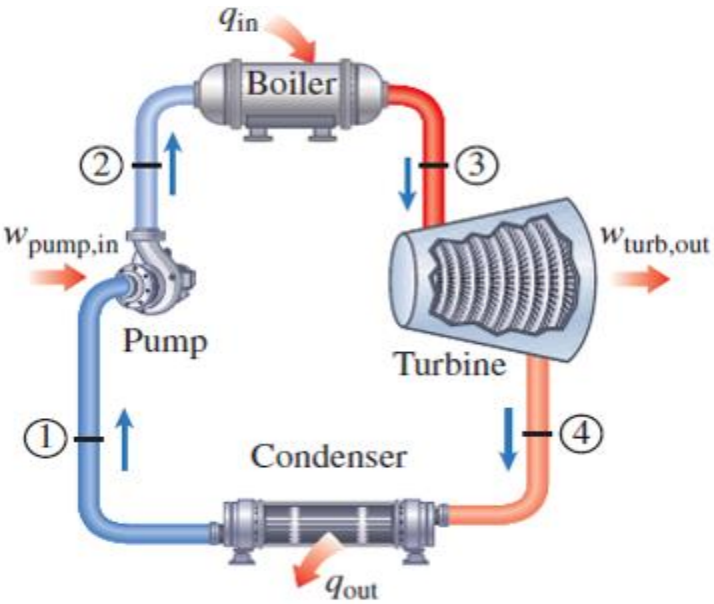
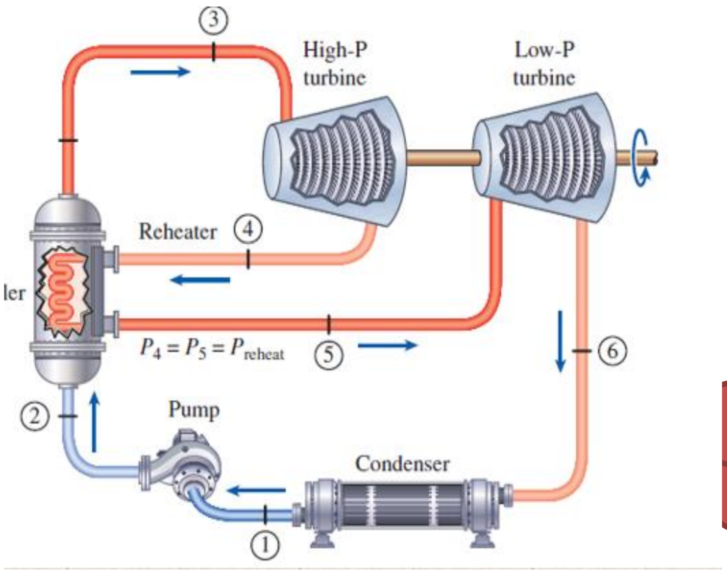
ENGINEERING THERMODYNAMICS -II

Debre Markos University
Institute of Technology
School of Mechanical and Industrial Engineering





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Lijalem A.

4. VAPOR AND COMBINED POWER CYCLES

Objectives

- Analyze vapor power cycles in which the working fluid is alternately vaporized and condensed.
- Analyze power generation coupled with process heating called cogeneration.
- Investigate ways to modify the basic Rankine vapor power cycle to increase the cycle thermal efficiency.
- Analyze the reheat and regenerative vapor power cycles.
- Analyze power cycles that consist of two separate cycles known as combined cycles and binary cycles.

THE CARNOT VAPOR CYCLE

The Carnot cycle is the most efficient cycle operating between two specified temperature limits but it is not a suitable model for power cycles. Because:

Process 1-2 Limiting the heat transfer processes to two-phase systems severely limits the maximum temperature that can be used in the cycle (374°C for water)

Process 2-3 The turbine cannot handle steam with a high moisture content because of the impingement of liquid droplets on the turbine blades causing erosion and wear.

Process 4-1 It is not practical to design a compressor that handles two phases.

The cycle in (b) is not suitable since it requires isentropic compression to extremely high pressures and isothermal heat transfer at variable pressures.

1-2 isothermal heat addition in a boiler

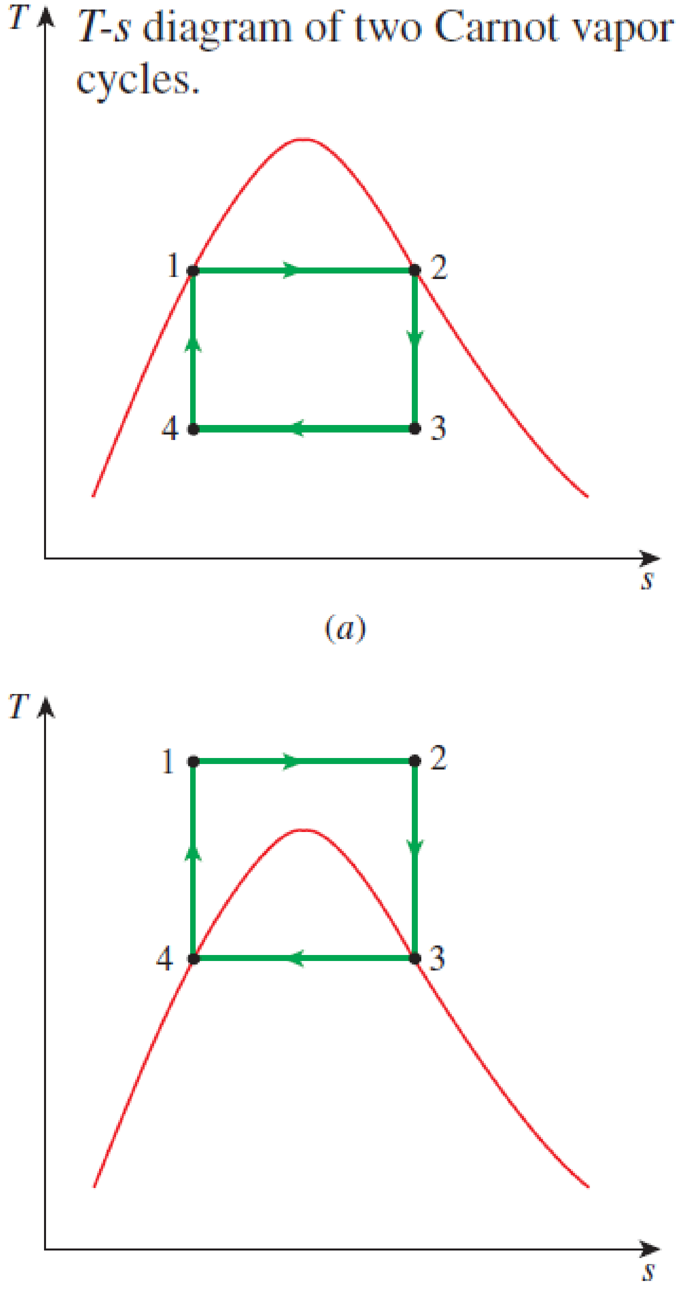
2-3 isentropic expansion in a turbine

3-4 isothermal heat rejection in a condenser

4-1 isentropic compression in a compressor

FIGURE 10–1

T-s diagram of two Carnot vapor cycles.



(*a*)

(*b*)

Assignment: 1

A steady-flow Carnot cycle uses water as the working fluid. Water changes from saturated liquid to saturated vapor as heat is transferred to it from a source at 250°C. Heat rejection takes place at a pressure of 20kPa. Show the cycle on a *T-s diagram relative to the saturation lines, and*

Determine:

(*a) the thermal efficiency,*

(b) the amount of heat rejected, in kJ/kg, and

(*c) the net work output.*

RANKINE CYCLE: THE IDEAL CYCLE FOR VAPOR POWER CYCLES

- Many of the impracticalities associated with the Carnot cycle can be eliminated by superheating the steam in the boiler and condensing it completely in the condenser.
- The cycle that results is the **Rankine cycle**, which is the ideal cycle for vapor power plants.
- The ideal Rankine cycle does not involve any internal irreversibilities.

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

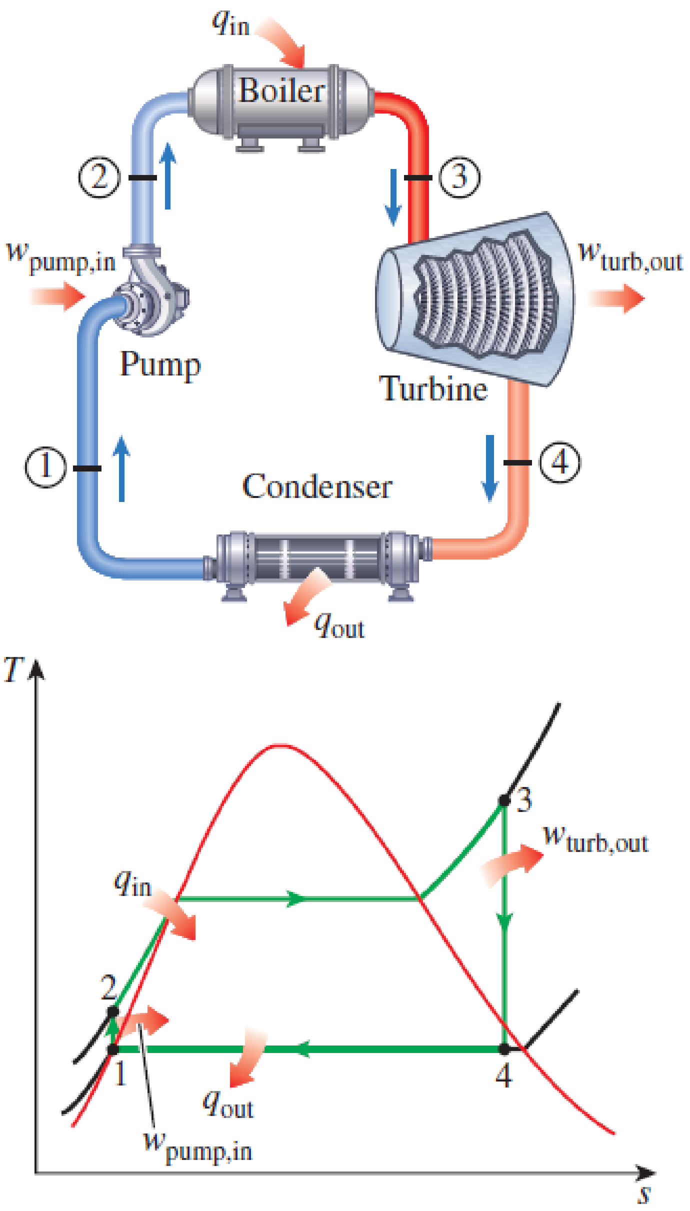
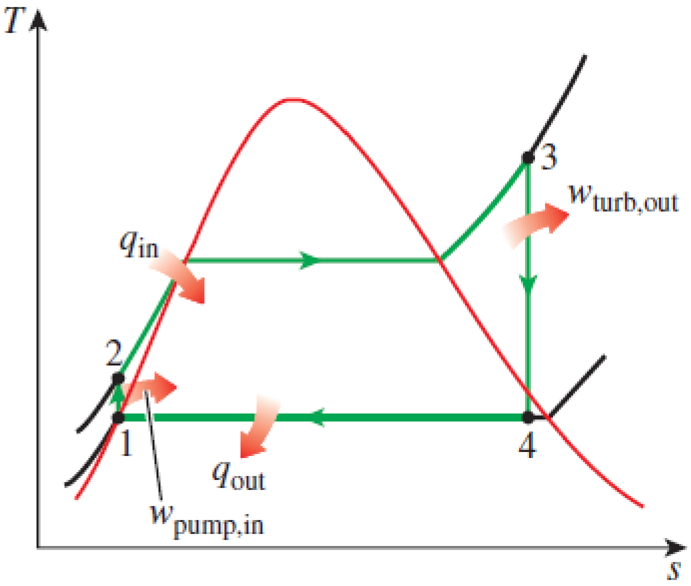


FIGURE 10–2
The simple ideal Rankine cycle.

