اسم المادة : ثرموداينميك 2
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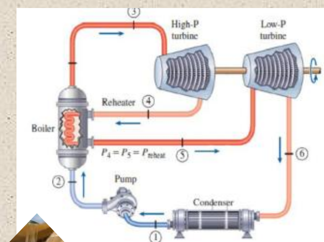
عنوان المحاضرة: دورات القدرة البخارية 2

Thermodynamic II

LECTURE 5

Vapor Power Cycles II



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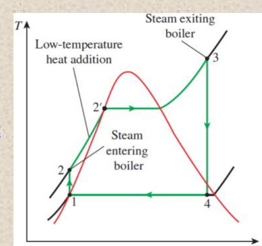
THE IDEAL REHEAT RANKINE CYCLE

We noted , that increasing the boiler pressure increases the thermal efficiency of the Rankine cycle, but it also increases the moisture content of the steam to unacceptable levels.



Then it is natural to ask the following question:

How can we take advantage of the increased efficiencies at higher boiler pressures without facing the problem of excessive moisture at the final stages of the turbine?

Two possibilities come to mind:

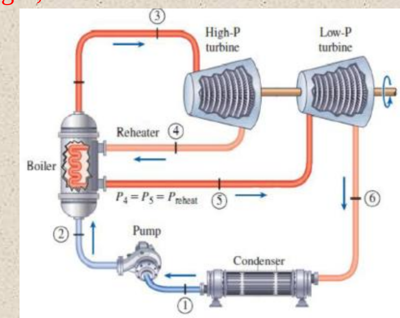
1. Superheat the steam to very high temperatures before it enters the turbine.

This would be the desirable solution since the average temperature at which heat is added would also increase, thus increasing the cycle efficiency.

This is not a viable solution, however, since it requires raising the steam temperature to metallurgically unsafe levels.

2. Expand the steam in the turbine in two stages, and reheat it in between.

- In other words, modify the simple ideal Rankine cycle with a **reheat** process.
- Reheating is a practical solution to the excessive moisture problem in turbines, and it is commonly used in modern steam power plants.
- The *T-s* diagram of the ideal reheat Rankine cycle and the schematic of the power plant operating on this cycle are shown in Fig.8



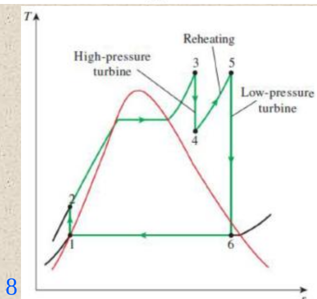
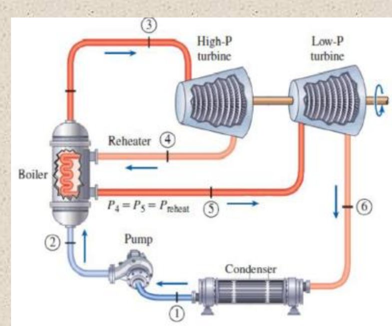
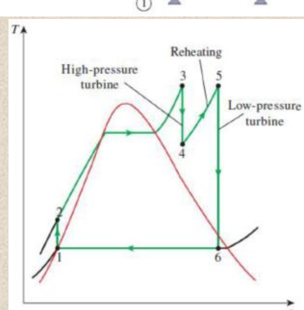


FIGURE 8
The ideal reheat Rankine cycle.

The ideal reheat Rankine cycle differs from the simple ideal Rankine cycle in that the expansion process takes place in two stages.

- In 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. Thus the total heat input and the total turbine work output for a reheat cycle become

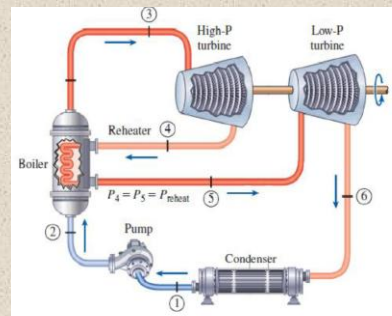




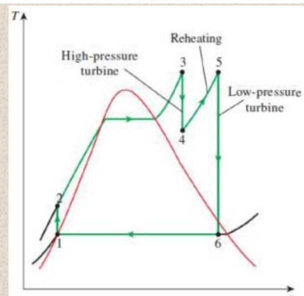
Thus the total heat input and the total turbine work output for a reheat cycle become:

$$q_{in} = q_{primary} + q_{reheat} = (h_3 - h_2) + (h_5 - h_4)$$

$$W_{turb,out} = W_{turb,I} + W_{turb,II} = (h_3 - h_4) + (h_5 - h_6)$$

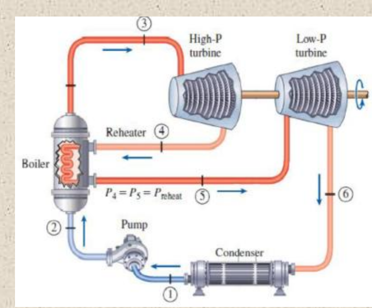


The incorporation of the single reheat in a modern power plant improves the cycle efficiency by 4 to 5 percent by increasing the average temperature at which heat is transferred to the steam.



