Chapter Two

The Rankine cycle

Prepared by Dr. Shatha Ammourah

The Ideal Rankine Cycle

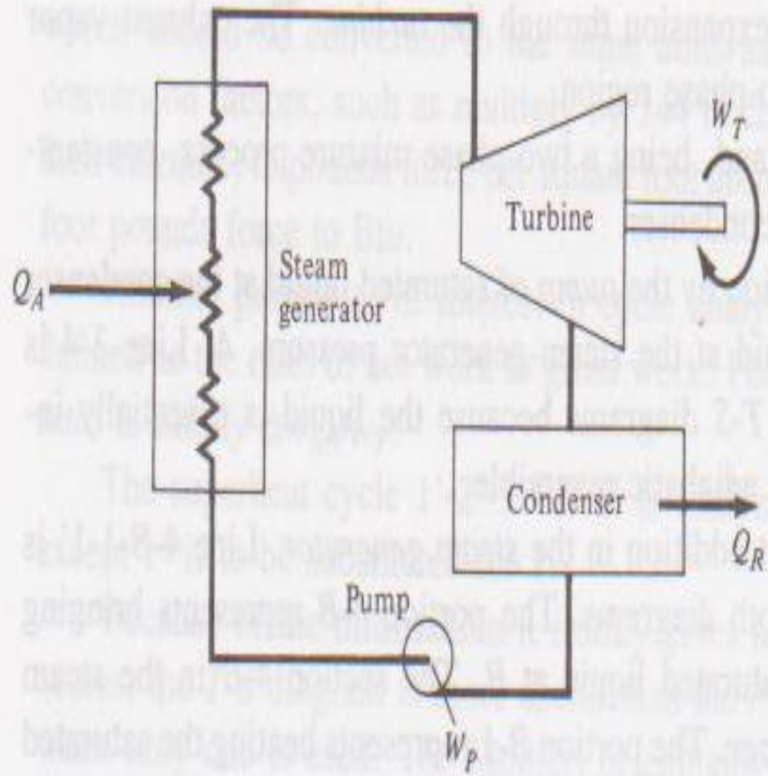


Figure 2-1 Schematic flow diagram of a Rankine cycle.

Schematic Diagram of ideal simple Rankine

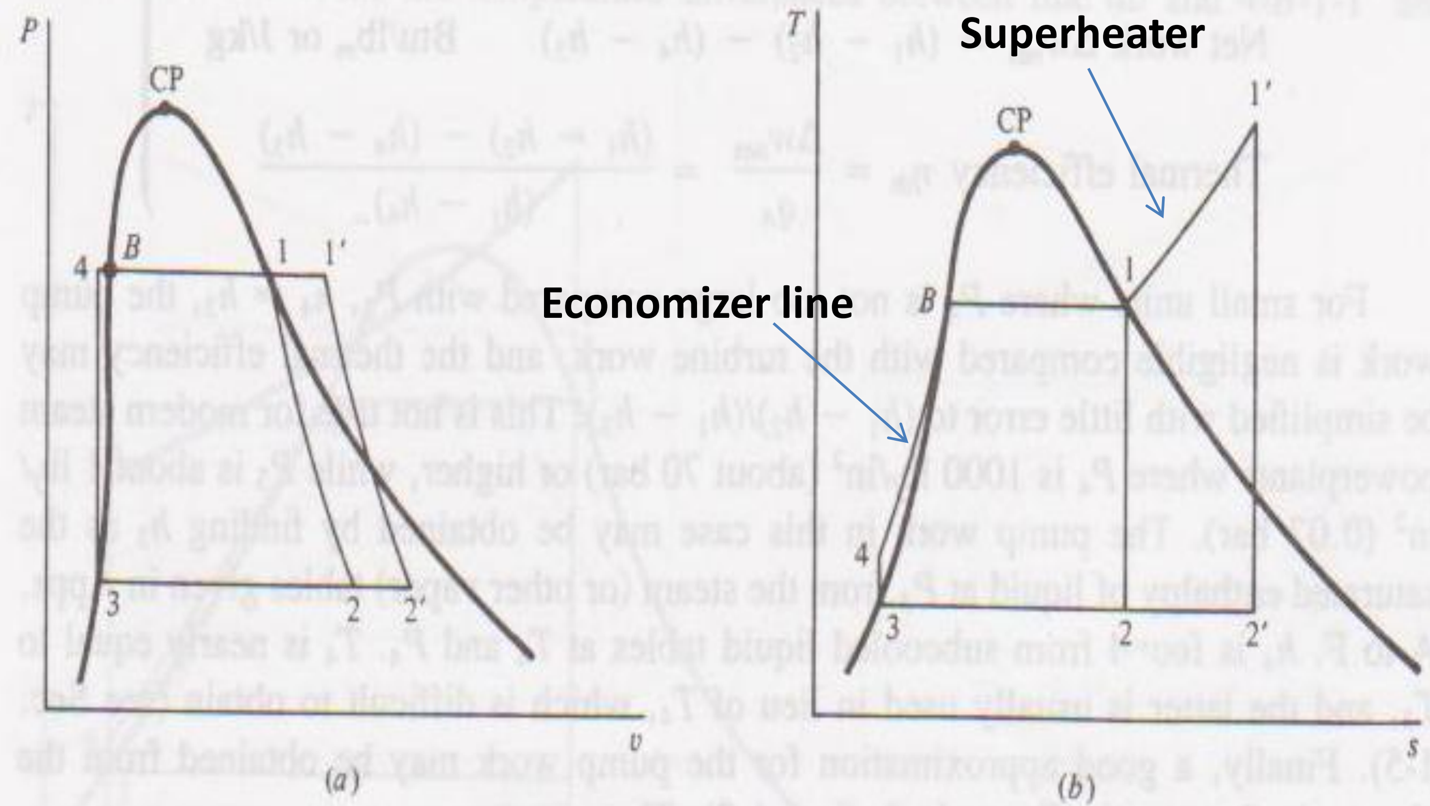


Figure 2-2 Ideal Rankine cycles of the (*a*) *P*-*v* and (*b*) *T*-*s* diagrams. 1-2-3-4-*B*-1 = saturated cycle. 1^1-2^1-3-4-*B*-1^1 = superheated cycle. CP = critical point.

Heat Addition Types In The Steam Generator

- Sensible heat addition in the economizer and the superheater Line (4-B, B-$1^{/}$).

