Lecture Five

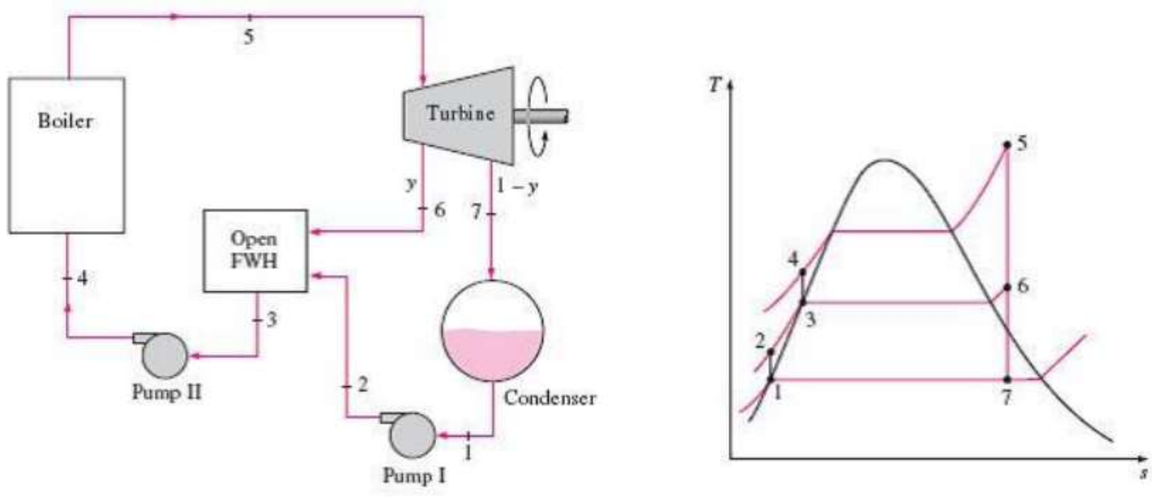
The Regenerative Rankine Cycle

A practical regeneration process in steam power plants is accomplished by extracting or (bleeding) steam from the turbine at various points. 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). Therefore, regeneration has been used in all modern steam power plants since its introduction in the early 1920s.

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). Regeneration with both types of feedwater heaters is discussed below.

1. Open Feedwater Heaters: It is an open (or direct-contact) feedwater heater, it 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. The schematic of a steam power plant with one open feedwater heater (also called single-stage regenerative cycle) and the (*T-S*) diagram of the cycle are shown in figure below.



Ideal Rankine Cycle with (Open Feedwater Heater)

In an ideal regenerative Rankine cycle, steam enters the turbine at the boiler pressure (state 5) and 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). A 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).

In the analysis of steam power plants, it is more convenient to work with quantities expressed per unit mass of the steam flowing through the boiler. For each 1 kg of steam leaving the boiler, (y) kg expands partially in the turbine and is extracted at state 6. The remaining $(1-y)$ kg expands completely to the condenser pressure. Therefore, the mass flow rates are different in different components. If the mass flow rate through the boiler is m°, for example, it is $(1-y)\times m^{\circ}$ through the condenser. This aspect of the regenerative Rankine cycle should be considered in the analysis of the cycle as well as in the interpretation of the areas on the (*T-S*) diagram. The heat and work interactions of a regenerative Rankine cycle with one feedwater heater can be expressed per unit mass of steam flowing through the boiler as follows:

