FUNDAMENTALS AND APPLICATIONS OF
Renewable ENERGY

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Dr. Kanoğlu has served as an instructor in certified energy manager training programs and as an expert for the United Nations Development Programme (UNDP) for renewable energy and energy efficiency projects. He instructed numerous training courses and gave lectures and presentations on renewable energy systems and energy efficiency. He has also served as advisor for state research funding organizations and industrial companies.

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Dr. Çengel is also the author or coauthor of the widely adopted textbooks *Thermodynamics: An Engineering Approach* (9th ed., 2019), *Heat and Mass Transfer: Fundamentals and Applications* (6th ed., 2020), *Fluid Mechanics: Fundamentals and Applications* (4th ed., 2018), *Fundamentals of Thermal-Fluid Sciences* (5th ed., 2017), and *Differential Equations for Engineers and Scientists* (2013), all published by McGraw-Hill Education. Some of his textbooks have been translated into Chinese (long and short forms), Japanese, Korean, Spanish, French, Portuguese, Italian, Turkish, Greek, Tai, and Basq.

Dr. Çengel is the recipient of several outstanding teacher awards, and he has received the ASEE Meriam/Wiley Distinguished Author Award for excellence in authorship in 1992 and again in 2000. Dr. Çengel is a registered professional engineer in the State of Nevada, and is a member of the American Society of Mechanical Engineers (ASME) and the American Society for Engineering Education (ASEE).

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Dr. Cimbala is the coauthor of four other textbooks: *Indoor Air Quality Engineering: Environmental Health and Control of Indoor Pollutants* (2003), published by Marcel-Dekker, Inc.; *Fluid Mechanics: Fundamentals and Applications* (4th ed., 2018), *Essentials of Fluid Mechanics* (2008); and *Fundamentals of Thermal-Fluid Sciences* (5th ed., 2017), all published by McGraw-Hill Education. He has also contributed to parts of other books, and is the author or coauthor of dozens of journal and conference papers. He has also recently ventured into writing novels. More information can be found at www.mne.psu.edu/cimbala.

Professor Cimbala is the recipient of several outstanding teaching awards and views his book writing as an extension of his love of teaching. He is a member and Fellow of the American Society of Mechanical Engineers (ASME). He is also a member of the American Society for Engineering Education (ASEE), and the American Physical Society (APS).

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Preface

BACKGROUND

The concern over the depletion of fossil fuels and pollutant and greenhouse emissions associated by their combustion can be tackled by essentially two methods: (1) using renewable energy sources to replace fossil fuels; (2) implementing energy efficiency practices in all aspects of energy production, distribution, and consumption so that less fuel is used while obtaining the same useful output. Energy efficiency can only reduce fossil fuel use while renewable energy can directly replace fossil fuels. The main renewable energy sources include solar, wind, hydropower, geothermal, and biomass. Wave and tidal energies are also renewable sources but they are currently not economical and the technologies are still in the developmental stage.

ABOUT THE BOOK

The study of renewable energy typically involves many different sciences including thermodynamics, heat transfer, fluid mechanics, geophysics, and chemistry. In this textbook, the primary emphasis is on thermodynamics, heat transfer, and fluid mechanics aspects of renewable energy systems and applications. This book provides an overview of common systems and applications for renewable energy sources. Systems are described and their fundamental analyses are provided.

The importance of renewable energy is relatively well-understood and there are numerous books written on the subject. However, most of these books are concentrated on providing general information and practical guidance for practicing engineers and the public, and most books are not suitable as a textbook for classroom use. This book is primarily intended as a textbook for an upper level undergraduate textbook for all relevant engineering majors. It may also be used as a convenient reference book for engineers, researchers, policy makers, and anyone else interested in the subject. This book provides insight into both the scientific foundations and the engineering practice of renewable energy systems. The thermodynamics, heat transfer, fluid mechanics, and thermochemistry background needed for the study of renewable energy is readily provided and thus the need for prerequisite courses is greatly minimized. This allows the use of this book for a variety of engineering majors since not all students may have backgrounds related to all thermal science courses. The book features both technical and economic analyses of renewable systems. It contains numerous practical examples and end-of-chapter problems and concept questions as well as multiple-choice questions.

OVERVIEW OF TOPICS

The first chapter covers the general energy picture of the world, a brief introduction to renewable energy systems, and a discussion of various fossil fuels. Chapter 2 provides a comprehensive review of thermal-fluid sciences needed for studying renewable energy systems

including thermodynamics, heat transfer, fluid mechanics, thermochemistry, power plants, and refrigeration systems. Chapter 3 is on fundamentals of solar energy and Chap. 4 is on solar energy systems and applications. Chapters 5, 6, 7, 8, and 9 cover wind, hydro, geothermal, biomass, and ocean (OTEC, wave, and tidal) energies, respectively. Hydrogen is introduced as an energy carrier and the principles of fuel cells are described in Chap. 10. Chapter 11 describes engineering economic analyses of renewable energy projects. Finally, environmental effects of energy are covered in Chap. 12.

KEY FEATURES

- A comprehensive review of thermodynamics, heat transfer, fluid mechanics, thermochemistry, power plants, and refrigeration systems
- Technical and economic analysis of renewable energy systems
- Rigorous descriptions and analyses of renewable energy systems and applications including concepts and formulations
- Approximately 75 worked-out example problems throughout the chapters
- Over 850 end-of-chapter problems including conceptual and multiple-choice questions

UNIT SYSTEM

In recognition of the fact that English units are still widely used in some industries, both SI and English units are used in this text, with a primary emphasis on SI. The material in this text can be covered using combined SI/English units or SI units alone, depending on the preference of the instructor. The property tables in the appendices are presented in both units.

ACKNOWLEDGMENTS

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CHAPTER 1

Introduction to Renewable Energy

1-1 WHY RENEWABLE ENERGY?

To meet its energy needs, the world community currently depends heavily on fossil fuels that are nonrenewable and unfriendly to the environment. Table 1-1 presents total world delivered energy consumption based on end-use sector and fuel type. Breakdown of each fuel by sector and each sector by fuel is also provided. As shown in Fig. 1-1, more than half of the global energy is used by the industrial sector (54.6%), followed by the transportation sector with 25.6 percent, the residential sector with 12.7 percent, and the commercial sector with 7.1 percent (EIA, 2018). Energy use is expected to increase worldwide, driven mainly by industry, but this will mostly take place in developing countries with strong economic growth.

Total global energy supply in 2017 was 589 Quad Btu, which is equivalent to 5.6×10^{17} kJ. Fossil fuels accounted for 82.7 percent (27.1% coal, 33.4% oil, 22.2% natural gas) of this total energy production. Renewable energy (including hydroelectric power), which is environment-friendly and can be harvested indefinitely, was responsible for 12.7 percent of the total energy supply globally. Nuclear power supplied the remaining 4.6 percent of the total energy supply (Fig. 1-2) (EIA, 2018).

In 2015, total electricity generation in the world was 24,255 TWh (or 24.255×10^{12} kWh since 1 TWh = 1 billion kWh = 10^9 kWh). Fossil fuels accounted for 66.3 percent of total electricity generation in the world with 39.3 percent for coal, 22.9 percent for natural gas, and 4.1 percent for oil. Renewable energy (including hydroelectric power) and nuclear power were responsible for 23.1 percent and 10.6 percent of global electricity generation, respectively (Fig. 1-3). A total of 5603 TWh (or 5.603×10^{12} kWh) of renewable electricity was generated that year (IEA, 2017).

Total installed capacity of electricity in the United States in 2016 was 1074 GW, and the U.S. power plants generated 4077 TWh (4.077×10^{12} kWh) of electricity that year. Figure 1-4 shows the percentages of electricity generation in the United States by the fuel type and source. Approximately 83.9 percent of electricity was generated by coal, natural gas, and nuclear power plants. The remaining 16.1 percent was generated mostly by renewable sources including hydro (6.5%) and wind (5.5%). The remaining generation was due to biomass, solar, and geothermal (EIA, 2018).

A comparison of U.S. electricity production data to global electricity generation data shows that the share of renewable electricity in the United States is considerably less than that in the world. Therefore, great potential exists to increase the share of renewables in

TABLE 1-1   **Total World Delivered Energy Consumption by End-Use Sector and Fuel in 2017** (EIA, 2018)

All values are in Quad Btu (quadrillion Btu). (1 quadrillion Btu = 1×10^{15} Btu = 0.95×10^{15} kJ)

Fuel	Total	Electricity	Residential	Commercial	Industrial	Transportation	All End-Use Sectors
Oil*	196.7	6.7	8.5	3.9	69.7	106.7	188.8
Natural gas	130.7	44.0	20.6	8.8	53.2	4.1	86.6
Coal	159.8	90.5	4.3	1.6	63.5	0.0	69.4
Nuclear	26.9	26.9	—	—	—	—	—
Electricity	—	—	21.0	16.8	35.1	1.6	74.5[†]
Renewables	74.9	55.5	1.3	0.2	17.9	—	19.4
Total	589.0	223.6[†]	55.7	31.3	239.4	112.4	438.8

*The values given for oil also include other nonpetroleum liquid fuels such as ethanol, biodiesel, coal-to-liquids, natural gas liquids, and liquid hydrogen.

