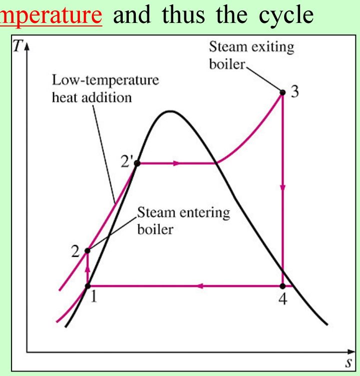
Chapter 9:

Vapor and Combined Power Cycles

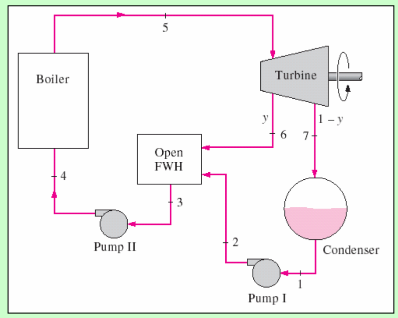
THE IDEAL REGENERATIVE RANKINE CYCLE

- A careful examination of the *T-s* diagram of the Rankine cycle 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, that is, to use **regeneration**.



THE IDEAL 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.
- 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).



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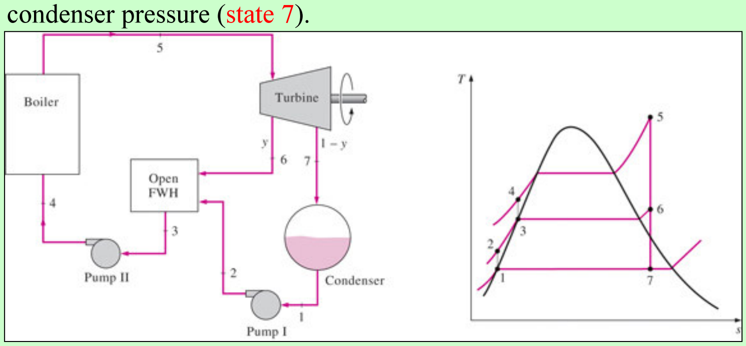
Open Feedwater Heaters

- 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.
- 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).



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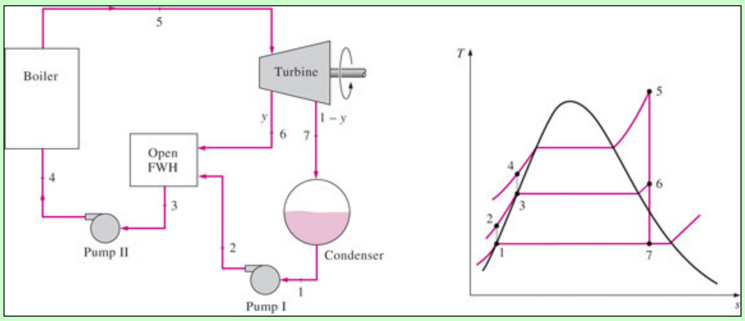
Open Feedwater Heaters

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 (y) 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).



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Open Feedwater Heaters

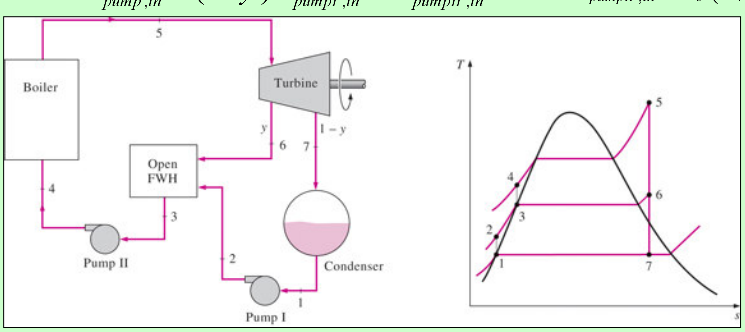
the mass flow rates are different in different components. If the mass flow rate through the boiler is *m,* for example, it is (1 - *y*)*m* through the condenser. This aspect of the regenerative Rankine cycle should be considered in the analysis of the cycle:

$$q_{in} = h_5 - h_4 \qquad where$$

$$q_{out} = (1-y)(h_7 - h_1) \qquad y = \dot{m}_6 / \dot{m}_5$$

$$w_{turb,out} = (h_5 - h_6) + (1-y)(h_6 - h_7) \qquad w_{pumpI,in} = v_1(P_2 - P_1)$$

$$w_{pump,in} = (1-y)w_{pumpI,in} + w_{pumpII,in} \qquad w_{pumpII,in} = v_3(P_4 - P_3)$$