Example 3

A steam power plant operates on the ideal reheat Rankine cycle. Steam enters the high pressure turbine at 8 MPa and 500°C and leaves at 3 MPa. Steam is then reheated at constant pressure to 500°C before it expands to 20 kPa in the low-pressure turbine. Determine the turbine work output, in kJ/kg, and the thermal efficiency of the cycle. Also, show the cycle on a *T-s* diagram with respect to saturation lines.



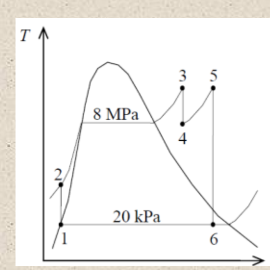
Analysis From the steam tables (Tables A-4, A-5, and A-6),

$$h_1 = h_{f@\,20\text{ kPa}} = 251.42 \text{ kJ/kg}$$

$$v_1 = v_{f@\,20\text{ kPa}} = 0.001017 \text{ m}^3\text{/kg}$$

$$w_{p,in} = v_1(P_2 - P_1) = (0.001017 \text{ m}^3\text{/kg})(8000 - 20 \text{ kPa})\left(\frac{1 \text{ kJ}}{1 \text{ kPa}\cdot\text{m}^3}\right) = 8.12 \text{ kJ/kg}$$

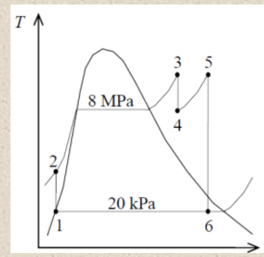
$$h_2 = h_1 + w_{p,in} = 251.42 + 8.12 = 259.54 \text{ kJ/kg}$$



$$P_3 = 8 \text{ MPa}, \; T_3 = 500°C \quad \Big\} \quad h_3 = 3399.5 \text{ kJ/kg}, \; s_3 = 6.7266 \text{ kJ/kg}\cdot\text{K}$$

$$P_4 = 3 \text{ MPa}, \; s_4 = s_3 \quad \Big\} \quad h_4 = 3105.1 \text{ kJ/kg}$$

$$P_5 = 3 \text{ MPa}, \; T_5 = 500°C \quad \Big\} \quad h_5 = 3457.2 \text{ kJ/kg}, \; s_5 = 7.2359 \text{ kJ/kg}\cdot\text{K}$$



$$P_6 = 20 \text{ kPa}, \; s_6 = s_5 \quad \Big\} \quad x_6 = \frac{s_6 - s_f}{s_{fg}} = \frac{7.2359 - 0.8320}{7.0752} = 0.9051$$

$$h_6 = h_f + x_6 h_{fg} = 251.42 + (0.9051)(2357.5) = 2385.2 \text{ kJ/kg}$$

The turbine work output and the thermal efficiency are determined from

$$w_{\text{T,out}} = (h_3 - h_4) + (h_5 - h_6) = 3399.5 - 3105.1 + 3457.2 - 2385.2 = \mathbf{1366.4 \;\; kJ/kg}$$

and

$$q_{\text{in}} = (h_3 - h_2) + (h_5 - h_4) = 3399.5 - 259.54 + 3457.2 - 3105.1 = 3492.0 \text{ kJ/kg}$$

$$w_{\text{net}} = w_{T,out} - w_{p,\text{in}} = 1366.4 - 8.12 = 1358.3 \text{ kJ/kg}$$

Thus,

$$\eta_{\text{th}} = \frac{w_{\text{net}}}{q_{\text{in}}} = \frac{1358.3 \text{ kJ/kg}}{3492.5 \text{ kJ/kg}} = \mathbf{38.9\%}$$

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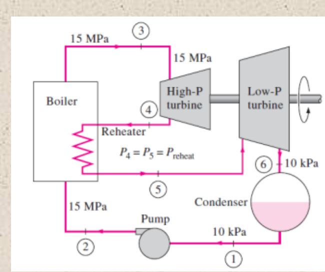
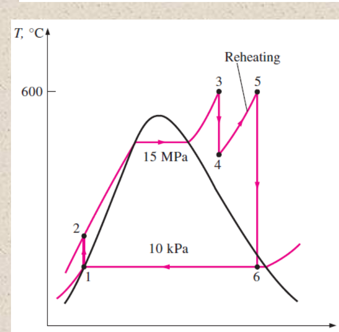
Example 5

