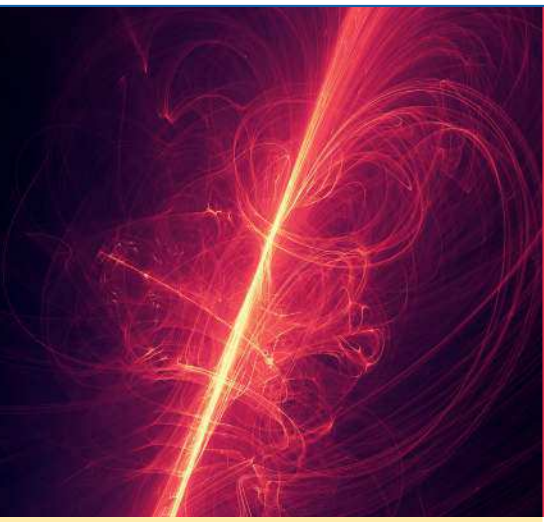
Cambridge University Press
978-1-107-17971-4 — Thermodynamics
2nd Edition
Excerpt
More Information



CHAPTER 1
Beginnings

LEARNING OBJECTIVES

After studying Chapter 1, you should:

- Have a basic idea of what thermodynamics is and the kinds of engineering problems to which it applies.
- Be able to distinguish between a closed system and an open system (control volume).
- Have an understanding of and be able to state the formal definitions of thermodynamic properties, states, processes, and cycles.
- Understand the concept of thermodynamic equilibrium and its requirement of simultaneously satisfying thermal, mechanical, phase, and chemical equilibria.
- Be able to explain the meaning of a quasi-equilibrium process.
- Understand the distinction between primary dimensions and derived dimensions, and the distinction between dimensions and units.
- Be able to convert SI units of force, mass, energy, and power to US customary units, and vice versa.

CHAPTER 1 OVERVIEW

IN THIS CHAPTER, we introduce and define the subject of thermodynamics. We also introduce three complex practical applications of our study of thermodynamics: the fossil-fueled steam power plant, jet engines, and the spark-ignition reciprocating engine. To set the stage for more detailed developments later in the book, several of the most important concepts and definitions are presented here. These include the concepts of: open and closed thermodynamic systems; thermodynamic properties, states, and cycles; and equilibrium and quasi-equilibrium processes. The chapter concludes with an organizational overview of engineering thermodynamics and presents some ideas of how you might optimize the use of this textbook based on your particular educational objectives.

1.1 What Is Thermodynamics?

Thermodynamics is one of three disciplines known collectively as the thermal-fluid sciences, sometimes as just the thermal sciences: thermodynamics, heat transfer, and fluid mechanics. We begin with a dictionary definition [1] of thermodynamics:

***Thermodynamics* is the science that deals with the relationship of heat and mechanical energy and conversion of one into the other.**

The Greek roots, *therme*, meaning heat, and *dynamis*, meaning power or strength, suggest a more elegant definition: *the power of heat*. In its common usage in engineering, thermodynamics has come to mean the broad study of energy and its various interconversions from one form to another. Figure 1.1 illustrates a few examples that motivate our study of thermodynamics.

FIGURE 1.1 Examples of energy conversion systems: Hybrid engine converts energy stored in chemical bonds of fuel molecules or from batteries to shaft power (left) (GreenPimp / E+ / Getty images); photovoltaic solar panels and wind turbines convert solar radiation and wind energy to electricity, respectively (right) (GIPhotoStock / Cultura / Getty Images).

1.2 Some Applications

Practical applications of thermodynamics abound. Biological systems provide many examples. Consider yourself as a thermodynamic system. All of your physical activities require energy transformation. Energy stored in the chemical bonds of foodstuffs is transformed to power temperature regulation, respiration, blood circulation, muscle movements, and other body functions. Electronic devices are ubiquitous. Consider your smart phone. Charging the phone involves converting electrical energy from a wall outlet to chemical energy stored in the phone's battery. The energy in the battery then powers the electronic circuits and is ultimately transported to the surroundings as thermal energy. Another natural example of the application of thermodynamics is provided by the physical processes associated with the weather. Radiant energy from the sun heats the ground, which in turn heats the air and results in thermals and downdrafts. The evaporation and condensation of water to form clouds involve thermodynamic processes. Some of the problems at the end of this chapter focus on everyday applications of thermodynamics.