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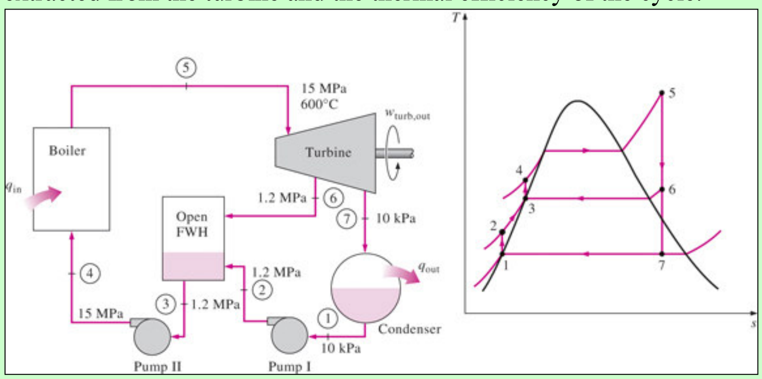
EXAMPLE 9–5

The Ideal Regenerative Rankine Cycle

- 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.



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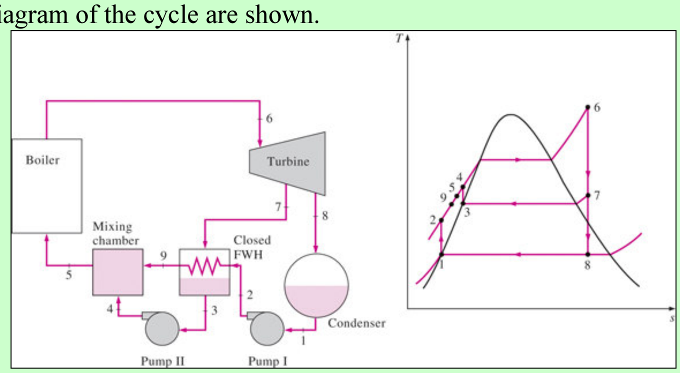
Closed Feedwater Heaters

Another type of feedwater heater frequently 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.



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Closed vs. Open Feedwater Heaters

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.

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

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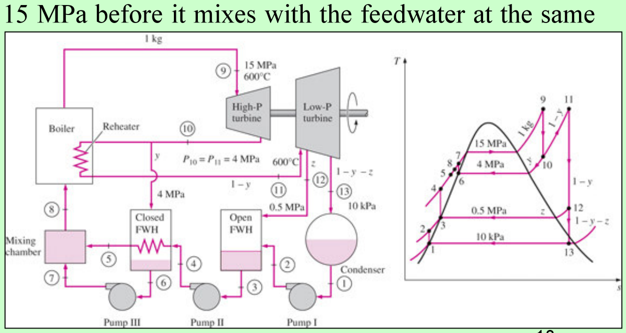
EXAMPLE 9–6

The Ideal Reheat-Regenerative Rankine Cycle

Consider a steam power plant that operates on an ideal reheat–regenerative Rankine cycle with one open feedwater heater, one closed feedwater heater, and one reheater. Steam enters the turbine at 15 MPa and 600°C and is condensed in the condenser at a pressure of 10 kPa. Some steam is extracted from the turbine at 4 MPa for the closed feedwater heater, and the remaining steam is reheated at the same pressure to 600°C. The extracted steam is completely condensed in the heater and is pumped to 15 MPa before it mixes with the feedwater at the same pressure. Steam for the open feedwater heater is extracted from the low-pressure turbine at a pressure of 0.5 MPa. Determine the fractions of steam extracted from the turbine as well as the thermal efficiency of the cycle.



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EXAMPLE 9–6

The Ideal Reheat-Regenerative Rankine Cycle

$h_1 = 191.81$ kJ/kg	$h_9 = 3155.0$ kJ/kg
$h_2 = 192.30$ kJ/kg	$h_{10} = 3155.0$ kJ/kg
$h_3 = 640.09$ kJ/kg	$h_{11} = 3674.9$ kJ/kg
$h_4 = 643.92$ kJ/kg	$h_{12} = 3014.8$ kJ/kg
$h_5 = 1087.4$ kJ/kg	$h_{13} = 2335.7$ kJ/kg
$h_6 = 1087.4$ kJ/kg	$w_{\text{pump I,in}} = 0.49$ kJ/kg
$h_7 = 1101.2$ kJ/kg	$w_{\text{pump II,in}} = 3.83$ kJ/kg
$h_8 = 1089.8$ kJ/kg	$w_{\text{pump III,in}} = 13.77$ kJ/kg