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





Solution:

a) State 6: at $P_6 = 10$ kPa and $x_6 = 0.896$

$$s_6 = sf + x_6 s_{fg} = 0.6492 + 0.896 \times (7.34996)$$
$$= 7.3688 \text{ kJ/kg. K}$$

$$h_6 = h_f + x_6 h_{fg} = 191.8 + 0.896 \times (2392.1)$$
$$= 2335.1 \text{ kJ/kg}$$

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Thus, $T_5 = 600°C$ and $s_5 = s_6 = 7.3688$ kJ/kg. K

And, $P_5 = 4$ MPa and $h_5 = 3674.9$ kJ/kg
From steam table at T_5 and s_5

So the steam should be reheated at a pressure of 4 MPa to prevent a moisture content greater than 10.4%.

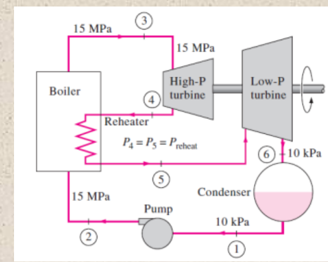
b) The thermal efficiency is calculated as follows:
State 1: at $P_1 = 10$ kPa
$h_1 = h_f = 191.81$ kJ/kg and $v_1 = v_f = 0.00101$ m³/kg

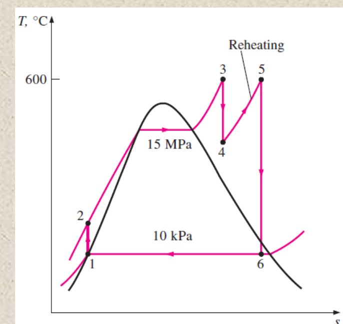
State 2: at $P_2 = 15$ MPa and $s_2 = s_1$

$$w_{pump} = v_1(P_2 - P_1) = 0.00101 \times (15 \times 103 - 10)$$
$$= 15.14 \text{ kJ/kg}$$
$$w_{pump} = h_2 - h_1 \rightarrow h_2 = 191.81 + 15.14$$
$$= 206.96 \text{ kJ/kg}$$

State 3: at $P_3 = 15$ MPa and $T_3 = 600°C$

From superheated steam tables: $h_3 = 3583.1$ kJ/kg and $s_3 = 6.6796$ kJ/kg. K





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

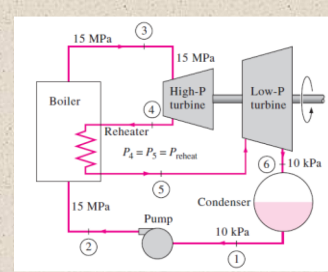
From superheated steam tables: $h_4 = 3155$ kJ/kg and $T_4 = 375.5°C$

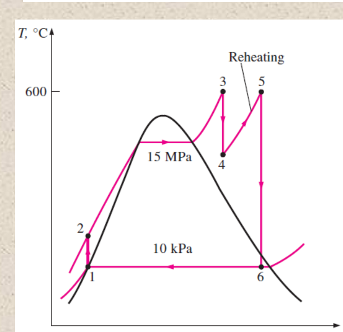
$$q_{in} = (h_3 - h_2) + (h_5 - h_4)$$
$$q_{in} = (3583.1 - 206.95) + (3674.9 - 3155.0)$$
$$= 3896.1 \text{ kJ/kg}$$

$$q_{out} = h_6 - h_1 = 2335.1 - 191.8 = 2143.3 \text{ kJ/kg}$$

$$\eta_{th} = 1 - \frac{q_{out}}{q_{in}} = 1 - \frac{2143.3}{3896.1}$$

$\boldsymbol{\eta_{th} = 45\%}$ **Ans.**





THE IDEAL REGENERATIVE RANKINE CYCLE

- A careful examination of the *T-s* diagram of the Rankine cycle redrawn in Fig. 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.
- To remedy this shortcoming, we look for ways to raise the temperature of the liquid leaving the pump (called the *feedwater*) before it enters the boiler.
- One such possibility is to transfer heat to the feedwater from the expanding steam in a counterflow heat exchanger built into the turbine, that is, to use **regeneration**.

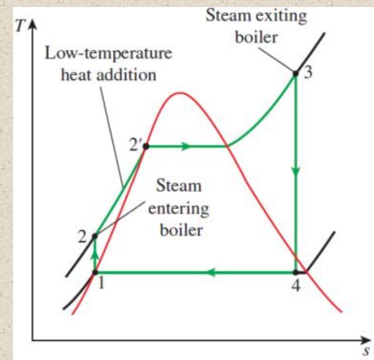


FIGURE 9
The first part of the heat-addition process in the boiler takes place at relatively low temperatures

This solution is also impractical because it is difficult to design such a heat exchanger and because it would increase the moisture content of the steam at the final stages of the turbine.

