CEN 202 THERMODYNAMICS

CHAPTER 8: PRODUCTION OF POWER FROM HEAT

Text Book: : J. M. Smith, H. C. Van Ness, M. M. Abbott, M. T. Swihart. "INTRODUCTION TO CHEMICAL ENGINEERING THERMODYNAMICS", EIGHTH EDITION. 2018

Production of Power from Heat

The objective of this chapter is the conversion of energy from a form capable of producing mechanical work into heat and/or transfer of heat from a source at higher temperature to a lower temperature. These processes generate entropy. Minimum entropy generation is required to use energy most efficiently.

Source of power:

Solar,
Nuclear
Wind,
Fossil fuels,
Photovoltaic cells,
Chemical (molecular) energy (fuel cell, battery..)

In this chapter, steam power plants (Carnot, Rankine, and regenerative cycles) will be examined.

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Production of Power from Heat

8.1 THE STEAM POWER PLANT

Figure 8.1 shows a simple steady-state steady-flow cyclic 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 processes that occur as the working fluid flows around the cycle are represented by lines on the *TS* diagram of Fig. 8.2.

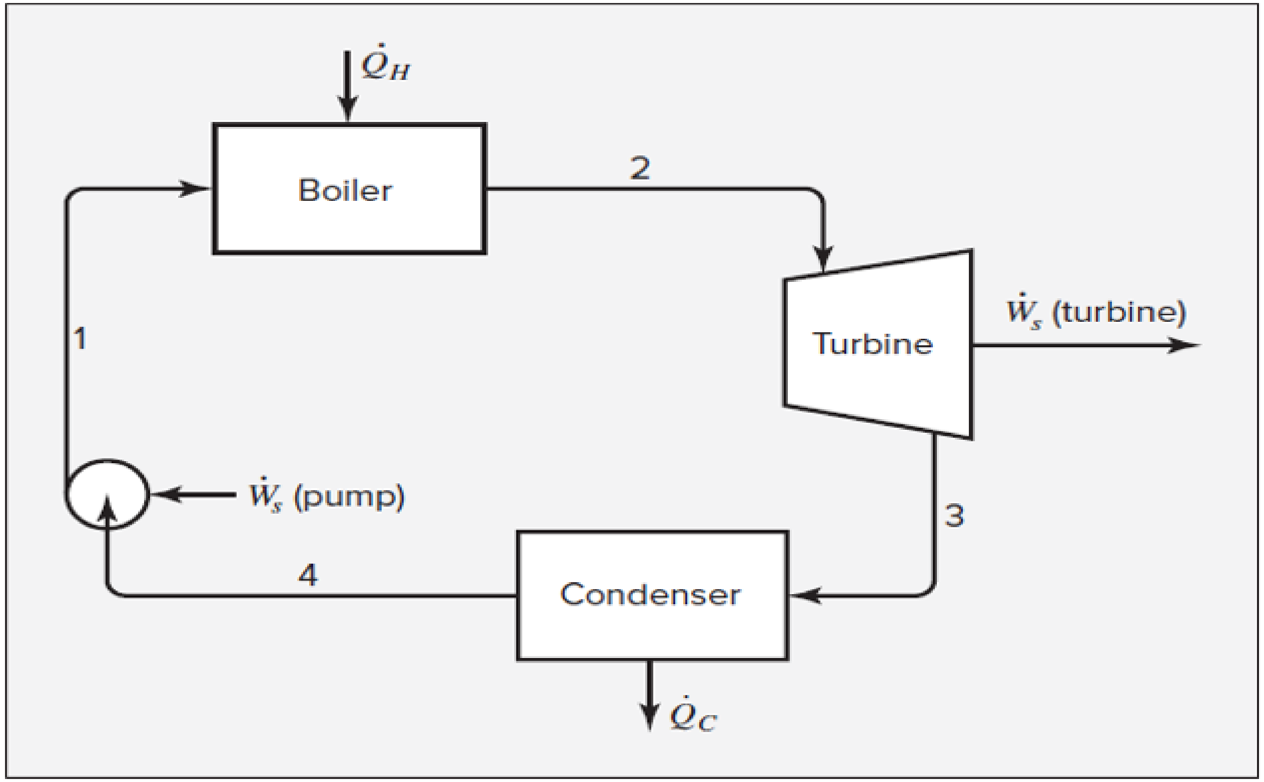

Fig. 8.1 Simple steam power plant