- Latent heat transfer in the boiler (B-1).

$$\left.\begin{aligned}
&\text{Heat added } q_A = h_1 - h_4 \quad \text{Btu/lb}_m \text{ or J/kg}\\
&\text{Turbine work } w_T = h_1 - h_2 \quad \text{Btu/lb}_m \text{ or J/kg}\\
&\text{Heat rejected } |q_R| = h_2 - h_3 \quad \text{Btu/lb}_m \text{ or J/kg}\\
&\text{Pump work } |w_p| = h_4 - h_3\\
&\text{Net work } \Delta w_{\text{net}} = (h_1 - h_2) - (h_4 - h_3) \quad \text{Btu/lb}_m \text{ or J/kg}\\
&\text{Thermal efficiency } \eta_{\text{th}} = \frac{\Delta w_{\text{net}}}{q_A} = \frac{(h_1 - h_2) - (h_4 - h_3)}{(h_1 - h_4)}
\end{aligned}\right\} \quad (2\text{-}1)$$

$$|w_p| = v_3(P_4 - P_3) \quad (2\text{-}2)$$

The Externally Irreversible Rankine Cycle

- External irreversibility is a result of the temperature difference between the primary heat source and the working fluid.
- Temperature difference between condensing working fluid and the heat sink fluid, which is usually the condenser cooling water.

1-Effect of the heat source type (heat exchanger)

- There are two types of heat exchangers: 1- parallel flow 2- Counter flow

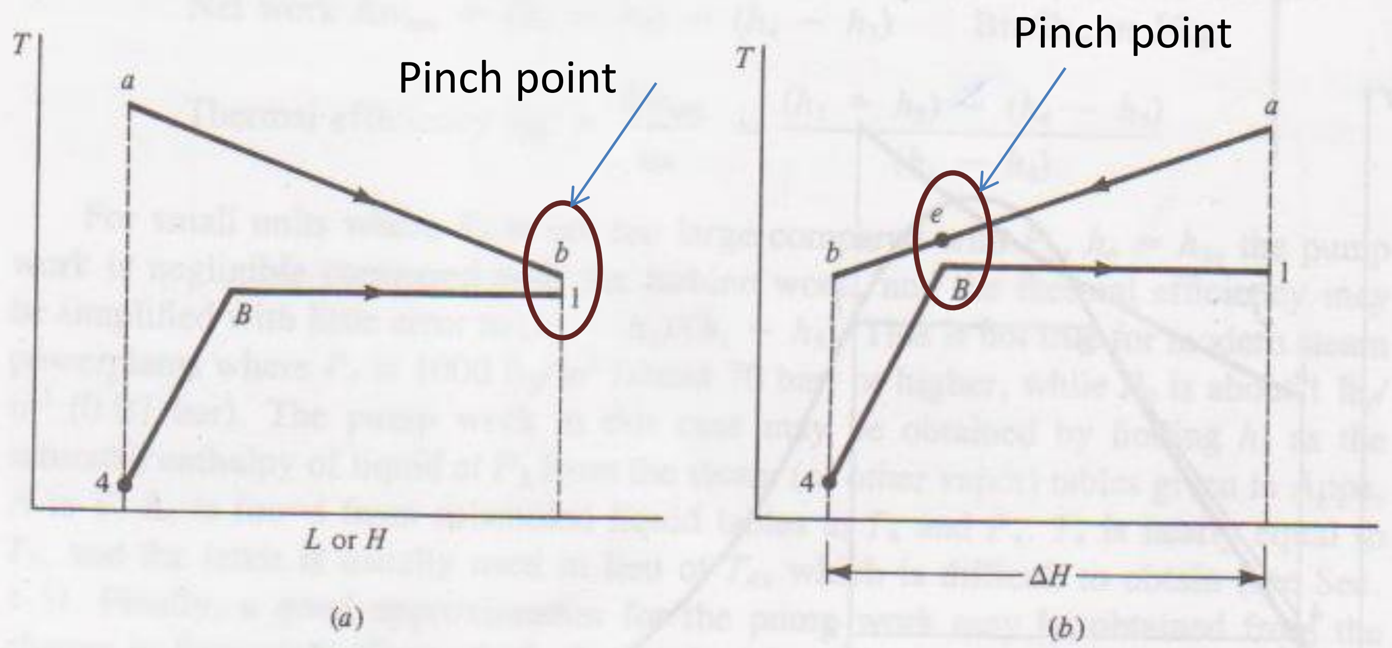


Figure 2-4 Effect of flow direction on external irreversibility: (a) parallel flow, (b) counterflow.

- Pinch-point: is the minimum approach between the working fluid line and the primary heat source line and it must be finite
- Too small a pinch-point temperature difference results in lower irreversibility and higher efficiency, but costly steam generator.
- Too large a pinch-point temperature difference results in more irreversibility and small but cheap steam generator.
- The most economical point is obtained by optimization that takes into account the (a) fixed charges (based on the capital costs) (b) operating costs (based on efficiency and thence fuel costs).
- Counter flow heat exchangers are preferred over parallel flow ones from both thermodynamics and heat transfer point of view.

2-Effect of the type of heat source fluid

- There are different types of heat source fluids such as: 1-combustion gases 2- water from a pressurized-water reactor, or molten sodium from a liquid metal fast breeder reactor.
- These fluids has different mass flow rate and specific heat c_p . Water has higher c_p than gases.

Assuming that a differential amount of heat dQ exchanged between the two fluids is proportional to a path length dL and that $dQ = \dot{m}c_p\,dT$, where dT is the change in primary-fluid temperature in dL, the slope of line ab is then proportional to the reciprocal of $\dot{m}c_p$ or

$$\frac{dT}{dL} \propto \frac{1}{\dot{m}c_p} \quad \text{(primary fluid)} \qquad (2\text{-}3)$$

- For a given pinch point temperature difference over all temperature difference between the primary and the working fluid is greater in the case of gases than water especially in the boiler section, which determines whether or not to use superheat or reheat.

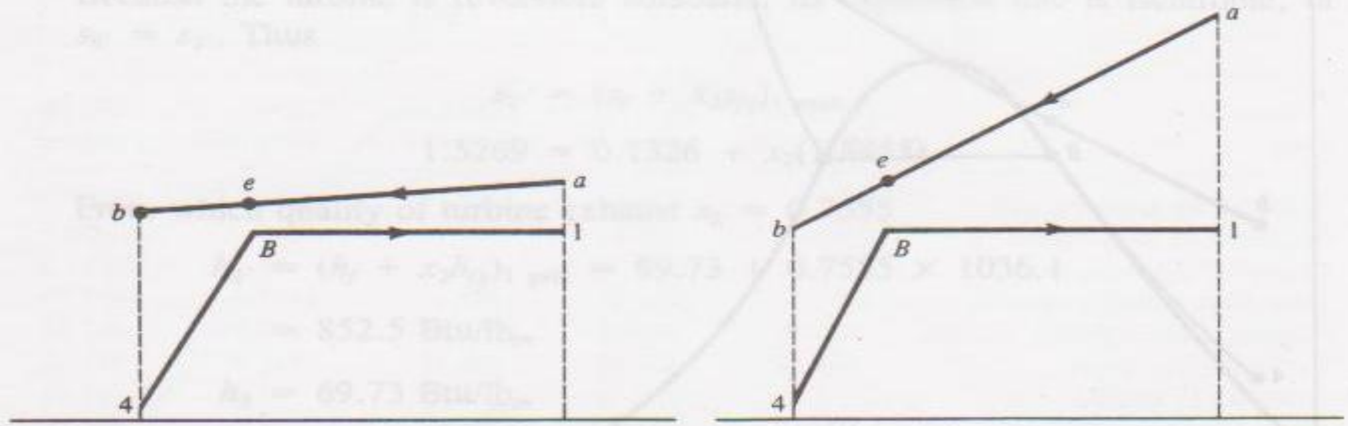


Figure 2-5 Effect of primary fluid type on external irreversibility: (*a*) water, (*b*) gases or liquid metal.

