Engineering Thermodynamics

Module -3.1

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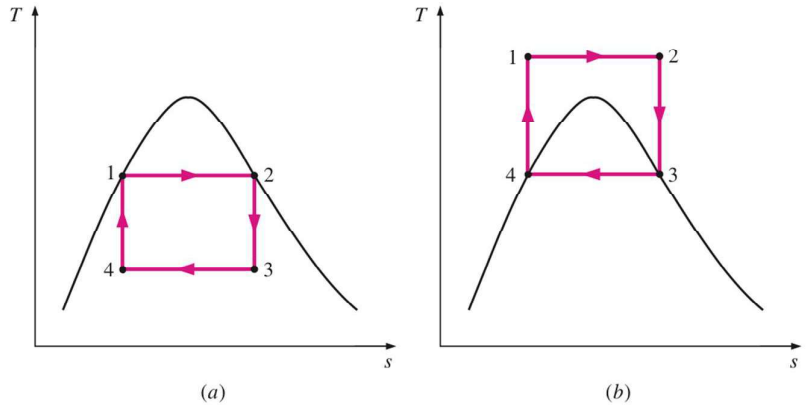
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Chapter 10: Vapor And Combined Power Cycles

10-1 The Carnot Vapor Cycle

A steady-flow Carnot cycle within the saturation dome of a pure substance (see Fig. 10-1a) consists of:

- Isentropic expansion in a turbine (2-3),
- Reversible isothermal condensation in a condenser (3-4),
- Isentropic compression by a compressor to the initial state (4-1),
- And reversible isothermal heating in a boiler (1-2).



This cycle has several impracticalities.

1. Isothermal heat transfer is straightforward in two-phase systems. However, restricting heat transfer to these systems limits the maximum cycle temperature to below the critical point, which for water is 374°C.
2. A well-designed turbine can closely approximate the isentropic expansion process (process 2-3).
    i. During this, steam quality drops, as seen in the T-s diagram (Fig. 10–1a), leading the turbine to handle steam with higher moisture.
    ii. Liquid droplets striking the blades cause erosion, which is a primary source of turbine wear.
3. The isentropic compression process (4-1) compresses a liquid–vapor mix to a saturated liquid. This process has two main challenges:
    a. Controlling condensation precisely to achieve the desired quality at state 4 is difficult.
    b. Designing a compressor for two-phase flow is impractical.
4. Some of these issues can be resolved by modifying the Carnot cycle as shown in Fig. 10–1b, though this approach creates new challenges:
    a. isentropic compression to very high pressure
    b. isothermal heat transfer at varying pressures.

10-2 RANKINE CYCLE: THE IDEAL CYCLE FOR VAPOR POWER CYCLES

The ideal Rankine cycle does not involve any internal irreversibilities and consists of the following four processes:

1-2 Isentropic compression in a pump
2-3 Constant pressure heat addition in a boiler
3-4 Isentropic expansion in a turbine
4-1 Constant pressure heat rejection in a condenser