[†]The difference between the total energy value of fuel consumption to produce electricity (223.6 Quad Btu) and the actual amount of electricity consumed by all end-use sectors (74.5 Quad Btu) is equal to the energy lost during the production of electricity, which is equal to 223.6 − 74.5 = 149.1 Quad Btu. As a result, the difference between the totals in the second and last column is also equal to 589.0 − 438.8 = 150.2 Quad Btu, which is very close to 149.1 Quad Btu.
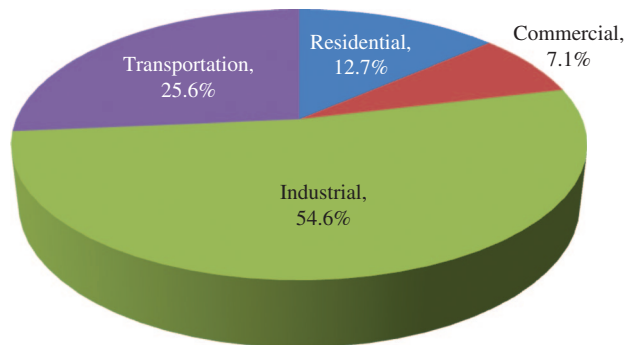
Figure 1-1   Percentages of global energy use by end-use sectors in 2017 (*EIA, 2018*).
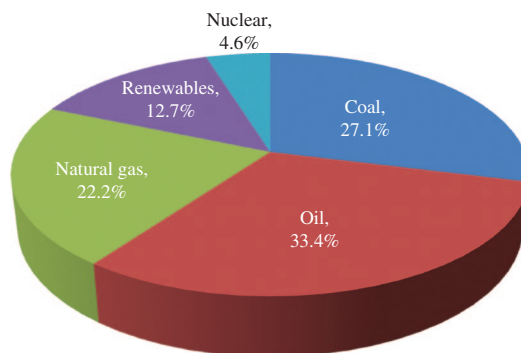
Figure 1-2   Percentages of total world primary energy supply by fuel in 2017 (*EIA, 2018*).
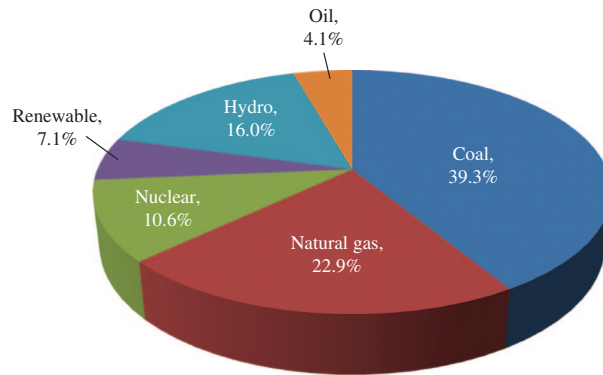
Figure 1-3   Percentages of global electricity generation by fuel type and source in 2015. Total electricity generation = 24,255 TWh (*IEA, 2017*).
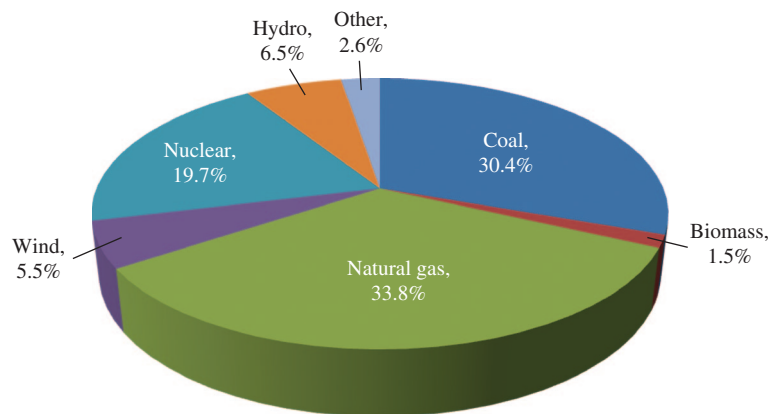
Figure 1-4   Percentages of electricity generation by fuel type and source in the United States in 2016 (*EIA, 2018*).

the U.S. energy mixture. In 2000, only nine percent of electricity came from renewables, and EIA (2018) projections indicate that the renewables will constitute 18 percent of electricity generation by 2040. Coal- and nuclear-based electricity generations are expected to decrease in the coming years, but natural gas electricity generation is expected to increase due to additional shale gas reserves.

Renewable electricity generation by source in the United States is given in Fig. 1-5. Total generation by renewables was about 640 billion kWh in 2017. This is projected to increase above 1600 billion kWh by the year 2050. Renewable electricity generation in 2017 is dominated by hydropower and wind, but solar electricity increased at the highest rate among all energy sources. Solar electricity is estimated to take the greatest share by the year 2050, followed by wind, hydropower, and geothermal. Other renewables represented in Fig. 1-5 are due mostly to biomass electricity production by the means of MSW/LFG (municipal solid waste/land fill gas) (EIA, 2018).

Renewables are currently the fastest-growing energy source in the world. Depletion and emission concerns over fossil fuel use and increasing government incentives can cause even higher growth in the use of renewables in the coming decades. The fastest-growing
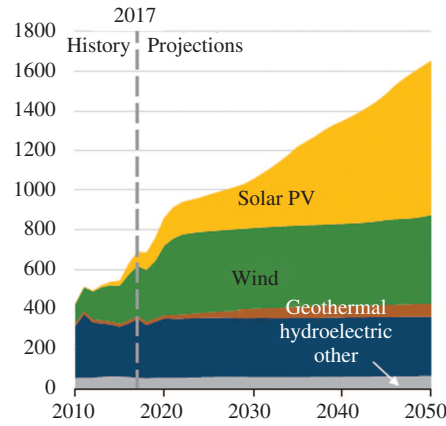
Figure 1-5 Renewable electricity generation by source in the United States, in billion kWh (*EIA, 2018*).

renewable sources are solar and wind. The installed wind capacity has increased from 18 GW in 2000 to 539 GW by the end of 2017. The solar power capacity has increased by 97 GW in 2017 bringing the global capacity to over 400 GW. The installed capacity of hydropower exceeds 1250 GW worldwide. Hydroelectric, geothermal, and wind power generation technologies are able to compete with fossil fuel–based electricity generation economically, but solar electricity generation is still expensive. However, steady decreases in solar electricity cost combined with increased government incentives are likely to help wider use of solar electricity in the coming years.

EXAMPLE 1-1
An Analysis of World Energy Consumption

In Table 1-1, the total energy consumption by different energy sources is given to be 589.0 Quad Btu while the total energy use by all end-use sectors is 438.8 Quad Btu. Explain the difference between these two values. Using the data in Table 1-1, calculate the total amount of energy lost during the production of electricity by all energy sources. Also, calculate the amount of electricity produced in kWh and the overall thermal efficiency of electricity production by all energy sources.

SOLUTION   The difference between the total energy value of fuel consumption to produce electricity (223.6 Quad Btu, third column, last row) and the actual amount of electricity consumed by all end-use sectors (74.5 Quad Btu, last column, fifth row) is equal to the energy lost during the production and distribution of electricity, which is equal to

$$\text{Energy lost} = 223.6 - 74.5 = \textbf{149.1 Quad Btu}$$

The difference between the totals in the second and last column is equal to

$$\text{Energy lost} = 589.0 - 438.8 = 150.2 \text{ Quad Btu}$$

which is very close to the value of 149.1 Quad Btu.
    The amount of electricity produced is expressed in kWh as

$$\text{Electricity produced} = (74.5 \times 10^{15} \text{ Btu})\left(\frac{1 \text{ kJ}}{0.94782 \text{ Btu}}\right)\left(\frac{1 \text{ kWh}}{3600 \text{ kJ}}\right)$$

$$= 21.83 \times 10^{12} \text{ kWh} = \textbf{21.83 trillion kWh}$$

The thermal efficiency of a power plant is defined as the power produced divided by the energy consumed. According to the data in Table 1-1, 223.6 Quad Btu of energy is consumed in all power plants worldwide, and 74.5 Quad Btu of electricity is produced. The overall thermal efficiency of producing electricity is then

$$\eta_{\text{th,overall}} = \frac{\text{Electricity produced}}{\text{Energy consumed}} = \frac{74.5 \times 10^{15} \text{ Btu}}{223.6 \times 10^{15} \text{ Btu}} = 0.333 = \mathbf{33.3\%}$$

That is, about 67 percent of energy is lost during the conversion of energy sources (coal, oil, natural gas, renewable) into electricity. ▲

EXAMPLE 1-2
Ton of Oil Equivalent (toe) Unit

Ton of oil equivalent (toe) is an amount of energy unit commonly used to express large amounts of energy. It represents the amount of energy released by burning 1 ton (1000 kg) of crude oil. One toe is taken equal to 41.868 GJ, sometimes rounded to 42 GJ. The power plants in the United States generated 4.05×10^9 MWh of electricity in a year. According to the data in Table 1-1, 74.5 Quad Btu of electricity is produced. Express these values in the toe unit. Also, determine the percentage of global electricity generation that occurred in the United States.

SOLUTION   Noting that 1 MWh = 1000 kWh, 1 kWh = 3600 kJ, 1 GJ = 1×10^6 kJ, and 1 toe = 41.868 GJ, we express electricity generation in the United States in toe, as follows:

$$\text{Electricity generation (in U.S.)} = (4.05 \times 10^9 \text{ MWh})\left(\frac{1000 \text{ kWh}}{1 \text{ MWh}}\right)\left(\frac{3600 \text{ kJ}}{1 \text{ kWh}}\right)\left(\frac{1 \text{ GJ}}{1 \times 10^6 \text{ kJ}}\right)\left(\frac{1 \text{ toe}}{41.868 \text{ GJ}}\right)$$

$$= \mathbf{3.48 \times 10^8 \text{ toe}}$$

Noting that 1 Quad = 1×10^{15} Btu and 1 toe = 41.868 GJ, we express global electricity generation in toe, as follows:

$$\text{Electricity generation (world)} = (74.5 \text{ Quad})\left(\frac{1 \times 10^{15} \text{ Btu}}{1 \text{ Quad}}\right)\left(\frac{1.055 \text{ kJ}}{1 \text{ Btu}}\right)\left(\frac{1 \text{ GJ}}{1 \times 10^6 \text{ kJ}}\right)\left(\frac{1 \text{ toe}}{41.868 \text{ GJ}}\right)$$

$$= \mathbf{1.88 \times 10^9 \text{ toe}}$$

The percentage of global electricity generation that occurred in the United States is determined to be

$$\text{Percent generation in U.S.} = \frac{\text{Electricity generation (U.S.)}}{\text{Electricity generation (world)}} = \frac{3.48 \times 10^8 \text{ toe}}{1.88 \times 10^9 \text{ toe}} = 0.185 = \mathbf{18.5\%}$$

That is, 348 million toe of electricity is generated in the United States and 1.88 billion toe of electricity is generated in the world. The U.S. electricity generation represents 18.5 percent of global generation. Note that toe unit is not normally used to express the amount of electricity. Instead some multiples of kWh such as MWh, GWh, and TWh are used. ▲

Consequences of Fossil Fuel Combustion

Fossil fuels have been powering industrial development and the amenities of modern life since the 1700s, but this has not been without undesirable side effects. Pollutants emitted during the combustion of fossil fuels are responsible for smog, acid rain, and numerous other adverse effects on the environment. Environmental pollution has reached such high levels that it has become a serious threat to vegetation, wildlife, and human health. Air pollution has been the cause of numerous health problems including asthma and cancer. But this fossil fuel–based economy is not sustainable since the estimated life of known reserves is limited. Therefore, the switch to renewable energy sources is inevitable.

Carbon dioxide (CO_2) is the primary greenhouse gas that contributes to global warming. Global climate change is widely regarded as due to the excessive use of fossil fuels such as coal, petroleum products, and natural gas in electric power generation, transportation, buildings, and manufacturing, and it has been a concern in recent decades. The concentration of CO_2 in the atmosphere as of 2019 is about 410 ppm (or 0.41%). This is 20 percent higher than the level a century ago. Various scientific reports indicate that the earth has already warmed about 0.5°C during the last century, and it is estimated that the earth's temperature will rise another 2°C by the year 2100. A rise of this magnitude is feared to cause severe changes in weather patterns with storms and heavy rains and flooding at some parts and drought in others, major floods due to the melting of ice at the poles, loss of wetlands and coastal areas due to rising sea levels, variations in water supply, changes in the ecosystem due to the inability of some animal and plant species to adjust to the changes, increases in epidemic diseases due to the warmer temperatures, and adverse side effects on human health and socioeconomic conditions in some areas.