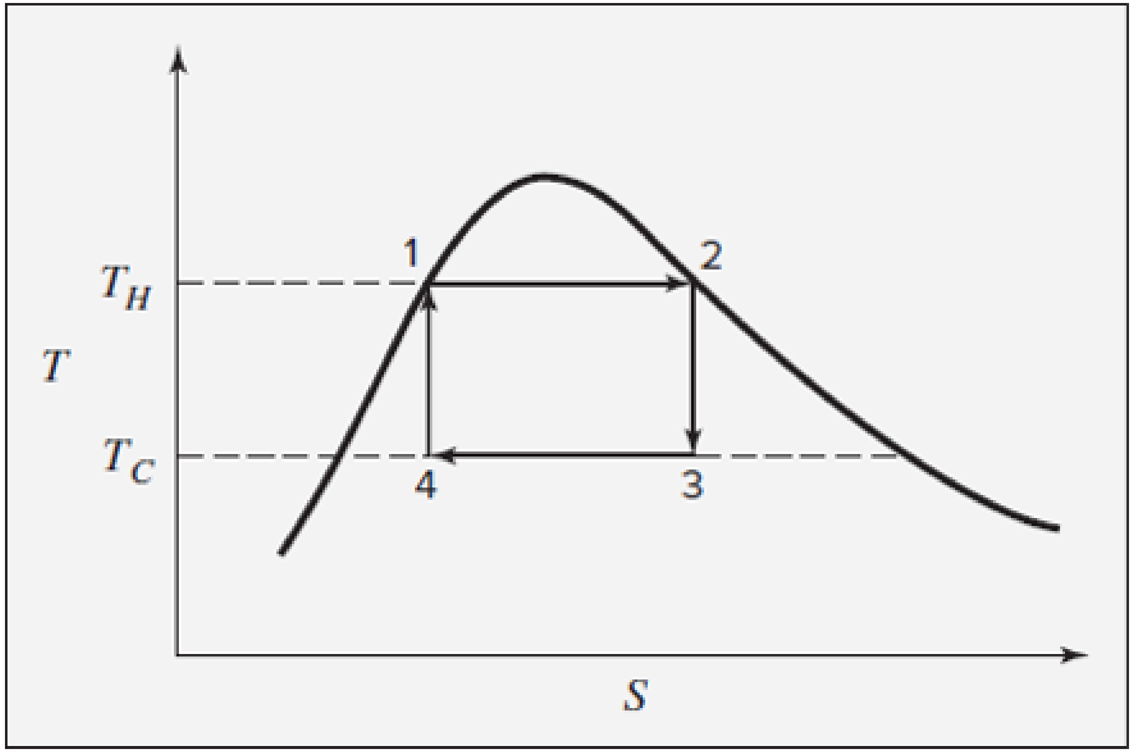

Fig. 8.2 Carnot cycle on a T-S diagram

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The operation as represented is reversible, consisting of **two isothermal steps** connected by **two adiabatic steps**.

Step 1 → 2 is isothermal vaporization taking place in a boiler at temperature T_H, wherein heat is transferred to saturated-liquid water at rate $\dot{Q}_H$, producing saturated vapor.

Step 2 → 3 is reversible adiabatic expansion of saturated vapor in a turbine producing a two-phase mixture of saturated liquid and vapor at T_C. This isentropic expansion is represented by a vertical line.

Step 3 → 4 is an isothermal partial-condensation process at lower temperature TC, wherein heat is transferred to the surroundings at rate Q·C.

Step 4 → 1 is an isentropic compression in a pump. Represented by a vertical line, it takes the cycle back to its origin, producing saturated liquid water at point 1.

The power produced by the turbine, $\dot{W}$, is much greater than the power requirement of the pump $\dot{W}_{pump}$, The net power output is equal to the difference between the rate of heat input in the boiler and the rate of heat rejection in the condenser.