We introduce the following three practical applications, which we use as recurring themes throughout the book:

- Steam power plants,
- Spark-ignition engines, and
- Jet engines.

These applications, and others, provide a practical context for our study of thermodynamics. Many of the examples presented in subsequent chapters revisit these specific applications, as do many of the end-of-chapter problems. Where these particular examples appear, a note reminds the reader that the example relates to one of these three themes.

1.2a Steam Power Plants

There are many reasons to choose the steam power plant as an application of thermodynamics. First, and foremost, is the overwhelming importance of such power plants to our daily existence. Imagine how your life would be changed if you did not have access to electrical power (Fig. 1.2) or, less severely, if electricity had to be rationed so that it would be available to you only a few hours each day! It is easy to forget the blessings of essentially limitless electrical power available to residents of the United States. From Table 1.1, we see that the combustion of fossil fuels is the dominant source of our electricity; approximately 63.4% of the electricity produced in the United States in 2018 had its origin in the combustion of a fossil fuel, that is, coal, gas, or oil. Figure 1.3 shows a German coal-fired power plant. Nuclear power is the second largest source with approximately 19.3% of the total generation. We also note that, with 8.2%, the combined amount of electricity generated by solar and wind power has increased by almost a factor of six from 2008 to 2018. A second reason for our choice of steam power plants as an integrating application is the historical significance of steam power. The science of thermodynamics was born, in part, from a desire to understand and improve the earliest steam engines. John Newcomen's first coal-fired steam engine in 1712 (Fig. 1.4) predates the discovery of the fundamental principles of thermodynamics by more than a hundred years! The idea later to be

TABLE 1.1 Electricity Generation in the United States for 2018 [2]

Source		Billion kW·hr	%
Fossil fuels			
Coal		1146.4	27.4
Petroleum		24.6	0.6
Natural gas		1468.0	35.1
Other gases		12.2	0.3
	Subtotal	2651.2	63.4
Nuclear		807.1	19.3
Hydro pumped storage		–5.9	–0.1
Renewables			
Hydro		291.7	7.0
Wood		41.4	1.0
Waste		21.4	0.5
Geothermal		16.7	0.4
Solar		66.6	1.6
Wind		275.0	6.6
	Subtotal	712.8	17.1
Other		12.6	0.3
TOTAL		4177.8	100.0

FIGURE 1.2 A complex electrical transmission grid transmits electricity from power plants to users throughout the USA. How to deal with the intermittent power production from solar and wind energy sources is a major concern associated with integrating these renewable sources into the electrical grid (Jeff_Hu / iStock / Getty Images Plus).

known as the second law of thermodynamics was published by Sadi Carnot in 1824; and Julius Mayer first presented the conservation of energy principle, or the first law of thermodynamics, in 1842.

A timeline of important people and events in the history of the thermal sciences is presented in Appendix A.

FIGURE 1.3 Modern coal-fired power plant (Germany) (acilo / E+ / Getty Images).

In this chapter, we present the basic steam power plant cycle and illustrate some of the hardware used to accomplish this cycle. In subsequent chapters, we will add devices and complexity to the basic cycle. Figure 1.5 shows the basic steam power cycle, or Rankine cycle. (William Rankine (1820–1872), a Scottish engineer, was the author of the *Manual of the Steam Engine and Other Prime Movers* (1859) and made significant contributions to the fields of civil and mechanical engineering.) Water

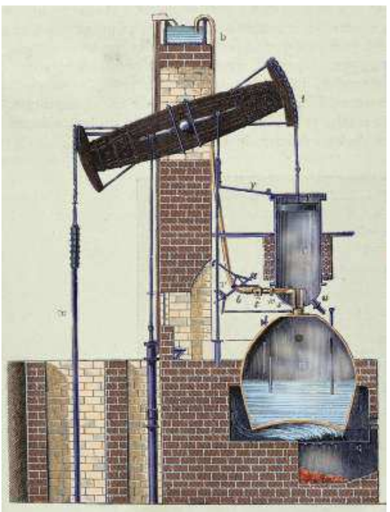


FIGURE 1.4 Newcomen's first coal-fired steam engine (PRISMA ARCHIVO / Alamy Stock Photo).