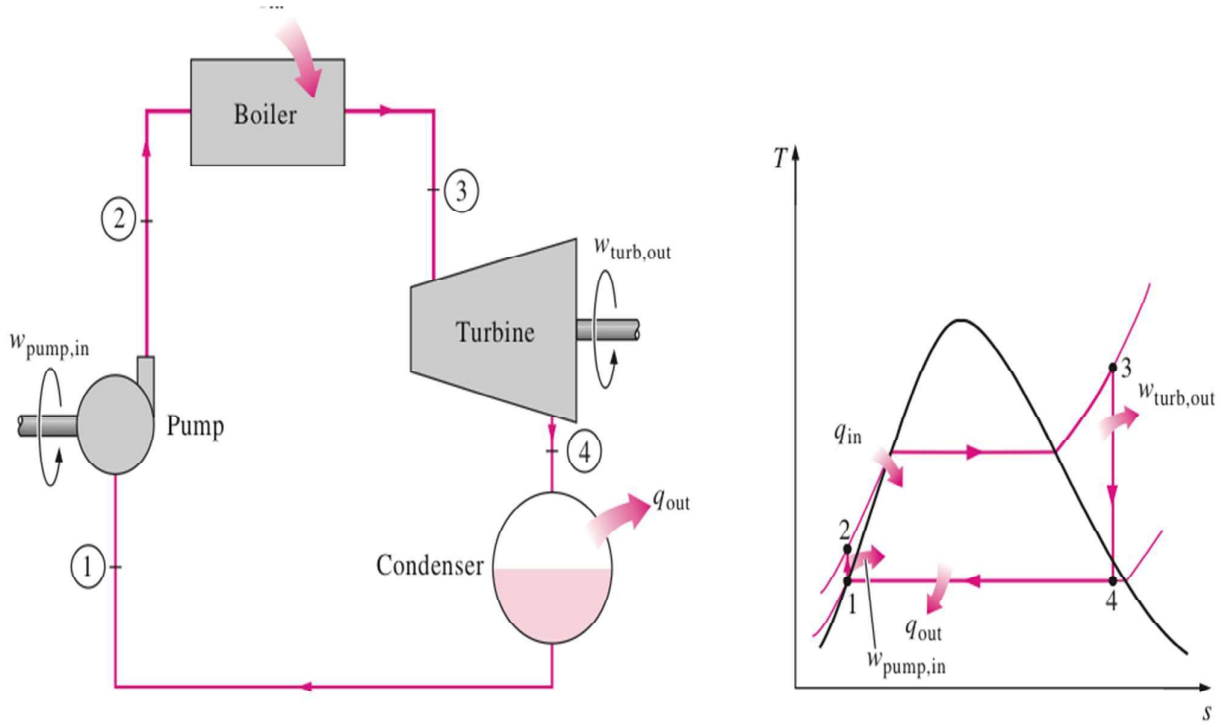


FIGURE 10–2
The simple ideal Rankine cycle.

- Water enters the pump at state 1 as a saturated liquid and is compressed isentropically to boiler pressure.
- In the boiler (state 2), water is heated at constant pressure and becomes superheated vapor at state 3.
- The boiler acts as a heat exchanger, transferring energy from combustion gases or other sources to the water.
- Superheated vapor (state 3) enters the turbine, expands isentropically, and drives a generator.
- At state 4, steam (typically a high-quality mixture) enters the condenser.
- Steam condenses at constant pressure in the condenser, releasing heat to a cooling medium like a lake, river, or atmosphere.

Energy Analysis of the Ideal Rankine Cycle

- All four components associated with the Rankine cycle (the pump, boiler, turbine, and condenser) are steady-flow devices, and thus all four processes that make up the Rankine cycle can be analyzed as steady-flow processes
- Then the steady-flow energy equation per unit mass of steam reduces to

$$(q_{in} - q_{out}) + (w_{in} - w_{out}) = h_e - h_i \qquad (kJ/kg) \qquad (10\text{–}1)$$

Then the conservation of energy relation for each device can be expressed as follows:

Pump ($q = 0$):
$$w_{pump,in} = h_2 - h_1 \qquad (10\text{–}2)$$

or,

$$w_{pump,in} = v(P_2 - P_1) \qquad (10\text{–}3)$$

where

$$h_1 = h_{f\,@\,P_1} \quad \text{and} \quad v \cong v_1 = v_{f\,@\,P_1} \qquad (10\text{–}4)$$

Boiler ($w = 0$):
$$q_{in} = h_3 - h_2 \qquad (10\text{–}5)$$

Turbine ($q = 0$):
$$w_{turb,out} = h_3 - h_4 \qquad (10\text{–}6)$$

Condenser ($w = 0$):
$$q_{out} = h_4 - h_1 \qquad (10\text{–}7)$$

The *thermal efficiency* of the Rankine cycle is determined from

$$\eta_{th} = \frac{w_{net}}{q_{in}} = 1 - \frac{q_{out}}{q_{in}} \qquad (10\text{–}8)$$

