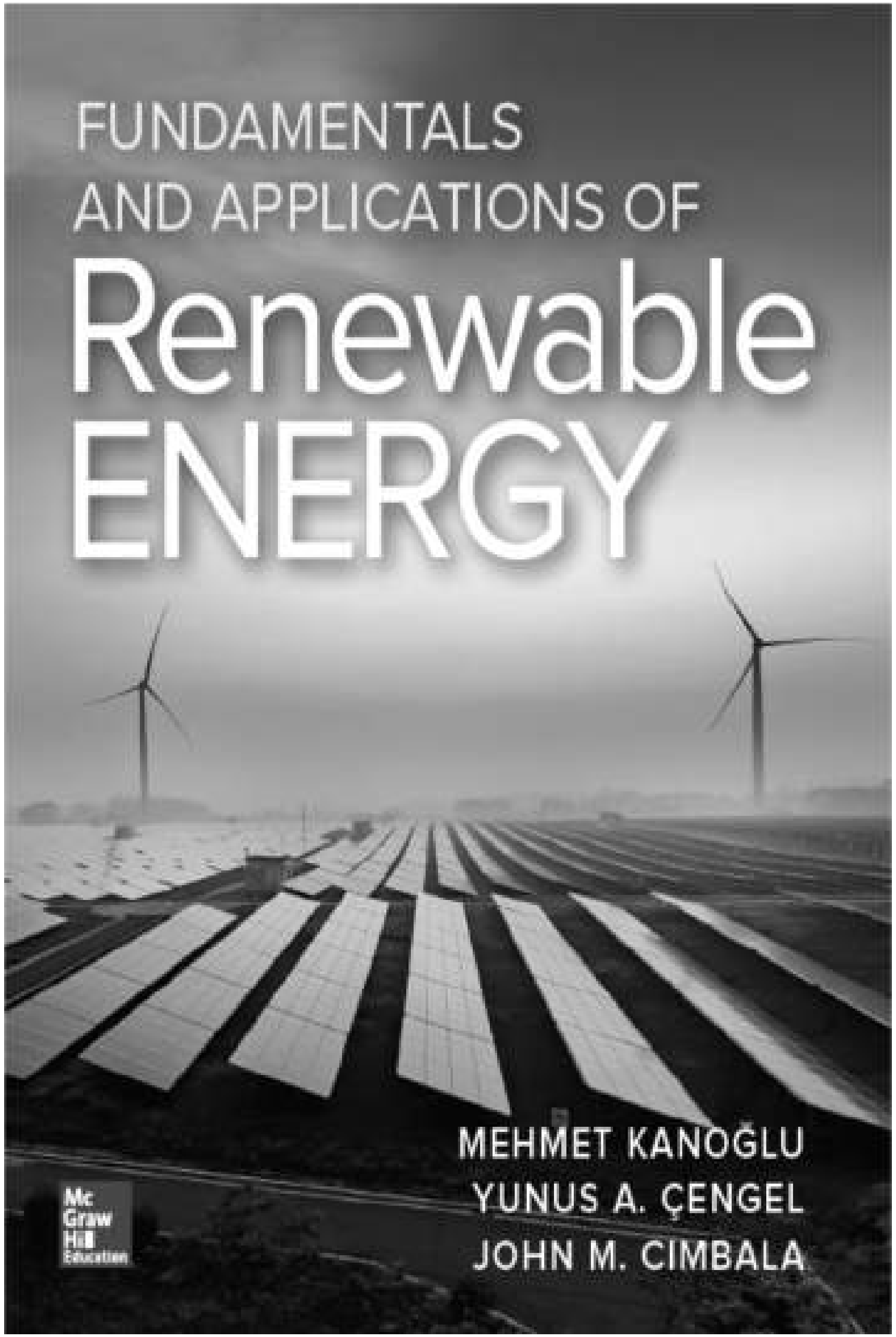


Chapter 1
INTRODUCTION TO RENEWABLE ENERGY

Fundamentals and Applications of

Renewable Energy

Mehmet Kanoglu
Yunus A. Cengel
John M. Cimbala

McGraw-Hill, 2020

1-1 WHY RENEWABLE ENERGY?

To meet its energy needs, the world community currently depends heavily on fossil fuels.

Fossil fuels: non-renewable and unfriendly to the environment

Renewable energy: environment friendly and can be harvested indefinitely

Fossil fuels: 82.7% of total energy use in the world

Coal: 27.1%   Oil: 33.4%   Natural gas: 22.2%

Fossil fuels: 66.3% of total electricity generation in the world

Renewable energy: 12.7% of energy use

Renewable energy: 23.1% of electricity generation

Nuclear power: 4.6% of energy use

Nuclear power: 10.6% of electricity generation

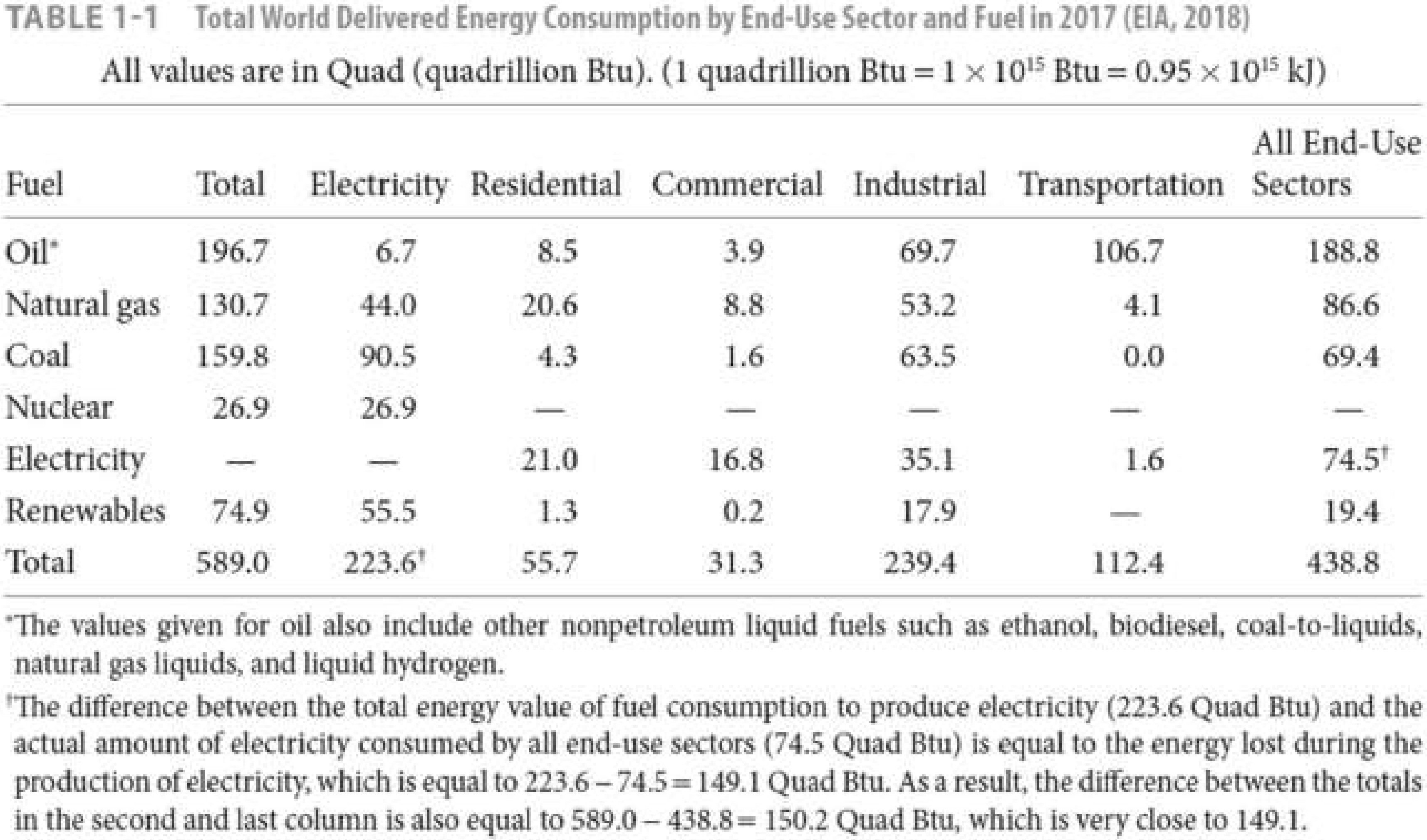


TABLE 1-1 **Total World Delivered Energy Consumption by End-Use Sector and Fuel in 2017 (EIA, 2018)**

All values are in Quad (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.

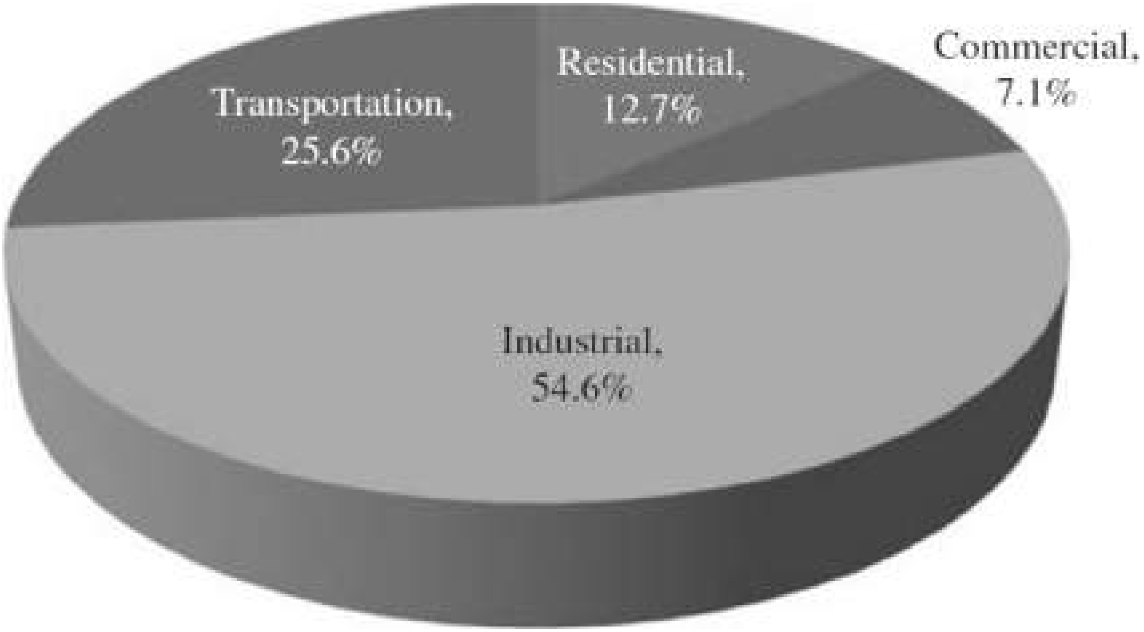


Figure 1-1
Percentages of global energy use by end-use sectors in 2017

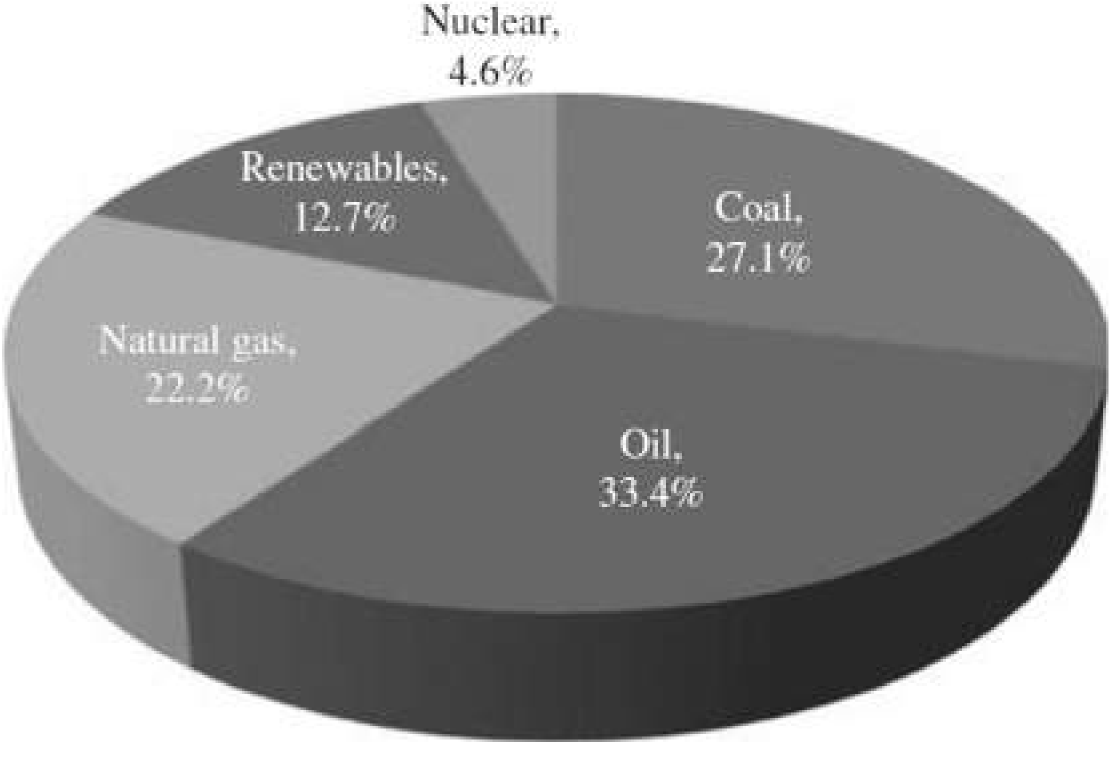


Figure 1-2
Percentages of total world primary energy supply by fuel in 2017

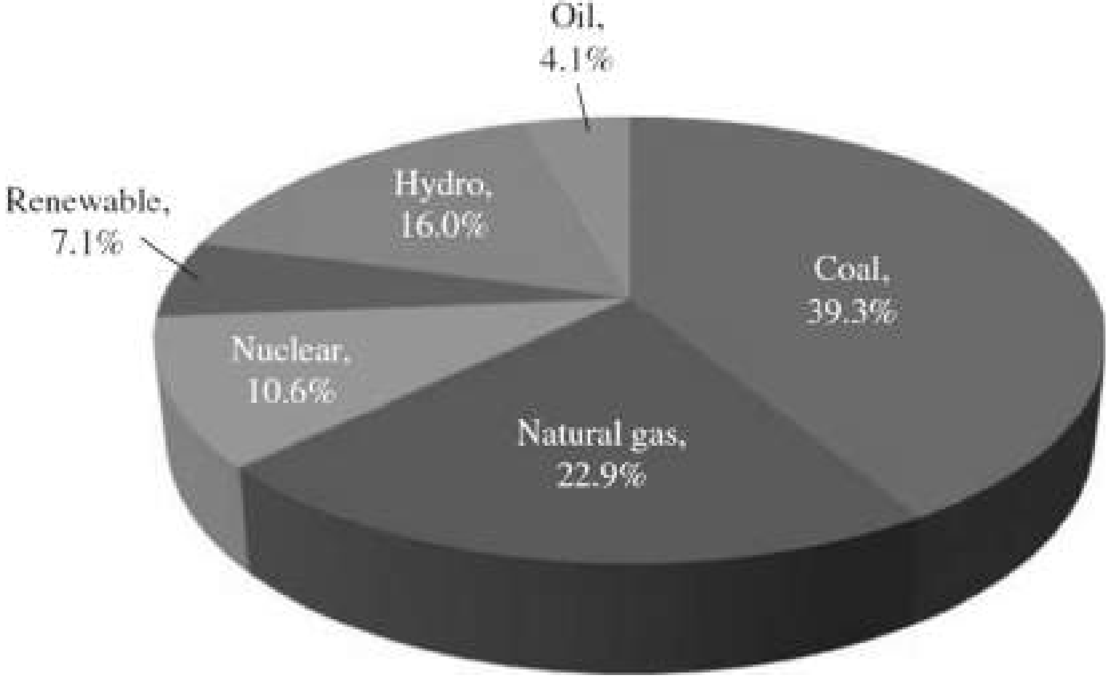


Figure 1-3
Percentages of global electricity generation by fuel type and source in 2015. Total electricity generation = 24,255 TWh

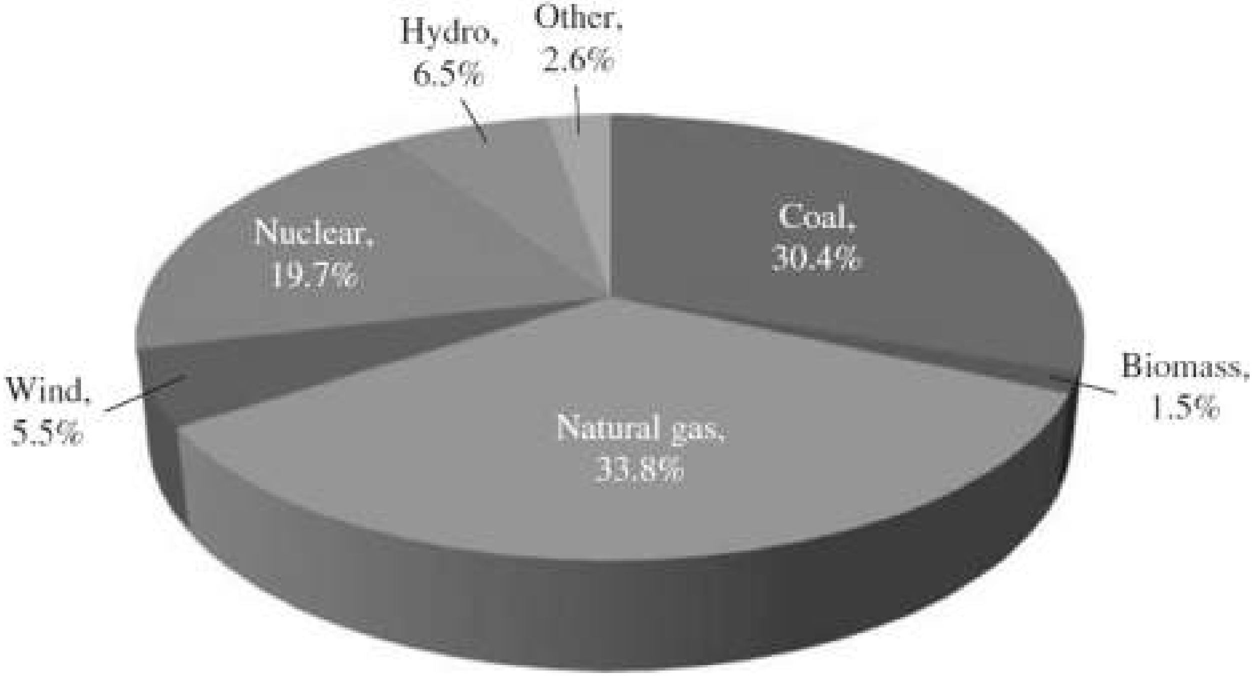


Figure 1-4
Percentages of electricity generation by fuel type and source in the United States in 2016

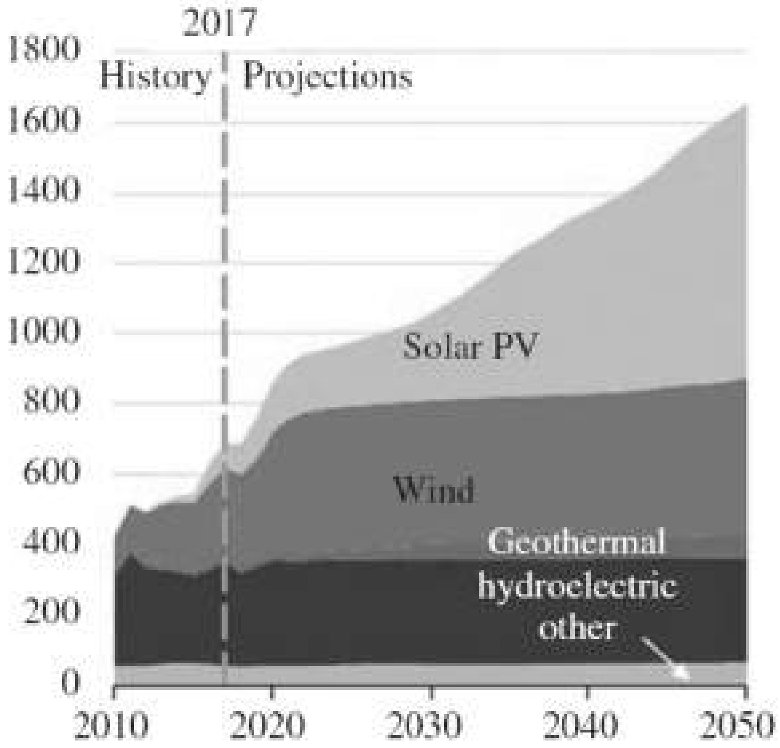


Figure 1-5
Renewable electricity generation by source in the United States, in billion kWh

Total generation by renewables: 640 billion kWh

By the year 2050: 1600 billion kWh

Most renewable electricity generation by: hydropower and wind

The highest rate of increase in 2017: solar

By the year 2050: Solar electricity is estimated to take the greatest share followed by wind, hydropower, and geothermal.

Other renewables in the figure: Biomass electricity production by the means of MSW/LFG (municipal solid waste/land fill gas)

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 renewable sources: solar and wind.

Installed wind capacity: 18 GW in 2000, 539 GW in 2017

Solar power capacity: over 400 GW (97 GW added in 2017)

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.

Consequences of Fossil Fuel Combustion

Fossil fuels have been powering the industrial development and the amenities of modern life since the 1700s, but this has not been without the undesirable side effects.

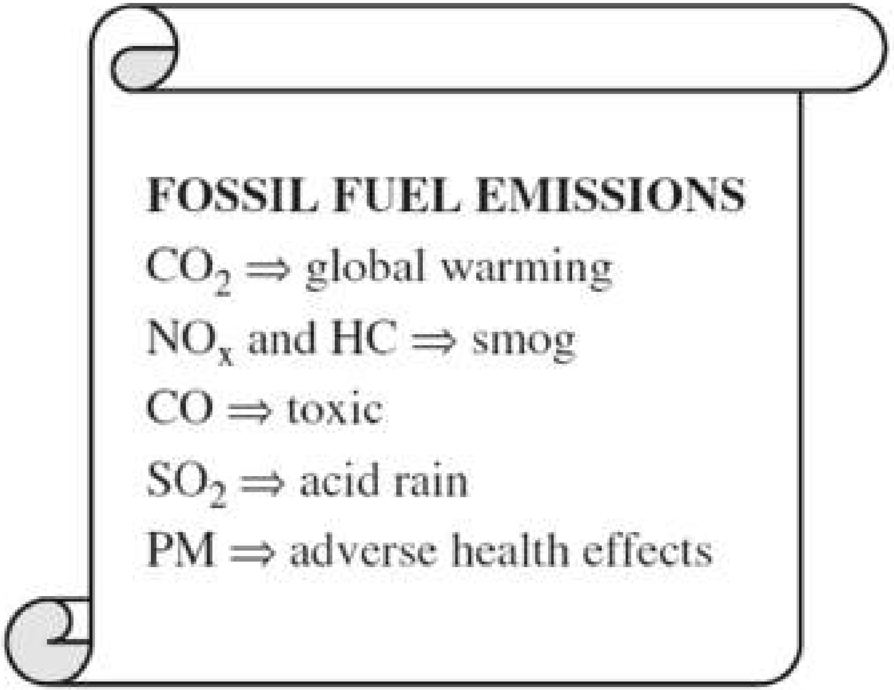
Pollutants emitted during the combustion of fossil fuels are responsible for: smog, acid rain, and global warming.

The environmental pollution has reached such high levels that it has become a serious threat to vegetation, wild life, and human health.

Air pollution causes: numerous health problems including asthma and cancer

Fossil fuel based economy is not sustainable since the estimated life of known reserves is limited.

The switch to renewable energy sources is inevitable.



FOSSIL FUEL EMISSIONS

CO_2 ⇒ global warming

NO_x and HC ⇒ smog

CO ⇒ toxic

SO_2 ⇒ acid rain

PM ⇒ adverse health effects

Figure 1-6
Effects of undesirable emissions from the combustion of fossil fuels.

The combustion of fossil fuels produces these undesirable emissions:

CO_2: primary greenhouse gas, contributes to global warming.

Nitrogen oxides (NO_x), Hydrocarbons (HC): cause smog

Carbon monoxide (CO): toxic

Sulfur dioxide (SO_2): causes acid rain

Particulate matter (PM): causes adverse health effects

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 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.

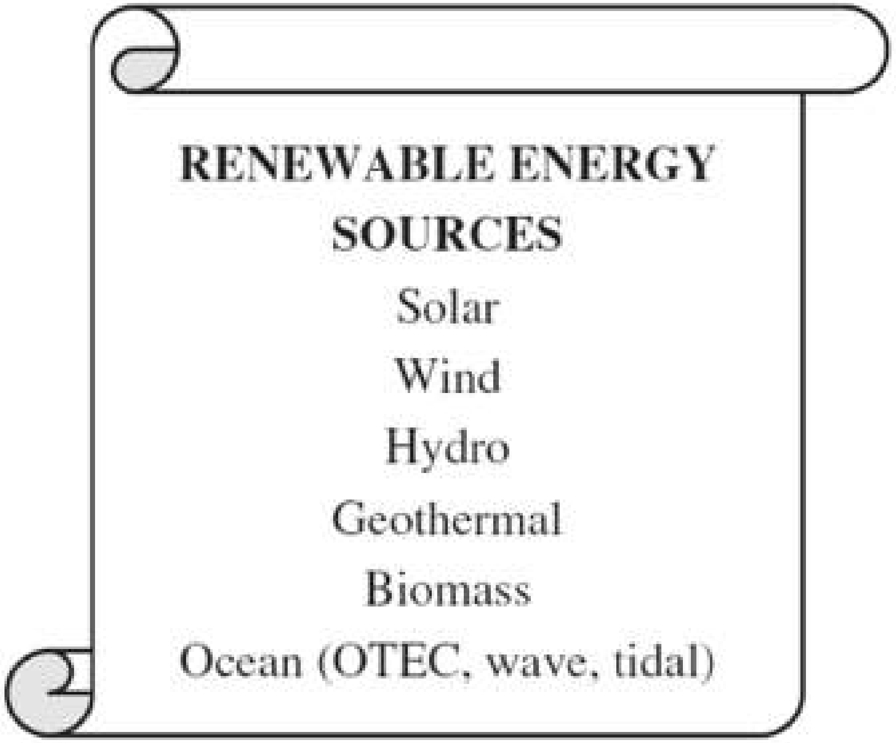
Energy efficiency: It is to reduce energy use to the minimum level, but to do so without reducing the standard of living, the production quality, and the profitability.

Energy efficiency is an expression for the most effective use of the energy resources, and it results in energy conservation.

Energy efficiency can only reduce the fossil fuel use.

Renewable energy can directly replace fossil fuels.

Renewable Energy Sources



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 SOURCE: An energy source is called renewable if it can be renewed and sustained without any depletion and any significant effect on the environment.

Renewable source: also called alternative, sustainable, or green energy source.

Fossil fuels: coal, oil, and natural gas; not renewable; depleted by use.

Fossil fuels: emit harmful pollutants and greenhouse gases.

SOLAR*:* The best-known renewable source.

It is sufficient to meet the entire energy needs of the world.

It is not economical because of the low concentration of solar energy on earth and the high capital cost of harnessing it.

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

WIND: The conversion of kinetic energy of wind into electricity via wind turbines represents wind energy.

It is one of the fastest growing renewables.

HYDRO: The collection of river water into large dams at some elevation and 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 electricity production among renewables.

It supplies most of electricity needs of some countries.

GEOTHERMAL: Geothermal energy refers to heat of earth.

High temperature underground geothermal fluid found in some locations is extracted and the energy of 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.

BIOMASS: Organic renewable energy is referred to as biomass and a variety of sources (agriculture, forest, residues, crops, etc.) can be used to produce biomass energy.

Biomass is becoming more popular with the help of the variety of available sources.

WAVE AND TIDAL ENERGIES: They are renewable energy sources.

They are usually considered as part of ocean energy since they are available mostly in oceans.

Wave and tidal energies are mechanical forms of ocean energy since they represent potential and kinetic energies of ocean water.

OTEC: Thermal energy of oceans due to absorption of solar energy by ocean surfaces.

This energy can be utilized using the OTEC (*Ocean Thermal Energy Conversion*) system.

HYDROGEN: an energy carrier that can be used to store renewable electricity.

It is still a developing technology, and many research activities are underway to make it viable.

FUEL CELLS: convert chemical energy of fuels (e.g., hydrogen) into electricity directly without a highly irreversible combustion process.

It is more efficient than combustion-based conversion to electricity.

Are electric cars zero emission vehicles?

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.

However, the electricity used by the electric cars is generated somewhere else mostly by burning fuel and thus emitting pollution.

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.

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 biomass.

For example, no hydroelectric power plant can generate electricity year after year unless the water evaporates by absorbing solar energy and comes back as a rainfall to replenish the water source

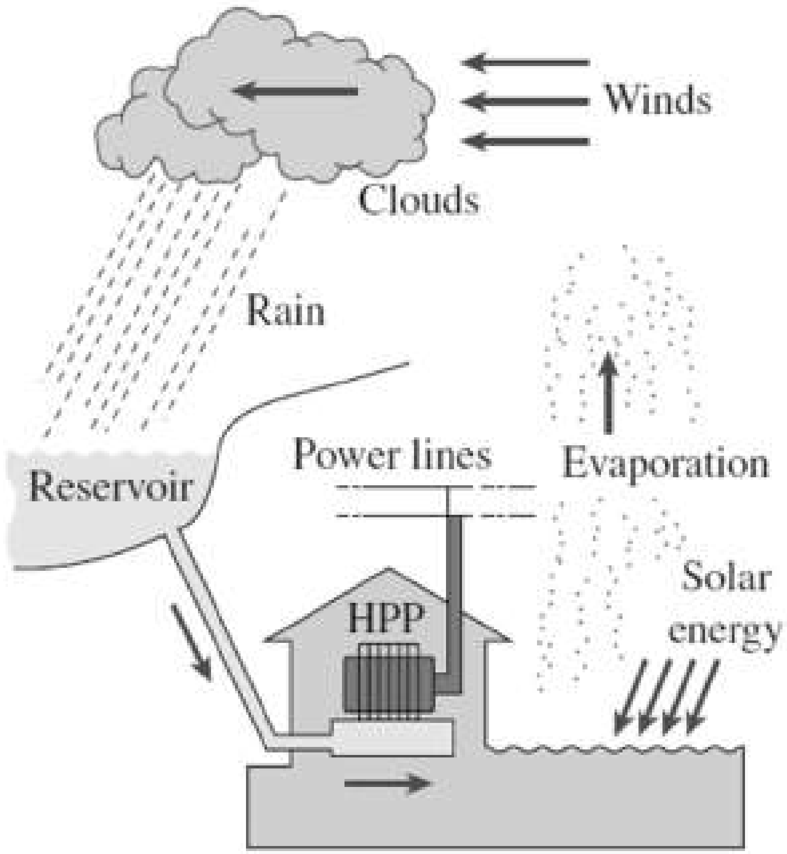
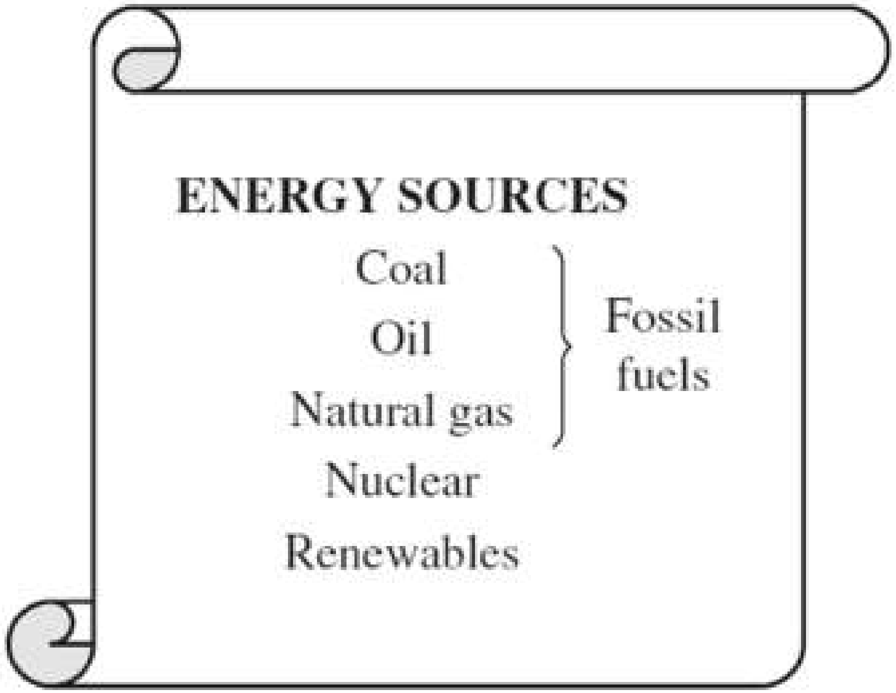


Figure 1-9
The cycle that water undergoes in a hydroelectric power plant (HPP).

1-2 FOSSIL FUELS AND NUCLEAR ENERGY

Fossil fuels are responsible for more than 90 percent of global combustion-related CO_2 emissions.

CO_2 emissions in 2017: 37 gigatons (37,000 million tons)



The shares of fossil fuels to the global CO_2 emissions:

Coal: 45%

Oil: 35%

Natural gas: 20%

Coal

Coal content: Carbon, hydrogen, oxygen, nitrogen, sulfur, ash (non-combustibles).

The percentages of carbon and other components vary depending on the production site.

Heating value of carbon: 32,800 kJ/kg

Important characteristics of coal: Heating value and sulfur content

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.

When coal burns: Hydrogen and sulfur burn first and carbon burns last.

All sulfur burns into SO_2 and all hydrogen burns into H_2O.

$$S + O_2 \rightarrow SO_2$$

$$H_2 + \tfrac{1}{2}O_2 \rightarrow H_2O$$

Coal types

Bituminous coal: It is also known as soft coal. It has high energy content but unfortunately also has high sulfur content. 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. It 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. 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. It is used mainly for electricity generation.

$$C + \frac{1}{2}O_2 \rightarrow CO$$

$$CO + \frac{1}{2}O_2 \rightarrow CO_2$$

CO formation: If some of 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.

This can happen even in the presence of stoichiometric or excess oxygen due to incomplete mixing and short time of combustion process.

Coal combustion produces: pollutant emissions of unburned carbon particles (smoke), unburned hydrocarbon (HC), sulfur compounds, and nitrogen oxide (NO_x).

Coal: the most polluting fuel compared to liquid and gaseous fuels

Coal: the largest contributor of CO_2 emissions

Coal is used for: electricity production in steam power plants, space and water heating, steam generation in boilers

Oil

Oil content: A mixture of a large number of hydrocarbons (HC) with different compositions.

Crude oil content: 83 to 87 percent carbon and 11 to 14 percent hydrogen with small amounts of other components

Oil end products: gasoline, light diesel fuel, jet fuel, LPG (liquefied petroleum gas), heavy diesel fuel (fuel-oil)

How are they obtained: by distillation and cracking in oil refinery plants

Non-petroleum liquid fuels: ethanol, biodiesel, coal-to-liquids, natural gas liquids, liquid hydrogen

OIL PRODUCTS

Gasoline
Light diesel fuel
Heavy diesel fuel
Jet fuel
LPG
Natural gas

Gasoline and light diesel: used in automobiles and motor vehicles

Gasoline: approximated as C_8H_{15}

HHV = 47,300 kJ/kg

Diesel fuel: approximated as $C_{12}H_{22}$

HHV = 46,100 kJ/kg

Diesel fuel also includes some sulfur.

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).

Oil is not commonly used for electricity generation.

There are two groups of oil used in

power plants, industrial heating applications

Distillate oils: These are higher-quality oils that are highly refined. They contain much less sulfur compared to residual oils.

Typical composition: 87.2% carbon, 12.5% hydrogen, and 0.3% sulfur

HHV = 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.

Typical composition: 85.6% carbon, 9.7% hydrogen, 2.3% sulfur, 1.2% nitrogen, 0.8% oxygen, 0.1% ash, and 0.3% moisture

HHV = 42,500 kJ/kg.

Natural Gas

Natural gas content: Methane (CH_4): 60 to 98%. It also contains nitrogen, helium, carbon dioxide and other gases.

Phase: It exists as a gas under atmospheric conditions and stored as a gas under high pressure (15 to 25 MPa).

Transportation: It is mostly transported in gas phase by pipelines between the cities and countries.

LNG: When pipeline transportation is not feasible, it is first liquefied into about -160°C using non-conventional refrigeration technologies before being carried in large insulated tanks in marine ships.

Natural gas use: space heating (in boilers), hot water and steam generation, industrial furnaces, electricity production (in power plants), internal combustion engines

Is natural gas clean? Compared to coal and oil, natural gas is cleaner as it emits less hydrocarbon, smoke, carbon monoxide, and nitrous oxides in a combustion process.

Air quality in certain cities has improved dramatically when natural gas pipeline has reached the city and common boilers running on coal were replaced by natural gas counterparts.

Using natural gas in public transportation (buses and taxis) is used as a measure to improve air quality in cities.

Natural gas use: About 40% of natural gas is used by industrial sector while 33% is used for electricity generation in power plants.

Also used for residential and commercial applications mostly for space and water heating.

Shale gas: The supply of natural gas has been rising substantially in the U.S., Canada, and China.

This is mostly due to exploitation of shale gas which is made possible by horizontal drilling and hydraulic fracturing technologies.

The higher heating value of natural gas mainly depend on fraction of methane.

Methane: HHV = 55,530 kJ/kg, LHV = 50,050 kJ/kg

The heating value of natural gas is usually expressed in kJ/m^3 unit.

HHV ranges between 33,000 kJ/m^3 to 42,000 kJ/m^3 depending on the location of the resource.

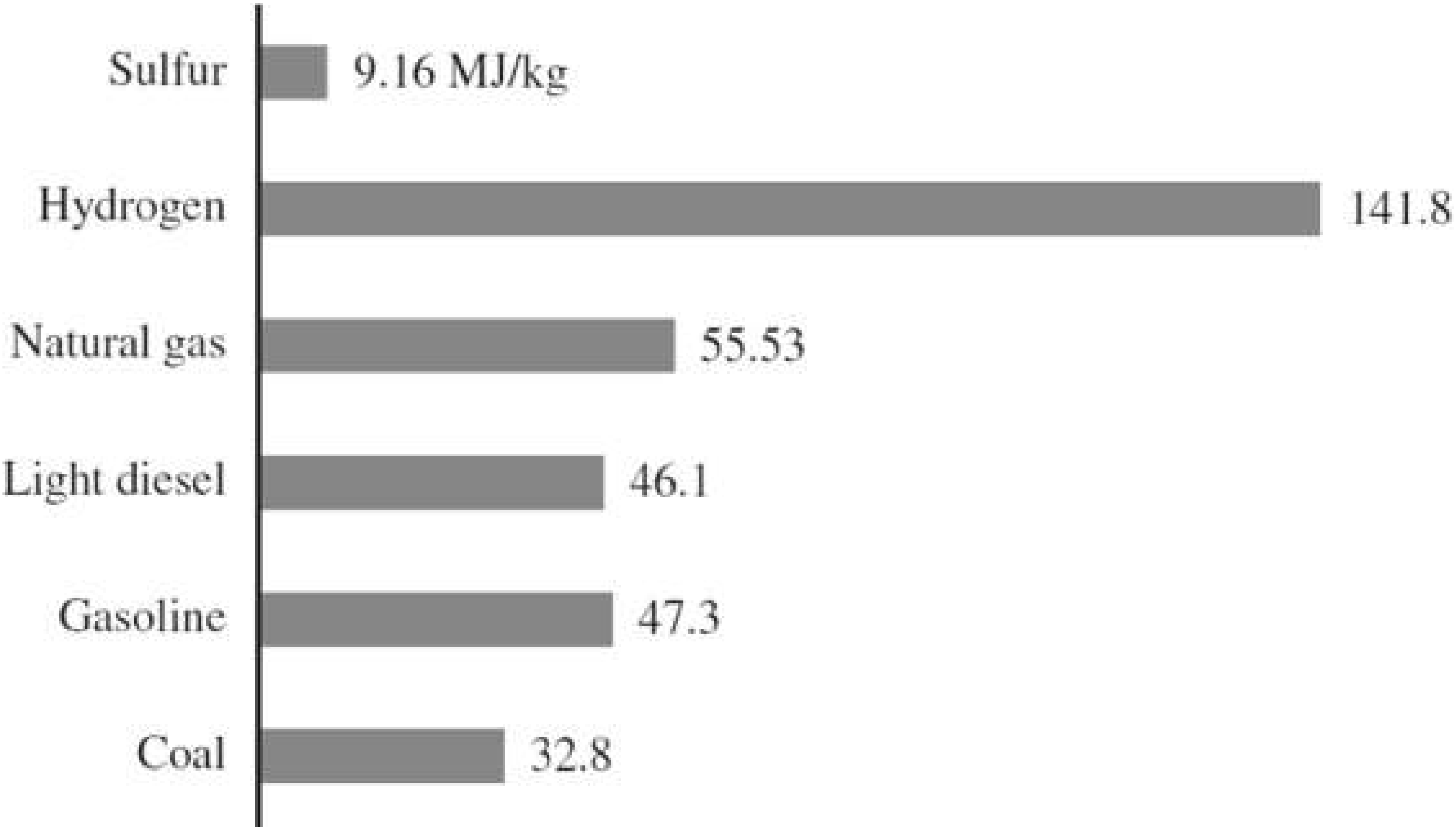


Figure 1-12

Higher heating values of various fuels, in MJ/kg. Coal is roughly approximated as carbon and natural gas as methane.

Nuclear Energy

What is nuclear energy? The tremendous amount of energy associated with the strong bonds within the nucleus of the atom.

Fission: The most widely known fission reaction involves splitting the uranium atom (the U-235 isotope) into other elements.

Nuclear energy use: to generate electricity in nuclear power plants, to power nuclear submarines, aircraft carriers, and even spacecraft, and as a component of nuclear bombs.

Fusion: Nuclear energy by fusion is released when two small nuclei combine into a larger one.

Cold fusion? The 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.

How much energy? 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.

Problem of nuclear energy? The safe disposal of used nuclear fuel remains a concern.

Number and capacity: over 450 nuclear reactors worldwide with a total capacity of about 400,000 MW.

Dozens of new reactors are under construction in 15 countries.

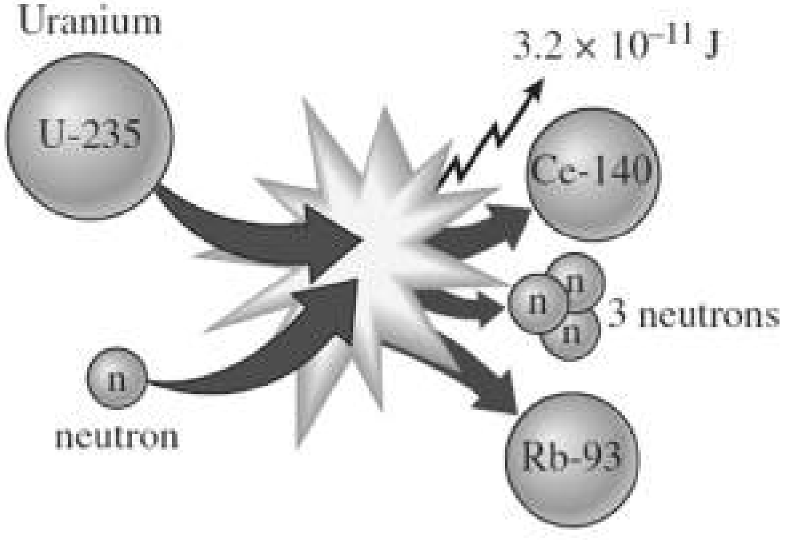
US nuclear: 61 nuclear power plants with 99 reactors.

Percentages: The percentage of electricity produced by nuclear power is 76% in France, 19% in Russia and the United Kingdom, 14% in Germany, and 20% in the United States

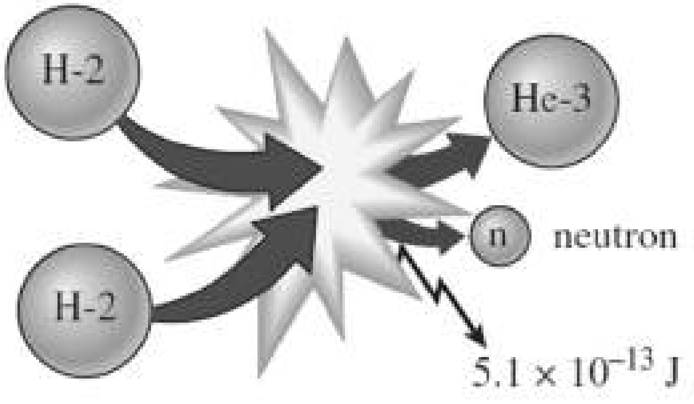
Fission process: Nuclear energy by fusion is released when two small nuclei combine into a larger one.

Fusion process: 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.



(*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 replace it because vast majority of devices, equipment, and appliances used by people operate on electricity.

How is it produced? In power plants 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.

Smart grid: 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.

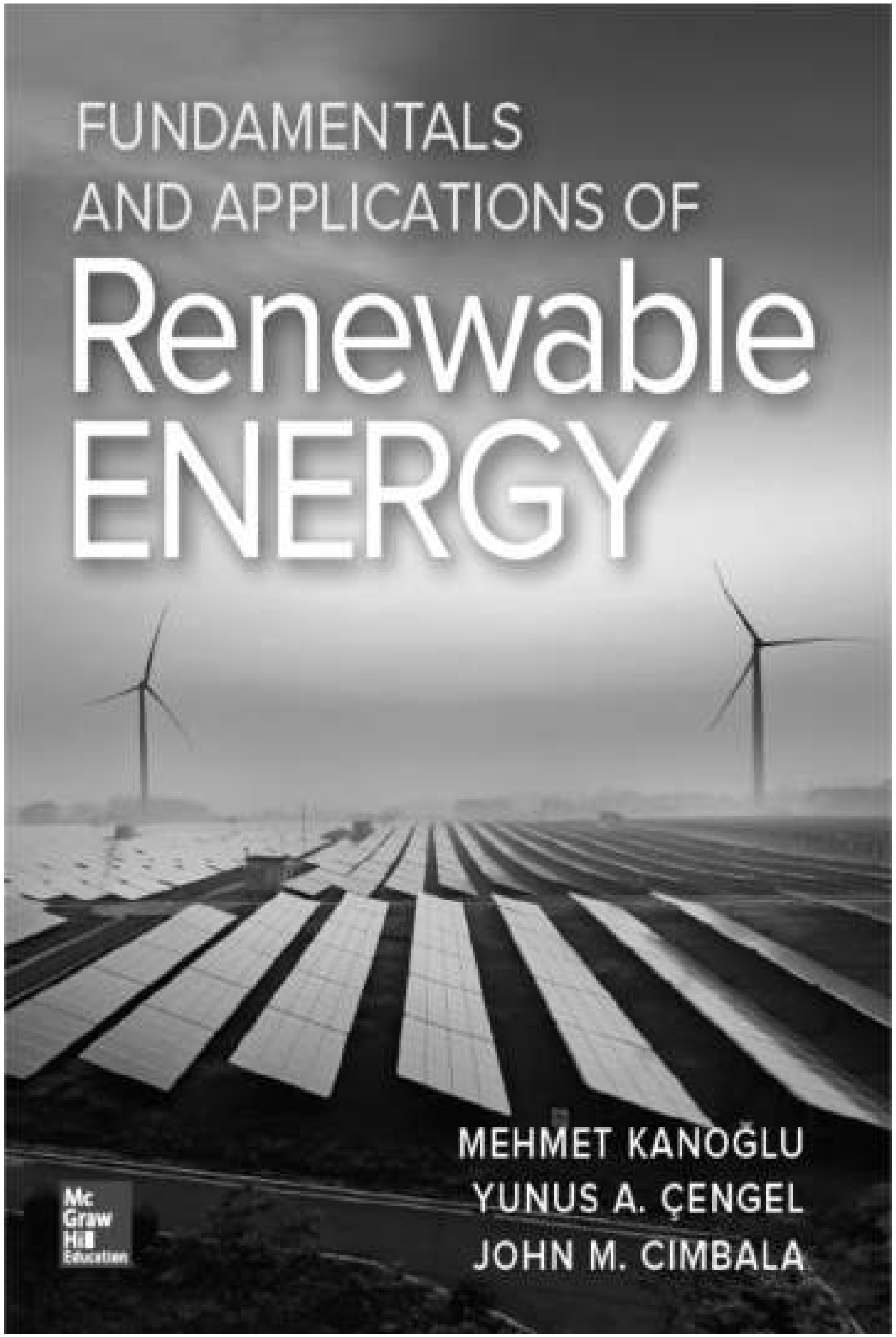
Energy storage systems: help to deal with the irregularities of wind and solar electricity generation.

Storage techniques: Two most common types are batteries and pumped storage.

Batteries: Well known since we all use rechargeable batteries in our cars, portable computers, cell phones, and other electronic devices.

Pumped storage: It 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.



Chapter 2
A REVIEW OF THERMAL SCIENCES

Fundamentals and Applications of

Renewable Energy

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McGraw–Hill, 2020

2-1 THERMAL SCIENCES

The analysis of renewable energy systems requires a solid understanding of

- energy conversion processes
- transformation between various forms of energy
- ways of defining efficiencies of energy systems

We review fundamental concepts of

- thermodynamics
- heat transfer
- fluid mechanics
- thermochemistry
- power plants
- refrigeration systems

Thermal-fluid sciences (Thermal sciences): The physical sciences that deal with energy and the transfer, transport, and conversion of energy

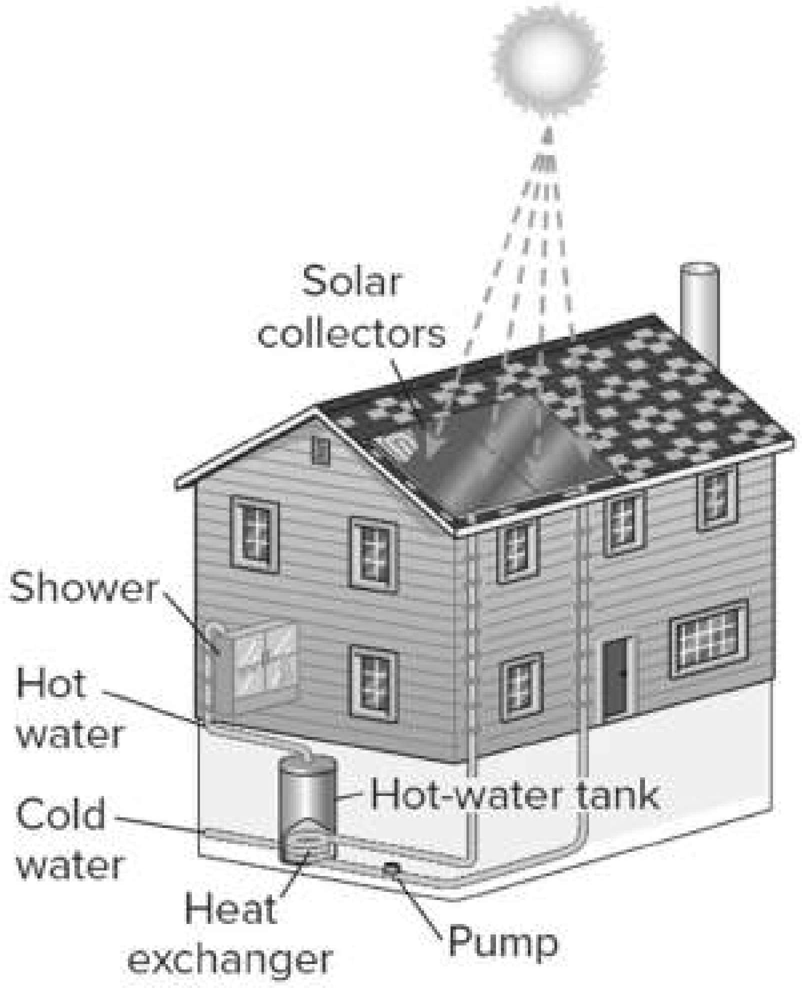


Figure 2-1
The design and analysis of renewable energy systems, such as this solar hot water system, involves thermal sciences.

Designing a solar collector involves

thermodynamics: the determination of the amount of energy transfer

heat transfer: the determination of the size of the heat exchanger

fluid mechanics: the determination of the size and type of the pump

2-2 THERMODYNAMICS

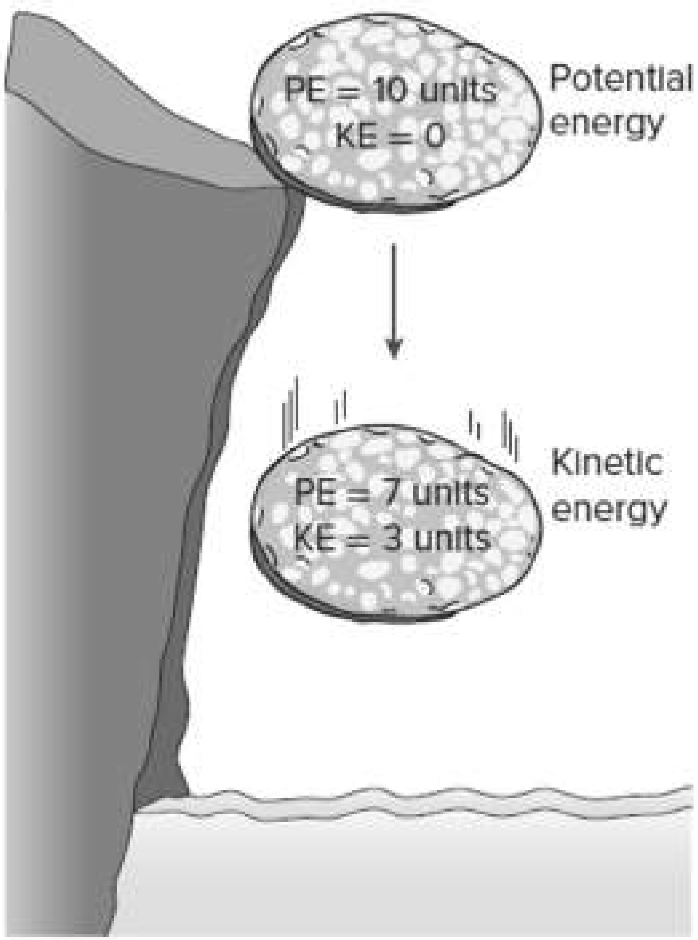
Thermodynamics: The science of *energy.*

Conservation of energy principle: During an interaction, energy can change from one form to another but the total amount of energy remains constant.