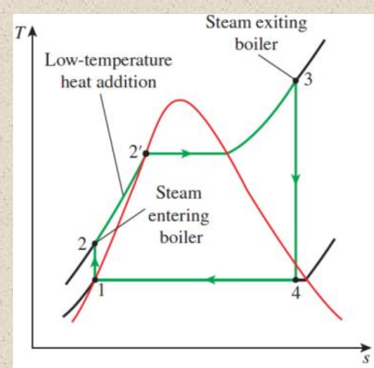


FIGURE 9
The first part of the heat-addition process in the boiler takes place at relatively low temperatures

OPEN FEEDWATER HEATERS

- 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. 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 Fig. 10.
- 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).

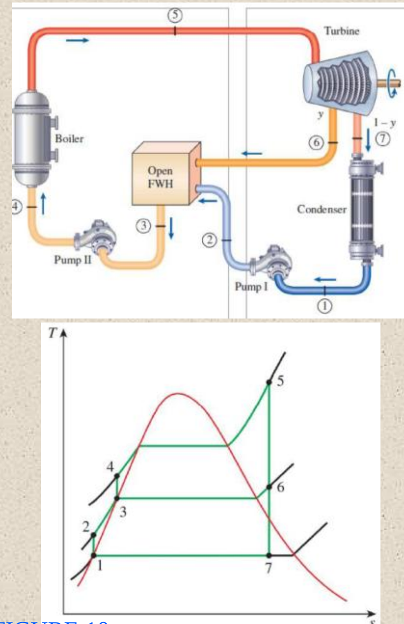
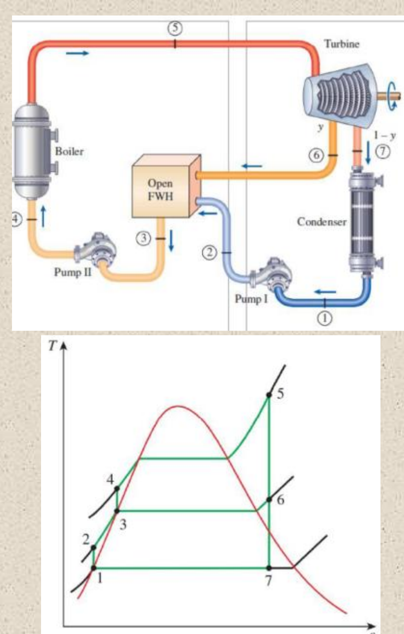
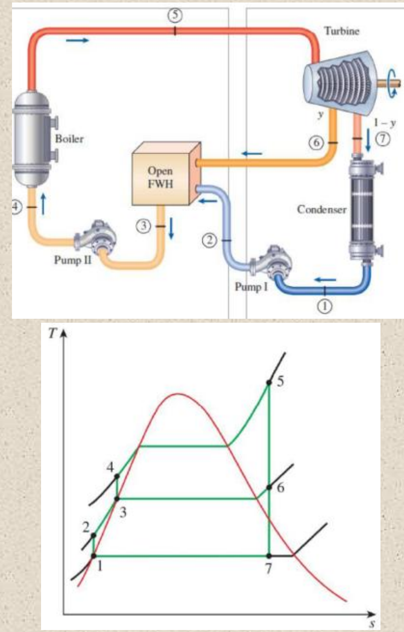


FIGURE 10
The ideal regenerative Rankine cycle with an open feedwater heater.

- 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 $\dot{m}$, for example, it is $(1 - y)\,\dot{m}$ 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.



- In light of Fig. 10, 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:

$$\dot{m}_2 + \dot{m}_6 = \dot{m}_3$$

Satisfied with the *extraction fraction* as

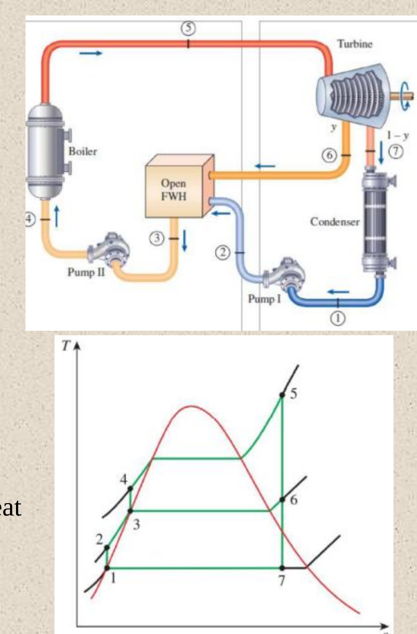
$$y = \dot{m}_6/\dot{m}_5$$

so

$$\dot{m}_7 = (1 - y)\,\dot{m}_5 = \dot{m}_1 = \dot{m}_2$$

The energy equation with no external heat transfer and no work becomes

$$\dot{m}_2 h_2 + \dot{m}_6 h_6 = \dot{m}_3 h_3$$



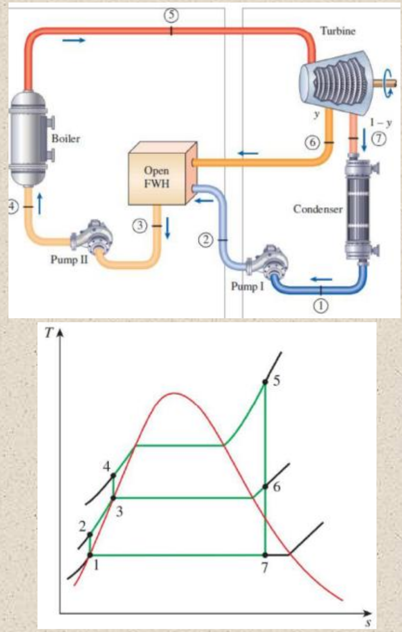
into which we substitute the mass flow rates

$(\dot{m}_3 = \dot{m}_5)$ as

$$(1 - y)\,\dot{m}_5 h_2 + y\dot{m}_5 h_6 = \dot{m}_5 h_3$$

We take state 3 as the limit of saturated liquid (we do not want to heat it further, as it would move into the two-phase region and damage the pump P_2) and then solve for y:

$$y = \frac{h3 - h2}{h6 - h2}$$



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

$$q_{out} = (1 - y)(h_7 - h_1)$$

$$W_{turb,out} = (h_5 - h_6) + (1 - y)(h_6 - h_7)$$

$$W_{pump,in} = (1 - y)\,W_{pump\ I,in} + W_{pump\ II,in}$$

where

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

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

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

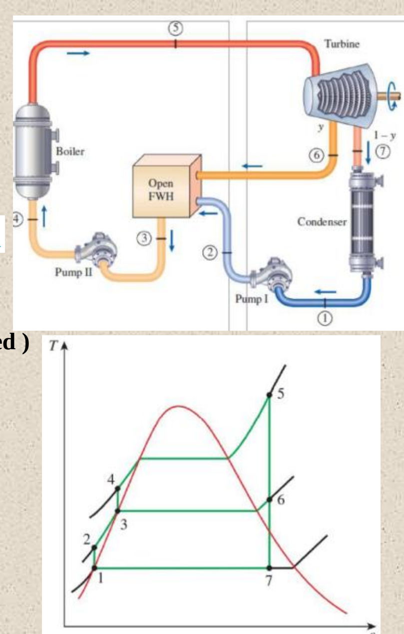

FIGURE 10

The ideal regenerative Rankine cycle with an open feedwater heater.

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- 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.
- The optimum number of feedwater heaters is determined from economic considerations. The use of an additional feedwater heater cannot be justified unless it saves more in fuel costs than its own cost.

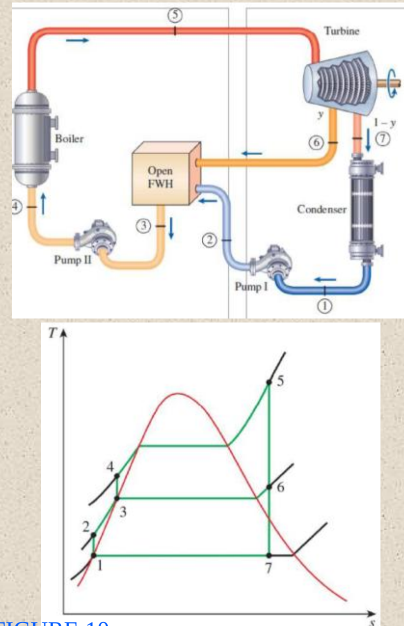


FIGURE 10
The ideal regenerative Rankine cycle with an open feedwater heater.

CLOSED FEEDWATER HEATERS

- Another type of feedwater heater often used in steam power plants is the **closed feedwater heater**, 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 Fig. 11.
- In an ideal closed feedwater heater, the feedwater is heated to the exit temperature of the extracted steam, which ideally leaves the heater as a saturated liquid at the extraction pressure.