Energy Analysis of the Ideal Rankine Cycle



Steady-flow energy equation

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

Pump ($q = 0$):

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

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

$$h_1 = h_{f\,@\,P_1} \quad \text{and} \quad v \cong v_1 = v_{f\,@\,P_1}$$

Boiler ($w = 0$):

$$q_{\text{in}} = h_3 - h_2$$

Turbine ($q = 0$):

$$w_{\text{turb,out}} = h_3 - h_4$$

Condenser ($w = 0$):

$$q_{\text{out}} = h_4 - h_1$$

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

$$\eta_{\text{th}} = \frac{w_{\text{net}}}{q_{\text{in}}} = 1 - \frac{q_{\text{out}}}{q_{\text{in}}}$$

The thermal efficiency can be interpreted as the ratio of the area enclosed by the cycle on a *T*-*s* diagram to the area under the heat-addition process.

The efficiency of power plants in the U.S. is often expressed in terms of **heat rate**, which is the amount of heat supplied, in Btu's, to generate 1 kWh of electricity.

$$\eta_{\text{th}} = \frac{3412\ \text{(Btu/kWh)}}{\text{Heat rate (Btu/kWh)}}$$

Example 1

A steam power plant operates on a simple ideal Rankine cycle between the pressure limits of 3MPa and 50kPa. The temperature of the steam at the turbine inlet is 300°C, and the mass flow rate of steam through the cycle is 35 kg/s. Show the cycle on a *T-s diagram with respect to saturation* lines, and determine (*a*) *the thermal efficiency of the* cycle and (*b*) *the net power output of the power plant.*

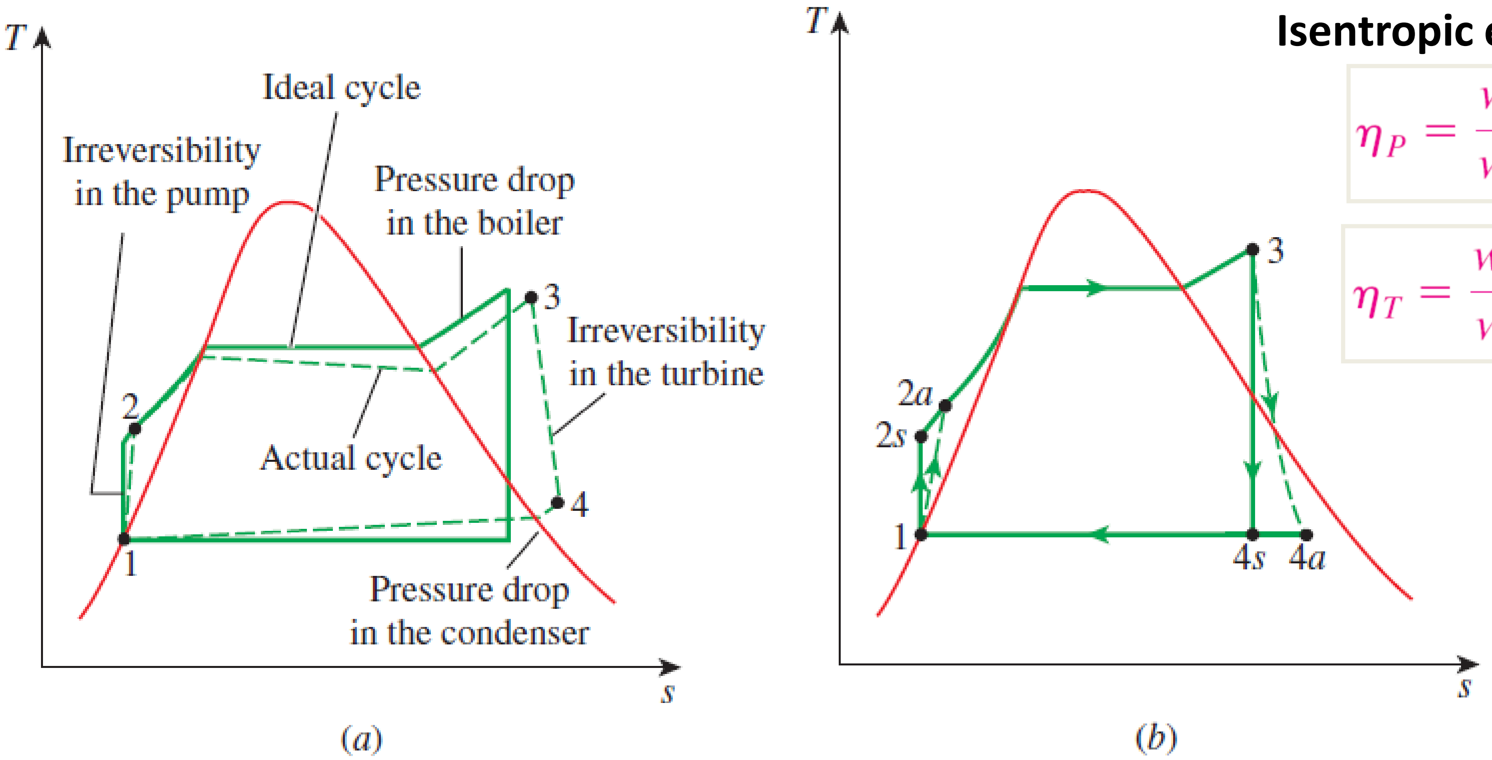
Assignment 2

Consider a 210-MW steam power plant that operates on a simple ideal Rankine cycle. Steam enters the turbine at 10MPa and 500°C and is cooled in the condenser at a pressure of 10kPa. Show the cycle on a *T-s diagram with respect* to saturation lines, and determine (*a*) *the quality of the steam* at the turbine exit, (*b*) *the thermal efficiency of the cycle*, and (*c*) *the mass flow rate of the steam.*

DEVIATION OF ACTUAL VAPOR POWER CYCLES FROM IDEALIZED ONES

✓The actual vapor power cycle differs from the ideal Rankine cycle as a result of irreversibilities in various components.

✓Fluid friction and heat loss to the surroundings are the two common sources of irreversibilities.



Isentropic efficiencies

$$\eta_P = \frac{w_s}{w_a} = \frac{h_{2s} - h_1}{h_{2a} - h_1}$$

$$\eta_T = \frac{w_a}{w_s} = \frac{h_3 - h_{4a}}{h_3 - h_{4s}}$$

(*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.

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: Increase the average temperature at which heat is transferred to the working fluid in the boiler, or decrease the average temperature at which heat is rejected from the working fluid in the condenser.

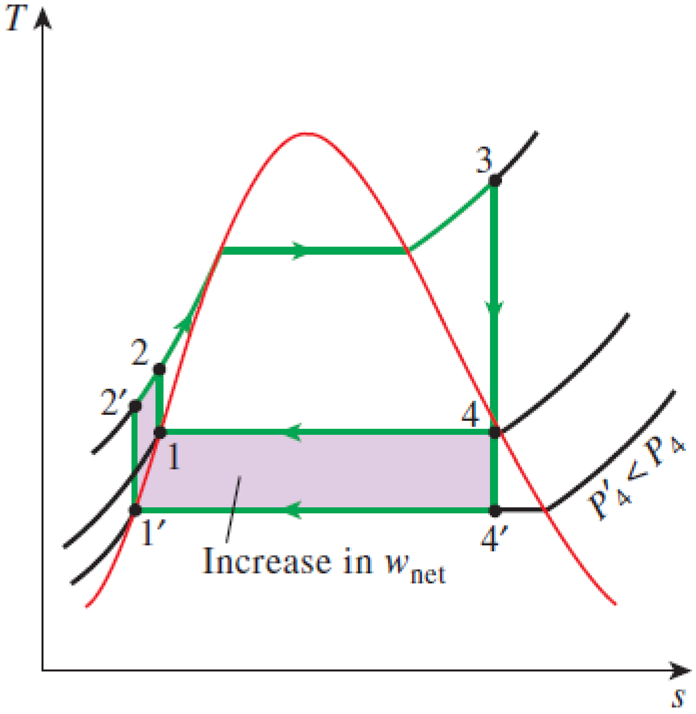


FIGURE 10–6

The effect of lowering the condenser pressure on the ideal Rankine cycle.

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

➢To take advantage of the increased efficiencies at low pressures, the condensers of steam power plants usually operate well below the atmospheric pressure. There is a lower limit to this pressure depending on the temperature of the cooling medium

✓**Side effect:** Lowering the condenser pressure increases the moisture content of the steam at the final stages of the turbine.

