Production of Power from Heat

In a conventional power plant the molecular energy of fuel is released by a combustion process. The function of the work-producing device is to convert part of the heat of combustion into mechanical energy. In a nuclear power plant the fission process releases energy of the nucleus of the atom as heat, which is then partially converted into work. Thus, the thermodynamic analysis of heat engines, as presented in this chapter, applies equally well to conventional (fossil-fuel) and nuclear power plants.

The steam power plant is a large-scale heat engine in which the working fluid (H_2O) is in steady-state flow successively through a pump, a boiler, a turbine, and a condenser in a cyclic process. The working fluid is separated from the heat source, and heat is transferred across a physical boundary. In a fossil-fuel-fired plant the combustion gases are separated from the steam by boiler-tube walls.

THE STEAM POWER PLANT

The Carnot-engine cycle operates reversibly and consists of two isothermal steps connected by two adiabatic steps. In the isothermal step at higher temperature T_H, heat $|Q_H|$ is absorbed by the working fluid of the engine, and in the isothermal step at lower temperature T_C, heat $|Q_C|$ is discarded by the fluid. The work produced is $|W| = |Q_H| - |Q_C|$, and the thermal efficiency of the Carnot engine is:

$$\eta = \frac{|W|}{|Q_H|} = 1 - \frac{T_C}{T_H}$$

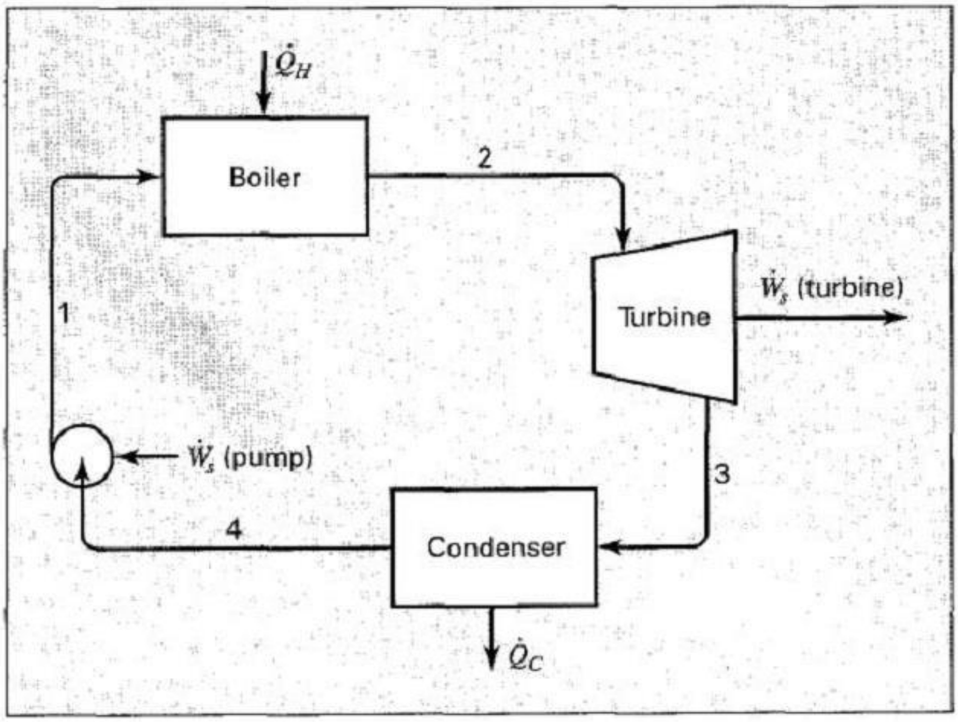

Figure 8.1 Simple steam power plant

Figure above shows a simple steady-state steady-flow process in which steam generated in a boiler is expanded in an adiabatic turbine to produce work. The discharge stream from the turbine passes to a condenser from which it is pumped adiabatically back to the boiler. The power produced by the turbine is much greater than the pump requirement, and the net power output is equal to the difference between the rate of heat input in the boiler | Q_H | and the rate of heat rejection in the condenser | Q_C |.

Carnot cycle

The processes that occur as the working fluid flows around the cycle of Fig. above are represented by lines on the TS diagram of Fig. below. The sequence of lines shown conforms to a Carnot cycle. Step 1 - 2 is the vaporization process taking place in the boiler, wherein saturated liquid water absorbs heat at the constant temperature T_H, and produces saturated vapor. Step 2 - 3 is a reversible, adiabatic expansion of saturated vapor into the two-phase region to produce a mixture of saturated liquid and vapor at T_C. This isentropic expansion is represented by a vertical line. Step 3 - 4 is a partial condensation process wherein heat is rejected at T_C. Step 4 - 1 takes the cycle back to its origin, producing saturated-liquid water at point 1. It is an isentropic compression process represented by a vertical line.

