.2 MPa
⑥
⑦
10 kPa
Open
FWH
④
1.2 MPa
②
$q_{out}$
③
1.2 MPa
15 MPa
①
Condenser
10 kPa
Pump II
Pump I


T
5
4
6
3
2
1
7
s

# Example 10-5

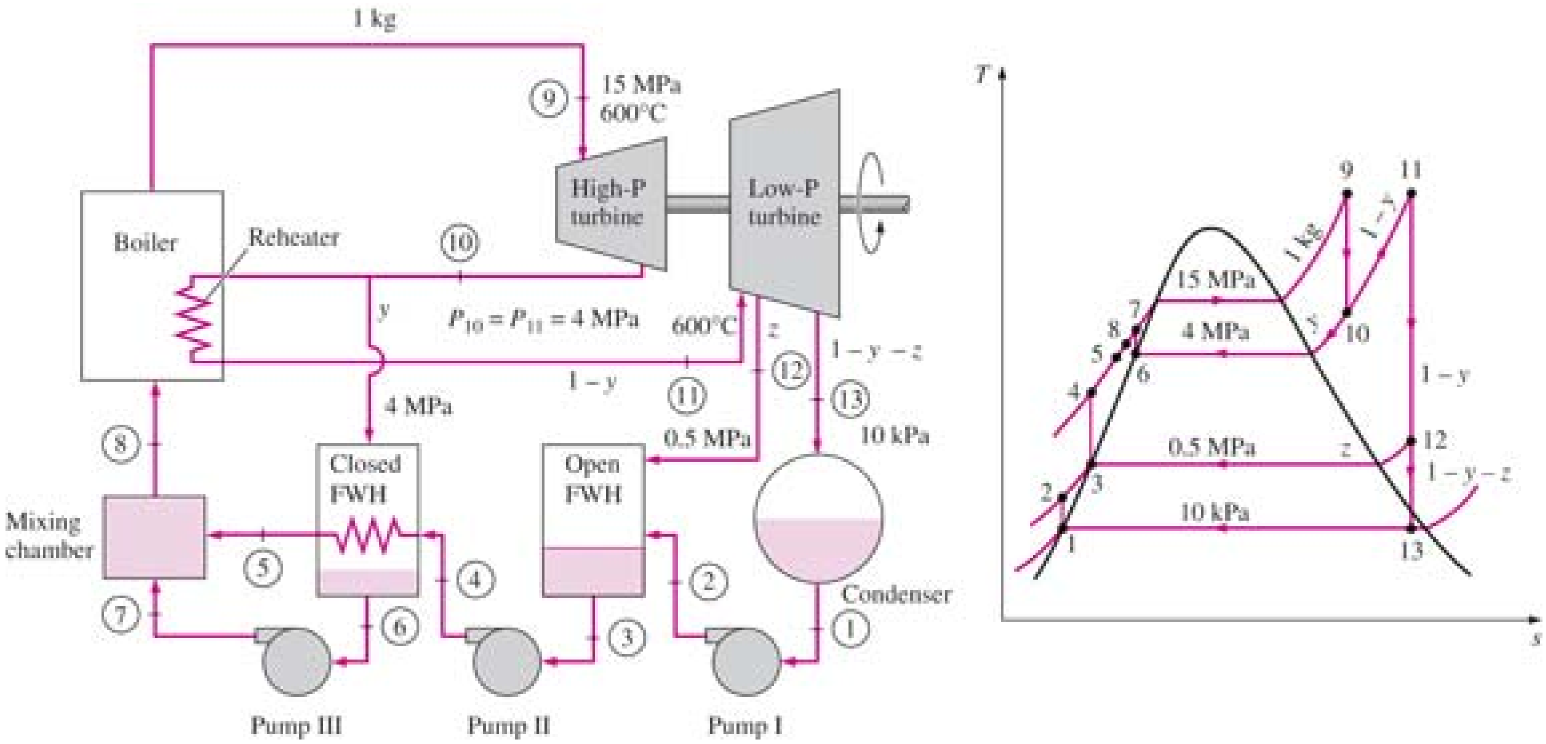
# Example 10-5

# Example 10-5

# Example 10-5

# Example 10-6

# Example 10-6


1 kg
15 MPa
600°C
⑨
High-P turbine
Low-P turbine
Boiler
Reheater
⑩
y
$P_{10} = P_{11} = 4$ MPa
600°C
z
1 − y − z
1 − y
⑪
⑫
⑬
4 MPa
0.5 MPa
10 kPa
⑧
Closed FWH
Open FWH
Mixing chamber
⑤
④
②
⑦
⑥
③
①
Condenser
Pump III
Pump II
Pump I
T
s
9
11
1 kg
1 − y
15 MPa
7
8
5
4 MPa
6
10
y
4
1 − y
0.5 MPa
z
12
1 − y − z
2
3
10 kPa
1
13

# Example 10-6

# Example 10-6

# Example 10-6

# Example 10-6

# Summary