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The thermal efficiency of this cycle is:

$$\eta_{Carnot} = 1 - \frac{T_C}{T_H} \tag{5.7}$$

Clearly, η increases as T_H increases and as T_C decreases. Although the efficiencies of practical heat engines are lowered by irreversibilities, it is still true that their efficiencies are increased when the average temperature at which heat is absorbed in the boiler is increased and when the average temperature at which heat is rejected in the condenser is decreased.

Production of Power from Heat

8.1 THE STEAM POWER PLANT

The Rankine Cycle

The thermal efficiency of the Carnot cycle just described 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.

A. Turbines that take in saturated steam produce an exhaust with high liquid content, which causes severe erosion problems.

B. 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 cycle is taken as the standard, at least for fossil-fuel-burning power plants. It is called the ***Rankine cycle***, and it 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 in Fig. 8.3 and described as follows:

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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.

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8.1 THE STEAM POWER PLANT

The Rankine Cycle

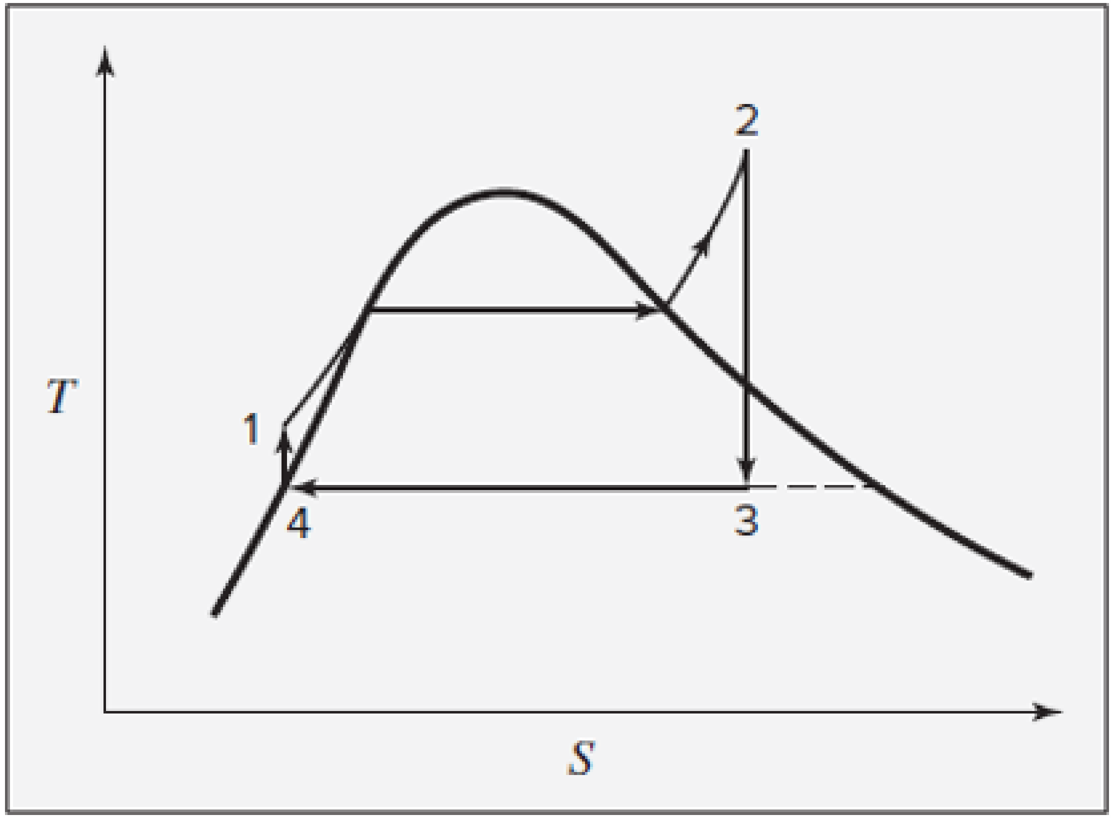

Figure 8.3: Rankine cycle on a *TS* diagram.