Energy cannot be created or destroyed.

The first law of thermodynamics: An expression of the conservation of energy principle.

The second law of thermodynamics: It asserts that energy has *quality* as well as *quantity,* and actual processes occur in the direction of decreasing quality of energy.



Heat and other forms of energy

Energy can exist in numerous forms such as

- ✓ thermal
- ✓ mechanical
- ✓ kinetic
- ✓ potential
- ✓ electrical
- ✓ magnetic
- ✓ chemical
- ✓ nuclear

Their sum constitutes the **total energy** of a system.

Internal energy: The sum of all microscopic forms of energy

Internal energy: May be viewed as the sum of the kinetic and potential energies of the molecules.

Sensible heat: The kinetic energy of the molecules.

Latent heat: The internal energy associated with the phase of a system.

Chemical (**bond**) **energy**: The internal energy associated with the atomic bonds in a molecule.

Nuclear energy: The internal energy associated with the bonds within the nucleus of the atom itself.

In the analysis of systems that involve fluid flow, we frequently encounter the combination of properties u and Pv.

Enthalpy: The combination $u + Pv$ is defined as enthalpy

$$h = u + Pv$$

Flow energy: The term Pv represents the flow energy of the fluid.

It is also called the flow work.

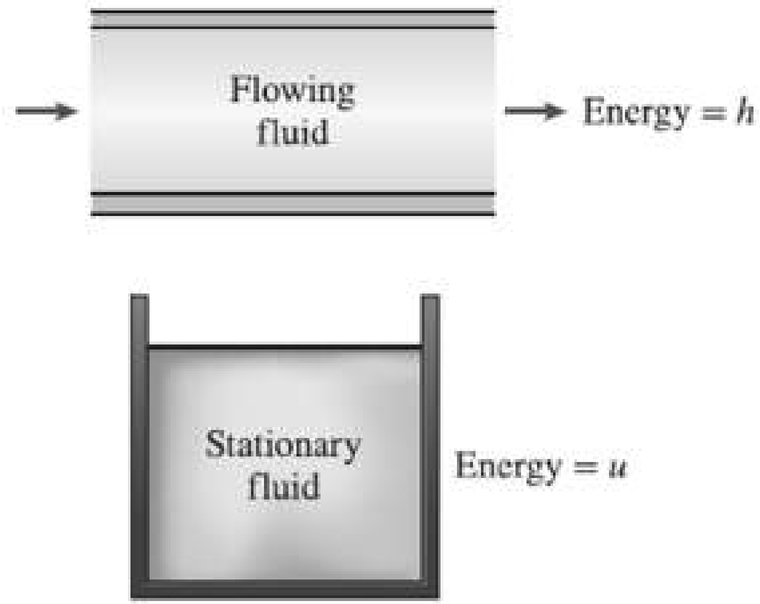


Figure 2-2
The *internal energy u* represents the microscopic energy of a nonflowing fluid, whereas *enthalpy h* represents the microscopic energy of a flowing fluid.

Specific Heats of Gases, Liquids, and Solids

$Pv = RT \quad P = \rho RT$ Ideal gas relation

Specific heat: The energy required to raise the temperature of a unit mass of a substance by one degree

Two kinds of specific heats:

✓ specific heat at constant volume c_v

✓ specific heat at constant pressure c_p

At low pressures all real gases approach ideal gas behavior, and therefore their specific heats depend on temperature only.

$$c_p = c_v + R$$

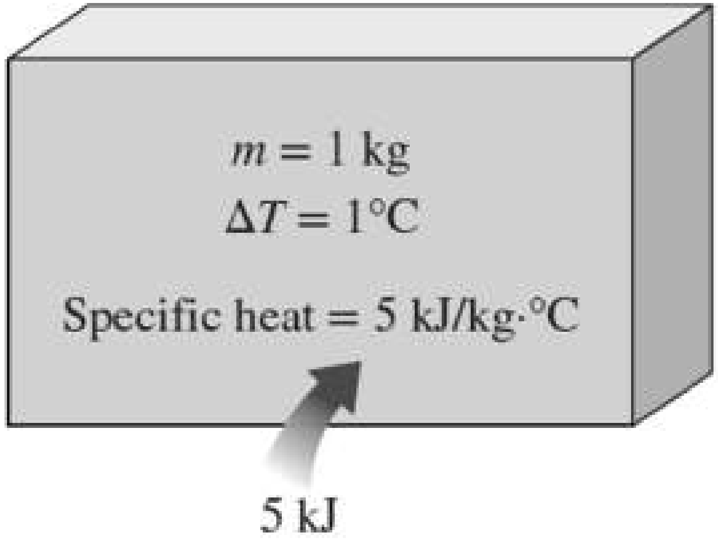


Figure 2-3
Specific heat is the energy required to raise the temperature of a unit mass of a substance by 1 degree in a specified way.

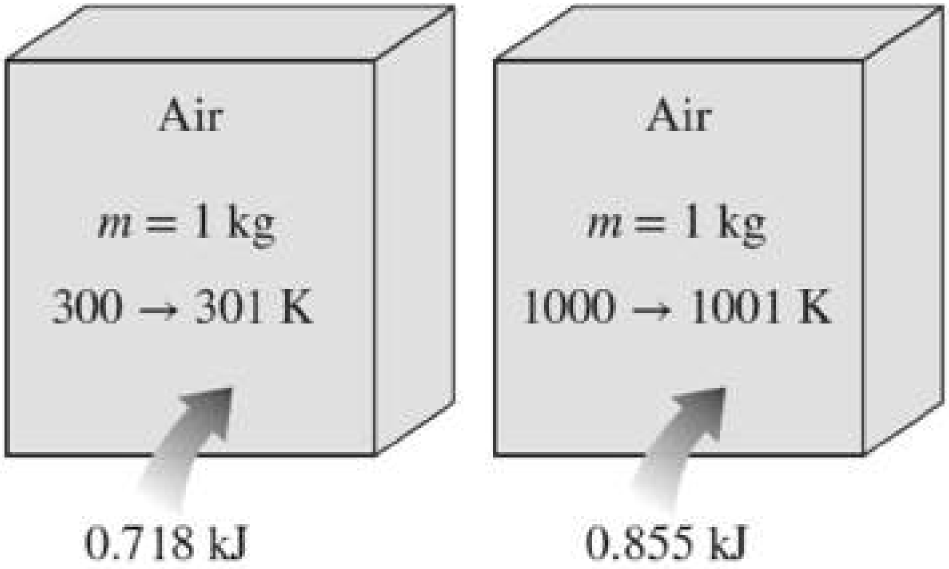


Figure 2-4
The specific heat of a substance changes with temperature.

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

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

$$du = c_v dT \qquad \text{and} \qquad dh = c_p dT$$

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

$$\Delta U = mc_{v,\text{avg}} \Delta T \qquad \text{and} \qquad \Delta H = mc_{p,\text{avg}} \Delta T \qquad (\text{kJ})$$

Incompressible substance: A substance whose specific volume (or density) does not change with temperature or pressure.

The constant-volume and constant-pressure specific heats are identical for incompressible substances.

The specific heats of incompressible substances depend on temperature only.

$$\Delta U = mc_{\text{avg}} \Delta T \qquad (\text{kJ})$$

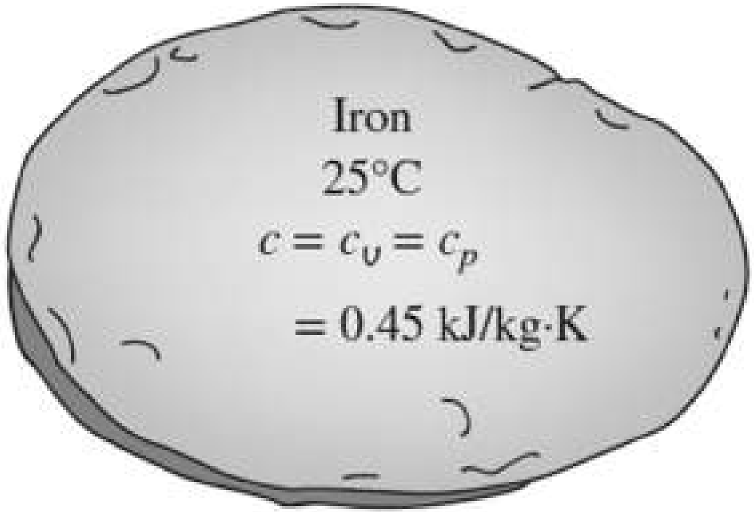


Figure 2-5
The c_v and c_p values of incompressible substances are identical and are denoted by c.

Energy Transfer

Energy can be transferred to or from a given mass by two mechanisms:

- heat transfer

- work

Heat transfer rate: The amount of heat transferred per unit time.

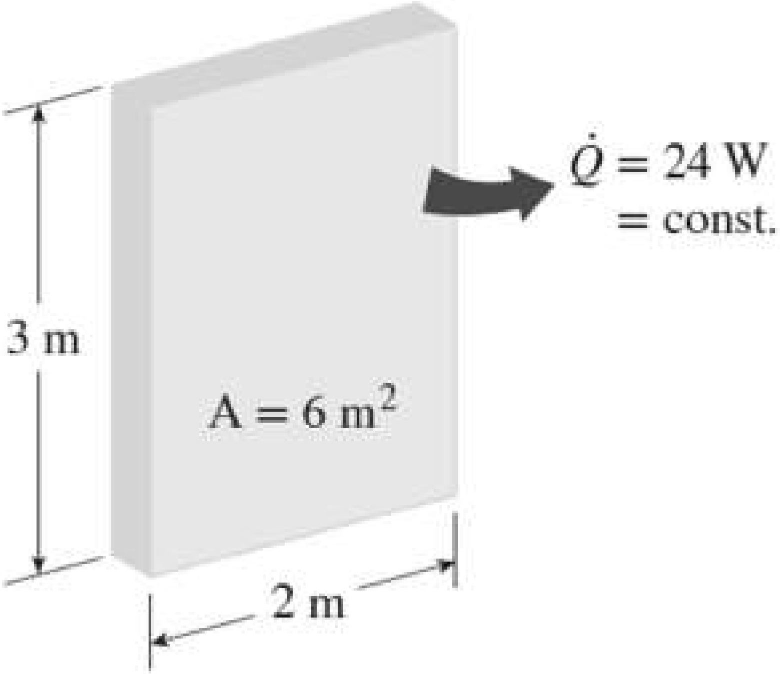
Heat flux: The rate of heat transfer per unit area normal to the direction of heat transfer.

Power: The work done *per unit time.*

$$Q = \int_0^{\Delta t} \dot{Q}\, dt$$

$$Q = \dot{Q}\, \Delta t \qquad \text{(kJ)}$$

$$\dot{q} = \frac{\dot{Q}}{A} \qquad (\text{W/m}^2)$$



$$\dot{q} = \frac{\dot{Q}}{A} = \frac{24\ \text{W}}{6\ \text{m}^2} = 4\ \text{W/m}^2$$

Heat flux is heat transfer *per unit time* and *per unit area*, and is equal to $\dot{q} = \dot{Q}/A$ when $\dot{Q}$ is uniform over the area A.

The First Law of Thermodynamics

First law of thermodynamics = Conservation of energy Principle: Energy can neither be created nor destroyed during a process; it can only change forms.

$$\begin{pmatrix}\text{Total energy}\\ \text{entering the}\\ \text{system}\end{pmatrix} - \begin{pmatrix}\text{Total energy}\\ \text{leaving the}\\ \text{system}\end{pmatrix} = \begin{pmatrix}\text{Change in the}\\ \text{total energy of}\\ \text{the system}\end{pmatrix}$$

$$\underbrace{E_{\text{in}} - E_{\text{out}}}_{\substack{\text{Net energy transfer}\\ \text{by heat, work, and mass}}} = \underbrace{\Delta E_{\text{system}}}_{\substack{\text{Change in internal, kinetic,}\\ \text{potential, etc., energies}}} \qquad \text{(J)}$$

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.

$$E_{\text{in}} - E_{\text{out}} = \Delta E_{\text{system}} \qquad \text{(kJ)}$$

$$\Delta E_{\text{system}} = \Delta U_{\text{system}}$$

stationary simple compressible systems

$$\underbrace{\dot{E}_{\text{in}} - \dot{E}_{\text{out}}}_{\substack{\text{Rate of net energy transfer}\\ \text{by heat, work, and mass}}} = \underbrace{dE_{\text{system}}/dt}_{\substack{\text{Rate of change in internal}\\ \text{kinetic, potential, etc., energies}}} \qquad \text{(W)}$$

The energy balance for any system undergoing any process in the rate form

$$\dot{E}_{\text{in}} - \dot{E}_{\text{out}} = dE_{\text{system}}/dt \qquad \text{(kW)}$$

$$\dot{E}_{\text{in}} = \dot{E}_{\text{out}} \qquad \text{(kW)}$$ Steady- flow process

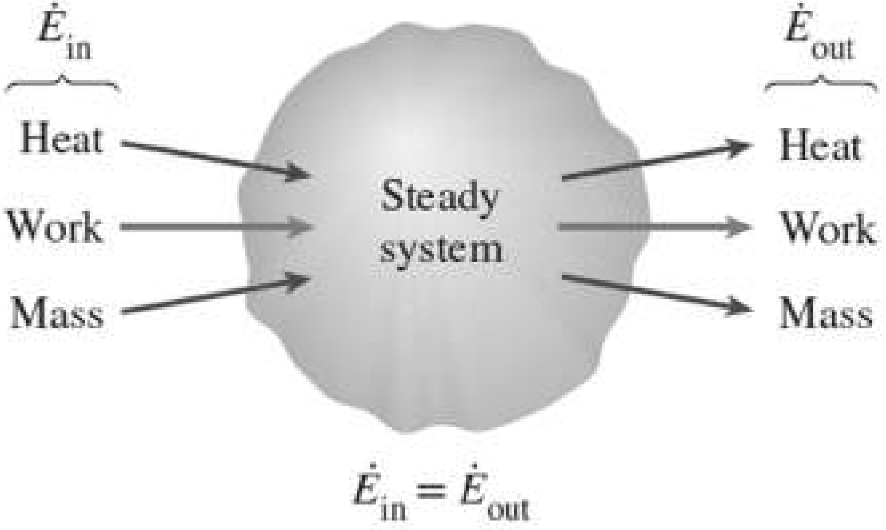


Figure 2-6
In steady operation, the rate of energy transfer to a system is equal to the rate of energy transfer from the system.

Energy Balance for Closed Systems

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 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 don't involve any changes in their velocity or elevation during a process.

Stationary closed system:

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

Stationary closed system, no work:

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

Energy Balance for Steady-Flow Systems

Control volume: A large number of engineering devices such as water heaters and car radiators involve mass flow in and out of a system.

Most control volumes are analyzed under steady operating conditions.

Steady: No change with time at a specified location.

Mass flow rate: The amount of mass flowing through a cross section of a flow device per unit time.

Volume flow rate: The volume of a fluid flowing through a pipe or duct per unit time.

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

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

$$\dot{Q} = \dot{m}\Delta h = \dot{m} c_p \Delta T \qquad \text{(kW)}$$

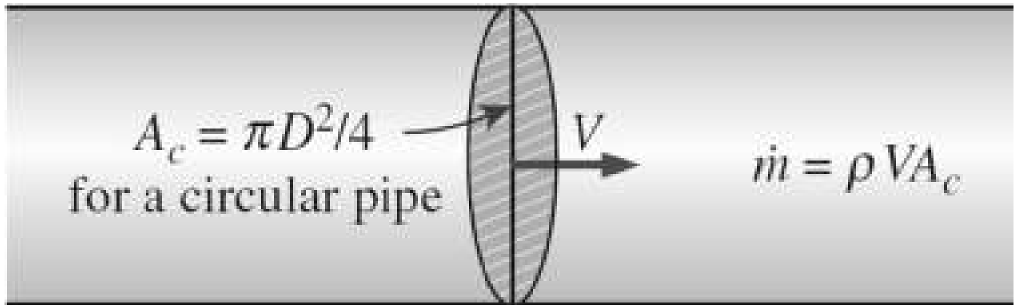


Figure 2-8
The mass flow rate of a fluid at a cross section is equal to the product of the fluid density, average fluid velocity, and the cross-sectional area.

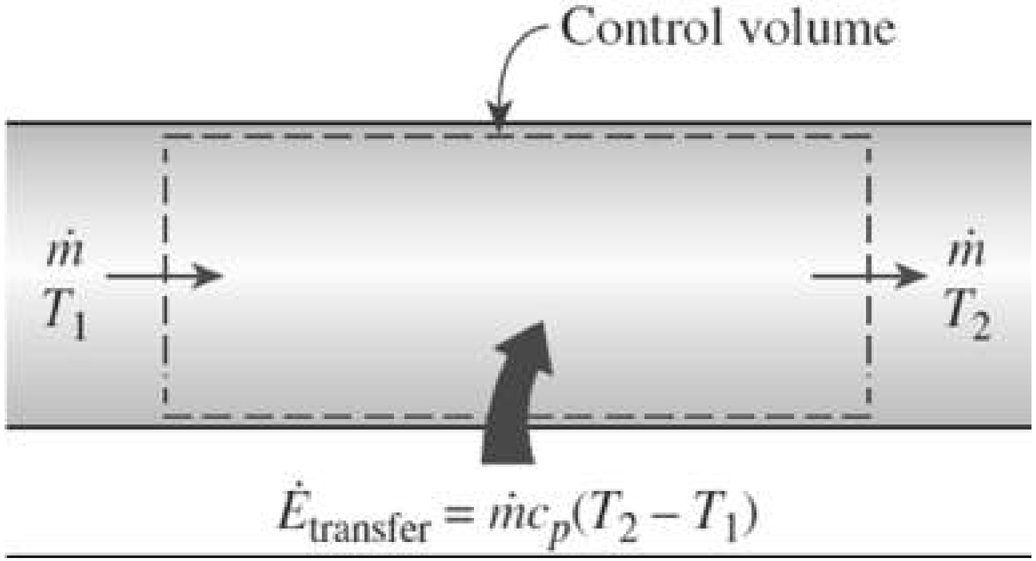


Figure 2-9
Under steady conditions, the net rate of energy transfer to a fluid in a control volume is equal to the rate of increase in the energy of the fluid stream flowing through the control volume.

Saturation Temperature and Saturation Pressure

The temperature at which water starts boiling depends on the pressure; therefore, if the pressure is fixed, so is the boiling temperature.

Water boils at 100℃ at 1 atm pressure.

Saturation temperature T_{sat}: The temperature at which a pure substance changes phase at a given pressure.

Saturation pressure P_{sat}: The pressure at which a pure substance changes phase at a given temperature.

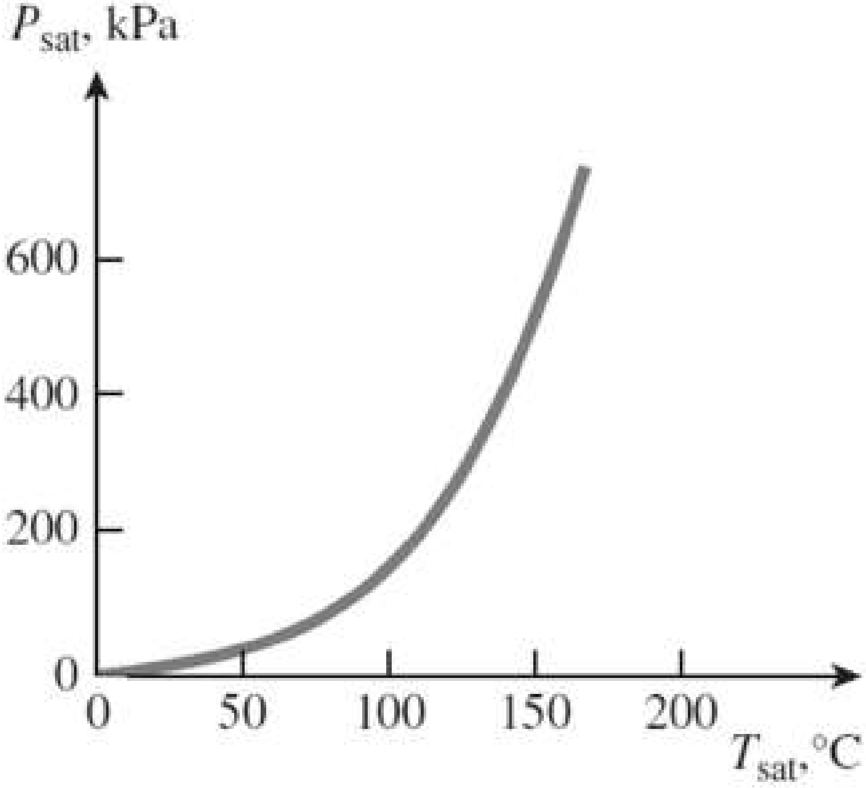


Figure 2-11
The liquid-vapor saturation curve of a pure substance (numerical values are for water).

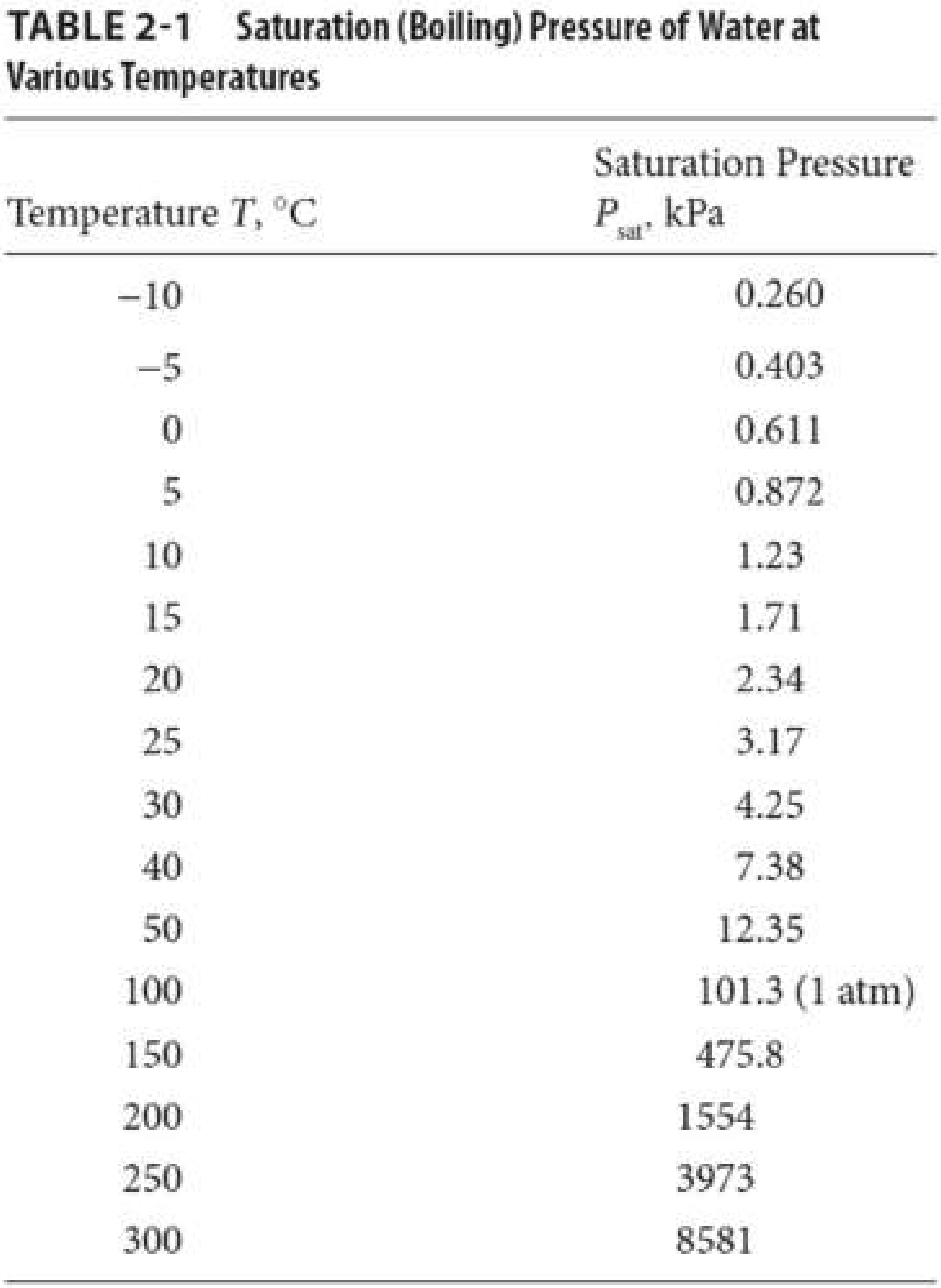


TABLE 2-1 **Saturation (Boiling) Pressure of Water at Various Temperatures**

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

Latent heat: The amount of energy absorbed or released during a phase-change process.

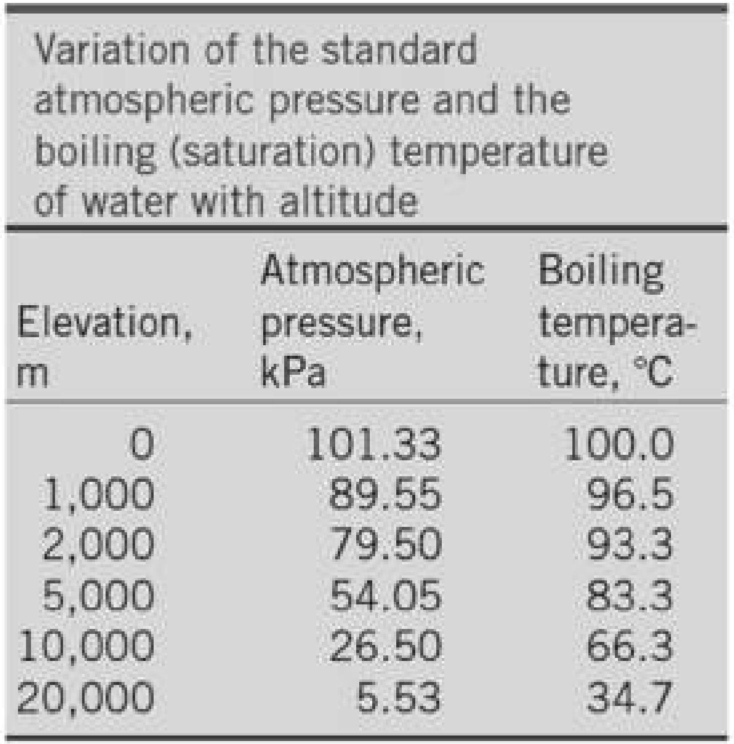
Latent heat of fusion: The amount of energy absorbed during melting. It is equivalent to the amount of energy released during freezing.

Latent heat of vaporization: The amount of energy absorbed during vaporization and it 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 334 kJ/kg and the latent heat of vaporization is 2257 kJ/kg.

The atmospheric pressure, and thus the boiling temperature of water, decreases with elevation.



Variation of the standard atmospheric pressure and the boiling (saturation) temperature of water with altitude

Elevation, m	Atmospheric pressure, kPa	Boiling temperature, °C
0	101.33	100.0
1,000	89.55	96.5
2,000	79.50	93.3
5,000	54.05	83.3
10,000	26.50	66.3
20,000	5.53	34.7

2-3 HEAT TRANSFER

Heat: The form of energy that can be transferred from one system to another as a result of temperature difference.

Thermodynamics: A thermodynamic analysis is concerned with the *amount* of heat transfer as a system undergoes a process from one equilibrium state to another.

Heat transfer: The science that deals with the determination of the *rates* of such energy transfers.

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 transfer modes:

- conduction
- convection
- radiation

All modes of heat transfer require the existence of a temperature difference.

Conduction Heat Transfer

Conduction: The transfer of energy from the more energetic particles of a substance to the adjacent less energetic ones as a result of interactions between the particles.

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.*

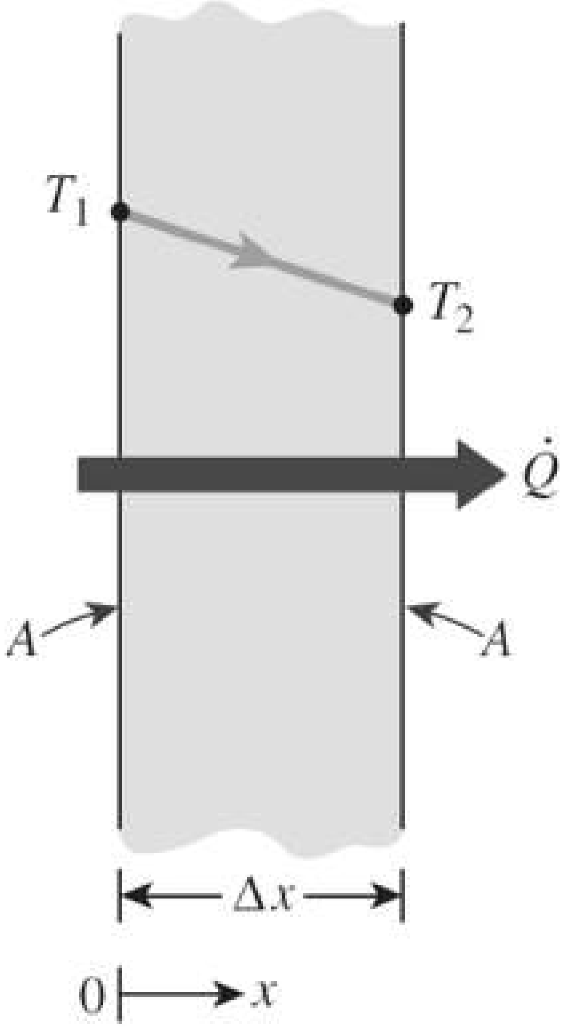


Figure 2-12
Heat conduction through a large plane wall.

$$\text{Rate of heat conduction} \propto \frac{\text{(Area)(Temperature difference)}}{\text{Thickness}}$$

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

When $x \rightarrow 0$

$$\dot{Q}_{\text{cond}} = -kA\frac{dT}{dx}$$

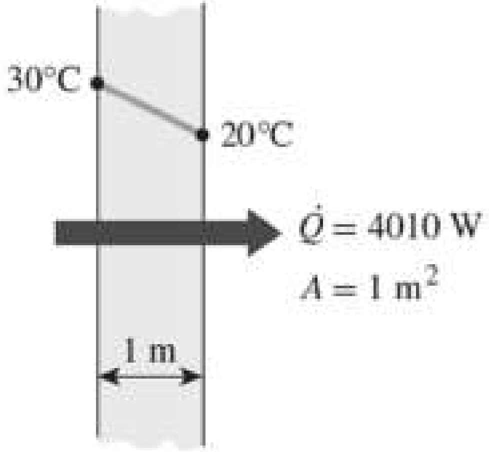
Fourier's law of heat conduction

Thermal conductivity *k*: A measure of the ability of a material to conduct heat.

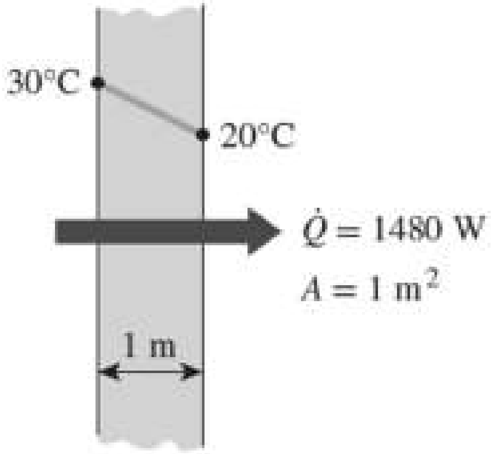
Temperature gradient *dT/dx*: The slope of the temperature curve on a *T*-*x* diagram.

Heat is conducted in the direction of decreasing temperature, and the temperature gradient becomes negative when temperature decreases with increasing *x.*

The *negative sign* in the equation ensures that heat transfer in the positive *x* direction is a positive quantity.



(*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.

Thermal Conductivity

Thermal conductivity: The rate of heat transfer through a unit thickness of the material per unit area per unit temperature difference.

The thermal conductivity of a material is a measure of the ability of the material to conduct heat.

A high value for thermal conductivity indicates that the material is a good heat conductor, and a low value indicates that the material is a poor heat conductor or *insulator.*

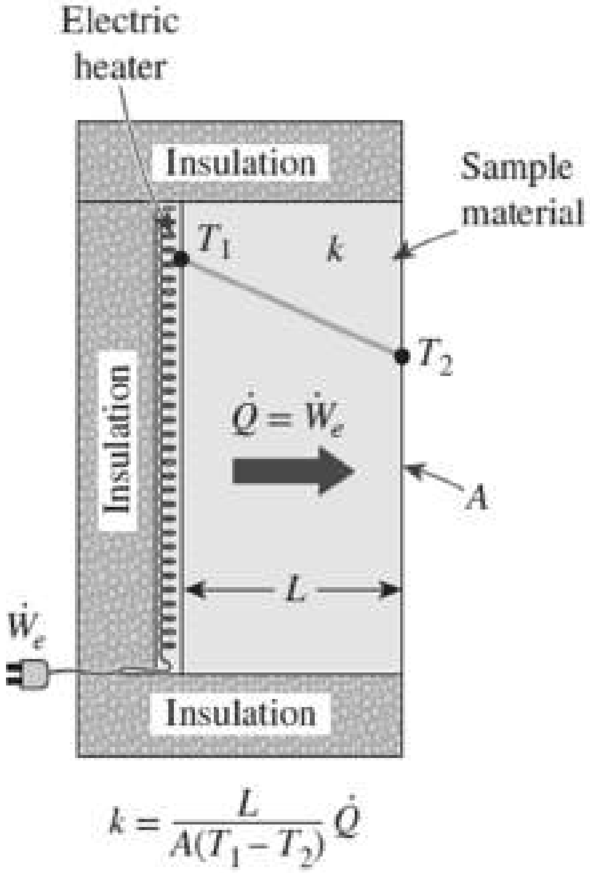


Figure 2-14
A simple experimental setup to determine the thermal conductivity of a material.

TABLE 2-2 Thermal Conductivities of Some Materials at Room Temperature

Material	Thermal Conductivity k, W/m·K*
Diamond	2300
Silver	429
Copper	401
Gold	317
Aluminum	237
Iron	80.2
Mercury (*l*)	8.54
Glass	0.78
Brick	0.72
Water (*l*)	0.607
Human skin	0.37
Wood (oak)	0.17
Helium (*g*)	0.152
Soft rubber	0.13
Glass fiber	0.043
Air (*g*)	0.026
Urethane, rigid foam	0.026

*Multiply by 0.5778 to convert to Btu/h·ft·°F.

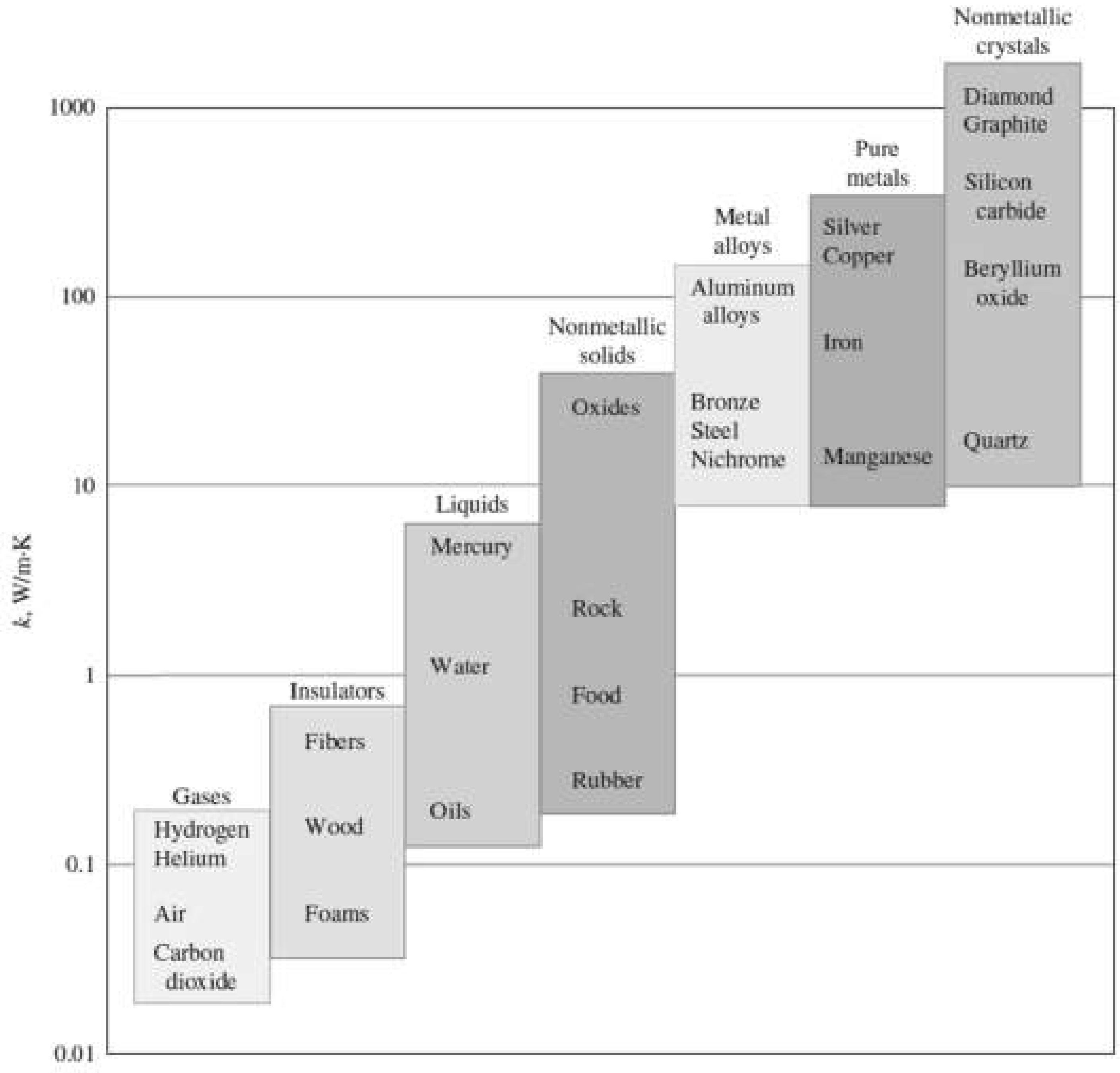
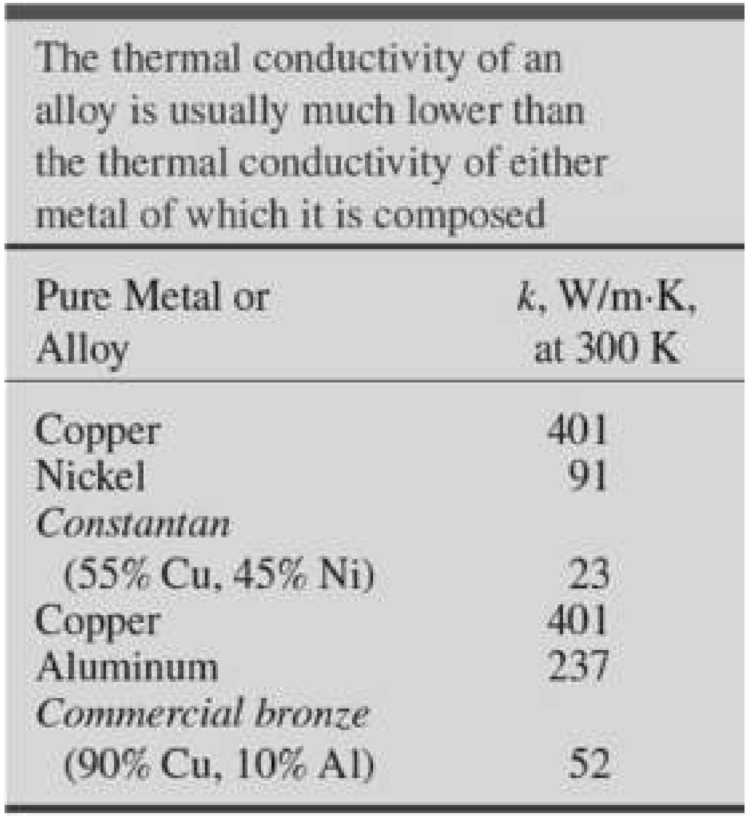


Figure 2-15 The range of thermal conductivity of various materials at room temperature.

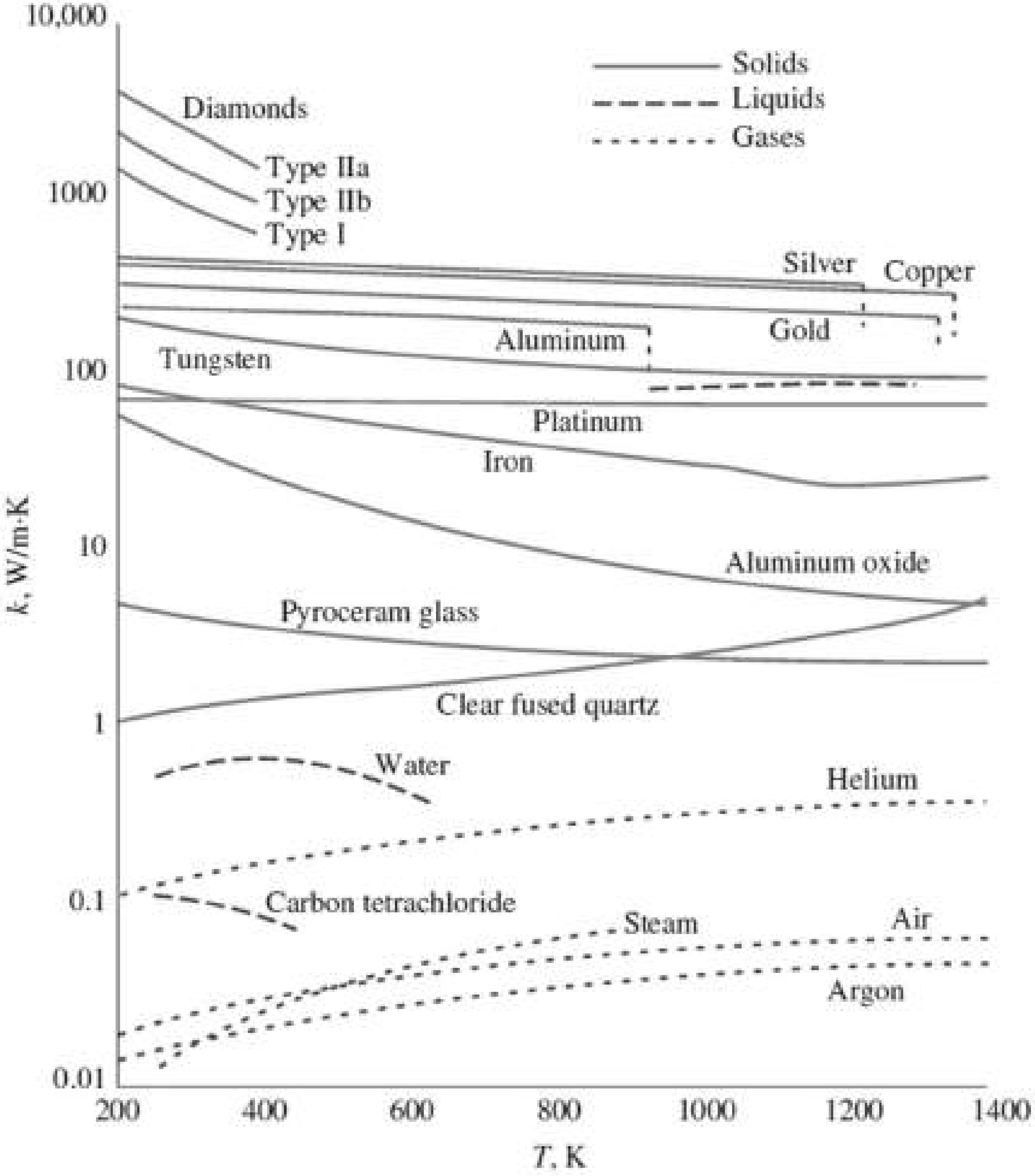
The thermal conductivities of gases such as air vary by a factor of 10^4 from those of pure metals such as copper.

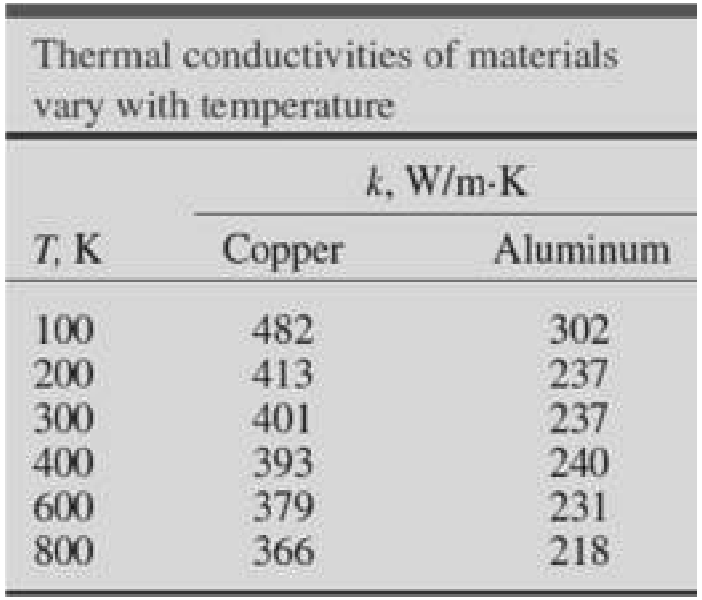
Pure crystals and metals have the highest thermal conductivities, and gases and insulating materials the lowest.



The thermal conductivity of an alloy is usually much lower than the thermal conductivity of either metal of which it is composed

Pure Metal or Alloy	k, W/m·K, at 300 K
Copper	401
Nickel	91
Constantan (55% Cu, 45% Ni)	23
Copper	401
Aluminum	237
Commercial bronze (90% Cu, 10% Al)	52





Thermal conductivities of materials vary with temperature

	k, W/m·K	
T, K	Copper	Aluminum
100	482	302
200	413	237
300	401	237
400	393	240
600	379	231
800	366	218

Figure 2-16
The variation of the thermal conductivity of various solids, liquids, and gases with temperature.

Convection Heat Transfer

Convection: The mode of energy transfer between a solid surface and the adjacent liquid or gas that is in motion, and it involves the combined effects of *conduction* and *fluid motion.*

The faster the fluid motion, the greater the convection heat transfer.

In the absence of any bulk fluid motion, heat transfer between a solid surface and the adjacent fluid is by pure conduction.

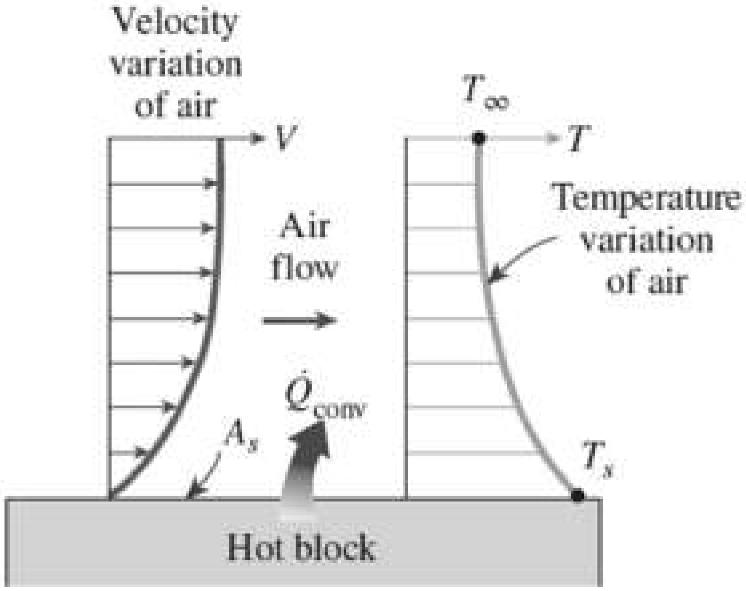


Figure 2-18
Heat transfer from a hot surface to air by convection.

Forced convection: If the fluid is forced to flow over the surface by external means such as a fan, pump, or the wind.

Natural (or free) convection: If the fluid motion is caused by buoyancy forces that are induced by density differences due to the variation of temperature in the fluid.

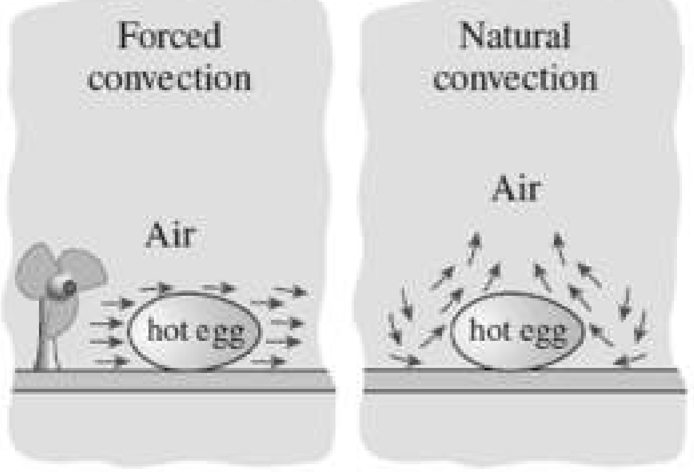


Figure 2-19
The cooling of a boiled egg by forced and natural convection.

Heat transfer processes that involve *change of phase* of a fluid are also considered to be convection because of the fluid motion induced during the process, such as the rise of the vapor bubbles during boiling or the fall of the liquid droplets during condensation.

$$\dot{Q}_{\text{conv}} = hA_s(T_s - T_\infty) \qquad (\text{kW})$$ Newton’s law of cooling

h	convection heat transfer coefficient, W/m^2 · °C
$\boldsymbol{A_s}$	the surface area through which convection heat transfer takes place
$\boldsymbol{T_s}$	the surface temperature
$\boldsymbol{T_\infty}$	the temperature of the fluid sufficiently far from the surface.

Convection heat transfer coefficient *h*:

Not a property of the fluid. It is an experimentally determined parameter.

***h* depends on:**

- the surface geometry
- the nature of fluid motion
- the properties of the fluid
- the bulk fluid velocity

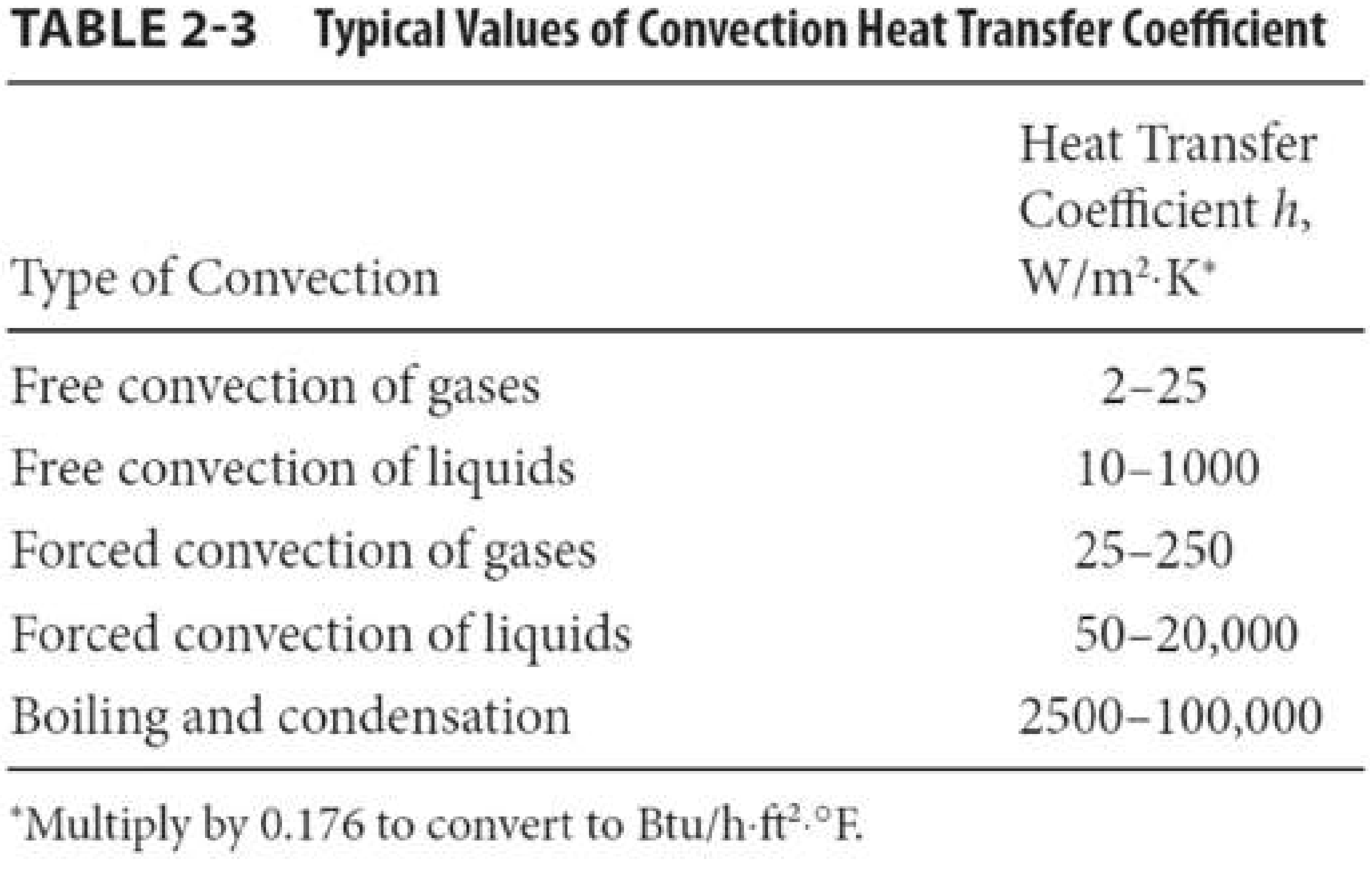


TABLE 2-3 Typical Values of Convection Heat Transfer Coefficient

Type of Convection	Heat Transfer Coefficient *h*, W/m²·K*
Free convection of gases	2–25
Free convection of liquids	10–1000
Forced convection of gases	25–250
Forced convection of liquids	50–20,000
Boiling and condensation	2500–100,000

*Multiply by 0.176 to convert to Btu/h·ft²·°F.