$$q_{add} = h_5 - h_4$$

$$q_{rej} = (1-y)\times(h_7 - h_1)$$

$$w_{turbine,out} = (h_5 - h_6) + (1-y)\times(h_6 - h_7)$$

$$w_{pump,in} = (1-y)\times w_{pump\ 1} + w_{pump\ 2}$$

$$y = m_6^{\circ}/m_5^{\circ}$$

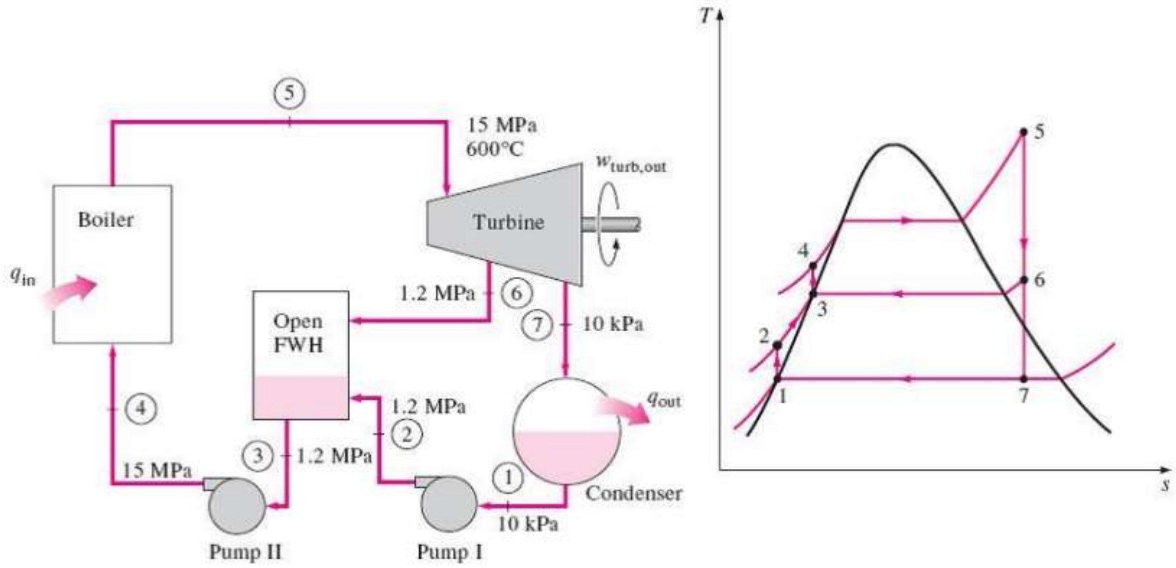
$$w_{pump,I} = v_1(P_2 - P_1) = h_2 - h_1$$

$$w_{pump,II} = v_3(P_4 - P_3) = h_4 - h_3$$

The thermal efficiency of the Rankine cycle increases as a result of regeneration. The cycle efficiency increases further as the number of feedwater heaters is increased. The optimum number of feedwater heaters is determined from economic considerations.

Example (5.5) Consider a steam power plant operating on the ideal regenerative Rankine cycle with one open feedwater heater. Steam enters the turbine at 15 MPa and 600°C and is condensed in the condenser at a pressure of 10 kPa. Some steam leaves the turbine at a pressure of 1.2 MPa and enters the open feedwater heater. Determine the fraction of steam extracted from the turbine and the thermal efficiency of the cycle.

Solution:



State1 : at $P_1 = 10$ kPa and saturated liquid:
$h_1 = h_f = 191.81$ kJ/kg and $v_1 = v_f = 0.00101$ m^3/kg

State 2: at $P_2 = 1.2$ MPa and $s_2 = s_1$

$$w_{pump,I} = v_1(P_2 - P_1) = 0.00101 \times (1.2 \times 10^3 - 10) = 1.2 \text{ kJ/kg}$$

$$w_{pump,I} = h_2 - h_1 \rightarrow h_2 = 191.81 + 1.2 = 193.01 \text{ kJ/kg}$$

State 3: at $P_3 = 1.2$ MPa and saturated liquid:

$v_3 = v_f = 0.001138$ m^3/kg and $h_3 = h_f = 798.33$ kJ/kg

State 4: at $P_4 = 15$ MPa and $s_4 = s_3$

$$w_{pump,II} = v_3(P_4 - P_3) = 0.001138 \times (15 \times 10^3 - 1.2 \times 10^3) = 15.7 \text{ kJ/kg}$$

$$w_{pump,II} = h_4 - h_3 \rightarrow h_4 = 798.33 + 15.7 = 814.03 \text{ kJ/kg}$$