where

$$w_{net} = q_{in} - q_{out} = w_{turb,out} - w_{pump,in}$$

10-3 DEVIATION OF ACTUAL VAPOR POWER CYCLES FROMIDEALIZED ONES

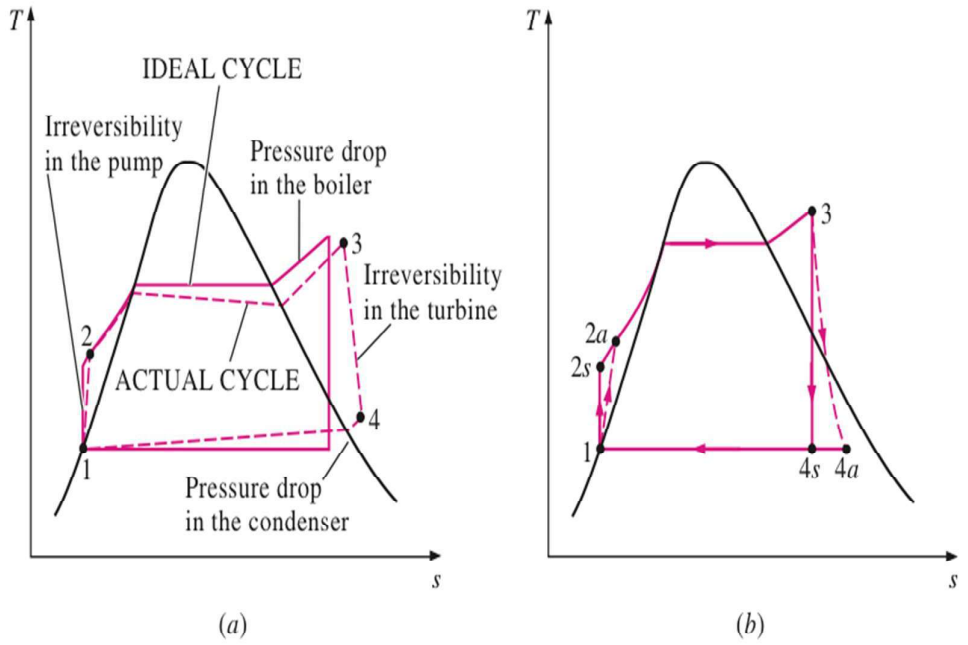


FIGURE 10–4

(*a*) Deviation of actual vapor power cycle from the ideal Rankine cycle. (*b*) The effect of pump and turbine irreversibilities on the ideal Rankine cycle.

- **Fluid friction** and **heat loss to the surroundings** are the two common sources of irreversibilities
    - Fluid friction reduces pressure in the boiler, condenser, and connecting pipes, so steam exits the boiler at a lower pressure.
    - The turbine inlet pressure is lower than the boiler exit pressure due to these pressure drops in the pipes.

- Heat loss from steam to the surroundings is a key cause of irreversibility in the cycle.
    - To keep net work output constant, extra heat must be added to the steam in the boiler, which lowers cycle efficiency.

- Irreversibilities occur in both the pump and turbine.
    - Due to irreversibilities, pumps need more input work and turbines yield less output.

$$\eta_P = \frac{w_s}{w_a} = \frac{h_{2s} - h_1}{h_{2a} - h_1} \qquad (10\text{–}10)$$

$$\eta_T = \frac{w_a}{w_s} = \frac{h_3 - h_{4a}}{h_3 - h_{4s}} \qquad (10\text{–}11)$$

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- Other problems
  - the liquid is usually subcooled to prevent the onset of cavitation, the rapid vaporization and condensation of the fluid at the low-pressure side of the pump impeller, which may damage it

10-4 · HOW CAN WE INCREASE THE EFFICIENCY OF THE RANKINE CYCLE?

The basic idea behind all the modifications to increase the thermal efficiency of a power cycle is the same:

- Raise the boiler's average heat transfer temperature.
- Lower the condenser's average heat rejection temperature.

1. Lowering the Condenser Pressure (Lowers $T_{low,avg}$)

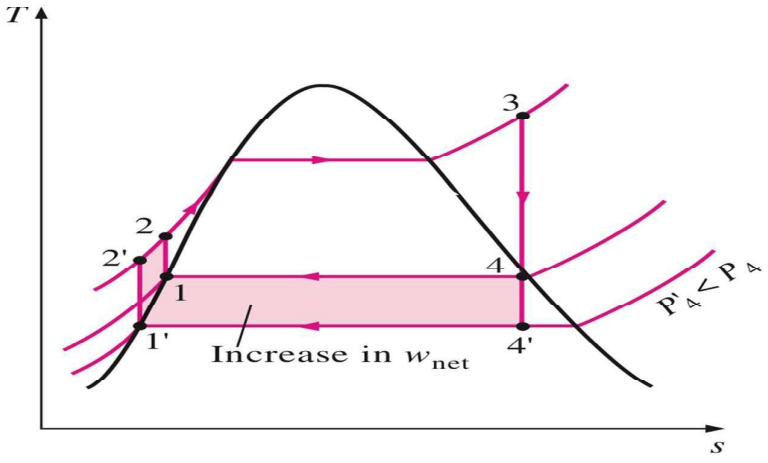


FIGURE 10–6
The effect of lowering the condenser pressure on the ideal Rankine cycle.

