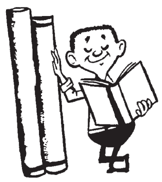
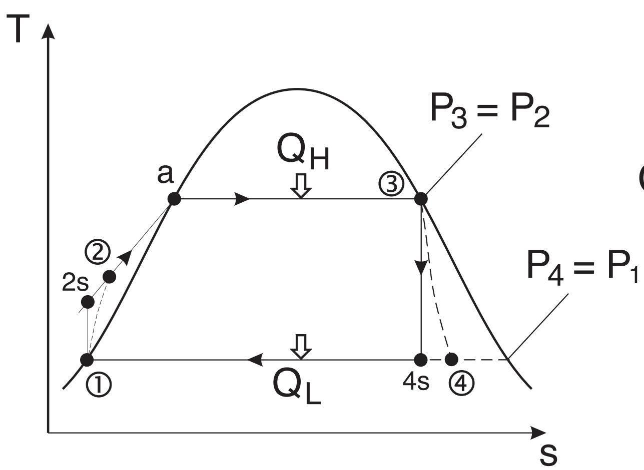
Rankine Cycle

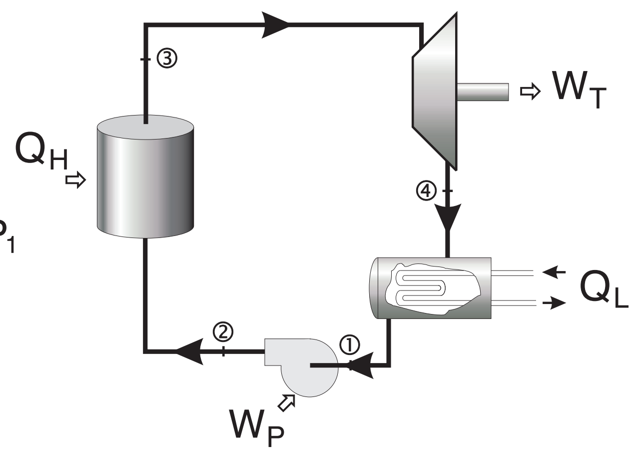


Reading	Problems
11.1 $\rightarrow$ 11.7	11.29, 11.36, 11.43, 11.47, 11.52, 11.55, 11.58, 11.74

Definitions

- working fluid is alternately vaporized and condensed as it recirculates in a closed cycle
- the standard vapour cycle that excludes internal irreversibilities is called the **Ideal Rankine Cycle**





Analyze the Process

Device	1st Law Balance			
Boiler	$h_2 + q_H = h_3$	$\Rightarrow$	$q_H = h_3 - h_2$	(in)
Turbine	$h_3 = h_4 + w_T$	$\Rightarrow$	$w_T = h_3 - h_4$	(out)
Condenser	$h_4 = h_1 + q_L$	$\Rightarrow$	$q_L = h_4 - h_1$	(out)
Pump	$h_1 + w_P = h_2$	$\Rightarrow$	$w_P = h_2 - h_1$	(in)

The Rankine efficiency is

$$\eta_R = \frac{net\ work\ output}{heat\ supplied\ to\ the\ boiler}$$
$$= \frac{(h_3 - h_4) + (h_1 - h_2)}{(h_3 - h_2)}$$

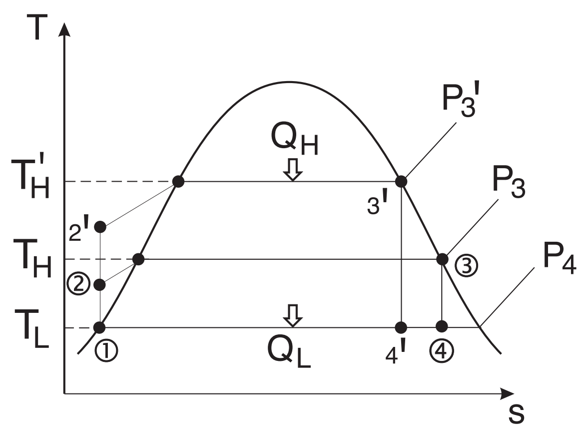
Effects of Boiler and Condenser Pressure

We know the efficiency is proportional to

$$\eta \propto 1 - \frac{T_L}{T_H}$$

The question is $\rightarrow$ how do we increase efficiency $\Rightarrow$ $T_L \downarrow$ and/or $T_H \uparrow$.