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8.1 THE STEAM POWER PLANT

The Rankine Cycle

Power plants actually operate on a cycle that departs from the Rankine cycle due to irreversibilities of the expansion and compression 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 with sufficiently low moisture content, erosion problems are not serious. Slight subcooling of the condensate in the condenser may occur, but the effect is inconsequential.

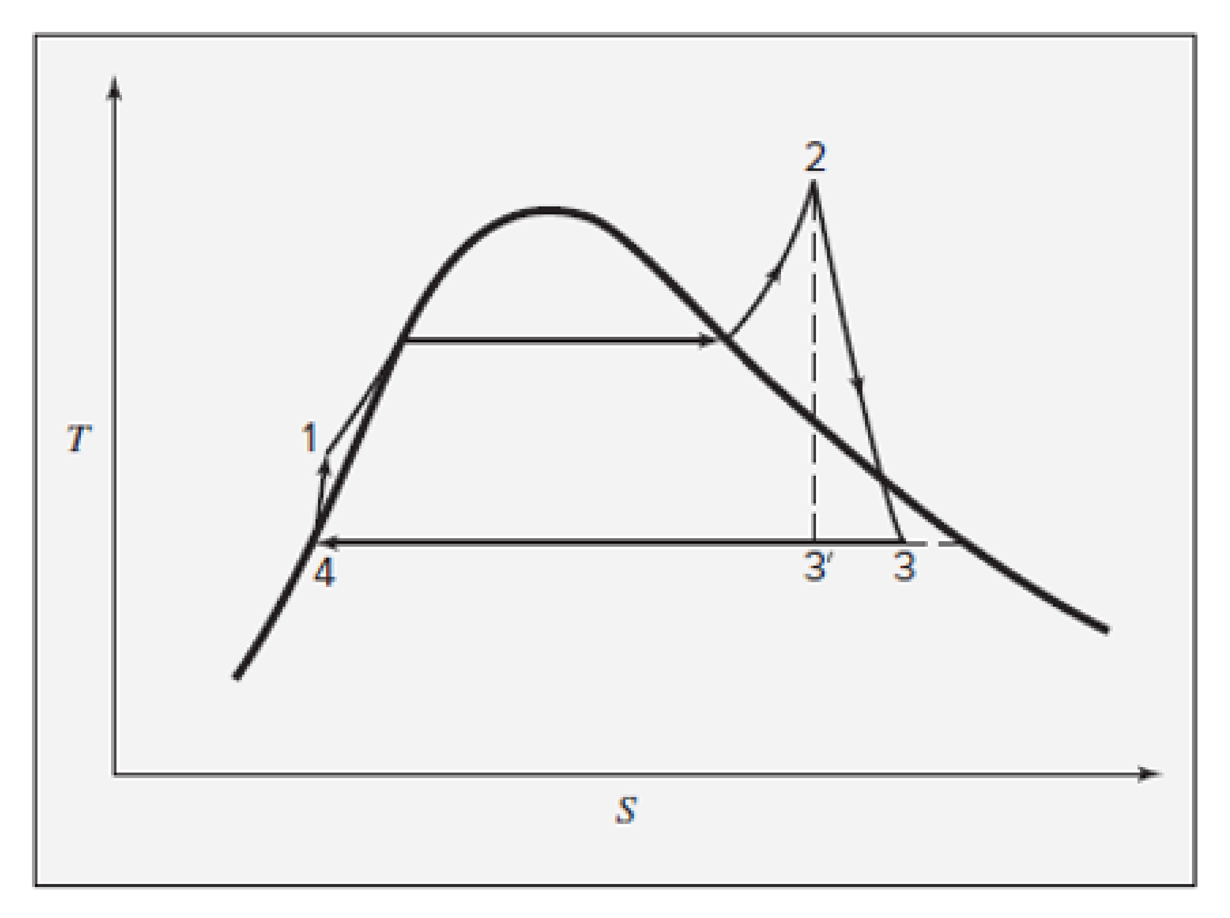

Fig. 8.4 Simple practical power plant

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8.1 THE STEAM POWER PLANT

The Rankine Cycle

The boiler serves to transfer heat from a burning fuel (or from a nuclear reactor or even a solar-thermal heat source) to the cycle, and the condenser transfers heat from the cycle to the surroundings. Neglecting kinetic- and potential-energy changes reduces the energy relations to:

$\dot{Q} = \dot{m}\Delta H \qquad Q = \Delta H$

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Production of Power from Heat, THE STEAM POWER PLANT

The Regenerative Cycle

The thermal efficiency of a steam power cycle is increased when the pressure and hence the vaporization temperature in the boiler is raised. Therefore the regenerative cycles are used in power plants.

Most modern power plants operate on a modification of the Rankine cycle that incorporates feedwater heaters. Water from the condenser, rather than being pumped directly back to the boiler, is first heated by steam extracted from the turbine. This is normally done in several stages, with steam taken from the turbine at several intermediate states of expansion. An arrangement with four feedwater heaters is shown in Fig. 8.5. The operating conditions indicated on this figure and described in the following paragraphs are typical, and are the basis for the illustrative calculations of Ex. 8.2.

The conditions of steam generation in the boiler are the same as in Ex. 8.1: 8600 kPa and 500 °C. The exhaust pressure of the turbine, 10 kPa, is also the same. The saturation temperature of the exhaust steam is therefore 45.83°C. Allowing for slight subcooling of the condensate we fix the temperature of the liquid water from the condenser at 45 °C. The feedwater pump, which operates under exactly the conditions of the pump in Ex. 7.10, causes a temperature rise of about 1 °C, making the temperature of the feedwater entering the series of heaters equal to 46 °C.

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Production of Power from Heat, THE STEAM POWER PLANT, The Regenerative Cycle