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Lowering the condenser pressure is not without any side effects

- It can cause air leakage into the condenser.
- It raises steam moisture content in the turbine's final stages (see Fig. 10).
- Excess moisture decreases turbine efficiency and erodes blades.

2. Superheating the Steam to High Temperatures

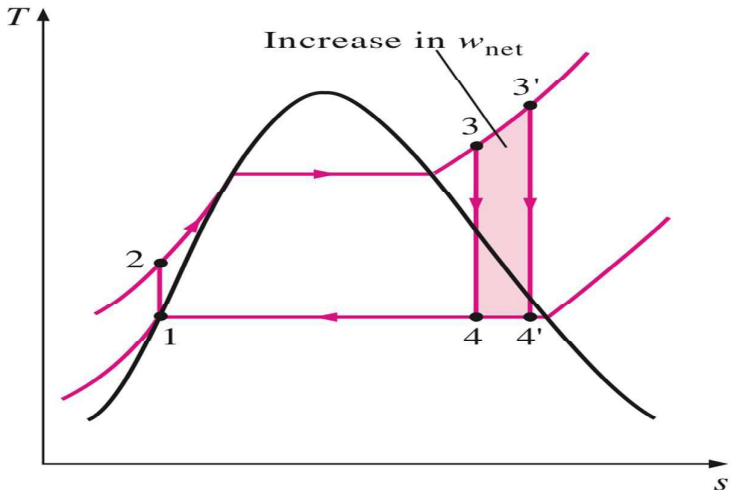


FIGURE 10–7
The effect of superheating the steam to higher temperatures on the ideal Rankine cycle.

- The coloured area in the diagram shows the net work increase.
- The total area below curve 3-3' indicates higher heat input.
- Superheating steam to a higher temperature raises both net work and heat input.
- Overall, thermal efficiency improves because heat is added at a higher average temperature.
- Superheating the steam to higher temperatures has another very desirable effect:
  - **It decreases the moisture content of the steam at the turbine exit**
  - Metallurgical factors place a limit on how hot steam can be superheated.

Increasing the Boiler Pressure

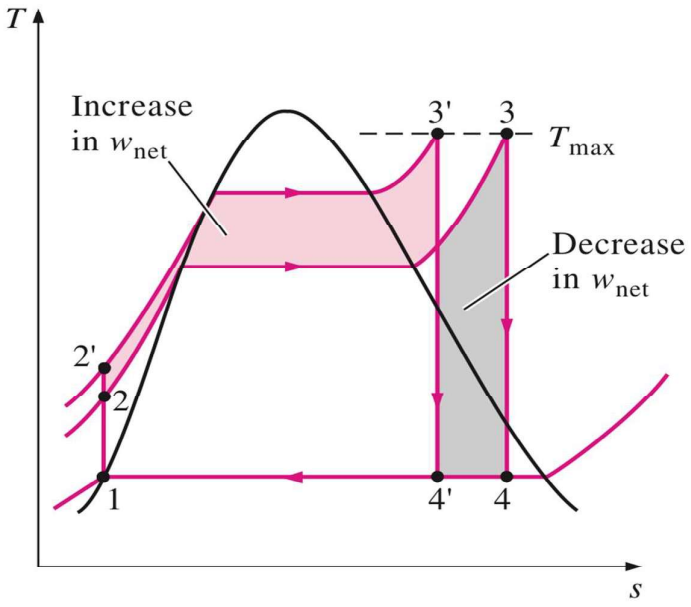


FIGURE 10–8

The effect of increasing the boiler pressure on the ideal Rankine cycle.