1. INCREASED BOILER PRESSURE:



- an increase in boiler pressure results in a higher T_H for the same T_L, therefore $\eta \uparrow$.
- but $4'$ has a lower quality than 4
  - wetter steam at the turbine exhaust
  - results in cavitation of the turbine blades
  - $\eta \downarrow$ plus $\uparrow$ maintenance
- quality should be $> 80 - 90\%$ at the turbine exhaust

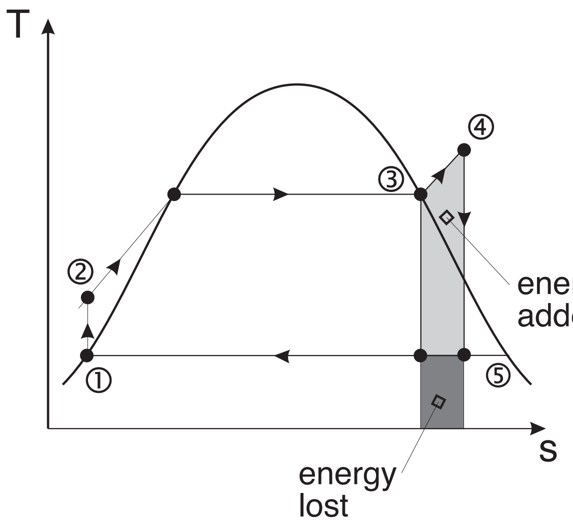
2. LOWER T_L:

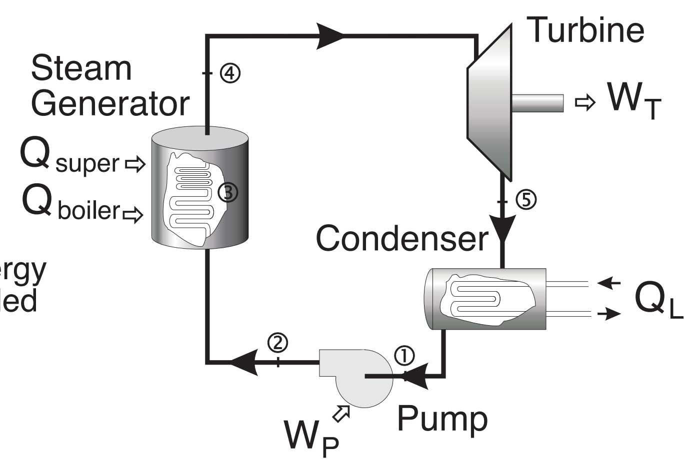
- we are generally limited by the $\boldsymbol{TER}$ (lake, river, etc.)

  eg. lake @ $\mathbf{15\,^\circ}\boldsymbol{C} + \underbrace{\boldsymbol{\Delta T = 10\,^\circ C}}_{\boldsymbol{resistance\ to\ HT}} = \mathbf{25\,^\circ}\boldsymbol{C}$

  $\Rightarrow\ \boldsymbol{P_{sat} = 3.169\ kPa}.$
- this is why we have a condenser
  - the pressure at the exit of the turbine can be less than atmospheric pressure