We note that there are two distinct regions where the external irreversibility exists at the higher-temperature end of the cycle. These are: (1) between the primary fluid and the working fluid in the boiler section, i.e., between *ae* and *B*-1, and (2) between the primary fluid and the working fluid in the economizer section, i.e., between *be* and 4-*B*. We shall deal with these in turn in the next two sections.

Superheat

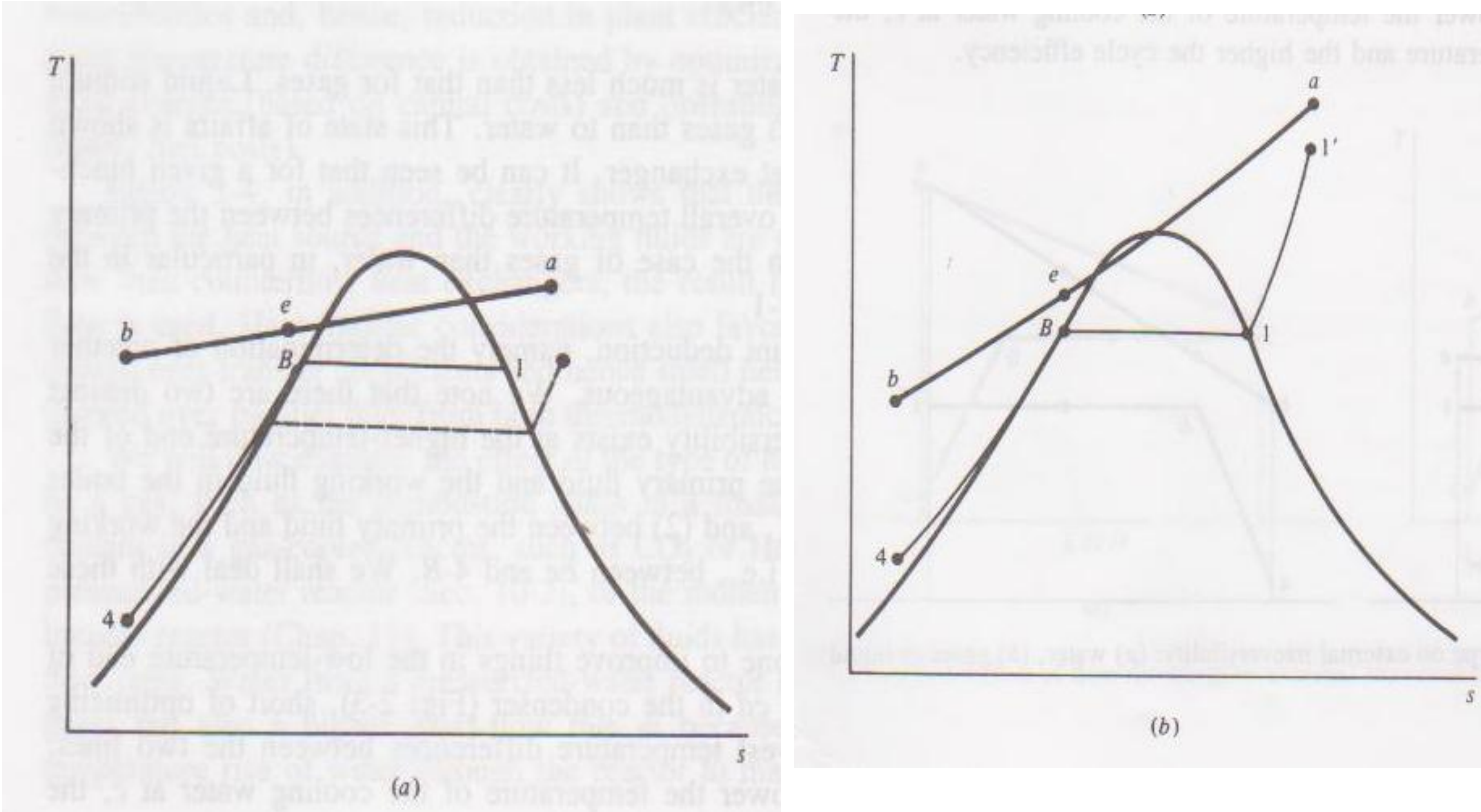


Figure 2-6 Superheat with (*a*) water as primary fluid, (*b*) gases or liquid metal as primary fluid.

- For a given pinch point temperature difference gases and liquid metals have larger and increasing temperature difference (between line ae and B-1) as the working fluid boils from B-1 than is the case of water where the slope of line ae is much lower.
- Due to the large temperature difference between line ae and B-1 in the gases case, more irreversibility is produced due to larger heat loss. To overcome this problem, superheat is needed when gas and liquid metals are used as primary heat sources.
- In the case of water, superheat is not practical as the differences between ae and B-1 vary little.
- If superheat is to be used with water, then the boiling temperature of water is lowered and thence the saturation pressure, which results in reducing the cycle efficiency rather than increasing it. This is why pressurized water reactors mainly do not use superheat.
- Superheat is also results in drier steam at turbine exhaust, which helps protecting the turbine blades from corrosion.

Reheat

- It is an additional improvement in cycle efficiency with gaseous primary fluids as in fossil-fuled and gas-cooled power plants is achieved by the use of reheat.