2. Superheating the Steam to High Temperatures (*Increases* $T_{high,avg}$)

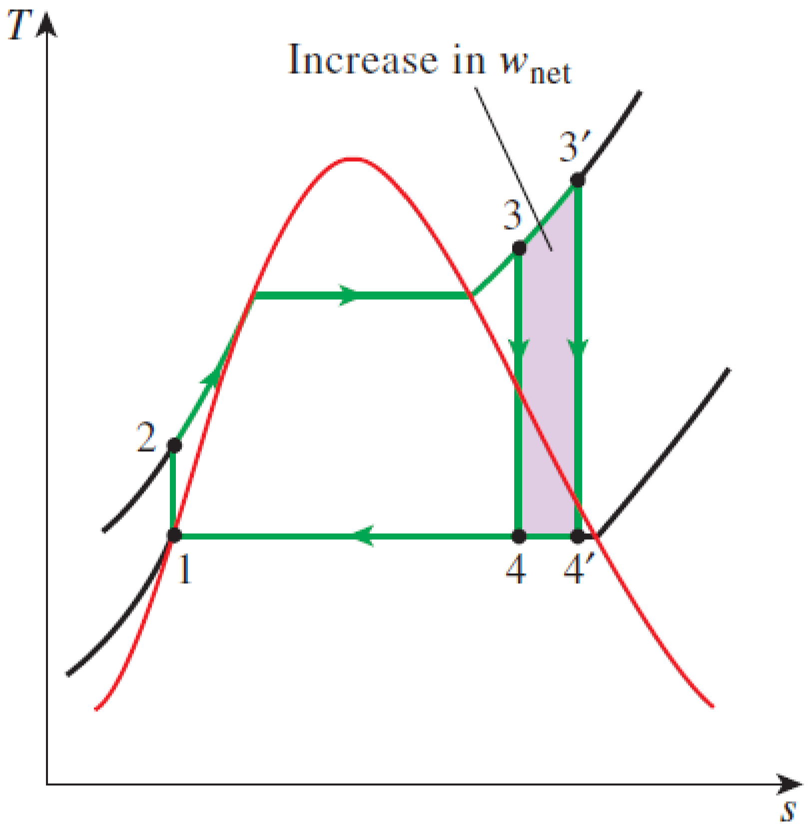


FIGURE 10–7
The effect of superheating the steam to higher temperatures on the ideal Rankine cycle.

✓Both the net work and heat input increase as a result of superheating the steam to a higher temperature.

✓The overall effect is an increase in thermal efficiency since the average temperature at which heat is added increases.

❖Superheating to higher temperatures decreases the moisture content of the steam at the turbine exit, which is desirable.

❑The temperature is limited by metallurgical considerations. Presently the highest steam temperature allowed at the turbine inlet is about 620°C.

3. Increasing the Boiler Pressure (*Increases $T_{high,avg}$*)

❖For a fixed turbine inlet temperature, the cycle shifts to the left and the moisture content of steam at the turbine exit increases.

❖This side effect can be corrected by reheating the steam.

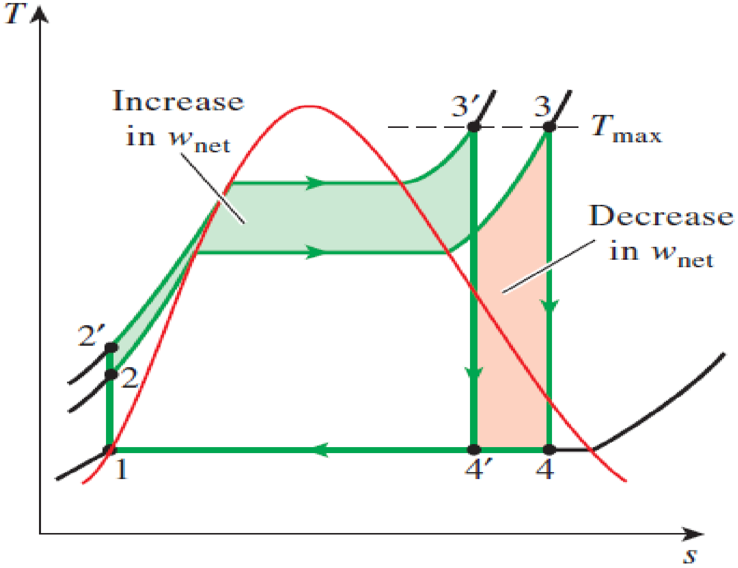


FIGURE 10–8
The effect of increasing the boiler pressure on the ideal Rankine cycle.

Today many modern steam power plants operate at supercritical pressures (P > 22.06 MPa) and have thermal efficiencies of about 40% for fossil-fuel plants and 34% for nuclear plants.

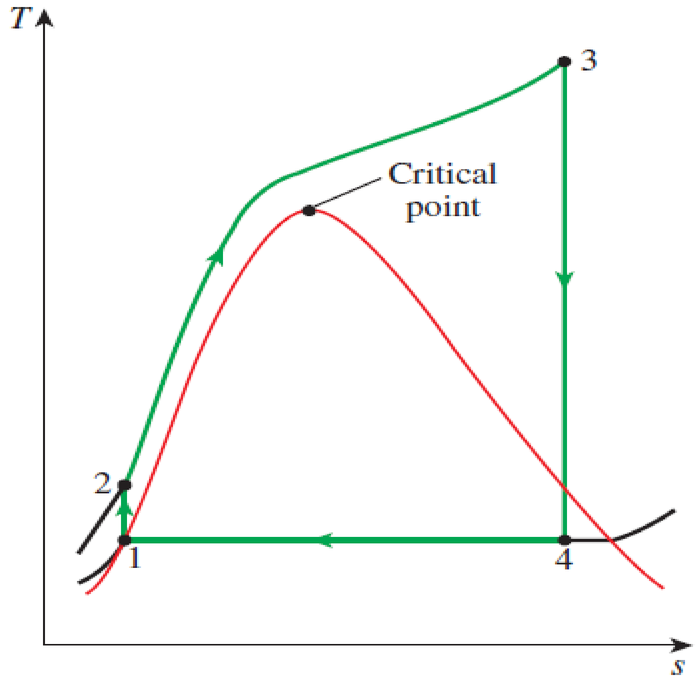


FIGURE 10–9
A supercritical Rankine cycle.

THE IDEAL REHEAT RANKINE CYCLE

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?

1. Superheat the steam to very high temperatures. It is limited metallurgic ally.
2. Expand the steam in the turbine in two stages, and reheat it in between (**reheat**)

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

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

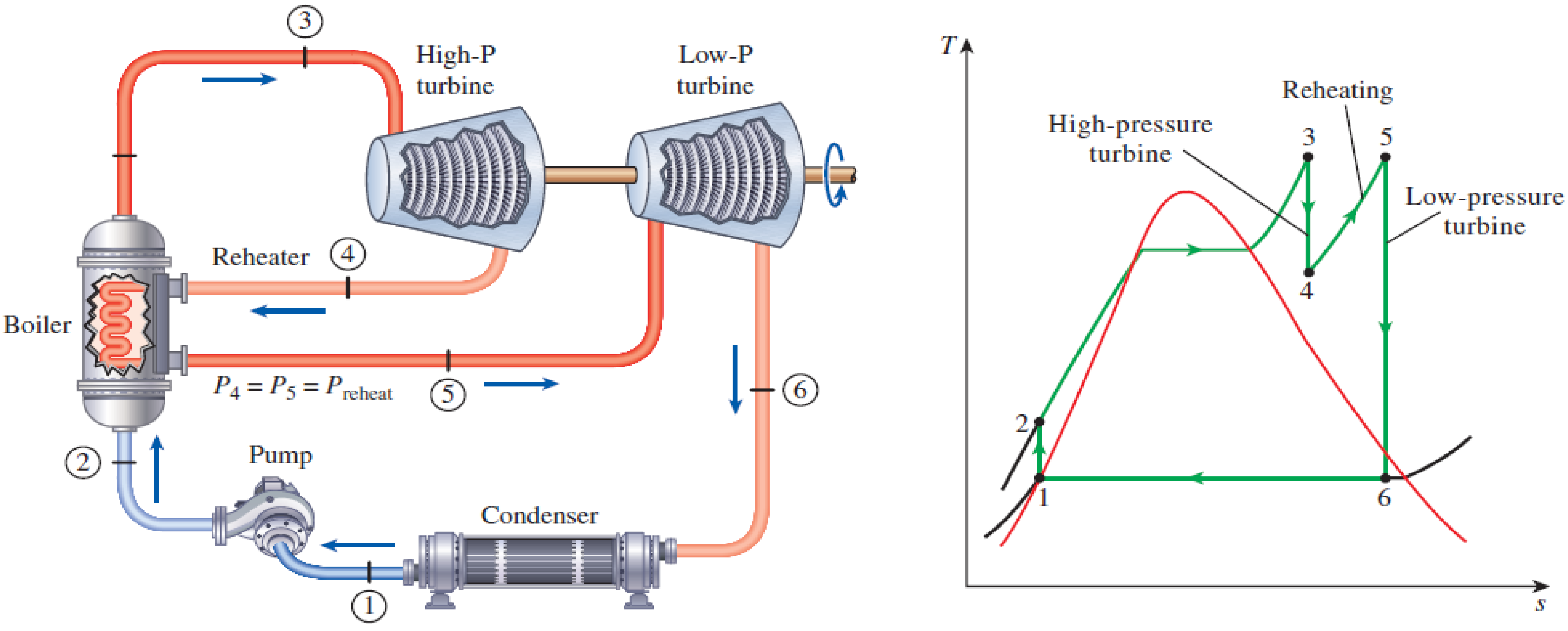


FIGURE 10–11
The ideal reheat Rankine cycle.

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

- The average temperature during the reheat process can be increased by increasing the number of expansion and reheat stages.

- As the number of stages is increased, the expansion and reheat processes approach an isothermal process at the maximum temperature.

- The reheat temperatures are very close or equal to the turbine inlet temperature.

- The optimum reheat pressure is about one-fourth of the maximum cycle pressure.

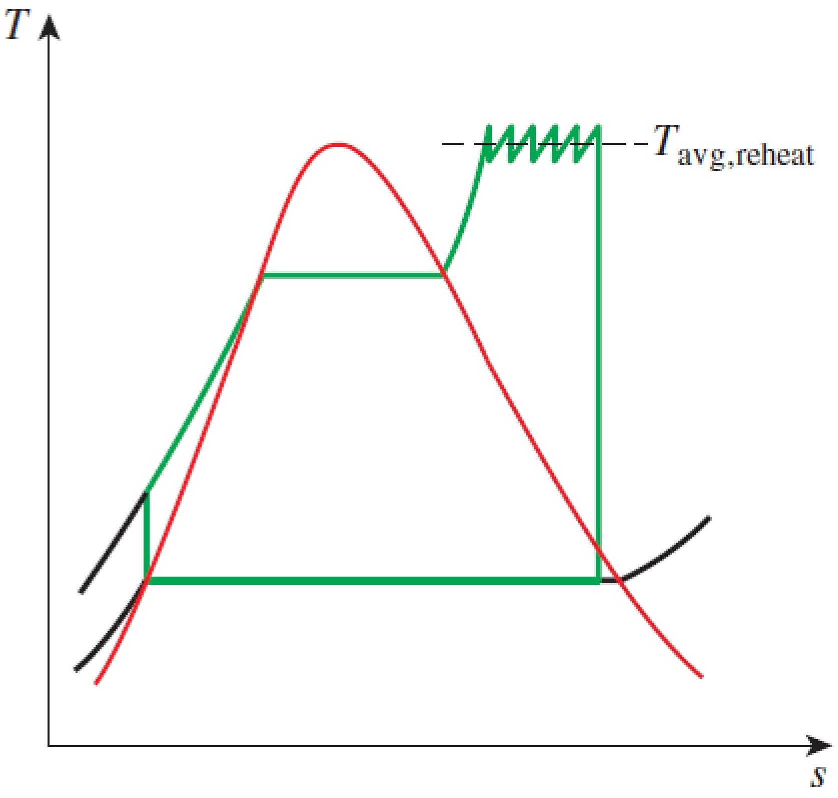


FIGURE 10–12

The average temperature at which heat is transferred during reheating increases as the number of reheat stages is increased.