The combustion of fossil fuels produces the following undesirable emissions (Fig. 1-6):

- CO_2, primary greenhouse gas: contributes to global warming
- Nitrogen oxides (NO_x) and hydrocarbons (HC): cause smog
- Carbon monoxide (CO): toxic
- Sulfur dioxide (SO_2): causes acid rain
- Particulate matter (PM): causes adverse health effects

Notice from this emissions list that CO_2 is different from the other emissions in that CO_2 is a greenhouse gas and a natural product of fossil fuel combustion while other emissions are harmful air pollutants.

The concern over the depletion of fossil fuels and pollutant and greenhouse emissions associated with their combustion can be tackled by essentially two methods:

1. Using renewable energy sources such as solar, wind, hydroelectric, biomass, and geothermal to replace fossil fuels.

2. Implementing energy efficiency practices in all aspects of energy production, distribution, and consumption so that less fuel is used while obtaining the same useful output.

Energy efficiency is to reduce energy use to the minimum level, but to do so without reducing the standard of living, production quality, and profitability. Energy efficiency is an expression for the most effective use of energy resources, and it results in energy conservation. Energy efficiency can only *reduce* fossil fuel use while renewable energy can directly *replace* it.

FOSSIL FUEL EMISSIONS
$CO_2 \Rightarrow$ global warming
NO_x and HC $\Rightarrow$ smog
$CO \Rightarrow$ toxic
$SO_2 \Rightarrow$ acid rain
PM $\Rightarrow$ adverse health effects
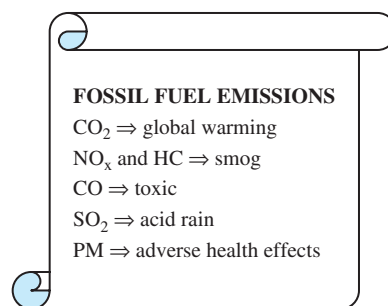
Figure 1-6   Effects of undesirable emissions from the combustion of fossil fuels.

**RENEWABLE ENERGY
SOURCES**
Solar
Wind
Hydro
Geothermal
Biomass
Ocean (OTEC, wave, tidal)
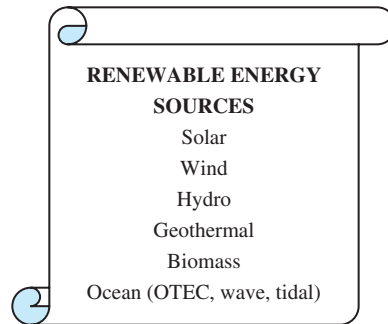
Figure 1-7   The switch from fossil fuels to renewable energy sources is inevitable.

Renewable Energy Sources

The main renewable energy sources include solar, wind, hydro, biomass, and geothermal (Fig. 1-7). Energy sources from the ocean, including ocean thermal energy conversion (OTEC), wave, and tidal, are also renewable sources, but they are currently not economical and the technologies are still in the experimental and developmental stage.

An energy source is called *renewable* if it can be renewed and sustained without any depletion and any significant effect on the environment. It is also called an *alternative*, *sustainable*, or *green* energy source (Fig. 1-8). Fossil fuels such as coal, oil, and natural gas, on the other hand, are not renewable, and they are depleted by use. They also emit harmful pollutants and greenhouse gases.

The best-known renewable source is *solar energy*. Although solar energy is sufficient to meet the entire energy needs of the world, currently it is not used as extensively as fossil fuels because of the *low concentration* of solar energy on earth and the *relatively high*

Figure 1-8   Renewable energies such as solar water collectors are called *green energy* since they emit no pollutants or greenhouse gases.

capital cost of harnessing it. The conversion of kinetic energy of wind into electricity via wind turbines represents *wind energy*, and it is one of the fastest-growing renewables as wind turbines are being installed all over the world. The collection of river water in large dams at some elevation and then directing the collected water into a hydraulic turbine is the common method of converting water energy into electricity. *Hydro* or *water energy* represents the greatest amount of renewable electricity production, and it supplies most of the electricity needs of some countries.

Geothermal energy refers to the heat of the earth. High-temperature underground geothermal fluid found in some locations is extracted, and the energy of the geothermal fluid is converted to electricity or heat. Geothermal energy conversion is one of the most mature renewable energy technologies. Geothermal energy is mostly used for electricity generation and district heating. Organic renewable energy is referred to as *biomass*, and a variety of sources (agriculture, forest, residues, crops, etc.) can be used to produce bio-mass energy. Biomass is becoming more popular with the help of the variety of available sources.

Wave and tidal energies are renewable energy sources, and they are usually considered as part of ocean energy since they are available mostly in oceans. Thermal energy of oceans due to absorption of solar energy by ocean surfaces is also considered as part of ocean energy, and this energy can be utilized using the OTEC system. Wave and tidal energies are mechanical forms of ocean energy since they represent potential and kinetic energies of ocean water.

Hydrogen is an energy carrier that can be used to store renewable electricity. It is still a developing technology, and many research activities are under way to make it viable. *Fuel cells* convert chemical energy of fuels (e.g., hydrogen) into electricity directly without a highly irreversible combustion process, and it is more efficient than combustion-based conversion to electricity.

All renewable energy sources can be used to produce useful energy in the form of electricity and some renewables can also produce thermal energy for heating and cooling applications. Wind and water energies are converted to electricity only while solar, biomass, and geothermal can be converted to both electricity and thermal energy (i.e., heat).

Electric cars (and other electricity-driven equipment) are often touted as "zero-emission" vehicles, and their widespread use is seen by some as the ultimate solution to the air pollution problem. It should be remembered, however, that the electricity used by the electric cars is generated somewhere else mostly by burning fossil fuels. Therefore, each time an electric car consumes 1 kWh of electricity, it bears the responsibility for the pollutants emitted as 1 kWh of electricity (plus the conversion and transmission losses generated elsewhere). The electric cars can be claimed to be zero-emission vehicles only when the electricity they consume is generated by emission-free renewable resources such as hydroelectric, solar, wind, and geothermal energy. Therefore, the use of renewable energy should be encouraged worldwide, with incentives, as necessary, to make the earth a better place to live.

We should point out that what we call *renewable energy* is usually nothing more than the manifestation of solar energy in different forms. Such energy sources include wind energy, hydroelectric power, ocean thermal energy, ocean wave energy, and wood. For example, no hydroelectric power plant can generate electricity year after year unless the water evaporates by absorbing solar energy and comes back as rainfall to replenish the water source (Fig. 1-9).
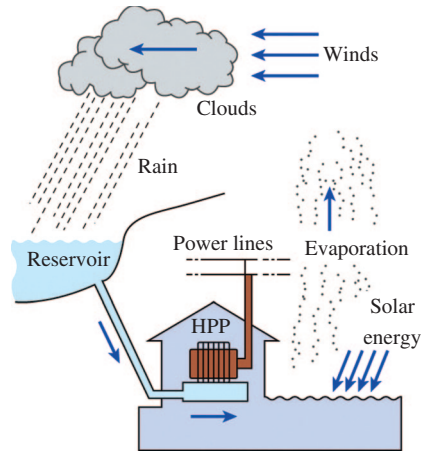
Figure 1-9 The cycle that water undergoes in a hydroelectric power plant (HPP).

1-2 FOSSIL FUELS AND NUCLEAR ENERGY

The main energy sources include coal, oil, natural gas, nuclear energy, and renewable energy (Fig. 1-10). Among these, coal, oil, and natural gas are fossil fuels. Fossil fuels are responsible for more than 90 percent of global combustion-related CO_2 emissions with 37 gigatons (37,000 million tons) in 2017. The shares of fossil fuels to the global CO_2 emissions are 45 percent for coal, 35 percent for oil, and 20 percent for natural gas (IEA, 2017). Here, we provide a short review of fossil fuels.

Coal

Coal is made of mostly carbon, and it also contains hydrogen, oxygen, nitrogen, sulfur, and ash (noncombustibles). The heating value of carbon is 32,800 kJ/kg. The percentages of carbon and other components vary depending on the production site. Energy content per unit mass (i.e., heating value) and sulfur content are among the important characteristics of coal. High energy content allows extraction of more heat from coal, making the fuel more valuable. Low sulfur content is crucial to meet emission limits of sulfur compounds. Coal is used mostly for electricity production in steam power plants. It is also used for space heating, water heating, and steam generation.
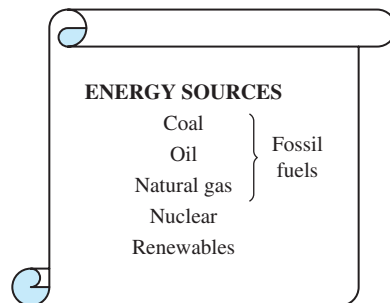
Figure 1-10 Main energy sources.

There are four common types of coal with the following general characteristics.

Bituminous coal: It is also known as *soft coal*. It has high energy content but unfortunately also has high sulfur content. A representative composition (referred to in the industry as an "assay") of this coal by mass is 67 percent carbon, 5 percent hydrogen, 8.7 percent oxygen, 1.5 percent nitrogen, 1.5 percent sulfur, 9.8 percent ash, and 6.7 percent moisture. The higher heating value for this particular composition of coal is 28,400 kJ/kg. Bituminous coal is primarily used for electricity generation in power plants.

Subbituminous coal: It has lower energy content due to lower fractions of carbon and hydrogen but also lower-sulfur content compared to bituminous coal. A representative composition of this coal by mass is 48.2 percent carbon, 3.3 percent hydrogen, 11.9 percent oxygen, 0.7 percent nitrogen, 0.4 percent sulfur, 5.3 percent ash, and 30.2 percent moisture. The higher heating value for this particular composition of coal is 19,400 kJ/kg. Subbituminous coal is primarily used for electricity generation and heating applications.

Anthracite coal: It is also known as *hard coal*. It is far less common compared to bituminous and subbituminous coals. It is used mainly for residential and industrial heating applications. Few coal-fired plants burn it. It contains 80 to 95 percent carbon with low sulfur and nitrogen content. The ash content is between 10 and 20 percent and the moisture content is 5 to 15 percent. Its heating value is typically higher than 26,000 kJ/kg.

Lignite: It is also known as *brown coal*. It is the lowest-quality coal with low energy content and high sulfur and moisture fraction. The carbon content is only 25 to 35 percent with a low heating value of less than 15,000 kJ/kg. The moisture and ash content can be as high as 75 and 20 percent, respectively. It is used mainly for electricity generation.

In the combustion of coal, hydrogen and sulfur burn first and carbon burns last. As a result, nearly all of the sulfur burns into SO_2 and nearly all of the hydrogen burns into H_2O by the following reactions:

$$S + O_2 \rightarrow SO_2$$
$$H_2 + \tfrac{1}{2}O_2 \rightarrow H_2O$$
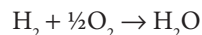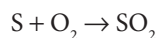
Carbon burns according to the following reactions:

$$C + \tfrac{1}{2}O_2 \rightarrow CO$$
$$CO + \tfrac{1}{2}O_2 \rightarrow CO_2$$
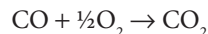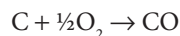
If some CO cannot find sufficient oxygen to burn with by the time combustion is completed, some CO is found in the combustion products. This represents a very undesirable emission as well as the waste of fuel as CO has energy content (the heating value of CO is 10,100 kJ/kg). This can happen even in the presence of stoichiometric or excess oxygen due to incomplete mixing and a short time for the combustion process.