- to increase the operating pressure of the boiler, which automatically raises the temperature at which boiling takes place
- This, in turn, raises the average temperature at which heat is transferred to the steam and thus raises the thermal efficiency of the cycle.
- Notice that for a fixed turbine inlet temperature, the cycle shifts to the left and the moisture content of steam at the turbine exit increases. This undesirable side effect can be corrected, however, by reheating the steam

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10-5 · THE IDEAL REHEAT RANKINE CYCLE

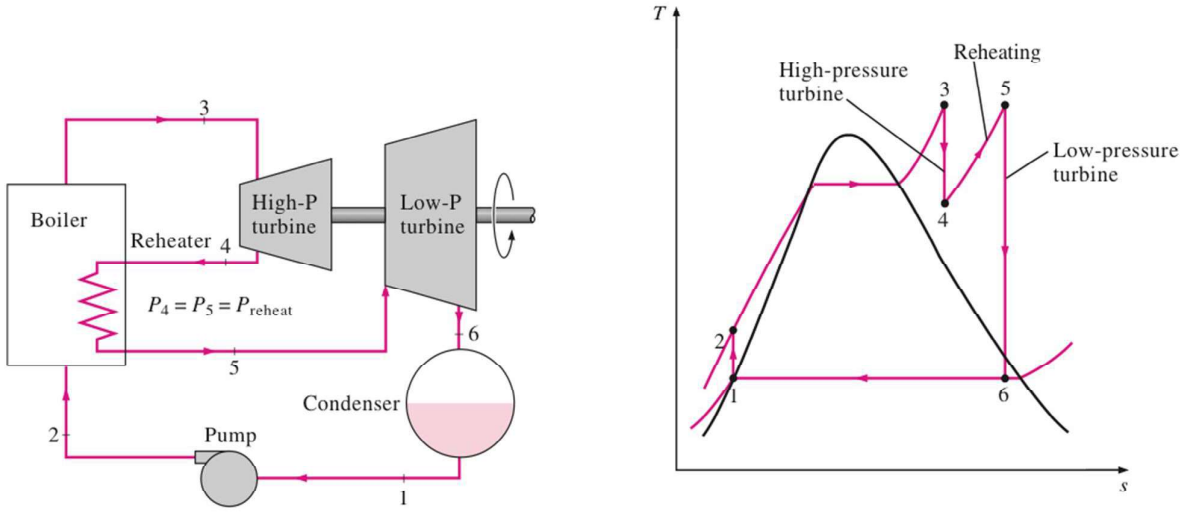


FIGURE 10–11
The ideal reheat Rankine cycle.

Expansion process takes place in two stages

- the first stage (the high pressure turbine), steam is expanded isentropically to an intermediate pressure and sent back to the boiler where it is reheated at constant pressure usually to the inlet temperature of the first turbine stage.
- Steam then expands isentropically in the second stage (low-pressure turbine) to the condenser pressure.

The total heat input and the total turbine work output for a reheat cycle become

$$q_{in} = q_{primary} + q_{reheat} = (h_3 - h_2) + (h_5 - h_4) \qquad (10\text{–}12)$$

and

$$w_{turb,out} = w_{turb,I} + w_{turb,II} = (h_3 - h_4) + (h_5 - h_6) \qquad (10\text{–}13)$$

- The incorporation of the single reheat in a modern power plant improves the cycle efficiency by 4 to 5 percent by increasing the average temperature at which heat is transferred to the steam.

- Remember that the sole purpose of the reheat cycle is to reduce the moisture content of the steam at the final stages of the expansion process. If we had materials that could withstand sufficiently high temperatures, there would be no need for the reheat cycle.

10-6 · THE IDEAL REGENERATIVE RANKINE CYCLE

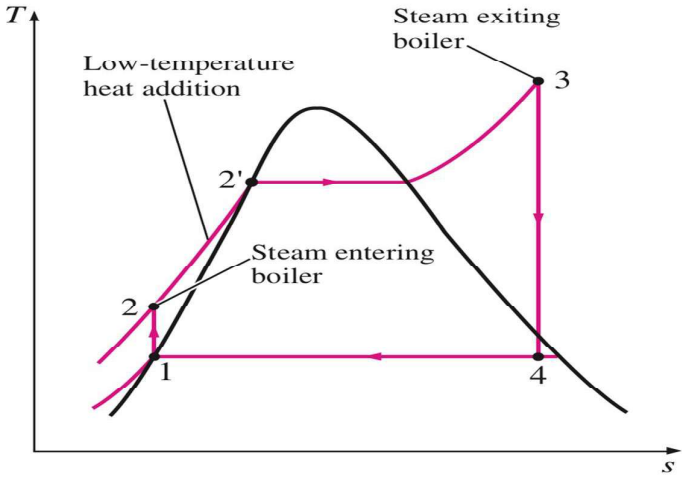


FIGURE 10–14

The first part of the heat-addition process in the boiler takes place at relatively low temperatures.