3. INCREASED T_H BY ADDING SUPERHEAT:

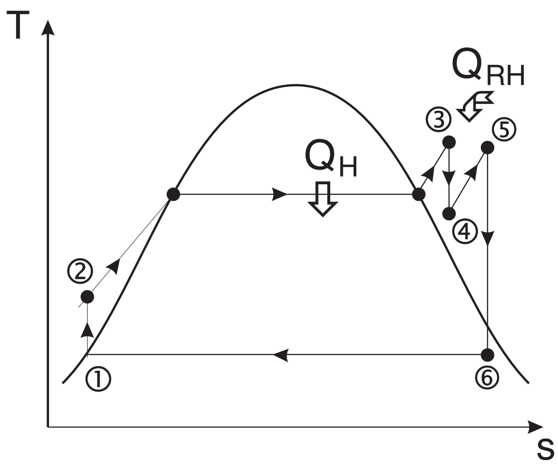


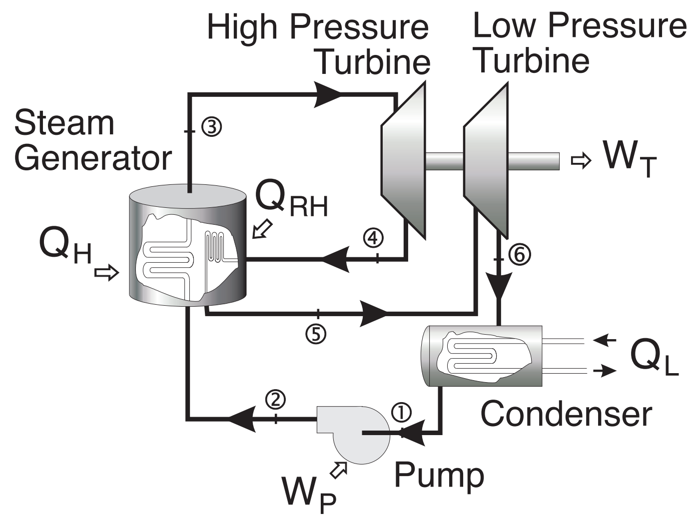


- the average temperature at which heat is supplied in the boiler can be increased by superheating the steam
  - dry saturated steam from the boiler is passed through a second bank of smaller bore tubes within the boiler until the steam reaches the required temperature
  - The value of $\overline{T}_H$, the mean temperature at which heat is added, increases, while $\overline{T_L}$ remains constant. Therefore the efficiency increases.

Rankine Cycle with Reheat

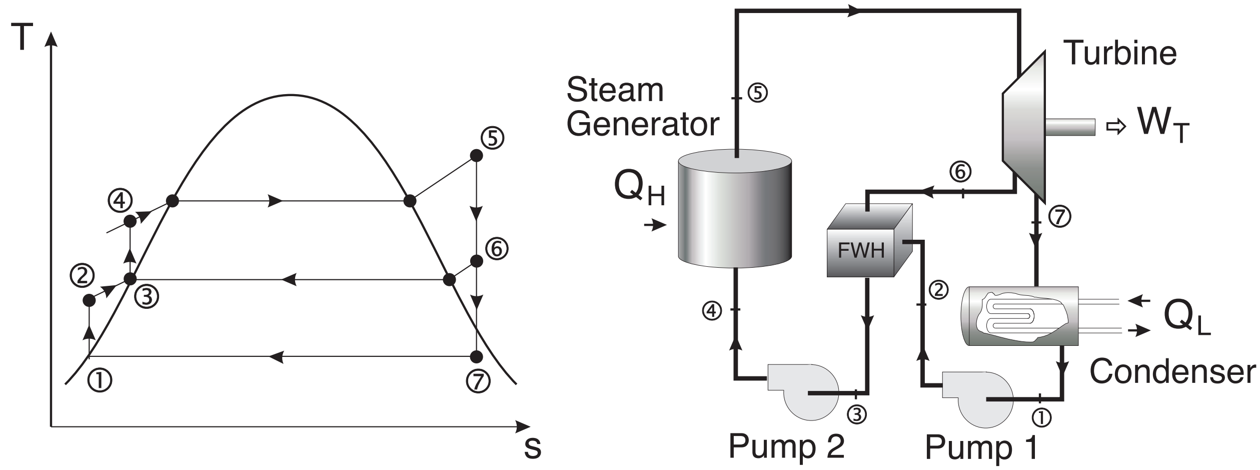
- the wetness at the exhaust of the turbine should be no greater that 10% - this can result in physical erosion of the turbine blades
- but high boiler pressures are required for high efficiency - tends to lead to a high wetness ratio
- to improve the exhaust steam conditions, the steam can be reheated with the expansion carried out in two steps