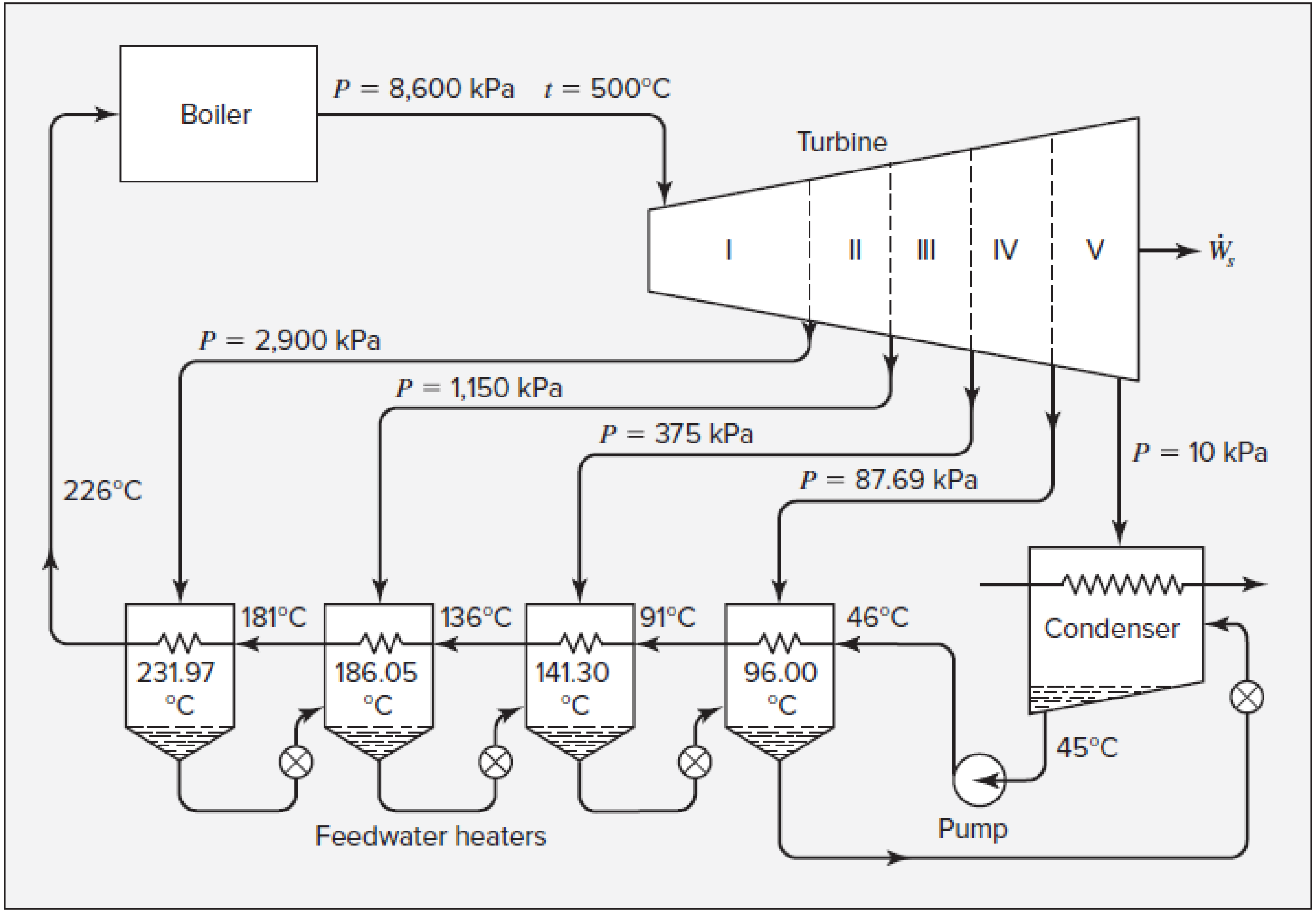

Figure 8.5: Steam power plant with feedwater heating.

Production of Power from Heat,

8.2 INTERNAL-COMBUSTION ENGINES

In a steam power plant, the steam is an inert medium to which heat is transferred from an external source (e.g., burning fuel). It is therefore characterized by large heat-transfer surfaces:

(1) for the absorption of heat by the steam at a high temperature in the boiler, and

(2) for the rejection of heat from the steam at a relatively low temperature in the condenser.

In an internal-combustion engine, on the other hand, a fuel is burned within the engine itself, and the combustion products serve as the working medium, acting for example on a piston in a cylinder. High temperatures are internal and do not involve heat-transfer surfaces.

The Otto Engine
The Diesel Engine
The Gas-Turbine Engine

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8.2 INTERNAL-COMBUSTION ENGINES

The Gas-Turbine Engine

The gas turbine is driven by high-temperature gases from a combustion chamber, as indicated in Fig. 8.11. The entering air is compressed (supercharged) to a pressure of several bars before combustion. The higher the temperature of the combustion gases entering the turbine, the higher the efficiency of the unit, i.e., the greater the work produced per unit of fuel burned.

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8.2 INTERNAL-COMBUSTION ENGINES; The Gas-Turbine Engine