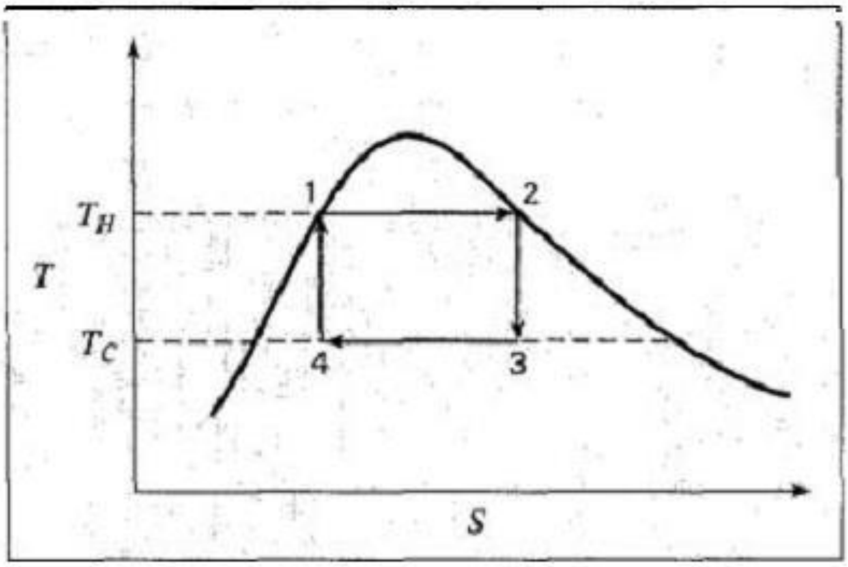

Figure 8.2 Carnot cycle on a *TS* diagram

The Rankine Cycle

The thermal efficiency of the Carnot cycle just described is given by Equation of the thermal efficiency of the Carnot engine. As a reversible cycle, it could serve as a standard of comparison for actual steam power plants. **However, severe practical difficulties attend the operation of equipment intended to carry out steps 2 - 3 and 4 - 1. Turbines that take in saturated steam produce an exhaust with high liquid content, which causes severe erosion problems. Even more difficult is the design of a pump that takes in a mixture of liquid and vapor (point 4) and discharges a saturated liquid (point 1).**

For these reasons, an alternative model cycle is taken as the standard, at least for fossil-fuel-burning power plants. It is called the Rankine cycle, and differs from the cycle of Fig. 8.2 in two major respects. First, the heating step 1 - 2 is carried well beyond vaporization, so as to produce a superheated vapor, and second, the cooling step 3 - 4 brings about complete condensation, yielding saturated liquid to be pumped to the boiler. The Rankine cycle therefore consists of the four steps shown by Fig. below, and described as follows:

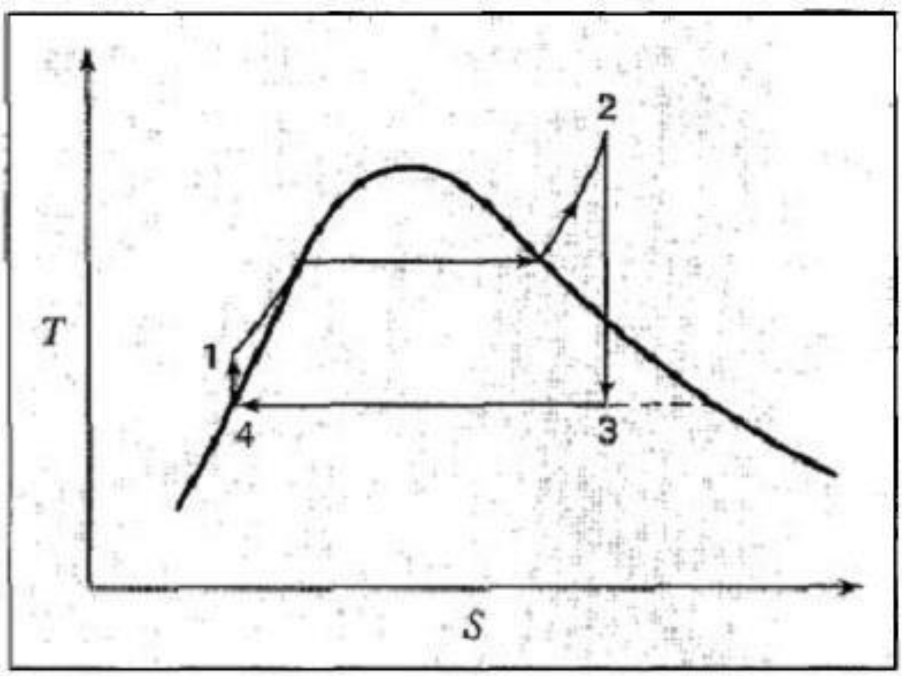

Figure 8.3 The Rankine cycle

- 1 - 2 A constant-pressure heating process in a boiler. The step lies along an isobar (the pressure of the boiler), and consists of three sections: heating of subcooled liquid water to its saturation temperature, vaporization at constant temperature and pressure, and superheating of the vapor to a temperature well above its saturation temperature.
- 2 - 3 Reversible, adiabatic (isentropic) expansion of vapor in a turbine to the pressure of the condenser. The step normally crosses the saturation curve, producing a wet exhaust. However, the superheating accomplished in step 1- 2 shifts the vertical line far enough to the right on Fig. 8.3 that the moisture content is not too large.

- 3 - 4 A constant-pressure, constant-temperature process in a condenser to produce saturated liquid at point 4.
- 4 - 1 Reversible, adiabatic (isentropic) pumping of the saturated liquid to the pressure of the boiler, producing compressed (subcooled) liquid. The vertical line (whose length is exaggerated in Fig. 8.3) is very short, because the temperature rise associated with compression of a liquid is small.

Practical power cycle

Power plants can be built to operate on a cycle that departs from the Rankine cycle solely because of the irreversibilities of the work-producing and work-requiring steps. Figure 8.4 illustrates the effects of these irreversibilities on steps 2 - 3 and 4 - 1. The lines are no longer vertical, but tend in the direction of increasing entropy. The turbine exhaust is normally still wet, but as long as the moisture content is less than about l0%, erosion problems are not serious. Slight subcooling of the condensate in the condenser may occur, but the effect is inconsequential.

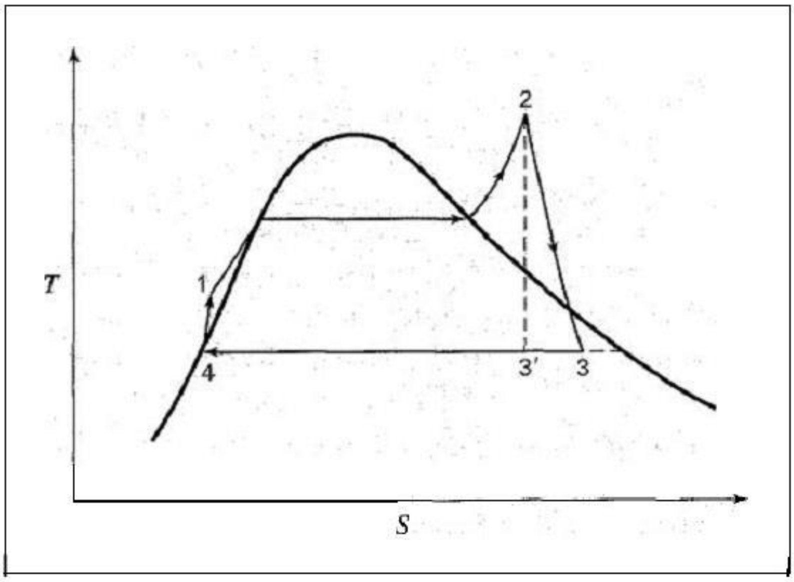

Figure 8.4 Simple practical power cycle

The boiler serves to transfer heat from a burning fuel (or from a nuclear reactor) to the cycle, and the condenser transfers heat from the cycle to the surroundings. Neglecting kinetic and potential energy changes reduces the energy relations, Eqs. (2.31) and (2.32),

$$\Delta\left(H + \tfrac{1}{2}u^2 + zg\right)\dot{m} = \dot{Q} + \dot{W}_s \qquad (2.31)$$

$$\boxed{\Delta H + \frac{\Delta u^2}{2} + g\,\Delta z = Q + W_s} \qquad (2.32a)$$

in either case to:

$$\dot{Q} = \dot{m}\,\Delta H \qquad (8.1)$$

$$Q = \Delta H \qquad (8.2)$$

Example 8.1

Steam generated in a power plant at a pressure of 8,600 kPa and a temperature of 500°C is fed to a turbine. Exhaust from the turbine enters a condenser at 10 kPa, where it is condensed to saturated liquid, which is then pumped to the boiler.

(*a*) What is the thermal efficiency of a Rankine cycle operating at these conditions?

(*b*) What is the thermal efficiency of a practical cycle operating at these conditions if the turbine efficiency and pump efficiency are both 0.75?

(*c*) If the rating of the power cycle of part (*b*) is 80,000 kW, what is the steam rate and what are the heat-transfer rates in the boiler and condenser?