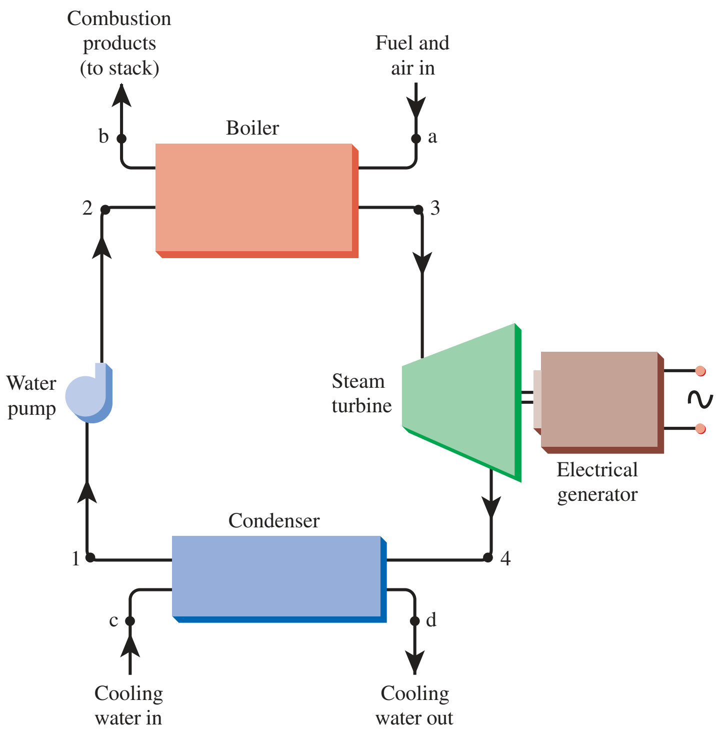


FIGURE 1.5 This basic steam power cycle is also known as the Rankine cycle.

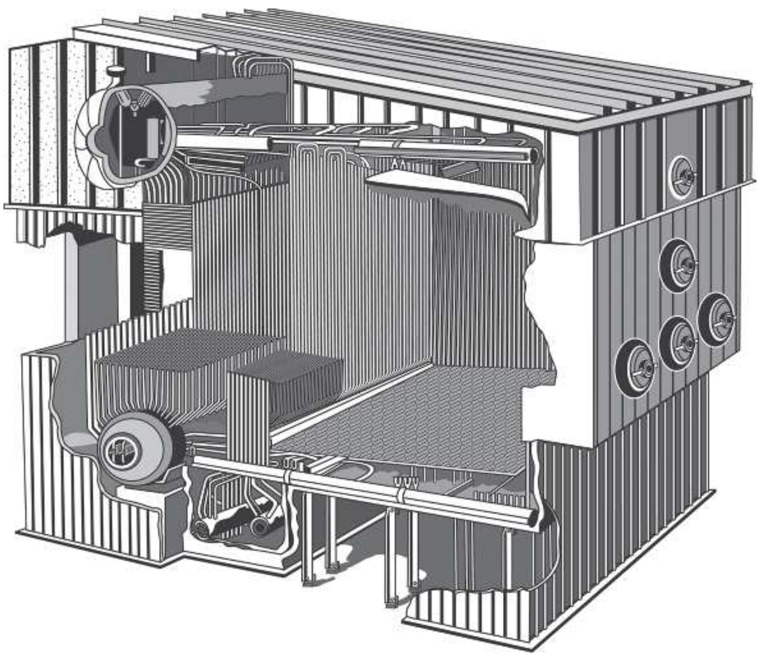


FIGURE 1.6 Cutaway view of boiler showing gas- or oil-fired burners on the right wall. Hot combustion products heat liquid water flowing through the tubes. The steam produced resides in the steam drum (tank) at the top left. This boiler has a nominal 8-m width, 12-m height, and 10-m depth. Adapted from Ref. [3]. (Courtesy of the Babcock & Wilcox Company.)