Combustion of coal also causes pollutant emissions of unburned carbon particles, CO, unburned HC, SO_2, ash, and NO_x. The amount of CO_2 emission depends on the percentage of carbon in coal and the degree of completion of the combustion of carbon. Coal is considered to be the most polluting fossil fuel compared to liquid and gaseous fuels as well as being the largest contributor to global CO_2 emissions with about 40 percent.

EXAMPLE 1-3
Heating Value of Coal

The assay of particular coal from Illinois is as follows by mass: 67.40 percent carbon (C), 5.31 percent hydrogen (H_2), 15.11 percent oxygen (O_2), 1.44 percent nitrogen (N_2), 2.36 percent sulfur (S), and 8.38 percent ash (noncombustibles). What are the higher and lower heating values of this coal? The heating value of sulfur is 9160 kJ/kg.

SOLUTION   The combustible constituents in the coal are carbon C, hydrogen H_2, and sulfur S. The heating value of sulfur is given to be 9160 kJ/kg. The higher and lower heating values of hydrogen are 141,800 kJ/kg and 120,000 kJ/kg, respectively, and the heating value of carbon is 32,800 kJ/kg (Table A-7 in Appendix). Note that if the combustion of a fuel does not yield any water in the combustion of gases, the higher and lower heating values are equivalent for that fuel.

Using their mass fractions (mf), the higher heating value of this particular coal is determined as

$$\text{HHV} = \text{mf}_C \times \text{HHV}_C + \text{mf}_{H2} \times \text{HHV}_{H2} + \text{mf}_S \times \text{HHV}_S$$

$$= (0.674)(32{,}800 \text{ kJ/kg}) + (0.0531)(141{,}800 \text{ kJ/kg}) + (0.0236)(9160 \text{ kJ/kg})$$

$$= \mathbf{29{,}850 \text{ kJ/kg}}$$

Similarly, the lower heating value of the coal is

$$\text{LHV} = \text{mf}_C \times \text{LHV}_C + \text{mf}_{H2} \times \text{LHV}_{H2} + \text{mf}_S \times \text{LHV}_S$$

$$= (0.674)(32{,}800 \text{ kJ/kg}) + (0.0531)(120{,}000 \text{ kJ/kg}) + (0.0236)(9160 \text{ kJ/kg})$$

$$= \mathbf{28{,}695 \text{ kJ/kg}}$$

The difference between the higher and lower heating values is about 4 percent.   ▲

Oil

Oil or petroleum is a mixture of a large number of HC with different compositions. Crude oil has 83 to 87 percent carbon and 11 to 14 percent hydrogen with small amounts of other components such as sulfur, nitrogen, oxygen, ash, and moisture. End products such as gasoline, light diesel fuel, jet fuel, LPG (liquefied petroleum gas), natural gas, and heavy diesel fuel (fuel oil) are obtained by distillation and cracking in oil refinery plants (Fig. 1-11). Nonpetroleum liquid fuels may include ethanol, biodiesel, coal-to-liquids, natural gas liquids, and liquid hydrogen.

Gasoline and light diesel fuel are used in automobiles and can be approximated by C_8H_{15} and $C_{12}H_{22}$, respectively. Diesel fuel also includes some sulfur, but the regulations in the United States and European Union already reduced the sulfur limit from about 300 to 50 and then to 10 ppm (parts per million). The higher heating values of gasoline and light diesel fuel are 47,300 and 46,100 kJ/kg, respectively.

OIL PRODUCTS
Gasoline
Light diesel fuel
Heavy diesel fuel
Jet fuel
LPG
Natural gas
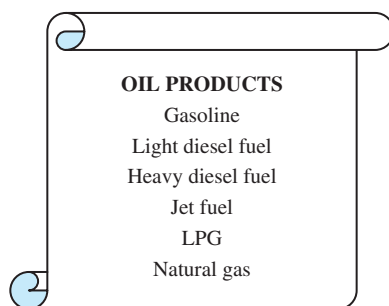
Figure 1-11   Main petroleum fuel products.

Oil is less commonly used for electricity generation compared to coal and natural gas. There are two groups of oil used in power plants and industrial heating applications:

Distillate oils: These are higher-quality oils that are highly refined. They contain much less sulfur compared to residual oils. A typical composition of distillate oils is 87.2 percent carbon, 12.5 percent hydrogen, and 0.3 percent sulfur. The higher heating value for this composition is 45,200 kJ/kg.

Residual oils: These oils undergo less refining. They are thicker with higher molecular mass, higher level of impurities, and higher sulfur content. A typical composition is 85.6 percent carbon, 9.7 percent hydrogen, 2.3 percent sulfur, 1.2 percent nitrogen, 0.8 percent oxygen, 0.1 percent ash, and 0.3 percent moisture. The higher heating value for this composition is 42,500 kJ/kg.

Natural Gas

Natural gas is mostly methane (CH_4) where its percentage varies between 60 and 98 percent. It also contains small amounts of ethane, propane, butane, nitrogen, oxygen, helium, CO_2, and other gases. It exists as a gas under atmospheric conditions and is stored as a gas under high pressure (15 to 25 MPa). It is mostly transported in gas phase by pipelines in and between cities and countries. When pipeline transportation is not feasible, it is first liquefied to about −160°C using advanced refrigeration technologies before being carried in large insulated tanks in marine ships. Natural gas is used in boilers for space heating, hot water and steam generation, industrial furnaces, power plants for electricity production, and internal combustion engines.

The higher and lower heating values of methane are 55,530 kJ/kg and 50,050 kJ/kg, respectively. The heating value of natural gas depends mainly on the fraction of methane. The higher is the methane fraction, the higher is the heating value. Natural gas is commonly approximated as methane without much sacrifice in accuracy. The heating value of natural gas is usually expressed in kJ/m^3 unit, and the higher heating value ranges from 33,000 to 42,000 kJ/m^3, depending on the resource. The lower heating value of natural gas is about 90 percent of its higher heating value. A comparison of higher heating values for various fuels is shown in Fig. 1-12.

Compared to coal and oil, natural gas is a cleaner fuel as it emits less pollutant emissions. Air quality in certain cities has improved dramatically when natural gas pipelines reached

Fuel	Higher heating value
Sulfur	9.16 MJ/kg
Hydrogen	141.8
Natural gas	55.53
Light diesel	46.1
Gasoline	47.3
Coal	32.8
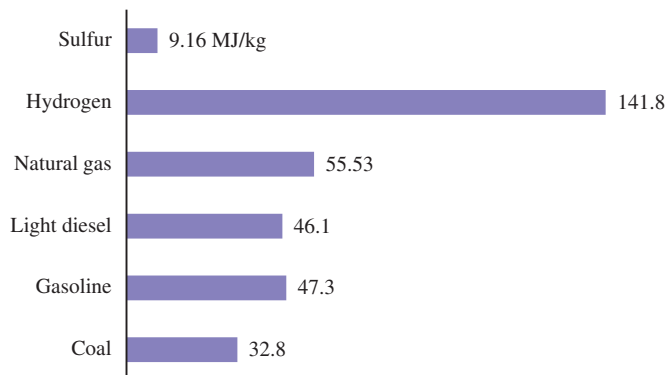
Figure 1-12   Higher heating values of various fuels, in MJ/kg. Coal is roughly approximated as carbon and natural gas as methane.

the city and heating systems running on coal were replaced by their natural gas counterparts. Usage of natural gas in public transportation (buses and taxis) is used as a measure to improve air quality in cities.

About 40 percent of the supply of natural gas is used by the industrial sector, while 33 percent is used for electricity generation in power plants (EIA, 2018). Residential and commercial applications account for the remaining use of natural gas. The supply of natural gas has recently risen substantially in the United States, Canada, and China. This is mostly due to exploitation of shale gas, which was made possible by horizontal drilling and hydraulic fracturing technologies.

EXAMPLE 1-4
Higher Heating Value of Methane in Different Units

The lower heating value of methane (CH_4) is 50,050 kJ/kg. Determine its higher heating value in kJ/kg, m^3/kg, and therm/lbm units. The enthalpy of vaporization of water at 25°C is h_{fg} = 2442 kJ/kg. Assume natural gas is at 1 atm and 25°C.

SOLUTION   The molar masses of CH_4 and H_2O are 16 and 18 kg/kmol, respectively. When 1 kmol of methane (CH_4) is burned with theoretical air, 2 kmol of water (H_2O) is formed. Then the mass of water formed when 1 kg of methane is burned is determined from

$$m_{H2O} = \frac{N_{H2O}M_{H2O}}{N_{CH4}M_{CH4}} = \frac{(2 \text{ kmol})(18 \text{ kg/kmol})}{(1 \text{ kmol})(16 \text{ kg/kmol})} = 2.25 \text{ kg } H_2O/\text{kg } CH_4$$

The amount of heat released as 2.25 kg water is condensed is

$$Q_{latent} = m_{H2O}h_{fg} = (2.25 \text{ kg } H_2O/\text{kg } CH_4)(2442 \text{ kJ/kg } H_2O) = 5495 \text{ kJ/kg } CH_4$$

Then the higher heating value of methane becomes

$$HHV = LHV + Q_{latent} = 50,050 \text{ kJ/kg} + 5495 \text{ kJ/kg} = \textbf{55,545 kJ/kg}$$

The gas constant of methane is R = 0.5182 kPa·m^3/kg·K (Table A-1) and 1 atm = 101 kPa. The density of methane is determined from the ideal gas relation as

$$\rho = \frac{P}{RT} = \frac{101 \text{ kPa}}{(0.5182 \text{ kPa} \cdot m^3/\text{kg} \cdot \text{K})(25 + 273 \text{ K})} = 0.6540 \text{ kg/m}^3$$

The higher heating value of methane in kg/m^3 unit is

$$HHV = (55,545 \text{ kJ/kg})(0.6540 \text{ kg/m}^3) = \textbf{36,330 kJ/m}^3$$

Noting that 1 therm = 100,000 Btu = 105,500 kJ and 1 lbm = 0.4536 kg, the higher heating value of methane in therm/lbm unit is

$$HHV = (55,545 \text{ kJ/kg})\left(\frac{1 \text{ therm}}{105,500 \text{ kJ}}\right)\left(\frac{0.4536 \text{ kg}}{1 \text{ lbm}}\right) = \textbf{0.2388 therm/lbm} \quad \triangle$$

Nuclear Energy

The tremendous amount of energy associated with the strong bonds within the nucleus of the atom is called *nuclear energy*. The most widely known fission reaction involves splitting the uranium atom (the U-235 isotope) into other elements and is commonly used to generate electricity in nuclear power plants, to power nuclear submarines, aircraft carriers, and even spacecraft, and as a component of nuclear bombs.