Solution 8.1

(*a*) The turbine operates under the same conditions as the turbine of Ex. 7.6, where:

$$(\Delta H)_S = -1{,}274.2 \text{ kJ kg}^{-1}$$

Thus $\qquad W_s(\text{isentropic}) = (\Delta H)_S = -1{,}274.2 \text{ kJ kg}^{-1}$

Moreover, the enthalpy at the end of isentropic expansion, H_2' in Ex. 7.6, is here:

$$H_3' = 2{,}117.4 \text{ kJ kg}^{-1}$$

The enthalpy of saturated liquid at 10 kPa (and $t^{sat} = 45.83°C$) is:

$$H_4 = 191.8 \text{ kJ kg}^{-1}$$

Thus by Eq. (8.2) applied to the condenser,

$$Q(\text{condenser}) = H_4 - H_3' = 191.8 - 2{,}117.4 = -1{,}925.6 \text{ kJ kg}^{-1}$$

where the minus sign signifies that heat flows out of the system.

The pump operates under essentially the same conditions as the pump of Ex. 7.10, where:

$$W_s(\text{isentropic}) = (\Delta H)_S = 8.7 \text{ kJ kg}^{-1}$$

Whence, $\qquad H_1 = H_4 + (\Delta H)_S = 191.8 + 8.7 = 200.5 \text{ kJ kg}^{-1}$

The enthalpy of superheated steam at 8,600 kPa and 500°C is:

$$H_2 = 3{,}391.6 \text{ kJ kg}^{-1}$$

By Eq. (8.2) applied to the boiler,

$$Q(\text{boiler}) = H_2 - H_1 = 3{,}391.6 - 200.5 = 3{,}191.1 \text{ kJ kg}^{-1}$$

The net work of the Rankine cycle is the sum of the turbine work and the pump work:

$$W_s(\text{Rankine}) = -1{,}274.2 + 8.7 = -1{,}265.5 \text{ kJ kg}^{-1}$$

This result is of course also:

$$W_s(\text{Rankine}) = -Q(\text{boiler}) - Q(\text{condenser})$$
$$= -3{,}191.1 + 1{,}925.6 = -1{,}265.5 \text{ kJ kg}^{-1}$$

The thermal efficiency of the cycle is:

$$\eta = \frac{|W_s(\text{Rankine})|}{Q(\text{boiler})} = \frac{1{,}265.5}{3{,}191.1} = 0.3966$$

(*b*) With a turbine efficiency of 0.75, then also from Ex. 7.6:

$$W_s(\text{turbine}) = \Delta H = -955.6 \text{ kJ kg}^{-1}$$

Whence $\quad H_3 = H_2 + \Delta H = 3{,}391.6 - 955.6 = 2{,}436.0 \text{ kJ kg}^{-1}$

For the condenser,

$$Q(\text{condenser}) = H_4 - H_3 = 191.8 - 2{,}436.0 = -2{,}244.2 \text{ kJ kg}^{-1}$$

By Ex. 7.10 for the pump,

$$W_s(\text{pump}) = \Delta H = 11.6 \text{ kJ kg}^{-1}$$

The net work of the cycle is therefore:

$$\dot{W}_s(\text{net}) = -955.6 + 11.6 = -944.0 \text{ kJ kg}^{-1}$$

and $\quad H_1 = H_4 + \Delta H = 191.8 + 11.6 = 203.4 \text{ kJ kg}^{-1}$

Then $\quad Q(\text{boiler}) = H_2 - H_1 = 3{,}391.6 - 203.4 = 3{,}188.2 \text{ kJ kg}^{-1}$

The thermal efficiency of the cycle is therefore:

$$\eta = \frac{|W_s(\text{net})|}{Q(\text{boiler})} = \frac{944.0}{3{,}188.2} = 0.2961$$

which may be compared with the result of part (*a*).

(*c*) For a power rating of 80,000 kW:

$$\dot{W}_s(\text{net}) = \dot{m} W_s(\text{net})$$

or $\quad \dot{m} = \dfrac{\dot{W}_s(\text{net})}{W_s(\text{net})} = \dfrac{-80{,}000 \text{ kJ s}^{-1}}{-944.0 \text{ kJ kg}^{-1}} = 84.75 \text{ kg s}^{-1}$

Then by Eq. (8.1),

$$\dot{Q}(\text{boiler}) = (84.75)(3{,}188.2) = 270.2 \times 10^3 \text{ kJ s}^{-1}$$

$$\dot{Q}(\text{condenser}) = (84.75)(-2{,}244.2) = -190.2 \times 10^3 \text{ kJ s}^{-1}$$

Note that $\quad \dot{Q}(\text{boiler}) + \dot{Q}(\text{condenser}) = -\dot{W}_s(\text{net})$