Example 2

Consider a steam power plant that operates on a reheat Rankine cycle and has a net power output of 80 MW. Steam enters the high-pressure turbine at 10MPa and 500°C and the low-pressure turbine at 1MPa and 500°C. Steam leaves the condenser as a saturated liquid at a pressure of 10kPa. The isentropic efficiency of the turbine is 80 percent, and that of the pump is 95 percent. Show the cycle on a *T*-*s* diagram with respect to saturation lines, and

Determine (*a*) the quality (or temperature, if superheated) of the steam at the turbine exit, (*b*) the thermal efficiency of the cycle, and (*c*) the mass flow rate of the steam.

Assignment 3

10–38 .A steam power plant operates on the reheat Rankine cycle. Steam enters the high-pressure turbine at 12.5Mpa and 550°C at a rate of 7.7 kg/s and leaves at 2MPa. Steam is then reheated at constant pressure to 450°C before it expands in the low-pressure turbine. The isentropic efficiencies of the turbine and the pump are 85 percent and 90 percent, respectively. Steam leaves the condenser as a saturated liquid. If the moisture content of the steam at the exit of the turbine is not to exceed 5 percent,

determine (*a*) the condenser pressure, (*b*) the net power output, and (*c*) the thermal efficiency.

THE IDEAL REGENERATIVE RANKINE CYCLE

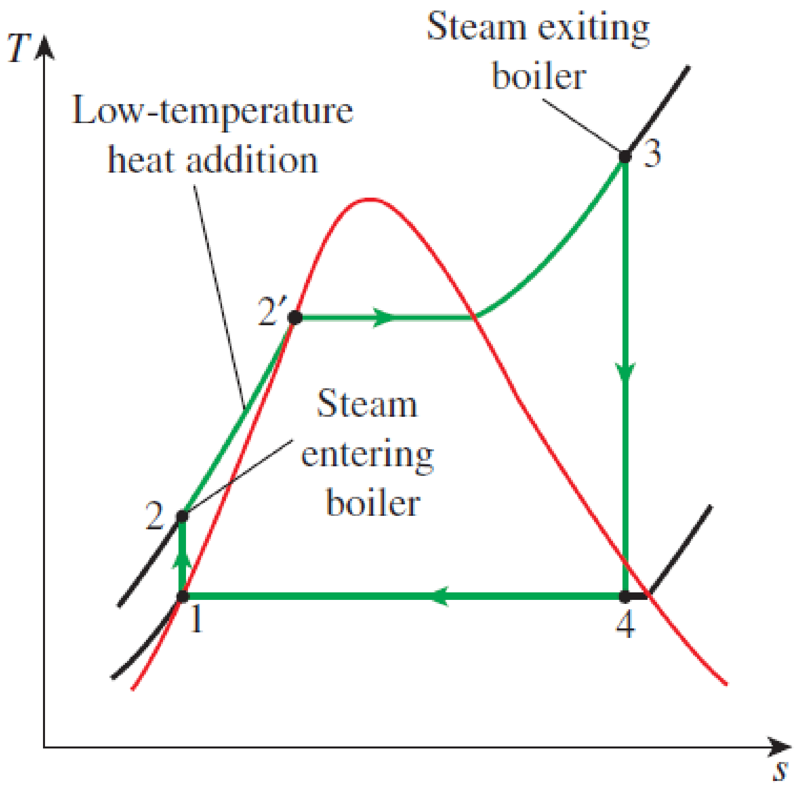


FIGURE 10–14

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

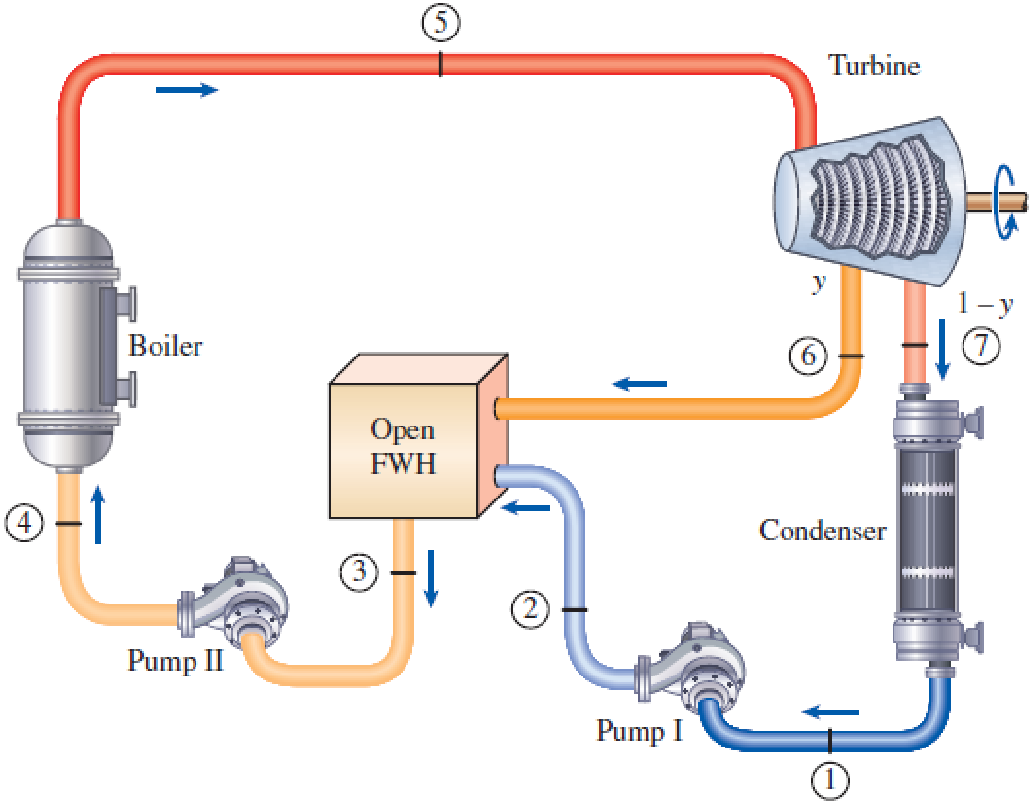
- ➢Heat is transferred to the working fluid during process 2-2’ at a relatively low temperature. This lowers the average heat-addition temperature and thus the cycle efficiency.
- ➢In steam power plants, steam is extracted from the turbine at various points. This steam, which could have produced more work by expanding further in the turbine, is used to heat the feed water instead. The device where the feed water is heated by regeneration is called a **regenerator**, or a **feed water heater** (FWH).
- ➢A feed water heater is basically a heat exchanger where heat is transferred from the steam to the feed water either by mixing the two fluid streams (**open feed water heaters**) or without mixing them (**closed feed water heaters**).

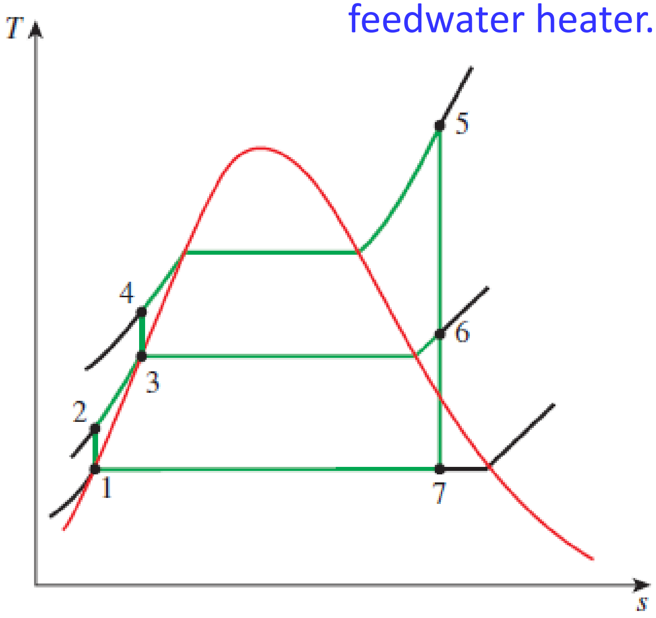
Open Feedwater Heaters

- ➢An **open** (or **direct-contact**) **feed water heater** is basically a *mixing chamber*, where the steam extracted from the turbine mixes with the feed water exiting the pump.
- ➢Ideally, the mixture leaves the heater as a saturated liquid at the heater pressure.

$$q_{\text{in}} = h_5 - h_4$$
$$q_{\text{out}} = (1 - y)(h_7 - h_1)$$
$$w_{\text{turb,out}} = (h_5 - h_6) + (1 - y)(h_6 - h_7)$$
$$w_{\text{pump,in}} = (1 - y)w_{\text{pump I,in}} + w_{\text{pump II,in}}$$

$$y = \dot{m}_6/\dot{m}_5 \qquad \text{(fraction of steam extracted)}$$
$$w_{\text{pump I,in}} = v_1(P_2 - P_1)$$
$$w_{\text{pump II,in}} = v_3(P_4 - P_3)$$





The ideal regenerative Rankine cycle with an open feedwater heater.

Closed Feedwater Heaters

❖Another type of feed water heater frequently used in steam power plants is the **closed feed water heater**, in which heat is transferred from the extracted steam to the feed water without any mixing taking place. The two streams now can be at different pressures, since they do not mix.