Rankine Cycle with Regeneration

- Carnot cycle has efficiency: $\eta = 1 - T_L/T_H$
  - add Q_H at as high a T_H as possible
  - reject Q_L at as low a T_L as possible
- the Rankine cycle can be used with a ***Feedwater Heater*** to heat the high pressure sub-cooled water at the pump exit to the saturation temperature
  - most of the heat addition (Q_H) is done at high temperature



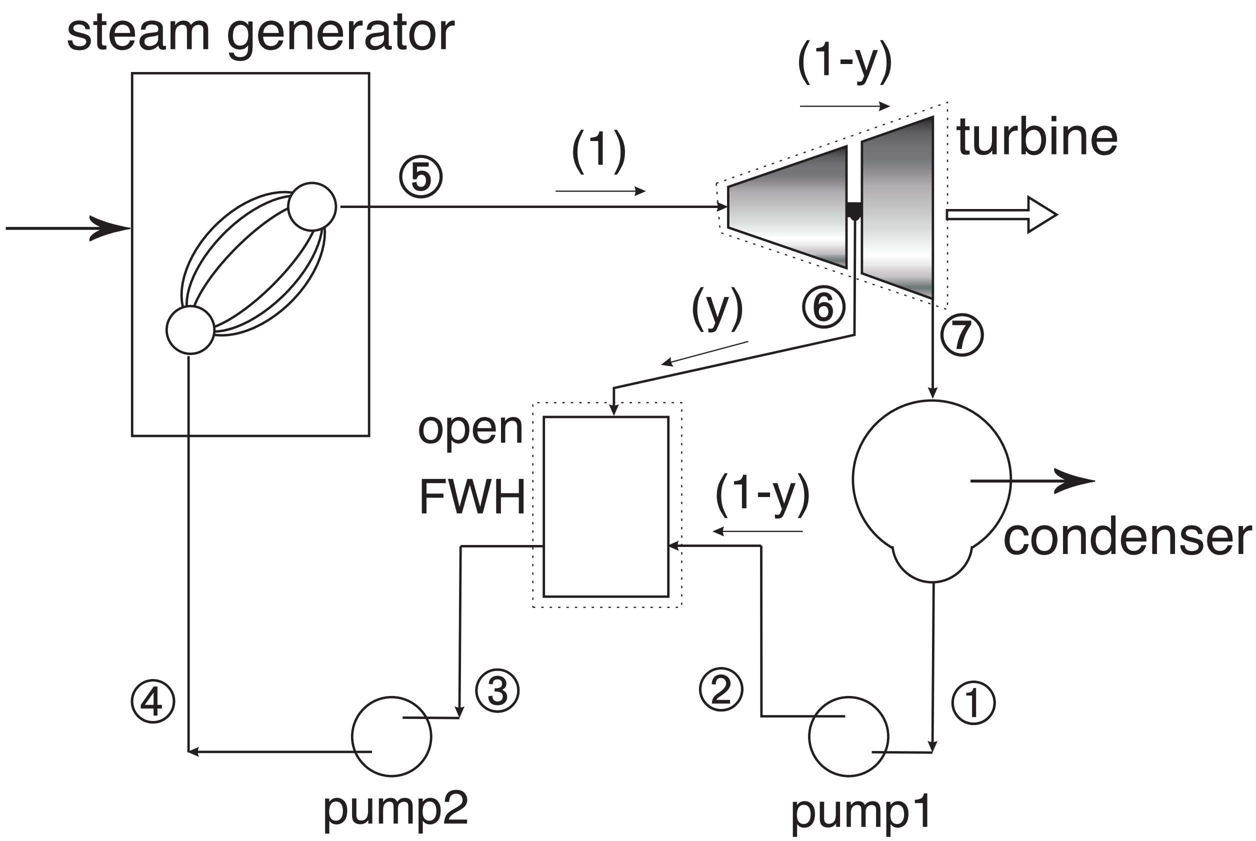
Feedwater Heaters

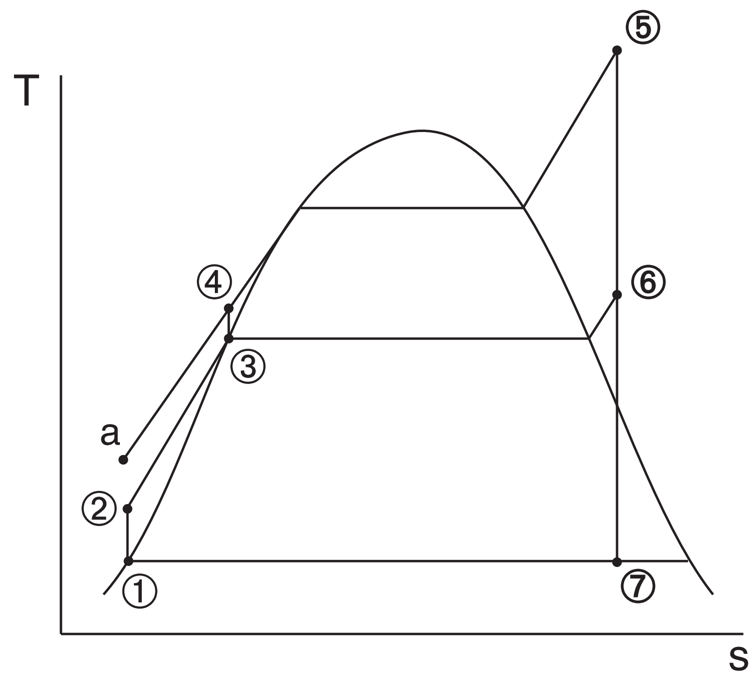
There are two different types of feedwater heaters

1. ***OPEN FWH:*** the streams mix → high temperature steam with low temperature water at constant pressure