- The T-s diagram of the Rankine cycle redrawn in Fig. 10–14 reveals that heat is transferred to the working fluid during process 2-2' at a relatively low temperature
  - This lowers the average heat addition temperature and thus the cycle efficiency.
  - This steam, which could have produced more work by expanding further in the turbine, is used to heat the feedwater instead.
  - The device where the feedwater is heated by regeneration is called a regenerator, or a feedwater heater (FWH)
  - Regeneration not only improves cycle efficiency, but also provides a convenient means of deaerating the feedwater (removing the air that leaks in at the condenser) to prevent corrosion in the boiler
  - It also helps control the large volume flow rate of the steam at the final stages of the turbine (due to the large specific volumes at low pressures
  - A feedwater heater is basically a heat exchanger where heat is transferred from the steam to the feedwater either by mixing the two fluid streams (open feedwater heaters) or without mixing them (closed feedwater heaters

Open Feedwater Heaters

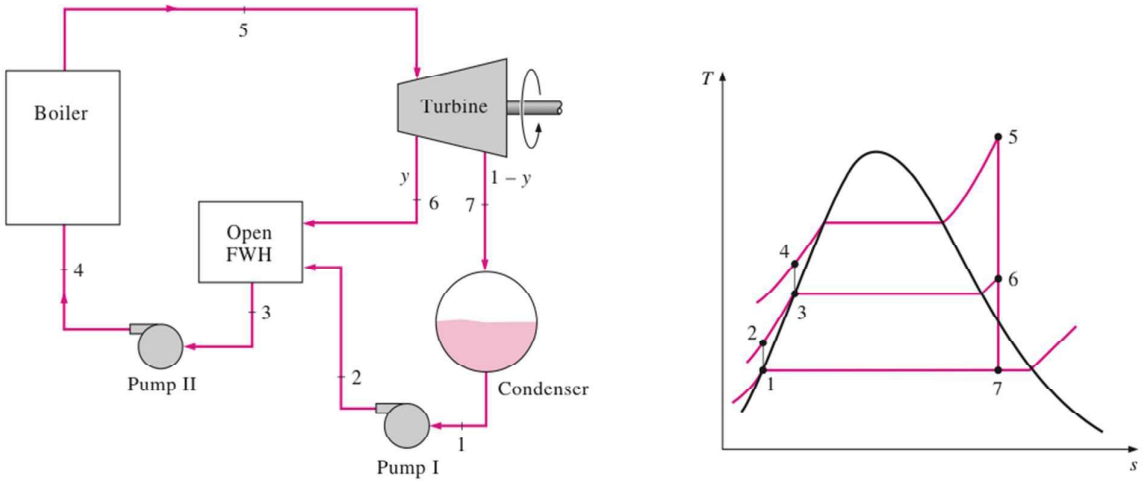


FIGURE 10–15
The ideal regenerative Rankine cycle with an open feedwater heater.

- Refer to above figure for the schematic diagram
- An open (or direct-contact) feedwater heater is basically a mixing chamber, where the steam extracted from the turbine mixes with the feedwater exiting the pump
- Ideally, the mixture leaves the heater as a saturated liquid at the heater pressure(state 3).
- In an ideal regenerative Rankine cycle, steam enters the turbine at the boiler pressure (state 5)
- expands isentropically to an intermediate pressure (state 6)
- Some steam is extracted at this state and routed to the feedwater heater, while the remaining steam continues to expand isentropically to the condenser pressure (state 7
- This steam leaves the condenser as a saturated liquid at the condenser pressure (state 1)
- The condensed water, which is also called the feedwater, then enters an isentropic pump, where it is compressed to the feedwater heater pressure (state 2) and is routed to the feedwater heater, where it mixes with the steam extracted from the turbine
- The fraction of the steam extracted is such that the mixture leaves the heater as a saturated liquid at the heater pressure (state 3)
- second pump raises the pressure of the water to the boiler pressure (state 4).
- The cycle is completed by heating the water in the boiler to the turbine inlet state (state 5).