(liquid and vapor) is the working fluid in the closed loop 1–2–3–4–1. The water undergoes four processes:

Process 1–2 A pump boosts the pressure of the liquid water prior to entering the boiler. To operate the pump, an input of energy is required.

Process 2–3 Energy is added to the water in the boiler, resulting, first, in an increase in the water temperature and, second, in a phase change. The hot products of combustion provide this energy. The working fluid is liquid at state 2 and all vapor (steam) at state 3.

Process 3–4 Energy is removed from the high-temperature, high-pressure steam as it expands through a steam turbine. The output shaft of the turbine is connected to an electrical generator for the production of electricity.

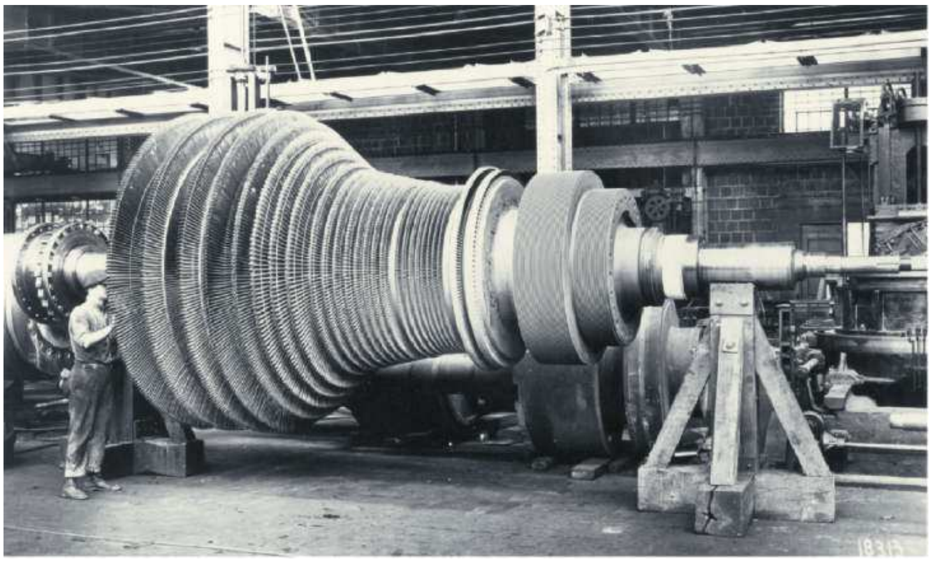
Process 4–1 The low-pressure steam is returned to the liquid state as it flows through the condenser. The energy from the condensing steam is transferred to the cooling water.

Figures 1.6–1.10 illustrate the various generic components used in the Rankine cycle. Figure 1.6 shows a cutaway view of an industrial boiler; a much larger central power station utility boiler is shown in Figure 1.7. Although the design of boilers [3–6] is well beyond the scope of this book, the text offers much about the fundamental principles of their operation. For example, you will learn about the properties of water and steam in Chapter 2, whereas the necessary aspects of mass and energy conservation needed to deal with the components are treated in Chapters 3–5. Chapter 8 considers the components of a power plant (see Figs. 1.8–1.10); and Chapter 9 considers the system as whole.

As we begin our study, we emphasize the importance of safety in both the design and operation of power generation equipment. Fluids at high pressure contain enormous quantities of energy, as do spinning turbine rotors. Figure 1.11 shows the results

FIGURE 1.7 Boilers for public utility central power generation can be quite large, as are these natural gas-fired units (Ron_Thomas / E+ / Getty Images).

FIGURE 1.8 Steam turbine for power generation. Photograph and original caption reproduced with permission of the Smithsonian Institution.