Radiation Heat Transfer

Radiation: The energy emitted by matter in the form of *electromagnetic waves* (or *photons*) as a result of the changes in the electronic configurations of the atoms or molecules.

Unlike conduction and convection, the transfer of heat by radiation does not require the presence of an *intervening medium.*

In fact, heat transfer by radiation is fastest (at the speed of light) and it suffers no attenuation in a vacuum.

This is how the energy of the sun reaches the earth.

Thermal radiation: In heat transfer studies we are interested in *thermal radiation,* which is the form of radiation emitted by bodies because of their temperature.

All bodies at a temperature above absolute zero emit thermal radiation.

$$\dot{Q}_{\text{emit,max}} = \sigma A_s T_s^4 \qquad \text{(kW)}$$ Stefan–Boltzmann law

$\sigma = 5.670 \times 10^{-8}\ \text{W/m}^2 \cdot \text{K}^4$ Stefan–Boltzmann constant

Blackbody: The idealized surface that emits radiation at the maximum rate.

Radiation emitted by real surfaces

$$\dot{Q}_{\text{emit}} = \varepsilon \sigma A_s T_s^4 \qquad \text{(kW)}$$

Emissivity ε: A measure of how closely a surface approximates a blackbody for which $\varepsilon = 1$ of the surface. $0 \le \varepsilon \le 1$

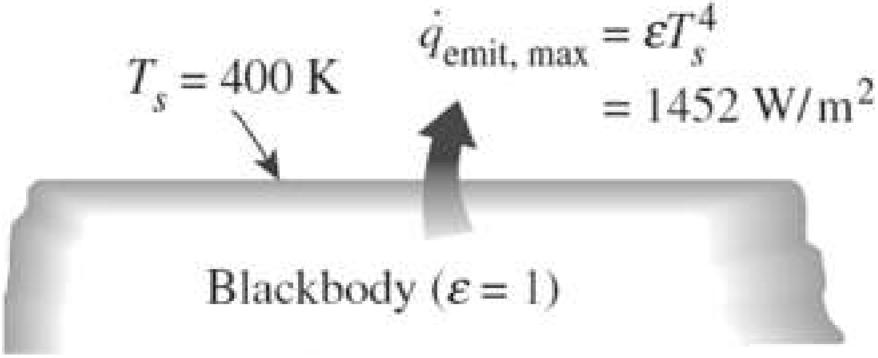


Figure 2-20
Blackbody radiation represents the maximum amount of radiation that can be emitted from a surface at a specified temperature.

TABLE 2-4 Emissivities of Some Materials at 300 K

Material	Emissivity ε
Aluminum foil	0.07
Anodized aluminum	0.82
Polished copper	0.03
Polished gold	0.03
Polished silver	0.02
Polished stainless steel	0.17
Black paint	0.98
White paint	0.90
White paper	0.92–0.97
Asphalt pavement	0.85–0.93
Red brick	0.93–0.96
Human skin	0.95
Wood	0.82–0.92
Soil	0.93–0.96
Water	0.96
Vegetation	0.92–0.96

Absorptivity α: The fraction of the radiation energy incident on a surface that is absorbed by the surface. $0 \leq \alpha \leq 1$

A blackbody absorbs the entire radiation incident on it ($\alpha = 1$).

Kirchhoff's law: The emissivity and the absorptivity of a surface at a given temperature and wavelength are equal.

$$\dot{Q}_{\text{absorbed}} = \alpha \dot{Q}_{\text{incident}} \qquad \text{(kW)}$$

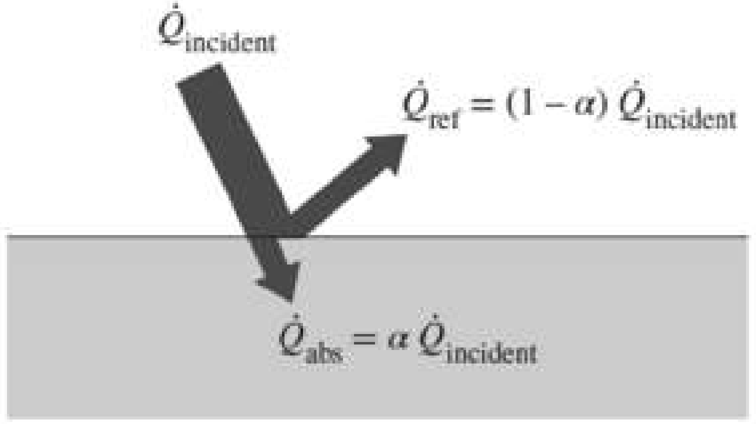


Figure 2-21
The absorption of radiation incident on an opaque surface of absorptivity.

Net radiation heat transfer: The difference between the rates of radiation emitted by the surface and the radiation absorbed.

The determination of the net rate of heat transfer by radiation between two surfaces is a complicated matter since it depends on

- the properties of the surfaces

- their orientation relative to each other

- the interaction of the medium between the surfaces with radiation

Radiation is usually significant relative to conduction or natural convection, but negligible relative to forced convection.

When a surface is *completely enclosed* by a much larger (or black) surface at temperature T_{surr} separated by a gas (such as air) that does not intervene with radiation, the net rate of radiation heat transfer between these two surfaces is given by

$$\dot{Q}_{\text{rad}} = \varepsilon \sigma A_s (T_s^4 - T_{\text{surr}}^4) \qquad \text{(kW)}$$

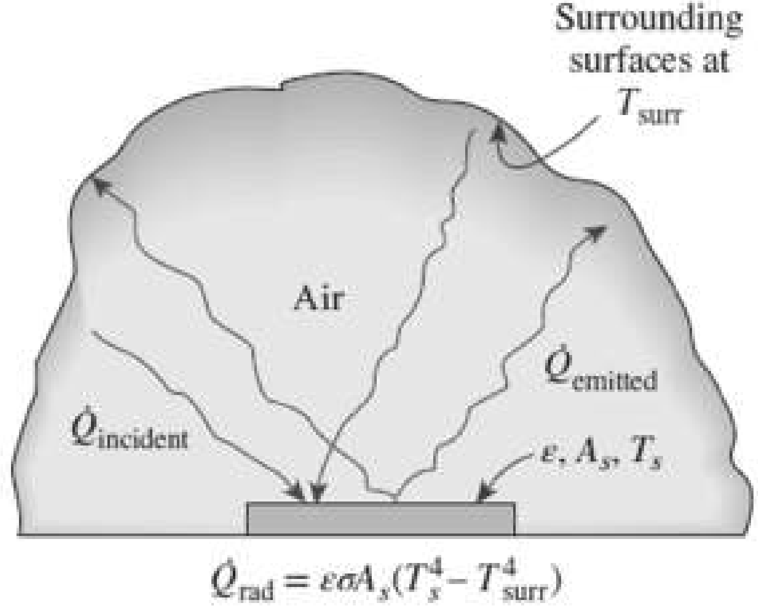


Figure 2-22
Radiation heat transfer between a surface and the surfaces surrounding it.

When radiation and convection occur simultaneously between a surface and a gas:

$$\dot{Q}_{\text{total}} = h_{\text{combined}} A_s (T_s - T_\infty) \qquad \text{(W)}$$

Combined heat transfer coefficient *h*$_{\text{combined}}$

Includes the effects of both convection and radiation

$$\dot{Q}_{\text{total}} = \dot{Q}_{\text{conv}} + \dot{Q}_{\text{rad}} = h_{\text{conv}} A_s (T_s - T_\infty) + \varepsilon \sigma A_s (T_s^4 - T_{\text{surr}}^4)$$

$$\dot{Q}_{\text{total}} = h_{\text{combined}} A_s (T_s - T_\infty)$$

$$h_{\text{combined}} = h_{\text{conv}} + h_{\text{rad}} = h_{\text{conv}} + \varepsilon \sigma (T_s + T_{\text{surr}})(T_s^2 + T_{\text{surr}}^2)$$

2-4 FLUID MECHANICS

Fluid mechanics: The science that deals with the behavior of fluids at rest (*fluid statics*) or in motion (*fluid dynamics*), and the interaction of fluids with solids or other fluids at the boundaries.

Fluid: A substance in the liquid or gas phase.

A solid can resist an applied shear stress by deforming, whereas a fluid deforms continuously under the influence of shear stress, no matter how small.

Fluid mechanics deals with liquids and gases in motion or at rest.

Categories of Fluid mechanics:

Hydrodynamics: The study of the motion of fluids that can be approximated as incompressible (such as liquids, especially water, and gases at low speeds)

Hydraulics: A subcategory of hydrodynamics, which deals with liquid flows in pipes and open channels.

Gas dynamics: It deals with the flow of fluids that undergo significant density changes, such as the flow of gases through nozzles at high speeds.

Aerodynamics: It deals with the flow of gases (especially air) over bodies such as aircraft, rockets, and automobiles at high or low speeds.

Meteorology, Oceanography, Hydrology: They deal with naturally occurring flows.

Solid can resist an applied shear stress by deforming, whereas a fluid deforms continuously under the influence of a shear stress, no matter how small.

In solids, stress is proportional to strain, but in fluids, stress is proportional to strain rate.

When a constant shear force is applied, a solid eventually stops deforming at some fixed strain angle, whereas a fluid never stops deforming and approaches a constant rate of strain.

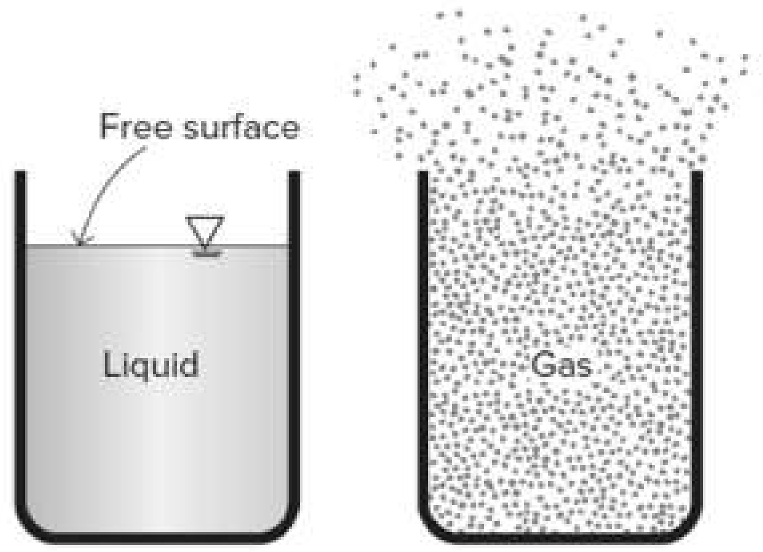


Figure 2-24
Unlike a liquid, a gas does not form a free surface, and it expands to fill the entire available space.

Viscosity

Viscosity: A property that represents the internal resistance of a fluid to motion or the "fluidity".

Drag force: The force a flowing fluid exerts on a body in the flow direction. The magnitude of this force depends, in part, on viscosity.

The viscosity of a fluid is a measure of its "*resistance to deformation*."

Viscosity is due to the internal frictional force that develops between different layers of fluids as they are forced to move relative to each other.

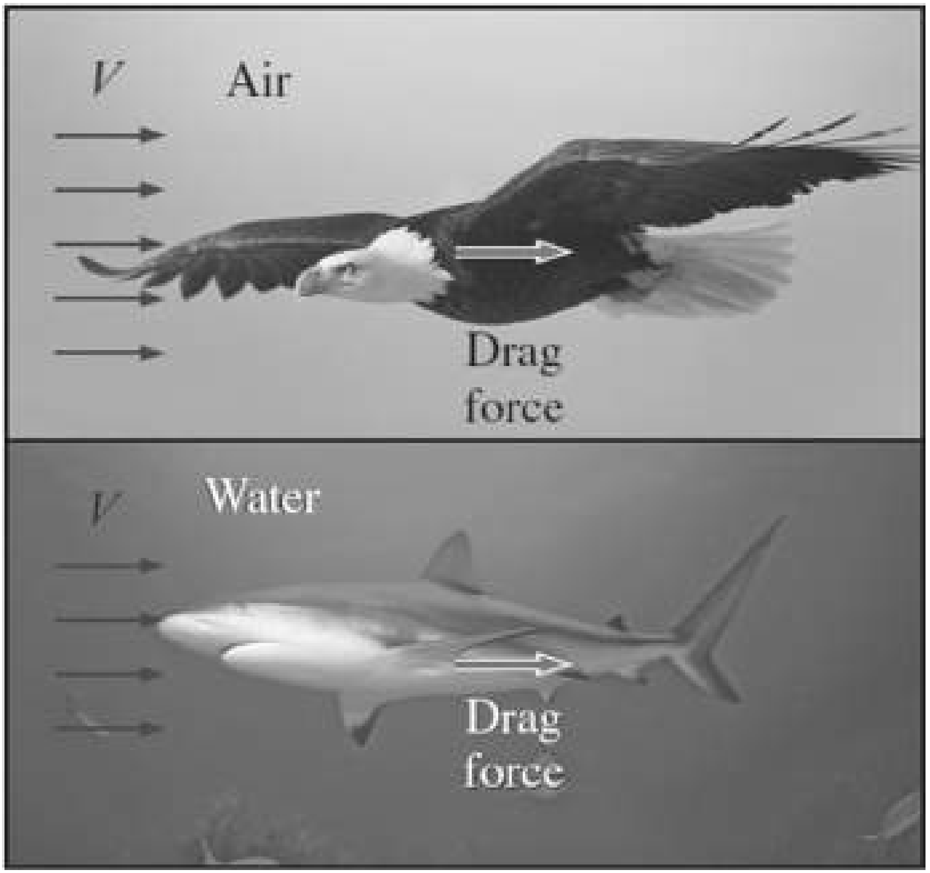


Figure 2-25
A fluid moving relative to a body exerts a drag force on the body, partly because of friction caused by viscosity.

Newtonian fluids: Fluids for which the rate of deformation is proportional to the shear stress

$$\tau \propto \frac{d(d\beta)}{dt} \qquad \text{or} \qquad \tau \propto \frac{du}{dy}$$

$$\tau = \mu \frac{du}{dy} \qquad (\mathrm{N/m^2})$$

Shear stress

$$F = \tau A = \mu A \frac{du}{dy} \qquad (\mathrm{N})$$

Shear force

μ **coefficient of viscosity**

Dynamic (absolute) viscosity

kg/m·s or N·s/m^2 or Pa·s

1 poise = 0.1 Pa·s

Kinematic viscosity

$$\nu = \mu/\rho$$

m^2/s or stoke

1 stoke = 1 cm^2/s

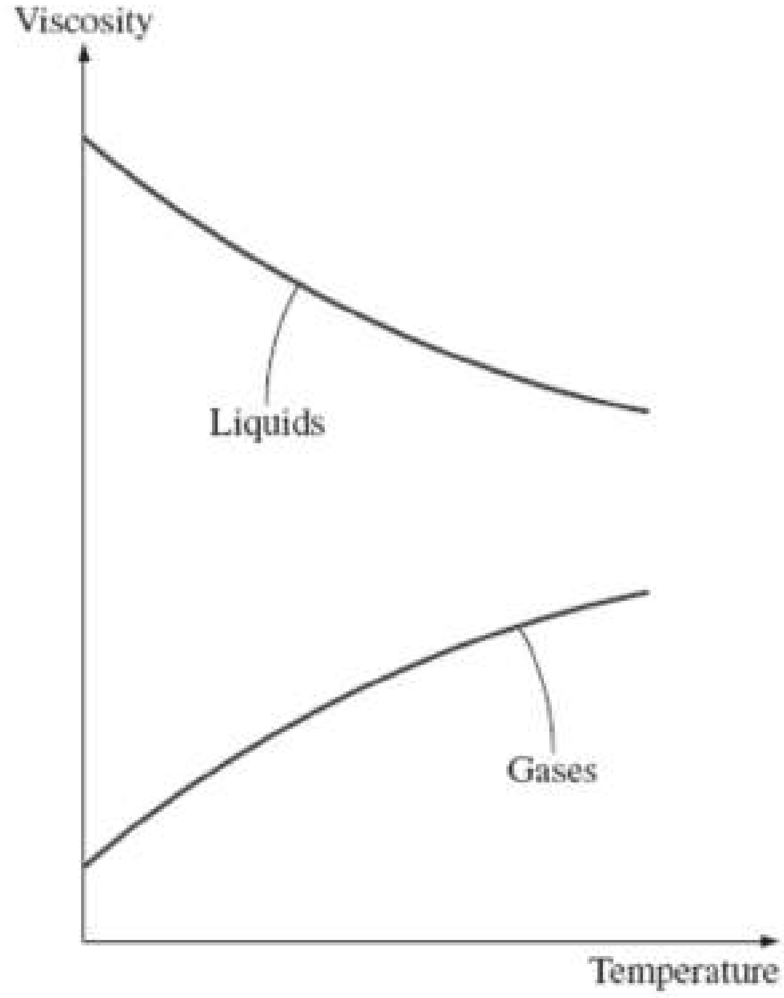


Figure 2-26
The viscosity of liquids decreases and the viscosity of gases increases with temperature.

The viscosity of a fluid is directly related to the pumping power needed to transport a fluid in a pipe or to move a body through a fluid.

Viscosity is caused by the cohesive forces between the molecules in liquids and by the molecular collisions in gases, and it varies greatly with temperature.

In a liquid, the molecules possess more energy at higher temperatures, and they can oppose the large cohesive intermolecular forces more strongly. As a result, the energized liquid molecules can move more freely.

In a gas, the intermolecular forces are negligible, and the gas molecules at high temperatures move randomly at higher velocities. This results in more molecular collisions per unit volume per unit time and therefore in greater resistance to flow.

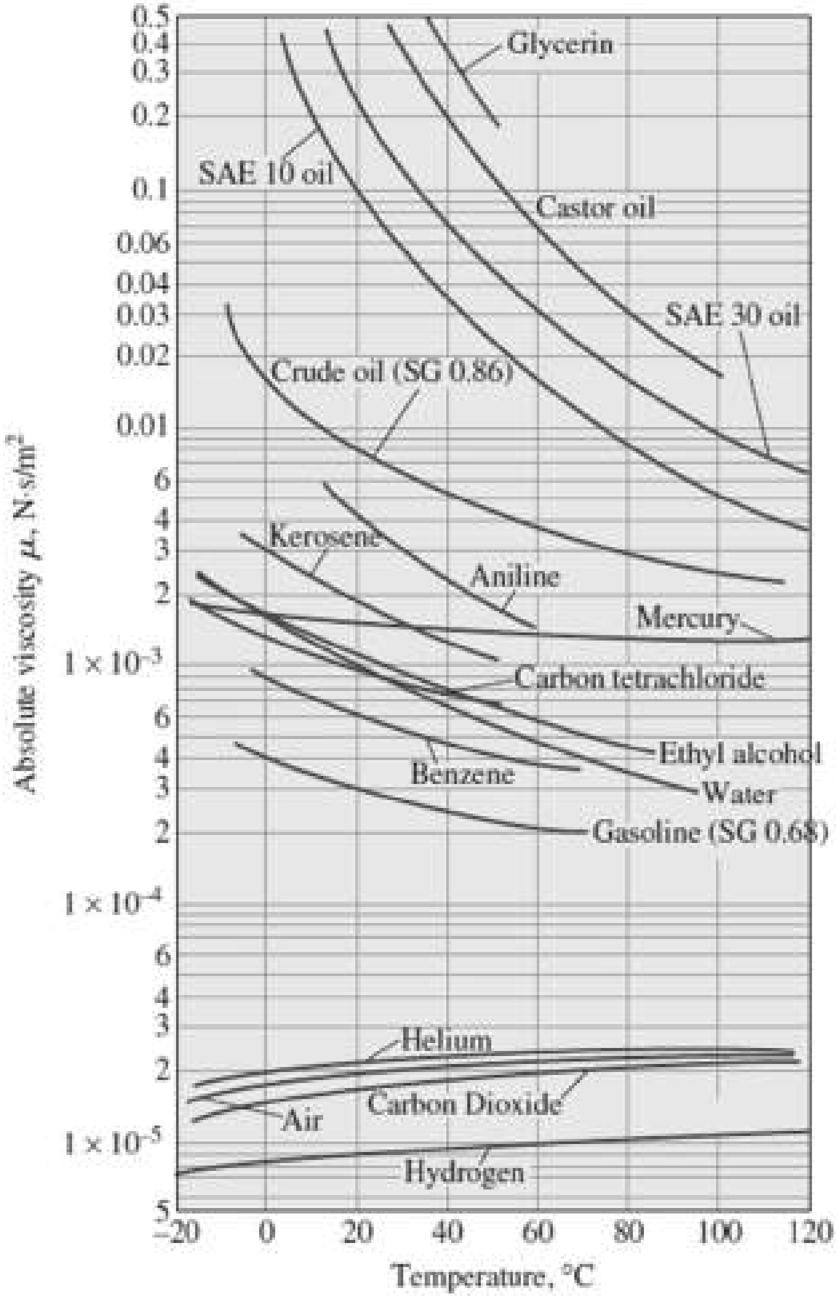


Figure 2-27

The variation of dynamic (absolute) viscosity of common fluids with temperature at 1 atm

(1 N·s/m^2 = 1 kg/m·s = 0.020886 lbf·s/ft^2)

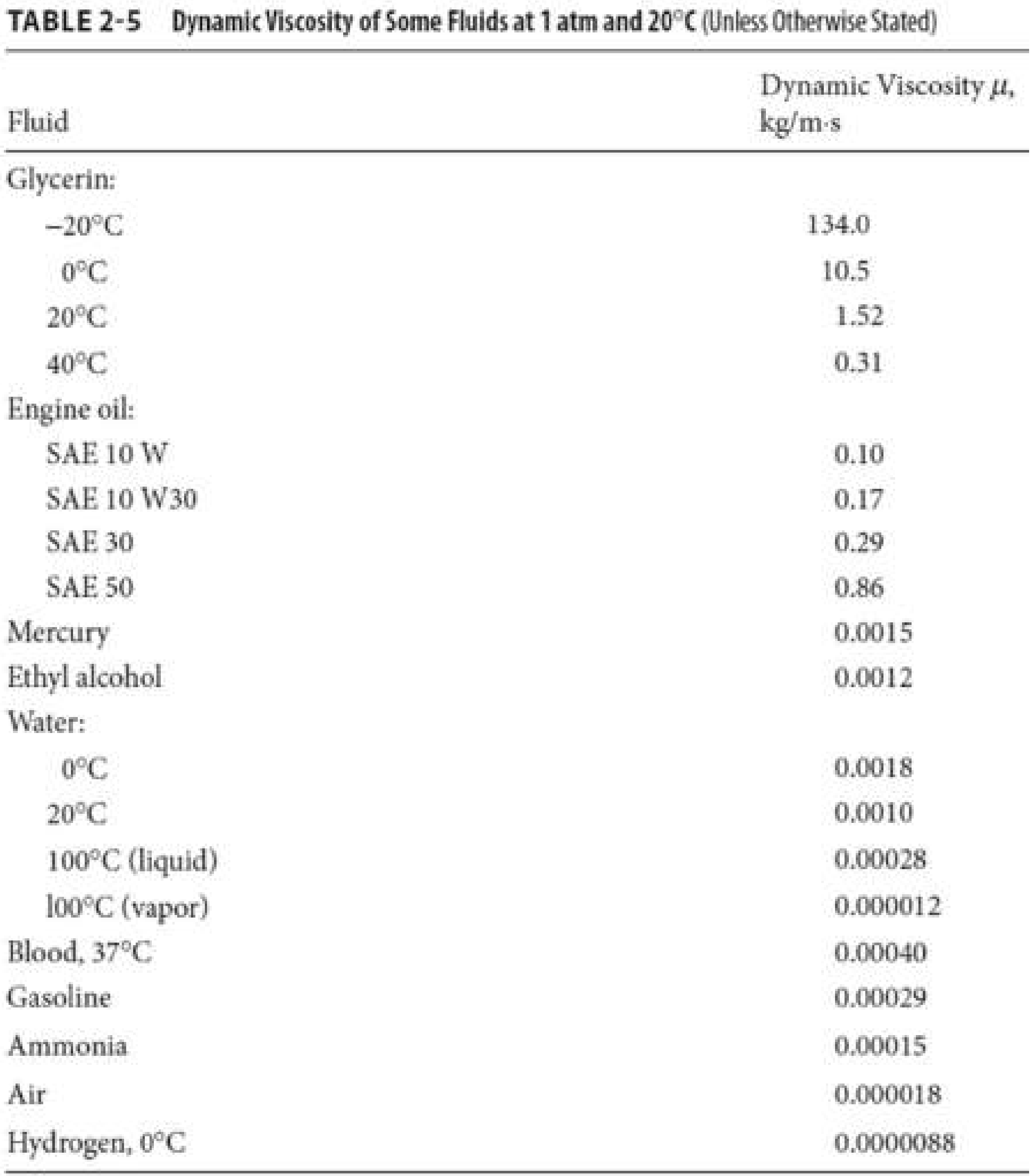


TABLE 2-5 **Dynamic Viscosity of Some Fluids at 1 atm and 20°C** (Unless Otherwise Stated)

Fluid	Dynamic Viscosity μ, kg/m·s
Glycerin:	
−20°C	134.0
0°C	10.5
20°C	1.52
40°C	0.31
Engine oil:	
SAE 10 W	0.10
SAE 10 W30	0.17
SAE 30	0.29
SAE 50	0.86
Mercury	0.0015
Ethyl alcohol	0.0012
Water:	
0°C	0.0018
20°C	0.0010
100°C (liquid)	0.00028
100°C (vapor)	0.000012
Blood, 37°C	0.00040
Gasoline	0.00029
Ammonia	0.00015
Air	0.000018
Hydrogen, 0°C	0.0000088

Pressure Drop in Fluid Flow in Pipes

$$\Delta P_L = f\frac{L}{D}\frac{\rho V^2}{2}$$

$$h_L = \frac{\Delta P_L}{\rho g} = f\frac{L}{D}\frac{V^2}{2g}$$

The pressure loss and head loss for all types of internal flows (laminar or turbulent, in circular or noncircular pipes, smooth or rough surfaces)

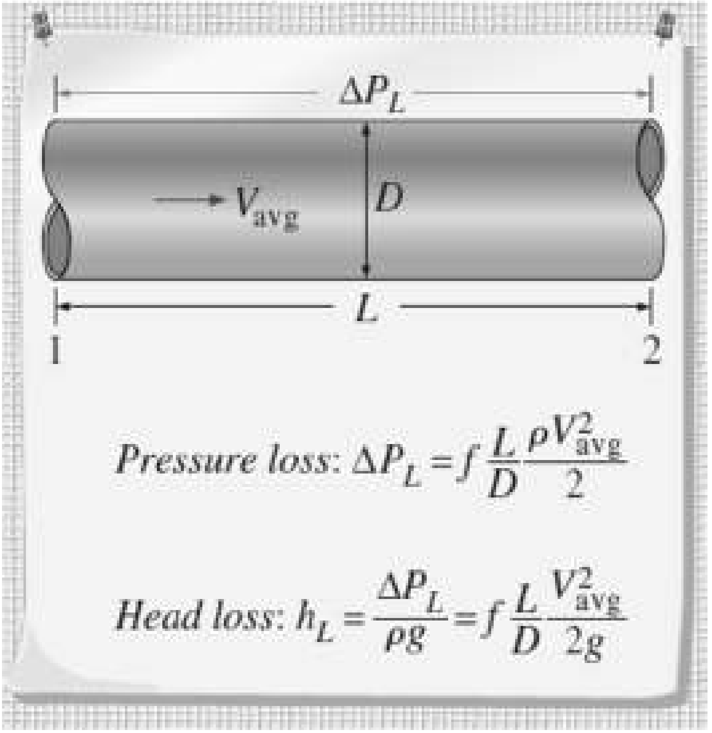


Figure 2-28
The relation for pressure loss (and head loss) is one of the most general relations in fluid mechanics, and it is valid for laminar or turbulent flows, circular or noncircular pipes, and pipes with smooth or rough surfaces.

$$\Delta P = \frac{32\mu L V_{avg}}{D^2}$$

$$\dot{V} = V_{avg} A_c = \frac{\Delta P \pi D^4}{128\mu L}$$

For a specified flow rate, the pressure drop and thus the required pumping power is proportional to the length of the pipe and the viscosity of the fluid, but it is inversely proportional to the fourth power of the diameter of the pipe.

$$\dot{W}_{pump,L} = \dot{V}\Delta P_L = \dot{V}\rho g h_L = \dot{m} g h_L$$

Pumping power to overcome the pressure loss

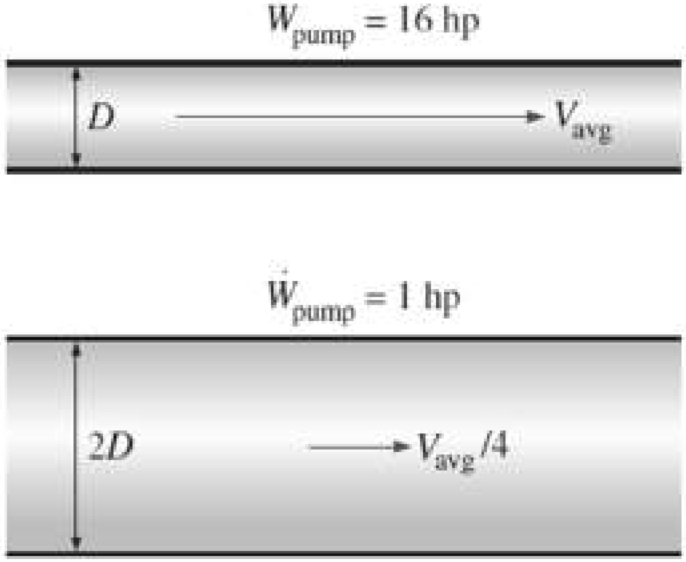


Figure 2-29
The pumping power requirement for a laminar flow piping system can be reduced by a factor of 16 by doubling the pipe diameter.

$$\frac{1}{\sqrt{f}} = -2.0\log\left(\frac{\varepsilon / D}{3.7} + \frac{2.51}{\mathrm{Re}\sqrt{f}}\right)$$

Colebrook equation (for smooth and rough pipes)

The friction factor in fully developed turbulent pipe flow depends on the Reynolds number and the relative roughness ε / D.

The plot of this formula is known as the *Moody chart.*

$$f = 8\left[\left(\frac{8}{\mathrm{Re}}\right)^{12} + (A+B)^{-1.5}\right]^{\frac{1}{12}}$$

Churchill Equation

$$A = \left\{-2.457 \cdot \ln\left[\left(\frac{7}{\mathrm{Re}}\right)^{0.9} + 0.27\frac{\varepsilon}{D}\right]\right\}^{16}$$

It is explicit and valid over the entire range of Reynolds numbers and roughnesses.

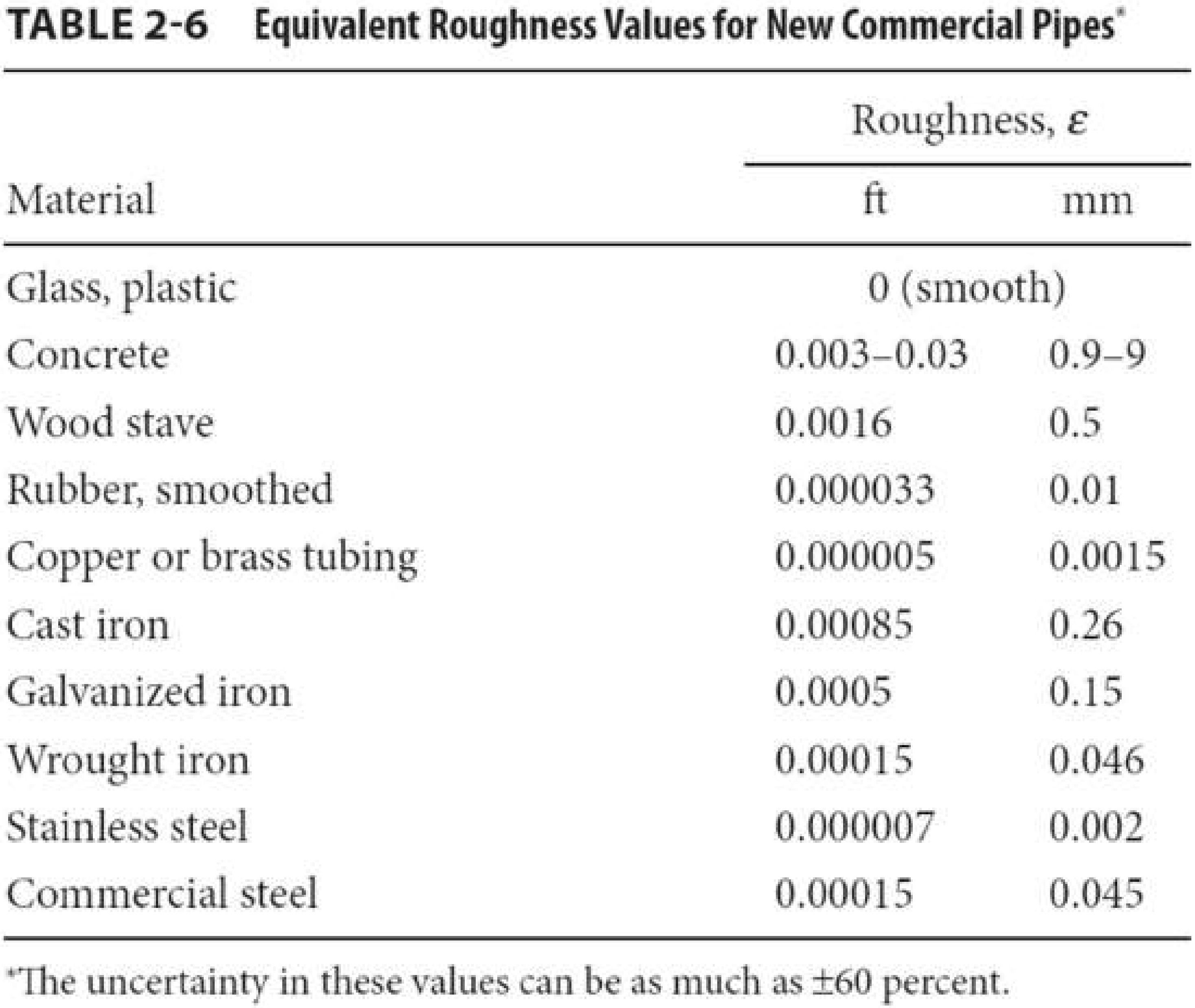
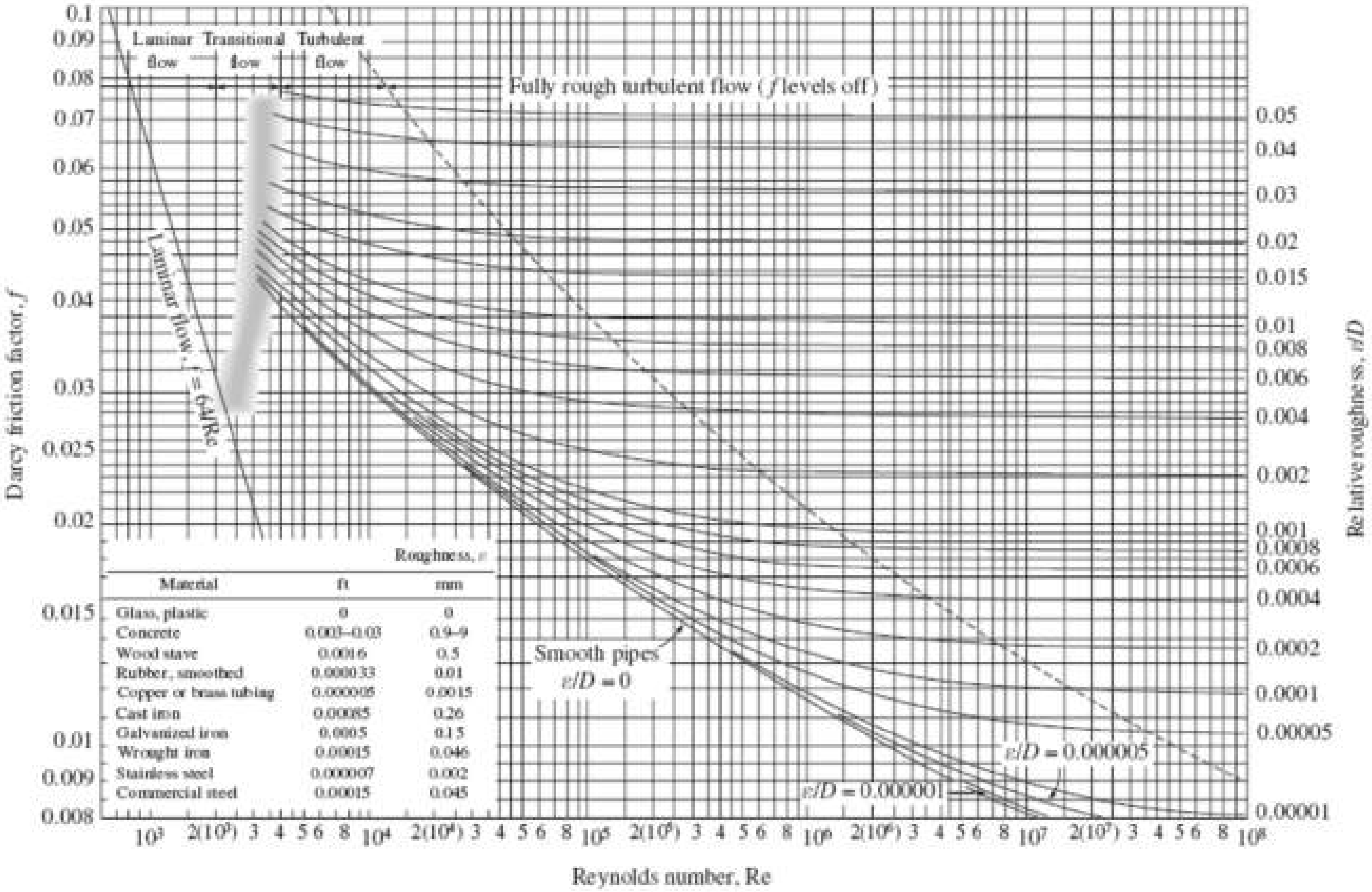


TABLE 2-6 Equivalent Roughness Values for New Commercial Pipes*

Material	Roughness, ε	
	ft	mm
Glass, plastic	0 (smooth)	
Concrete	0.003–0.03	0.9–9
Wood stave	0.0016	0.5
Rubber, smoothed	0.000033	0.01
Copper or brass tubing	0.000005	0.0015
Cast iron	0.00085	0.26
Galvanized iron	0.0005	0.15
Wrought iron	0.00015	0.046
Stainless steel	0.000007	0.002
Commercial steel	0.00015	0.045

*The uncertainty in these values can be as much as ±60 percent.



	Roughness, ε	
Material	ft	mm
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Commercial steel	0.00015	0.045

The Moody Chart

2-5 THERMOCHEMISTRY

Thermochemistry: Thermodynamic study of chemical reactions, particularly combustion reaction.

Fuels and Combustion

Fuel: Any material that can be burned to release thermal energy.

Hydrocarbon fuels: Most familiar fuels consist primarily of hydrogen and carbon. They are called *hydrocarbon fuels* and are denoted by the general formula C_nH_m.

Hydrocarbon fuels exist in all phases. Some examples are

- coal
- gasoline
- natural gas

The oxidizer most often used in combustion processes is air. Why?

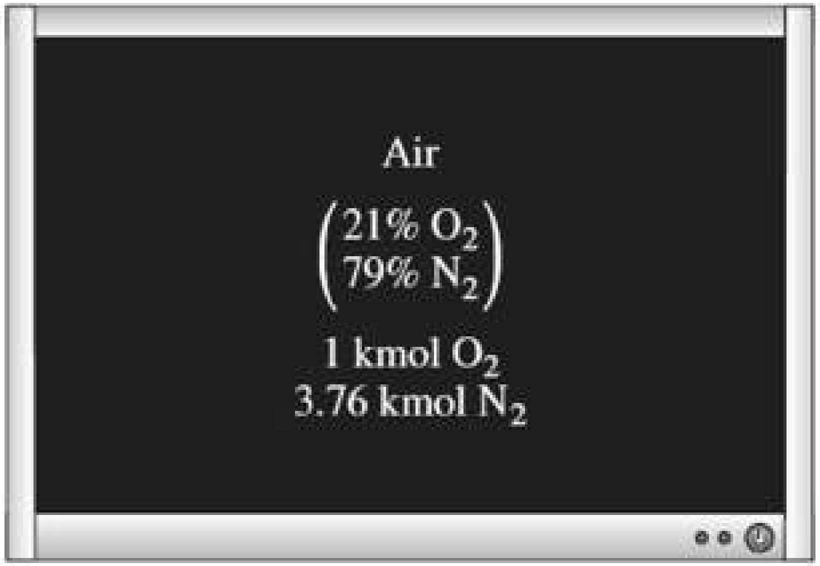
On a mole or a volume basis, dry air is composed of

20.9% O_2, 78.1% N_2, 0.9% Ar, and small amounts of CO_2, He, Ne, H_2

In the analysis of combustion processes, dry air is approximated as
21% O_2 and 79% N_2 by mole numbers

$$1 \text{ kmol } O_2 + 3.76 \text{ kmol } N_2 = 4.76 \text{ kmol air}$$

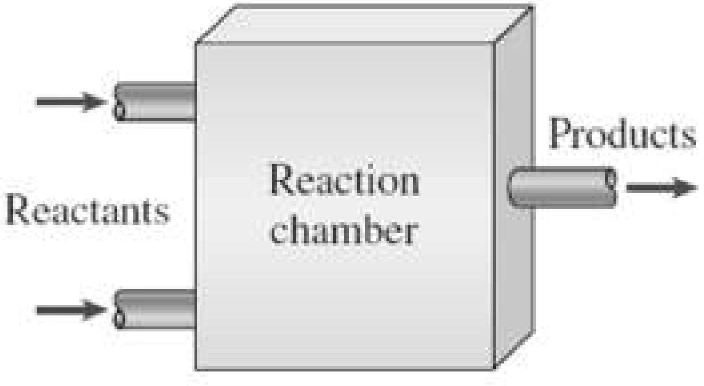
Combustion: A chemical reaction during which a fuel is oxidized and a large quantity of energy is released.



The fuel must be brought above its ignition temperature to start the combustion.

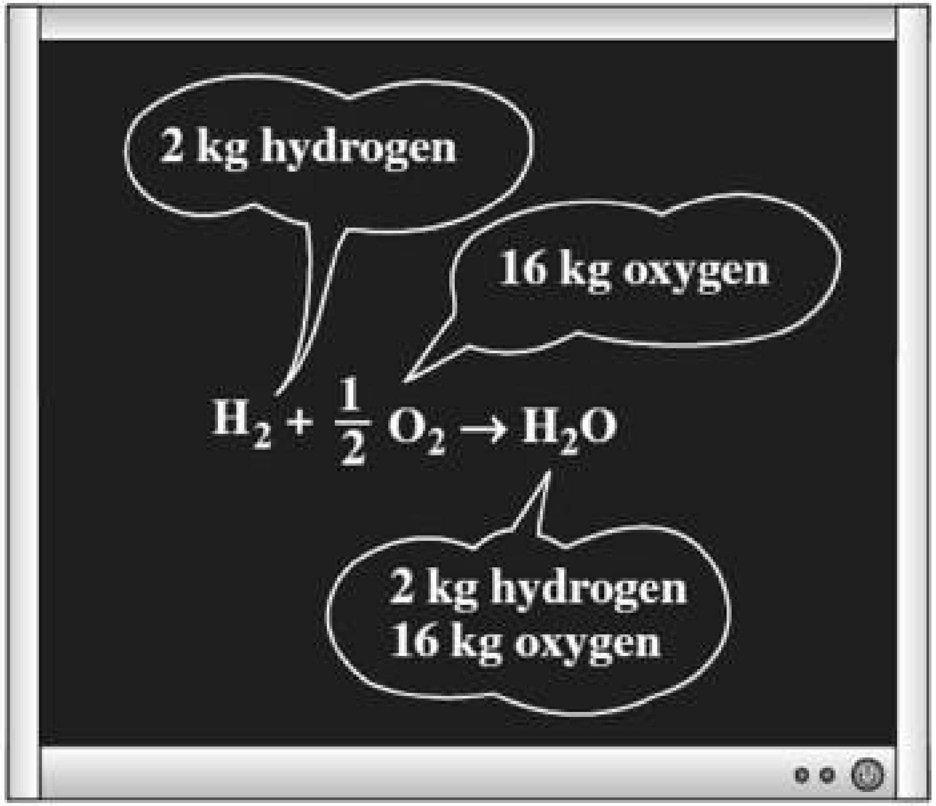
The minimum ignition temperatures in atmospheric air are:

- 260°C for gasoline
- 400°C for carbon
- 580°C for hydrogen
- 610°C for carbon monoxide
- 630°C for methane.



Proportions of the fuel and air must be in the proper range for combustion to begin.

For example, natural gas does not burn in air in concentrations less than 5% or greater than about 15%.



The total number of moles is not conserved during a chemical reaction.

$$C + O_2 \rightarrow CO_2$$

Air-fuel ratio (AF): The ratio of the mass of air to the mass of fuel for a combustion process.

Fuel–air ratio (FA): The reciprocal of air–fuel ratio.

$$\mathrm{AF} = \frac{m_{\text{air}}}{m_{\text{fuel}}}$$

$$m = NM$$

m mass

N number of moles

M molar mass

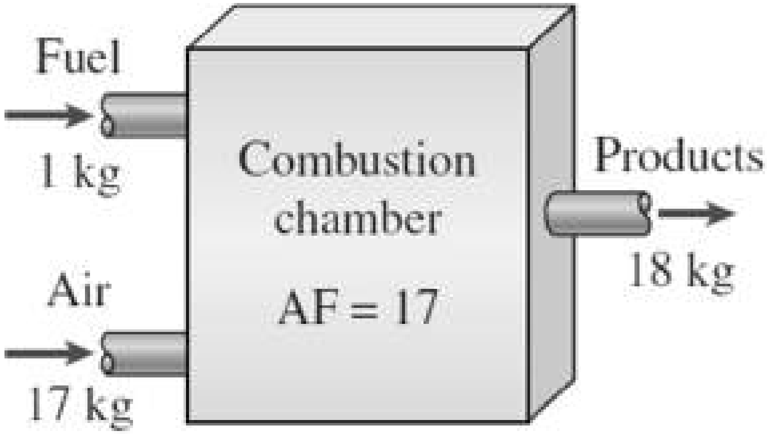


Figure 2-31
The air-fuel ratio (AF) represents the amount of air used per unit mass of fuel during a combustion process.

Theoretical and Actual Combustion Processes

Complete combustion: If all the carbon in the fuel burns to CO_2, all the hydrogen burns to H_2O, and all the sulfur (if any) burns to SO_2.

Incomplete combustion: If the combustion products contain any unburned fuel or components such as C, H_2, CO, or OH.

Reasons for incomplete combustion:

- *Insufficient oxygen*
- *Insufficient mixing* in the combustion chamber during the limited time that the fuel and the oxygen are in contact
- *Dissociation* (at high temperatures)

Oxygen has a much greater tendency to combine with hydrogen than it does with carbon. Therefore, the hydrogen in the fuel normally burns to completion, forming H_2O.

Stoichiometric or **theoretical air:** The minimum amount of air needed for the complete combustion of a fuel. Also referred to as the *chemically correct amount of air,* or *100% theoretical air.*

Stoichiometric or **theoretical combustion:** The ideal combustion process during which a fuel is burned completely with theoretical air.

Excess air: The amount of air in excess of the stoichiometric amount. Usually expressed in terms of the stoichiometric air as *percent excess air* or *percent theoretical air.*

Deficiency of air: Amounts of air less than the stoichiometric amount. Often expressed as *percent deficiency of air.*

Equivalence ratio: The ratio of the actual fuel–air ratio to the stoichiometric fuel–air ratio.

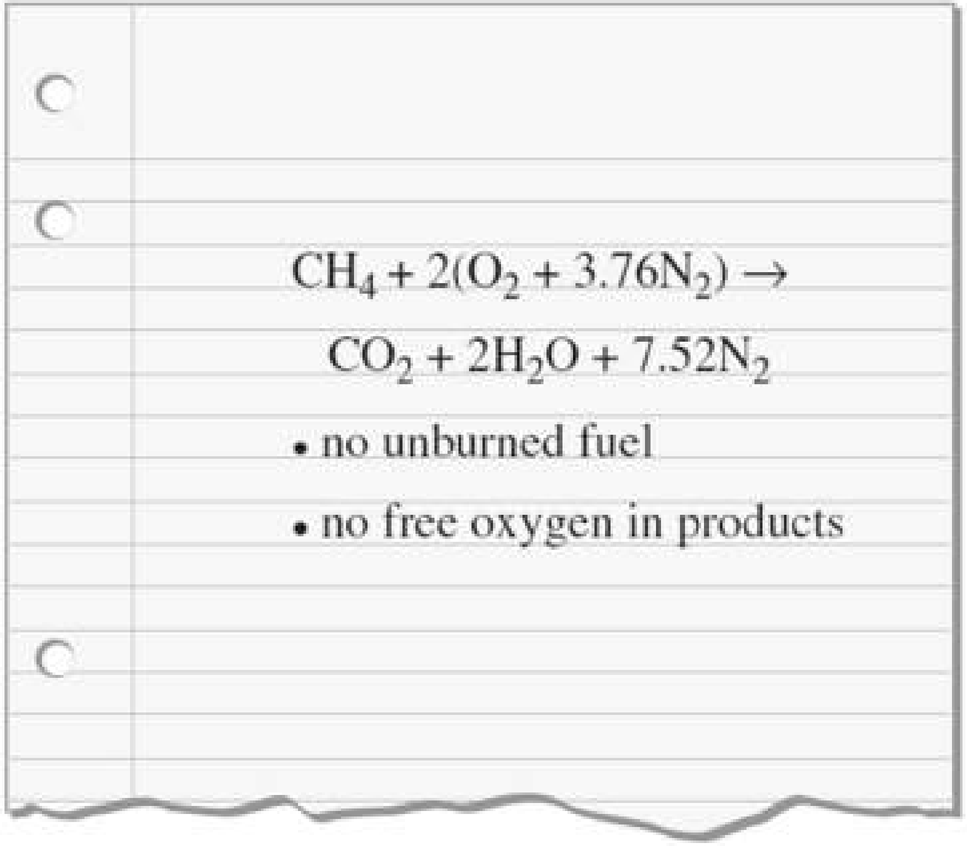
50% excess air = 150% theoretical air

200% excess air = 300% theoretical air.