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EXAMPLE 9–6

The Ideal Reheat-Regenerative Rankine Cycle

Closed feedwater heater:

$$\dot{E}_{\text{in}} = \dot{E}_{\text{out}}$$

$$yh_{10} + (1 - y)h_4 = (1 - y)h_5 + yh_6$$

Open feedwater heater:

$$\dot{E}_{\text{in}} = \dot{E}_{\text{out}}$$

$$zh_{12} + (1 - y - z)h_2 = (1 - y)h_3$$

$$q_{\text{in}} = (h_9 - h_8) + (1 - y)(h_{11} - h_{10})$$

$$q_{\text{out}} = (1 - y - z)(h_{13} - h_1)$$

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COGENERATION

- In all the cycles discussed so far, the sole purpose was to convert a portion of the heat transferred to the working fluid to work, which is the most valuable form of energy.
- The remaining portion of the heat is rejected to rivers, lakes, oceans, or the atmosphere as waste heat, because its quality (or grade) is too low to be of any practical use.
- Wasting a large amount of heat is a price we have to pay to produce work, because electrical or mechanical work is the only form of energy on which many engineering devices (such as a fan) can operate.

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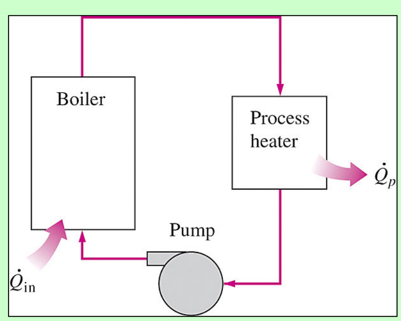
COGENERATION

- Many systems or devices, however, require energy input in the form of heat, called *process heat.*
- Some industries that rely heavily on process heat are chemical, pulp and paper, oil production and refining, steel making, food processing, and textile industries.
- Process heat in these industries is usually supplied by steam at 5 to 7 atm and 150 to 200°C (300 to 400°F).
- Energy is usually transferred to the steam by burning coal, oil, natural gas, or another fuel in a furnace.
- All the heat transferred to the steam in the boiler is used in the process-heating units, as shown.



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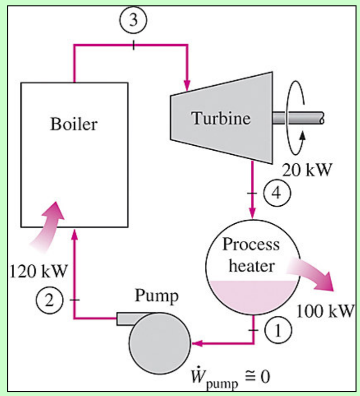
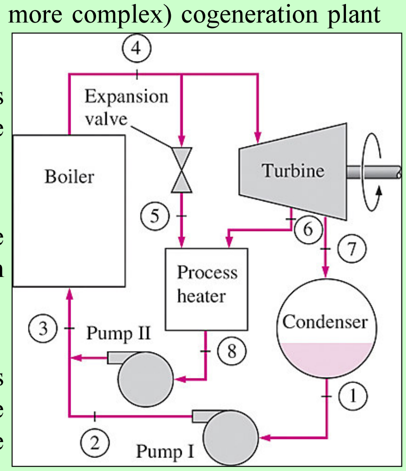
COGENERATION

- Industries that use large amounts of process heat also consume a large amount of electric power.
- Therefore, it makes economical as well as engineering sense to use the already-existing work potential to produce power instead of letting it go to waste.
- The result is a plant that produces electricity while meeting the process-heat requirements of certain industrial processes.
- Such a plant is called a *cogeneration plant*.
- In general, **cogeneration** is *the production of more than one useful form of energy (such as process heat and electric power) from the same energy source.*



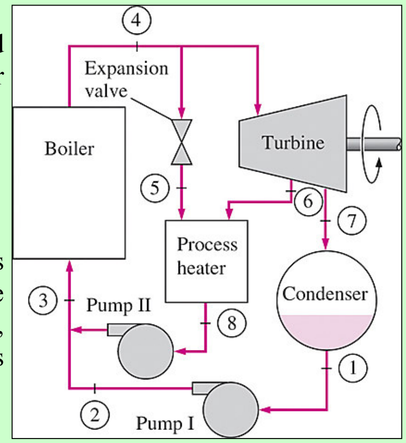
COGENERATION

- The ideal steam-turbine cogeneration plant described above is not practical because it cannot adjust to the variations in power and process-heat loads.
- The schematic of a more practical (but more complex) cogeneration plant is shown.
- Under normal operation, some steam is extracted from the turbine at some predetermined intermediate pressure P_6.
- The rest of the steam expands to the condenser pressure P_7 and is then cooled at constant pressure.
- At times of high demand for process heat, all the steam is routed to the process-heating units and none to the condenser (m_7=0).