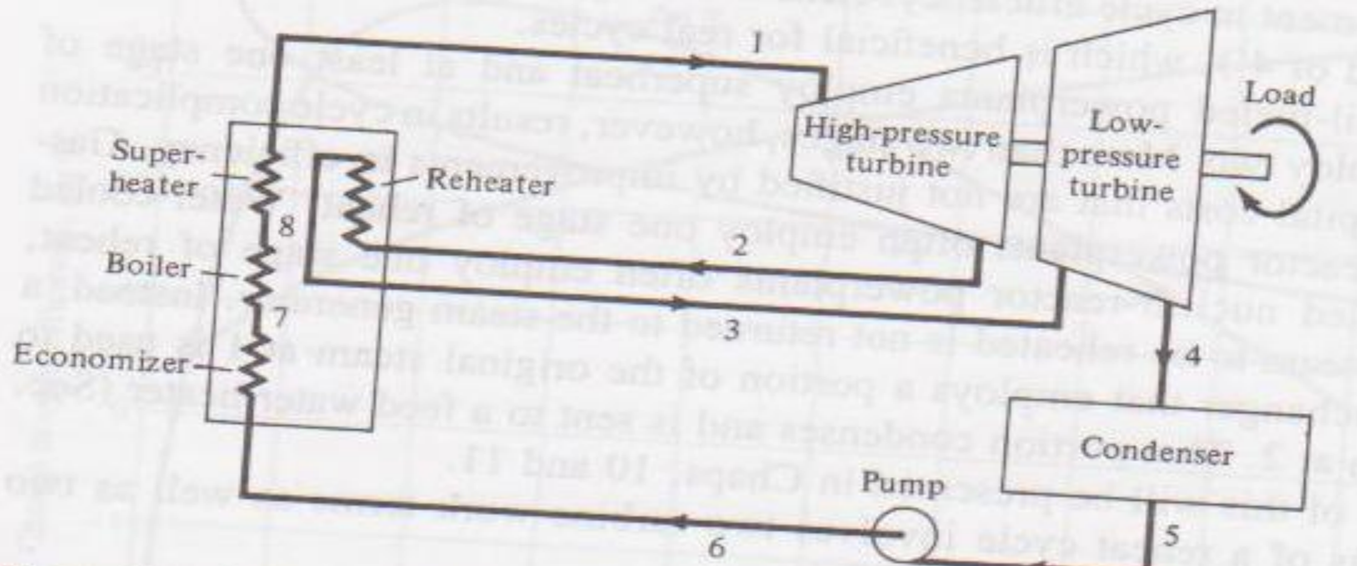


Figure 2-7 Schematic of a Rankine cycle with superheat and reheat.

- Reheat allows heat addition twice that results in increasing the average temperature at which heat is added and keeps the boiler-superheat-reheat portion close to the primary fluid line ae, which results in improvement in the cycle efficiency. One of the benefits as well is more drier at the turbine exit.

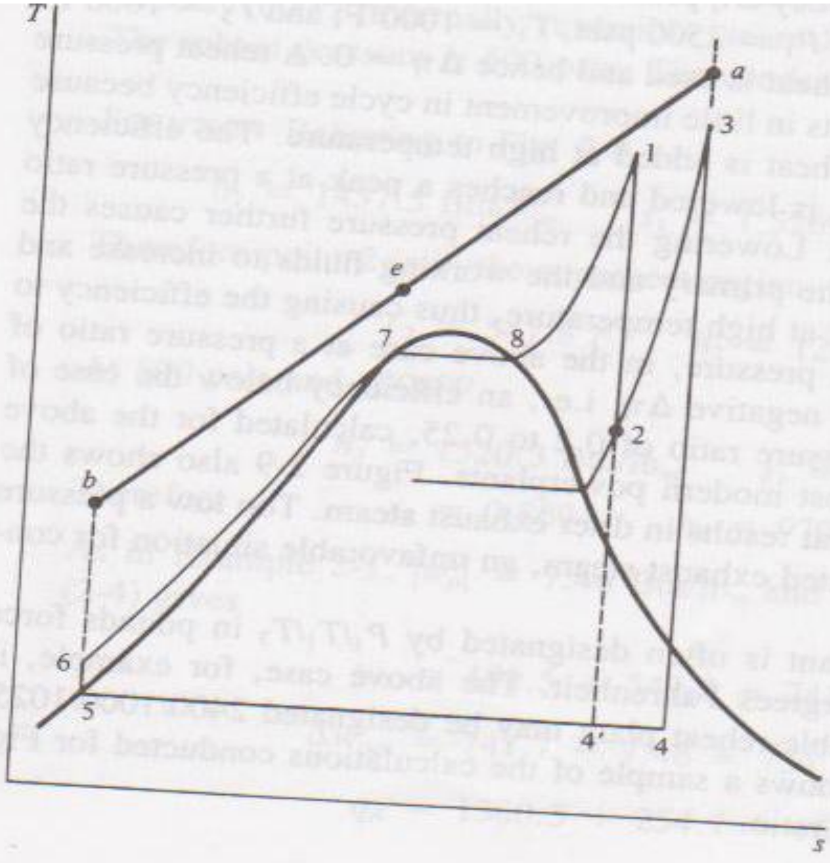
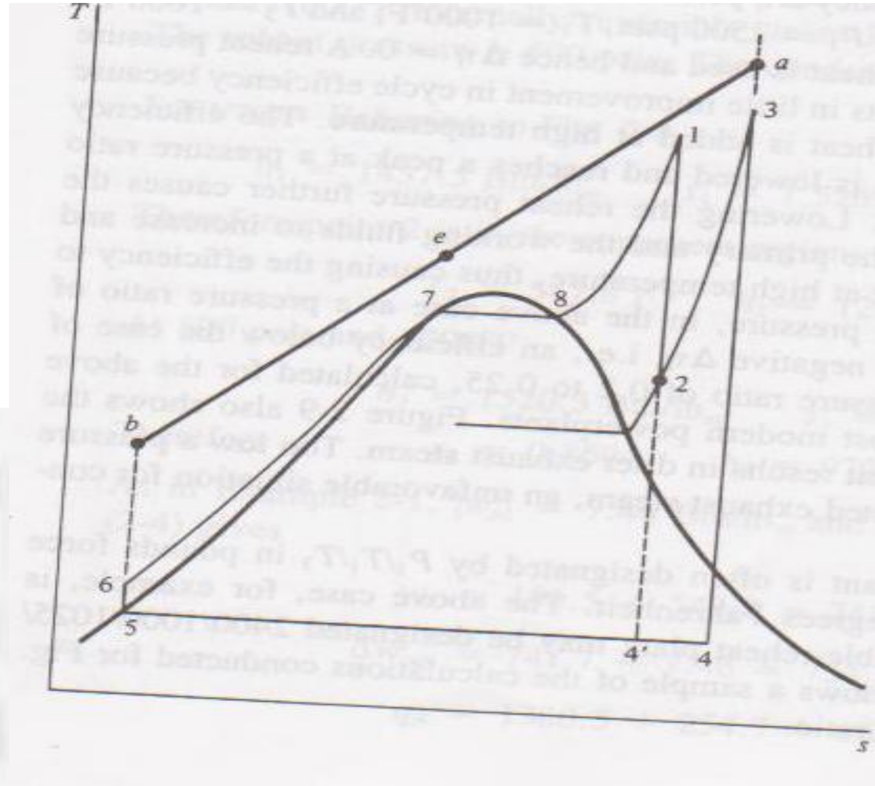