2. ***CLOSED FWH:*** a heat exchanger is used to transfer heat between the two streams but the streams do *not* mix. The two streams can be maintained at different pressures.

OPEN FWH:

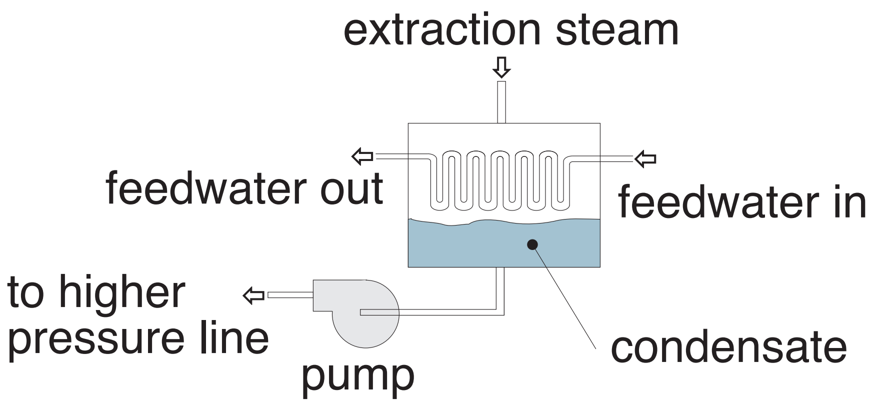
- working fluid passes isentropically through the turbine stages and pumps
- steam enters the first stage turbine at state 5 and expands to state 6 - where a fraction of the total flow is bled off into an open feedwater heater
- the rest of the steam expands into the second stage turbine at state point 7 - this portion of the fluid is condensed and pumped as a saturated liquid to the FWH at state 2
- a single mixed stream exists the FWH at state point 3