90% theoretical air = 10% deficiency of air

Theoretical combustion of methane

$$CH_4 + 2(O_2 + 3.76N_2) \rightarrow CO_2 + 2H_2O + 7.52N_2$$



$$CH_4 + 2(O_2 + 3.76N_2) \rightarrow$$

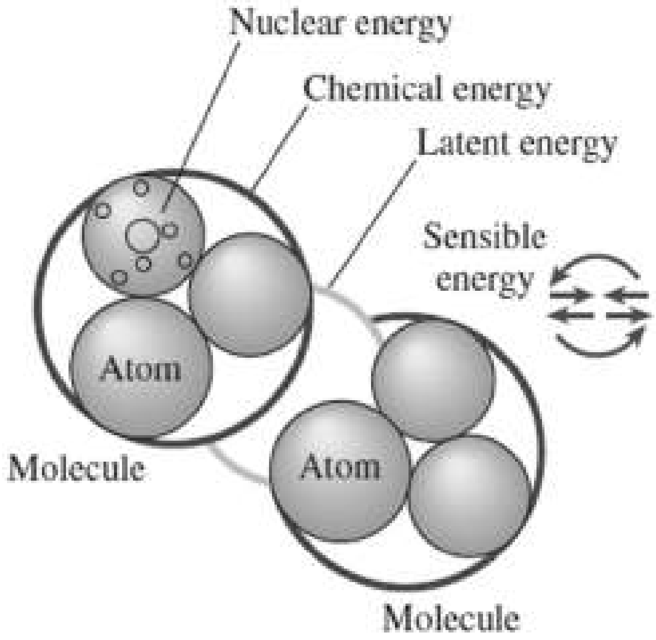
$$CO_2 + 2H_2O + 7.52N_2$$

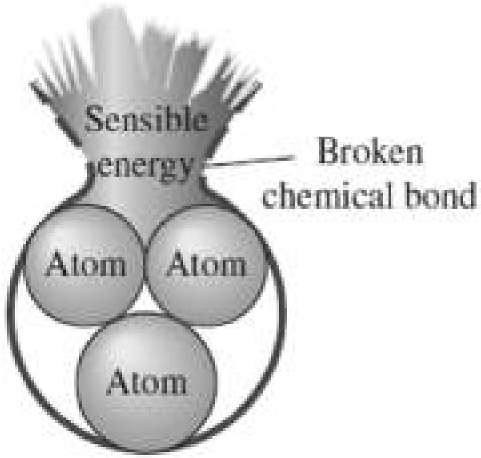
- no unburned fuel
- no free oxygen in products

Enthalpy of Formation and Enthalpy of Combustion

Disregarding any changes in kinetic and potential energies, the energy change of a system during a chemical reaction is due to a change in state and a change in chemical composition.

$$\Delta E_{sys} = \Delta E_{state} + \Delta E_{chem}$$





Enthalpy of reaction h_R : The difference between the enthalpy of the products at a specified state and the enthalpy of the reactants at the same state for a complete reaction.

Enthalpy of combustion h_C : It is the enthalpy of reaction for combustion processes. It represents the amount of heat released during a steady-flow combustion process when 1 kmol (or 1 kg) of fuel is burned completely at a specified temperature and pressure.

Enthalpy of formation h_f : The amount of energy absorbed or released as the component is formed from its stable elements during a steady-flow process at a specified state.

To establish a starting point, we assign the enthalpy of formation of all stable elements (such as O_2, N_2, H_2, and C) a value of zero at the standard reference state of 25°C and 1 atm.

$$Q = H_{\text{prod}} - H_{\text{react}} = -393{,}520 \text{ kJ/kmol}$$

$$h_R = h_C = H_{\text{prod}} - H_{\text{react}}$$

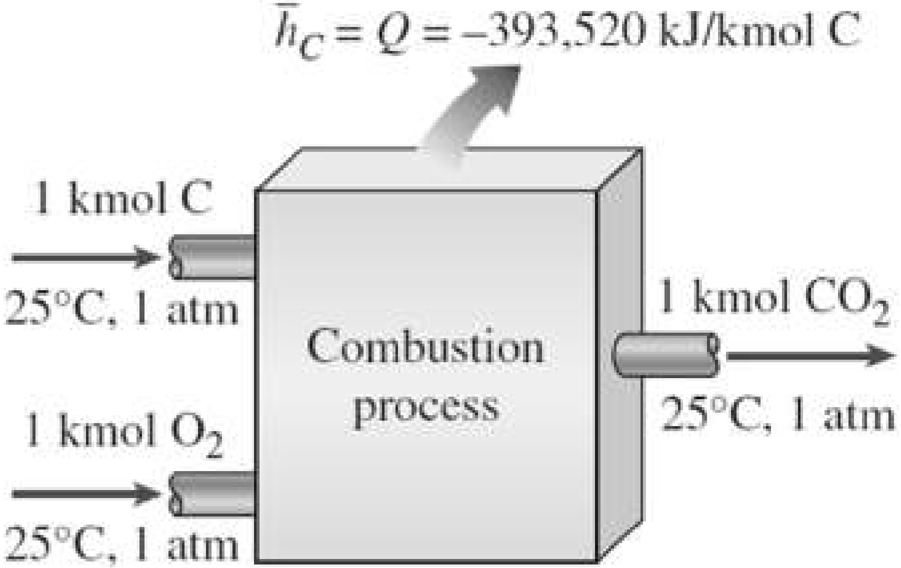
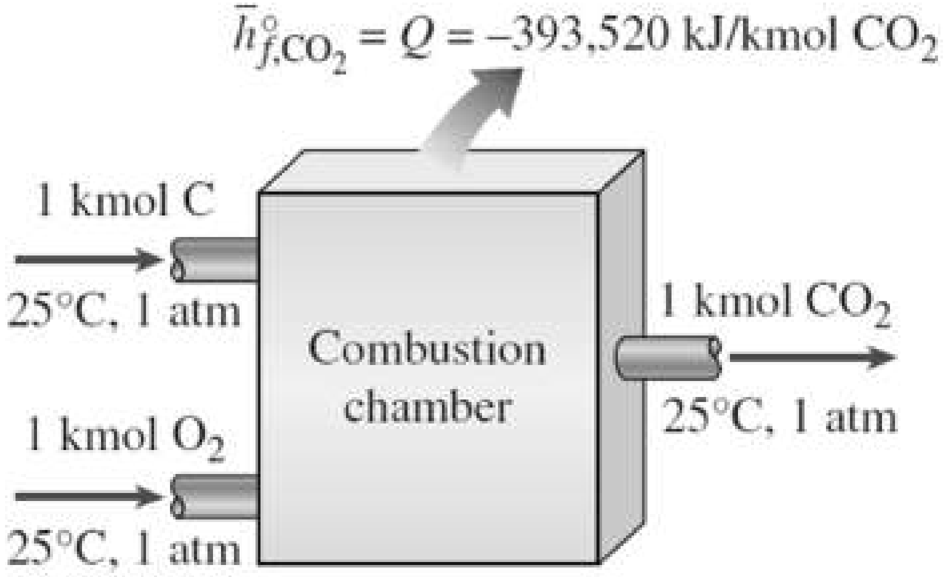


Figure 2-32
The enthalpy of combustion represents the amount of energy released as a fuel is burned during a steady-flow process at a specified state.



Enthalpy of formation: The enthalpy of a substance at a specified state due to its chemical composition.

The enthalpy of formation of a compound represents the amount of energy absorbed or released as the component is formed from its stable elements during a steady-flow process at a specified state.

$\overline{h}^{\circ}_{f,\mathrm{CO_2}} = -393{,}520\ \mathrm{kJ/kmol}$ Enthalpy of formation of CO_2

The negative sign is due to the fact that the enthalpy of 1 kmol of CO_2 at 25°C and 1 atm is 393,520 kJ less than the enthalpy of 1 kmol of C and 1 kmol of O_2 at the same state.

In other words, 393,520 kJ of chemical energy is released (leaving the system as heat) when C and O_2 combine to form 1 kmol of CO_2.

Therefore, a negative enthalpy of formation for a compound indicates that heat is released during the formation of that compound from its stable elements.

A positive value indicates heat is absorbed.

Heating value: The amount of heat released when a fuel is burned completely in a steady-flow process and the products are returned to the state of the reactants. The heating value of a fuel is equal to the absolute value of the enthalpy of combustion of the fuel.

Higher heating value (HHV): When the H_2O in the products is in the liquid form.

Lower heating value (LHV): When the H_2O in the products is in the vapor form.

$$\text{Heating value} = |h_C| \qquad \text{(kJ/kg fuel)}$$

$$\text{HHV} = \text{LHV} + (mh_{fg})_{\text{H}_2\text{O}} \qquad \text{(kJ/kg fuel)}$$

For the fuels with variable composition (i.e., coal, natural gas, fuel oil), the heating value may be determined by burning them directly in a **bomb calorimeter**.

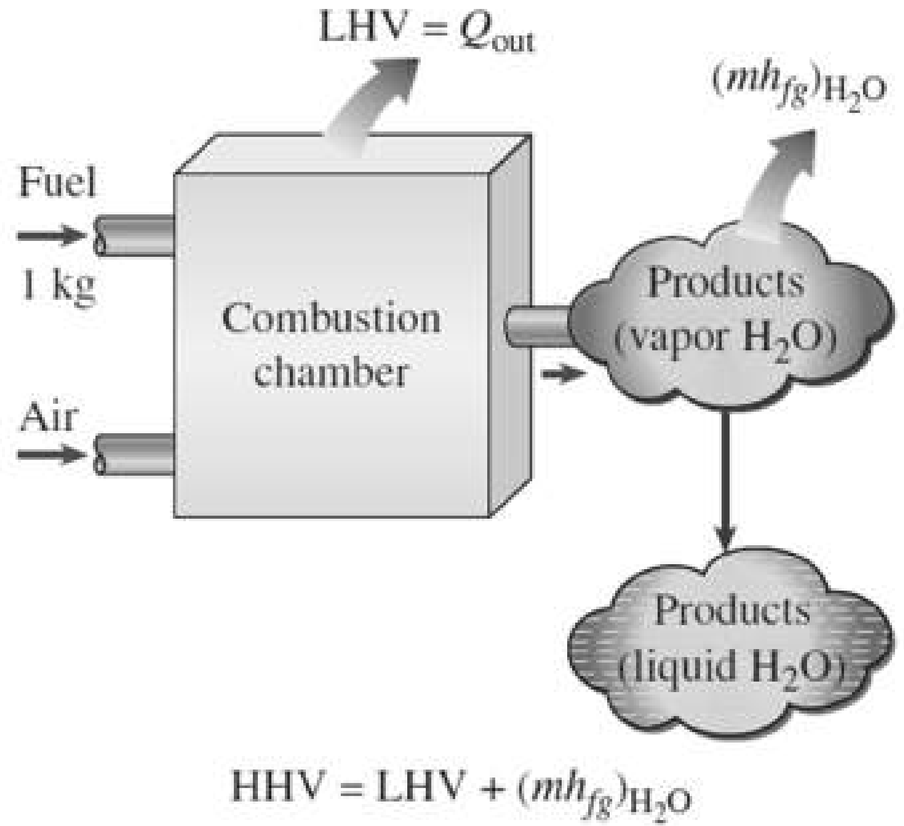


Figure 2-33
The higher heating value of a fuel is equal to the sum of the lower heating value of the fuel and the latent heat of vaporization of the H2O in the products.

First-Law Analysis of Reacting Systems

The energy balance (the first-law) relations given earlier are applicable to both reacting and nonreacting systems. We rewrite the energy balance relations including the changes in chemical energies.

$$\text{Enthalpy} = \bar{h}_f^\circ + (\bar{h} - \bar{h}^\circ) \qquad \text{(kJ/kmol)}$$

$$(\bar{h} - \bar{h}^\circ) \cong \bar{c}_p \Delta T$$

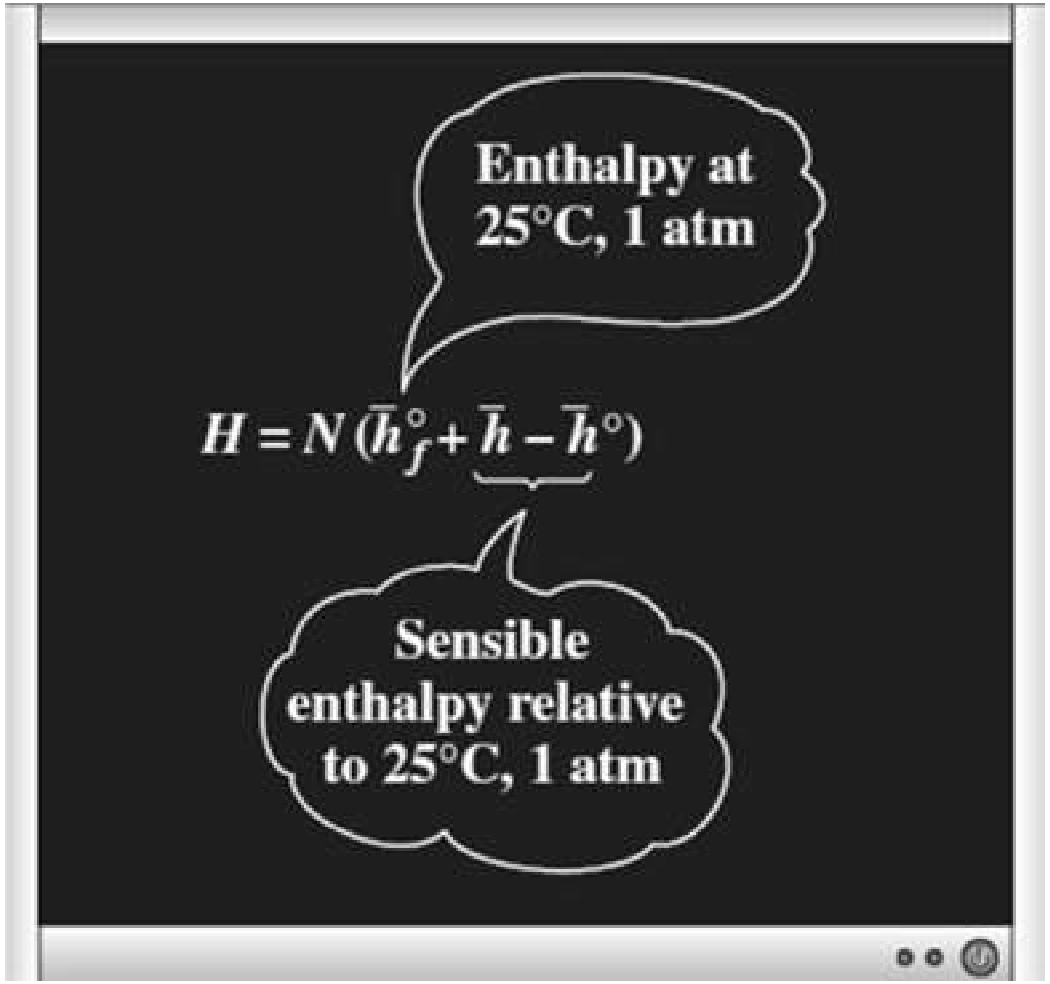
When the changes in kinetic and potential energies are negligible; the steady-flow energy balance for a *chemically reacting steady-flow system:*

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

$$\dot{Q}_{\text{in}} + \dot{W}_{\text{in}} + \sum \dot{n}_r (\bar{h}_f^\circ + \bar{h} - \bar{h}^\circ)_r = \dot{Q}_{\text{out}} + \dot{W}_{\text{out}} + \sum \dot{n}_p (\bar{h}_f^\circ + \bar{h} - \bar{h}^\circ)_p$$

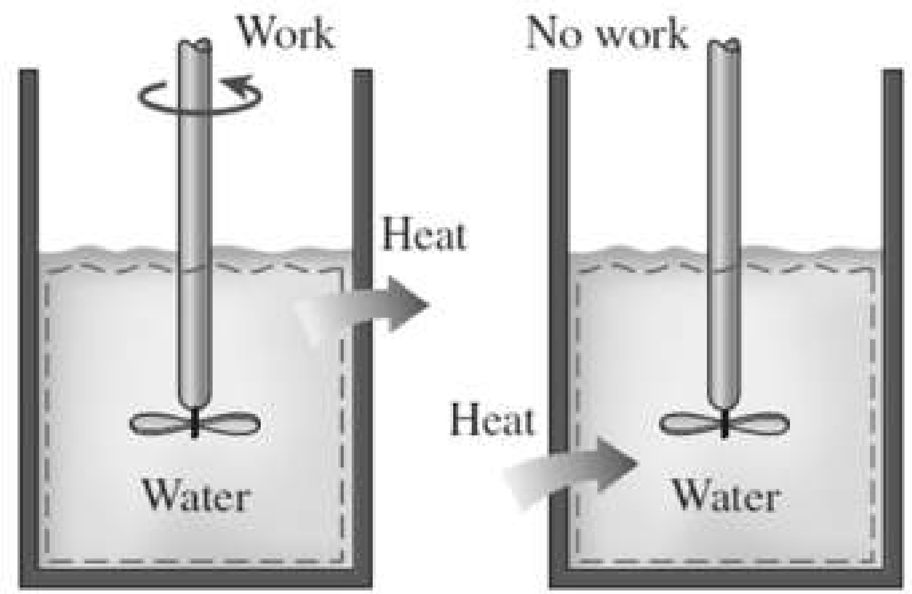
$$Q_{\text{in}} + W_{\text{in}} + \sum N_r (\bar{h}_f^\circ + \bar{h} - \bar{h}^\circ)_r = Q_{\text{out}} + W_{\text{out}} + \sum N_p (\bar{h}_f^\circ + \bar{h} - \bar{h}^\circ)_p$$

$$Q_{\text{out}} = \sum N_r (\bar{h}_f^\circ + \bar{h} - \bar{h}^\circ)_r - \sum N_p (\bar{h}_f^\circ + \bar{h} - \bar{h}^\circ)_p$$



$$H = N(\bar{h}_f^\circ + \underbrace{\bar{h} - \bar{h}^\circ})$$

2-6 HEAT ENGINES AND POWER PLANTS



Heat engines and other cyclic devices usually involve a fluid to and from which heat is transferred while undergoing a cycle.

This fluid is called the **working fluid**.

Work can be converted to heat directly and completely, but converting heat to work requires the use of some special devices. These devices are called *heat engines.*

HEAT ENGINES: The devices that convert heat to work.

1. They receive heat from a high-temperature source (solar energy, oil furnace, nuclear reactor, etc.).
2. They convert part of this heat to work (usually in the form of a rotating shaft.)
3. They reject the remaining waste heat to a low-temperature sink (the atmosphere, rivers, etc.).
4. They operate on a cycle.

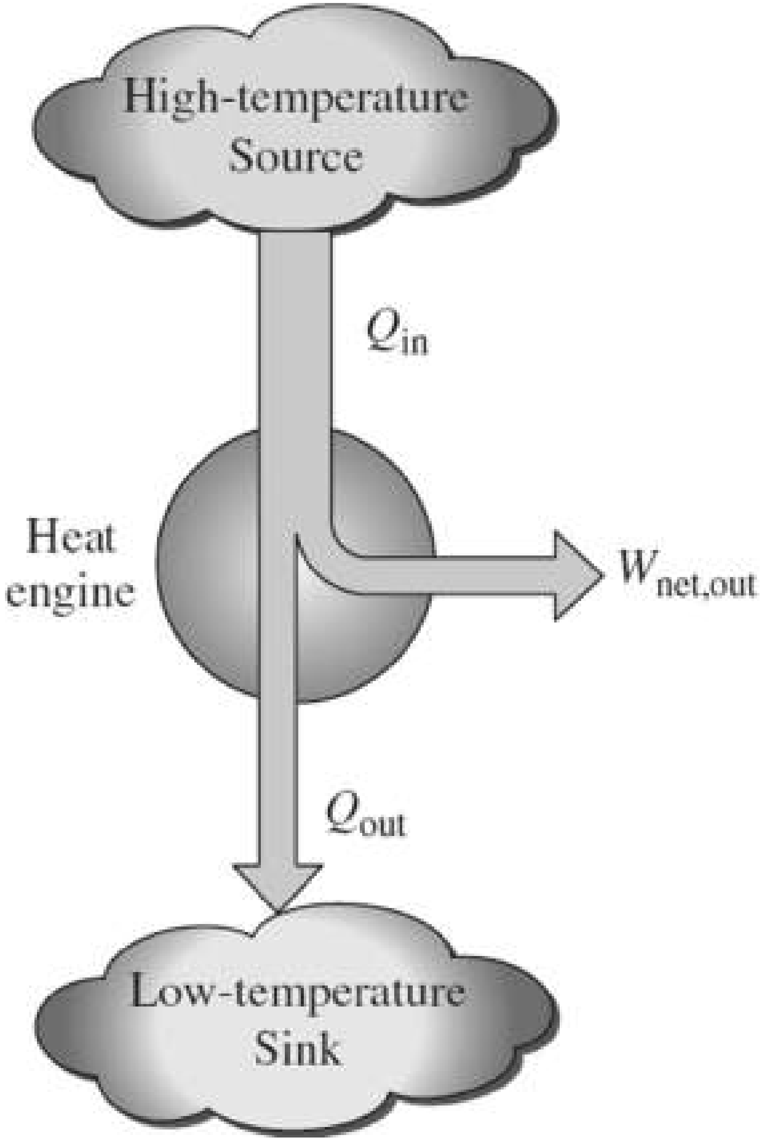
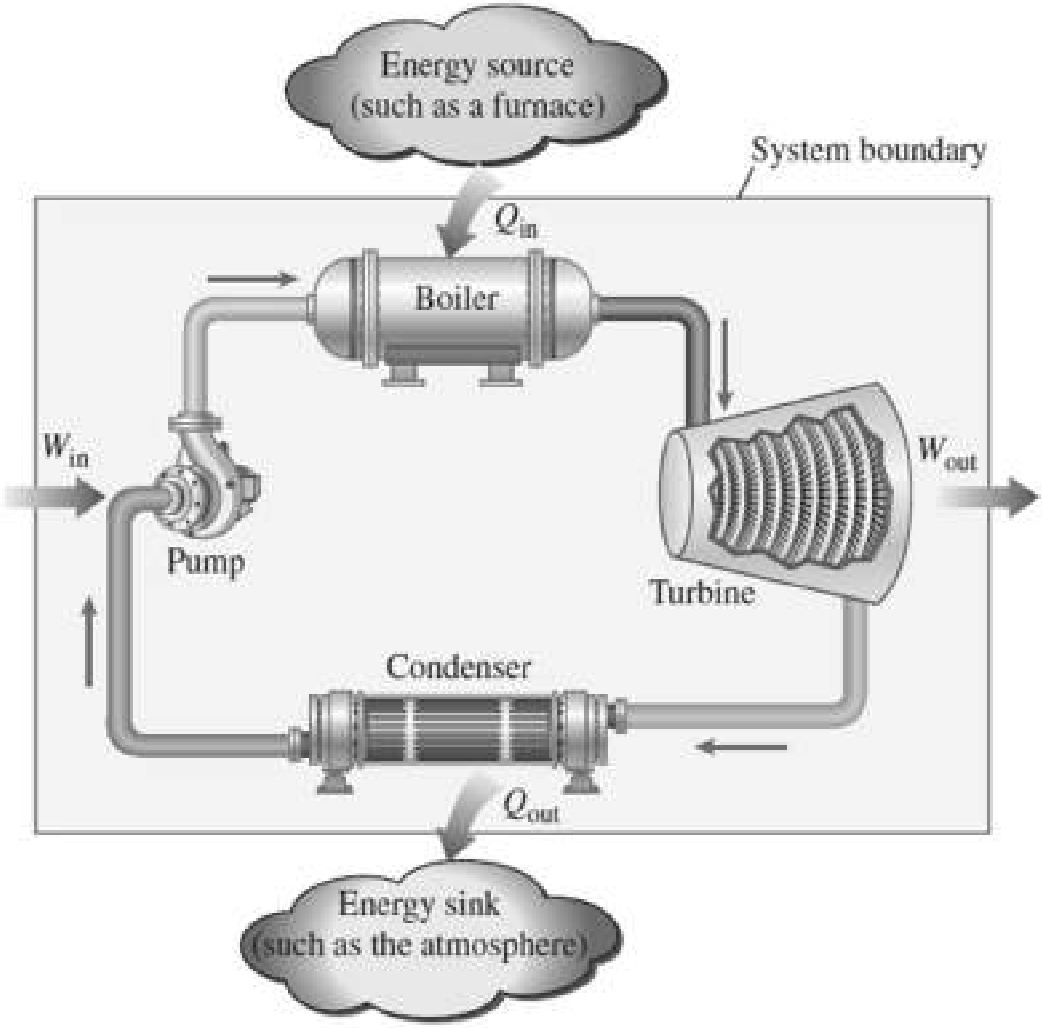


Figure 2-35 Part of the heat received by a heat engine is converted to work, while the rest is rejected to a sink.

A steam power plant



$$W_{net,out} = W_{out} - W_{in} \quad (\text{kJ})$$

$$W_{net,out} = Q_{in} - Q_{out} \quad (\text{kJ})$$

Q_{in} = amount of heat supplied to steam in boiler from a high-temperature source (furnace)

Q_{out} = amount of heat rejected from steam in condenser to a low-temperature sink (the atmosphere, a river, etc.)

W_{out} = amount of work delivered by steam as it expands in turbine

W_{in} = amount of work required to compress water to boiler pressure

$$W_{\text{net, out}} = W_{\text{out}} - W_{\text{in}} \quad \text{(kJ)}$$

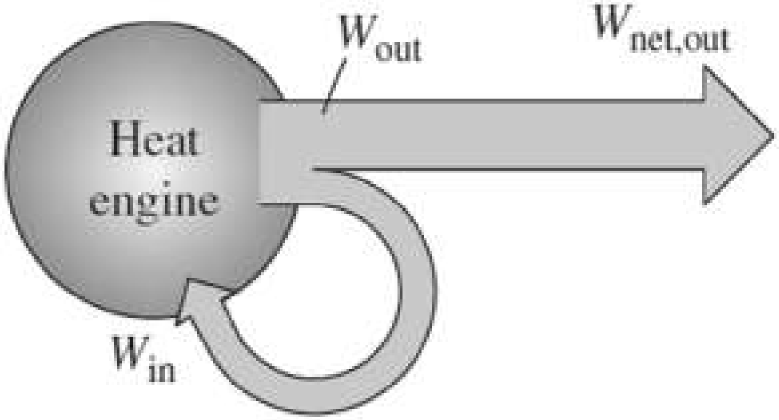


Figure 2-37
A portion of the work output of a heat engine is consumed internally to maintain continuous operation.

Thermal Efficiency

$$\text{Thermal efficiency} = \frac{\text{Net work output}}{\text{Total heat input}}$$

$$\eta_{th} = \frac{W_{net,out}}{Q_{in}}$$

$$W_{net,out} = Q_{in} - Q_{out}$$

$$\eta_{th} = 1 - \frac{Q_{out}}{Q_{in}}$$

Thermal efficiency: The fraction of the heat input that is converted to net work output. It is a measure of the performance of a heat engine.

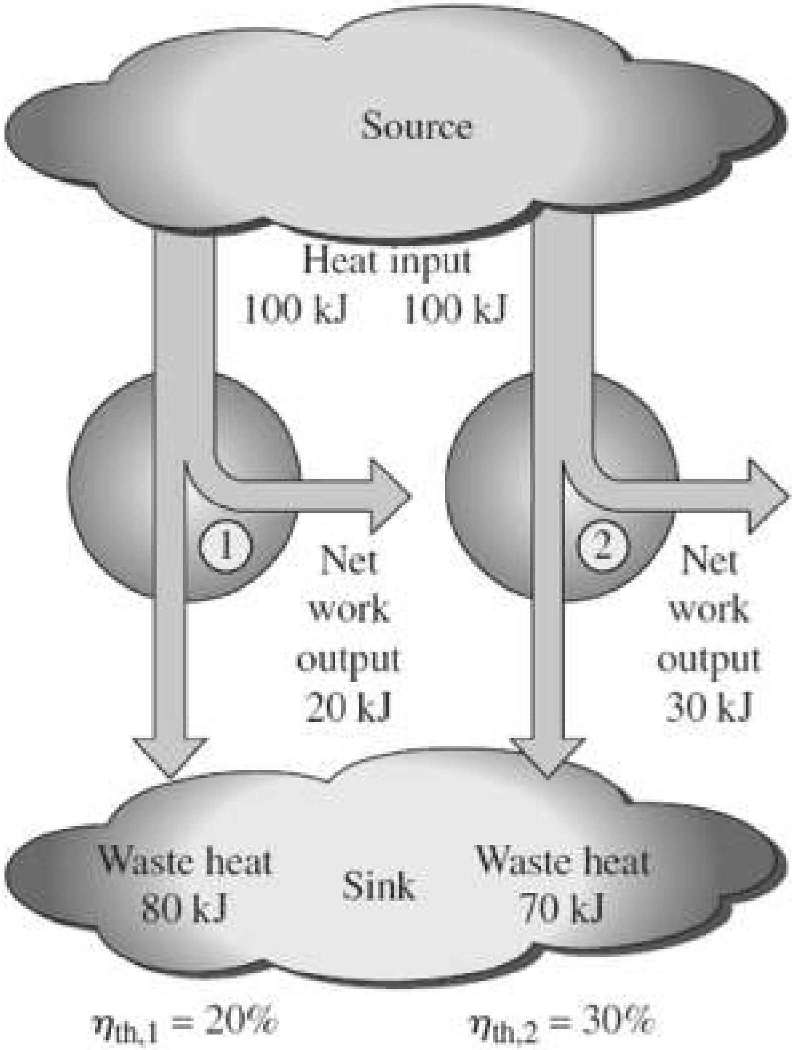
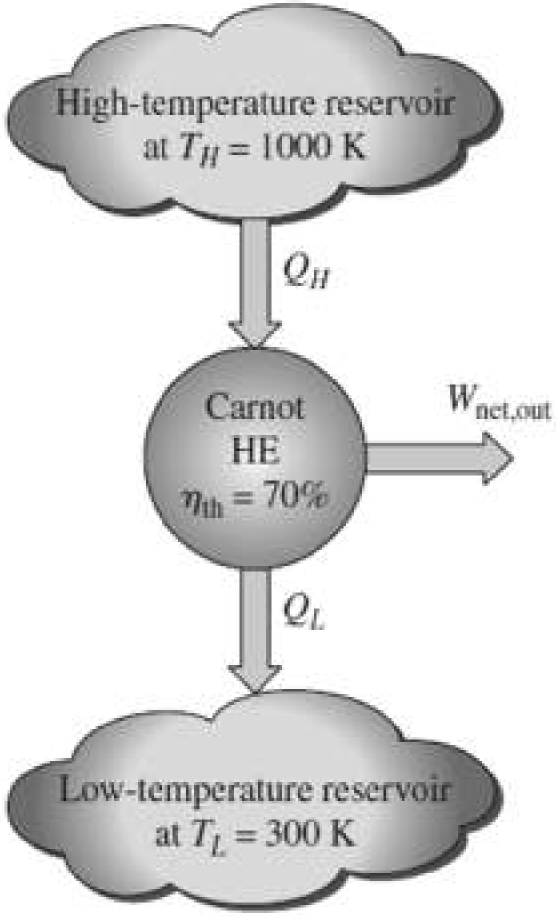


Figure 2-38
Some heat engines perform better than others (convert more of the heat they receive to work).

$$\eta_{\mathrm{th}} = 1 - \frac{Q_L}{Q_H}$$ Any heat engine

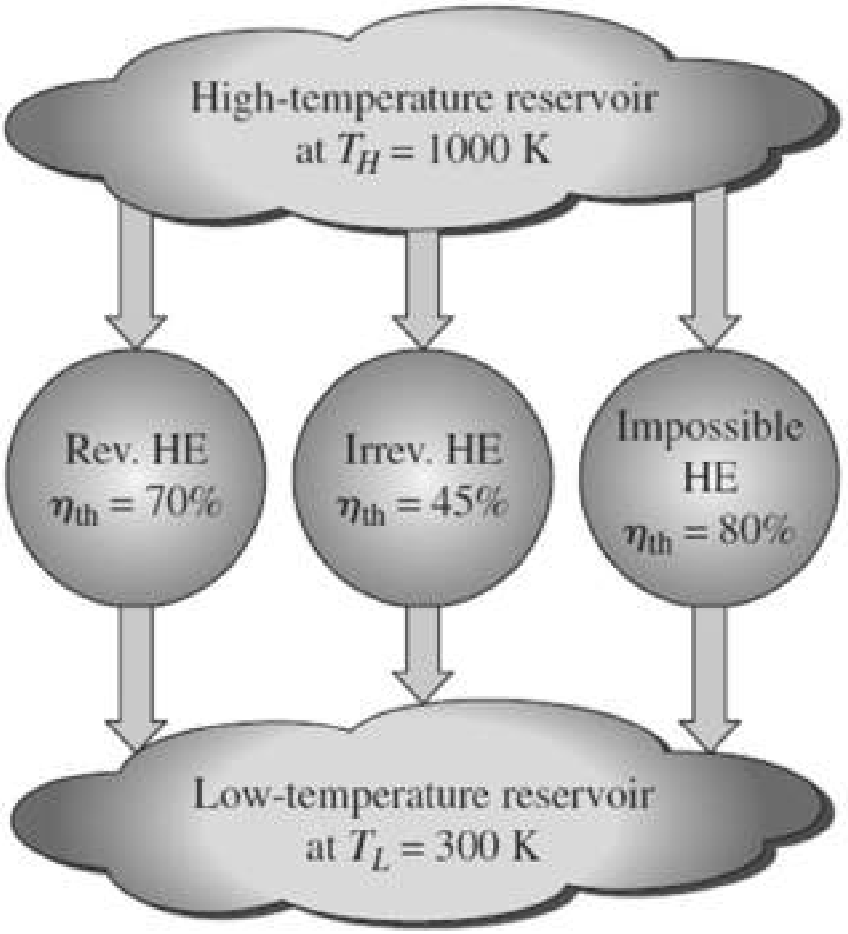
$$\eta_{\mathrm{th,rev}} = 1 - \frac{T_L}{T_H}$$ Carnot heat engine

$$\eta_{\mathrm{th}} \begin{cases} < & \eta_{\mathrm{th,rev}} \quad \text{irreversible heat engine} \\ = & \eta_{\mathrm{th,rev}} \quad \text{reversible heat engine} \\ > & \eta_{\mathrm{th,rev}} \quad \text{impossible heat engine} \end{cases}$$



Thermal efficiency of Carnot heat engine (also any actual heat engine) increases with increasing T_H and decreasing T_L values.

The Carnot cycle (or any reversible heat engine) is the most efficient heat engine cycle operating between two specified temperature levels.



No heat engine can have a higher efficiency than a reversible (Carnot) heat engine operating between the same high- and low-temperature reservoirs.

Overall Plant Efficiency

$$\eta_{\text{plant}} = \frac{\text{Net work output}}{\text{Total amount of heat input by fuel}} = \frac{W_{\text{net,out}}}{m_{\text{fuel}} \times \text{HV}_{\text{fuel}}}$$

$$\eta_{\text{plant}} = \frac{\text{Net power output}}{\text{Total rate of heat input by fuel}} = \frac{\dot{W}_{\text{net,out}}}{\dot{m}_{\text{fuel}} \times \text{HV}_{\text{fuel}}}$$

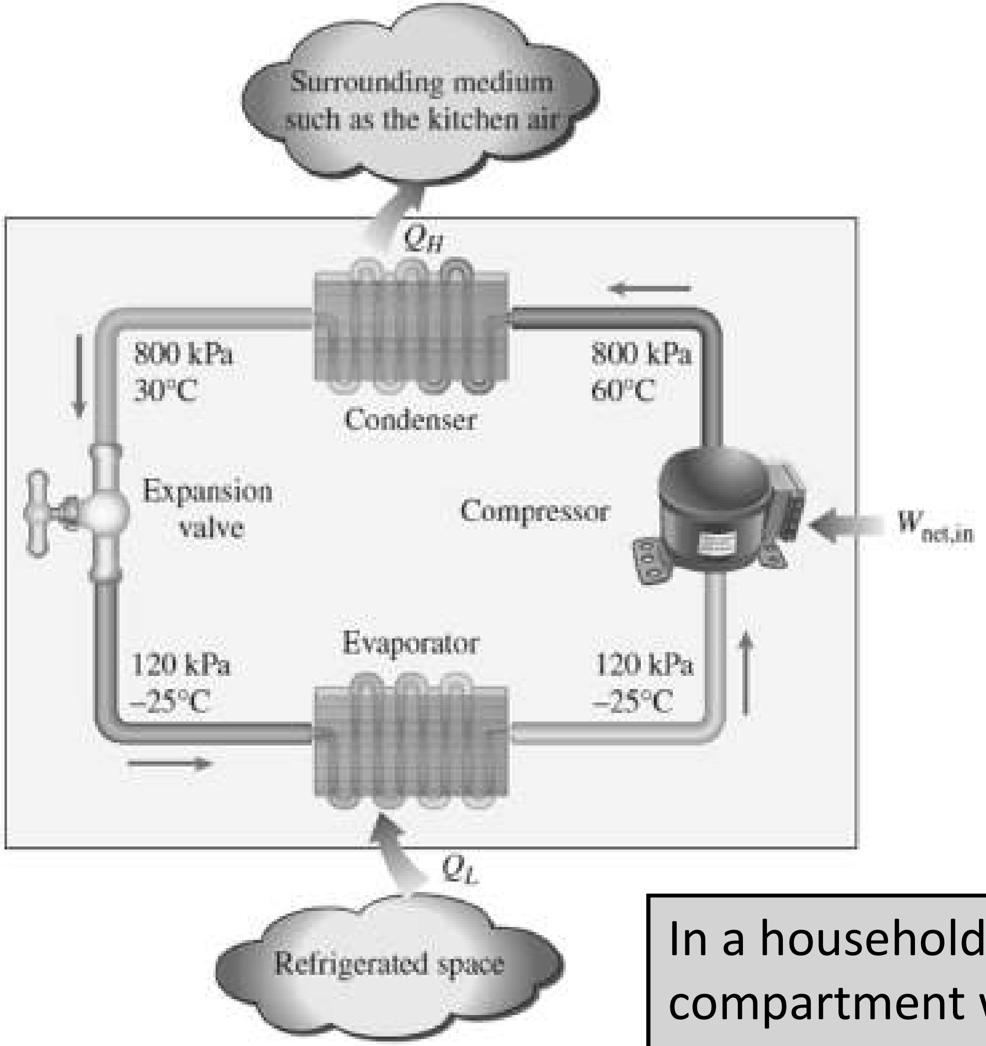
The overall plant efficiency can be used to express the performance of all power plants which burn a fuel such as steam power plants, gas-turbine power plants, and automobile engines.

Thermal efficiency and overall plant efficiency are sometimes used interchangeably.

Spark-ignition automobile engines have an efficiency of about 25 to 30%.

This number is as high as 40% for diesel engines and large gas-turbine plants and as high as 60% for large combined gas-steam power plants.

2-7 REFRIGERATORS AND HEAT PUMPS



The transfer of heat from a low-temperature medium to a high-temperature one requires special devices called **refrigerators**.

Refrigerators are cyclic devices.

The working fluid used in the refrigeration cycle is called a **refrigerant**.

The most frequently used refrigeration cycle is the ***vapor-compression refrigeration cycle*.**

In a household refrigerator, the freezer compartment where heat is absorbed by the refrigerant serves as the evaporator, and the coils usually behind the refrigerator where heat is dissipated to the kitchen air serve as the condenser.

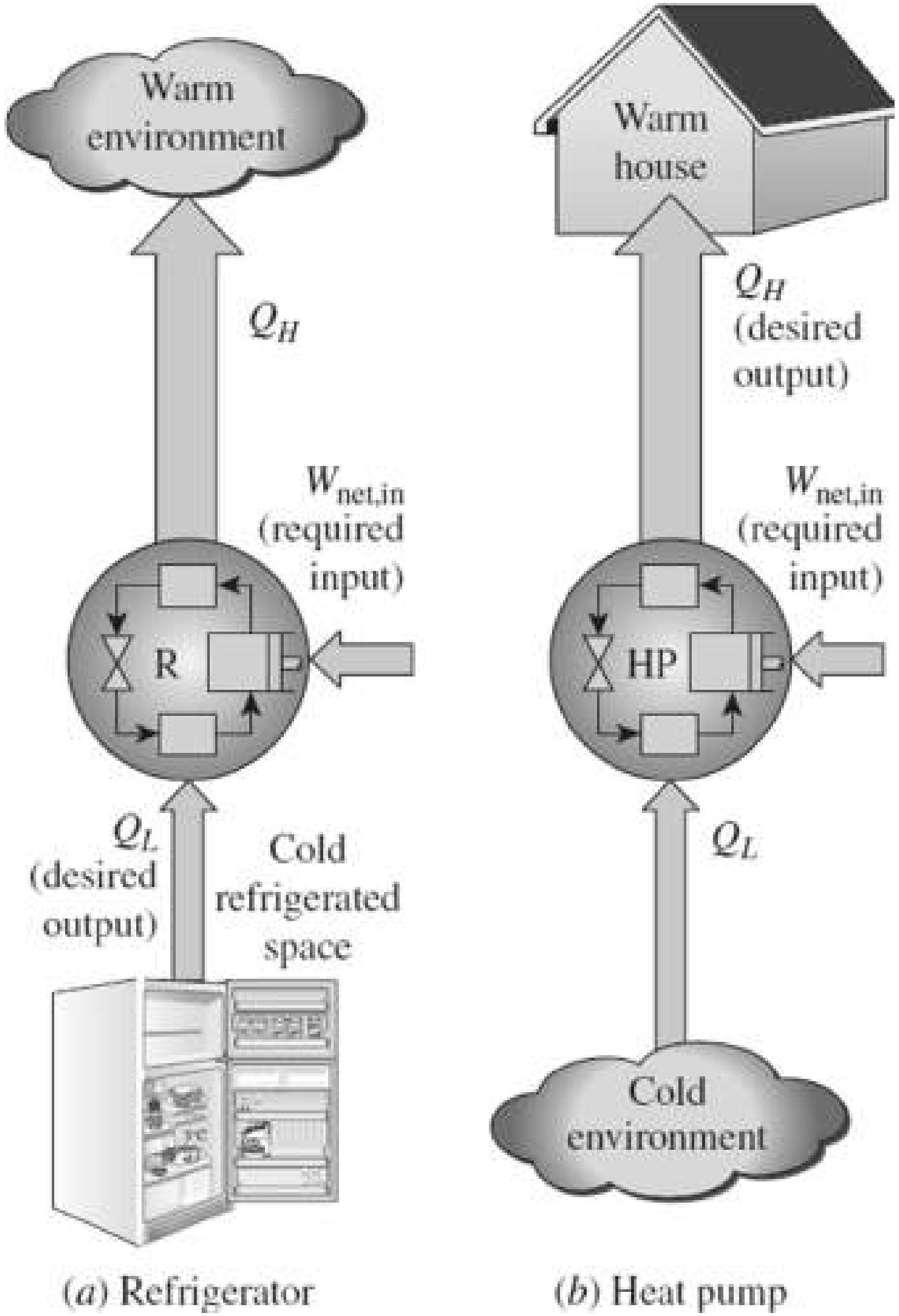
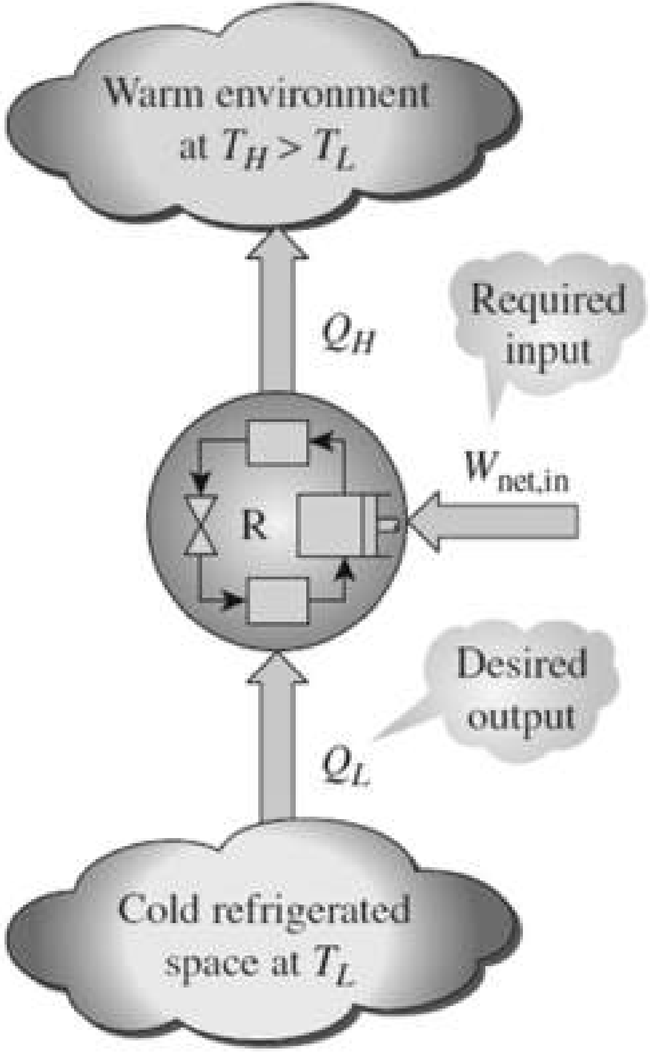


Figure 2-39
The objective of a refrigerator is to remove heat (Q_L) from the cold medium; the objective of a heat pump is to supply heat (Q_H) to a warm medium.



The *efficiency* of a refrigerator is expressed in terms of the **coefficient of performance** (COP).

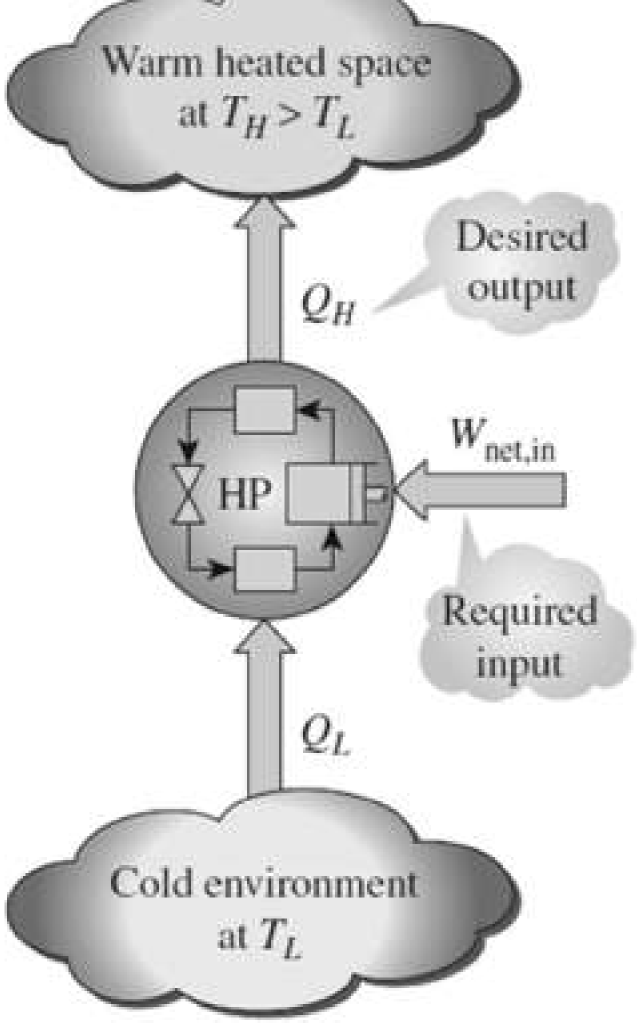
The objective of a refrigerator is to remove heat (Q_L) from the refrigerated space.

$$\text{COP}_R = \frac{\text{Cooling effect}}{\text{Work input}} = \frac{Q_L}{W_{\text{net,in}}}$$

$$W_{\text{net,in}} = Q_H - Q_L \qquad (\text{kJ})$$

$$\text{COP}_R = \frac{Q_L}{Q_H - Q_L} = \frac{1}{Q_H/Q_L - 1}$$

$$\text{COP}_R = \frac{\dot{Q}_L}{\dot{W}_{\text{net,in}}}$$



$$\text{COP}_{\text{HP}} = \frac{\text{Heating effect}}{\text{Work input}} = \frac{Q_H}{W_{\text{net,in}}}$$

$$\text{COP}_{\text{HP}} = \frac{Q_H}{Q_H - Q_L} = \frac{1}{1 - Q_L/Q_H}$$

$$\text{COP}_{\text{HP}} = \frac{\dot{Q}_H}{\dot{W}_{\text{net,in}}}$$

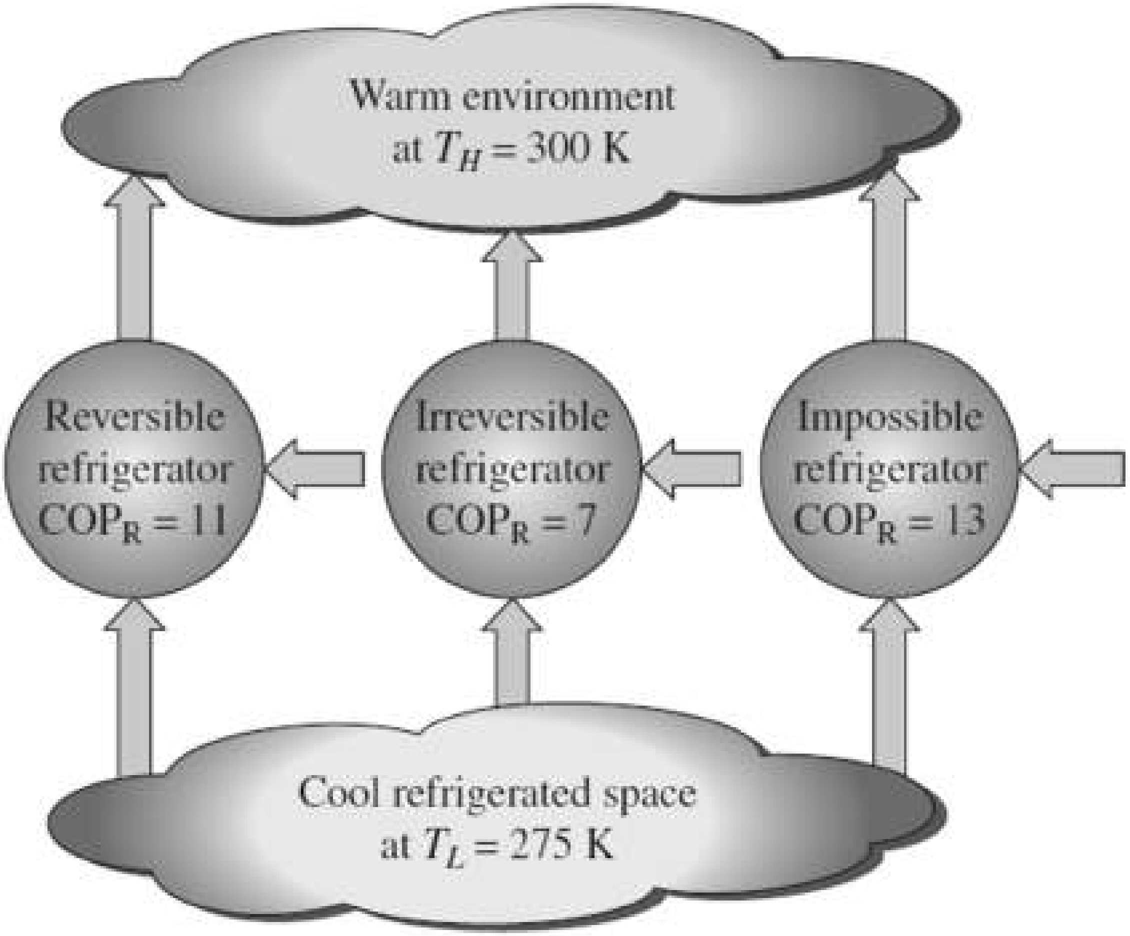
$$\text{COP}_{\text{HP}} = \text{COP}_{\text{R}} + 1$$

for fixed values of Q_L and Q_H

The objective of a heat pump is to supply heat (Q_H) to a warm medium.

$$\mathrm{COP}_{\mathrm{R,Carnot}} = \frac{1}{T_H/T_L - 1} = \frac{T_L}{T_H - T_L}$$ Carnot refrigerator

$$\mathrm{COP}_{\mathrm{HP,Carnot}} = \frac{1}{1 - T_L/T_H} = \frac{T_H}{T_H - T_L}$$ Carnot heat pump



Both COPs increase as the difference between the two temperatures decreases, that is, as T_L rises or T_H falls.

This conclusion is also applicable to actual refrigerators and heat pumps.

The reversed Carnot cycle is the most efficient refrigeration cycle operating between two specified temperature levels.