The first nuclear chain reaction was achieved by Enrico Fermi in 1942, and the first large-scale nuclear reactors were built in 1944 for the purpose of producing material for nuclear weapons. When a uranium-235 atom absorbs a neutron and splits during a fission process, it produces a cesium-140 atom, a rubidium-93 atom, 3 neutrons, and 3.2×10^{-11} J of energy. In practical terms, the complete fission of 1 kg of uranium-235 releases 6.73×10^{10} kJ of heat, which is more than the heat released when 3000 tons of coal are burned. Therefore, for the same amount of fuel, a nuclear fission reaction releases several million times more energy than a chemical reaction. The safe disposal of used nuclear fuel, however, remains a concern.

There are over 450 nuclear reactors operating worldwide with a total capacity of about 400,000 MW. Dozens of new reactors are under construction in 15 countries. The United States has 61 nuclear power plants with 99 reactors. The percentage of electricity produced by nuclear power is 76 percent in France, 19 percent in Russia and the United Kingdom, 14 percent in Germany, and 20 percent in the United States (IAEA, 2018).

Nuclear energy by fusion is released when two small nuclei combine into a larger one. The huge amount of energy radiated by the sun and other stars originates from such a fusion process that involves the combination of two hydrogen atoms into a helium atom. When two heavy hydrogen (deuterium) nuclei combine during a fusion process, they produce a helium-3 atom, a free neutron, and 5.1×10^{-13} J of energy (Fig. 1-13).

Fusion reactions are much more difficult to achieve in practice because of the strong repulsion between the positively charged nuclei, called *Coulomb repulsion*. To overcome this repulsive force and to enable the two nuclei to fuse together, the energy level of the nuclei must be raised by heating them to about 100 million °C. But such high temperatures are found only in stars or in exploding atomic bombs (A-bombs). In fact, the uncontrolled fusion reaction in a hydrogen bomb (H-bomb) is initiated by a small atomic bomb. The first uncontrolled fusion reaction was achieved in the early 1950s, but all the efforts since then to achieve controlled fusion by massive lasers, powerful magnetic fields, and electric currents to generate power have failed.

(a) Fission of uranium

(b) Fusion of hydrogen
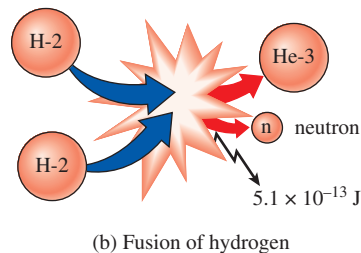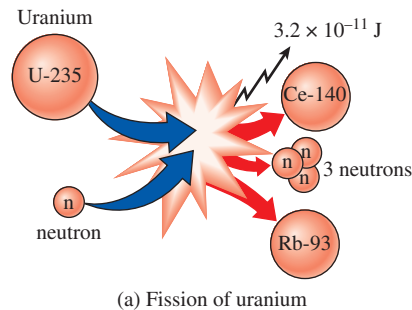
Figure 1-13 The fission of uranium and the fusion of hydrogen during nuclear reactions, and the release of nuclear energy.

Electricity

Electricity is the most valuable form of energy. Fuels cannot directly replace it because the vast majority of devices, equipment, and appliances operate on electricity. Electricity is produced in power plants by burning coal, oil, and natural gas and in nuclear power stations. Renewable energy sources such as solar, wind, geothermal, and hydro are also used to produce electricity.

The contribution of renewable electricity is expected to increase in the coming years, but the incorporation of wind power and solar power into the grid involves some irregularities and uncertainties due to changing wind and solar conditions on hourly, daily, and seasonal basis. This requires a more flexible electrical grid system than the existing conventional system in order to accommodate the inconsistent supply of renewable electricity. This new grid system is called a *smart grid*, which is an important area of research and development for electrical engineers.

Energy storage systems also help to deal with the irregularities of wind and solar electricity generation. Several techniques for storing energy have been suggested, but the two most common types are batteries and pumped storage. The former is well known since we all use rechargeable batteries in our cars, portable computers, cell phones, and other electronic devices. The latter involves pumping water "uphill" from a lower reservoir to a higher one when excess power is available, and then reversing the process ("turbining") when electricity demand is high. As more renewable energy sources go online, the need for such energy storage systems is also expected to grow significantly.

REFERENCES

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IEA. 2017. International Energy Agency, Key World Energy Statistics.
EIA. 2018. U.S. Energy Information Administration, Annual Energy Outlook.

PROBLEMS

WHY RENEWABLE ENERGY?

1-1   Which undesirable emissions are produced by the combustion of fossil fuels? What adverse effects are produced by these emissions?

1-2   Is CO_2 an air pollutant? How does it differ from other emissions resulting from the combustion of fossil fuels?

1-3   What are the two main methods of tackling the concern over the depletion of fossil fuels and pollutant and greenhouse emissions associated by their combustion?

1-4   What is energy efficiency? How is it different from renewable energy use?

1-5   What are the main renewable energy sources? Why are ocean, wave, and tidal energies not considered as main renewable sources?

1-6   How do you define a renewable energy source? Why are coal, oil, and natural gas not renewable energy sources?

1-7   Solar energy is the most widely available renewable energy source and it is sufficient to meet entire needs of the world. However, it is not used extensively. Why?

1-8   Which renewable sources are growing at the fastest rate? Which renewable source is used to produce most electricity?

1-9   Which renewable energy sources are only used for electricity generation? Which renewable sources are converted to both electricity and thermal energy?

1-10   Some consider electric cars as "zero-emission" vehicles and an ultimate solution to the air pollution problem. Do you agree? Explain.

1-11   Under what conditions can electric cars be considered as "zero-emission" vehicles?

1-12   Total world delivered oil consumption by end-use sectors in 2017 was 188.8 Quad while the renewable consumption was 19.4 Quad. Express these consumptions in Btu, GJ, and kWh.

1-13   Ton of oil equivalent (toe) is an amount of energy unit commonly used to express large amounts of energy. It represents the amount of energy released by burning 1 ton (1000 kg) of crude oil. One toe is taken equal to 41.868 GJ, sometimes rounded to 42 GJ. Total world delivered energy consumption in 2010 by fuel was 523.9 Quad while that by end-use sector was 382.0 Quad. Express these values in toe units.

1-14   The overall thermal efficiency of coal-burning steam power plants in the world can be taken to be 30 percent. Using the data in Table 1-1, determine the amount of electricity produced by coal-burning power plants, in GWh.

1-15   In 2013, 21.7 percent of global electricity is generated from natural gas–burning power plants. Total electricity generation in that year was 23,332 terawatt-hours (TWh) and it is estimated that 45 Quad natural gas is consumed to generate electricity. Determine the overall thermal efficiency of natural gas–burning power plants in 2013.

1-16   According to a 2007 report, 19,028 TWh electricity is produced in the world in 2006, and 55.3 percent of this production took place in OECD countries. The report also indicates that the average efficiency of thermal power plants in OECD countries in 2006 was 38 percent. Determine the amount of energy consumed in OECD countries in TWh, Quad, and toe.

1-17   The average annual electricity consumption by a household refrigerator has decreased from 1800 kWh in 1974 to 450 kWh today. Consider a country with 10 million households with a market penetration of 100 percent for modern refrigerators. If the refrigerators in this country were to continue to consume electric power at the 1974 levels, how much of additional installed power would be needed to meet this extra demand? Assume that the load factor (average fraction of installed power load that is actually produced) of the power plants is 0.8 and the power plants operate 90 percent of the time on an annual basis.

1-18   Most energy in the world is consumed by the _____ sector.
(*a*) residential   (*b*) commercial   (*c*) industrial   (*d*) transportation   (*e*) service

1-19   The emission from fossil fuel combustion that is *not* an air pollutant is
(*a*) CO   (*b*) CO_2 (*c*) NO_x (*d*) SO_2 (*e*) PM

1-20   Which emission causes acid rain?
(*a*) CO   (*b*) CO_2 (*c*) NO_x (*d*) SO_2 (*e*) PM

1-21   Which source should not be considered as a main renewable energy source?
(*a*) Wind   (*b*) Hydro   (*c*) Tidal   (*d*) Biomass   (*e*) Geothermal

1-22   The fastest-growing renewable energy sources in the world are
(*a*) Wind and solar   (*b*) Hydro and biomass   (*c*) Solar and hydro
(*d*) Biomass and hydro   (*e*) Geothermal and biomass

1-23   Which renewable energy source produces the greatest amount of electricity?
(*a*) Wind   (*b*) Hydro   (*c*) Solar   (*d*) Biomass   (*e*) Geothermal

1-24   Which renewable energy sources are only used for electricity generation?
(*a*) Wind and solar   (*b*) Hydro and solar   (*c*) Solar and geothermal
(*d*) Wind and hydro   (*e*) Hydro and geothermal

1-25   Which renewable energy source should not be considered as the manifestation of solar energy in different forms?
(*a*) Wind   (*b*) Hydro   (*c*) Wave   (*d*) Biomass   (*e*) Geothermal

FOSSIL FUELS AND NUCLEAR ENERGY

1-26   What are the main energy sources? What are the main fossil fuels?

1-27   What are the common coal types?

1-28   What causes CO emission in a combustion process? Will there be any CO emission when fuel is burned with stoichiometric or excess air? Explain.

1-29   What are the most common uses of coal and petroleum products?

1-30   What are the categories of oil used in power plants and industrial heating applications? Briefly describe their characteristics.

1-31   How is natural gas transported? Explain.

1-32   What are the common uses of natural gas?

1-33   What is nuclear energy? Briefly describe fission and fusion reactions.

1-34   Why is electricity the most valuable form of energy?

1-35   What is smart grid? Explain.

1-36   The ultimate analysis of a coal from Colorado is as follows by mass: 79.61 percent carbon (C), 4.66 percent hydrogen (H_2), 4.76 percent oxygen (O_2), 1.83 percent nitrogen (N_2), 0.52 percent sulfur (S), and 8.62 percent ash (noncombustibles). What is the higher and lower heating value of this coal? The heating value of sulfur is 9160 kJ/kg,

1-37   Gasoline can be approximated by C_8H_{15}. Using this chemical formula, determine the higher and lower heating values of gasoline.

1-38   Light diesel fuel can be approximated by $C_{12}H_{22}$. Using this chemical formula, determine the higher and lower heating values of light diesel fuel.

1-39   The higher heating value of gasoline (approximated as octane C_8H_{18}) is 47,300 kJ/kg. Determine its lower heating value. The enthalpy of vaporization of water at 25°C is $h_{fg} = 2442$ kJ/kg.

1-40   In 2012, the United States produced 37.4 percent of its electricity in the amount of 1.51×10^{12} kWh from coal-fired power plants. Taking the average thermal efficiency to be 34 percent, determine the amount of coal consumed by these power plants. Take the heating value of coal to be 25,000 kJ/kg.