steam generator
⑤
(1)
(1-y)
turbine
(y)
⑥
⑦
open
FWH
(1-y)
condenser
④
③
②
①
pump2
pump1

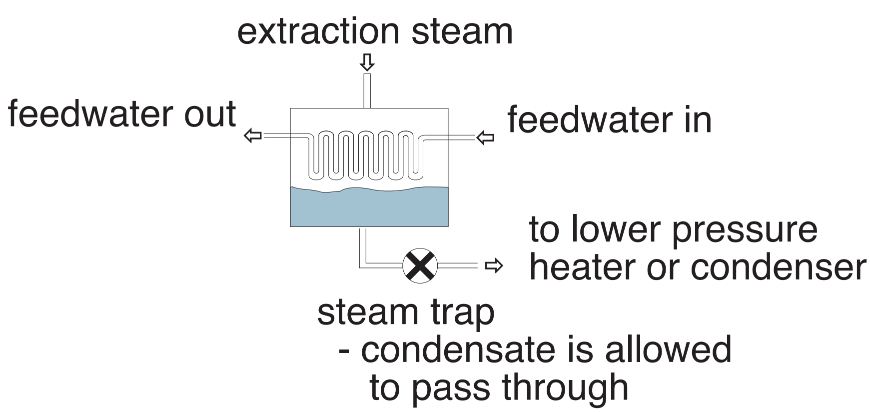

T
s
⑤
④
⑥
③
a
②
①
⑦

CLOSED FWH: two variations exist

Case 1: pump the condensate back to the high pressure line

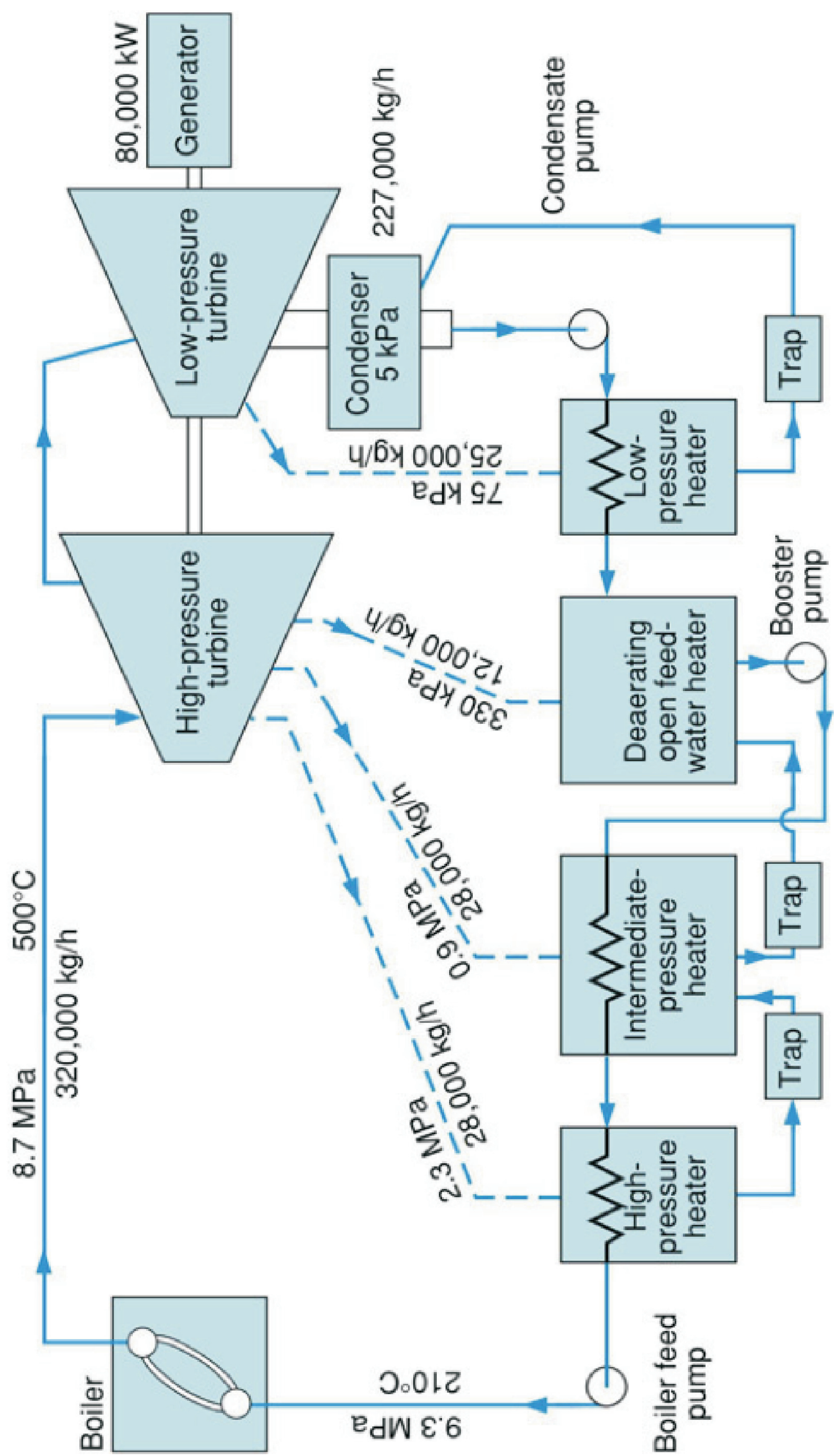


- a steam trap is inserted in the condensed steam line that allows only liquid to pass