The "Heart" of the Huge Westinghouse Turbine – An unusual detailed picture showing the maze of minutely fashioned blades – approximately five thousand – of the Westinghouse turbine rotor, or "spindle". Though only twenty-five feet in length this piece of machinery weighs one hundred and fifteen thousand pounds. At full speed the outside diameter of the spindle, on the left, is running nearly ten miles per minute, or a little less than 600 miles per hour. The problem of excessive heat resulting from such tremendous speed has been overcome by working the bearings under forced lubrication, about two barrels of oil being circulated through the bearings every sixty seconds to lubricate and carry away the heat generated by the rotation. The motor is that of the 45000 H.P. generating unit built by the South Philadelphia Works, Westinghouse Electric & Mfg. Co. for the Los Angeles Gas and Electric Company (Getty).

of a catastrophic boiler explosion. Similarly, environmental concerns are extremely important in power generation. Examples here are the emission of potential air pollutants from the combustion process (Fig. 1.12) and thermal interactions with the environment associated with steam condensation. Control of sulfur dioxide emissions

FIGURE 1.9 Cutaway view of shell-and-tube heat exchanger. Energy is transferred from the hot fluid passing through the shell to the cold fluid flowing through the tubes.

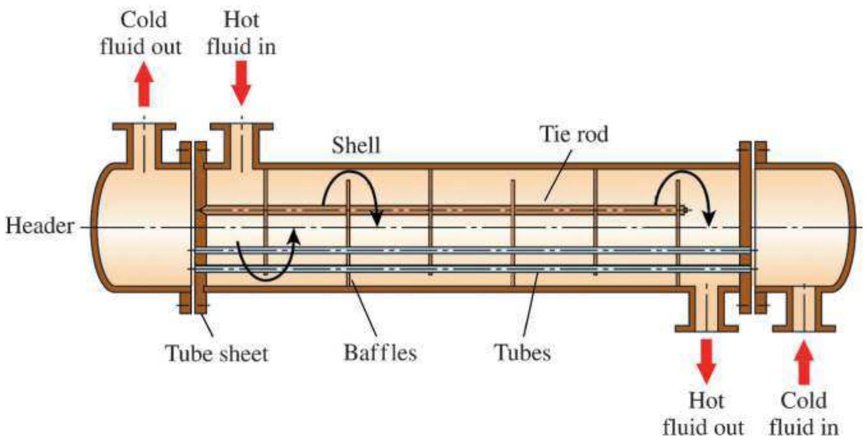


FIGURE 1.10 This pump was designed for nuclear reactor and steam generator feed applications. Feedwater pumps may be driven by electric motors or from auxiliary steam turbines. Courtesy of Flowserve Corporation.

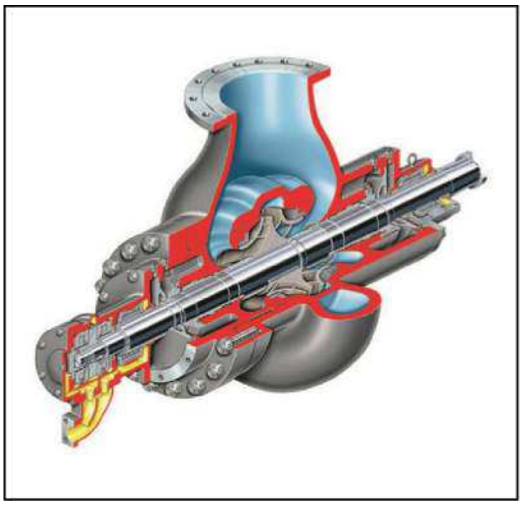


FIGURE 1.11 A policeman inspects the site of an explosion near Bangkok, Thailand, August 19, 2014. A large boiler in a cloth dyeing factory exploded, injuring 22 people (Xinhua / Alamy Stock Photo).

FIGURE 1.12 Smog in Shanghai, China (left) (Wenjie Dong / E+ / Getty Images). Pollution controls are important components of fossil-fueled power plants. Shown here (right) is an electrostatic precipitator, which removes particulate matter from the flue gases of a power plant (nsf / Alamy Stock Photo).

from coal combustion generates large quantities of sludge requiring disposal or storage. You can find entire textbooks devoted to these topics [7, 8].