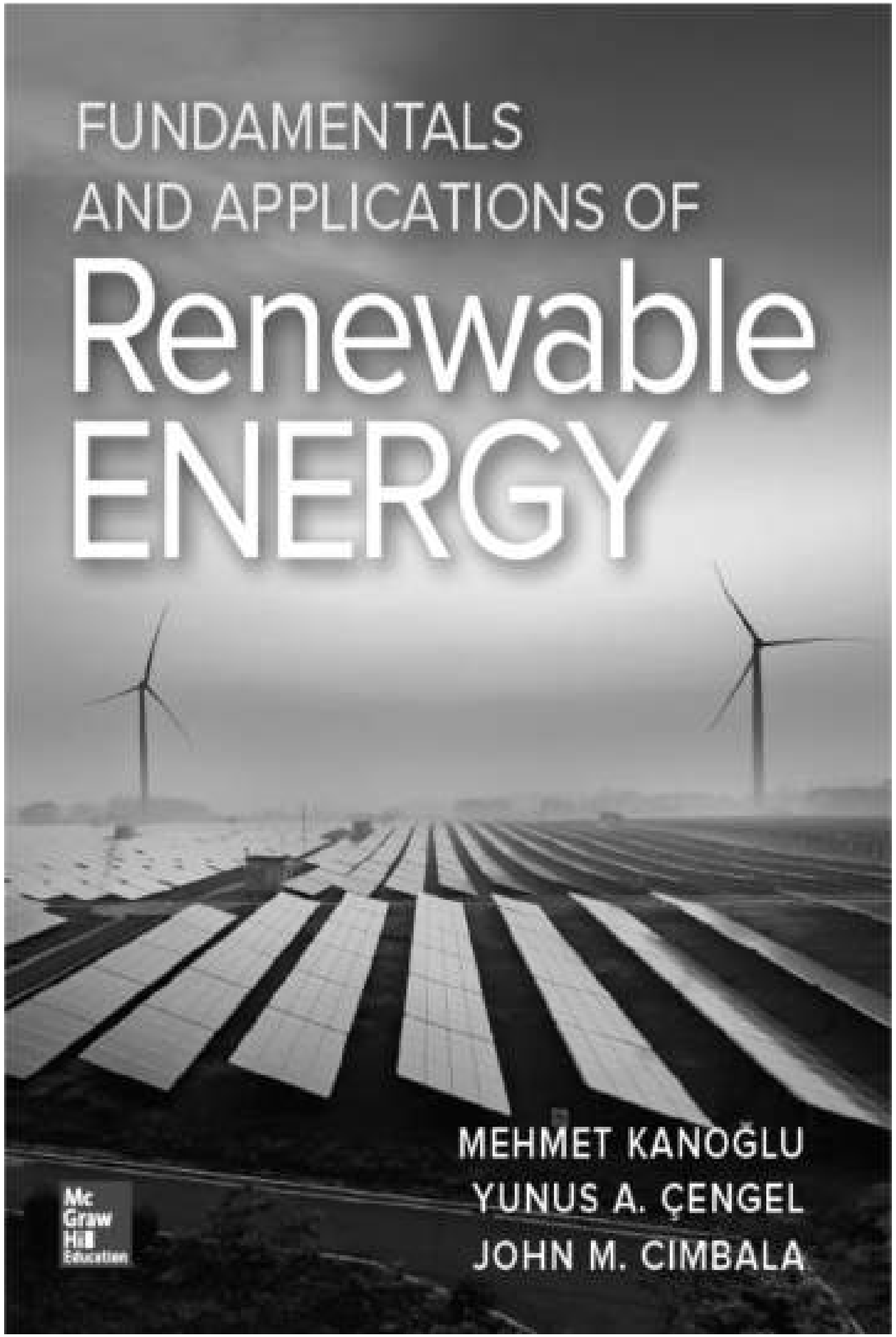
$$\mathrm{COP_R}\begin{cases} < \mathrm{COP_{R,rev}} & \text{irreversible refrigerator} \\ = \mathrm{COP_{R,rev}} & \text{reversible refrigerator} \\ > \mathrm{COP_{R,rev}} & \text{impossible refrigerator} \end{cases}$$

The COP of a reversible refrigerator or heat pump is the maximum theoretical value for the specified temperature limits.

Actual refrigerators or heat pumps may approach these values as their designs are improved, but they can never reach them.

The COPs of both the refrigerators and the heat pumps decrease as T_L *decreases.*

That is, it requires more work to absorb heat from lower-temperature media.



Chapter 3
FUNDAMENTALS OF SOLAR ENERGY

Fundamentals and Applications of

Renewable Energy

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McGraw-Hill, 2020

3-1 INTRODUCTION

Solar radiation (solar energy) (solar heat): The electromagnetic energy emitted by the sun.

Tremendous amounts of energy are created within the sun and only a fraction of this energy reaches earth.

This keeps earth at a temperature suitable for life.

Amount of solar energy: The amount of solar energy reaching earth’s surface can easily meet entire energy needs of the world.

However, this is not practical due to low concentration of solar energy and its relatively high cost.

Solar vs. other renewables: Other renewable energies such as geothermal, wind, hydro, and biomass appear to be less costly than direct solar energy but their potentials with the current technologies are also much less than direct solar energy.

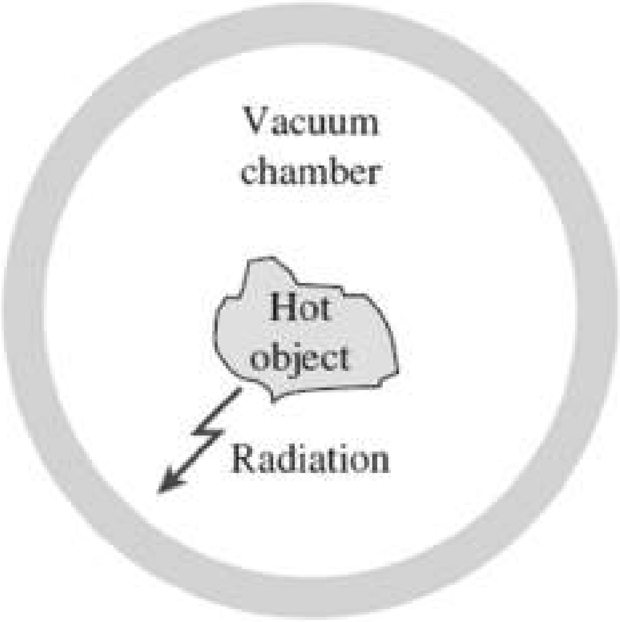
Solar energy reaches earth by radiation.

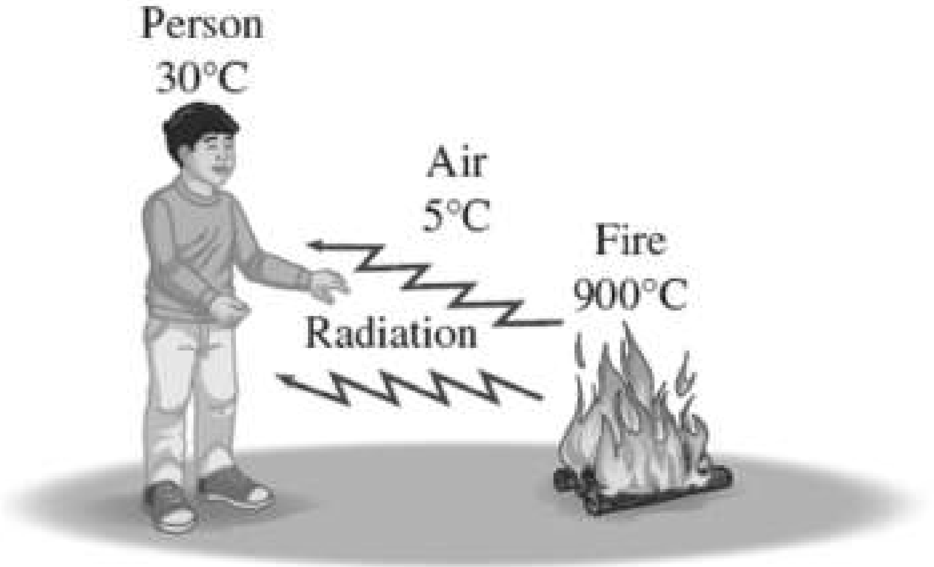
3-2 RADIATION FUNDAMENTALS

The hot object in vacuum chamber will eventually cool down and reach thermal equilibrium with its surroundings by a heat transfer mechanism: radiation.

How does radiation differ from conduction and convection: It does not require the presence of a material medium to take place.

Radiation transfer occurs in solids as well as liquids and gases.





Accelerated charges or changing electric currents give rise to electric and magnetic fields. These rapidly moving fields are called electromagnetic waves or electromagnetic radiation, and they represent the energy emitted by matter as a result of the changes in the electronic configurations of the atoms or molecules.

Electromagnetic waves transport energy and they are characterized by their *frequency* ν or *wavelength* λ.

$$\lambda = \frac{c}{\nu}$$

$c = c_0 / n$
c, the speed of propagation of a wave in that medium
$c_0 = 2.9979 \times 10^8$ m/s, the *speed of light* in a vacuum
n, the *index of refraction* of that medium
$n = 1$ for air and most gases, $n = 1.5$ for glass, and $n = 1.33$ for water

It has proven useful to view electromagnetic radiation as the propagation of a collection of discrete packets of energy called photons or quanta.
In this view, each photon of frequency n is considered to have an energy of

$$e = h\nu = \frac{hc}{\lambda}$$

The energy of a photon is inversely proportional to its wavelength.

$h = 6.626069 \times 10^{-34}$ J·s is *Planck's constant*

Thermal radiation: The type of electromagnetic radiation that is pertinent to heat transfer is the thermal radiation.

It is emitted as a result of energy transitions of molecules, atoms, and electrons of a substance.

Effect of temperature on thermal radiation: Temperature is a measure of the strength of these activities at the microscopic level, and the rate of thermal radiation emission increases with increasing temperature.

Thermal radiation is continuously emitted by all matter whose temperature is above absolute zero.

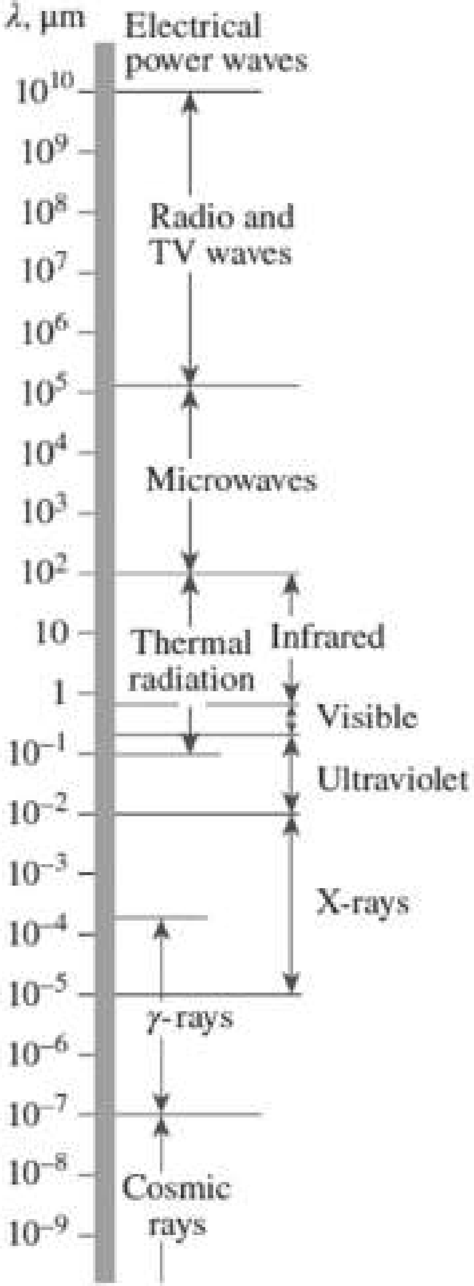


Figure 3-1
The electromagnetic wave spectrum.

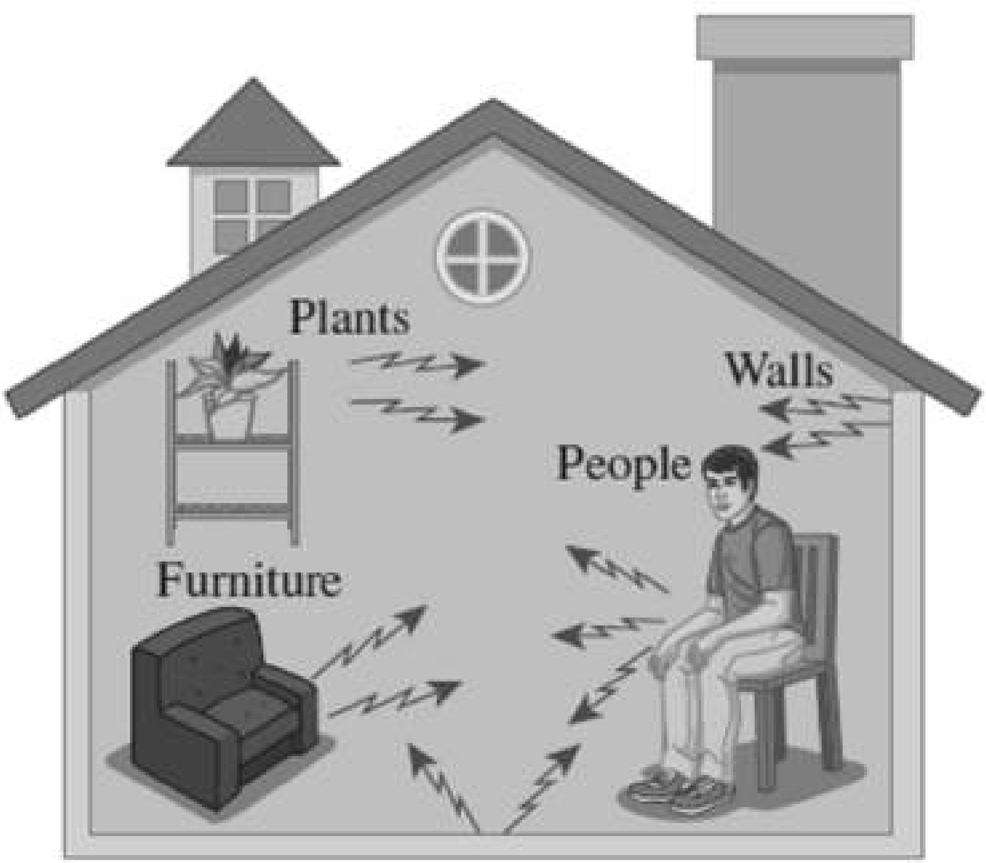


Figure 3-2
Everything around us constantly emits thermal radiation.

Light: It is simply the *visible* portion of the electromagnetic spectrum that lies between 0.40 and 0.76 μm.

Light source: A body that emits some radiation in the visible range.

Our primary light source: Sun

Solar radiation: The electromagnetic radiation emitted by the sun is known as solar radiation, and nearly all of it falls into the wavelength band 0.3–3 μm.

Almost *half* of solar radiation is light (i.e., it falls into the visible range), with the remaining being ultraviolet and infrared.

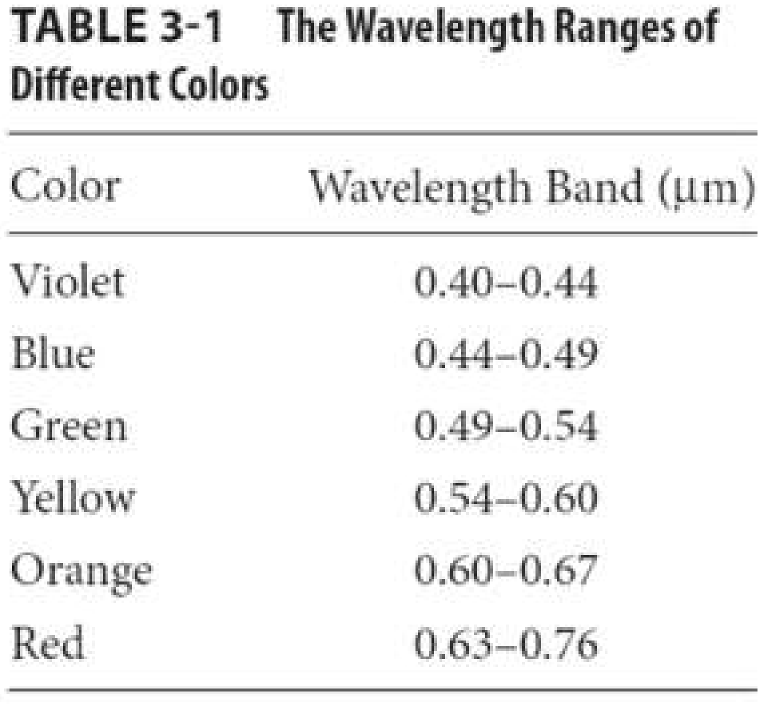


TABLE 3-1 The Wavelength Ranges of Different Colors

Color	Wavelength Band (μm)
Violet	0.40–0.44
Blue	0.44–0.49
Green	0.49–0.54
Yellow	0.54–0.60
Orange	0.60–0.67
Red	0.63–0.76

Infrared radiation: The radiation emitted by bodies at room temperature falls into the infrared region of the spectrum, which extends from 0.76 to 100 μm.

Ultraviolet radiation: The ultraviolet radiation includes the low-wavelength end of the thermal radiation spectrum and lies between the wavelengths 0.01 and 0.40 μm.

Ultraviolet rays are to be avoided since they can kill microorganisms and cause serious damage to humans and other living beings.

About 12 percent of solar radiation is in the ultraviolet range.

The ozone (O_3) layer in the atmosphere acts as a protective blanket and absorbs most of this ultraviolet radiation.

Blackbody Radiation

Different bodies may emit different amounts of radiation per unit surface area.

Blackbody: It emits the *maximum* amount of radiation by a surface at a given temperature.

It is an *idealized body* to serve as a standard against which the radiative properties of real surfaces may be compared.

A blackbody is *a perfect emitter and absorber of radiation*.

A blackbody absorbs *all* incident radiation, regardless of wavelength and direction.

Blackbody emissive power: The radiation energy emitted by a blackbody

$$E_b(T) = \sigma T^4$$

Stefan–Boltzmann law

$$\sigma = 5.670 \times 10^{-8}\ \mathrm{W/m^2 \cdot K^4}$$

Stefan–Boltzmann constant

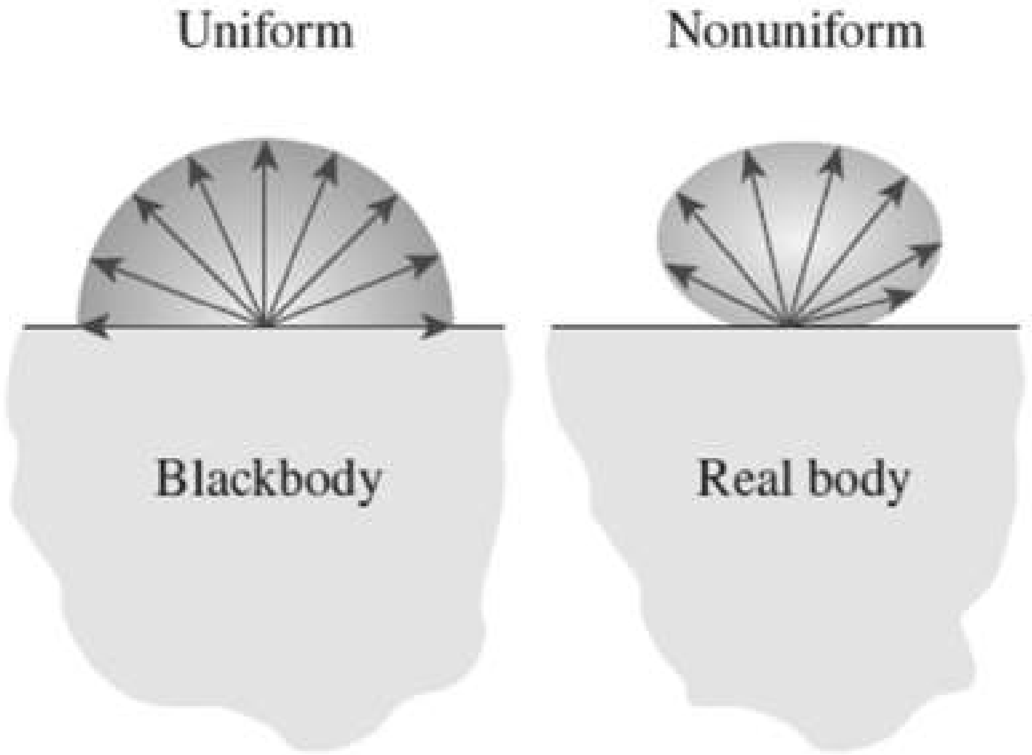


Figure 3-3
A blackbody is said to be a diffuse emitter since it emits radiation energy uniformly in all directions.

Spectral blackbody emissive power: The amount of radiation energy emitted by a blackbody at a thermodynamic temperature *T* per unit time, per unit surface area, and per unit wavelength about the wavelength λ.

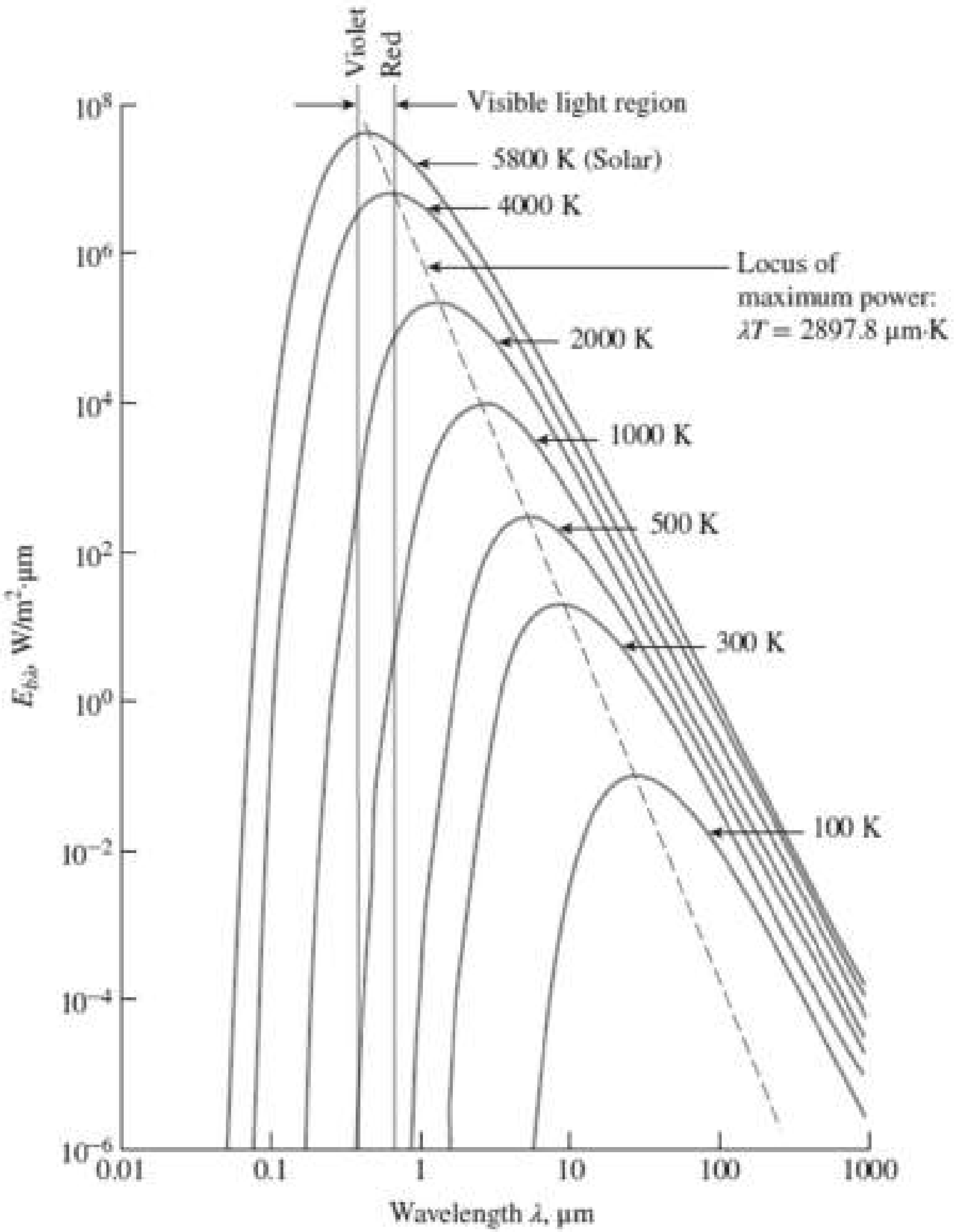
$$E_{b\lambda}(\lambda, T) = \frac{C_1}{\lambda^5[\exp(C_2/\lambda T) - 1]} \qquad (\mathrm{W/m^2 \cdot \mu m})$$

Planck's law

$$C_1 = 2\pi h c_0^2 = 3.74177 \times 10^8 \ \mathrm{W \cdot \mu m^4/m^2}$$

$$C_2 = hc_0/k = 1.43878 \times 10^4 \ \mathrm{\mu m \cdot K}$$

$k = 1.38065 \times 10^{-23}$ J/K Boltzmann's constant



The wavelength at which the peak occurs for a specified temperature is given by Wien’s displacement law

$$(\lambda T)_{\text{max power}} = 2897.8\ \mu\text{m} \cdot \text{K}$$

Figure 3-4
The variation of the blackbody emissive power with wavelength for several temperatures.

Observations from the figure

Effect of wavelength: The emitted radiation is a continuous function of *wavelength*. At any specified temperature, it *increases* with wavelength, reaches a peak, and then decreases with increasing wavelength.

Effect of temperature: At any wavelength, the amount of emitted radiation *increases* with increasing temperature.

As temperature increases, the curves shift to the left to the shorter wavelength region. Consequently, a larger fraction of the radiation is emitted at *shorter wavelengths* at higher temperatures.

Solar radiation: The radiation emitted by the *sun*, which is considered to be a blackbody at 5780 K, reaches its peak in the visible region of the spectrum. Therefore, the sun is in tune with our eyes.

Infrared radiation: On the other hand, surfaces at T < 800 K emit almost entirely in the infrared region and thus are not visible to the eye unless they reflect light coming from other sources.

$$E_b(T) = \int_0^\infty E_{b\lambda}(\lambda, T)\, d\lambda = \sigma T^4 \qquad (\mathrm{W/m^2})$$

Total blackbody emissive power

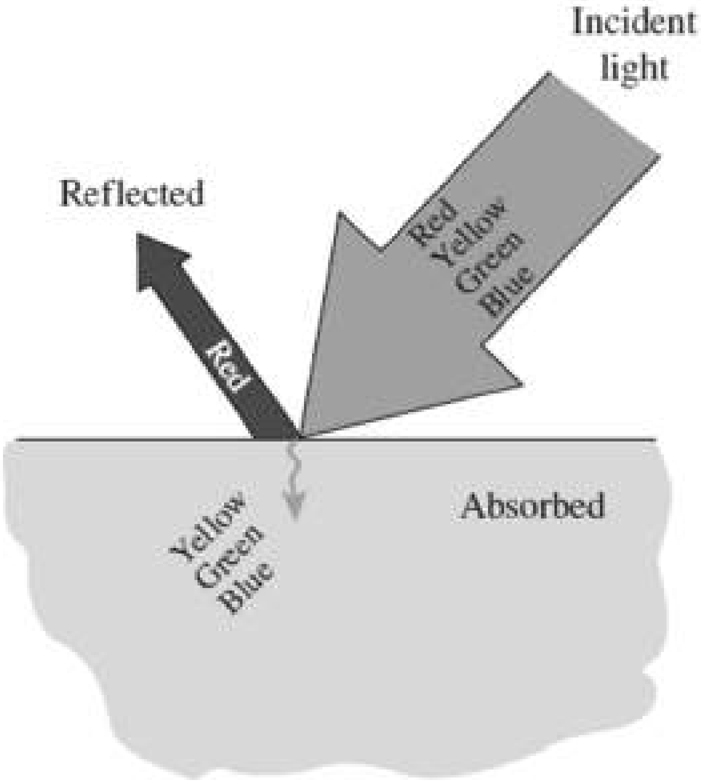


Figure 3-5
A surface that reflects red while absorbing the remaining parts of the incident light appears red to the eye.

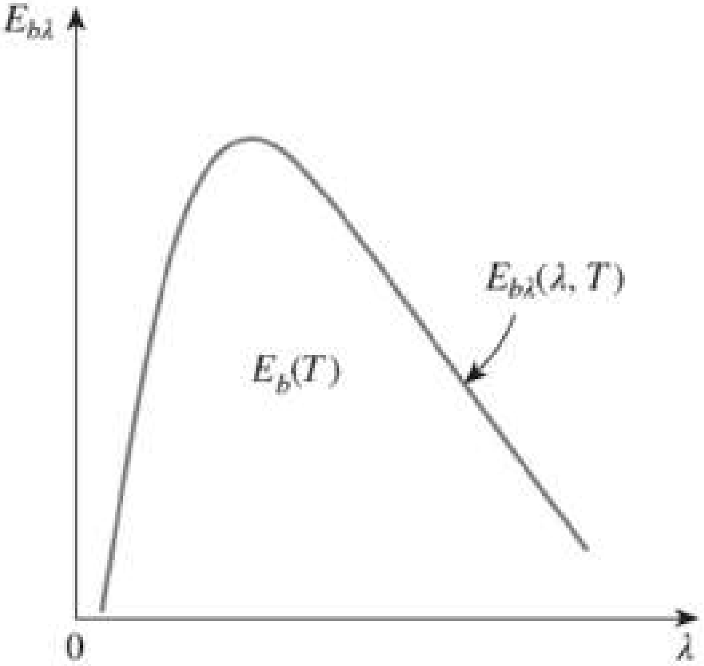


Figure 3-6
On an $E_{b\lambda} - \lambda$ chart, the area under a curve for a given temperature represents the total radiation energy emitted by a blackbody at that temperature.

3-3 RADIATIVE PROPERTIES

Most materials encountered in practice, such as metals, wood, and bricks, are *opaque* to thermal radiation, and radiation is considered to be a *surface phenomenon* for such materials.

Radiation through *semitransparent* materials such as glass and water cannot be considered to be a surface phenomenon since the entire volume of the material interacts with radiation.

A blackbody can serve as a convenient *reference* in describing the emission and absorption characteristics of real surfaces.

Emissivity

Emissivity: The ratio of the radiation emitted by the surface at a given temperature to the radiation emitted by a blackbody at the same temperature.

$$0 \leq \varepsilon \leq 1$$

Emissivity of blackbody: Emissivity is a measure of how closely a surface approximates a blackbody ($\varepsilon = 1$).

Metals generally have low emissivities, as low as 0.02 for polished surfaces, and nonmetals such as ceramics and organic materials have high ones.

Effect of temperature: The emissivity of metals increases with temperature.

Effect of oxidation: Oxidation causes significant increases in the emissivity of metals.

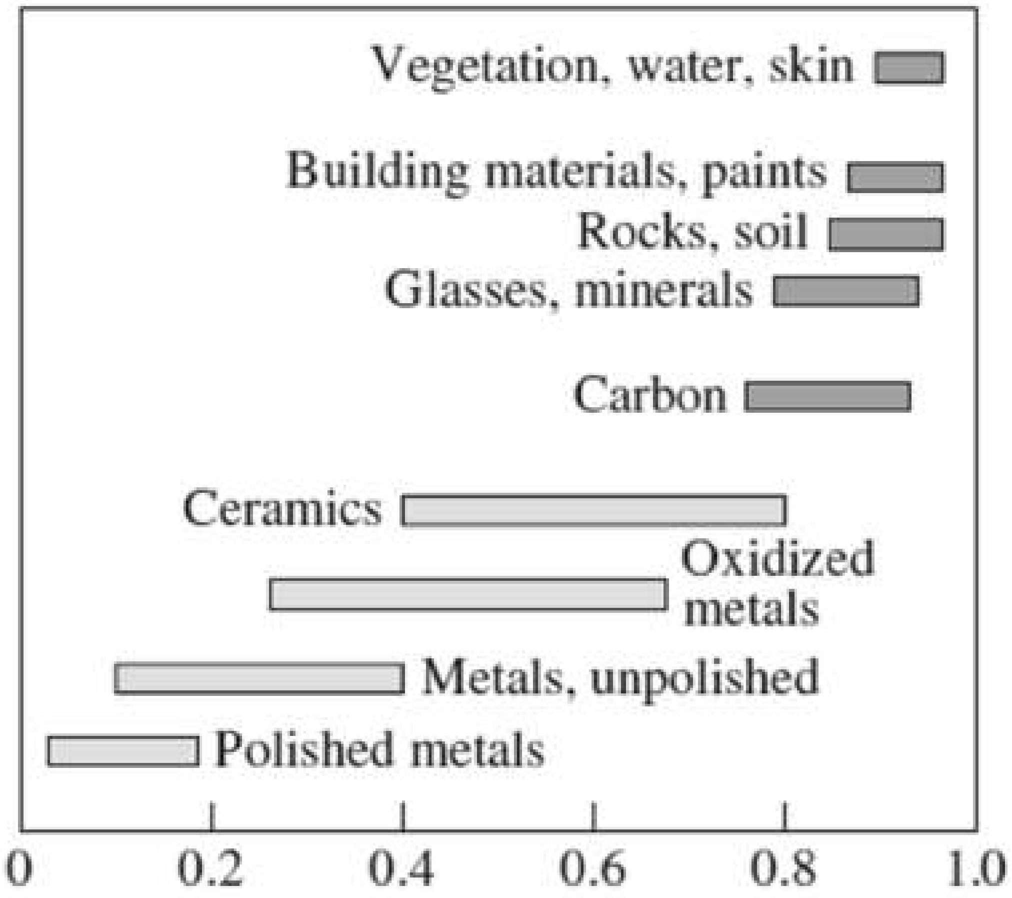


Figure 3-7
Typical ranges of emissivity for various materials.

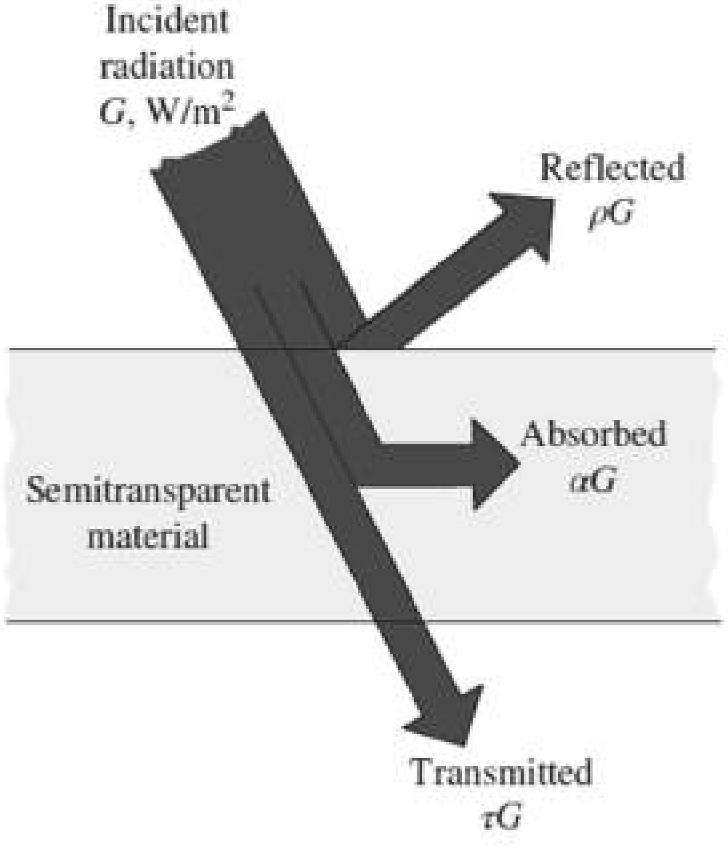
Absorptivity, Reflectivity, and Transmissivity

Absorptivity: $\alpha = \frac{G_{abs}}{G} \qquad 0 < \alpha < 1$

Reflectivity: $\rho = \frac{G_{ref}}{G} \qquad 0 < \rho < 1$

Transmissivity: $\tau = \frac{G_{tr}}{G} \qquad 0 < \tau < 1$

Irradiation, *G*: Radiation flux incident on a surface.



$$G_{abs} + G_{ref} + G_{tr} = G$$

$$\alpha + \rho + \tau = 1$$

$\alpha + \rho = 1$ for opaque surfaces

Figure 3-8
The absorption, reflection, and transmission of incident radiation by a semitransparent material.

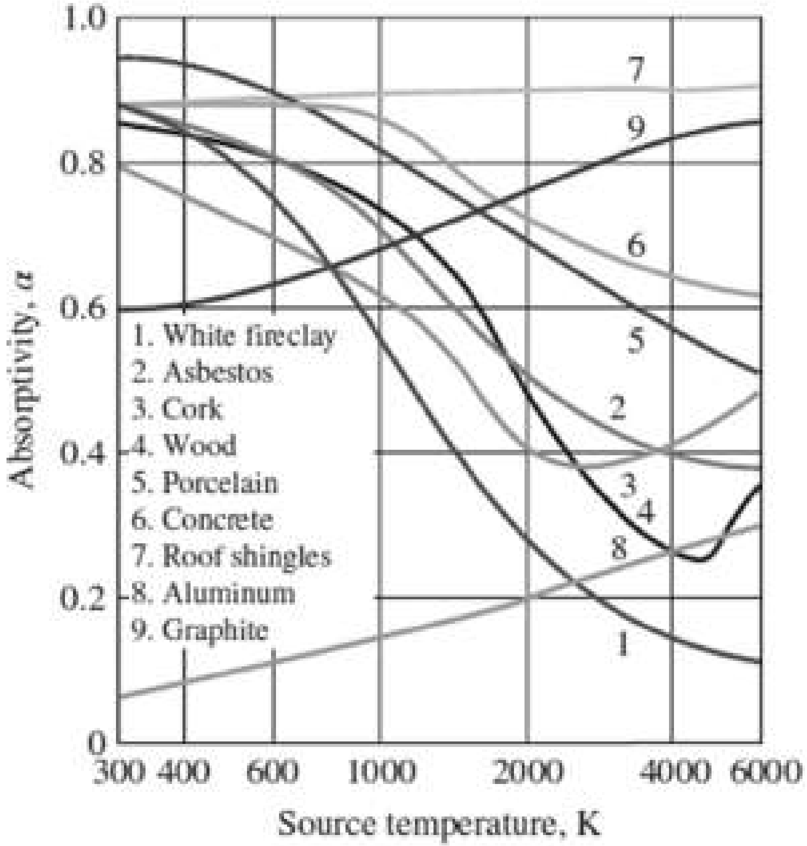


Figure 3-9
Variation of absorptivity with the temperature of the source of irradiation for various common materials at room temperature.

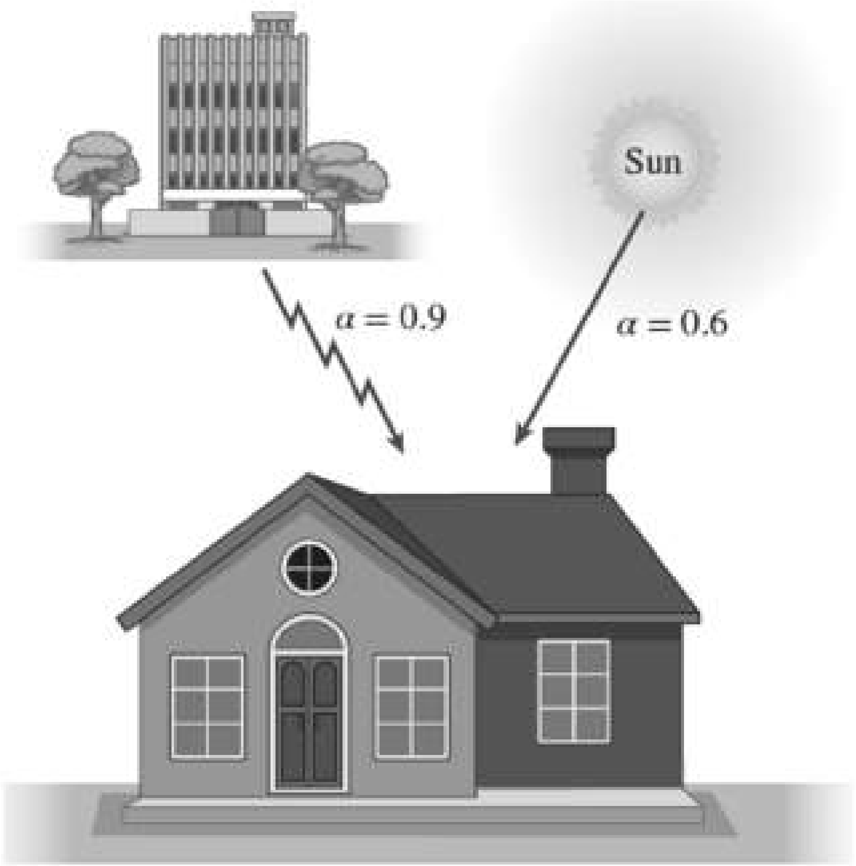


Figure 3-10
The absorptivity of a material may be quite different for radiation originating from sources at different temperatures.

$\varepsilon(T) = \alpha(T)$ Kirchhoff’s law

The emissivity of a surface at temperature *T* is equal to its absorptivity for radiation coming from a blackbody at the same temperature.

This relation is derived under the condition that the surface temperature is equal to the temperature of the source of irradiation, and the reader is cautioned against using it when considerable difference (more than a few hundred degrees) exists between the surface temperature and the temperature of the source of irradiation.

The Greenhouse Effect

Glass has a transparent window in the wavelength range 0.3 μm < λ < 3 μm in which over 90% of solar radiation is emitted.

The entire radiation emitted by surfaces at room temperature falls in the infrared region (λ > 3 μm).

Glass allows the solar radiation to enter but does not allow the infrared radiation from the interior surfaces to escape. This causes a rise in the interior temperature as a result of the energy buildup in the car.

This heating effect, which is due to the nongray characteristic of glass (or clear plastics), is known as the greenhouse effect.

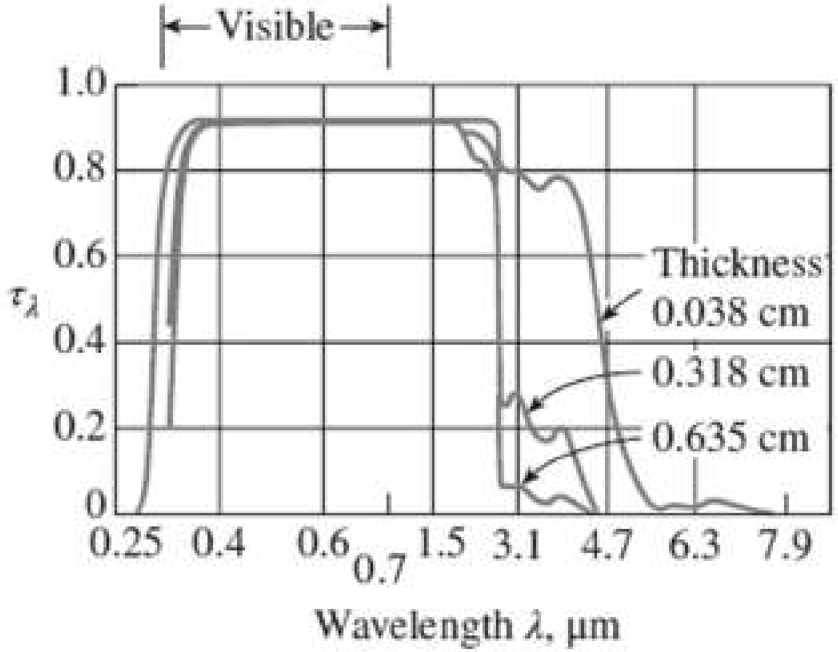


Figure 3-12
The spectral transmissivity of low-iron glass at room temperature for different thicknesses.

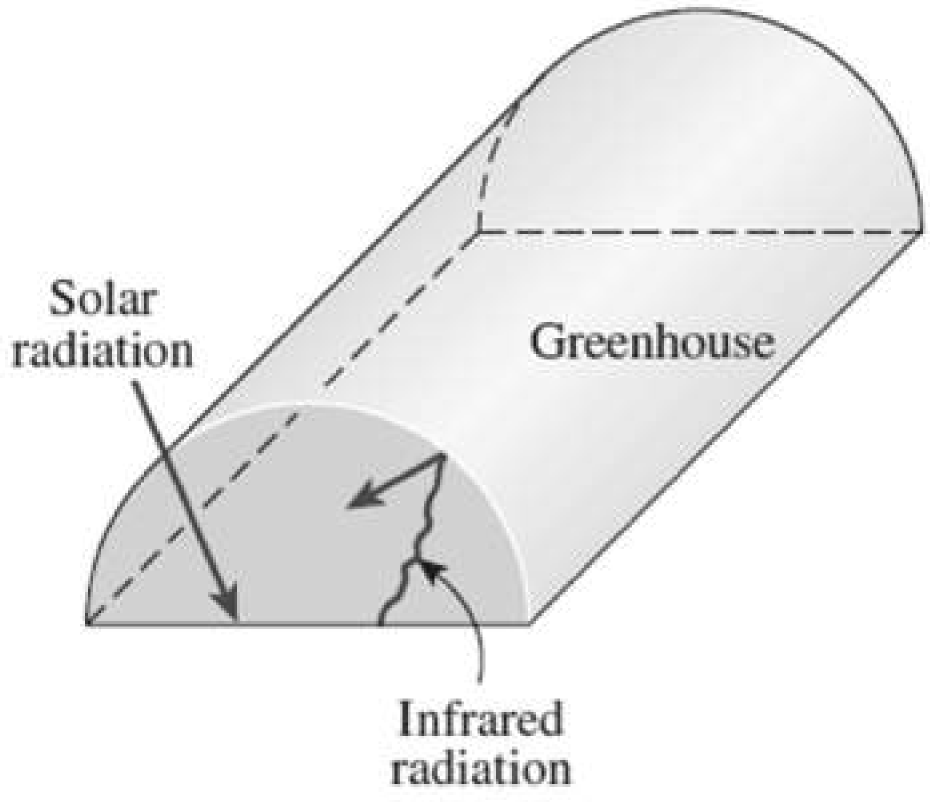


Figure 3-13
A greenhouse traps energy by allowing solar radiation to come in but not allowing IR radiation to go out.

3-4 SOLAR RADIATION

Atmospheric radiation: The radiation energy emitted or reflected by the constituents of the atmosphere.

Fusion: The energy of the sun is due to the continuous *fusion* reaction during which two hydrogen atoms fuse to form one atom of helium.

The sun is essentially a *nuclear reactor,* with temperatures as high as 40,000,000 K in its core region.

The temperature drops to about 5800 K in the outer region of the sun, called the convective zone, as a result of the dissipation of this energy by radiation.

Total solar irradiance G_s: The solar energy reaching the earth’s atmosphere.

Solar constant: The total solar irradiance. It represents the rate at which solar energy is incident on a surface normal to the sun’s rays at the outer edge of the atmosphere when the earth is at its mean distance from the sun.

$$G_s = 1373\ \text{W/m}^2$$

$$G_s = 1373\ \mathrm{W/m^2}$$

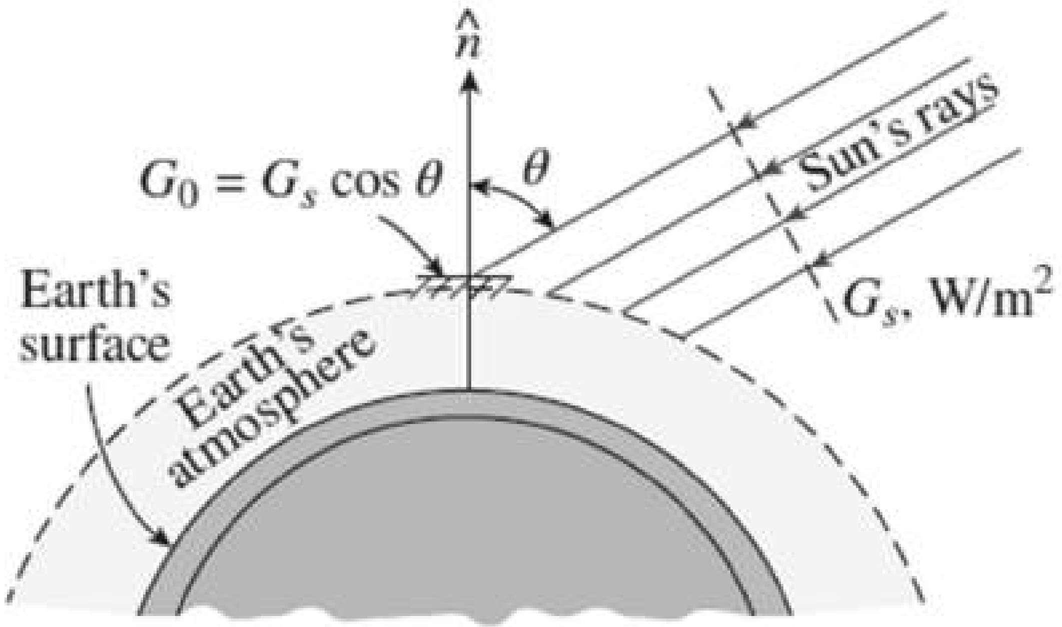
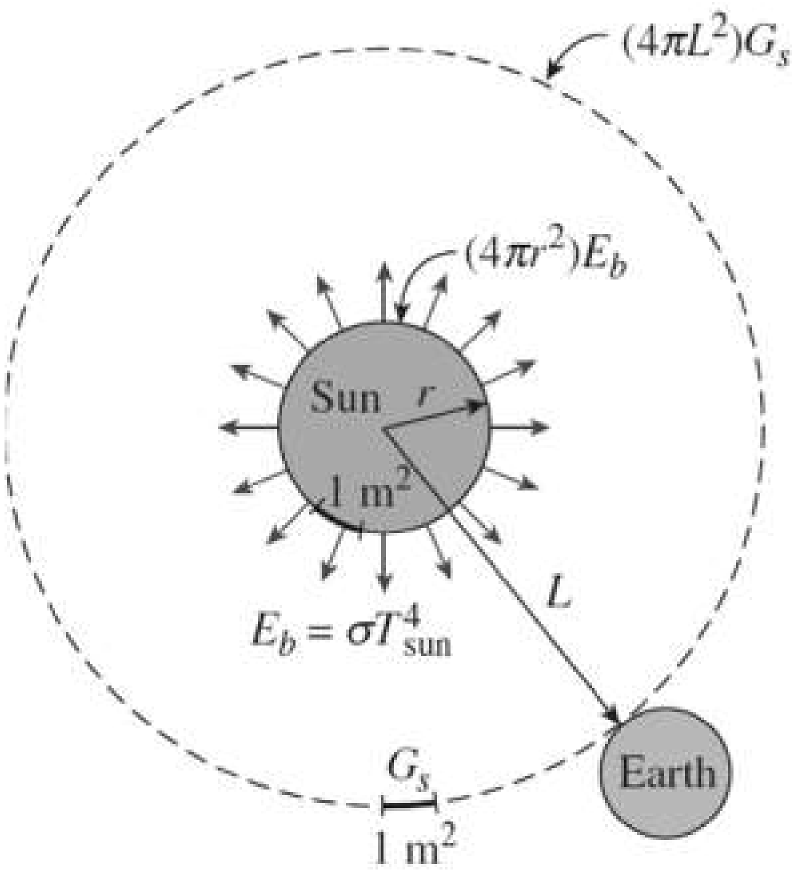


Figure 3-14
Solar radiation reaching the earth's atmosphere and the total solar irradiance.

The value of the total solar irradiance can be used to estimate the effective surface temperature of the sun from this equation:

$$(4\pi L^2)G_s = (4\pi r^2)\sigma T_{\text{sun}}^4$$

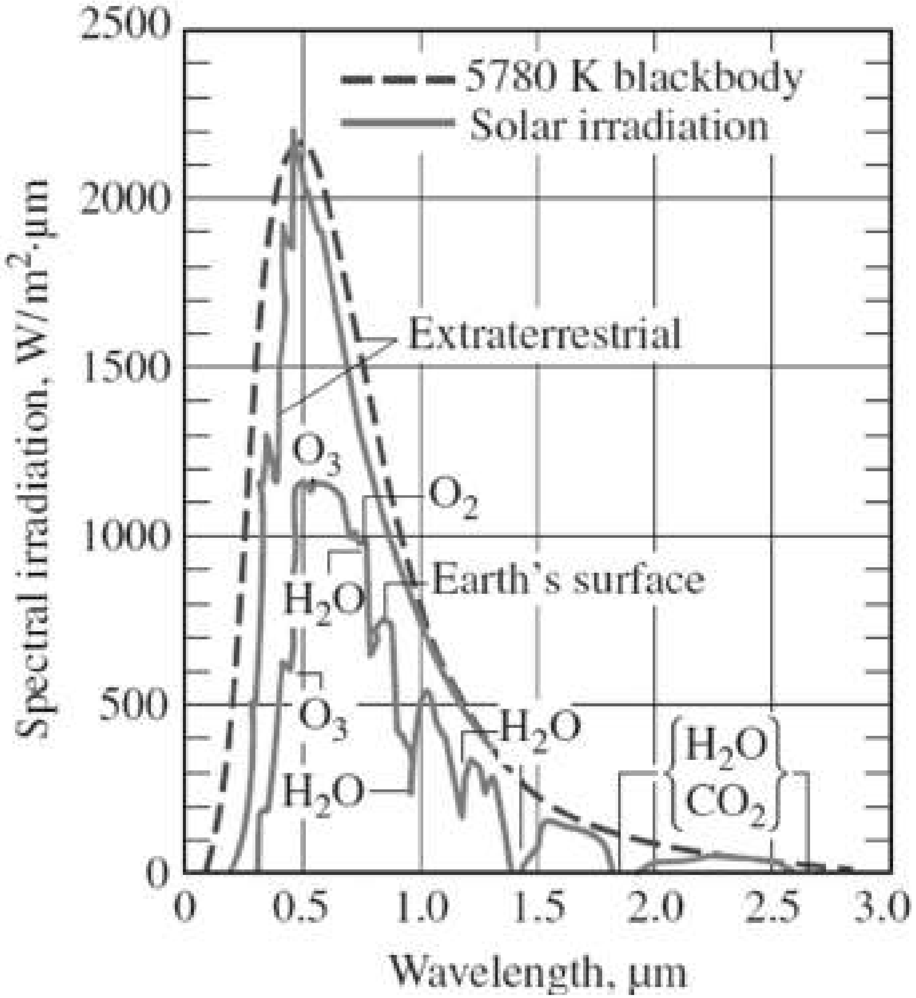
L the mean distance between the sun's center and the earth
r the radius of the sun



The effective surface temperature of the sun is T_{sun}= 5780 K.

The sun can be treated as a blackbody at a temperature of 5780 K.

Figure 3-15
The total solar energy passing through concentric spheres remains constant, but the energy falling per unit area decreases with increasing radius.



The spectral distribution of solar radiation on the ground plotted in Fig. 3-16 shows that the solar radiation undergoes considerable attenuation as it passes through the atmosphere as a result of absorption and scattering.

As a result, the solar energy reaching the earth's surface is weakened considerably, to about 950 W/m^2 on a clear day and much less on cloudy or smoggy days.

Figure 3-16
Spectral distribution of solar radiation just outside the atmosphere, at the surface of the earth on a typical day, and comparison with blackbody radiation at 5780 K.