Figure 2-8 *T-s* **diagram of Rankine cycle of Fig. 2-7.**



$$
\left.
\begin{aligned}
w_T &= (h_1 - h_2) + (h_3 - h_4)\\
|w_p| &= h_6 - h_5\\
\Delta w_{\text{net}} &= (h_1 - h_2) + (h_3 - h_4) - (h_6 - h_5)\\
q_A &= (h_1 - h_6) + (h_3 - h_2)\\
\eta_{\text{th}} &= \frac{\Delta w_{\text{net}}}{q_A}
\end{aligned}
\right\} \qquad (2\text{-}4)
$$

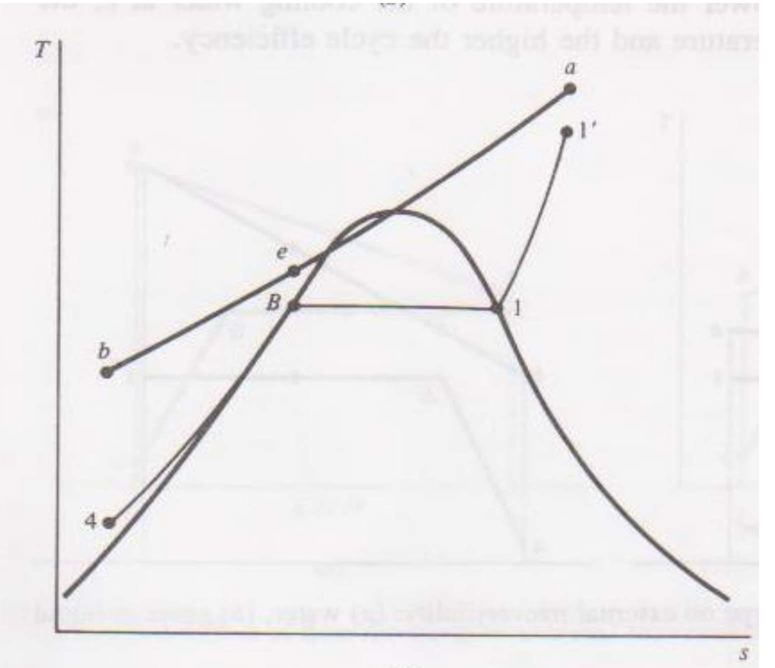
- Modern power plants have superheat and at least one stage of reheat. Some employ two stages. More than that results in cycle complications and increased capital costs that are not justified by improvements in efficiency.
- Gas cooled nuclear-reactor power plants often employ one stage of reheat. Water-cooled and sodium-cooled nuclear-reactor power plants also have on reheat stage, except that the steam is not reheated in the steam generator unite. It is reheated in outer heat exchanger unit.
- A superheat-reheat power plant is often designated by P_1 / T_1 / T_3

Effect of Reheat Pressure

- The reheat pressure affects the cycle a lot and it should be with a range. Assume that the initial pressure is P_1 and the reheat pressure is P_2 then P_2 / P_1 should be between 0.2-0.25 (20%-25%).
- Too close to the initial pressure results in little improvement in cycle efficiency.
- Too low reheat pressure results in negative efficiency difference.

Regeneration

- A great deal of external irreversibility occurs in the economizer section.
- To overcome this problem it is recommended to make use of the heat in cycle and admit water at point B rather than 4, this is called regeneration, where internal heat is exchanged between the expanding steam in the turbine and the water before heat addition. This theoretically indicates the elimination of the economizer



(b)

Theoretical Suggestion

This suggestion is not practical because of the following:

1. The vapour in the turbine does not have enough heat transfer surface to warm the water.
2. The water mass flow rate is very large so the effectiveness of such heat exchanger will be low.
3. The vapour in the turbine will have low quality, which is bad for its performance.

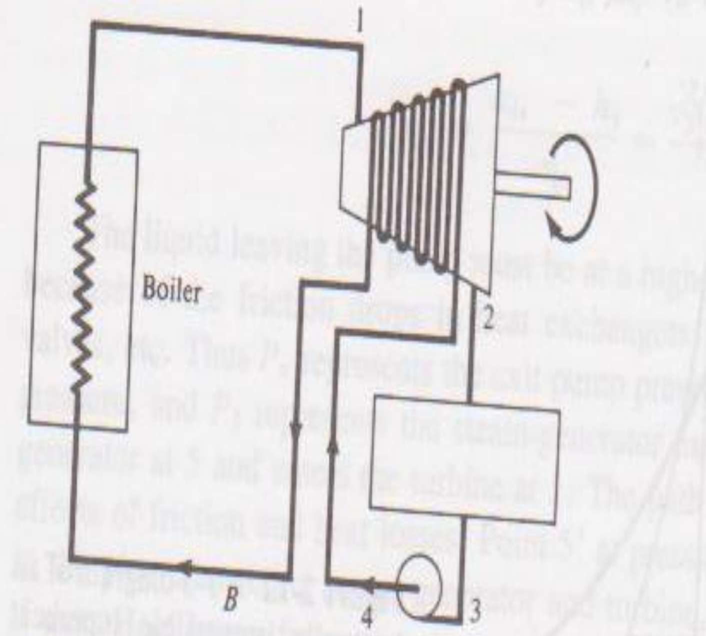


Figure 2-11 Ideal regeneration of a Rankine cycle.