1-41   Which one cannot be considered as a fossil fuel?
(*a*) Coal   (*b*) Natural gas   (*c*) Oil   (*d*) Hydrogen   (*e*) None of these

1-42   Which is not a fuel?
(*a*) Oil   (*b*) Natural gas   (*c*) Coal   (*d*) CO   (*e*) CO_2

1-43   Which is *not* a coal type?
(*a*) Bituminous coal   (*b*) Subbituminous coal   (*c*) Anthracite coal
(*d*) Lignite   (*e*) Green coal

1-44   Which coal type is of the lowest quality?
(*a*) Bituminous coal   (*b*) Subbituminous coal   (*c*) Anthracite coal
(*d*) Lignite   (*e*) Hard coal

1-45   Electricity is mostly produced from _____ burning power plants in the world.
(*a*) Coal   (*b*) Natural gas   (*c*) Oil   (*d*) Nuclear   (*e*) Solar

1-46   The most common use of petroleum products is in
(*a*) Motor vehicles   (*b*) Electricity generation   (*c*) Space heating
(*d*) Steam generation   (*e*) Industrial furnaces

1-47   Which fuel is the most polluting fuel and the largest contributor to global CO_2 emissions?
(*a*) Coal   (*b*) Natural gas   (*c*) Oil   (*d*) Nuclear   (*e*) Solar

1-48   Which fuel has the highest heating value?
(*a*) Coal   (*b*) Natural gas   (*c*) Oil   (*d*) Hydrogen   (*e*) Sulfur

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CHAPTER 2

A Review of Thermal Sciences

2-1 THERMAL SCIENCES

The analysis of renewable energy systems requires a solid understanding of energy conversion processes, transformation between various forms of energy, and ways of defining efficiencies of energy producing and consuming systems. In this chapter, we review fundamental concepts of thermodynamics, heat transfer, fluid mechanics, thermochemistry, power plants, and refrigeration systems to form a solid and useful foundation for the renewable energy systems to be covered in the upcoming chapters.

The physical sciences that deal with energy and the transfer, transport, and conversion of energy are usually referred to as *thermal-fluid sciences* or just *thermal sciences*. Traditionally, the thermal-fluid sciences are studied under the subcategories of thermodynamics, heat transfer, and fluid mechanics (Çengel and Ghajar, 2015; Çengel et al., 2016; Çengel and Cimbala, 2018; Çengel et al., 2019).

The design and analysis of most thermal systems such as power plants, automotive engines, refrigerators, building heating and cooling systems, boilers, heat exchangers, and other energy conversion equipment involve all categories of thermal sciences. For example, designing a solar collector involves the determination of the amount of energy transfer from a knowledge of *thermodynamics,* the determination of the size of the heat exchanger using *heat transfer,* and the determination of the size and type of the pump using *fluid mechanics* (Fig. 2-1).

2-2 THERMODYNAMICS

Thermodynamics can be defined as the science of *energy.* Although everybody has a feeling of what energy is, it is difficult to give a precise definition for it. Energy can be viewed as the ability to cause changes. The name *thermodynamics* stems from the Greek words *therme* (heat) and *dynamis* (power), which is most descriptive of the early efforts to convert heat into power. Today the same name is broadly interpreted to include all aspects of energy and energy transformations including power generation, refrigeration, and relationships among the properties of matter.

One of the most fundamental laws of nature is the *conservation of energy principle.* It simply states that during an interaction, energy can change from one form to another but the total amount of energy remains constant. That is, energy cannot be created or destroyed. A rock falling off a cliff, for example, picks up speed as a result of its potential energy being converted to kinetic energy. The conservation of energy principle also forms the backbone of the diet industry: A person who has a greater energy input (food) than energy output
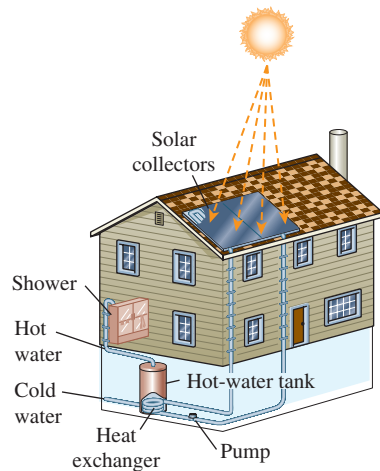
Figure 2-1 The design and analysis of renewable energy systems, such as this solar hot water system, involves thermal sciences.

(exercise) will gain weight (store energy in the form of fat), and a person who has a smaller energy input than output will lose weight. The change in the energy content of a body or any other system is equal to the difference between the energy input and the energy output, and the energy balance is expressed as $E_{in} - E_{out} = \Delta E_{system}$.

The *first law of thermodynamics* is simply an expression of the conservation of energy principle, and it asserts that *energy* is a thermodynamic property. The *second law of thermodynamics* asserts that energy has *quality* as well as *quantity,* and actual processes occur in the direction of decreasing quality of energy. For example, a cup of hot coffee left on a table eventually cools, but a cup of cool coffee in the same room never gets hot by itself. The high-temperature energy of the coffee is degraded (transformed into a less useful form at a lower temperature) once it is transferred to the surrounding air.

Heat and Other Forms of Energy

Energy can exist in numerous forms such as thermal, mechanical, kinetic, potential, electrical, magnetic, chemical, and nuclear, and their sum constitutes the *total energy E* (or *e* on a unit mass basis) of a system. The forms of energy related to the molecular structure of a system and the degree of the molecular activity are referred to as the *microscopic energy.* The sum of all microscopic forms of energy is called the *internal energy* of a system, and is denoted by *U* (or *u* on a unit mass basis).

The international unit of energy is *joule* (J) or *kilojoule* (1 kJ = 1000 J). In the English system, the unit of energy is the *British thermal unit* (Btu),which is defined as the energy needed to raise the temperature of 1 lbm of water at 60 by 1°F. The magnitudes of kJ and Btu are almost identical (1 Btu = 1.055056 kJ). Another well-known unit of energy is the *calorie* (1 cal = 4.1868 J), which is defined as the energy needed to raise the temperature of 1 g of water at 14.5 by 1°C.

Internal energy may be viewed as the sum of the kinetic and potential energies of the molecules. The portion of the internal energy of a system associated with the kinetic energy of the molecules is called *sensible energy* or *sensible heat*. The average velocity and the degree of activity of the molecules are proportional to the temperature. Thus, at higher temperatures the molecules possess higher kinetic energy, and as a result, the system has a higher internal energy.

The internal energy is also associated with the intermolecular forces between the molecules of a system. These are the forces that bind the molecules to each other, and, as one would expect, they are strongest in solids and weakest in gases. If sufficient energy is added to the molecules of a solid or liquid, they will overcome these molecular forces and simply break away, turning the system to a gas. This is a *phase change* process and because of this added energy, a system in the gas phase is at a higher internal energy level than it is in the solid or the liquid phase. The internal energy associated with the phase of system is called *latent energy* or *latent heat*.

The changes mentioned above can occur without a change in the chemical composition of a system. Most heat transfer problems fall into this category, and one does not need to pay any attention to the forces binding the atoms in a molecule together. The internal energy associated with the atomic bonds in a molecule is called *chemical* (or *bond*) *energy*, whereas the internal energy associated with the bonds within the nucleus of the atom itself is called *nuclear energy*. The chemical and nuclear energies are absorbed or released during chemical or nuclear reactions, respectively.

In the analysis of systems that involve fluid flow, we frequently encounter the combination of properties u and Pv. For the sake of simplicity and convenience, this combination is defined as *specific enthalpy h* or just *enthalpy*. We perefer the term *enthalpy* for convenience. That is, $h = u + Pv$, where the term Pv represents the *flow energy* of the fluid (also called the *flow work*), which is the energy needed to push a fluid and to maintain flow. In the energy analysis of flowing fluids, it is convenient to treat the flow energy as part of the energy of the fluid and to represent the microscopic energy of a fluid stream by enthalpy h (Fig. 2-2).

Specific Heats of Gases, Liquids, and Solids

An *ideal gas* is defined as a gas that obeys the relation

$$Pv = RT \qquad \text{or} \qquad P = \rho RT \qquad (2\text{-}1)$$

where P is the absolute pressure, v is the specific volume, T is the thermodynamic (or absolute) temperature, ρ is the density, and R is the gas constant. It has been experimentally observed that the ideal gas relation given above closely approximates the P-v-T behavior of real gases at low densities. At low pressures and high temperatures, the density of a gas decreases and the gas behaves like an ideal gas. In the range of practical interest, many familiar gases such as air, nitrogen, oxygen, hydrogen, helium, argon, neon, and krypton
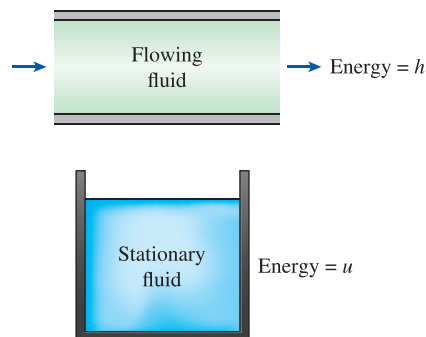
Figure 2-2 The *internal energy u* represents the microscopic energy of a nonflowing fluid, whereas *enthalpy h* represents the microscopic energy of a flowing fluid.
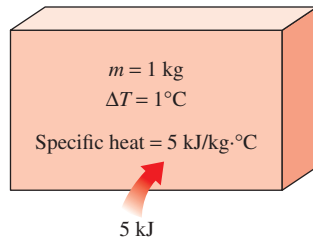
Figure 2-3   Specific heat is the energy required to raise the temperature of a unit mass of a substance by one degree in a specified way.

and even heavier gases such as carbon dioxide can be treated as ideal gases with negligible error (often less than 1%). Dense gases such as water vapor in steam power plants and refrigerant vapor in refrigerators, however, should not always be treated as ideal gases since they usually exist at a state near saturation.

Specific heat is defined as *the energy required to raise the temperature of a unit mass of a substance by one degree* (Fig. 2-3). In general, this energy depends on how the process is executed. We are usually interested in two kinds of specific heats: specific heat at constant volume c_v and specific heat at constant pressure c_p. The *specific heat at constant volume c_v* can be viewed as the energy required to raise the temperature of a unit mass of a substance by one degree as the volume is held constant. The energy required to do the same as the pressure is held constant is the specific heat at constant pressure c_p. The specific heat at constant pressure c_p is greater than c_v because at constant pressure the system is allowed to expand and the energy for this expansion work must also be supplied to the system. For ideal gases, these two specific heats are related to each other by $c_p = c_v + R$.