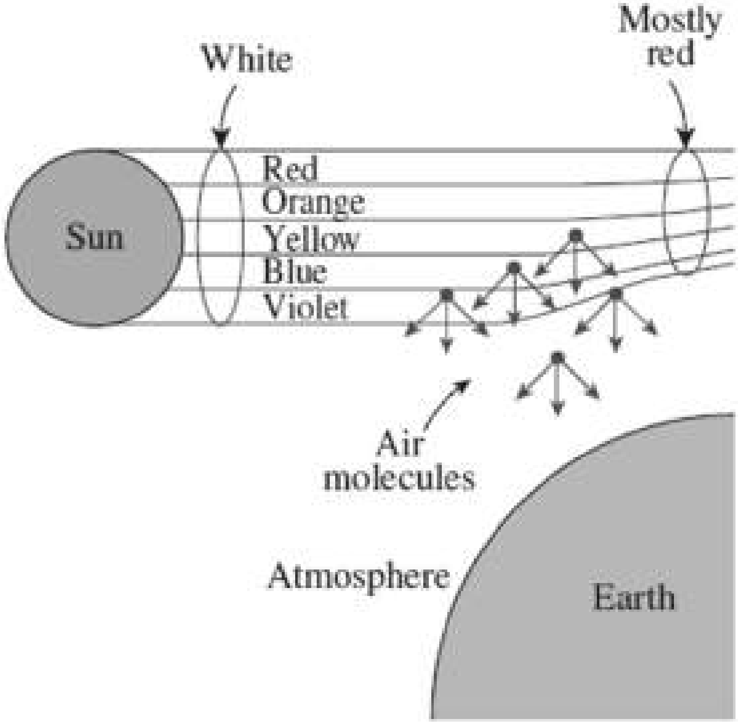


Figure 3-17
Air molecules scatter blue light much more than they do red light. At sunset, light travels through a thicker layer of atmosphere, which removes much of the blue from the natural light, allowing the red to dominate.

Another mechanism that attenuates solar radiation as it passes through the atmosphere is scattering or reflection by air molecules and the many other kinds of particles such as dust, smog, and water droplets suspended in the atmosphere.

The solar energy incident on a surface on earth is considered to consist of *direct* and *diffuse* parts.

Direct solar radiation G_D: The part of solar radiation that reaches the earth's surface without being scattered or absorbed by the atmosphere.

Diffuse solar radiation G_d: The scattered radiation is assumed to reach the earth's surface uniformly from all directions.

The *total* solar energy incident on the unit area of a *horizontal surface* on the ground is

$$G_{\text{solar}} = G_D \cos\theta + G_d$$

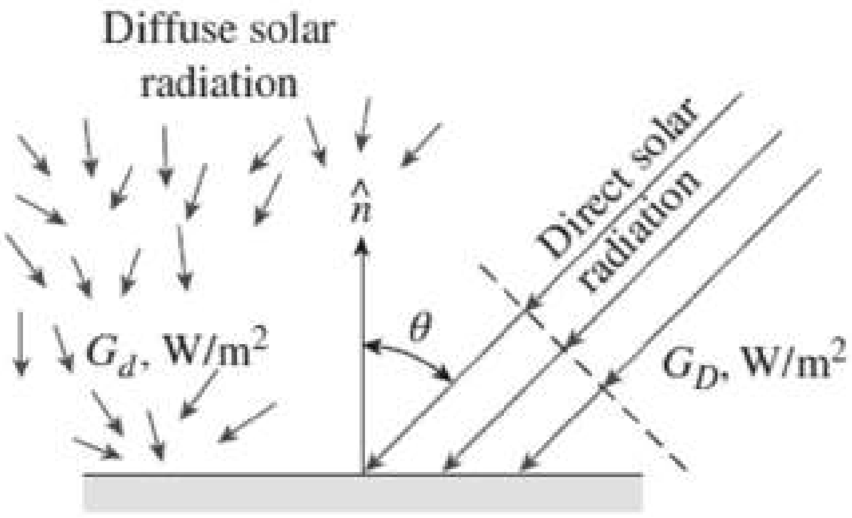


Figure 3-18
The direct and diffuse radiation incident on a horizontal surface on earth's surface.

It is found convenient in radiation calculations to treat the atmosphere as a blackbody at some lower fictitious temperature that emits an equivalent amount of radiation energy. This fictitious temperature is called the effective sky temperature T_{sky}. The radiation emission from the atmosphere to the earth's surface is

$$G_{sky} = \sigma T_{sky}^4 \qquad (W/m^2)$$

The value of T_{sky} depends on the atmospheric conditions. It ranges from about 230 K for cold, clear-sky conditions to about 285 K for warm, cloudy-sky conditions.

$$E_{sky,absorbed} = \alpha G_{sky} = \alpha \sigma T_{sky}^4 = \varepsilon \sigma T_{sky}^4 \qquad (W/m^2)$$

Net rate of radiation heat transfer to a surface exposed to solar and atmospheric radiation

$$\dot{q}_{net,rad} = E_{solar,absorbed} + E_{sky,absorbed} - E_{emitted}$$

$$= \alpha_s G_{solar} + \varepsilon \sigma T_{sky}^4 - \varepsilon \sigma T_s^4$$

$$= \alpha_s G_{solar} + \varepsilon \sigma (T_{sky}^4 - T_s^4)$$

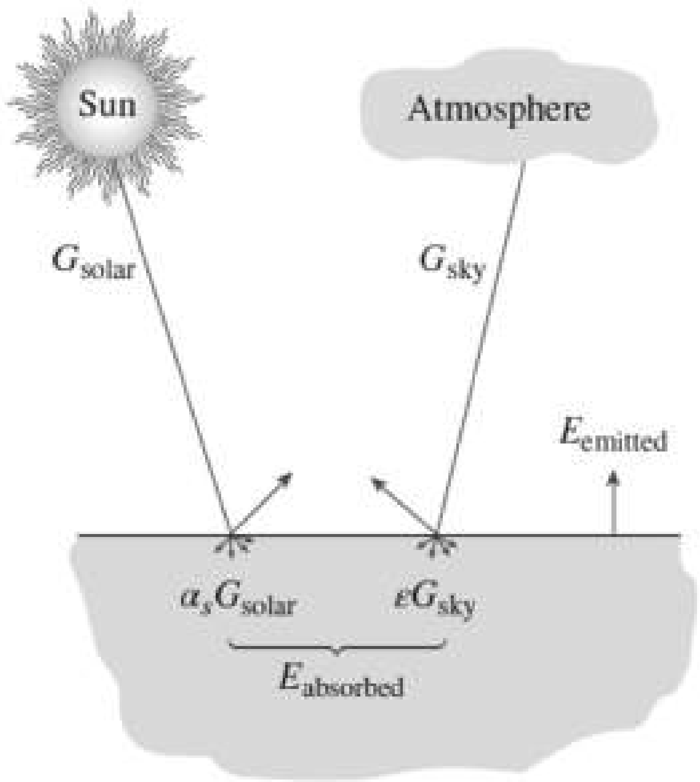


Figure 3-19
Radiation interactions of a surface exposed to solar and atmospheric radiation.

The absorption and emission of radiation by the *elementary gases* such as H_2, O_2, and N_2 at moderate temperatures are negligible, and a medium filled with these gases can be treated as a *vacuum* in radiation analysis.

The absorption and emission of gases with *larger molecules* such as H_2O and CO_2, however, can be *significant* and may need to be considered when considerable amounts of such gases are present in a medium.

For example, a 1-m-thick layer of water vapor at 1 atm pressure and 100°C emits more than 50 percent of the energy that a blackbody would emit at the same temperature.

The radiation properties of surfaces are quite different for the incident and emitted radiation.

The surfaces are assumed to have two sets of properties:

- one for solar radiation

- another for infrared radiation at room temperature.

Surfaces that are intended to collect solar energy, such as the absorber surfaces of solar collectors, are desired to have high solar absorptivity but low emissivity values to maximize the absorption of solar radiation and to minimize the emission of radiation.

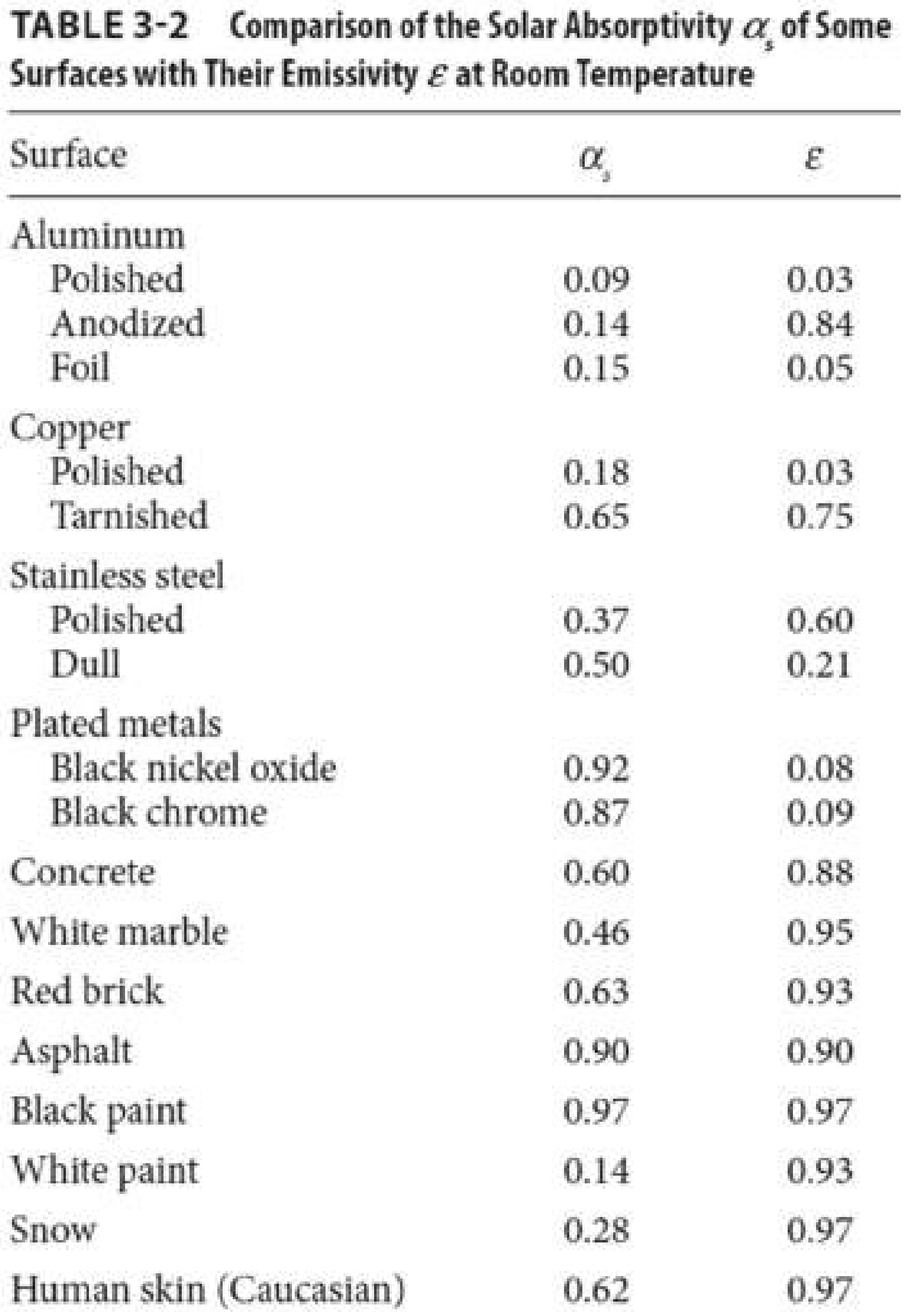


TABLE 3-2 Comparison of the Solar Absorptivity α_s of Some Surfaces with Their Emissivity ε at Room Temperature

Surface	α_s	ε
Aluminum		
Polished	0.09	0.03
Anodized	0.14	0.84
Foil	0.15	0.05
Copper		
Polished	0.18	0.03
Tarnished	0.65	0.75
Stainless steel		
Polished	0.37	0.60
Dull	0.50	0.21
Plated metals		
Black nickel oxide	0.92	0.08
Black chrome	0.87	0.09
Concrete	0.60	0.88
White marble	0.46	0.95
Red brick	0.63	0.93
Asphalt	0.90	0.90
Black paint	0.97	0.97
White paint	0.14	0.93
Snow	0.28	0.97
Human skin (Caucasian)	0.62	0.97

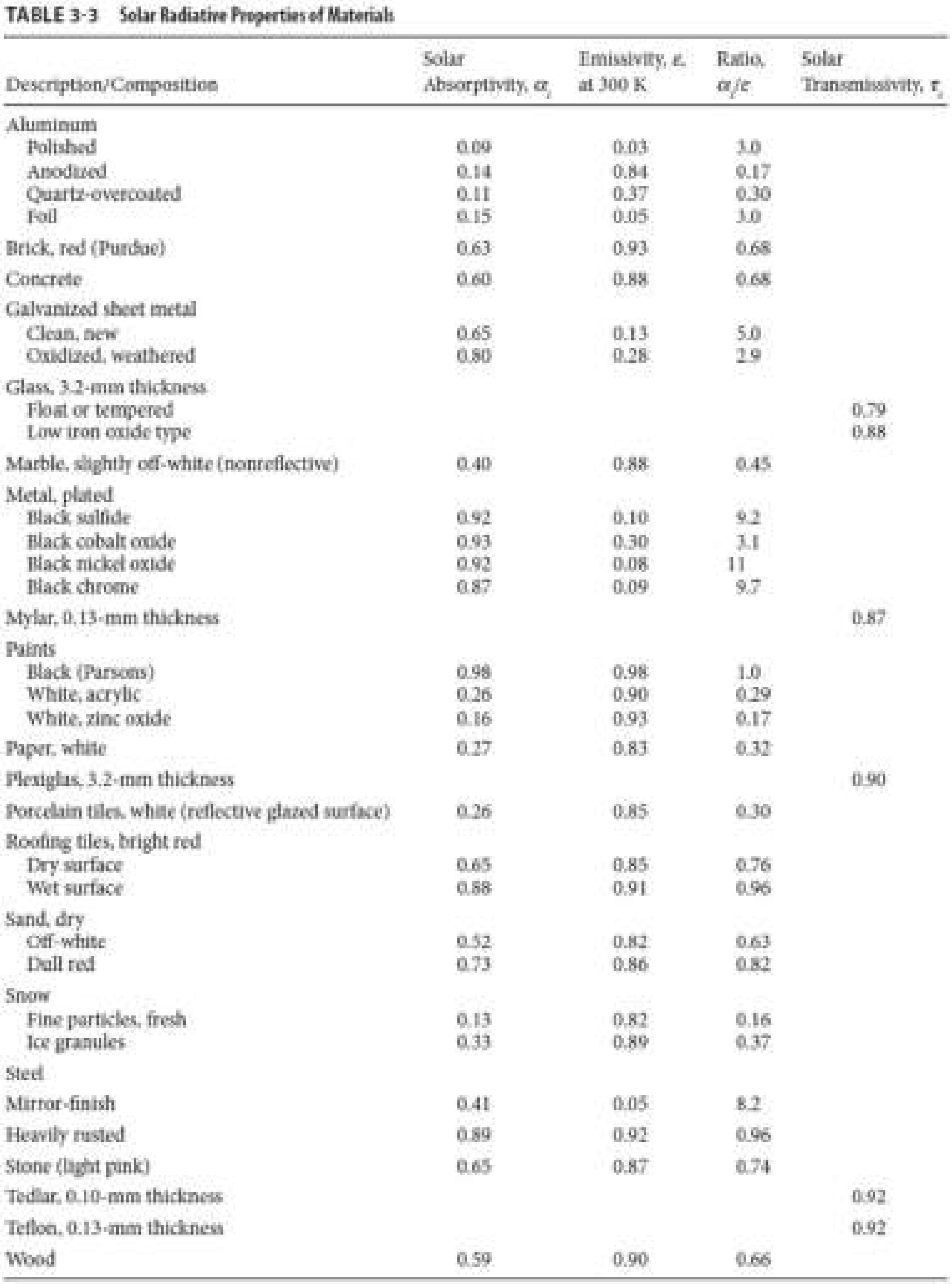


TABLE 3-3 Solar Radiative Properties of Materials

Description/Composition	Solar Absorptivity, α_s	Emissivity, ε, at 300 K	Ratio, α_s/ε	Solar Transmissivity, τ_s
Aluminum				
Polished	0.09	0.03	3.0	
Anodized	0.14	0.84	0.17	
Quartz-overcoated	0.11	0.37	0.30	
Foil	0.15	0.05	3.0	
Brick, red (Purdue)	0.63	0.93	0.68	
Concrete	0.60	0.88	0.68	
Galvanized sheet metal				
Clean, new	0.65	0.13	5.0	
Oxidized, weathered	0.80	0.28	2.9	
Glass, 3.2-mm thickness				
Float or tempered				0.79
Low iron oxide type				0.88
Marble, slightly off-white (nonreflective)	0.40	0.88	0.45	
Metal, plated				
Black sulfide	0.92	0.10	9.2	
Black cobalt oxide	0.93	0.30	3.1	
Black nickel oxide	0.92	0.08	11	
Black chrome	0.87	0.09	9.7	
Mylar, 0.13-mm thickness				0.87
Paints				
Black (Parsons)	0.98	0.98	1.0	
White, acrylic	0.26	0.90	0.29	
White, zinc oxide	0.16	0.93	0.17	
Paper, white	0.27	0.83	0.32	
Plexiglas, 3.2-mm thickness				0.90
Porcelain tiles, white (reflective glazed surface)	0.26	0.85	0.30	
Roofing tiles, bright red				
Dry surface	0.65	0.85	0.76	
Wet surface	0.88	0.91	0.96	
Sand, dry				
Off-white	0.52	0.82	0.63	
Dull red	0.73	0.86	0.82	
Snow				
Fine particles, fresh	0.13	0.82	0.16	
Ice granules	0.33	0.89	0.37	
Steel				
Mirror-finish	0.41	0.05	8.2	
Heavily rusted	0.89	0.92	0.96	
Stone (light pink)	0.65	0.87	0.74	
Tedlar, 0.10-mm thickness				0.92
Teflon, 0.13-mm thickness				0.92
Wood	0.59	0.90	0.66	

3-5 SOLAR DATA

The amount of solar radiation incident on a surface depends on

- orientation of the surface
- the latitude
- elevation of the location
- humidity of air
- clearness of the sky
- the time of the day

Table 3-4: It gives hourly solar radiation incident on various surfaces at 40° latitude. Data is also available at other latitudes.

Table 3-5: Average daily solar radiation values on a horizontal surface in the United States are given for selected cities in Table 3-5.

Extensive solar data at various latitudes and locations are available in literature.

There are also calculation methods of solar radiation input to various surfaces on earth.

TABLE 3-4 Hourly Variation of Solar Radiation Incident on Various Surfaces and the Daily Totals throughout the Year at 40° Latitude (ASHRAE, 1993)

		Solar Radiation Incident on the Surface,[a] W/m^2															
		Solar Time															
Date	Direction of Surface	5	6	7	8	9	10	11	12 noon	13	14	15	16	17	18	19	Daily Total
Jan.	N	0	0	0	20	43	66	68	71	68	66	43	20	0	0	0	446
	NE	0	0	0	63	47	66	68	71	68	59	43	20	0	0	0	489
	E	0	0	0	402	557	448	222	76	68	59	43	20	0	0	0	1863
	SE	0	0	0	483	811	875	803	647	428	185	48	20	0	0	0	4266
	S	0	0	0	271	579	771	884	922	884	771	579	271	0	0	0	5897
	SW	0	0	0	20	48	185	428	647	803	875	811	483	0	0	0	4266
	W	0	0	0	20	43	59	68	76	222	448	557	402	0	0	0	1863
	NW	0	0	0	20	43	59	68	71	68	66	47	63	0	0	0	489
	Horizontal	0	0	0	51	198	348	448	482	448	348	198	51	0	0	0	2568
	Direct	0	0	0	446	753	865	912	926	912	865	753	446	0	0	0	—
Apr.	N	0	41	57	79	97	110	120	122	120	110	97	79	57	41	0	1117
	NE	0	262	508	462	291	134	123	122	120	110	97	77	52	17	0	2347
	E	0	321	728	810	732	552	293	131	120	110	97	77	52	17	0	4006
	SE	0	189	518	682	736	699	582	392	187	116	97	77	52	17	0	4323
	S	0	18	59	149	333	437	528	559	528	437	333	149	59	18	0	3536
	SW	0	17	52	77	97	116	187	392	582	699	736	682	518	189	0	4323
	W	0	17	52	77	97	110	120	392	293	552	732	810	728	321	0	4006
	NW	0	17	52	77	97	110	120	122	123	134	291	462	508	262	0	2347
	Horizontal	0	39	222	447	640	786	880	911	880	786	640	447	222	39	0	6938
	Direct	0	282	651	794	864	901	919	925	919	901	864	794	651	282	0	—
July	N	3	133	109	103	117	126	134	138	134	126	117	103	109	133	3	1621
	NE	8	454	590	540	383	203	144	138	134	126	114	95	71	39	0	3068
	E	7	498	739	782	701	531	294	149	134	126	114	95	71	39	0	4313
	SE	2	248	460	580	617	576	460	291	155	131	114	95	71	39	0	3849
	S	0	39	76	108	190	292	369	395	369	292	190	108	76	39	0	2552
	SW	0	39	71	95	114	131	155	291	460	576	617	580	460	248	2	3849
	W	0	39	71	95	114	126	134	149	294	531	701	782	739	498	7	4313
	NW	0	39	71	95	114	126	134	138	144	203	383	540	590	454	8	3068
	Horizontal	1	115	320	528	702	838	922	949	922	838	702	528	320	115	1	3902
	Direct	7	434	656	762	818	850	866	871	866	850	818	762	656	434	7	—
Oct.	N	0	0	7	40	62	77	87	90	87	77	62	40	7	0	0	453
	NE	0	0	74	178	84	80	87	90	87	87	62	40	7	0	0	869
	E	0	0	163	626	652	505	256	97	87	87	62	40	7	0	0	2578
	SE	0	0	152	680	853	864	770	599	364	137	66	40	7	0	0	4543
	S	0	0	44	321	547	711	813	847	813	711	547	321	44	0	0	5731
	SW	0	0	7	40	66	137	364	599	770	864	853	680	152	0	0	4543
	W	0	0	7	40	62	87	87	97	256	505	652	626	163	0	0	2578
	NW	0	0	7	40	62	87	87	90	87	80	84	178	74	0	0	869
	Horizontal	0	0	14	156	351	509	608	640	608	509	351	156	14	0	0	3917
	Direct	0	0	152	643	811	884	917	927	917	884	811	643	152	0	0	—

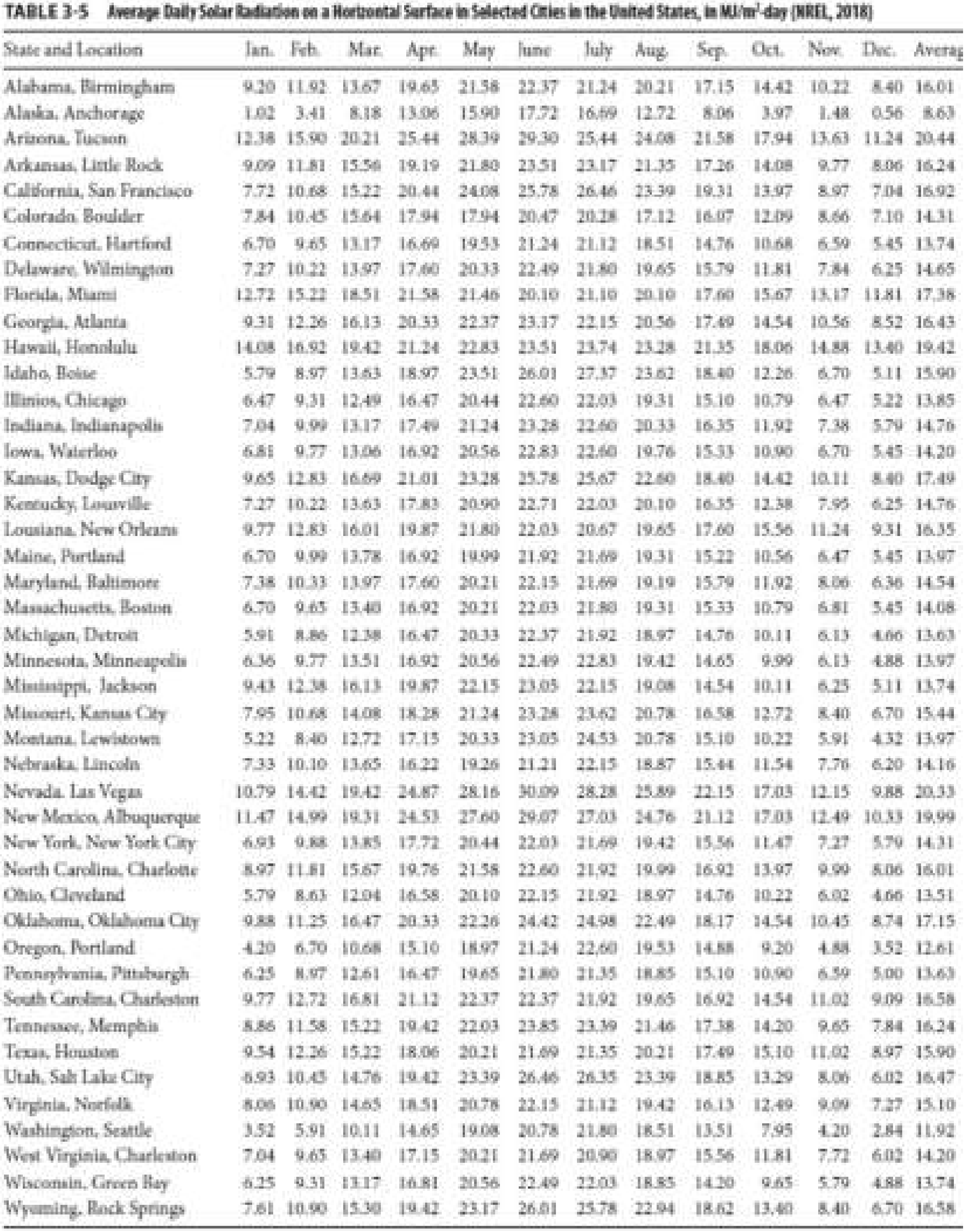
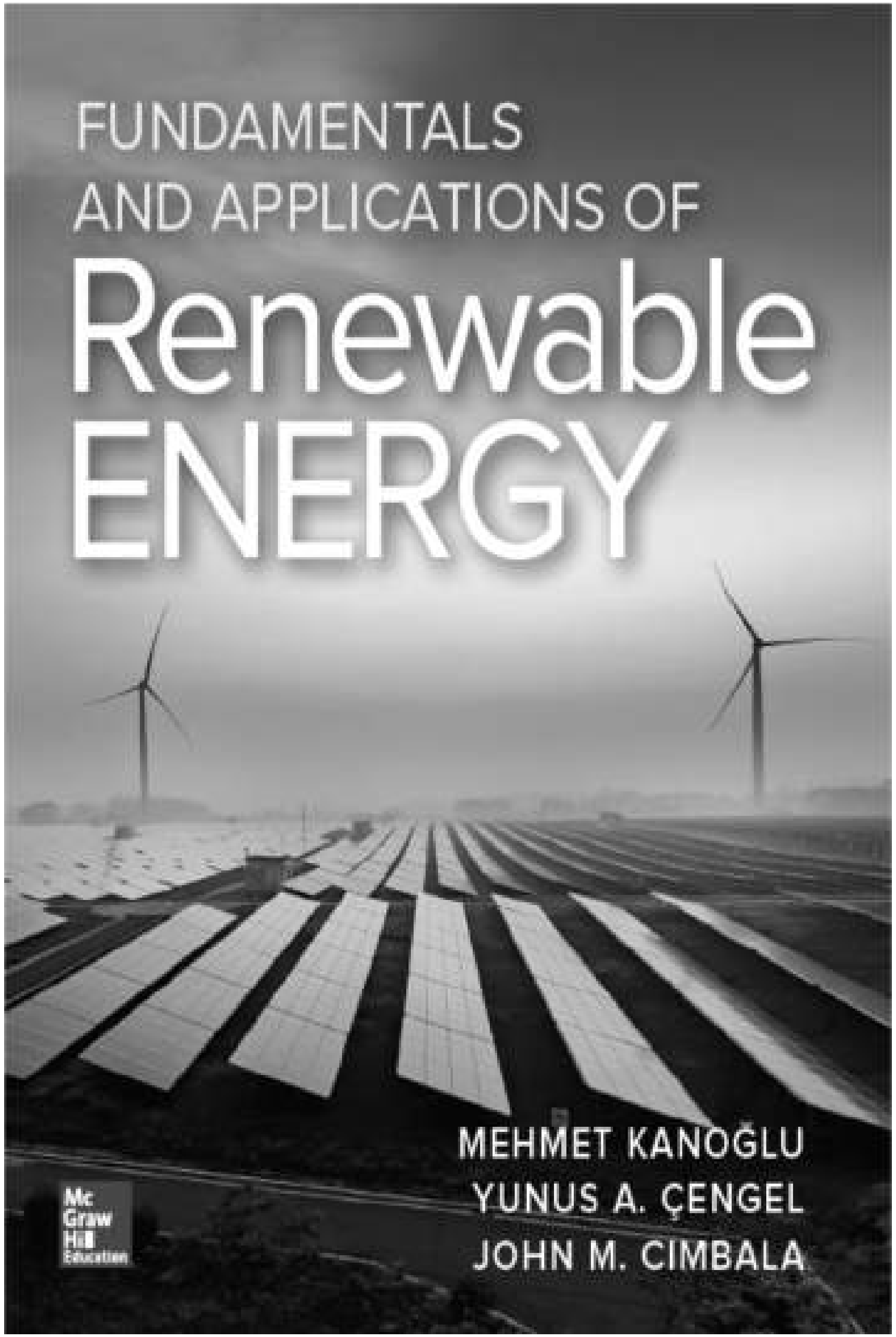


TABLE 3-5 Average Daily Solar Radiation on a Horizontal Surface in Selected Cities in the United States, in MJ/m^2-day (NREL, 2018)

State and Location	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.	Averag
Alabama, Birmingham	9.20	11.92	13.67	19.65	21.58	22.37	21.24	20.21	17.15	14.42	10.22	8.40	16.01
Alaska, Anchorage	1.02	3.41	8.18	13.06	15.90	17.72	16.69	12.72	8.06	3.97	1.48	0.56	8.63
Arizona, Tucson	12.38	15.90	20.21	25.44	28.39	29.30	25.44	24.08	21.58	17.94	13.63	11.24	20.44
Arkansas, Little Rock	9.09	11.81	15.56	19.19	21.80	23.51	23.17	21.35	17.26	14.08	9.77	8.06	16.24
California, San Francisco	7.72	10.68	15.22	20.44	24.08	25.78	26.46	23.39	19.31	13.97	8.97	7.04	16.92
Colorado, Boulder	7.84	10.45	15.64	17.94	17.94	20.47	20.28	17.12	16.07	12.09	8.66	7.10	14.31
Connecticut, Hartford	6.70	9.65	13.17	16.69	19.53	21.24	21.12	18.51	14.76	10.68	6.59	5.45	13.74
Delaware, Wilmington	7.27	10.22	13.97	17.60	20.33	22.49	21.80	19.65	15.79	11.81	7.84	6.25	14.65
Florida, Miami	12.72	15.22	18.51	21.58	21.46	20.10	21.10	20.10	17.60	15.67	13.17	11.81	17.38
Georgia, Atlanta	9.31	12.26	16.13	20.33	22.37	23.17	22.15	20.56	17.49	14.54	10.56	8.52	16.43
Hawaii, Honolulu	14.08	16.92	19.42	21.24	22.83	23.51	23.74	23.28	21.35	18.06	14.88	13.40	19.42
Idaho, Boise	5.79	8.97	13.63	18.97	23.51	26.01	27.37	23.62	18.40	12.26	6.70	5.11	15.90
Illinios, Chicago	6.47	9.31	12.49	16.47	20.44	22.60	22.03	19.31	15.10	10.79	6.47	5.22	13.85
Indiana, Indianapolis	7.04	9.99	13.17	17.49	21.24	23.28	22.60	20.33	16.35	11.92	7.38	5.79	14.76
Iowa, Waterloo	6.81	9.77	13.06	16.92	20.56	22.83	22.60	19.76	15.33	10.90	6.70	5.45	14.20
Kansas, Dodge City	9.65	12.83	16.69	21.01	23.28	25.78	25.67	22.60	18.40	14.42	10.11	8.40	17.49
Kentucky, Louisville	7.27	10.22	13.63	17.83	20.90	22.71	22.03	20.10	16.35	12.38	7.95	6.25	14.76
Lousiana, New Orleans	9.77	12.83	16.01	19.87	21.80	22.03	20.67	19.65	17.60	15.56	11.24	9.31	16.35
Maine, Portland	6.70	9.99	13.78	16.92	19.99	21.92	21.69	19.31	15.22	10.56	6.47	5.45	13.97
Maryland, Baltimore	7.38	10.33	13.97	17.60	20.21	22.15	21.69	19.19	15.79	11.92	8.06	6.36	14.54
Massachusetts, Boston	6.70	9.65	13.40	16.92	20.21	22.03	21.80	19.31	15.33	10.79	6.81	5.45	14.08
Michigan, Detroit	5.91	8.86	12.38	16.47	20.33	22.37	21.92	18.97	14.76	10.11	6.13	4.66	13.63
Minnesota, Minneapolis	6.36	9.77	13.51	16.92	20.56	22.49	22.83	19.42	14.65	9.99	6.13	4.88	13.97
Mississippi, Jackson	9.43	12.38	16.13	19.87	22.15	23.05	22.15	19.08	14.54	10.11	6.25	5.11	13.74
Missouri, Kansas City	7.95	10.68	14.08	18.28	21.24	23.28	23.62	20.78	16.58	12.72	8.40	6.70	15.44
Montana, Lewistown	5.22	8.40	12.72	17.15	20.33	23.05	24.53	20.78	15.10	10.22	5.91	4.32	13.97
Nebraska, Lincoln	7.33	10.10	13.65	16.22	19.26	21.21	22.15	18.87	15.44	11.54	7.76	6.20	14.16
Nevada, Las Vegas	10.79	14.42	19.42	24.87	28.16	30.09	28.28	25.89	22.15	17.03	12.15	9.88	20.33
New Mexico, Albuquerque	11.47	14.99	19.31	24.53	27.60	29.07	27.03	24.76	21.12	17.03	12.49	10.33	19.99
New York, New York City	6.93	9.88	13.85	17.72	20.44	22.03	21.69	19.42	15.56	11.47	7.27	5.79	14.31
North Carolina, Charlotte	8.97	11.81	15.67	19.76	21.58	22.60	21.92	19.99	16.92	13.97	9.99	8.06	16.01
Ohio, Cleveland	5.79	8.63	12.04	16.58	20.10	22.15	21.92	18.97	14.76	10.22	6.02	4.66	13.51
Oklahoma, Oklahoma City	9.88	11.25	16.47	20.33	22.26	24.42	24.98	22.49	18.17	14.54	10.45	8.74	17.15
Oregon, Portland	4.20	6.70	10.68	15.10	18.97	21.24	22.60	19.53	14.88	9.20	4.88	3.52	12.61
Pennsylvania, Pittsburgh	6.25	8.97	12.61	16.47	19.65	21.80	21.35	18.85	15.10	10.90	6.59	5.00	13.63
South Carolina, Charleston	9.77	12.72	16.81	21.12	22.37	22.37	21.92	19.65	16.92	14.54	11.02	9.09	16.58
Tennessee, Memphis	8.86	11.58	15.22	19.42	22.03	23.85	23.39	21.46	17.38	14.20	9.65	7.84	16.24
Texas, Houston	9.54	12.26	15.22	18.06	20.21	21.69	21.35	20.21	17.49	15.10	11.02	8.97	15.90
Utah, Salt Lake City	6.93	10.45	14.76	19.42	23.39	26.46	26.35	23.39	18.85	13.29	8.06	6.02	16.47
Virginia, Norfolk	8.06	10.90	14.65	18.51	20.78	22.15	21.12	19.42	16.13	12.49	9.09	7.27	15.10
Washington, Seattle	3.52	5.91	10.11	14.65	19.08	20.78	21.80	18.51	13.51	7.95	4.20	2.84	11.92
West Virginia, Charleston	7.04	9.65	13.40	17.15	20.21	21.69	20.90	18.97	15.56	11.81	7.72	6.02	14.20
Wisconsin, Green Bay	6.25	9.31	13.17	16.81	20.56	22.49	22.03	18.85	14.20	9.65	5.79	4.88	13.74
Wyoming, Rock Springs	7.61	10.90	15.30	19.42	23.17	26.01	25.78	22.94	18.62	13.40	8.40	6.70	16.58



Chapter 4
SOLAR ENERGY APPLICATIONS

Fundamentals and Applications of
Renewable Energy
Mehmet Kanoglu
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John M. Cimbala
McGraw-Hill, 2020

4-1 INTRODUCTION

Advantages of solar: Solar energy is free and nonpolluting.

Disadvantages of solar: The rate of solar radiation on a unit surface is quite low and solar collectors with large surface areas must be installed.

This is costly and requires a lot of space.

It is available in reasonable quantities only in certain locations of the world and certain seasons of the year and times of the day.

Heating of buildings is not needed in summer when solar energy is readily available.

Can we use solar for cooling? Solar heat can be used for cooling applications by absorption cooling systems but they are complex devices involving high initial cost.

Can solar energy be stored? Storage of solar energy for nighttime use is an option to tackle noncontinuous feature of solar energy but this adds to system cost.

Solar vision: We should try to get the best out of solar energy by utilizing the most current technologies and continue to work on improving the solar systems and making them more cost-effective.

Potential of solar: Solar energy has the most potential among all energy sources and there is no limit to how much of it can be utilized for our energy needs.

Cost: The cost of solar systems has been steadily decreasing.

Methods of converting solar energy into other useful forms of energy:

Heliochemical process: Basically photosynthesis process, and it is responsible for the production of fossil fuel and biomass.

Heliothermal process: Solar energy is collected and converted to thermal energy or heat.

Flat-plate collectors, concentrating collectors, and heliostats are common devices that collect solar radiation for conversion to useful heat.

Solar collectors are used for space and water heating and space cooling.

Heliostats are mirrors that reflect solar radiation into a single receiver. The resulting high temperature thermal energy is converted to electricity by a heat engine.

Helioelectrical process: The production of electricity by photovoltaic or solar cells.

Difference between heliostat and solar cell: Solar energy is converted to electricity directly in solar cells while it is first converted to thermal energy in heliostats.

Flat-plate collector: The single most common application of solar energy . It is used to meet hot water needs of residential and commercial buildings.

This method of obtaining hot water is cost-effective.

Solar photovoltaic cells: They are becoming more common despite their high cost. Solar cells are already cost-effective for off-grid electricity applications.

Heliostat: Solar thermal power plants utilizing heliostats require large investments with large areas and there have been only few such installations worldwide.

Solar engineering processes can be divided into two main categories :

Active solar applications: They involve some mechanical/electrical operation and device such as a pump in the system, and they include almost all solar collector, solar cell, and heliostat applications.

Active solar applications: Any application that aims to utilize solar energy by passive design of a system.

The architectural design of a house to collect most of solar energy in winter to reduce heating cost can be achieved by correct orientation of buildings, selection of correct wall materials with proper wall surface properties.

The selection of correct windows with proper glazing can help

- *maximize solar heat gain in winter*
- *minimize solar heat gain in summer*

Trombe wall: The use of trombe wall on south walls can maximize the dissipation of solar heat into the house even after daytime hours.

Capturing solar energy and producing useful energy from it requires some special devices.

Hot water: Most solar collectors in operation today are used to produce hot water.

This hot water is used in residential and commercial buildings for kitchen use, bathroom use, shower, etc.

Process heating: Another use of solar hot water is process heating in industrial facilities.

Space heating: Solar collectors can also be used for space heating in winter.

Most solar heat is available in summer when space heating is not needed.

Most solar collectors are used to produce hot water, and they are very common in southern Europe and Asia.

4-2 FLAT-PLATE SOLAR COLLECTOR

Figure 4-1
Solar water collectors on the roof of residential buildings

A thermosyphon solar water heater system: It operates on a natural circulation.

An active, closed loop solar water heater: It uses a pump for the circulation of water containing antifreeze fluid.

The use of antifreeze fluid ensures that there is no freezing during subfreezing ambient temperatures.

Water containing antifreeze is heated in the collector and gives up its heat to water in a heat exchanger.

The resulting hot water is used in the residence.

This system may be equipped with an electric resistance heater to provide hot water when solar energy is not available.

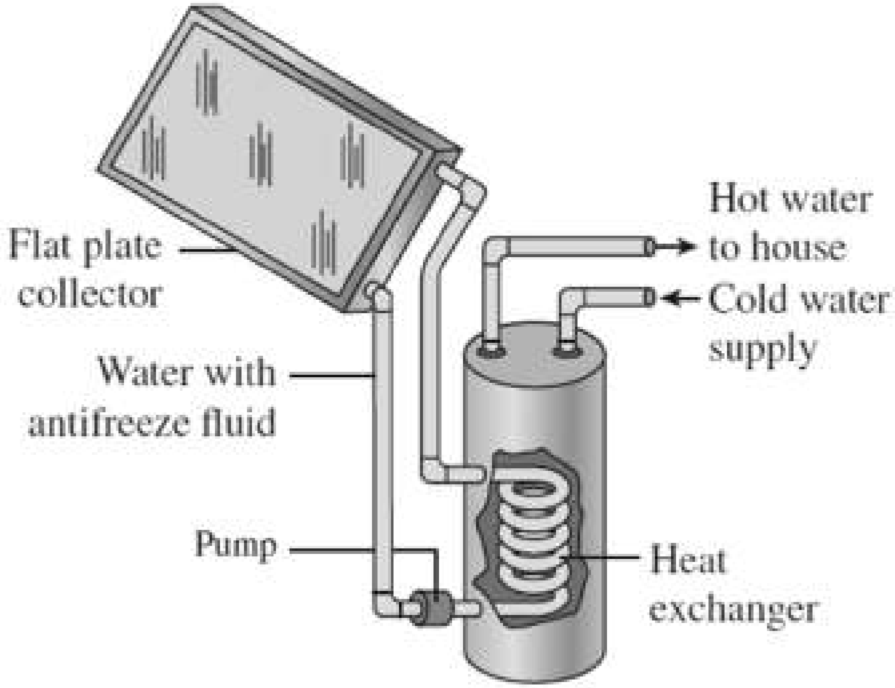


Figure 4-2
An active, closed loop solar water heater.

A flat-plate collector consists of

- glazing
- absorber plate
- flow tubes
- insulation
- glazing frame
- box enclosure

Absorber plate: absorbs solar energy transmitted through the glazing, which is a type of glass.

Flow tubes: are attached to the absorber plate and water is heated as it flows in the tubes by absorbing heat from the absorber plate.

Sides and back are insulated to minimize heat losses.

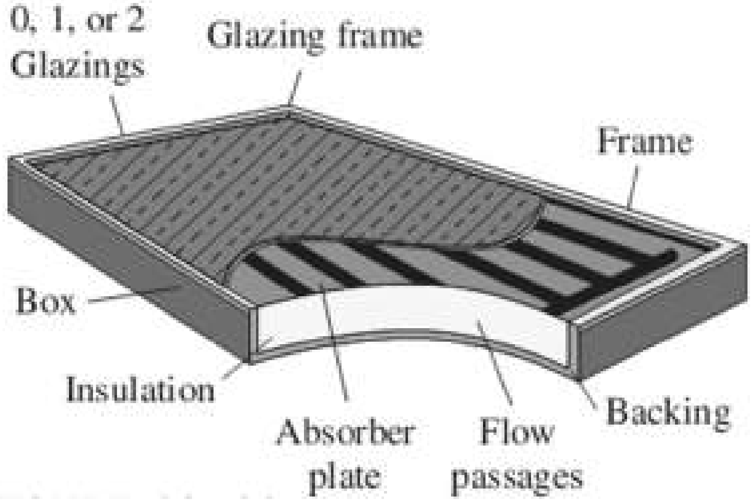


Figure 4-3
The cutaway view of a flat-plate solar collector.

Rate of solar heat absorbed by the absorber plate

$$\dot{Q}_{\text{abs}} = \tau \alpha A G$$

τ the transmissivity of the glazing

α the absorptivity of the absorber plate

A the area of the collector surface, in m^2

G the solar insolation or irradiation (solar radiation incident per unit surface area), in W/m^2

$$\dot{Q}_{\text{abs}} = \tau\alpha AG$$

The rate of solar heat absorbed by the absorber plate

$$\dot{Q}_{\text{loss}} = UA(T_c - T_a)$$

Heat loss from the collector by convection to the surrounding air and by radiation to the surrounding surfaces and sky

$$\begin{aligned} \dot{Q}_{\text{useful}} &= \dot{Q}_{\text{abs}} - \dot{Q}_{\text{loss}} \\ &= \tau\alpha AG - UA(T_c - T_a) \\ &= A[\tau\alpha G - U(T_c - T_a)] \end{aligned}$$

The useful heat transferred to the water is the difference between the heat absorbed and the heat lost

$$\dot{Q}_{\text{useful}} = \dot{m}c_p(T_{w,\text{out}} - T_{w,\text{in}})$$

If the mass flow rate of water flowing through the collector is known

U heat loss coefficient, W/m^2·°C.

c_p specific heat of water, J/kg·°C.

T_c average collector temperature, °C

T_a air temperature, °C

$T_{w,in}$, ***$T_{w,out}$*** inlet and outlet water temperatures, °C

The efficiency of a solar collector is the ratio of the useful heat delivered to water to the radiation incident on the collector:

$$\eta_c = \frac{\dot{Q}_{\text{useful}}}{\dot{Q}_{\text{incident}}} = \frac{\tau\alpha AG - UA(T_c - T_a)}{AG} = \tau\alpha - U\frac{T_c - T_a}{G}$$

Collector efficiency as a function of average temperature of the collector

$$\eta_c = \frac{\dot{Q}_{\text{useful}}}{\dot{Q}_{\text{incident}}} = \frac{\tau\alpha AG - UA(T_c - T_a)}{AG} = \tau\alpha - U\frac{T_c - T_a}{G}$$

If the collector efficiency is plotted against the term $(T_c - T_a)/G$, we obtain a straight line. The slope of this line is equal to $-U$.

An unglazed collector allows more solar radiation input to the collector due to higher $\tau\alpha$ values but also involves higher heat transfer coefficients.

Even though the $\tau\alpha$ values go down slightly from no glazing to single and double glazing cases, the U value decreases much more significantly.

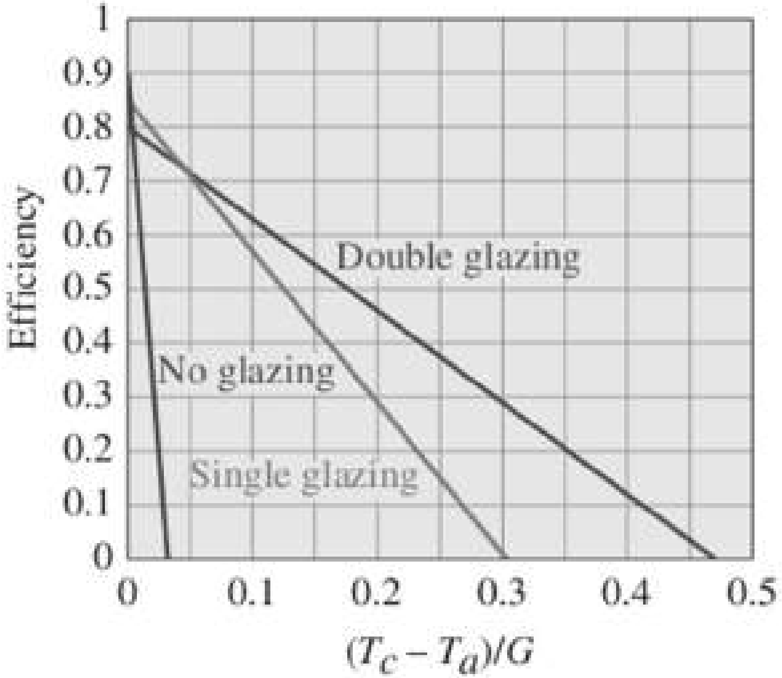


Figure 4-4
Collector efficiency for three different collectors.

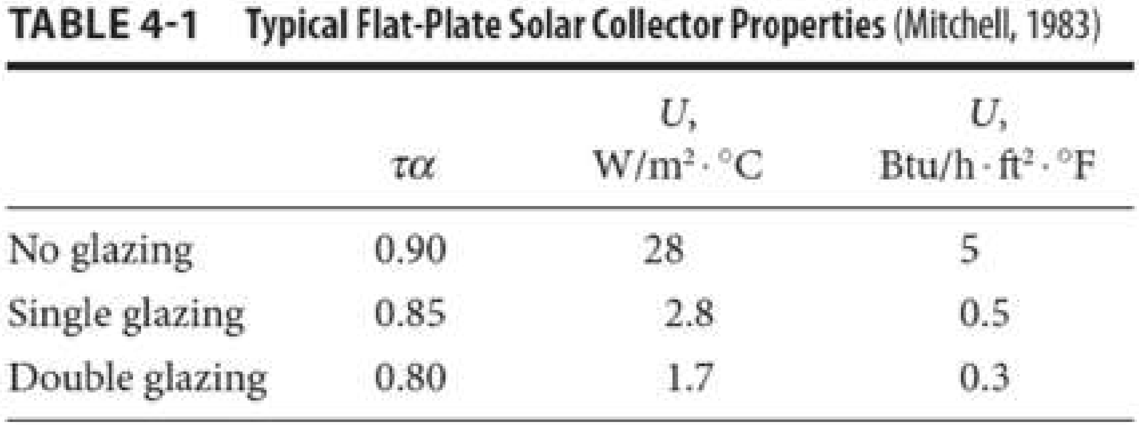
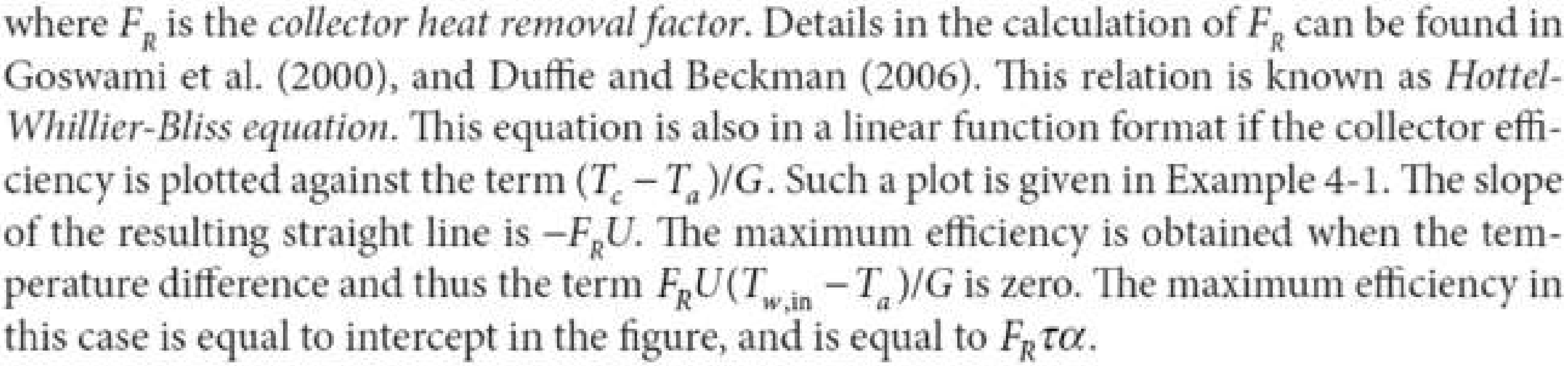


TABLE 4-1 Typical Flat-Plate Solar Collector Properties (Mitchell, 1983)

	$\tau\alpha$	U, W/m²·°C	U, Btu/h·ft²·°F
No glazing	0.90	28	5
Single glazing	0.85	2.8	0.5
Double glazing	0.80	1.7	0.3

When water temperature at the collector inlet is available, the collector efficiency may be defined as a function of the water inlet temperature

$$\eta_c = F_R\tau\alpha - F_RU\frac{T_{w,\text{in}} - T_a}{G}$$



where F_R is the *collector heat removal factor*. Details in the calculation of F_R can be found in Goswami et al. (2000), and Duffie and Beckman (2006). This relation is known as *Hottel-Whillier-Bliss equation*. This equation is also in a linear function format if the collector efficiency is plotted against the term $(T_c - T_a)/G$. Such a plot is given in Example 4-1. The slope of the resulting straight line is $-F_RU$. The maximum efficiency is obtained when the temperature difference and thus the term $F_RU(T_{w,\text{in}} - T_a)/G$ is zero. The maximum efficiency in this case is equal to intercept in the figure, and is equal to $F_R\tau\alpha$.

The solar collector is normally fixed in position. As the angle of solar incident radiation changes throughout the day, the product $\tau\alpha$ also changes.

This change can be accounted for by including an incident angle modifier $\boldsymbol{K}_{\tau\alpha}$

$$\eta_c = F_R K_{\tau\alpha} \tau\alpha - F_R U \frac{T_{w,\text{in}} - T_a}{G}$$

The value of $K_{\tau\alpha}$ is a function of the incident angle.

The standard collector test data are normally based on a value of 1 for $K_{\tau\alpha}$.