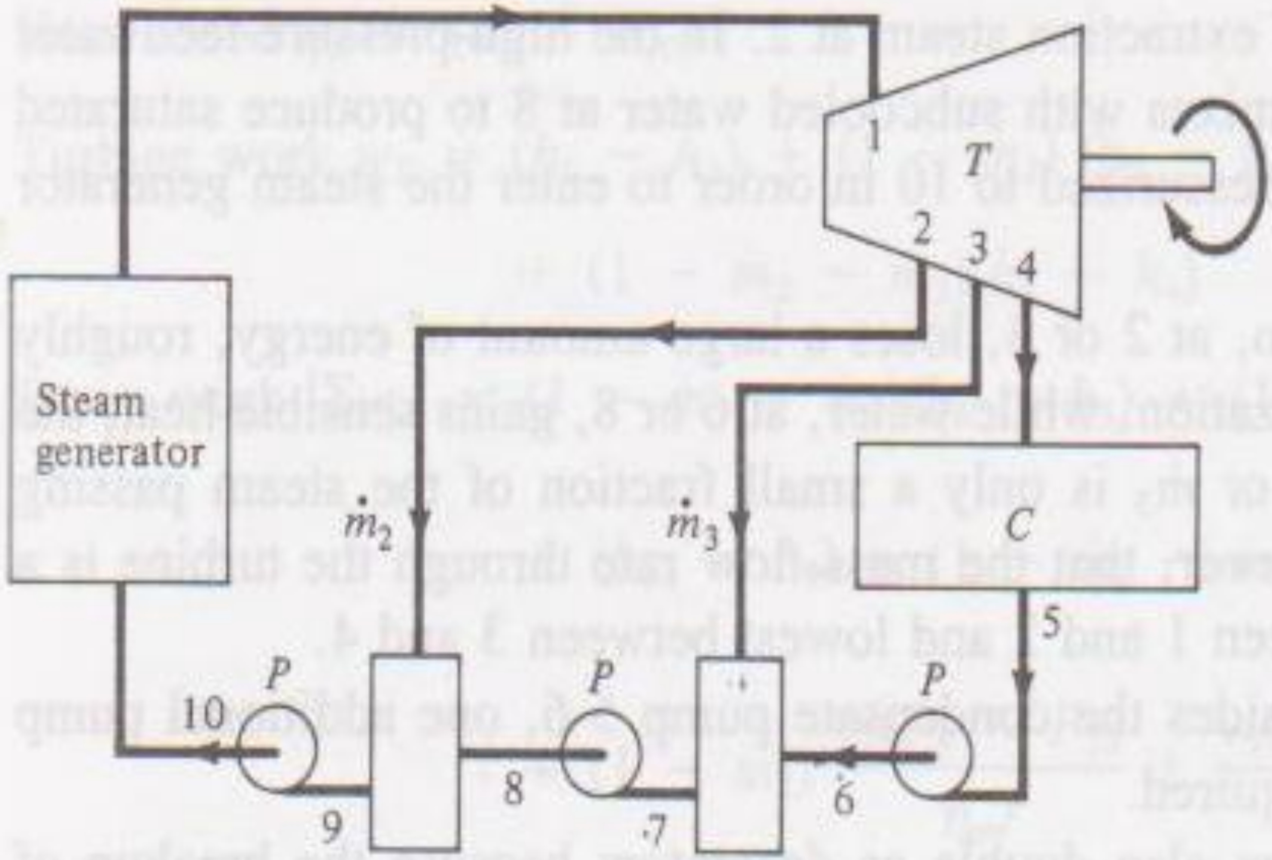
Feedwater Heating

- Feedwater heating means that the compressed water is heated by bled steam from the turbine at finite steps before entering the steam generator. This results in reducing the economizer area but not eliminating it at all.
- Most modern steam power plants use between 5-8 feedwater heaters.
- There are three types of feedwater heating:

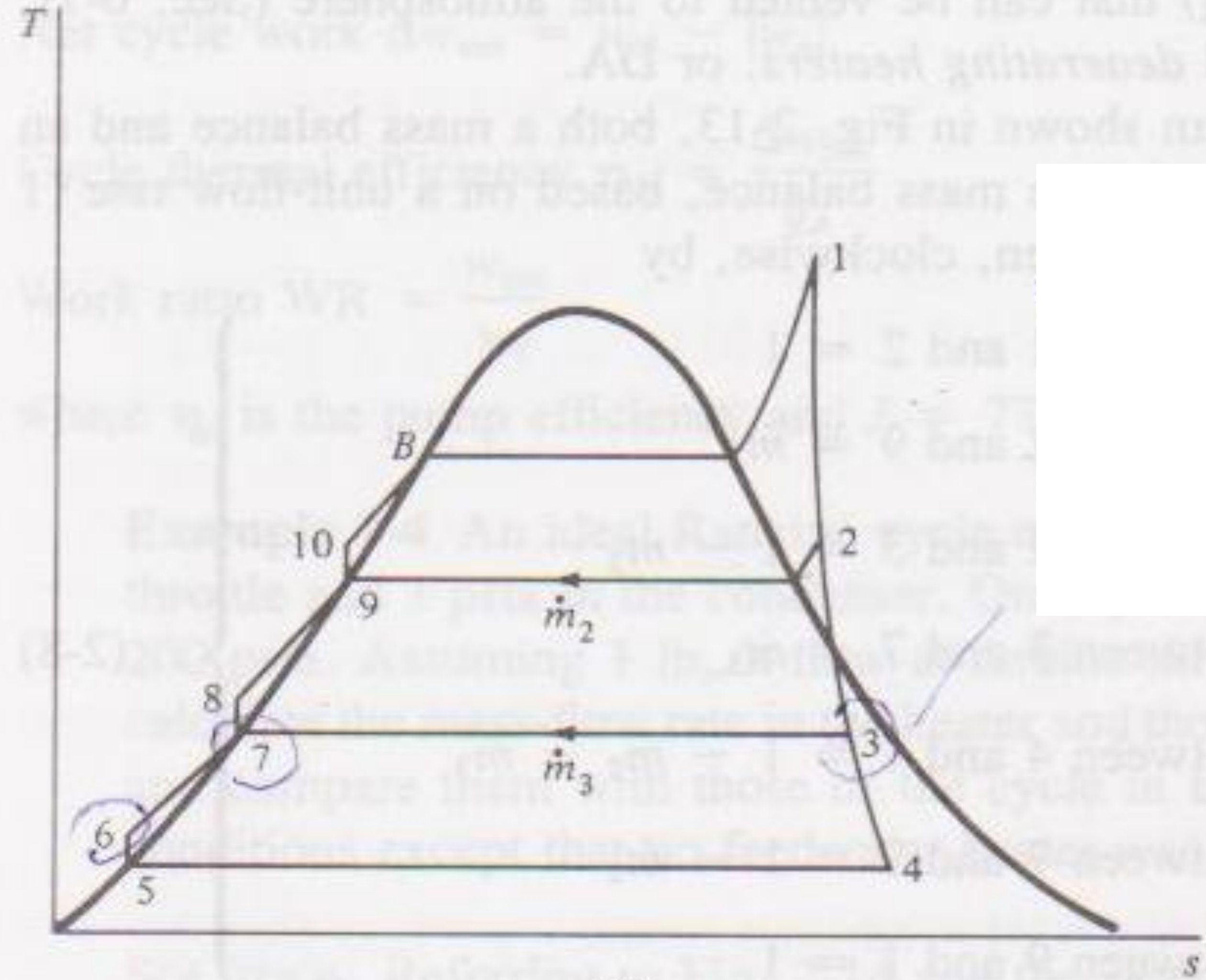
1. Open or direct contact type.
2. Closed type with drains cascaded backward.
3. Closed type with drains pumped forward.

Open Or Direct Contact Feedwater Heaters

- In the open feedwater heater the extracted steam from the turbine is mixed directly with the incoming subcooled water to produce saturated steam at the extraction steam pressure.
- The amount of bled steam should equal to that would saturate the subcooled water it is going to mix with. If it is much less it may negate the advantage of the feedwater heater. On the other hand if it is more it will affect the turbine work by causing losses, also it would result in two-phase mixture in the pump.
- Open type feedwater heaters is treated as mixing chambers.
- The mass flow rate in the turbine is a variable quantity in the case of feedwater heating.
- Besides the condensate pump there is one additional pump per open feedwater heater.
- Open feedwater heaters are also called deaerating heaters or DA, as the breakup of water in the mixing process results in non-condensable gases such as air, O_2 , CO_2, H_2.