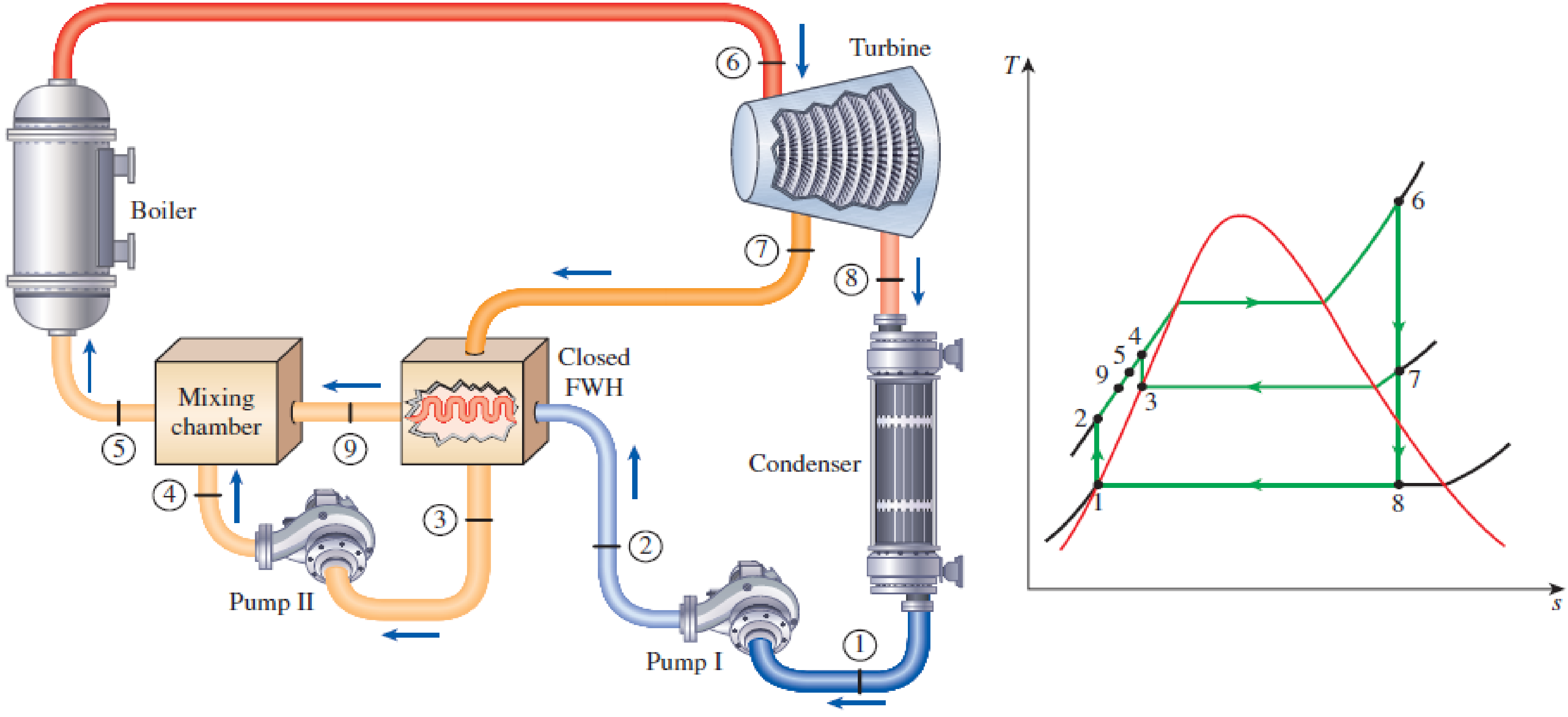


FIGURE 10–16

The ideal regenerative Rankine cycle with a closed feedwater heater.

➢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 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.

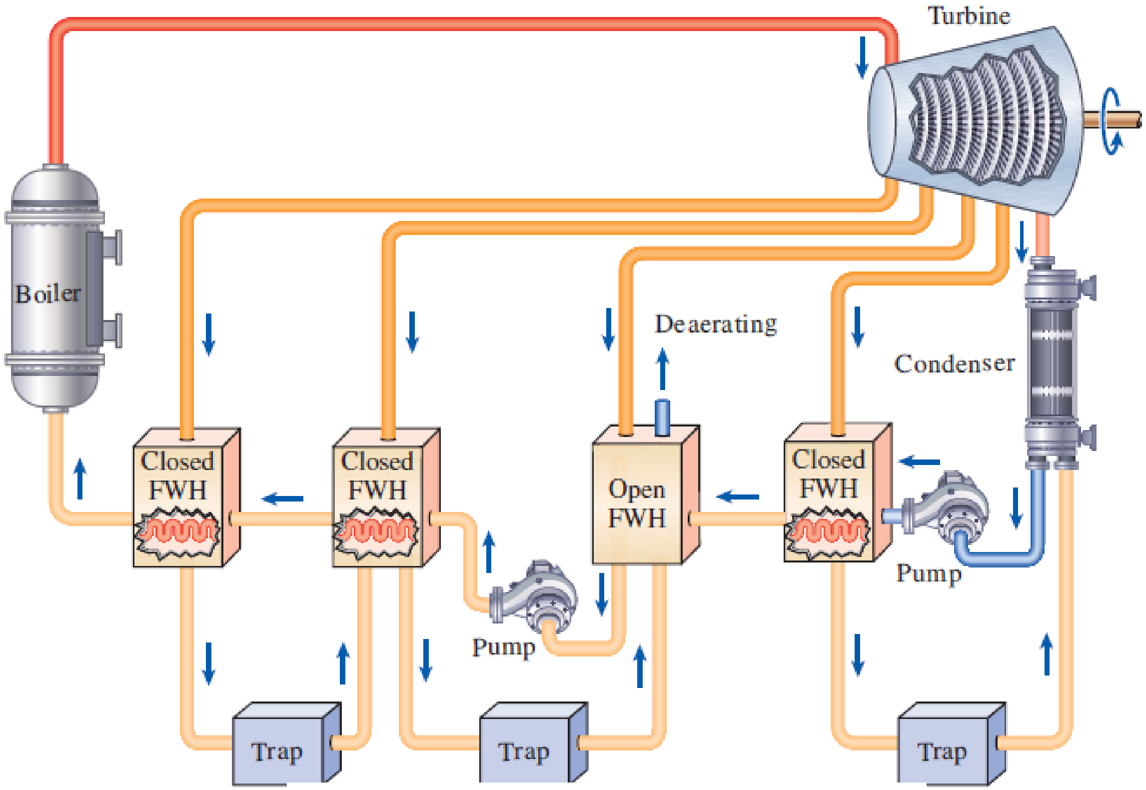


FIGURE 10–17
A steam power plant with one open and three closed feedwater heaters.

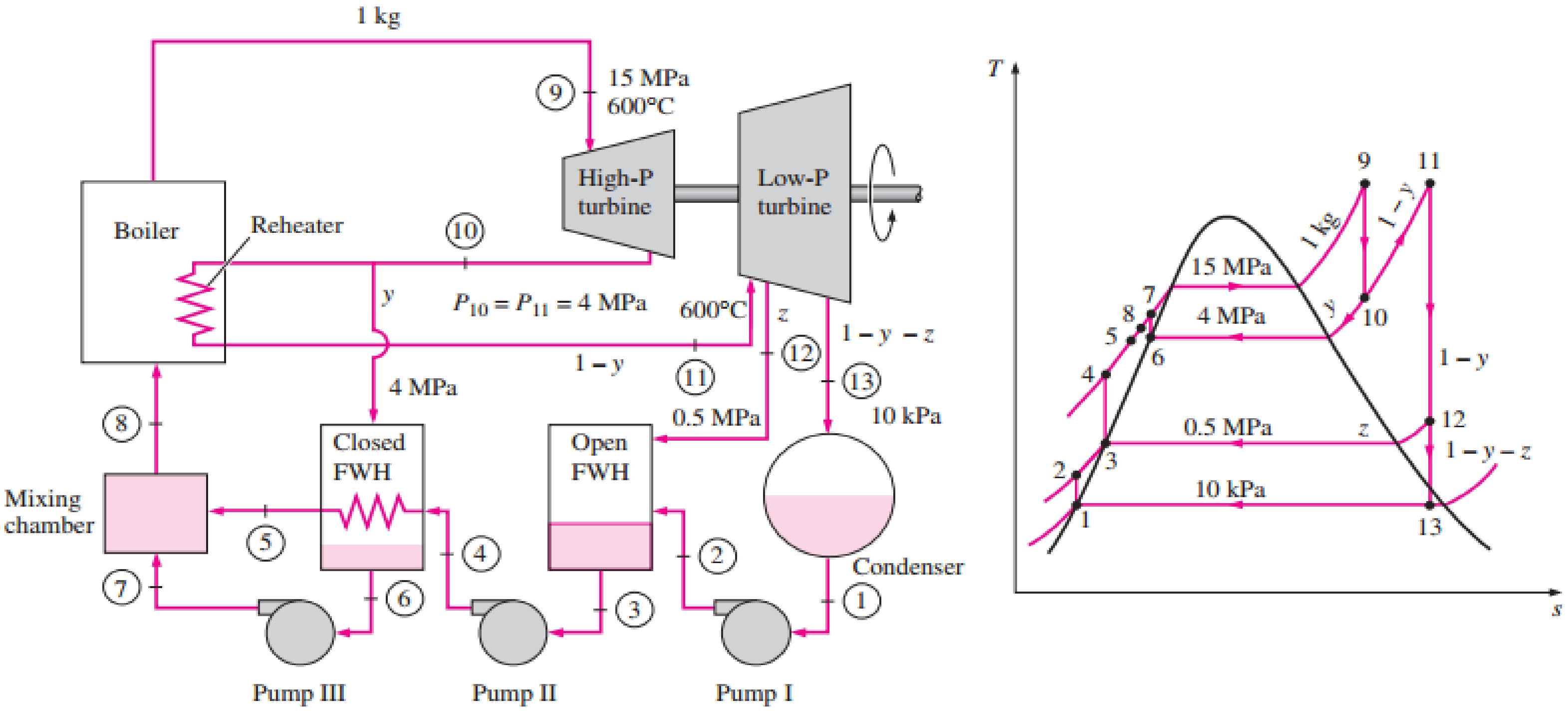
✓Open feedwater heaters are simple and inexpensive and have good heat transfer characteristics.

✓For each heater, however, a pump is required to handle the feedwater.