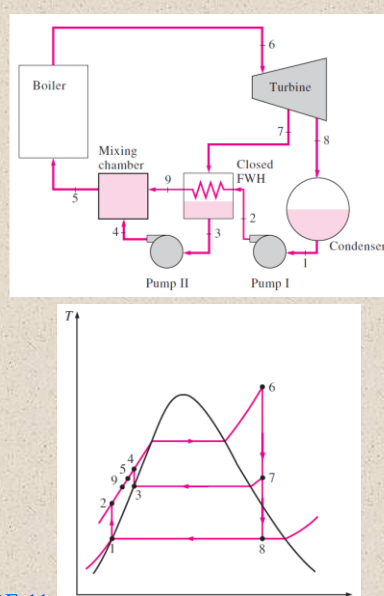


FIGURE 11
The ideal regenerative Rankine cycle with an closed feedwater heater.

- In actual power plants, the feedwater leaves the heater below the exit temperature of the extracted steam because a temperature difference of at least a few degrees is required for any effective heat transfer to take place.

- The condensed steam is then either pumped to the feedwater line or routed to another heater or to the condenser through a device called a **trap**. A trap allows the liquid to be throttled to a lower-pressure region but *traps* the vapor. The enthalpy of steam remains constant during this throttling process.

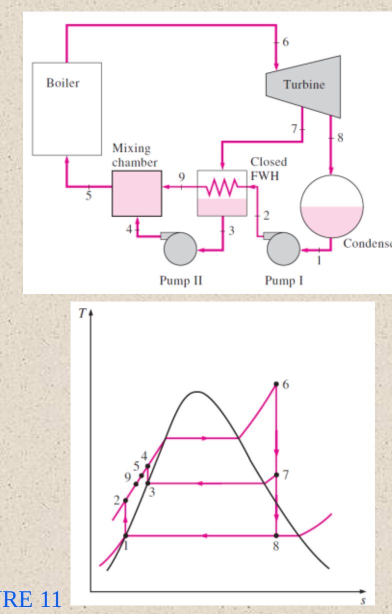


FIGURE 11
The ideal regenerative Rankine cycle with an closed feedwater heater.

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.
- The closed feedwater heaters are more complex because of the internal tubing network, and thus they are more expensive.
- Heat transfer in closed feedwater heaters is also less effective since the two streams are not allowed to be in direct contact. However, closed feedwater heaters do not require a separate pump for each heater since the extracted steam and the feedwater can be at different pressures.

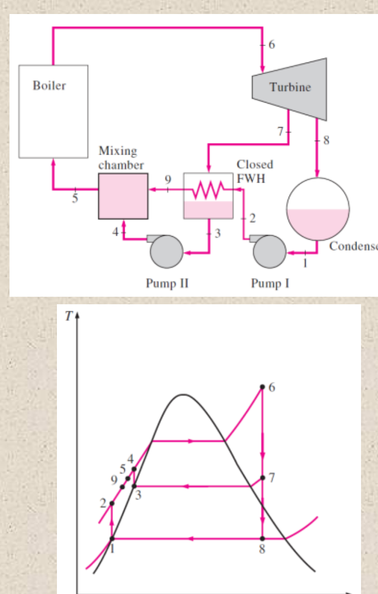


FIGURE 11
The ideal regenerative Rankine cycle with an closed feedwater heater.

Most steam power plants use a combination of open and closed feedwater heaters, as shown in Fig. 12

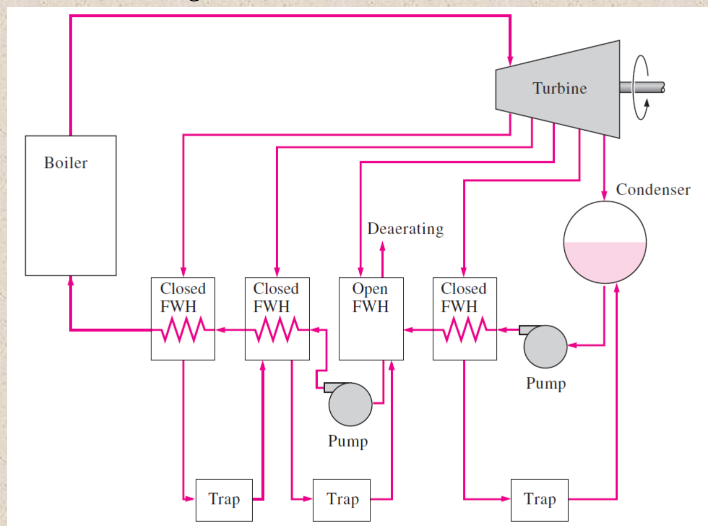
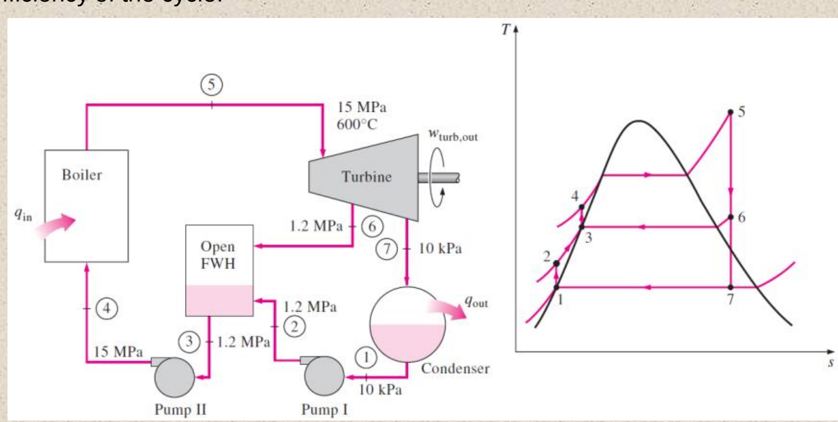