A common unit for specific heats is kJ/kg·°C or kJ/kg·K. Notice that these two units are identical since $\Delta T(°C) = \Delta T(K)$, and 1°C change in temperature is equivalent to a change of 1 K. Also,

$$1 \text{ kJ/kg·°C} = 1 \text{ J/g·°C} = 1 \text{ kJ/kg·K} = 1 \text{ J/g·K}$$

and

$$1 \text{ Btu/lbm·°F} = 1 \text{ Btu/lbm·R}$$

The specific heat of a substance, in general, depend on two independent properties such as temperature and pressure. For an ideal gas, however, they depend on temperature only (Fig. 2-4). At low pressures all real gases approach ideal gas behavior, and therefore their specific heats depend on temperature only.
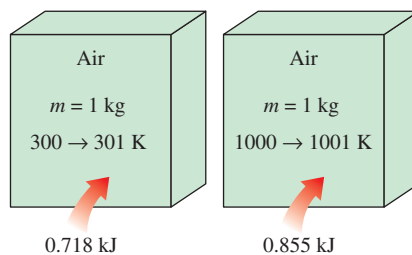
Figure 2-4   The specific heat of a substance changes with temperature.

The differential changes in the internal energy u and enthalpy h of an ideal gas can be expressed in terms of the specific heats as

$$du = c_v dT \qquad \text{and} \qquad dh = c_p dT \qquad\qquad (2\text{-}2)$$

The finite changes in the internal energy and enthalpy of an ideal gas during a process can be expressed approximately by using specific heat values at the average temperature as

$$\Delta u = c_{v,\text{avg}} \Delta T \qquad \text{and} \qquad \Delta h = c_{p,\text{avg}} \Delta T \qquad (\text{kJ/kg}) \qquad (2\text{-}3)$$

or

$$\Delta U = m c_{v,\text{avg}} \Delta T \qquad \text{and} \qquad \Delta H = m c_{p,\text{avg}} \Delta T \qquad (\text{kJ}) \qquad (2\text{-}4)$$

where m is the mass of the system.

A substance whose specific volume (or density) does not change with temperature or pressure is called an incompressible substance. The specific volumes of solids and liquids essentially remain constant during a process, and thus they can be approximated as incompressible substances without sacrificing much in accuracy.

The constant-volume and constant-pressure specific heats are identical for incompressible substances (Fig. 2-5). Therefore, for solids and liquids the subscripts on c_v and c_p can be dropped and both specific heats can be represented by a single symbol, c. That is, $c_p = c_v = c$. This result could also be deduced from the physical definitions of constant-volume and constant-pressure specific heats. Specific heats of several common gases, liquids, and solids are given in the appendix.

The specific heats of incompressible substances depend on temperature only. Therefore, the change in the internal energy of solids and liquids can be expressed as

$$\Delta U = m c_{\text{avg}} \Delta T \qquad (\text{kJ}) \qquad\qquad (2\text{-}5)$$

where c_{avg} is the average specific heat evaluated at the average temperature. Note that the internal energy change of the systems that remain in a single phase (liquid, solid, or gas) during the process can be determined very easily using average specific heats.

Energy Transfer

Energy can be transferred to or from a given mass by two mechanisms: *heat transfer Q* and *work W*. An energy interaction is heat transfer if its driving force is a temperature difference. Otherwise, it is work. A rising piston, a rotating shaft, and an electrical wire crossing the system boundaries are all associated with work interactions. Work done *per unit time* is called *power* and is denoted by $\dot{W}$. The unit of power is kW or hp (1 hp = 0.746 kW).

Iron
25°C
$c = c_v = c_p$
$= 0.45 \text{ kJ/kg·K}$
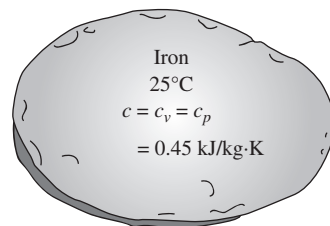
Figure 2-5 The c_v and c_p values of incompressible substances are identical and are denoted by c.

Car engines and hydraulic, steam, and gas turbines produce work; compressors, pumps, and mixers consume work. Notice that the energy of a system decreases as it does work, and increases as work is done on it.

The amount of heat transferred during the process is denoted by Q. The amount of heat transferred per unit time is called *heat transfer rate* and is denoted by $\dot{Q}$. The overdot stands for the time derivative, or "per unit time." The heat transfer rate $\dot{Q}$ has the unit kJ/s (or Btu/h), which is equivalent to kW. In cooling applications, the rate of cooling provided by the cooling equipment (cooling capacity) is often expressed in "ton of refrigeration" units where 1 ton = 12,000 Btu/h.

When the *rate* of heat transfer $\dot{Q}$ is available, then the total amount of heat transfer Q during a time interval Δt can be determined from

$$Q = \int_0^{\Delta t} \dot{Q}\, dt \tag{2-6}$$

provided that the variation of $\dot{Q}$ with time is known. For the special case of $\dot{Q}$ = constant, the equation above reduces to

$$Q = \dot{Q}\,\Delta t \quad \text{(kJ)} \tag{2-7}$$

The First Law of Thermodynamics

The *first law of thermodynamics*, also known as the *conservation of energy principle*, states that energy can neither be created nor be destroyed during a process; it can only change forms. Therefore, every bit of energy must be accounted for during a process. The conservation of energy principle (or the energy balance) for any system undergoing any process may be expressed as follows: The net change (increase or decrease) in the total energy of the system during a process is equal to the difference between the total energy entering and the total energy leaving the system during that process.

Noting that energy can be transferred to or from a system by *heat, work,* and *mass flow,* and that the total energy of a simple compressible system consists of internal, kinetic, and potential energies, the *energy balance* for any system undergoing any process can be expressed as

$$E_{\text{in}} - E_{\text{out}} = \Delta E_{\text{system}} \quad \text{(kJ)} \tag{2-8}$$

In the absence of significant electric, magnetic, motion, gravity, and surface tension effects (i.e., for stationary simple compressible systems), the change in the *total energy* of a system during a process is simply the change in its *internal energy*. That is, $\Delta E_{\text{system}} = \Delta U_{\text{system}}$.

Energy balance can be written in the *rate form*, as

$$\dot{E}_{\text{in}} - \dot{E}_{\text{out}} = dE_{\text{system}}/dt \quad \text{(kW)} \tag{2-9}$$

Energy is a property, and the value of a property does not change unless the state of the system changes. Therefore, the energy change of a system is zero if the state of the system does not change during the process, that is, the process is steady. The energy balance in this case reduces to (Fig. 2-6)

$$\dot{E}_{\text{in}} = \dot{E}_{\text{out}} \quad \text{(kW)} \tag{2-10}$$
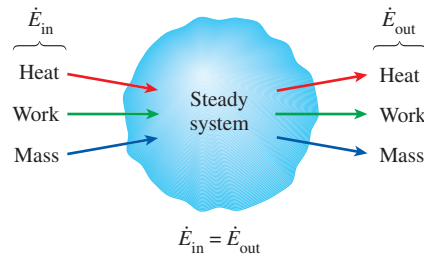
Figure 2-6   In steady operation, the rate of energy transfer to a system is equal to the rate of energy transfer from the system.

Energy Balance for Closed Systems

A closed system consists of a fixed mass. The total energy E for most systems encountered in practice consists of the internal energy U. This is especially the case for stationary systems since they do not involve any changes in their velocity or elevation during a process. The energy balance relation in that case reduces to

Stationary closed system:

$$E_{in} - E_{out} = \Delta U = mc_v \Delta T \qquad \text{(kJ)} \qquad (2\text{-}11)$$

where we expressed the internal energy change in terms of mass m, the specific heat at constant volume c_v, and the temperature change ΔT of the system. When the system involves heat transfer only and no work interactions across its boundary, the energy balance relation further reduces to (Fig. 2-7)

Stationary closed system, no work:

$$Q = mc_v \Delta T \qquad \text{(kJ)} \qquad (2\text{-}12)$$

where Q is the net amount of heat transfer to or from the system. This is the form of the energy balance relation we will use most often when dealing with a fixed mass.

Energy Balance for Steady-Flow Systems

A large number of engineering devices such as water heaters and car radiators involve mass flow in and out of a system, and are modeled as *control volumes.* Most control volumes are analyzed under steady operating conditions. The term *steady* means *no change with time* at

Specific heat $= c_v$
Mass $= m$
Initial temp $= T_1$
Final temp $= T_2$

$Q = mc_v(T_1 - T_2)$
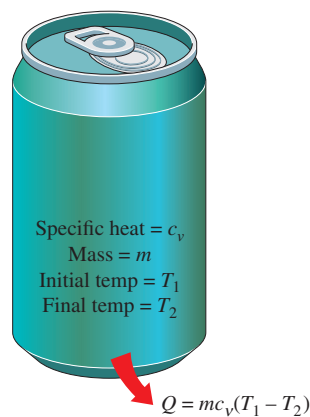
Figure 2-7   In the absence of any work interactions, the change in the energy content of a closed system is equal to the net heat transfer.

a specified location. The opposite of steady is *unsteady* or *transient*. Also, the term *uniform* implies *no change with position* throughout a surface or region at a specified time. These meanings are consistent with their everyday usage (steady job, uniform distribution, etc.). The total energy content of a control volume during *steady-flow process* remains constant (E_{CV} = constant). That is, the change in the total energy of the control volume during such a process is zero ($\Delta E_{CV} = 0$). Thus the amount of energy entering a control volume in all forms (heat, work, mass transfer) for a steady-flow process must be equal to the amount of energy leaving it. In rate form, it is expressed as $\dot{E}_{in} = \dot{E}_{out}$.

The amount of mass flowing through a cross section of a flow device per unit time is called the *mass flow rate*, and is denoted by $\dot{m}$. A fluid may flow in and out of a control volume through pipes or ducts. The mass flow rate of a fluid flowing in a pipe or duct is proportional to the cross-sectional area A_c of the pipe or duct, the density ρ, and the velocity V of the fluid. The flow of a fluid through a pipe or duct can often be approximated to be *one dimensional*. That is, the properties can be assumed to vary in one direction only (the direction of flow). As a result, all properties are assumed to be uniform at any cross section normal to the flow direction, and the properties are assumed to have *bulk average values* over the entire cross section. Under the one-dimensional flow approximation, the mass flow rate of a fluid flowing in a pipe or duct can be expressed as (Fig. 2-8)

$$\dot{m} = \rho V A_c \qquad \text{(kg/s)} \qquad (2\text{-}13)$$

The volume of a fluid flowing through a pipe or duct per unit time is called the *volume flow rate $\dot{V}$*, and is expressed as

$$\dot{V} = V A_c = \frac{\dot{m}}{\rho} \qquad \text{(m}^3\text{/s)} \qquad (2\text{-}14)$$

Note that the mass flow rate of a fluid through a pipe or duct remains constant during steady flow. This is not the case for the volume flow rate, however, unless the density of the fluid remains constant.