- liquid is passed to a low pressure region such as the condenser or a low pressure heater



Case 2: the incoming feedwater does not mix with the extracted steam

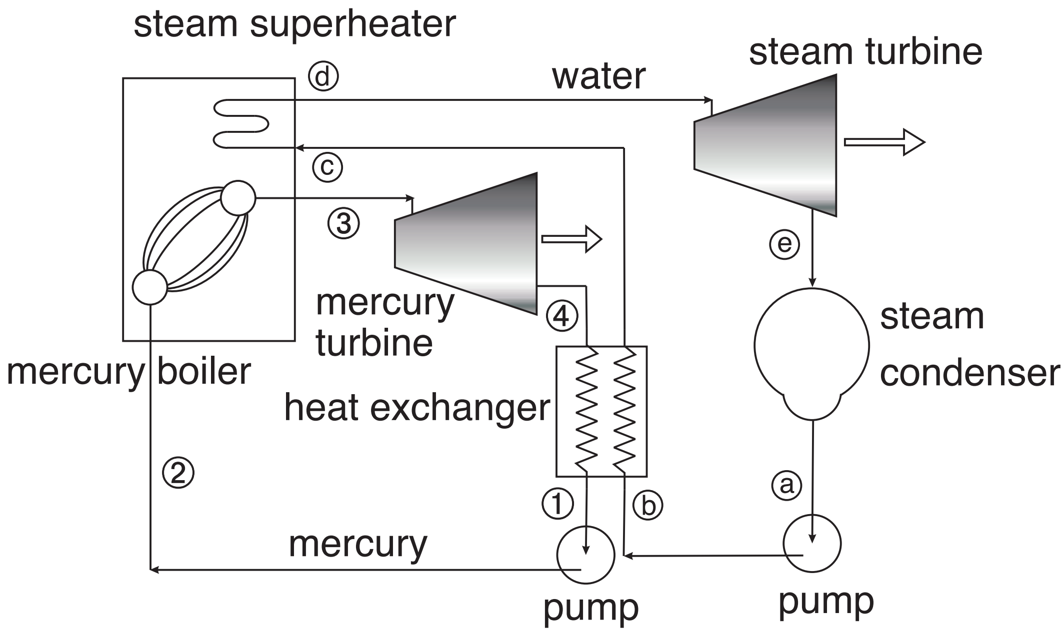
- both streams flow separately through the heater
- the two streams can have different pressures