1.2b Spark-Ignition Engines

We choose the spark-ignition engine as one of our applications to revisit because there are so many of them (Fig. 1.13) – approximately 200 million are installed in automobiles and light-duty trucks in the United States alone – and because many students are particularly interested in engines. Owing to these factors, and others, many schools offer entire courses dealing with internal combustion engines, and many books are devoted to this subject, among them Refs. [9–12].

FIGURE 1.13 Spark-ignition engines power hundreds of millions of vehicles in the USA and around the world (fotog / Getty Images).

Although you may be familiar with the four-stroke engine cycle, we present it here to make sure that all readers have the same understanding. Figure 1.14 illustrates the following sequence of events:

Intake Stroke The inlet valve is open and the downward motion of the piston pulls a fresh fuel-air mixture into the cylinder. At some point near the bottom of the stroke, the intake valve closes.

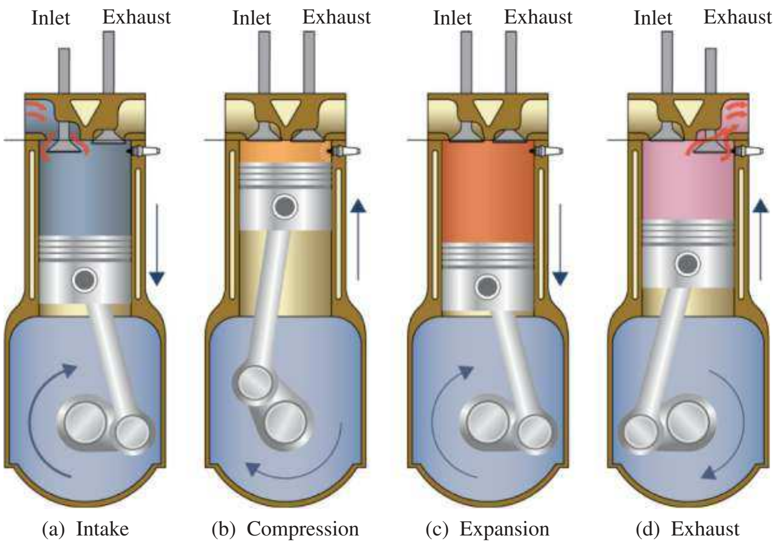


FIGURE 1.14 The mechanical cycle of the four-stroke spark-ignition engine consists of the intake stroke **(a)**, the compression stroke **(b)**, the expansion stroke **(c)**, and the exhaust stroke **(d)**. The sequence of events, however, does not execute a thermodynamic cycle. Adapted from Ref. [9] with permission. (Credit: Internal Combustion Engine Fundamentals, John Heywood. © McGraw-Hill Education.)

Compression Stroke The piston moves upward, compressing the mixture. The temperature and pressure increase. Prior to the piston reaching the top of its travel (i.e., the top center position), the spark plug ignites the mixture and a flame begins to propagate across the combustion chamber. The pressure rises above that due to compression alone.

Expansion Stroke The flame continues its travel across the combustion chamber, ideally burning all of the mixture before the piston has descended much from top center. The high pressure in the cylinder pushes the piston downward. Energy is extracted from the burned gases in the process.

Exhaust Stroke When the piston is near the bottom of its travel (bottom center), the exhaust valve opens. The hot combustion products flow rapidly out of the cylinder because of the relatively high pressure within the cylinder compared to that in the exhaust port. The piston ascends, pushing most of the remaining combustion products out of the cylinder. When the piston is somewhere near top center, the exhaust valve closes and the intake valve opens. The mechanical cycle now repeats.

In Chapters 5 and 12, we will analyze the processes that occur during the times in the cycle when both valves are closed and the gas contained within the cylinder can be treated as a thermodynamic system. With this analysis, we can model the compression, combustion, and expansion processes. A section of Chapter 9 also focuses on the Otto and diesel gas power cycles.

1.2c Jet Engines

Air travel is a common mode of transportation, with 571 billion passenger miles flown in the United States in 2012. Since you are likely to entrust your life from time to time to the successful performance of jet engines, you may find learning about these engines interesting. Figure 1.15 schematically illustrates the two general types of aircraft engines.