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

Example 3

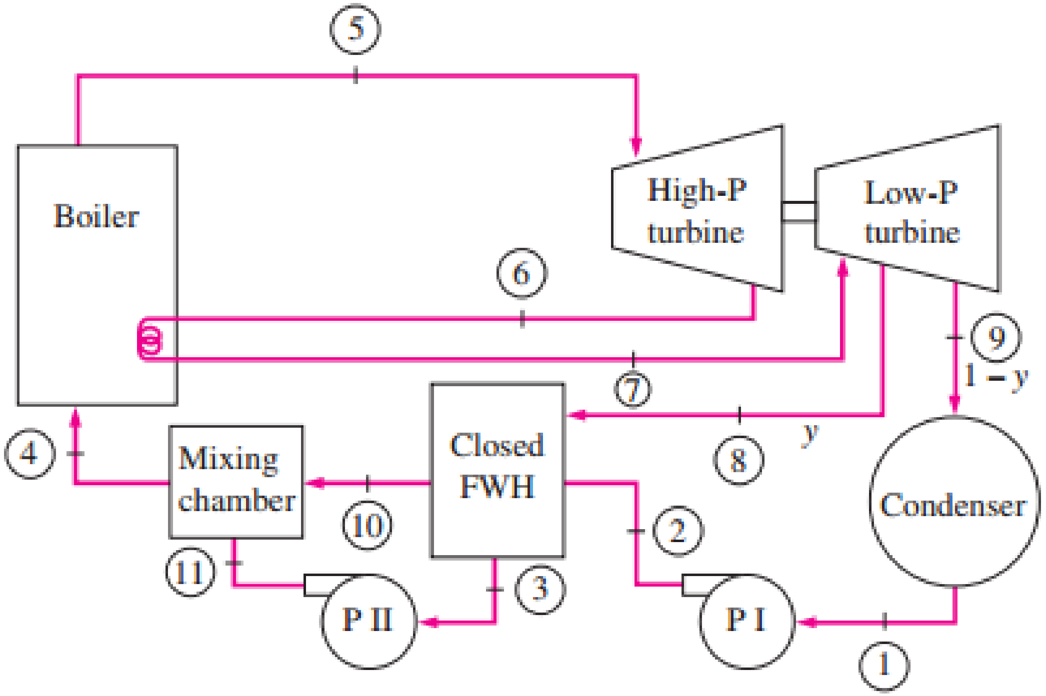
Consider a steam power plant that operates on an ideal reheat–regenerative Rankine cycle with one open feedwater heater, one closed feedwater heater, and one reheater. Steam enters the turbine at 15 MPa and 600°C and is condensed in the condenser at a pressure of 10 kPa. Some steam is extracted from 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.



Assignment 4

A steam power plant operates on the reheat regenerative Rankine cycle with a closed feedwater heater. Steam enters the turbine at 12.5 MPa and 550°C at a rate of 24 kg/s and is condensed in the condenser at a pressure of 20 kPa. Steam is reheated at 5 MPa to 550°C. Some steam is extracted from the low-pressure turbine at 1.0 MPa, is completely condensed in the closed feedwater heater, and pumped to 12.5 MPa before it mixes with the feedwater at the same pressure. Assuming an isentropic efficiency of 88 percent for both the turbine and the pump,

determine (*a*) the temperature of the steam at the inlet of the closed feedwater heater, (*b*) the mass flow rate of the steam extracted from the turbine for the closed feedwater heater, (*c*) the net power output, and (*d*) the thermal efficiency.



SECOND-LAW ANALYSIS OF VAPOR POWER CYCLES

A second-law analysis irreversibilities external to the system, such as heat transfer through a finite temperature difference of the cycles reveals; where the largest irreversibilities occur and what their magnitudes are:

Exergy destruction for a steady-flow system

$$\dot{X}_{\text{dest}} = T_0 \dot{S}_{\text{gen}} = T_0(\dot{S}_{\text{out}} - \dot{S}_{\text{in}}) = T_0\left(\sum_{\text{out}} \dot{m}s + \frac{\dot{Q}_{\text{out}}}{T_{b,\text{out}}} - \sum_{\text{in}} \dot{m}s - \frac{\dot{Q}_{\text{in}}}{T_{b,\text{in}}}\right) \quad (\text{kW})$$

$$x_{\text{dest}} = T_0 s_{\text{gen}} = T_0\left(s_e - s_i + \frac{q_{\text{out}}}{T_{b,\text{out}}} - \frac{q_{\text{in}}}{T_{b,\text{in}}}\right) \quad (\text{kJ/kg})$$

Steady-flow, one-inlet, one-exit

$$x_{\text{dest}} = T_0\left(\sum \frac{q_{\text{out}}}{T_{b,\text{out}}} - \sum \frac{q_{\text{in}}}{T_{b,\text{in}}}\right) \quad (\text{kJ/kg})$$

Exergy destruction of a cycle

$$x_{\text{dest}} = T_0\left(\frac{q_{\text{out}}}{T_L} - \frac{q_{\text{in}}}{T_H}\right) \quad (\text{kJ/kg})$$

For a cycle with heat transfer only with a source and a sink

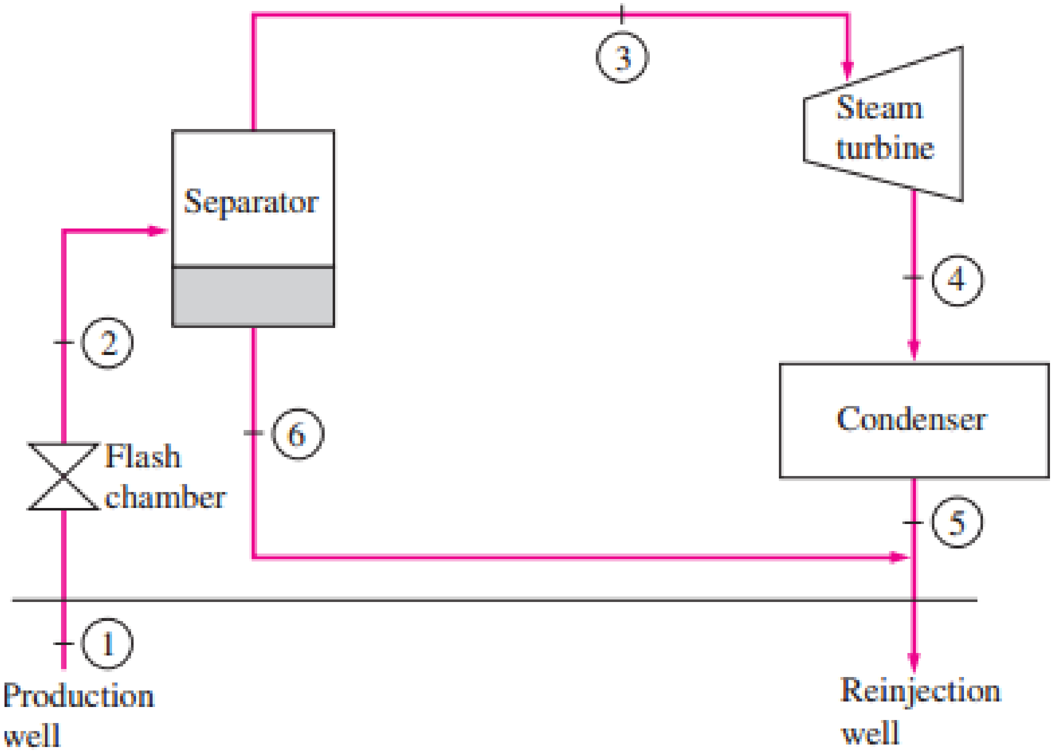
$$\psi = (h - h_0) - T_0(s - s_0) + \frac{V^2}{2} + gz \quad (\text{kJ/kg})$$

Stream exergy (work potential)

A second-law analysis of vaporpower cycles reveals where the largest irreversibilities occur and where to start improvements.

Assignment 5

The schematic of a single-flash geothermal power plant with state numbers is given in Fig. below. Geothermal resource exists as saturated liquid at 230°C. The geothermal liquid is withdrawn from the production well at a rate of 230kg/s and is flashed to a pressure of 500 kPa by an essentially isenthalpic flashing process where the resulting vapor is separated from the liquid in a separator and is directed to the turbine. The steam leaves the turbine at 10kPa with a moisture content of 5 percent and enters the condenser where it is condensed; it is routed to a reinjection well along with the liquid coming off the separator. Determine (*a*) the power output of the turbine and the thermal efficiency of the plant, (*b*) the exergy of the geothermal liquid at the exit of the flash chamber, and the exergy destructions and the second-law (exergetic) efficiencies for (*c*) the flash chamber, (*d*) the turbine, and (*e*) the entire plant.



COGENERATION

- Many industries require energy input in the form of heat, called ***process heat***.
- Process heat in these industries is usually supplied by steam at 5 to 7atm and 150 to 200°C.
- Energy is usually transferred to the steam by burning coal, oil, natural gas, or another fuel in a furnace.

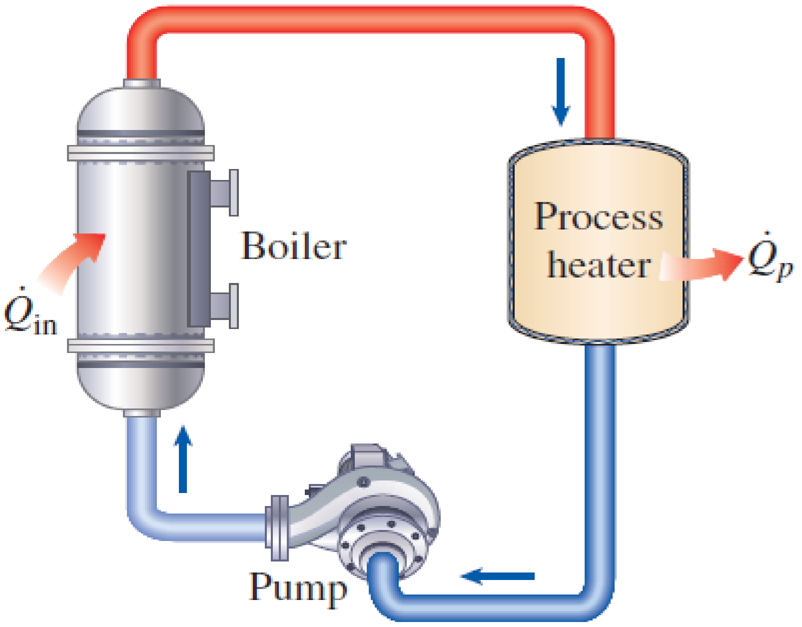


FIGURE 10–21

A simple process-heating plant.

- Industries that use large amounts of process heat also consume a large amount of electric power.
- It makes 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 (cogeneration plant)

Cogeneration: The production of more than one useful form of energy (such as process heat and electric power) from the same energy source.