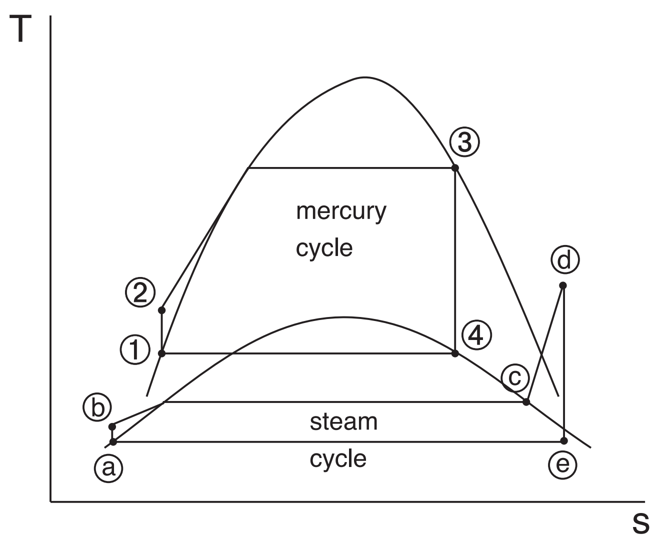
Boiler
9.3 MPa
210°C
Boiler feed pump
8.7 MPa
500°C
320,000 kg/h
High-pressure turbine
Low-pressure turbine
Generator
80,000 kW
Condenser 5 kPa
227,000 kg/h
Condensate pump
Trap
Low-pressure heater
75 kPa
25,000 kg/h
Deaerating open feed-water heater
330 kPa
12,000 kg/h
Booster pump
Intermediate-pressure heater
0.9 MPa
28,000 kg/h
Trap
Trap
High-pressure heater
2.3 MPa
28,000 kg/h

Binary Cycle

- involves two Rankine cycles running in tandem with different working fluids such as mercury and water
- why:
  - typically a boiler will supply energy at $1300 - 1400\ °C$
  - but $T_{critical}$ for water is $374.14\ °C$
    * most energy is absorbed below this temperature
    * high ΔT between the boiler source and the water leads to a major source of irreversibilities
  - $T_{critical}$ for mercury is about $1500\ °C$
    * no need for superheating



steam superheater
d
water
steam turbine
c
3
e
mercury
turbine
4
steam
condenser
mercury boiler
heat exchanger
2
a
1
b
mercury
pump
pump



T
3
mercury
cycle
d
2
4
1
c
b
steam
cycle
a
e
s

PROBLEM STATEMENT:

Water is the working fluid for a Rankine cycle process where the turbine and the pump have isentropic efficiencies of 85% and 70%, respectively. Superheated vapor enters the turbine at $8\ MPa$ and $500\ °C$. The condenser pressure is $7.5\ kPa$. The net power output of the cycle is $100\ MW$. Determine for the cycle:

a) the mass flow rate of the steam $[kg/s]$, for a net power output of $100\ MW$.
b) the rate of heat transfer $[MW]$ to the working fluid passing through the steam generator.
c) the thermal efficiency.
d) the mass flow rate of the condenser cooling water $[kg/h]$, if the cooling water enters the condenser at $15\ °C$ and exits at $35\ °C$, with negligible pressure change.