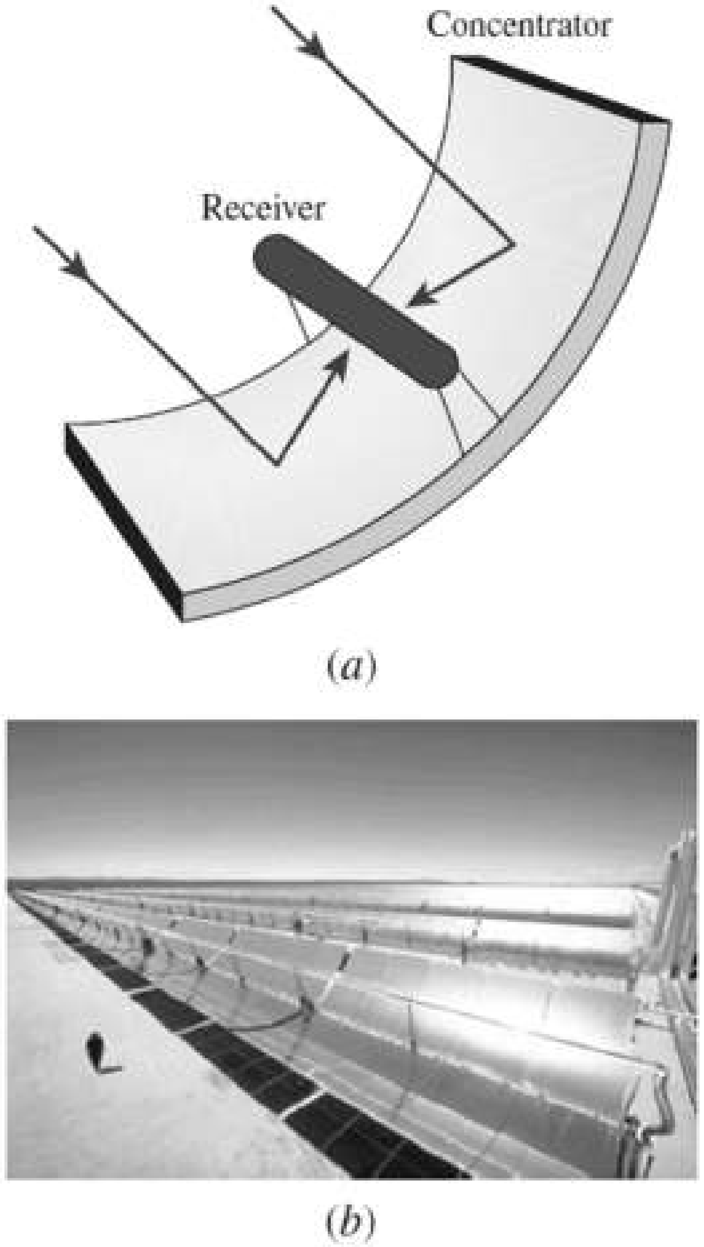
4-3 CONCENTRATİNG SOLAR COLLECTOR

For higher temperatures: Hot fluid (water, steam, air, or another fluid) at much higher temperatures can be produced using concentrating collectors by concentrating solar radiation on a smaller area.

Parabolic trough collector: The most common type of concentrating solar collector.

Concentration factor: In a concentrating collector, solar radiation is incident on the collector surface, called aperture area A_a and this radiation reflected or redirected into a smaller receiver area A_r. The concentration factor CR is greater than one.

$$\mathrm{CR} = \frac{A_a}{A_r}$$



(a)

(b)

Figure 4-6
Parabolic trough collector.

The effectiveness of the aperture-to-receiver process is functions of orientation of surfaces and their radiative properties such as absorptivity and reflectivity. This effectiveness is expressed by an **optical efficiency** term η_{ar} .

$$\dot{Q}_r = \eta_{ar} A_a G$$

Net rate of solar radiation supplied to the receiver

$$\dot{Q}_{\text{loss}} = UA_r(T_c - T_a)$$

The rate of heat loss from the collector

$$\dot{Q}_{\text{useful}} = \dot{Q}_r - \dot{Q}_{\text{loss}} = \eta_{ar} A_a G - UA_r(T_c - T_a)$$

The useful heat transferred to the fluid

$$\eta_c = \frac{\dot{Q}_{\text{useful}}}{\dot{Q}_{\text{incident}}} = \frac{\eta_{ar} A_a G - UA_r(T_c - T_a)}{A_a G}$$

$$= \eta_{ar} - \frac{UA_r(T_c - T_a)}{A_a G} = \eta_{ar} - \frac{U(T_c - T_a)}{\text{CR} \times G}$$

Collector efficiency: The ratio of the useful heat delivered to the fluid to the radiation incident on the collector

η_{ar}	optical efficiency	A_a	aperture area, m^2
A_r	receiver area, m^2	G	incident radiation, W/m^2
U	heat loss coefficient, W/m$^2\cdot$°C.	T_c	average collector temperature, °C
T_a	air temperature, °C	**CR** (= A_a/A_r)	concentration factor

If the collector efficiency is plotted against the term $(T_c - T_a)/(\mathrm{CR} \times G)$, we obtain a straight line. The slope of this line is equal to $-U$.

Temperatures in the receiver of a concentrating collector can reach 400°C.

The heated fluid is usually water and it can be used for space and process heating and cooling or to drive a steam turbine for electricity production.

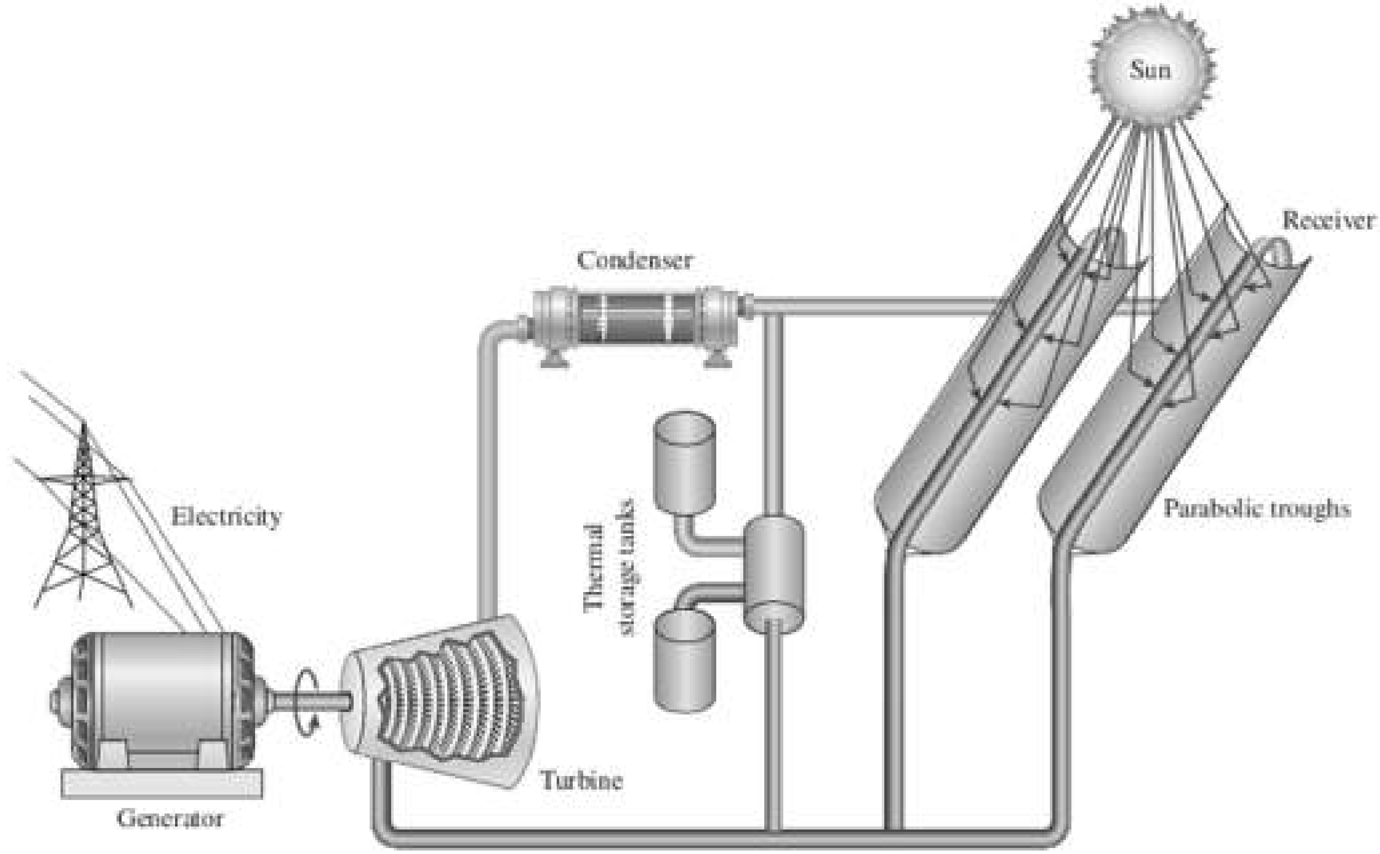


Figure 4-7 A solar concentrator power plant using parabolic trough collectors.

Linear concentrating solar power (CSP) collectors: used to capture and reflect solar radiation onto a linear receiver tube. The fluid contained in the tube is heated.

Operation: A common application is generating steam in the receiver tubes, and running this steam through a turbine to generate electricity. Water coming out of condenser is heated, boiled, and superheated by absorbing solar heat, and it is routed to turbine.

Some existing parabolic trough systems produce 80 MW of electricity.

Storage of solar: If the parabolic trough collectors are oversized, excess heat can be stored and this heat can be used during nighttime or cloudy days to produce electricity.

Integrating solar with conventional power plant: These solar plants can be integrated with conventional power plants utilizing natural gas or coal. The system may be designed such that electricity is supplied by solar as much as possible and conventional system is used as backup when solar heat is not available.

The efficiency of a solar system used to produce electricity may be defined as the power produced divided by the total solar irradiation.

$$\eta_{\text{th,solar}} = \frac{\dot{W}_{\text{out}}}{\dot{Q}_{\text{incident}}} = \frac{\dot{W}_{\text{out}}}{A_c G}$$

Efficiency of solar power plant

A_c the collector surface area receiving solar irradiation

G solar irradiation

4-4 SOLAR-POWER-TOWER PLANT

Heliostat: A solar-power-tower plant uses a large array of mirrors called heliostats that track the sun and reflects solar radiation into a receiver mounted on top of a tower.

Operation: Water is heated, boiled, and superheated by absorbing heat from the receiver system. The resulting steam is directed to a turbine to produce power. A generator is connected to turbine to convert turbine shaft power into electricity.

Energy storage in Solar 1 project: There is an *oil-sand storage unit* that can help supply electricity for 3 to 4 hours after sunset.

Cost of Solar 1 project: The total cost of Solar 1 plant was $14,000/kW, which is 5 to 10 times greater than the cost of electric power stations that run on fossil fuels and other renewables.

Example: Gemasolar power plant, Seville, Spain

Heliostat: It consists of 2650 heliostats that focus 95 percent of solar radiation onto a giant receiver.

Temperature: The temperatures as high as 900°C are obtained at the receiver.

Molten salt tanks are heated by concentrated solar heat reaching a temperature of above 500°C.

Water runs through the molten salt tanks in which it is boiled and superheated. The resulting steam is directed to turbines to produce power. Steam leaving the turbine is condensed and pumped back to the molten salt tanks to repeat the heat engine cycle.

Storage: The plant can store solar heat and use it for a period of 15 hours in the absence of daylight.

Capacity: The plant has an installed capacity of 19.9 MW and can produce 110 GWh of electricity per year.

Figure 4-8
A solar-power-tower plant uses large array of mirrors called *heliostats* that track the sun and reflect solar radiation into a receiver mounted on top of a tower.

Example: Ivanpah solar power plant

Started commercial operation in 2013 after a 3-year construction period, and consists of three separate units. The electricity generated can serve 140,000 homes during the peak hours of the day.

Location and capacity: The plant is located in Mojave desert in California and is the largest solar thermal power plant in the world with a capacity of 377 MW.

It is located at an area of 3500 acres (14.2 km^2) with 300,000 concentrated mirrors reflecting solar energy to receivers at the top of three towers in three plants. The towers are 140 m high.

The solar energy is absorbed by water flowing in the pipes of the boiler.

The water turns into superheated vapor, which is directed into a steam turbine located at the bottom of the tower. Electrical output from the turbine is sent to transmission lines.

Condenser type: This plant uses air-cooled condenser, which uses 95 percent less water than wet-cooled solar thermal plants.

Figure 4-9
Ivanpah solar thermal power plant.

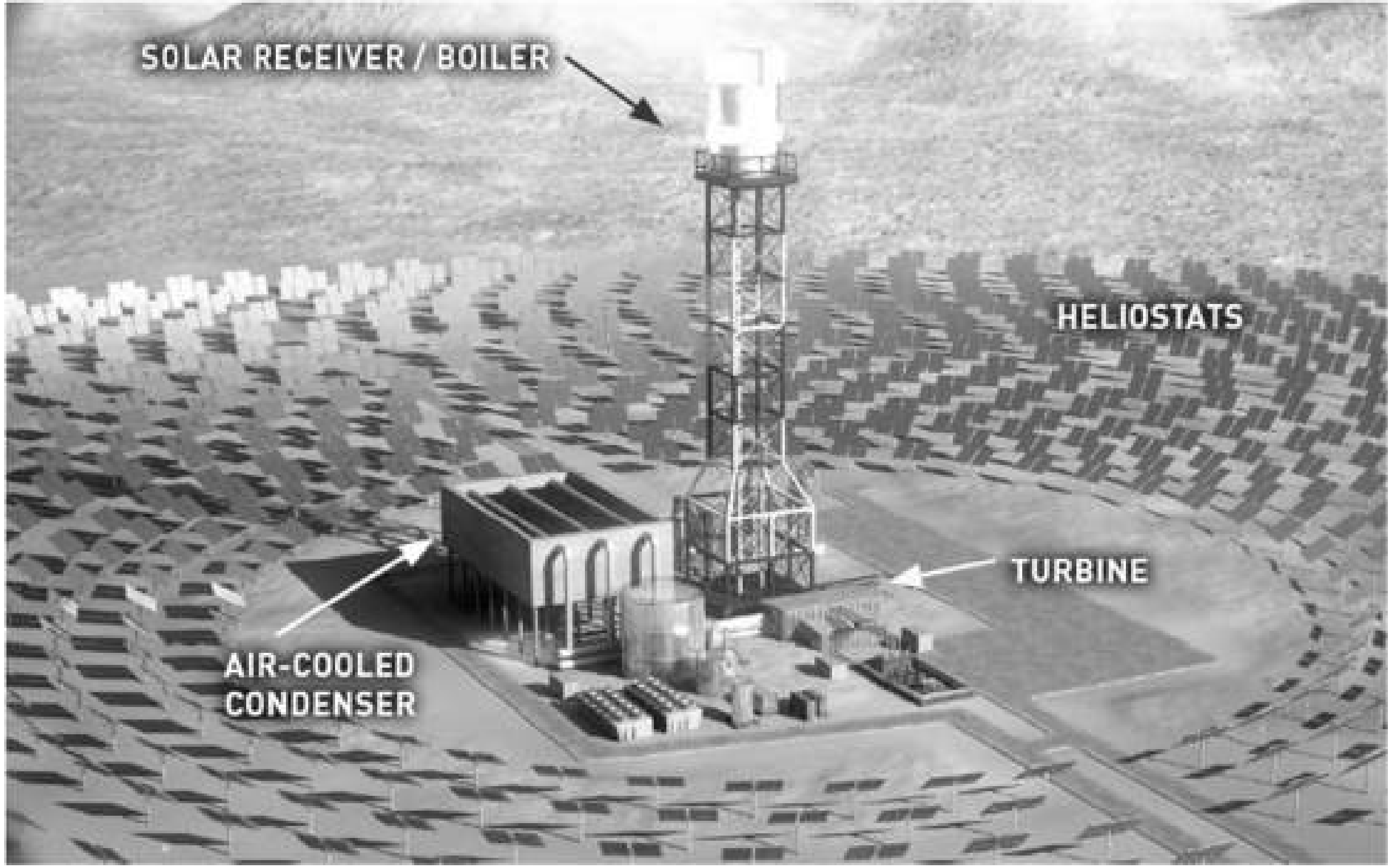


Figure 4-10
One of the three plants of Ivanpah solar system showing main components.

Solar Pond

A promising method of power generation involves collecting and storing solar energy in large artificial lakes a few meters deep, called solar ponds.

Solar energy is absorbed by all parts of the pond, and the water temperature rises everywhere.

The top part of the pond, however, loses to the atmosphere much of the heat it absorbs, and as a result, its temperature drops.

This cool water serves as insulation for the bottom part of the pond and helps trap the energy there.

Usually, salt is planted at the bottom of the pond to prevent the rise of this hot water to the top.

A power plant that uses an organic fluid, such as alcohol, as the working fluid can be operated between the top and the bottom portions of the pond.

The main disadvantage of a solar pond power plant is the low thermal efficiency. If the water temperature is 35°C near the surface and 80°C near the bottom of the pond, the maximum thermal efficiency can be determined as

$$\eta_{\text{th,max}} = 1 - \frac{T_L}{T_H} = 1 - \frac{(35+273)\ \text{K}}{(75+273)\ \text{K}} = 0.115 \text{ or } 11.5\%$$

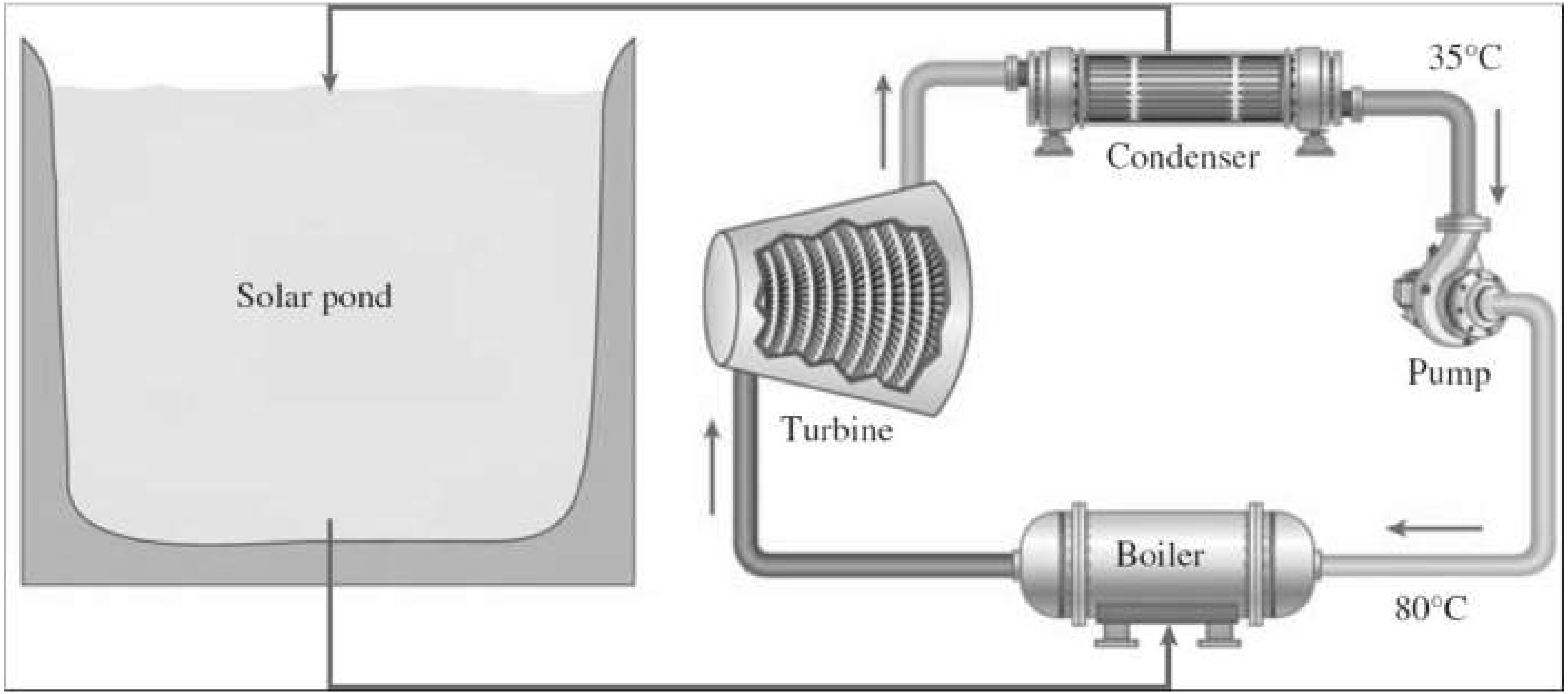


Figure 4-11 Operation of a solar pond power plant.

An **ocean thermal energy converter (OTEC)** system uses the same principle, but in this case the water at the sea or ocean surface is warmer as a result of solar energy absorption.

The water at a deeper location is cooler.

Then, a heat engine can be operated that utilizes the surface warm water as heat source and deep cold water as the heat sink.

Experiments have been performed using the OTEC principle but the results have not been promising due to large installation cost and low thermal efficiency.

4-6 PHOTOVOLTAIC CELL

Electricity can be produced from solar energy by using solar collectors to collect solar heat into a fluid and routing this fluid into a turbine.

This may be viewed as indirect conversion of solar energy into electricity.

Direct conversion of solar radiation into electricity is possible by the use of photovoltaic cell systems.

A photovoltaic system consists of an array of solar cells.

An understanding of the operation of solar cells requires physics of atomic theory and semiconductor theory.

The cell involves a *p*-type semiconductor and an *n*-type semiconductor.

Silicon is commonly used as a semiconductor material in solar cells.

The silicon is doped with phosphorus to produce the n-type semiconductor while it is doped with boron to produce the p-type semiconductor.

There is a current density flow at the *p*-*n* junction of a solar cell.

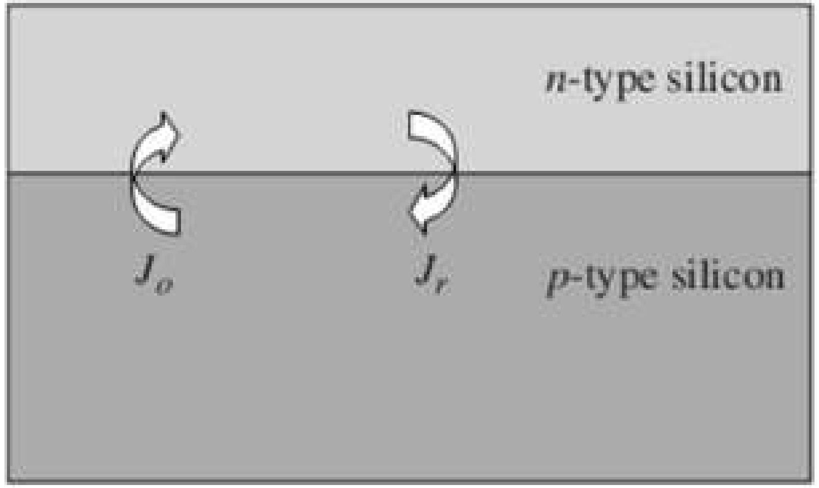


Figure 4-12
A simplified model for current density at p-n junction.

Current density *J*: The current *I* over the cell surface area *A*.

Light-induced recombination current J_r: The current density flow from n-type semiconductor to p-type semiconductor.

Dark current or reverse saturation current J_o : The current density flow from p-type to n-type.

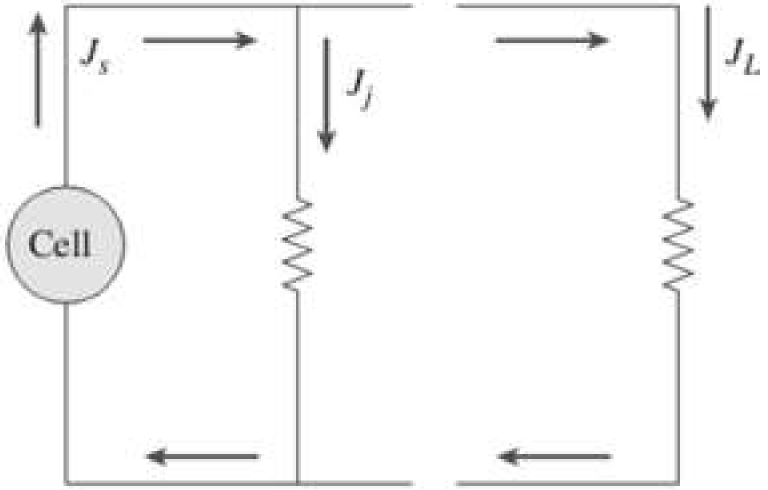


Figure 4-13
Equivalent circuit for solar cell.

$$J_r = J_o \exp\left(\frac{e_o V}{kT}\right)$$ In an illuminated solar cell

where $e_o = 1.6 \times 10^{-19}$ J/V is equal to charge of one electron, $k = 1.381 \times 10^{-23}$ J/K is Boltzmann's constant, V is voltage, and T is the cell temperature. The junction current density J_j is equal to algebraic sum of J_r and J_o:

$$J_j = J_r - J_o = J_o\left[\exp\left(\frac{e_o V}{kT}\right) - 1\right]$$

Current output density J_s: The current density flow through the junction or load.

$$J_L = J_s - J_j = J_s - J_o\left[\exp\left(\frac{e_o V}{kT}\right) - 1\right]$$

Load current density J_L

The voltage is zero $V = 0$ when the cell is short-circuited and thus $J_s = J_L$

The cell output is through the junction when the circuit is open and $J_L = 0$.

The voltage in this case is called the open circuit voltage, V_{oc}.

$$V_{oc} = \frac{kT}{e_o} \ln\left(\frac{J_s}{J_o} + 1\right)$$ Open circuit voltage

$$\frac{J_L}{J_s} = 1 - \frac{J_o}{J_s}\left[\exp\left(\frac{e_o V}{kT}\right) - 1\right]$$ An expression for the ratio of the load current density J_L to short circuit current density J_s

$$\dot{W} = J_L V A \qquad \dot{W} = VAJ_s - VAJ_o\left[\exp\left(\frac{e_o V}{kT}\right) - 1\right]$$

The power output delivered to the load

A: cell area

$$\exp\left(\frac{e_o V_{\max}}{kT}\right) = \frac{1 + J_s/J_o}{1 + \frac{e_o V_{\max}}{kT}}$$ The maximum load voltage for the maximum power output

The maximum voltage $V_{\max}$ is implicit in this equation. A trial-error approach or an equation solver is needed to solve for $V_{\max}$.

$$\dot{W}_{\max} = \frac{AV_{\max}(J_s + J_o)}{1 + \frac{kT}{e_o V_{\max}}}$$

The maximum power output of the cell

$$\eta_{\text{cell}} = \frac{\dot{W}}{AG}$$

The conversion efficiency of a solar cell

$$\eta_{\text{cell,max}} = \frac{\dot{W}_{\max}}{AG} = \frac{AV_{\max}(J_s + J_o)}{AG\left(1 + \frac{kT}{e_o V_{\max}}\right)} = \frac{V_{\max}(J_s + J_o)}{G\left(1 + \frac{kT}{e_o V_{\max}}\right)}$$

The maximum conversion efficiency of a solar cell

We can plot the current density ratio J_L/J_s as a function of load voltage for a specified value of open circuit voltage V_{oc}.

Also, we can plot power output normalized with respect to maximum power against load voltage.

The plots in Fig. 4-14 are obtained with V_{oc} = 0.55 V and T = 300 K.

Note that a high-quality silicon solar cell can produce an open circuit voltage of about 0.6 V.

For short circuit case ($J_L = J_s$ or $J_L/J_s = 1$), the voltage is zero, and the power output is zero.

For open circuit voltage case ($J_L = 0$), the voltage is 0.55 V, and the power output is also zero.

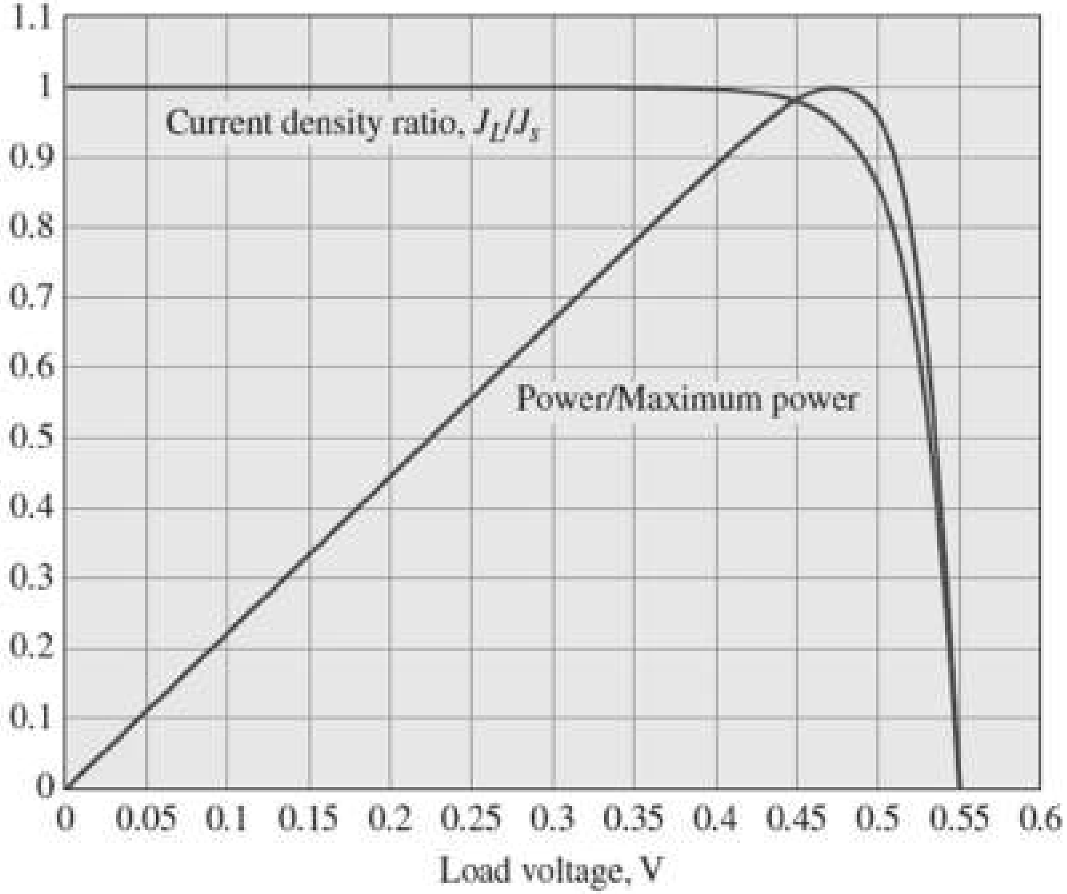


Figure 4-14 Current density ratio J_L/J_s and power output ratio $\dot{W}/\dot{W}_{max}$ in a solar cell as a function of load voltage.

The maximum power occurs at a voltage close to open circuit voltage, which is 0.47 V in this case.

The current density ratio remains close to unity until the open circuit voltage is approached.

Then, it decreases rapidly before it becomes zero at the open circuit case.

The trends and characteristics shown in the figure are typical of most solar cells.

Solar radiation incident on a solar cell is originated from the sun.

The upper limit for the efficiency of a fuel cell may be determined from the Carnot efficiency relation by using effective surface temperature of the sun (5780 K) and an ambient temperature of 298 K:

$$\eta_{\text{cell,max}} = 1 - \frac{T_L}{T_H} = 1 - \frac{298\text{ K}}{5780\text{ K}} = 0.948 \text{ or } 94.8\%$$

Silicon: It has been commonly used in solar cells but the commercial silicon solar cells have a low efficiency (between 15 and 20%).

Other materials have been tested extensively in order to increase solar cell efficiencies including cadmium telluride, cadmium sulfide, copper indium diselenide, gallium arsenide, gallium phosphide, indium phosphide

Copper indium diselenide and gallium arsenide are among the most promising materials.

Gallium arsenide solar cell efficiency: 40% has been approached in laboratory environment.

Using multiple junction design with high solar irradiation has resulted in a research efficiency of 43%.

Cost comparison: The cost of high-efficient solar cells is much greater than silicon solar cells.

Capacity: A single solar cell produces only 1 to 2 W of power.

Multiple cells should be connected to form modules and modules should be connected into arrays so that reasonable amounts of power can be generated.

This way, both small and large photovoltaic systems can be installed depending on the demand.

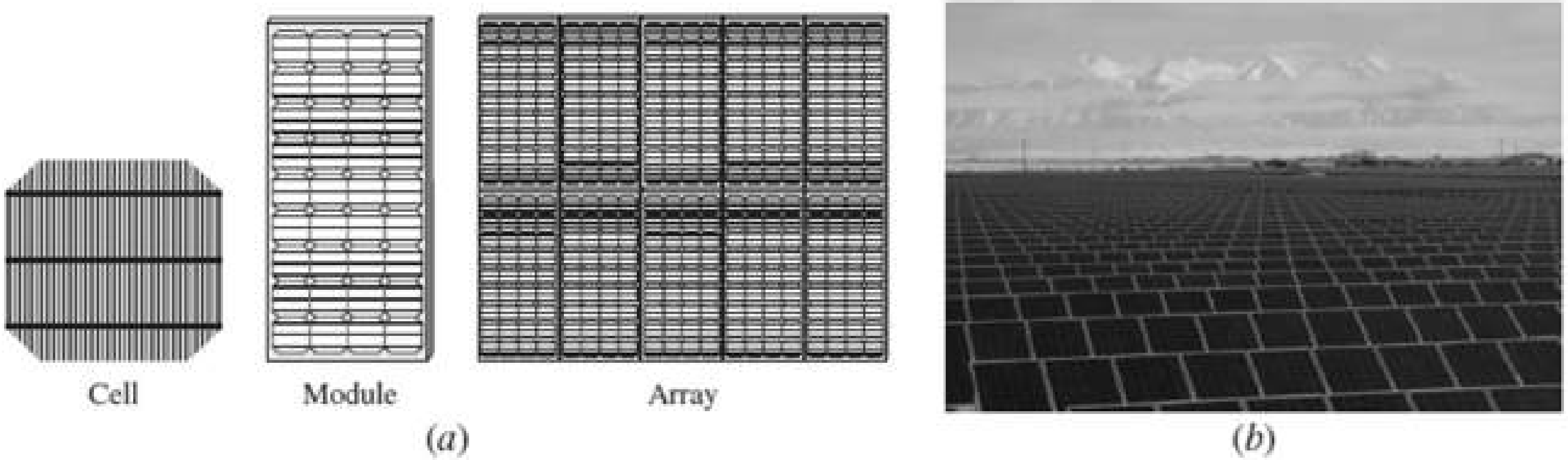


Figure 4-15 (a) A photovoltaic system typically consists of arrays, which are obtained by connecting modules, and modules consist of individual cells. (b) Solar arrays.

Lifespan: The lifespan of a solar cell is about 20 to 35 years.

Dust: Collection of dust on panel surfaces over the time reduces performance of solar panels.

Cost: The cost of solar panels has been decreasing steadily over the years reaching a value of about $2.5/W.

A solar panel that can provide a peak power of 1000 W costs about $2500.

Peak power is only realized in summer months during midday hours.

The power output will be less during other times and no power will be produced during nighttime and cloudy periods.

Future cost: The cost of solar power is expected to decrease steadily reaching a value of about $1.2/W by 2023.

Global solar power capacity: The solar power capacity has increased by 97 GW in 2017 (by 53 GW in China and 11 GW in US) bringing the world total to 400 GW. The capacity nearly quadrupled in the last 5 years.

A steady increase in solar power installations is expected in the coming years. Main reasons for this expected trend are:

- ❑ Cost of solar panels has been declining.
- ❑ There is a growing market in Asia particularly in China, India, and Japan especially after Fukushima nuclear disaster.
- ❑ Cost of financing solar projects is likely to decline.
- ❑ Public interest and awareness in renewable and particularly in solar energy is growing.
- ❑ Conversion efficiencies are getting higher due to extensive research and development.
- ❑ There are growth and improvements in complementary technologies to solar power such as storage and smart grid.

4-7 PASSIVE SOLAR APPLICATIONS

Passive solar: The use of solar energy by means of engineering design without the involvement of mechanical equipment is called passive use of solar energy.

Significant energy savings can be accomplished if a house is designed and built to receive maximum solar heat in winter (to reduce heating energy consumption) and minimum solar heat gain in summer (to reduce cooling energy consumption).

This may include correct selection of orientation of walls and windows, size and type of windows, wall materials, and surface color and finishing of wall surfaces.

Particular preferences in design and construction of buildings will be different in winter-dominated and summer-dominated climates.

The solar heating of swimming pools, food drying, and solar cookers are some other examples of passive solar applications.

Trombe Wall

Trombe wall: Dark painted thick masonry walls. They are commonly used on south sides of passive solar homes to absorb solar energy, store it during the day, and release it to the house during the night.

Air vents: Air vents are commonly installed at the bottom and top of the trombe walls so that the room air enters the parallel flow channel between the trombe wall and the glazing, rises as it is heated, and enters the room through the top vent.

Suitable climates: It is particularly effective in reducing heating energy consumption for mild winter climates where solar energy is available during a significant period of time in winter.

Suitable locations: Southern and western United States and southern Europe are well suited for trombe wall applications.

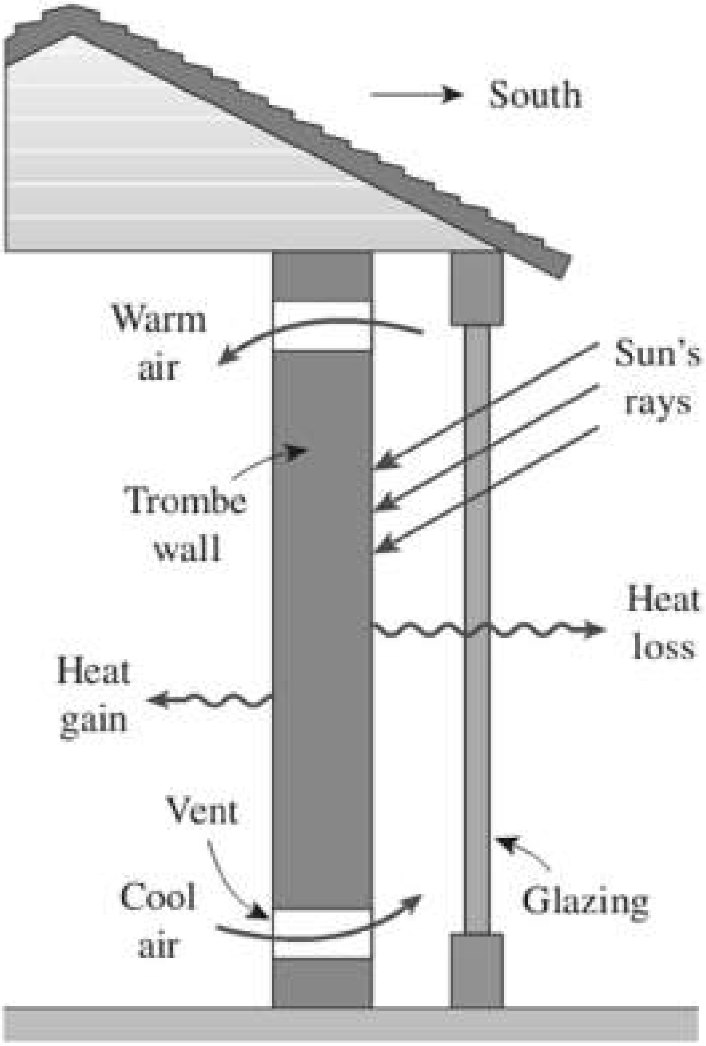


Figure 4-16 Schematic of a trombe wall.

Direct radiation: The part of solar radiation that reaches the earth's surface without being scattered or absorbed.

Diffuse radiation: Solar radiation that is scattered or reemitted by the constituents of the atmosphere.

Direct radiation comes directly from the sun following a straight path, whereas diffuse radiation comes from all directions in the sky.

The entire radiation reaching the ground on an overcast day is diffuse radiation.

The radiation reaching a surface consists of three components: 1 direct radiation, 2 diffuse radiation, and 3 radiation reflected onto the surface from surrounding surfaces.

Solar Heat Gain through Windows

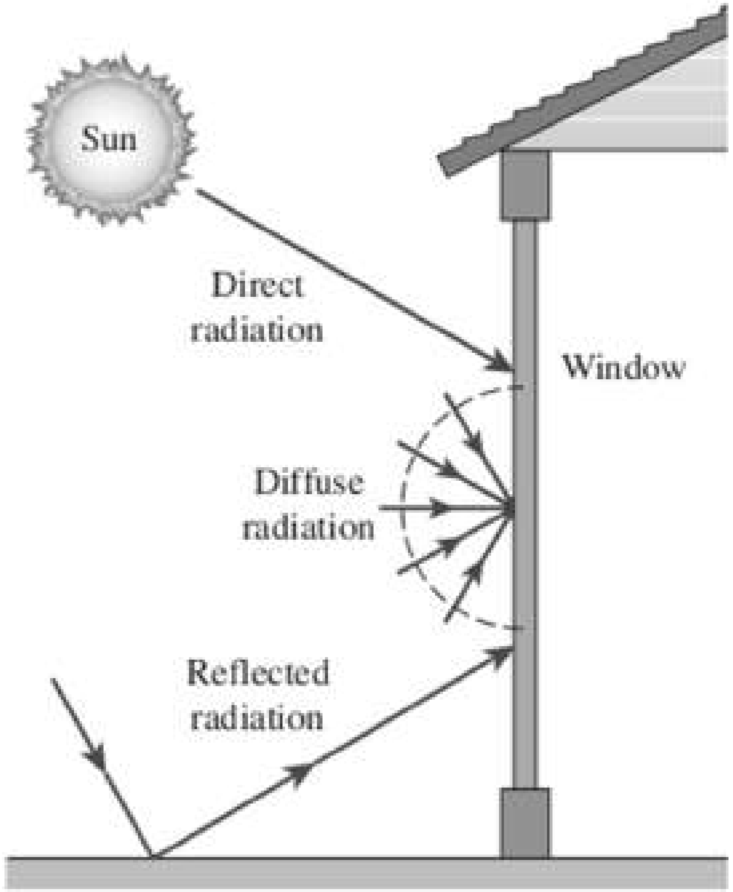


Figure 4-17 Direct, diffuse, and reflected components of solar radiation incident on a window.

When solar radiation strikes a glass surface,

- part of it (about 8 percent for uncoated clear glass) is reflected back to outdoors,

- part of it (5 to 50 percent, depending on composition and thickness) is absorbed within the glass,

- and the remainder is transmitted indoors.

The Standard 3-mm (1/8-in)-thick single-pane double-strength clear window glass

- transmits 86%

- reflects 8%

- absorbs 6%

of the solar energy incident on it.

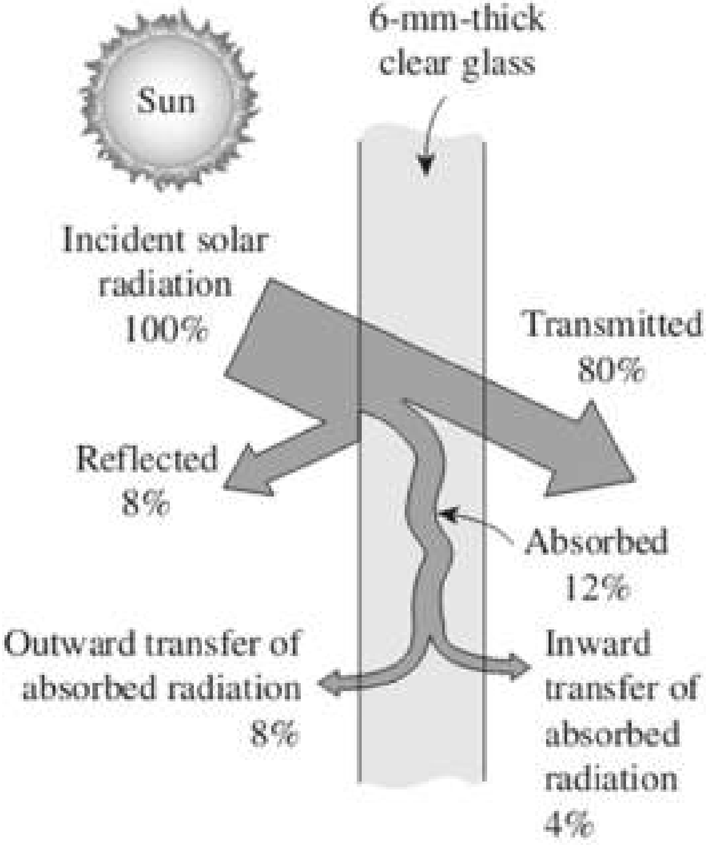
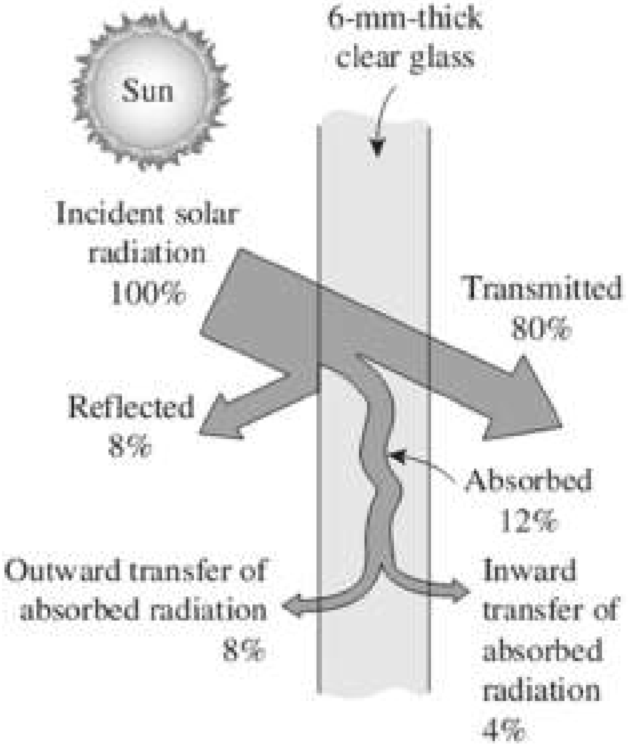


Figure 4-18 Distribution of solar radiation incident on a clear glass.

The solar energy transmitted inside a building represents a heat gain for the building.

Solar heat gain of the building: The sum of the transmitted solar radiation and the portion of the absorbed radiation.

Solar heat gain coefficient (SHGC): The fraction of incident solar radiation that enters through the glazing. SHGC = 0 - 1



$$\mathrm{SHGC} = \frac{\dot{q}_{\text{solar, gain}}}{G} = \tau_s + f_i\alpha_s$$

α_s	solar absorptivity of the glass
τ_s	solar transmissivity of the glass
f_i	the inward flowing fraction of the solar radiation absorbed by the glass

Total solar heat gain through window

$$\dot{Q}_{\text{solar, gain}} = \mathrm{SHGC} \times A_{\text{glazing}} \times G$$

A_{glazing}	glazing area of the window
G	solar heat flux incident on the outer surface of the window, in W/m^2

Another way of characterizing the solar transmission characteristics of different kinds of glazing and shading devices is to compare them to a well-known glazing material that can serve as a base case.

This is done by taking the standard 3-mm (1/8-in) thick double-strength clear window glass sheet whose SHGC is 0.87 as the reference glazing and defining a **shading coefficient SC** as

$$SC = \frac{SHGC}{SHGC_{ref}} = \frac{SHGC}{0.87} = 1.15 \times SHGC$$

The shading coefficient of a single-pane clear glass window is

SC = 1.0

The larger the shading coefficient, the smaller the shading effect, and thus the larger the amount of solar heat gain.

TABLE 4-2 Shading Coefficient SC and Solar Transmissivity τ_{solar} for Some Common Glass Types for Summer Design Conditions (ASHRAE, 1993)

	Nominal Thickness			
Types of Glazing	mm	in	τ_{solar}	SC[*]
(*a*) Single glazing				
Clear	3	⅛	0.86	1.0
	6	¼	0.78	0.95
	10	⅜	0.72	0.92
	13	½	0.67	0.88
Heat absorbing	3	⅛	0.64	0.85
	6	¼	0.46	0.73
	10	⅜	0.33	0.64
	13	½	0.24	0.58
(*b*) Double glazing				
Clear in	3[†]	⅛	0.71[‡]	0.88
Clear out	6	¼	0.61	0.82
Clear in, heat absorbing out[§]	6	¼	0.36	0.58

[*] Multiply by 0.87 to obtain SHGC.

[†] The thickness of each pane of glass.

[‡] Combined transmittance for assembled unit.

[§] Refers to gray-, bronze-, and green-tinted heat-absorbing float glass.

Solar heat entering a house through windows is preferable in winter since it reduces heating energy consumption but it should be avoided as much as possible in summer since it increases cooling energy consumption.

Shading devices are used to control solar heat gain through windows.

Shading devices are classified as internal shading and external shading, depending on whether the shading device is placed inside or outside .

External shading devices are more effective in reducing the solar heat gain since they intercept the sun's rays before they reach the glazing.

The sun is high in the horizon in summer and low in winter. A properly sized roof overhang or a horizontal projection blocks off the sun's rays completely in summer while letting in most of them in winter.

A window can also be shaded from outside by vertical or horizontal or architectural projections, insect or shading screens, and sun screens.

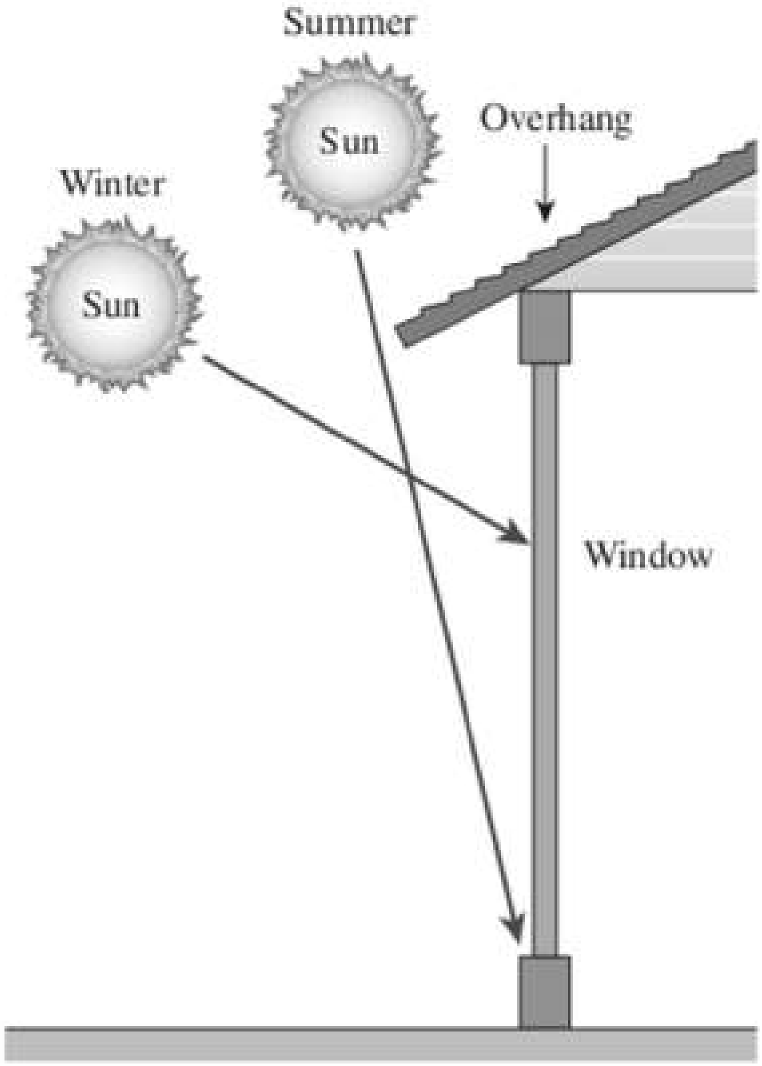


Figure 4-19 A properly sized overhang blocks off the sun rays completely in summer while letting them through in winter.

Internal shading: It is used in most windows to provide privacy and aesthetic effects as well as some control over solar heat gain.

Internal shading devices: They reduce solar heat gain by reflecting transmitted solar radiation back through the glazing before it can be absorbed and converted into heat in the building.

Draperies: They reduce the annual heating and cooling loads of a building by 5 to 20%, depending on the type and the user habits.

In summer, they reduce heat gain primarily by reflecting back direct solar radiation.

The reflectance of the surface of the drapery facing the glazing has a major effect on the amount of solar heat gain.

Light-colored draperies: They maximize the back reflection and thus minimize the solar gain.