For a steady-flow system with one inlet and one exit, the rate of mass flow into the control volume must be equal to the rate of mass flow out of it. That is, $\dot{m}_{in} = \dot{m}_{out} = \dot{m}$. When the changes in kinetic and potential energies are negligible, which is usually the case, and there is no work interaction, the energy balance for such a steady-flow system reduces to (Fig. 2-9)

$$\dot{Q} = \dot{m}\Delta h = \dot{m}c_p \Delta T \qquad \text{(kW)} \qquad (2\text{-}15)$$
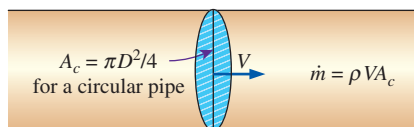
Figure 2-8 The mass flow rate of a fluid at a cross section is equal to the product of the fluid density, average fluid velocity, and the cross-sectional area.
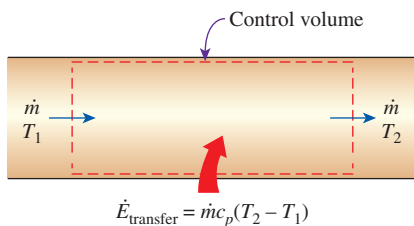

Figure 2-9 Under steady conditions, the net rate of energy transfer to a fluid in a control volume is equal to the rate of increase in the energy of the fluid stream flowing through the control volume.

where $\dot{Q}$ is the rate of net heat transfer into or out of the control volume. This is the form of the energy balance relation that we will use most often for steady-flow systems.

A house has an electric heating system that consists of a 250-W fan and an electric resistance heating element placed in a duct (Fig. 2-10). Air flows steadily through the duct at a rate of 0.5 kg/s and experiences a temperature rise of 7°C. The rate of heat loss from the air in the duct is estimated to be 400 W. Determine the power rating of the electric resistance heating element.
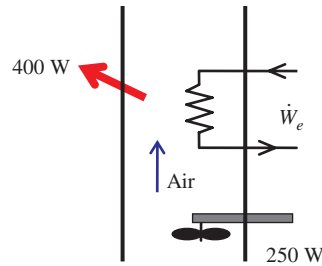
Figure 2-10   Schematic for Example 2-1.

SOLUTION   Air is considered as an ideal gas and constant specific heats at room temperature can be used for air. The specific heat of air at room temperature is $c_p = 1.005$ kJ/kg·°C (Table A-1). We take the heating duct as the system. This is a *control volume* since mass crosses the system boundary during the process. We observe that this is a steady-flow process since there is no change with time at any point and thus $\Delta m_{CV} = 0$ and $\Delta E_{CV} = 0$. Also, there is only one inlet and one exit and thus $\dot{m}_1 = \dot{m}_2 = \dot{m}$. The energy balance for this steady-flow system can be expressed in the rate form as

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

$$\dot{W}_{e,in} + \dot{W}_{fan,in} + \dot{m}h_1 = \dot{Q}_{out} + \dot{m}h_2$$

$$\dot{W}_{e,in} = \dot{Q}_{out} - \dot{W}_{fan,in} + \dot{m}(h_2 - h_1)$$

$$\dot{W}_{e,in} = \dot{Q}_{out} - \dot{W}_{fan,in} + \dot{m}c_p\Delta T$$

Substituting, the power rating of the heating element is determined to be

$$\dot{W}_{e,in} = (0.400 \text{ kW}) - (0.250 \text{ kW}) + (0.5 \text{ kg/s})(1.005 \text{ kJ/kg} \cdot °\text{C})(7°\text{C}) = \textbf{3.67 kW} \quad \blacktriangle$$

Saturation Temperature and Saturation Pressure

Water starts to boil at 100°C. Strictly speaking, the statement "water boils at 100°C" is incorrect. The correct statement is "water boils at 100°C at 1 atm pressure." At 500 kPa pressure, water boils at 151.8°C. That is, the temperature at which water starts boiling depends on the pressure; therefore, if the pressure is fixed, so is the boiling temperature.

At a given pressure, the temperature at which a pure substance changes phase is called the saturation temperature T_{sat}. Likewise, at a given temperature, the pressure at which a pure substance changes phase is called the saturation pressure P_{sat}. At a pressure of 101.3 kPa, T_{sat} is 100°C. Conversely, at a temperature of 100°C, P_{sat} is 101.3 kPa.

Saturation tables that list the saturation pressure against the temperature (or the saturation temperature against the pressure) are available for practically all substances. A partial listing of such a table is given in Table 2-1 for water. This table indicates that the pressure of

TABLE 2-1   Saturation (Boiling) Pressure of Water at Various Temperatures

| Temperature T, °C	Saturation Pressure P_{sat}, kPa
−10	0.260
−5	0.403
0	0.611
5	0.872
10	1.23
15	1.71
20	2.34
25	3.17
30	4.25
40	7.38
50	12.35
100	101.3 (1 atm)
150	475.8
200	1554
250	3973
300	8581

water changing phase (boiling or condensing) at 25°C must be 3.17 kPa, and the pressure of water must be maintained at 3976 kPa (about 40 atm) to have it boil at 250°C. Also, water can be frozen by dropping its pressure below 0.61 kPa.

It takes a large amount of energy to melt a solid or vaporize a liquid. The amount of energy absorbed or released during a phase-change process is called the *latent heat*. More specifically, the amount of energy absorbed during melting is called the *latent heat of fusion* and is equivalent to the amount of energy released during freezing. Similarly, the amount of energy absorbed during vaporization is called the *latent heat of vaporization* and is equivalent to the energy released during condensation. The magnitudes of the latent heats depend on the temperature or pressure at which the phase change occurs. At 1 atm pressure, the latent heat of fusion of water is 333.7 kJ/kg and the latent heat of vaporization is 2256.5 kJ/kg.

During a phase-change process, pressure and temperature are obviously dependent properties, and there is a definite relation between them, that is, $T_{sat} = f(P_{sat})$. A plot of T_{sat} versus P_{sat}, such as the one given for water in Fig. 2-11, is called a *liquid-vapor saturation curve*. A curve of this kind is the characteristic of all pure substances.

It is clear from Fig. 2-11 that T_{sat} increases with P_{sat}. Thus, a substance at higher pressures boils at higher temperatures. In the kitchen, higher boiling temperatures mean shorter cooking times and energy savings. A beef stew, for example, may take 1 to 2 h to cook in a regular pan that operates at 1 atm pressure, but only 20 min in a pressure cooker operating at 3 atm absolute pressure (corresponding boiling temperature: 134°C).

The atmospheric pressure, and thus the boiling temperature of water, decreases with elevation. Therefore, it takes longer to cook at higher altitudes than it does at sea level (unless a pressure cooker is used). For example, the standard atmospheric pressure at an
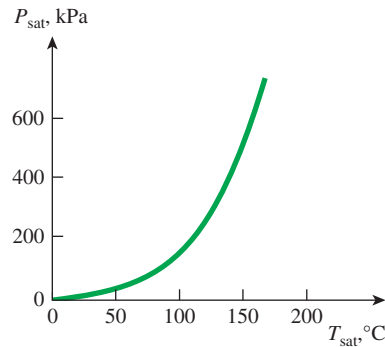
Figure 2-11 The liquid-vapor saturation curve of a pure substance (numerical values are for water).

elevation of 2000 m is 79.50 kPa, which corresponds to a boiling temperature of 93.3°C as opposed to 100°C at sea level (zero elevation). For each 1000 m increase in elevation, the boiling temperature drops by a little over 3°C.

2-3 HEAT TRANSFER

We define *heat* as the form of energy that can be transferred from one system to another as a result of temperature difference. A thermodynamic analysis is concerned with the *amount* of heat transfer as a system undergoes a process from one equilibrium state to another. The science that deals with the determination of the *rates* of such energy transfers is the *heat transfer*. The transfer of energy as heat is always from the higher-temperature medium to the lower-temperature one, and heat transfer stops when the two mediums reach the same temperature.

Heat can be transferred in three different modes: *conduction, convection,* and *radiation*. All modes of heat transfer require the existence of a temperature difference, and all modes are from the high-temperature medium to a lower-temperature one.

Conduction Heat Transfer

Conduction is the transfer of energy from the more energetic particles of substance to the adjacent less energetic ones as a result of interactions between the particles. Conduction can take place in solids, liquids, or gases. In gases and liquids, conduction is due to the *collisions* and *diffusion* of the molecules during their random motion. In solids, it is due to the combination of *vibrations* of the molecules in a lattice and the energy transport by *free electrons*. A cold canned drink in a warm room, for example, eventually warms up to the room temperature as a result of heat transfer from the room to the drink through the aluminum can by conduction.

The *rate* of heat conduction through a medium depends on the *geometry* of the medium, its *thickness,* and the *material* of the medium, as well as the *temperature difference* across the medium. We know that wrapping a hot water tank with glass wool (an insulating material) reduces the rate of heat loss from the tank. The thicker the insulation, the smaller the heat loss. We also know that a hot water tank loses heat at a higher rate when the temperature of the room housing the tank is lowered. Further, the larger the tank, the larger the surface area and thus the rate of heat loss.

Consider steady heat conduction through a large plane wall of thickness $\Delta x = L$ and area A, as shown in Fig. 2-12. The temperature difference across the wall is $\Delta T = T_2 - T_1$. Experiments have shown that the rate of heat transfer $\dot{Q}$ through the wall is *doubled* when the
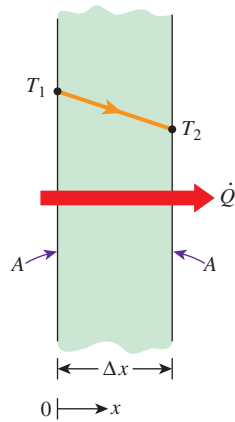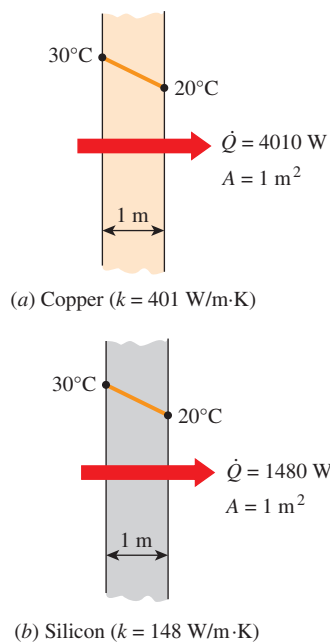
Figure 2-12 Heat conduction through a large plane wall.

temperature difference ΔT across the wall or the area A normal to the direction of heat transfer is doubled, but is *halved* when the wall thickness L is doubled. Thus we conclude that *the rate of heat conduction through a plane layer is proportional to the temperature difference across the layer and the heat transfer area, but is inversely proportional to the thickness of the layer.* That is,

$$\dot{Q}_{cond} = kA\frac{T_1 - T_2}{\Delta x} = -kA\frac{\Delta T}{\Delta x} \qquad (\text{kW}) \qquad (2\text{-}16)$$

where the constant of proportionality k is the *thermal conductivity* of the material, which is a *measure of the ability of a material to conduct heat* (Fig. 2-13). In the limiting case of $\Delta x \rightarrow 0$, the equation above reduces to the differential form

$$\dot{Q}_{cond} = -kA\frac{dT}{dx} \qquad (\text{kW}) \qquad (2\text{-}17)$$

(*a*) Copper ($k = 401$ W/m·K)

(*b*) Silicon ($k = 148$ W/m·K)

Figure 2-13 The rate of heat conduction through a solid is directly proportional to its thermal conductivity.