State 5: at $P_5 = 15$ MPa and $T_5 = 600°C$

Thus, $h_5 = 3583.1$ kJ/kg and $s_5 = 6.6796$ kJ/kg. K

State 6: $P_6 = 1.2$ MPa and $s_6 = s_5$

Thus, $h_6 = 2860.2$ kJ/kg and $T_6 = 218.4°C$

State 7: $P_7 = 10$ kPa and $s_7 = s_5$

$$s_7 = s_f + x_7.s_{fg} \rightarrow x_7 = \frac{s_7 - s_f}{s_{fg}} = \frac{6.679 - 0.6492}{7.4996} = 0.8041$$

$$h_7 = h_f + x_7 h_{fg} = 191.81 + 0.8041 \times 2392.1 = 2115.3 \text{ kJ/kg}$$

The energy analysis of open feedwater heaters is identical to the energy analysis of mixing chambers. The feedwater heaters are generally well insulated ($Q = 0$), and they do not involve any work interactions ($W = 0$). The energy balance of the feedwater heater is:

$$e_{in} = e_{out} \rightarrow \sum_{in} m^{\circ}h = \sum_{out} m^{\circ}h$$

$$y \times h_6 + (1-y) \times h_2 = 1 \times h_3 \rightarrow y = \frac{h_3 - h_2}{h_6 - h_2} = \frac{798.33 - 193.01}{2860.2 - 193.01} = 0.227$$

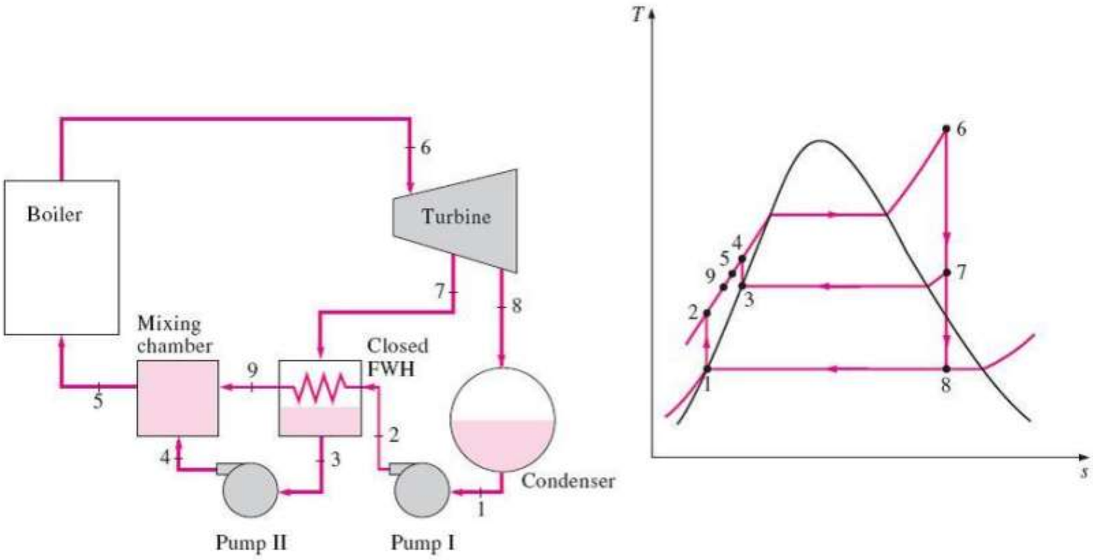
$$q_{add} = h_5 - h_4 = 3583.1 - 814.03 = 2769.1 \text{ kJ/kg}$$

$$q_{rej} = (1-y)(h_7 - h_1) = (1 - 0.227) \times (2115.3 - 191.81) = 1486.9 \text{ kJ/kg}$$

$$\eta_{th} = 1 - \frac{q_{rej}}{q_{add}} = 1 - \frac{1486.9}{2769.1}$$

$\boldsymbol{\eta_{th} = 46.29\%}$ **Ans.**

2. Closed Feedwater Heaters: It is another type of feedwater heater used in steam power plants, in which 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. The schematic of a steam power plant with one closed feedwater heater and the (*T-S*) diagram of the cycle are shown in figure.



Ideal Rankine Cycle with (Closed Feedwater Heater)

Most steam power plants use a combination of open and closed feedwater heaters or reheating with feedwater heaters.