Utilization factor

$$\epsilon_u = \frac{\text{Net power output} + \text{Process heat delivered}}{\text{Total heat input}} = \frac{\dot{W}_{\text{net}} + \dot{Q}_p}{\dot{Q}_{\text{in}}}$$

$$\epsilon_u = 1 - \frac{\dot{Q}_{\text{out}}}{\dot{Q}_{\text{in}}}$$

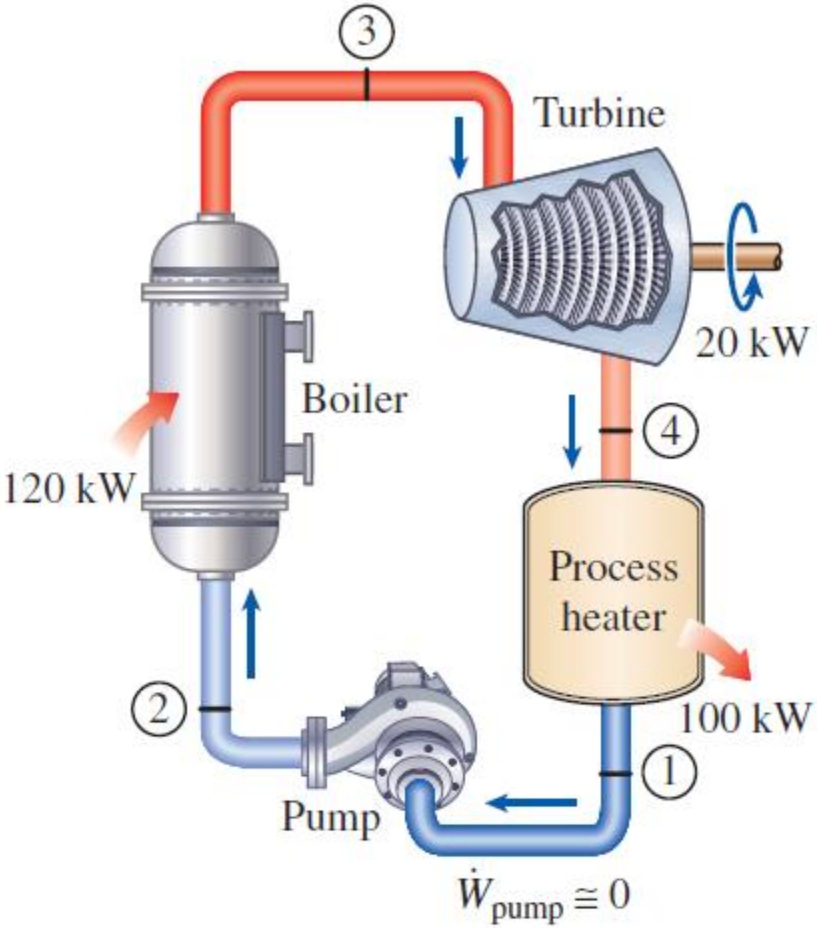


FIGURE 10–22

An ideal cogeneration plant.

- The utilization factor of the ideal steam-turbine cogeneration plant is 100%.
- Actual cogeneration plants have utilization factors as high as 80%.
- Some recent cogeneration plants have even higher utilization factors.

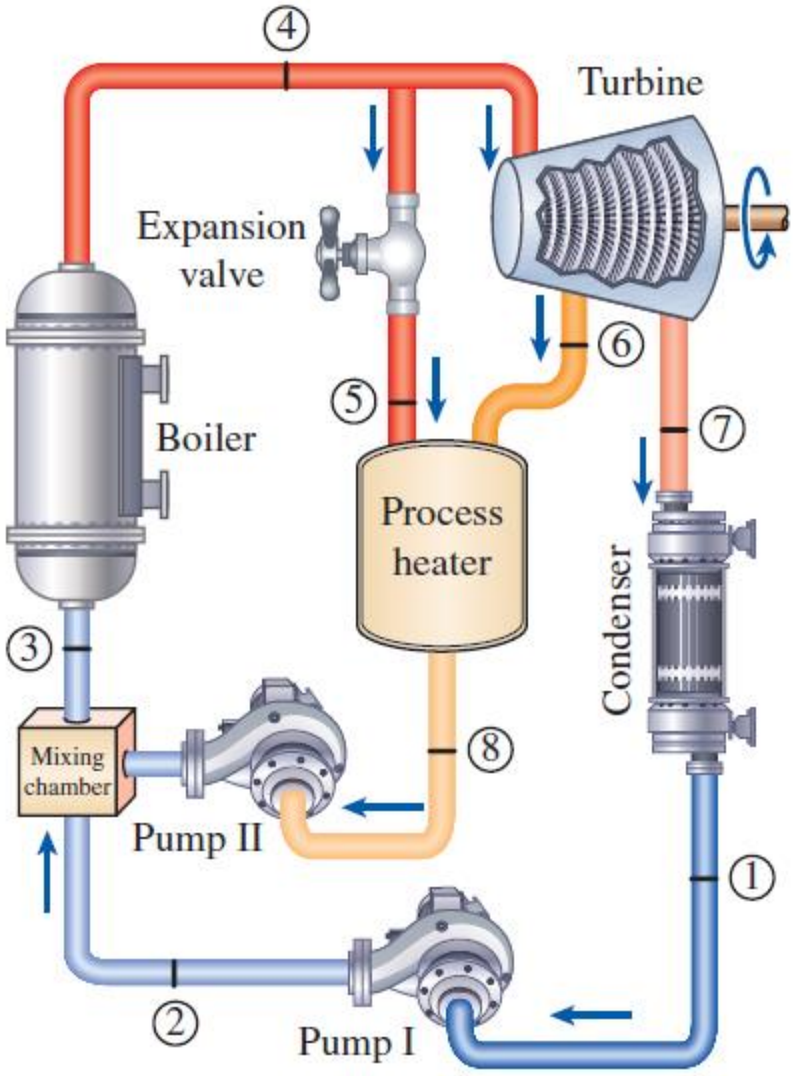


FIGURE 10–23

A cogeneration plant with adjustable loads.

✓At times of high demand for process heat, all the steam is routed to the process-heating units and none to the condenser ($m_7 = 0$). The waste heat is zero in this mode.

✓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.

$$\dot{Q}_{\text{in}} = \dot{m}_3(h_4 - h_3)$$

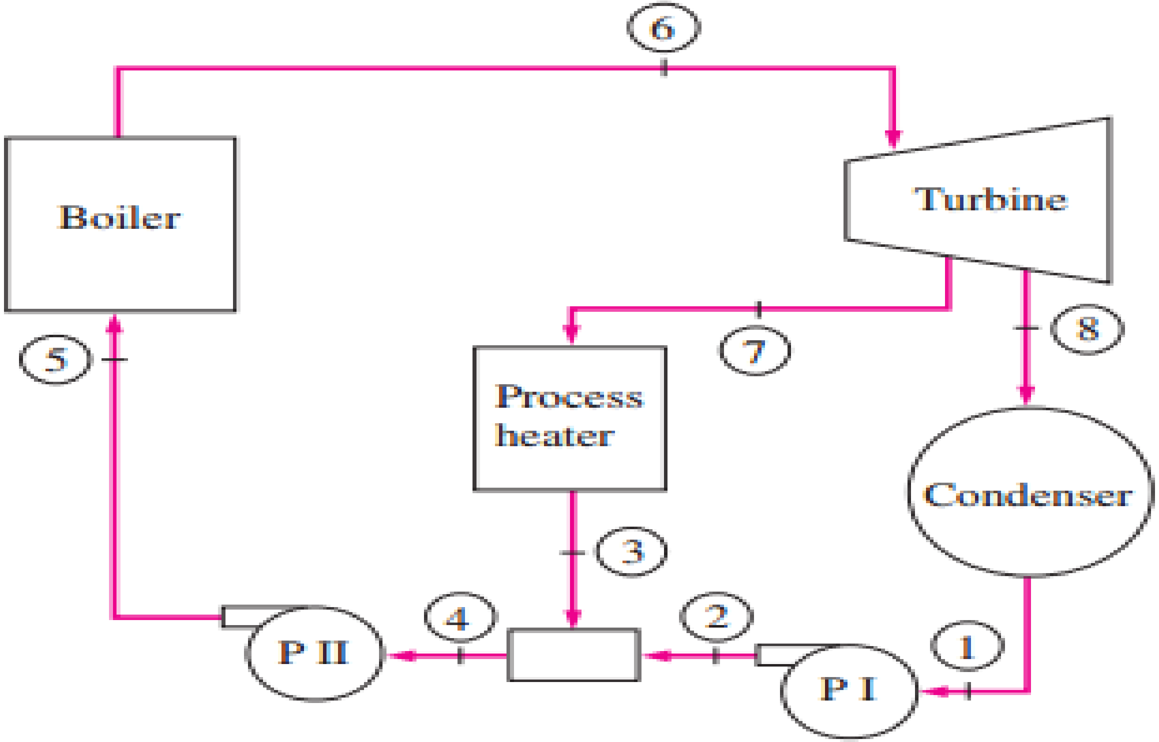
$$\dot{Q}_{\text{out}} = \dot{m}_7(h_7 - h_1)$$

$$\dot{Q}_p = \dot{m}_5 h_5 + \dot{m}_6 h_6 - \dot{m}_8 h_8$$

$$\dot{W}_{\text{turb}} = (\dot{m}_4 - \dot{m}_5)(h_4 - h_6) + \dot{m}_7(h_6 - h_7)$$

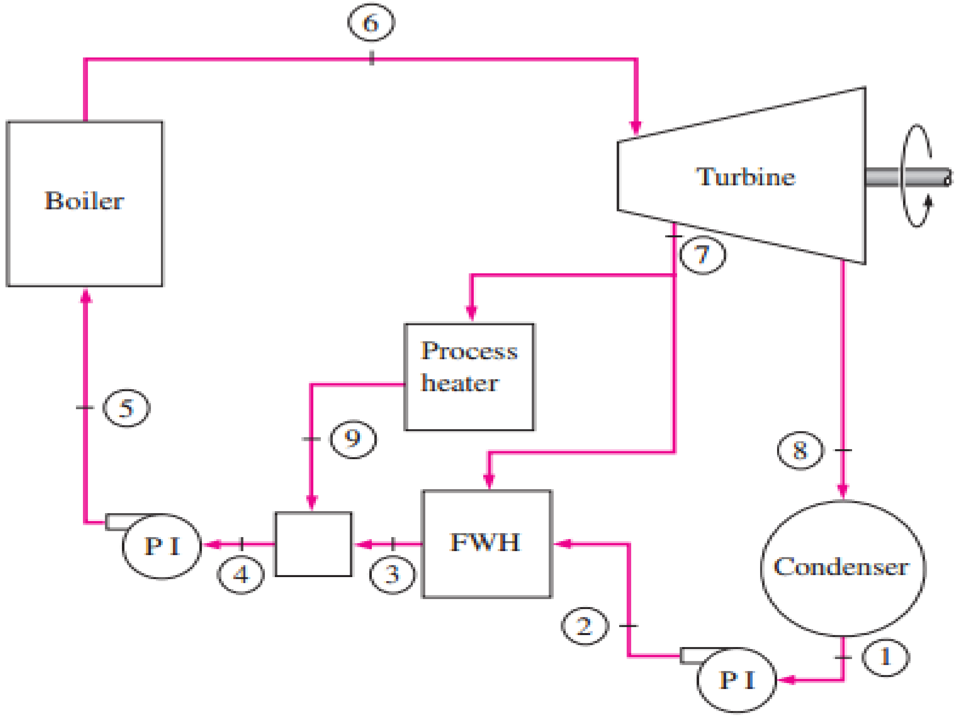
Example 4

A cogeneration plant is to generate power and 8600kJ/s of process heat. Consider an ideal cogeneration steam plant. Steam enters the turbine from the boiler at 7 MPa and 500°C. One-fourth of the steam is extracted from the turbine at 600-kPa pressure for process heating. The remainder of the steam continues to expand and exhausts to the condenser at 10 kPa. The steam extracted for the process heater is condensed in the heater and mixed with the feedwater at 600kPa. The mixture is pumped to the boiler pressure of 7 MPa. Show the cycle on a *T-s* diagram with respect to saturation lines, and determine (*a*) the mass flow rate of steam that must be supplied by the boiler, (*b*) the net power produced by the plant, and (*c*) the utilization factor.