Rankine cycle with one feedwater heater can be expressed per unit mass of steam flowing through the boiler as follows

$$q_{in} = h_5 - h_4 \quad \textbf{(10–14)}$$

$$q_{out} = (1 - y)(h_7 - h_1) \quad \textbf{(10–15)}$$

$$w_{turb,out} = (h_5 - h_6) + (1 - y)(h_6 - h_7) \quad \textbf{(10–16)}$$

$$w_{pump,in} = (1 - y)w_{pump\ I,in} + w_{pump\ II,in} \quad \textbf{(10–17)}$$

where

$$y = \dot{m}_6/\dot{m}_5 \qquad \text{(fraction of steam extracted}$$

$$w_{pump\ I,in} = v_1(P_2 - P_1)$$

$$w_{pump\ II,in} = v_3(P_4 - P_3)$$

- The thermal efficiency of the Rankine cycle increases as a result of regeneration. This is because regeneration raises the average temperature at which heat is transferred to the steam in the boiler by raising the temperature of the water before it enters the boiler
- The cycle efficiency increases further as the number of feedwater heaters is increased
- Many large plants in operation today use as many as eight feedwater heaters

Closed Feedwater Heaters

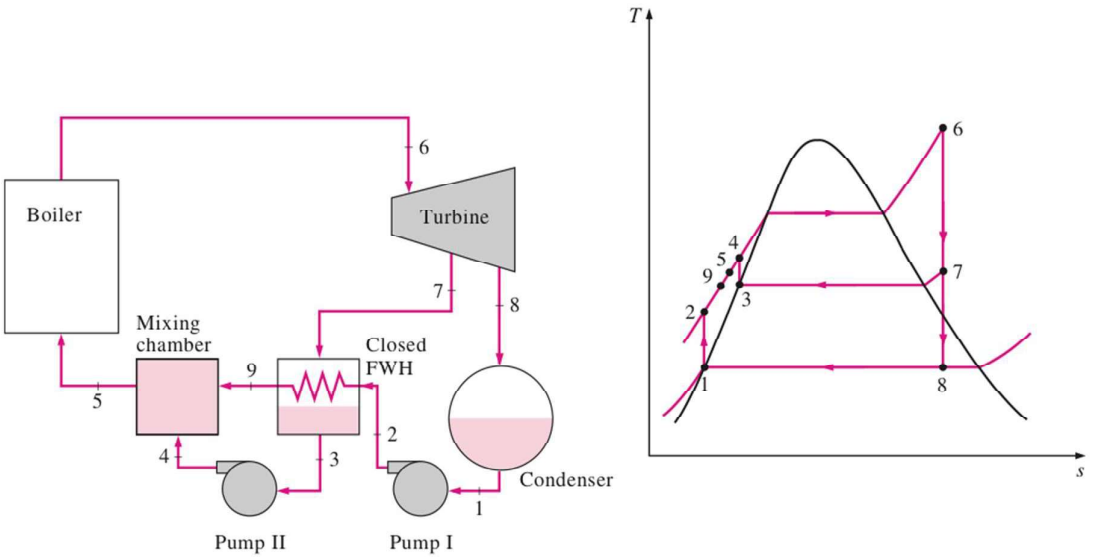


FIGURE 10–16
The ideal regenerative Rankine cycle with a closed feedwater heater.

- Here heat is transferred from the extracted steam to the feedwater without any mixing taking place
- The two streams now can be at different pressures, since they do not mix.
- In an ideal closed feedwater heater, the feedwater (at state 2) is heated to the exit temperature of the extracted steam(T at state 7),
- extracted steam (at state 7) ideally leaves the heater as a saturated liquid at the extraction pressure (i.e. state 3 is saturated liquid at extraction pressure)
- In actual power plants, the feedwater leaves the heater below the exit temperature(T9 <T7)
- The open and closed feedwater heaters can be compared as follows
    - Open feedwater heaters are simple and inexpensive and have good heat transfer characteristics
        - They also bring the feedwater to the saturation state
        - For each heater, however, a pump is required to handle the feedwater.
    - closed feedwater heaters do not require a separate pump for each heater since the extracted steam and the feedwater can be at different pressures
        - closed feed water heater is less effective since two streams are not allowed to mix together.

10-8 COGENERATION

10-7 SECOND-LAW ANALYSIS DF VAPOR POWER CYCLES