FIGURE 12
A steam power plant with one open and three closed feedwater heaters.

Example 4

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

State 1:

P_1 =10 kPa , Sat. liquid

$h_1 = h_{f@\,10\text{ kPa}} = 191.81$ kJ/kg

$v_1 = v_{f@\,10\text{ kPa}} = 0.00101\ \text{m}^3/\text{kg}$

State 2:

$$P_2 = 1.2\ \text{MPa}$$

$$s_2 = s_1$$

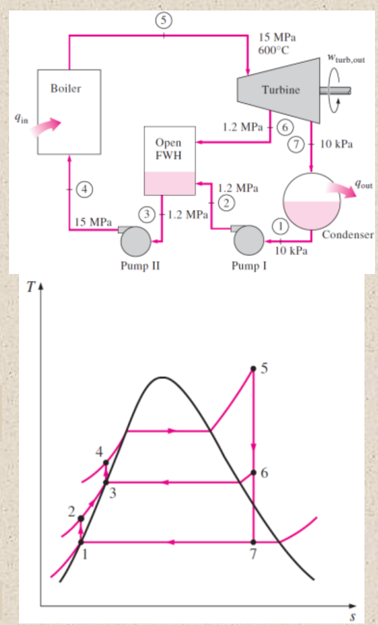
$$w_{\text{pump I,in}} = v_1(P_2 - P_1)$$

$$= (0.00101\ \text{m}^3/\text{kg})[(1200 - 10)\ \text{kPa}]\left(\frac{1\ \text{kJ}}{1\ \text{kPa}\cdot\text{m}^3}\right)$$

$$= 1.20\ \text{kJ/kg}$$

$$h_2 = h_1 + w_{\text{pump I,in}}$$

$$= (191.81 + 1.20)\ \text{kJ/kg} = 193.01\ \text{kJ/kg}$$



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State 3:

$$\left.\begin{array}{l} P_3 = 1.2\ \text{MPa} \\ \text{Sat. liquid} \end{array}\right\} \quad \begin{array}{l} v_3 = v_{f\,@\,1.2\text{ MPa}} = 0.001138\ \text{m}^3/\text{kg} \\ h_3 = h_{f\,@\,1.2\text{ MPa}} = 798.33\ \text{kJ/kg} \end{array}$$

State 4: $P_4 = 15$ MPa

$$s_4 = s_3$$

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

$$= (0.001138\ \text{m}^3/\text{kg})[(15{,}000 - 1200)\ \text{kPa}]\left(\frac{1\ \text{kJ}}{1\ \text{kPa}\cdot\text{m}^3}\right)$$

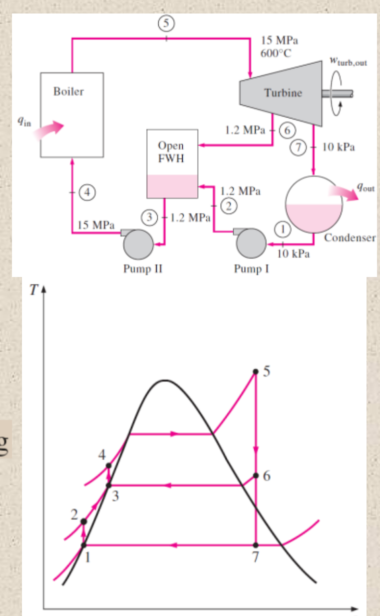
$$= 15.70\ \text{kJ/kg}$$

$$h_4 = h_3 + w_{\text{pump II,in}}$$

$$= (798.33 + 15.70)\ \text{kJ/kg} = 814.03\ \text{kJ/kg}$$

State 5:

$$\left.\begin{array}{l} P_5 = 15\ \text{MPa} \\ T_5 = 600^\circ\text{C} \end{array}\right\} \quad \begin{array}{l} h_5 = 3583.1\ \text{kJ/kg} \\ s_5 = 6.6796\ \text{kJ/kg}\cdot\text{K} \end{array}$$