COGENERATION

- If this is not sufficient, some steam leaving the boiler is throttled by an expansion or pressure-reducing valve (PRV) to the extraction pressure P_6 and is directed to the process-heating unit.
- Maximum process heating is realized when all the steam leaving the boiler passes through the PRV (m_5=m_4).
- No power is produced in this mode.
- When there is no demand for process heat, all the steam passes through the turbine and the condenser (m_5=m_6=0), and the cogeneration plant operates as an ordinary steam power plant.



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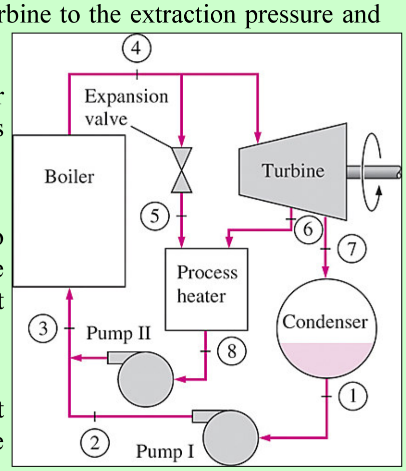
COGENERATION

- Under optimum conditions, a cogeneration plant simulates the ideal cogeneration plant discussed earlier.
- That is, all the steam expands in the turbine to the extraction pressure and continues to the process-heating unit.
- No steam passes through the PRV or the condenser; thus, no waste heat is rejected (m_4=m_6 and m_5=m_7=0).
- This condition may be difficult to achieve in practice because of the constant variations in the process-heat and power loads.
- But the plant should be designed so that the optimum operating conditions are approximated most of the time.



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COMBINED GAS–VAPOR POWER CYCLES

- The continued quest for higher thermal efficiencies has resulted in rather innovative modifications to conventional power plants.
- A more popular modification involves a gas power cycle topping a vapor power cycle, which is called the **combined gas–vapor cycle,** or just the **combined cycle.**
- The combined cycle of greatest interest is the gas-turbine (Brayton) cycle topping a steam turbine (Rankine) cycle, which has a higher thermal efficiency than either of the cycles executed individually.
- Gas-turbine cycles typically operate at considerably higher temperatures than steam cycles.
- The maximum fluid temperature at the turbine inlet is about 620°C (1150°F) for modern steam power plants, but over 1425°C (2600°F) for gas-turbine power plants

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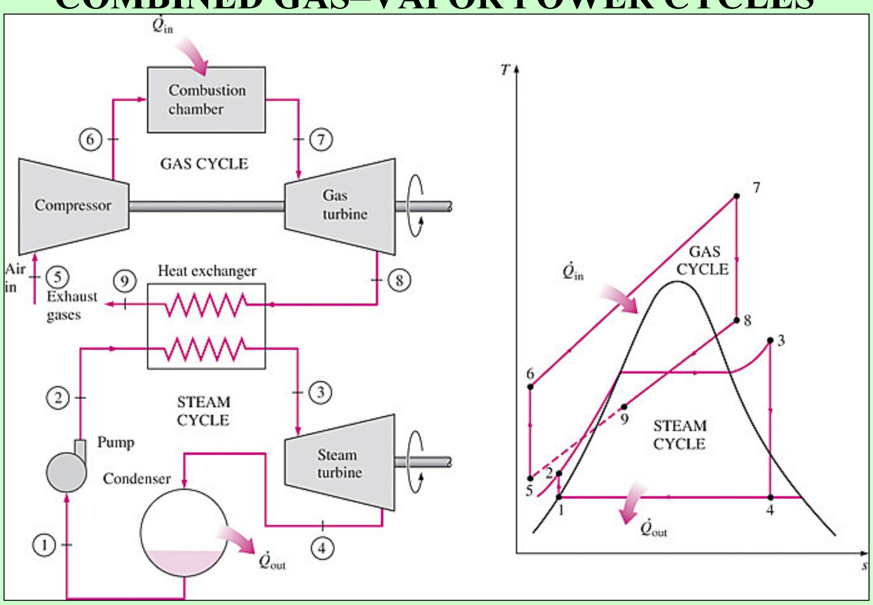
COMBINED GAS–VAPOR POWER CYCLES



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