(a)



(b)

$$\left.\begin{aligned}
&\text{Mass flow between 1 and 2} = 1\\
&\text{Mass flow between 2 and 9} = \dot{m}_2\\
&\text{Mass flow between 2 and 3} = 1 - \dot{m}_2\\
&\text{Mass flow between 3 and 7} = \dot{m}_3\\
&\text{Mass flow between 4 and 7} = 1 - \dot{m}_2 - \dot{m}_3\\
&\text{Mass flow between 7 and 9} = 1 - \dot{m}_2\\
&\text{Mass flow between 9 and 1} = 1
\end{aligned}\right\} \tag{2-8}$$

where $\dot{m}_2$ and $\dot{m}_3$ are small fractions of 1. Energy balances are now done on the high- and low-pressure feedwater heaters, respectively

$$\dot{m}_2(h_2 - h_9) = (1 - \dot{m}_2)(h_9 - h_8) \tag{2-9}$$

and

$$\dot{m}_3(h_3 - h_7) = (1 - \dot{m}_2 - \dot{m}_3)(h_3 - h_7) \tag{2-10}$$

Closed-Type Feedwater heaters With drains Cascaded Backward

- This type of feedwater heaters is the simplest and most commonly used.
- It is shell and tube heat exchanger with no moving parts.
- The feedwater passes in the tubes and the bled steam in the shell.
- Only one pump is required as the steam does not mix with the feedwater. This pump is doubles to be also a boiler feed pump.
- If a deaerating heater is used then another pump should be used after it to be the boiler feed pump.
- The bled steam is feed back to the next lower pressure feedwater heater by throttling and then led back to the condenser, which is called cascade from high pressure to low pressure.

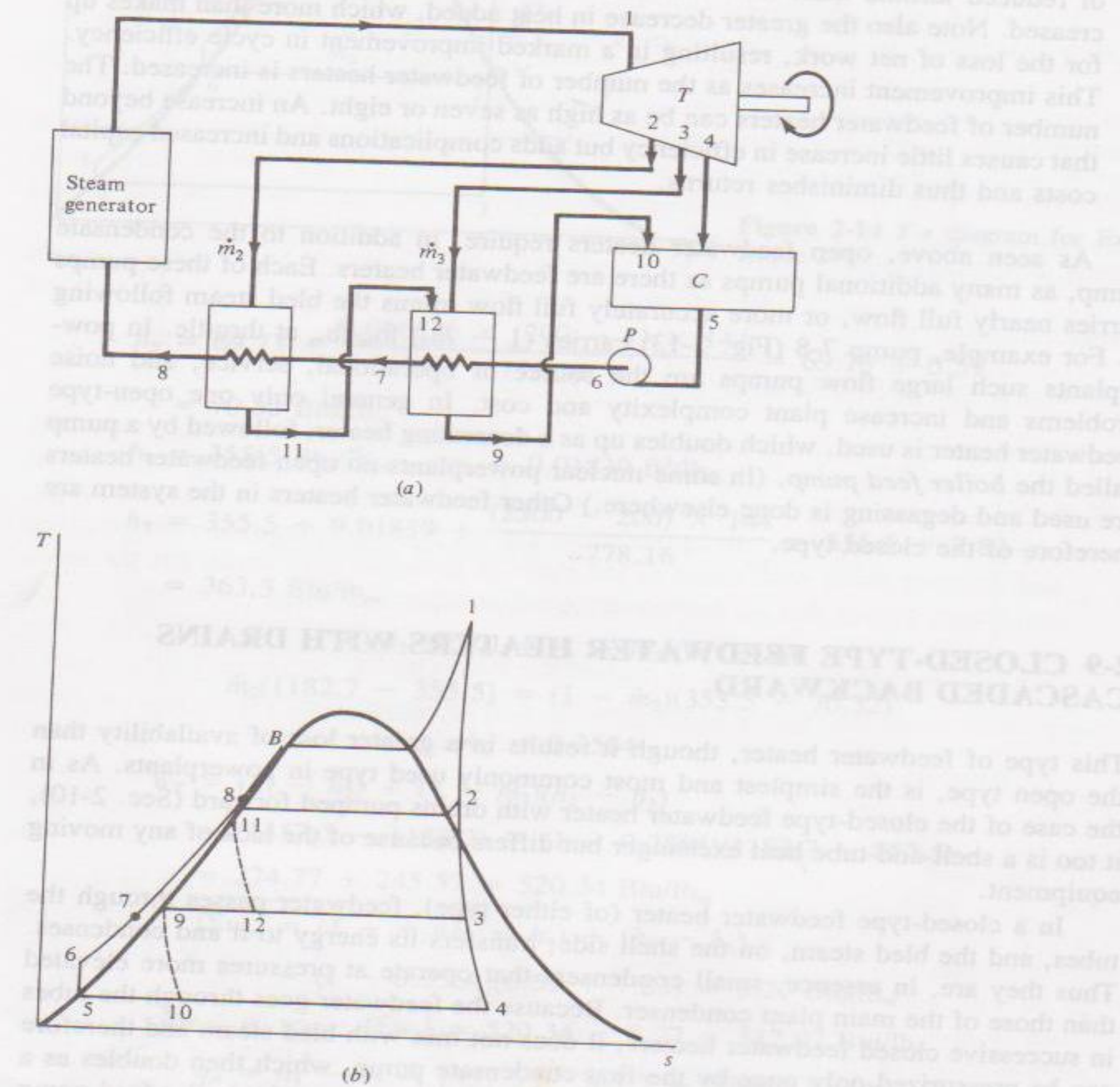
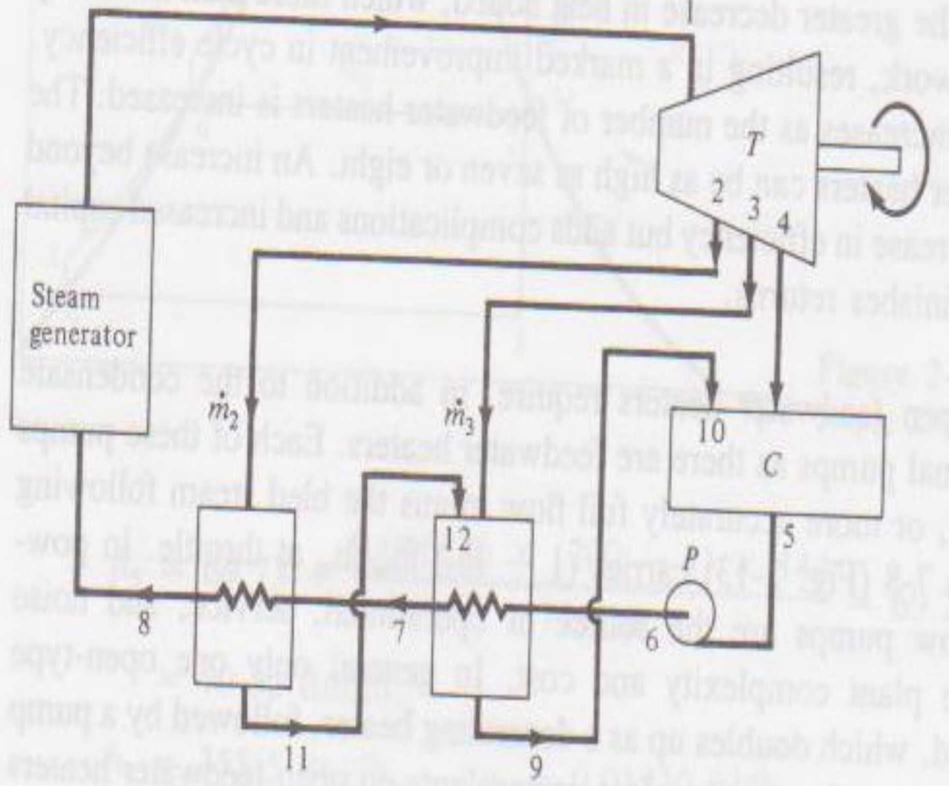