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State 6:

$$\left.\begin{array}{l} P_6 = 1.2 \text{ MPa} \\ s_6 = s_5 \end{array}\right\} \quad \begin{array}{l} h_6 = 2860.2 \text{ kJ/kg} \\ (T_6 = 218.4°\text{C}) \end{array}$$

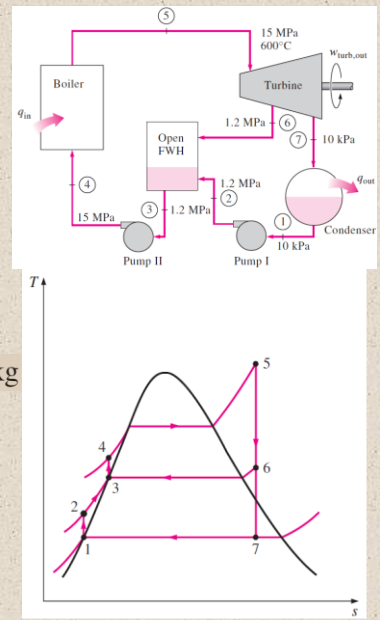
State 7: $P_7 = 10 \text{ kPa}$

$$s_7 = s_5$$

$$x_7 = \frac{s_7 - s_f}{s_{fg}} = \frac{6.6796 - 0.6492}{7.4996} = 0.8041$$

$$h_7 = h_f + x_7 h_{fg}$$

$$= 191.81 + 0.8041(2392.1) = 2115.3 \text{ kJ/kg}$$



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The energy analysis of open feedwater heaters is identical to the energy analysis of mixing chambers. The feedwater heaters are generally well insulated ($\dot{Q} = 0$), and they do not involve any work interactions ($\dot{W} = 0$) By neglecting the kinetic and potential energies of the streams, the energy balance reduces for a feedwater heater to

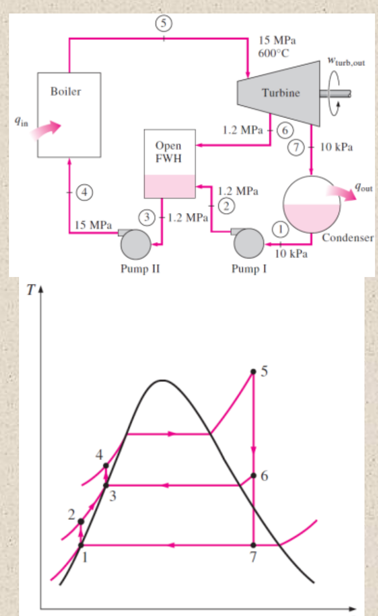
$$\dot{E}_{\text{in}} = \dot{E}_{\text{out}} \rightarrow \sum_{\text{in}} \dot{m}h = \sum_{\text{out}} \dot{m}h$$

or

$$yh_6 + (1 - y)h_2 = 1(h_3)$$

where *y* is the fraction of steam extracted from the turbine ($\dot{m}_6 / \dot{m}_5$). Solving for *y* and substituting the enthalpy values, we find

$$y = \frac{h_3 - h_2}{h_6 - h_2} = \frac{798.33 - 193.01}{2860.2 - 193.01} = \mathbf{0.2270}$$



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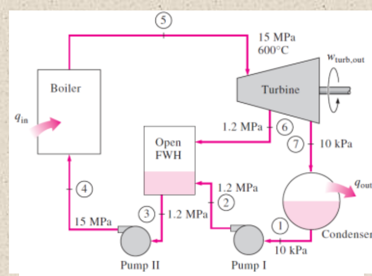
Thus,

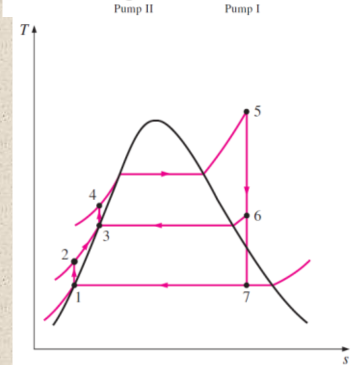
$q_{in} = h_5 - h_4 = (3583.1 - 814.03)$ kJ/kg
$= 2769.1$ kJ/kg

$q_{out} = (1 - y)(h_7 - h_1)$
$= (1 - 0.2270)(2115.3 - 191.81)$ kJ/kg
$= 1486.9$ kJ/kg

and

$$\eta_{th} = 1 - \frac{q_{out}}{q_{in}} = 1 - \frac{1486.9 \text{ kJ/kg}}{2769.1 \text{ kJ/kg}} = \mathbf{0.463 \text{ or } 46.3\%}$$





Any Questions???