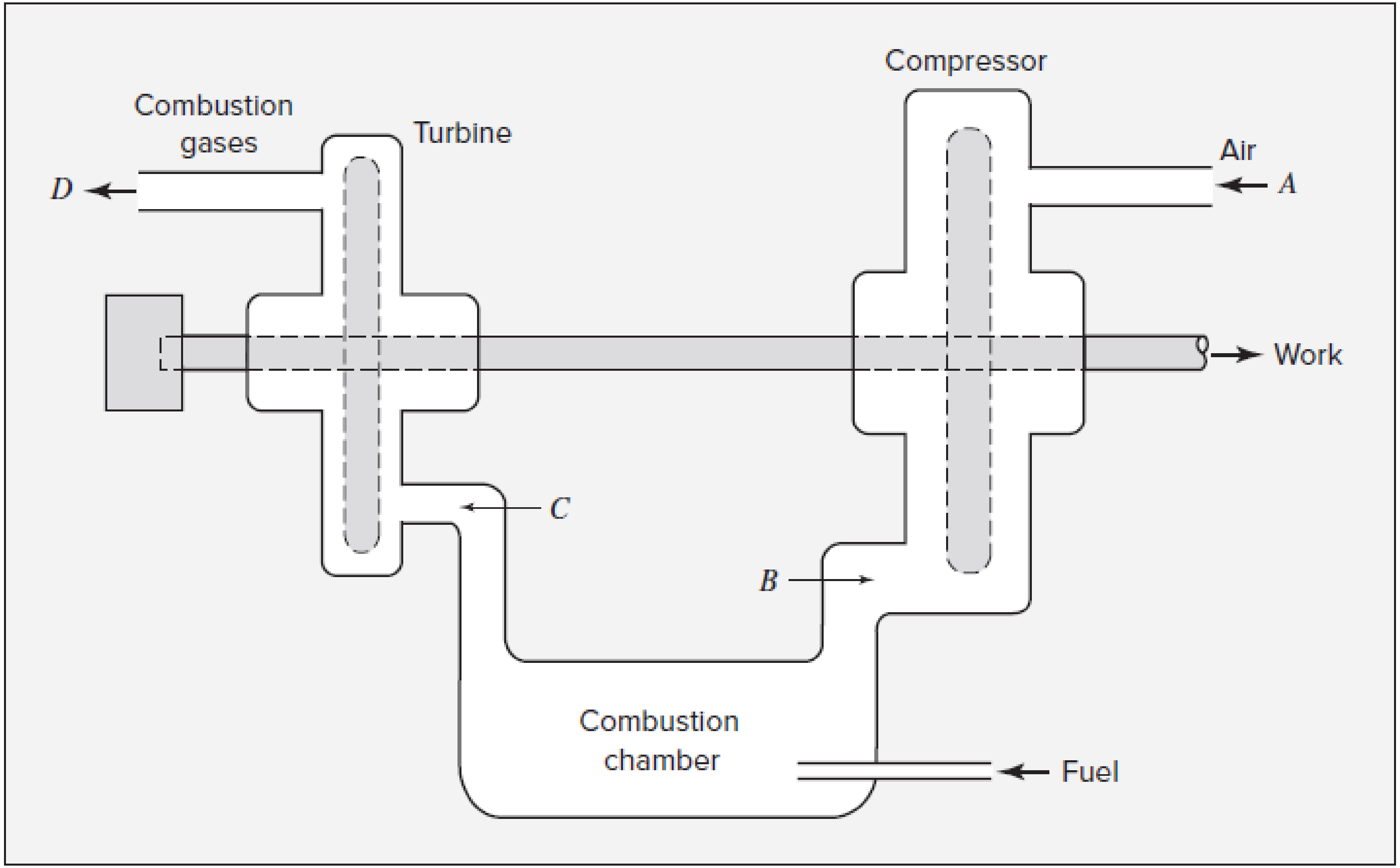

Figure 8.11: Gas-turbine engine.

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8.2 INTERNAL-COMBUSTION ENGINES; The Gas-Turbine Engine

The idealization of the gas-turbine engine, called the Brayton cycle, is shown on a *PV* diagram in Fig. 8.12. The working fluid is air in its ideal-gas state with constant heat capacities. Step *AB* is a reversible adiabatic compression from P_A (atmospheric pressure) to P_B. In step *BC* heat Q_{BC}, replacing combustion, is added at constant pressure, raising the air temperature. A work-producing isentropic expansion of the air reduces the pressure from P_C to P_D (atmospheric pressure). Step D_A is a constant-pressure cooling process that merely completes the cycle. The thermal efficiency of the cycle is:

$$\eta = \frac{-W(net)}{Q_{BC}} = \frac{-(W_{CD}+W_{AB})}{Q_{BC}}$$

where each energy quantity is based on 1 mol of air.