The schematic at the top shows a pure turbojet engine in which the jet of combustion products passing through the exhaust nozzle generates all of the thrust. This type

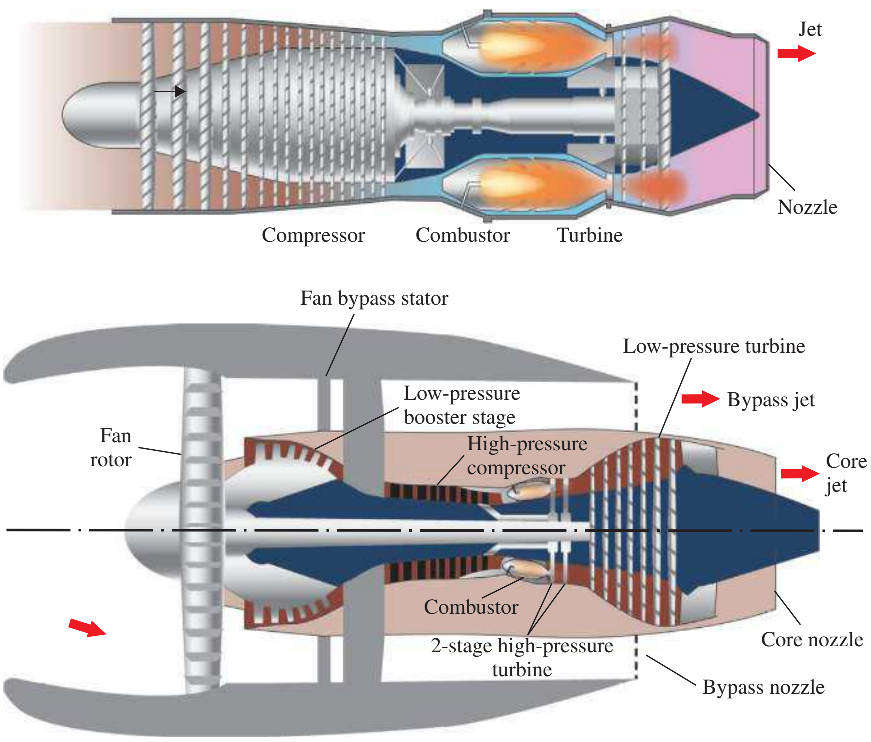


FIGURE 1.15 Schematic drawings of a single-shaft turbojet engine (top) and a two-shaft high-bypass turbofan engine (bottom). Adapted from Ref. [13].

of engine powered the supersonic J4 Phantom military jet fighter and the retired Concorde supersonic transport aircraft. In the turbojet, a multistage compressor boosts the pressure of the entering air. A portion of the high-pressure air enters the combustor, where fuel is added and burned, while the remaining air cools the combustion chamber. The hot products of combustion then mix with the cooling air, and these gases expand through a multistage turbine. In the final process, the gases accelerate through a nozzle and exit to the atmosphere to produce a high-velocity propulsive jet.[1] The compressor and turbine are rotary machines with spinning wheels of blades. Rotational speeds vary over a wide range but are of the order of 10,000–20,000 rpm. Other than that needed to drive accessories, all of the power delivered by the turbine is used to drive the compressor in the pure turbojet engine.

The second major type of jet engine is the turbofan engine (Fig. 1.15 bottom). This is the engine of choice for commercial aircraft. (See Fig. 1.16.) In the turbofan, a bypass air jet generates a significant proportion of the engine thrust. The large fan shown at the front of the engine creates this jet. A portion of the total air entering the engine bypasses the core of the engine containing the compressor and turbine, while the remainder passes through the core. The turbines drive the fan and the core compressors, generally using separate shafts for each. In the turbofan configuration, the exiting jets from both the bypass flow and the core flow provide the propulsive force.

To appreciate the physical size and performance of a typical turbojet engine, consider the GE F103 engine. These engines power the Airbus A300B, the DC-10–30, and the Boeing 747. The F103 engine has a nominal diameter of 2.7 m (9 ft) and a length of 4.8 m (16 ft), produces a maximum thrust of 125 kN (28,000 lb_f), and

[1] The basic principle here is similar to that of a toy balloon that is propelled by a jet of escaping air.