Figure 2-15 Schematic flow and *T-s* diagrams of a nonideal superheat Rankine cycle with two closed-type feedwater heaters with drains cascaded backward.



$$\left.\begin{aligned}
&\text{Mass flow between 1 and 2} &&= 1\\
&\text{Mass flow between 2 and 3} &&= 1 - \dot{m}_2\\
&\text{Mass flow between 3 and 10} &&= 1 - \dot{m}_2 - \dot{m}_3\\
&\text{Mass flow between 10 and 1} &&= 1\\
&\text{Mass flow between 2 and 12} &&= \dot{m}_2\\
&\text{Mass flow between 3 and 12} &&= \dot{m}_3\\
&\text{Mass flow between 12 and 10} &&= \dot{m}_2 + \dot{m}_3
\end{aligned}\right\} \quad (2\text{-}13)$$

The energy balances on the high- and low-pressure heaters are now given, respectively, by

$$\dot{m}_2(h_2 - h_{11}) = h_8 - h_7 \qquad (2\text{-}14)$$

and

$$\dot{m}_3(h_3 - h_9) + \dot{m}_2(h_{12} - h_9) = h_7 - h_6 \qquad (2\text{-}15)$$

Recalling that a throttling process is a constant enthalpy process so that

$$h_{12} = h_{11} \quad \text{and} \quad h_{10} = h_9$$

- There is always a temperature difference between the bled steam entering the feedwater heater and the exit temperature of the subcooled water in the pipes, this is called Terminal Temperature Difference (TTD) and it is represented as: TTD = Saturation temperature of bled steam – exit water temperature. The value of TTD varies with the heater pressure.
- TTD is positive and the optimum design TTD is 5^0 F. Too small TTD is good for the cycle efficiency, but would require a larger heater, which may not be justified economically. On the other hand too large a value will hurt the cycle efficiency.
- TTD can be negative at the case of high pressure feedwater heater, as the exit water may have a temperature higher than the saturation temperature of that steam, therefore TTD ranges from 0 to -5^0 F. The drain here is slightly subcooled.
- In the low pressure heater the steam can have a drain cooler, thus physically it is composed from condensing side and drain cooler side.
- Based on the previous discussion there are four possible section zones of the closed heaters: 1- condenser 2- condenser and drain cooler (DC) 3- desuperheater, condenser, drain cooler 4- desuperheater and condenser.

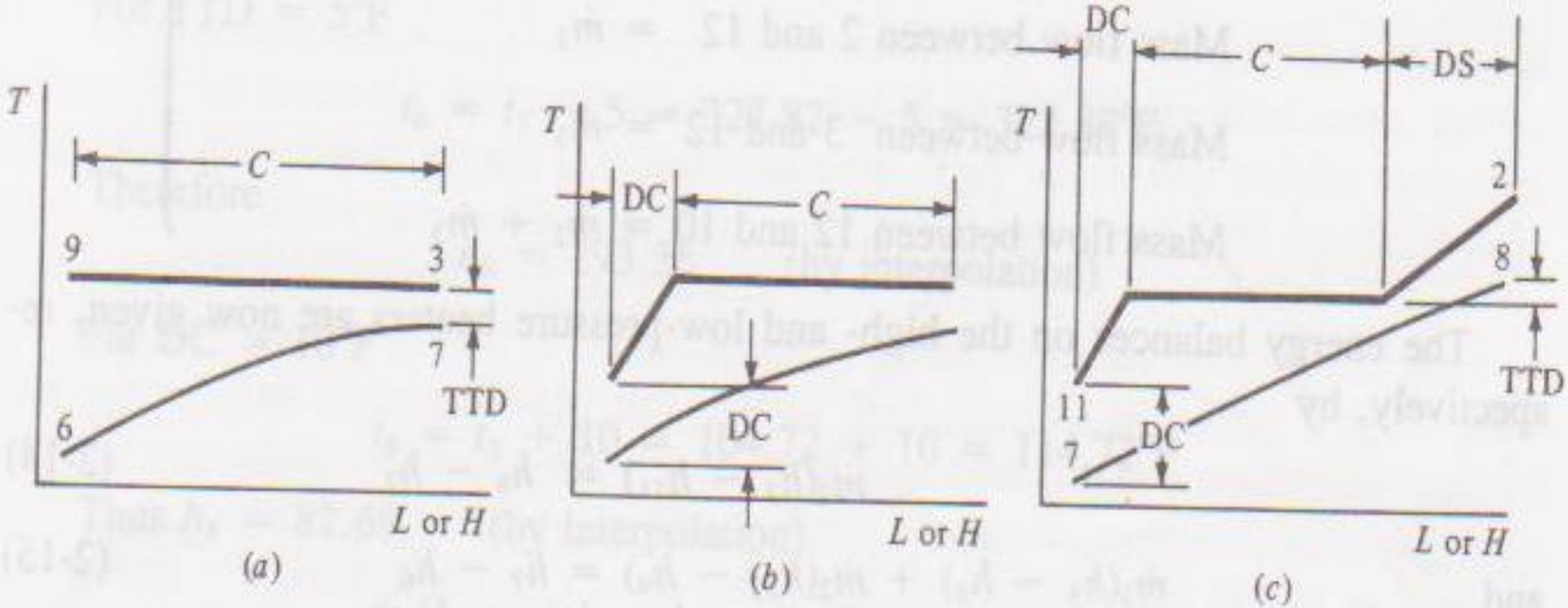


Figure 2-16 Temperature-enthalpy diagrams of (*a*) and (*b*) low-pressure and (*c*) high-pressure feedwater heaters of Fig. 2-15. TTD = terminal temperature difference, DS = desuperheater, C = condenser, DC = drain cooler.