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8.2 INTERNAL-COMBUSTION ENGINES; The Gas-Turbine Engine

The work done as air passes through the compressor, and for air in its ideal-gas state with constant heat capacities:

$$W_{AB} = H_B - H_A = C_P^{ig}(T_B - T_A)$$

Similarly, for the heat-addition and turbine processes,

$$Q_{BC} = C_P^{ig}(T_C - T_B) \quad and \quad W_{CD} = C_P^{ig}(T_C - T_D)$$

Substituting these equations into previous equation and simplifying leads to:

$$\eta = 1 - \frac{T_D - T_C}{T_C - T_B}$$

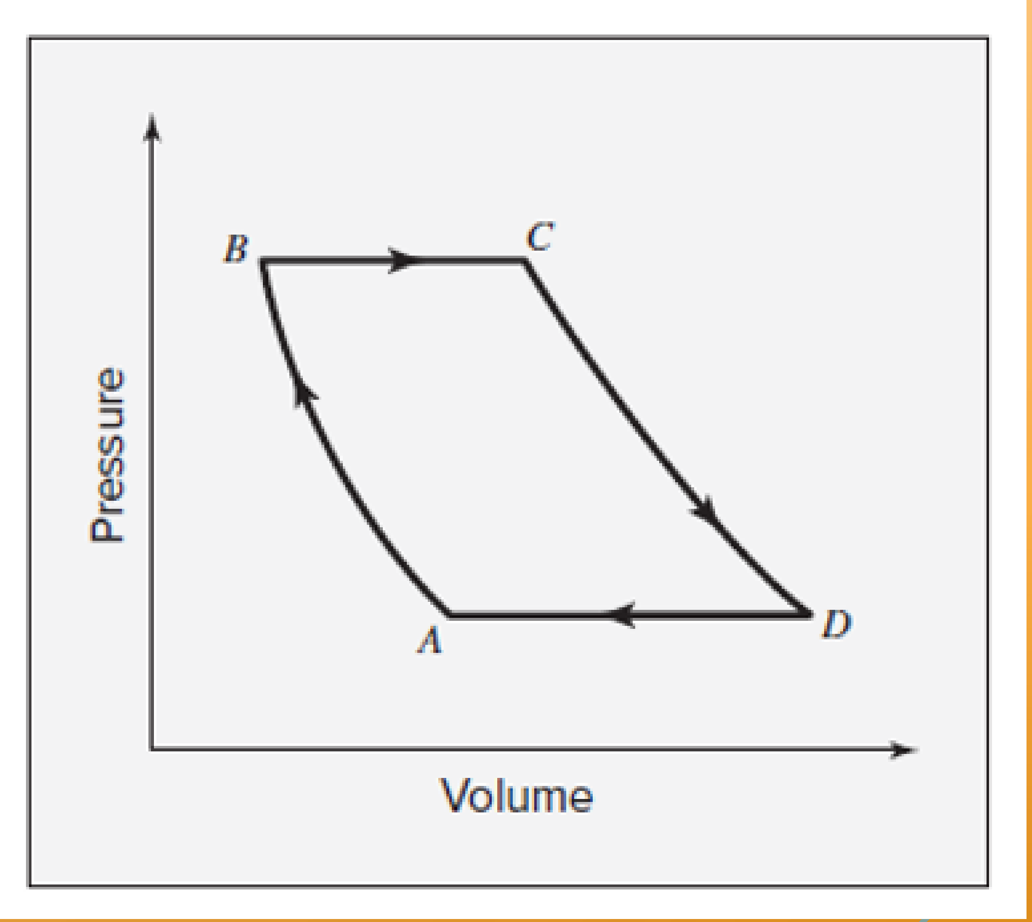

Fig. 8.12 Brayton cycle for the gas turbine engine

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8.2 INTERNAL-COMBUSTION ENGINES; The Gas-Turbine Engine

Because processes *AB* and *CD* are isentropic, the temperatures and pressures are related by the equation reported in Chapter 3;

$$\frac{T_A}{T_B} = \left(\frac{P_A}{P_B}\right)^{\frac{(\gamma-1)}{\gamma}}$$

and

$$\frac{T_D}{T_C} = \left(\frac{P_D}{P_C}\right)^{\frac{(\gamma-1)}{\gamma}} = \left(\frac{P_A}{P_B}\right)^{\frac{(\gamma-1)}{\gamma}}$$

From the equations and using previous knowledge;

$$\eta = 1 - \left(\frac{P_A}{P_B}\right)^{\frac{(\gamma-1)}{\gamma}}$$

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