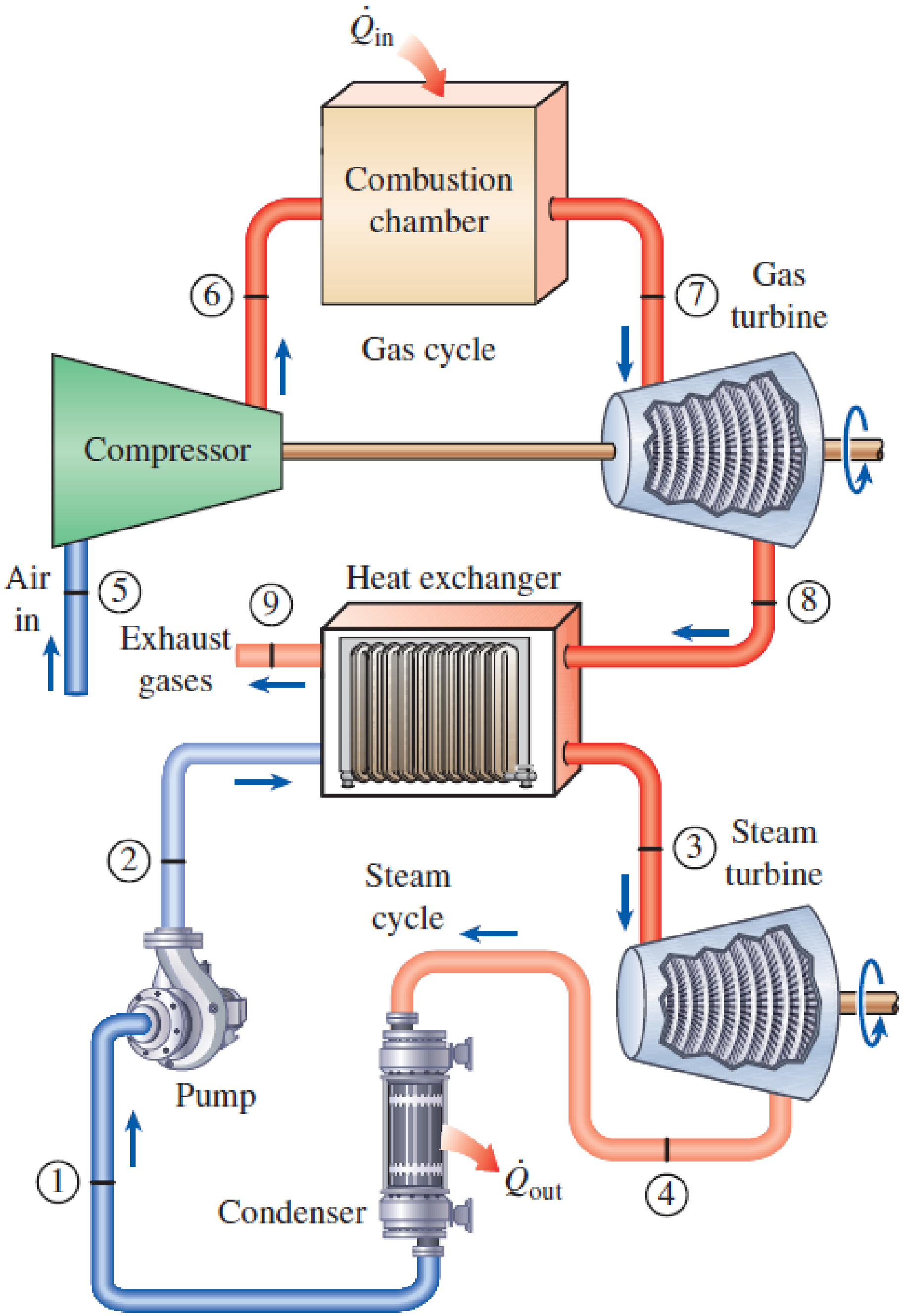
Assignment 6

Consider a cogeneration power plant modified with regeneration. Steam enters the turbine at 6 MPa and 450°C and expands to a pressure of 0.4MPa. At this pressure, 60 percent of the steam is extracted from the turbine, and the remainder expands to 10kPa. Part of the extracted steam is used to heat the feedwater in an open feedwater heater. The rest of the extracted steam is used for process heating and leaves the process heater as a saturated liquid at 0.4MPa. It is subsequently mixed with the feedwater leaving the feedwater heater, and the mixture is pumped to the boiler pressure. Assuming the turbines and the pumps to be isentropic, show the cycle on a *T*-*s* diagram with respect to saturation lines, and determine the mass flow rate of steam through the boiler for a net power output of 15 MW.



COMBINED GAS–VAPOR POWER CYCLES

- The continued quest for higher thermal efficiencies has resulted in rather innovative modifications to conventional power plants.
- A 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.
- It makes engineering sense to take advantage of the very desirable characteristics of the gas-turbine cycle at high temperatures *and* to use the high-temperature exhaust gases as the energy source for the bottoming cycle such as a steam power cycle. The result is a combined gas–steam cycle.
- Recent developments in gas-turbine technology have made the combined gas–steam cycle economically very attractive.
- The combined cycle increases the efficiency without increasing the initial cost greatly. Consequently, many new power plants operate on combined cycles, and many more existing steam- or gas-turbine plants are being converted to combined-cycle power plants.
- Thermal efficiencies over 50% are reported.



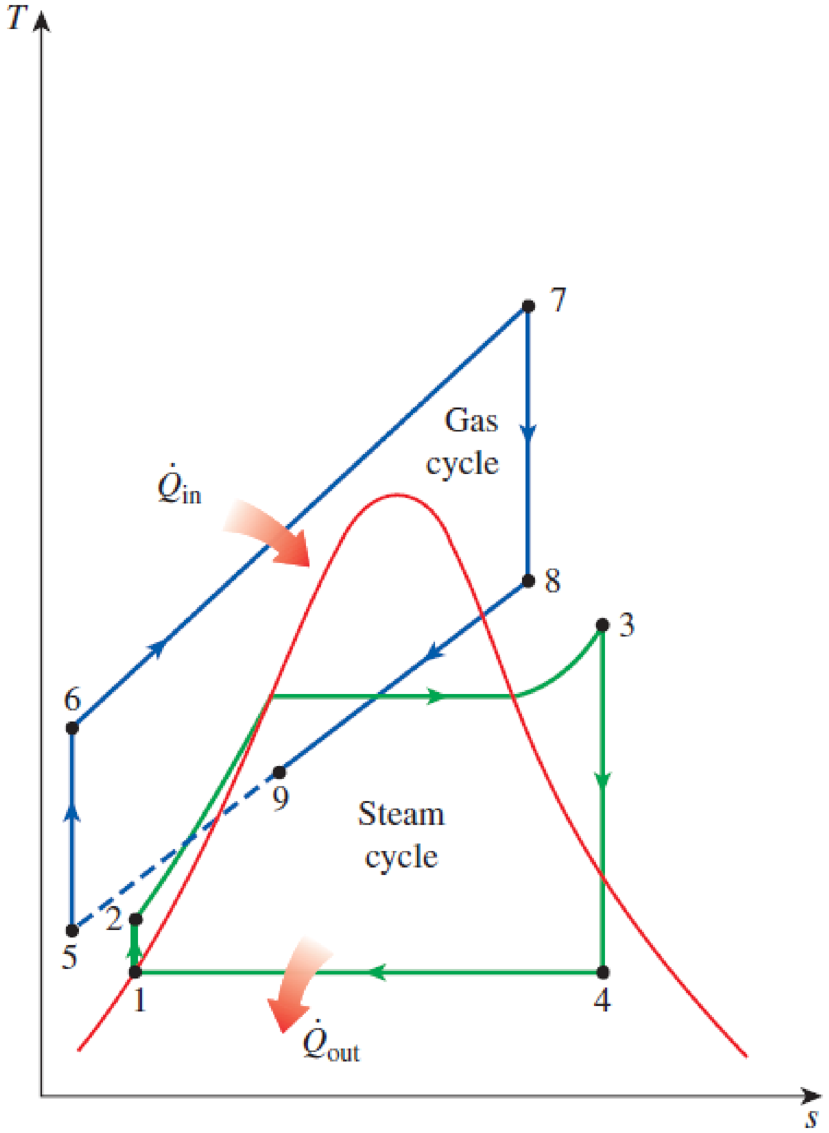


FIGURE 10–25

Combined gas–steam power plant.

Example 5

The gas-turbine portion of a combined gas–steam power plant has a pressure ratio of 16. Air enters the compressor at 300 K at a rate of 14 kg/s and is heated to 1500 K in the combustion chamber. The combustion gases leaving the gas turbine are used to heat the steam to 400°C at 10MPa in a heat exchanger. The combustion gases leave the heat exchanger at 420 K. The steam leaving the turbine is condensed at 15 kPa. Assuming all the compression and expansion processes to be isentropic, determine (*a*) the mass flow rate of the steam, (*b*) the net power output, and (*c*) the thermal efficiency of the combined cycle. For air, assume constant specific heats at room temperature.

Assignment 7

Consider a combined gas–steam power plant that has a net power output of 450 MW. The pressure ratio of the gas-turbine cycle is 14. Air enters the compressor at 300 K and the turbine at 1400 K. The combustion gases leaving the gas turbine are used to heat the steam at 8 MPa to 400°C in a heat exchanger. The combustion gases leave the heat exchanger at 460 K. An open feedwater heater incorporated with the steam cycle operates at a pressure of 0.6 MPa. The condenser pressure is 20 kPa. Assuming all the compression and expansion processes to be isentropic, determine (*a*) the mass flow rate ratio of air to steam, (*b*) the required rate of heat input in the combustion chamber, and (*c*) the thermal efficiency of the combined cycle.

Thank You for your attention!