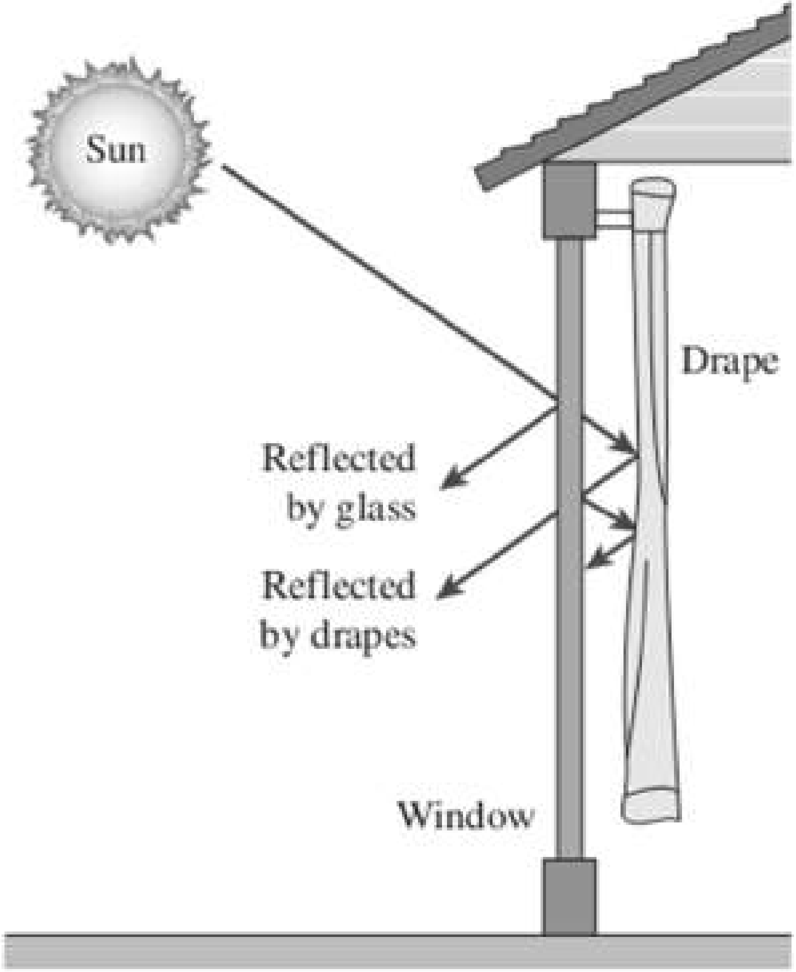


Figure 4-20 Draperies reduce heat gain in summer by reflecting back solar radiation, and reduce heat loss in winter by forming an air space before the window.

The shading coefficients of drapes also depend on the way they are hung.

Usually, the width of drapery used is twice the width of the draped area to allow folding of the drapes and to give them their characteristic “full” or “wavy” appearance.

A flat drape behaves like an ordinary window shade.

A flat drape has a higher reflectance and thus a lower shading coefficient than a full drape.

The primary function of an indoor shading device is to provide thermal comfort for the occupants.

An unshaded window glass allows most of the incident solar radiation in, and also dissipates part of the solar energy it absorbs by emitting infrared radiation to the room.

The emitted radiation and the transmitted direct sunlight may bother the occupants near the window.

The type of climate in an area usually dictates the type of windows to be used in buildings.

In cold climates where the heating load is much larger than the cooling load, the windows should have the highest transmissivity for the entire solar spectrum, and a high reflectivity (or low emissivity) for the far infrared radiation emitted by the walls and furnishings of the room.

In warm climates where the cooling load is much larger than the heating load, the windows should allow the visible solar radiation (light) in, but should block off the infrared solar radiation.

Such windows can reduce the solar heat gain by 60% with no appreciable loss in daylighting.

This behavior is approximated by window glazings that are coated with a heat-absorbing film outside and a low-e film inside.

Properly selected windows can reduce the cooling load by 15 to 30% compared to windows with clear glass.

Tinted glass and glass coated with reflective films reduce solar heat gain in summer and heat loss in winter.

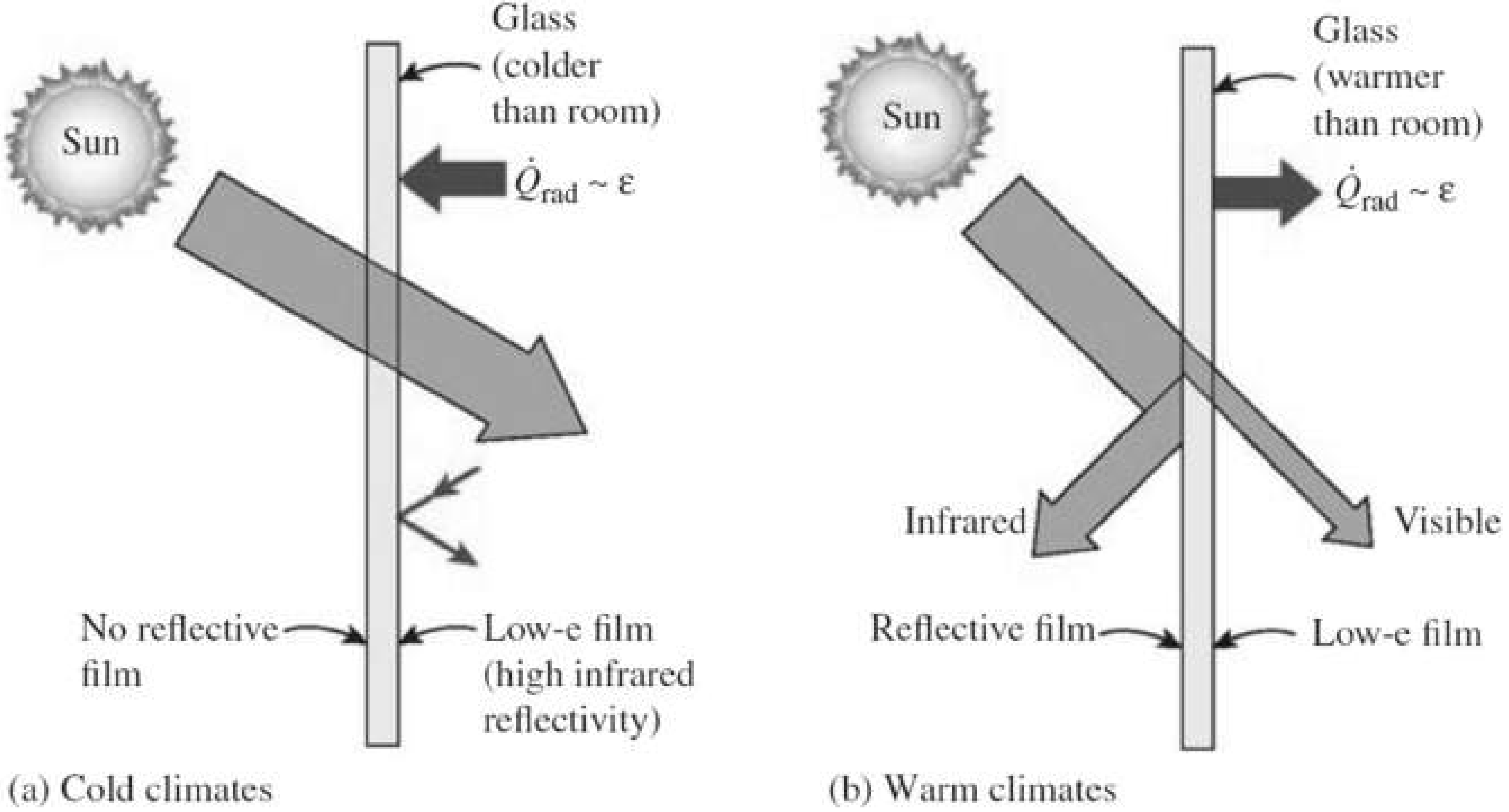
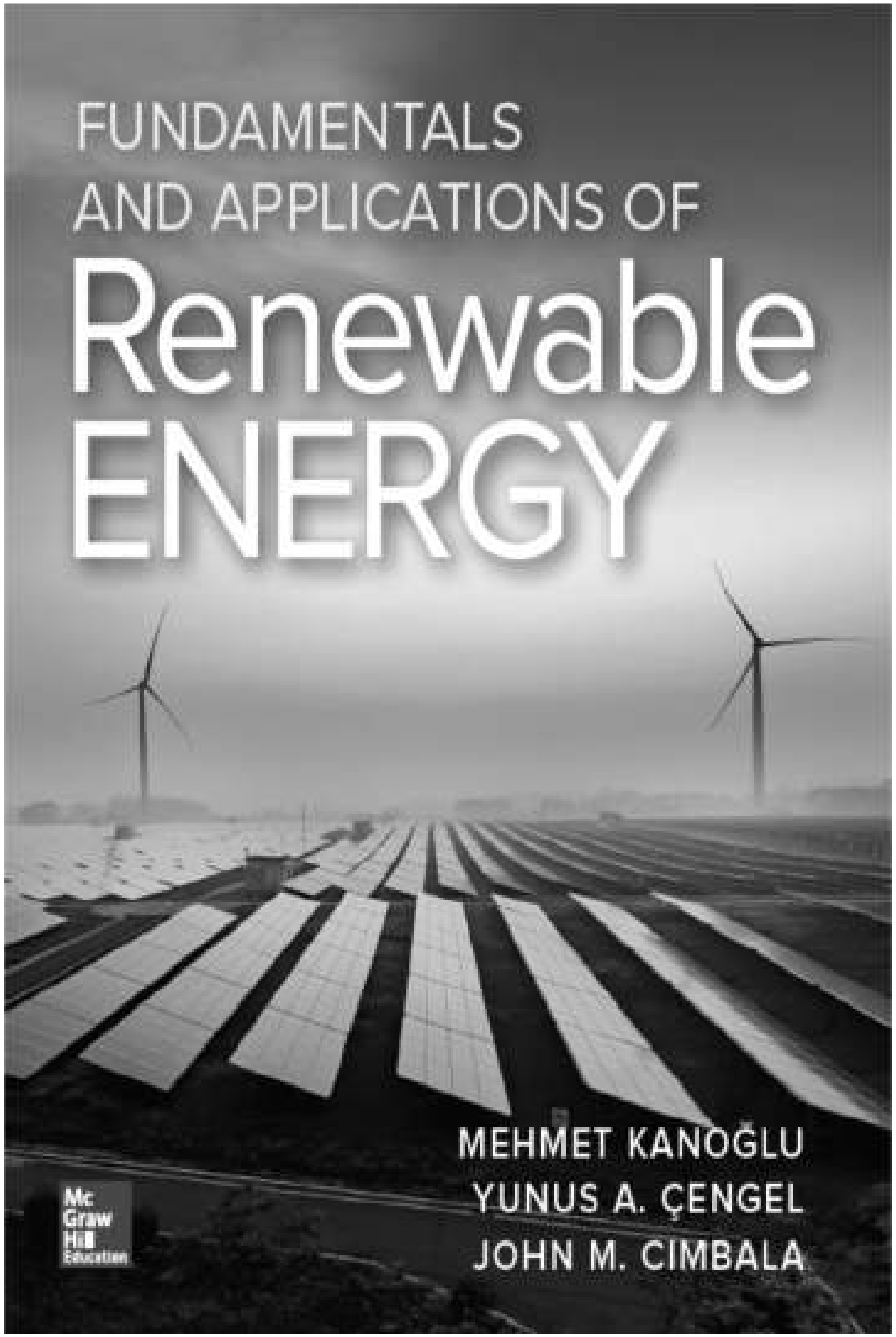


Figure 4-21 Radiation heat transfer between a room and its window is proportional to the emissivity of the glass surface, and low-e coatings on the inner surface of the windows reduce heat loss in winter and heat gain in summer.



FUNDAMENTALS
AND APPLICATIONS OF
Renewable
ENERGY

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Chapter 5
WIND ENERGY

Fundamentals and Applications of
Renewable Energy
Mehmet Kanoglu
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McGraw–Hill, 2020

5-1 INTRODUCTION

Windmill: It is used for mechanical power generation (grinding grain, pumping water, etc.).

Wind turbine: It is used for electrical power generation.

Technically both devices are turbines since they extract energy from the fluid.

Example: Altamont Pass in California is the world's largest wind farm with 15,000 modern wind turbines).

This farm and two others in California produce about 3 billion kWh of electricity per year, which is enough power to meet the electricity needs of San Francisco.

USA, Germany, Denmark, and Spain account for over 75% of current wind energy generating capacity worldwide.

Denmark uses wind turbines to supply 10% of its national electricity.

Speed: The rotation speed of rotors of wind turbines is usually under 40 rpm (under 20 rpm for large turbines).

Capacity: Commercial wind turbines generate from 100 kW to 3.2 MW of electric power each at peak design conditions. The largest one has over 8 MW capacity.

Rotor diameter: The blade span (or rotor) diameter of the 3.2 MW wind turbine built by Boeing Engineering is 320 ft (97.5 m).

Location: Wind turbines need to be located where the wind blows, which is often far from traditional power grids, requiring construction of new high-voltage power lines.

Wind turbines produce power only when the wind is blowing, and the power output of a wind turbine is not constant.

Wind turbines are expected to play an ever increasing role in the global supply of energy for the foreseeable future.

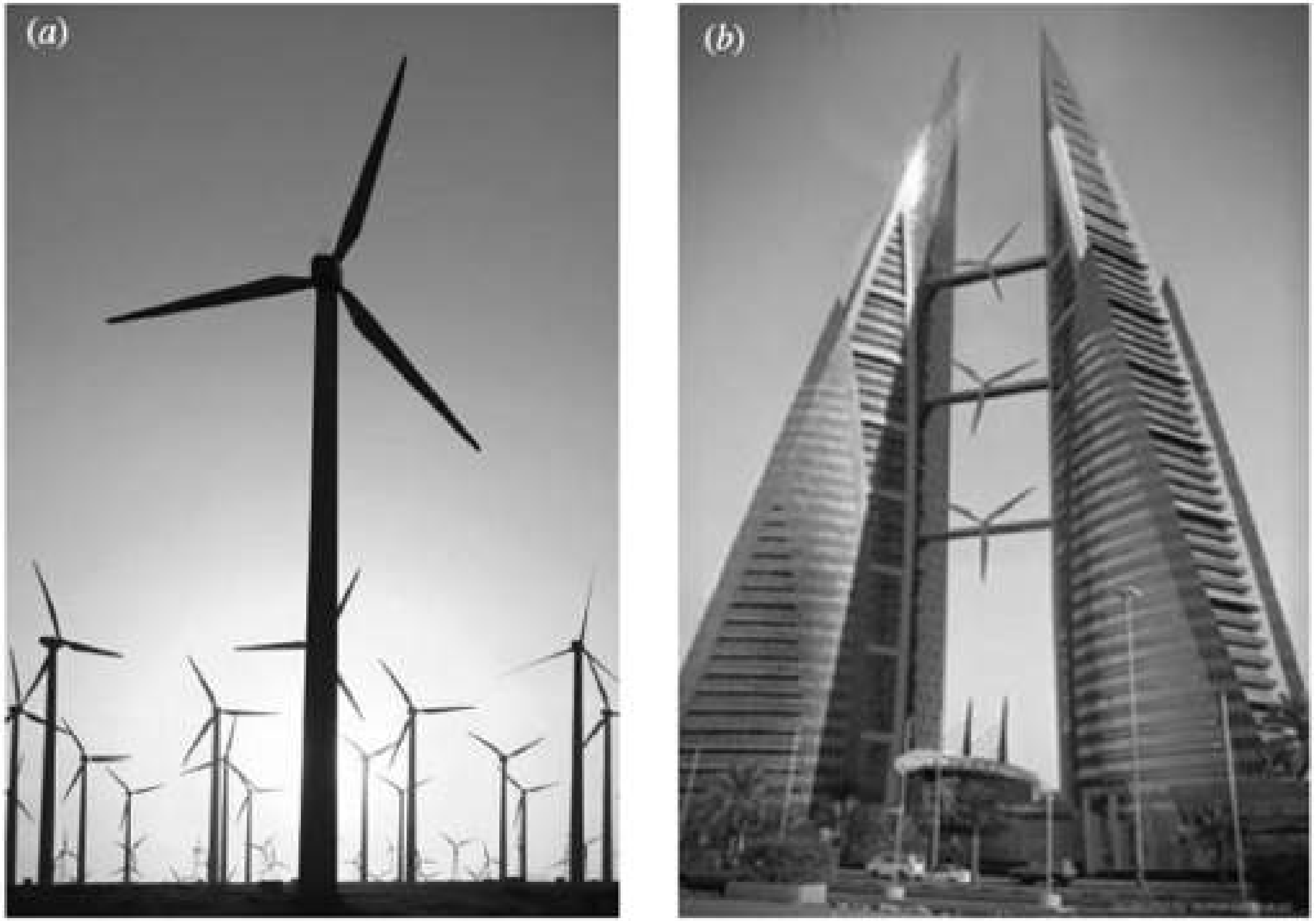


Figure 5-1
(a) Wind farms are popping up all over the world to help reduce the global demand for fossil fuels. (b) Some wind turbines are even being installed on buildings! These three turbines are on a building at the Bahrain World Trade Center.

5-2 WIND TURBINE TYPES AND POWER PERFORMANCE CURVE

Numerous innovative wind turbine designs have been proposed and tested over the centuries.

Categories: We generally categorize wind turbines by the orientation of their axis of rotation

- horizontal axis wind turbines (HAWTs)
- vertical axis wind turbines (VAWTs)

Alternative classification: An alternative way to categorize them is by the mechanism that provides torque to the rotating shaft:

- lift
- drag

Which type is used? Lift-type HAWT

Other designs have not achieved the same success.

Wind farm: Clusters of wind turbines.

Horizontal Axis Turbines

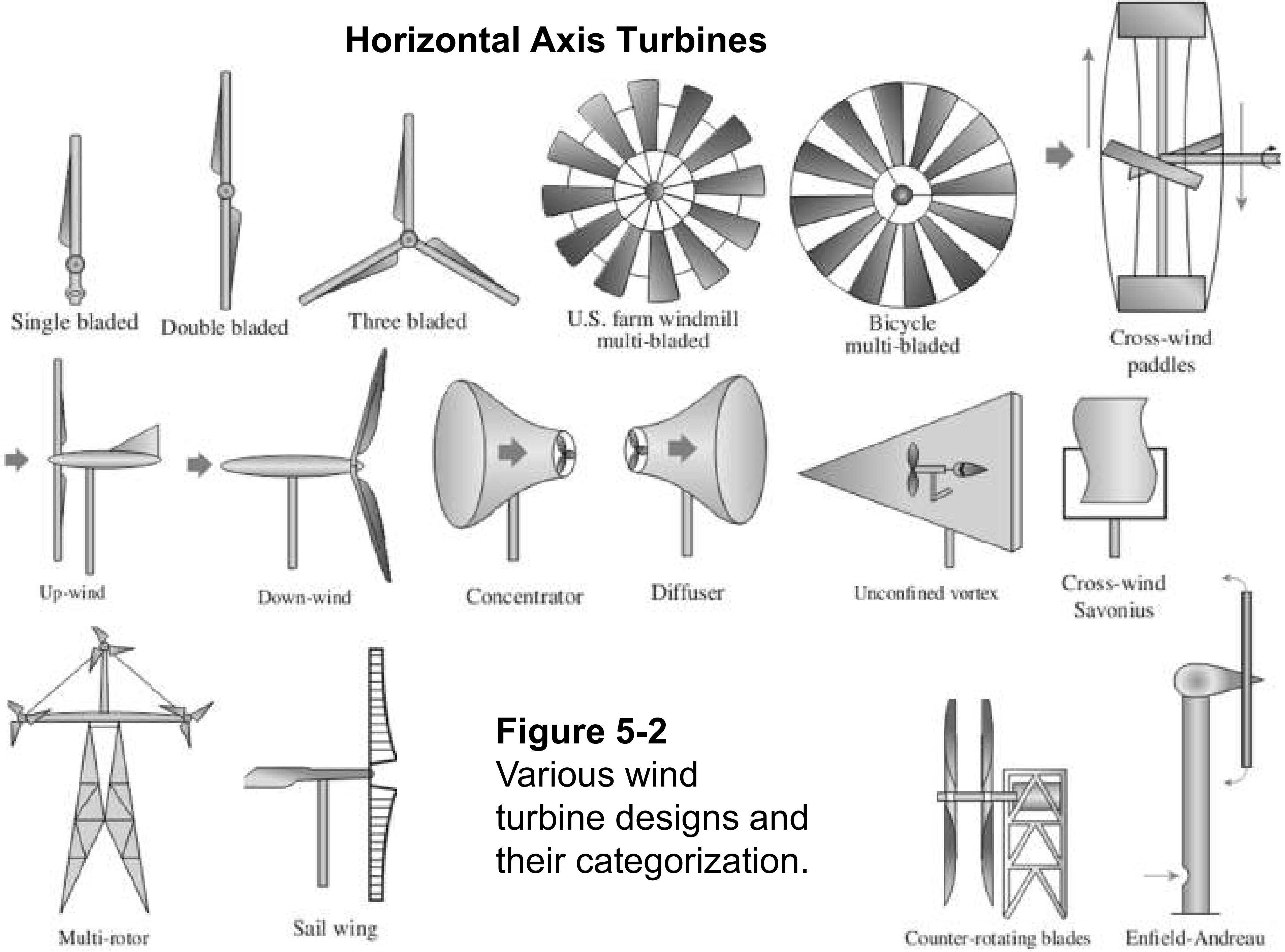
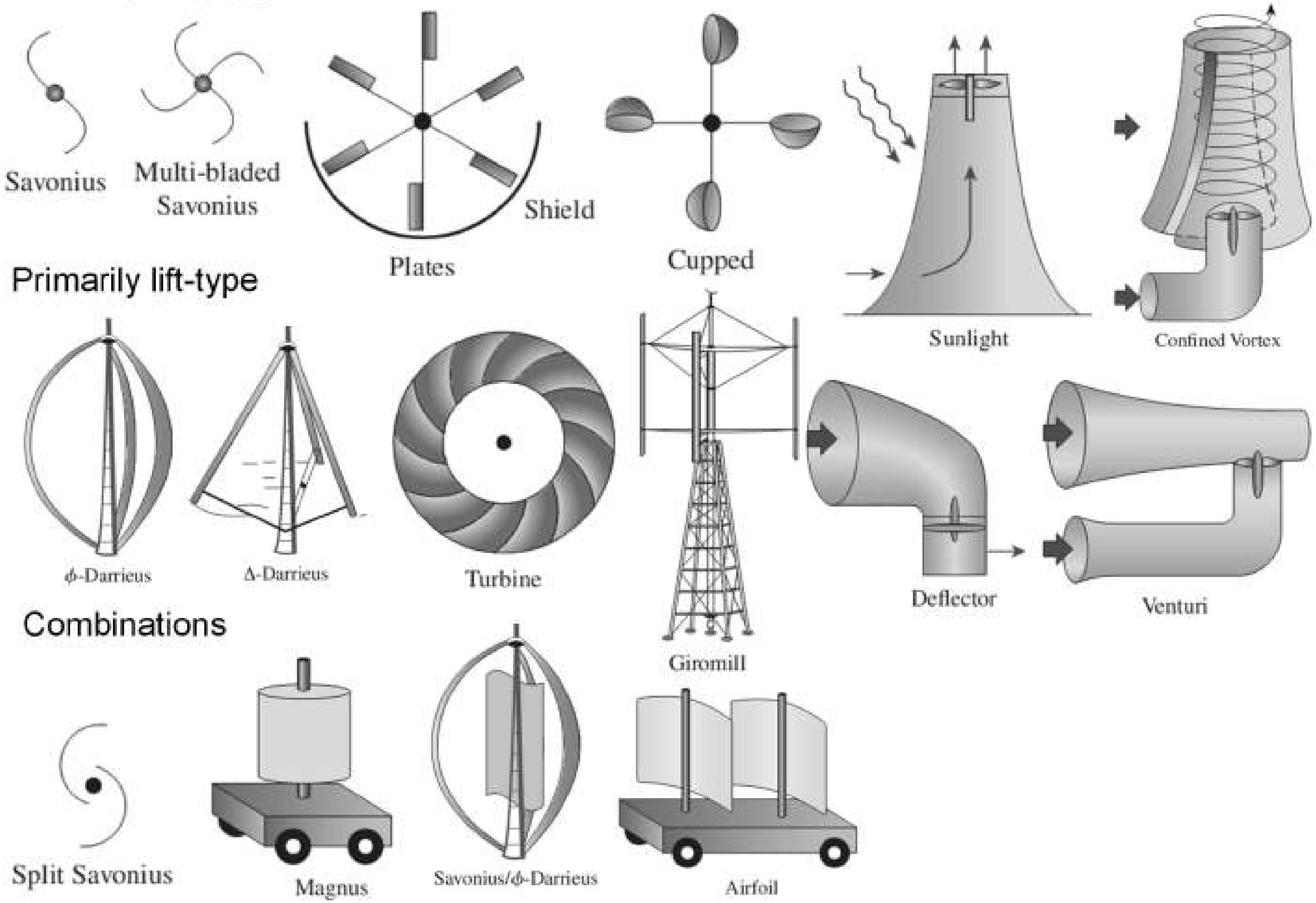


Figure 5-2 Various wind turbine designs and their categorization.

Vertical Axis Turbines

Primarily drag-type

Others



Primarily lift-type

Combinations

Every wind turbine has a characteristic power performance curve.

Cut-in speed is the minimum wind speed at which useful power can be generated.

Rated speed is the wind speed that delivers the rated power, usually the maximum power.

Cut-out speed is the maximum wind speed at which the wind turbine is designed to produce power. At wind speeds greater than the cut-out speed, the turbine blades are stopped by some type of braking mechanism to avoid damage and for safety issues. The short section of dashed blue line indicates the power that would be produced if cut-out were not implemented.

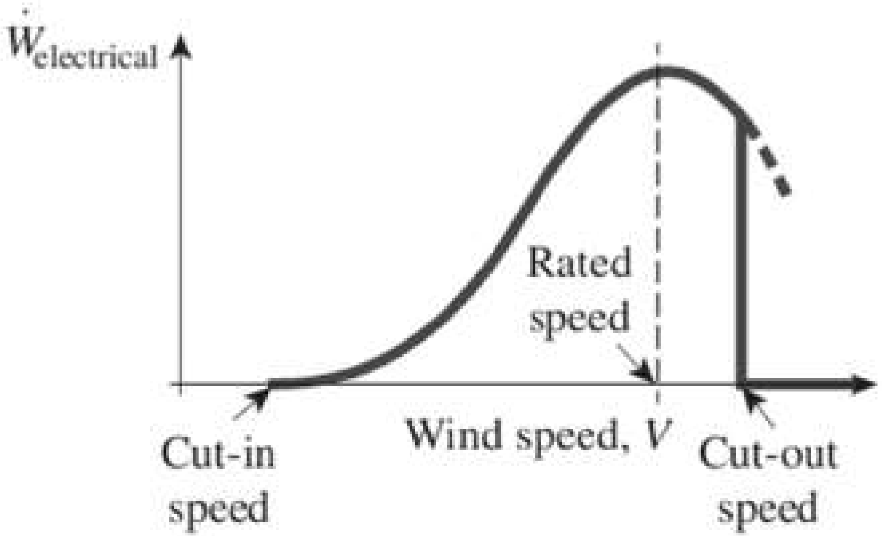


Figure 5-3
Typical qualitative wind-turbine power performance curve with definitions of cut-in, rated, and cut-out speeds.

The design of HAWT turbine blades includes tapering and twist to maximize performance.

While the fluid mechanics of wind turbine design is critical, the power performance curve also is influenced by

- electrical generator
- gearbox
- structural issues

Inefficiencies appear in every component.

5-3 WIND POWER POTENTIAL

Mechanical energy: The form of energy that can be converted to mechanical work completely and directly by an ideal mechanical device such as an ideal turbine.

$$\dot{E}_{\text{mech}} = \dot{m}\left(\frac{P}{\rho} + \frac{V^2}{2} + gz\right)$$

P/ρ	flow energy,
$V^2/2$	kinetic energy
gz	potential energy
$\dot{m}$	mass flow rate of the fluid

The pressures at the inlet and exit of a wind turbine are both equal to the atmospheric pressure and the elevation does not change across a wind turbine.

Flow energy and potential energy do not change across a wind turbine.

A wind turbine converts the kinetic energy of the fluid into power.

Available wind power: The maximum power a wind turbine can generate for the given wind velocity *V*.

$$\dot{W}_{\text{available}} = \frac{1}{2}\dot{m}V^2 \qquad \text{(kW)}$$

$$\dot{m} = \rho A V \qquad \text{(kg/s)}$$

Mass flow rate

$$\dot{W}_{\text{available}} = \frac{1}{2}\rho A V^3$$

Wind power potential

ρ	density of air
A	disk area of a wind turbine (the circular area swept out by the turbine blades as they rotate)

The available power relation indicates that the power potential of a wind turbine is proportional to density of air. As a result, cold air has a higher wind power potential than the warm air.

$P = \rho RT$ Ideal gas relation Gas constant, $R = 0.287$ kPa·m³/kg·K

$A = \pi D^2/4$ Disk area D: blade diameter

$$\dot{W}_{\text{available}} = \frac{1}{2}\rho A V^3 \qquad \dot{W}_{\text{available}} = \frac{\pi}{8}\frac{PD^2V^3}{RT}$$

Effect of velocity: The power potential of a wind turbine is proportional to cubic power of the wind velocity.

Effect of blade diameter: The power potential of a wind turbine is proportional to the square of the blade diameter.

Doubling blade diameter increases the power potential by a factor of four.

Consider a location where the wind with a density of 1.2 kg/m³ is blowing at a velocity of 4 m/s.

The maximum power a wind turbine with a rotor diameter of 1.03 m can generate is

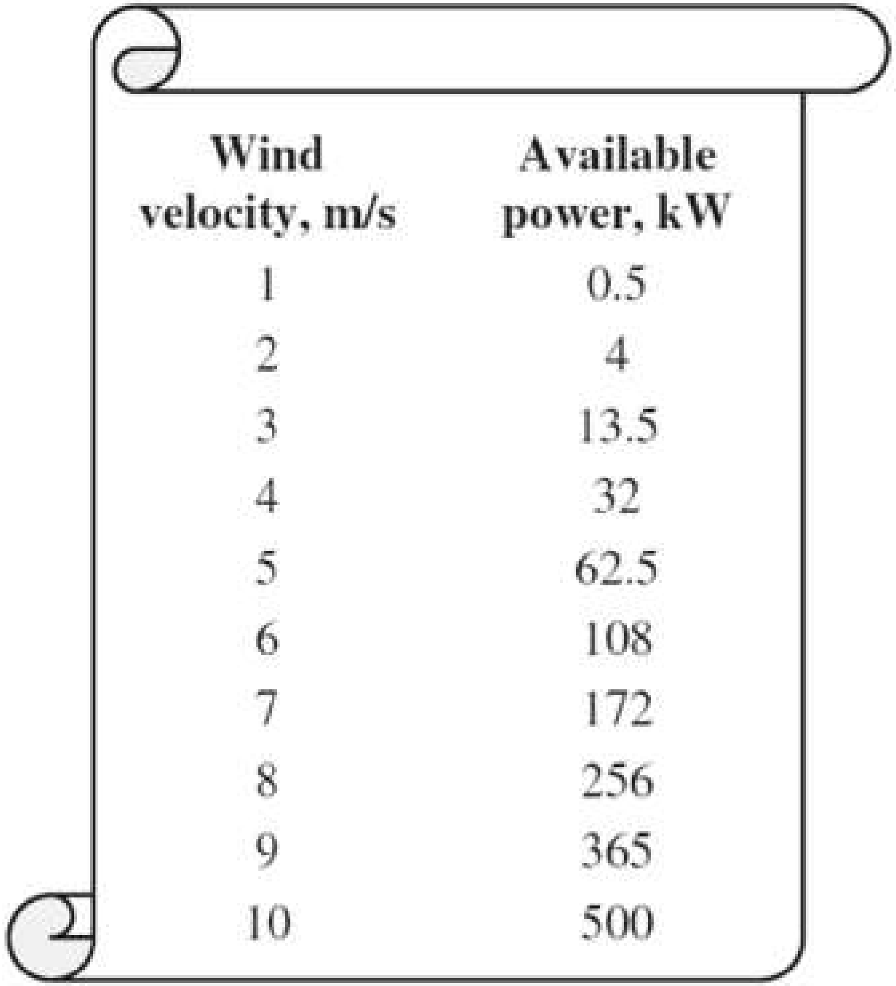
$$\dot{W}_{\text{available}} = \frac{1}{2}\rho A V^3 = \frac{1}{2}(1.2\ \text{kg/m}^3)\frac{\pi(1.03\ \text{m})^2}{4}(4\ \text{m/s})^3 = 32\ \text{kW}$$

If the wind velocity is doubled, the available power becomes 242 kW.

Doubling the wind velocity will increase the power potential by a factor of 8.

Minimum wind speed: A wind turbine investment is usually not justified if the location does not have a steady wind at a velocity of about 6 m/s or higher.

$$\dot{W}_{\text{available}} = \frac{1}{2}\rho A V^3 = \frac{1}{2}(1.2\ \text{kg/m}^3)\frac{\pi(1.03\ \text{m})^2}{4}(4\ \text{m/s})^3 = 32\ \text{kW}$$



Wind velocity, m/s	Available power, kW
1	0.5
2	4
3	13.5
4	32
5	62.5
6	108
7	172
8	256
9	365
10	500

Figure 5-4 The power potential of a wind turbine is proportional to cubic power of the wind velocity. Therefore, doubling the wind velocity will increase the power potential by a factor of 8.

5-4 WIND POWER DENSITY

Wind power density: Available wind power per unit area, typically in units of W/m²:

$$\mathrm{WPD} = \frac{\dot{W}_{\text{available}}}{A} = \frac{1}{2}\rho V^3 \qquad \mathrm{WPD}_{\text{avg}} = \frac{\bar{\dot{W}}_{\text{available}}}{A} = \frac{1}{2}\rho \overline{V^3}$$

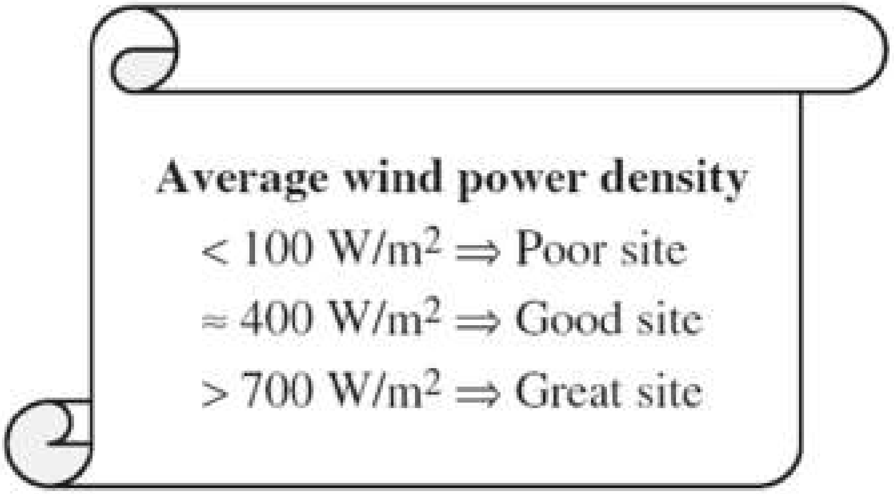
The average wind power density should be calculated based on hourly wind speed averages for the entire year. For the construction of wind turbines,

- WPD is less than about 100 W/m², poor site
- WPD is around 400 W/m², good site
- WPD is greater than about 700 W/m², great site

A wind power density of 100 W/m² corresponds to a wind speed of 5.5 m/s for an air density of 1.2 kg/m³.

Other factors affect the choice of a wind turbine site, such as atmospheric turbulence intensity, terrain, obstacles (buildings, trees, etc.), environmental impact, etc.

$$\text{WPD} = \frac{\dot{W}_{\text{available}}}{A} = \frac{1}{2}\rho V^3$$



Average wind power density

< 100 W/m^2 ⇒ Poor site

≈ 400 W/m^2 ⇒ Good site

> 700 W/m^2 ⇒ Great site

Figure 5-6 A rule of thumb criteria for construction of wind turbines in a proposed site.

5-5 WIND TURBINE EFFICIENCY

Wind turbine efficiency: The fraction of available power potential converted into actual shaft power.

$$\eta_{\text{wt}} = \frac{\dot{W}_{\text{shaft}}}{\dot{W}_{\text{available}}} = \frac{\dot{W}_{\text{shaft}}}{\frac{1}{2}\rho A V^3}$$

$\dot{W}_{\text{shaft}}$	rotor shaft power output
ρ	density of air
V	wind velocity

A gearbox/generator connected to the turbine converts shaft power into electrical power output $\dot{W}_{\text{electric}}$

$$\dot{W}_{\text{electric}} = \eta_{\text{gearbox/generator}} \dot{W}_{\text{shaft}} \quad \text{(kW)}$$

$\eta_{\text{gearbox/generator}}$ is the gearbox/generator efficiency,and is typically above 80 percent.

$$\eta_{\text{wt, overall}} = \frac{\dot{W}_{\text{electric}}}{\dot{W}_{\text{available}}} = \frac{\dot{W}_{\text{electric}}}{\frac{1}{2}\rho A V^3}$$

Overall wind turbine efficiency

$$\eta_{\text{wt, overall}} = \eta_{\text{wt}}\eta_{\text{gearbox/generator}} = \frac{\dot{W}_{\text{shaft}}}{\dot{W}_{\text{available}}}\frac{\dot{W}_{\text{electric}}}{\dot{W}_{\text{shaft}}} = \frac{\dot{W}_{\text{electric}}}{\dot{W}_{\text{available}}}$$

The efficiency of wind turbines usually ranges between 30 and 40%.

The efficiency of wind turbine is usually referred to as power coefficient C_p.

Using the wind turbine efficiency, the actual shaft power output from a wind turbine can be expressed as

$$\dot{W}_{\text{shaft}} = \frac{1}{2}\eta_{\text{wt}}\,\rho A V^3 \qquad (\text{kW})$$

If we neglect frictional effects in a wind turbine and take the wind velocity as the average velocity of air at the turbine inlet, the portion of incoming kinetic energy not converted to shaft power leaves the wind turbine as outgoing kinetic energy.

$$\dot{m}\frac{V_1^2}{2} = \dot{W}_{\text{shaft}} + \dot{m}\frac{V_2^2}{2}$$

$$\eta_{\text{wt}} = \frac{\dot{W}_{\text{shaft}}}{\dot{m}\frac{V_1^2}{2}}$$

$$\dot{m}\frac{V_2^2}{2} = \dot{m}\frac{V_1^2}{2}(1-\eta_{\text{wt}})$$

$$V_2 = V_1\sqrt{1-\eta_{\text{wt}}}$$

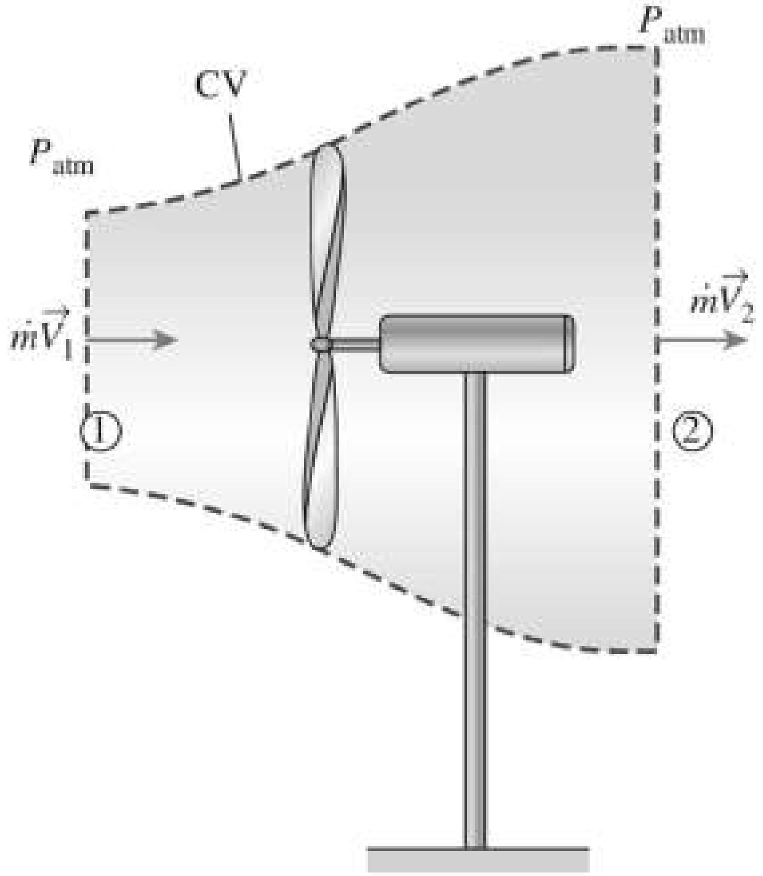


Figure 5-7
The flow of air across a wind turbine.

This relation enables us to determine the exit velocity when the turbine efficiency is known and the frictional effects are neglected.

Betz Limit for Wind Turbine Efficiency

A wind turbine converts kinetic energy of air into work.

This conversion is perfect (the wind turbine efficiency is 100 percent) under ideal conditions based on the second law of thermodynamics.

This would be the case only when the velocity of air at the turbine exit is zero.

This is not possible for practical reasons because air must be taken away at the turbine exit to maintain the mass flow through the turbine.

It turns out that there is a maximum possible efficiency for a wind turbine, called Betz limit.

We consider two control volumes surrounding the disk area a large control volume and a small control volume, with upstream wind speed V taken as V_1.

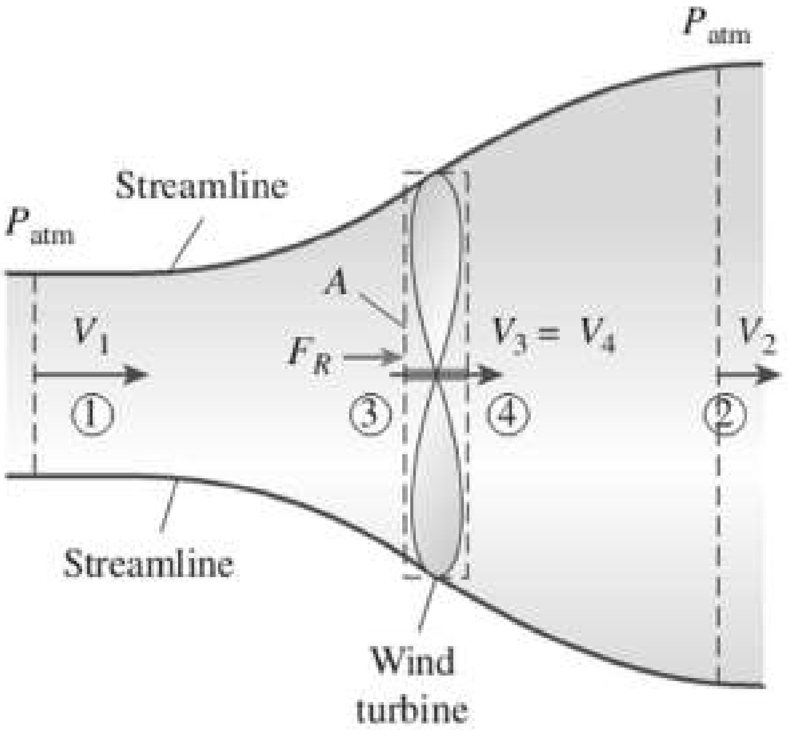


Figure 5-8
The large and small control volumes for analysis of ideal wind turbine performance bounded by an axisymmetric diverging stream tube.

$$F_R = \dot{m}(V_2 - V_1)$$

$$F_R + P_3A - P_4A = 0 \quad \rightarrow \quad F_R = (P_4 - P_3)A$$

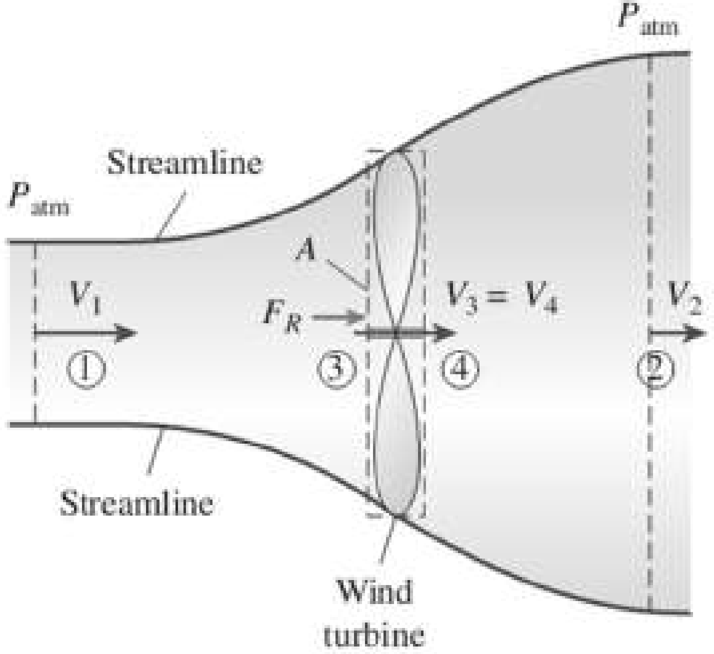
$$\frac{P_1}{\rho g} + \frac{V_1^2}{2g} + z_1 = \frac{P_3}{\rho g} + \frac{V_3^2}{2g} + z_3 \quad \text{and} \quad \frac{P_4}{\rho g} + \frac{V_4^2}{2g} + z_4 = \frac{P_2}{\rho g} + \frac{V_2^2}{2g} + z_2$$

$$\frac{V_1^2 - V_2^2}{2} = \frac{P_3 - P_4}{\rho} \qquad V_3 = \frac{V_1 + V_2}{2}$$

$$a = \frac{V_1 - V_3}{V_1} \qquad V_3 = V_1(1 - a).$$

$$\dot{m} = \rho V_3 A = \rho A V_1(1 - a)$$

$$V_2 = V_1(1 - 2a)$$



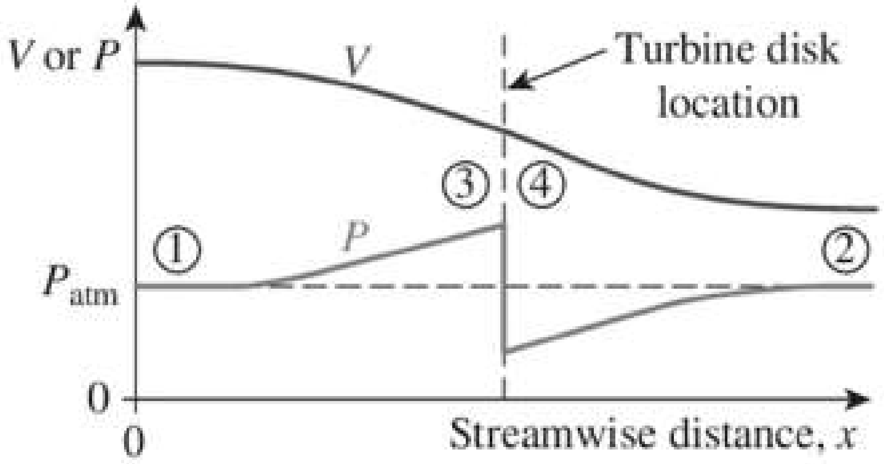


Figure 5-9 Qualitative sketch of average stream wise velocity and pressure profiles through a wind turbine.

$$\dot{W}_{\text{ideal}} = \dot{m}\frac{V_1^2 - V_2^2}{2} = \rho A V_1 (1-a)\frac{V_1^2 - V_1^2 (1-2a)^2}{2} = 2\rho A V_1^3 a (1-a)^2$$

$$\eta_{\text{wt}} = \frac{\dot{W}_{\text{shaft}}}{\frac{1}{2}\rho V_1^3 A} = \frac{\dot{W}_{\text{ideal}}}{\frac{1}{2}\rho V_1^3 A} = \frac{2\rho A V_1^3 a (1-a)^2}{\frac{1}{2}\rho V_1^3 A} = 4a(1-a)^2$$

We calculate the maximum possible value of η_{wt} by setting $d\eta_{\text{wt}}/da = 0$ and solving for a. This yields $a = 1$ or ⅓. Since $a = 1$ is the trivial case (no power generated), we conclude that a must equal ⅓ for maximum possible power coefficient. Substituting $a = ⅓$ into above equation gives

$$\eta_{\text{wt,max}} = 4a(1-a)^2 = 4\frac{1}{3}\left(1-\frac{1}{3}\right)^2 = \frac{16}{27} = 0.5926$$

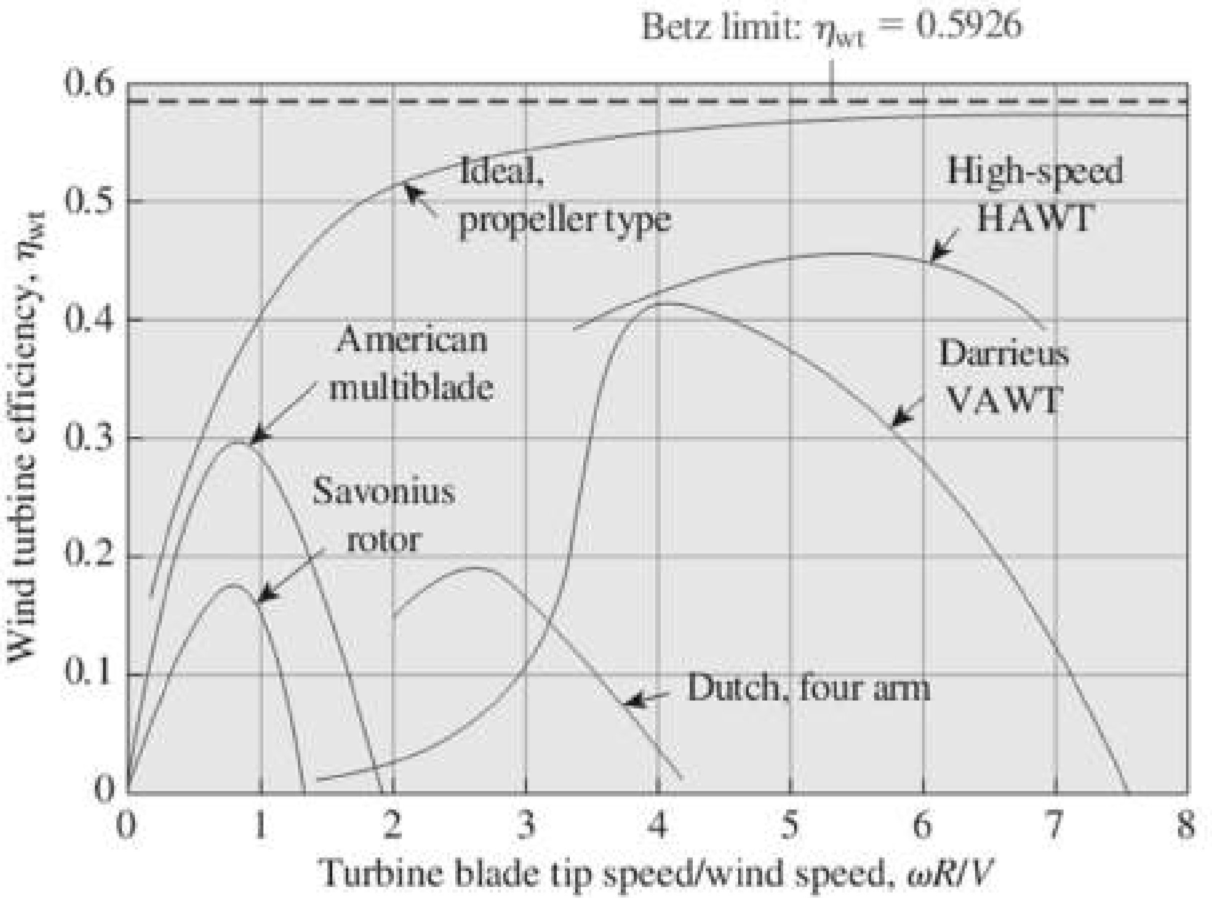


Figure 5-10

Wind turbine efficiency of various types of wind turbines as a function of the ratio of turbine blade tip speed to wind speed. So far, no design has achieved better performance than the horizontal axis wind turbine (HAWT).

The value of $\eta_{\text{wt,max}}$ = 0.5926 represents the maximum possible efficiency of any wind turbine and is known as the Betz limit.

All real wind turbines have a maximum achievable efficiency less than this due to irreversible losses which have been ignored in this ideal analysis.

From the wind turbine efficiency plot, we see that an ideal propeller-type wind turbine approaches the Betz limit as $\omega R/V$ approaches infinity.

However, the efficiency of real wind turbines reaches a maximum at some finite value of $\omega R/V$ and then drops beyond that.

In practice, three primary effects lead to a maximum achievable efficiency that is lower than the Betz limit:

- ❑ Rotation of the wake behind the rotor (swirl)
- ❑ Finite number of rotor blades and their associated tip losses (tip vortices are generated in the wake of rotor blades for the same reason they are generated on finite airplane wings since both produce “lift”).
- ❑ Non-zero aerodynamic drag on the rotor blades (frictional drag as well as induced drag)

In addition, mechanical losses due to shaft friction lead to even lower maximum achievable efficiencies.

Other mechanical and electrical losses in the gearbox, generator, etc., also reduce the overall wind turbine efficiency.

As seen in Fig. 5-10, the “best” wind turbine is the high-speed HAWT, and that is why you see this type of wind turbine being installed throughout the world.

5-6 CONSIDERATIONS IN WIND POWER APPLICATIONS

When a wind turbine project is underway on a windy site, many turbines are installed, and such sites are called as a wind farm or a wind park.

Advantages of wind farm: The use of a wind farm is highly desirable due to reduced site development costs, simplified transmission lines, and centralized access for operation and maintenance.

Single use of a wind turbine is used for off-grid homes, off-shore areas, and demonstration projects.

Figure 5-13 A wind park.

Spacing between the turbines: The number of wind turbines in a given site depends on the spacing between the turbines.

If the turbines are spaced too close to each other, the flow through one turbine affects the flow through the next turbine, and this reduces the turbine performance.

If the turbines are far from each other, this means a poor use of the site as the potential for the installation of additional turbines for greater power outputs is not realized.

Optimum spacing between the turbines: It is estimated to be 3 to 5 blade diameters between the turbines in a row and 5 to 9 blade diameters between rows.

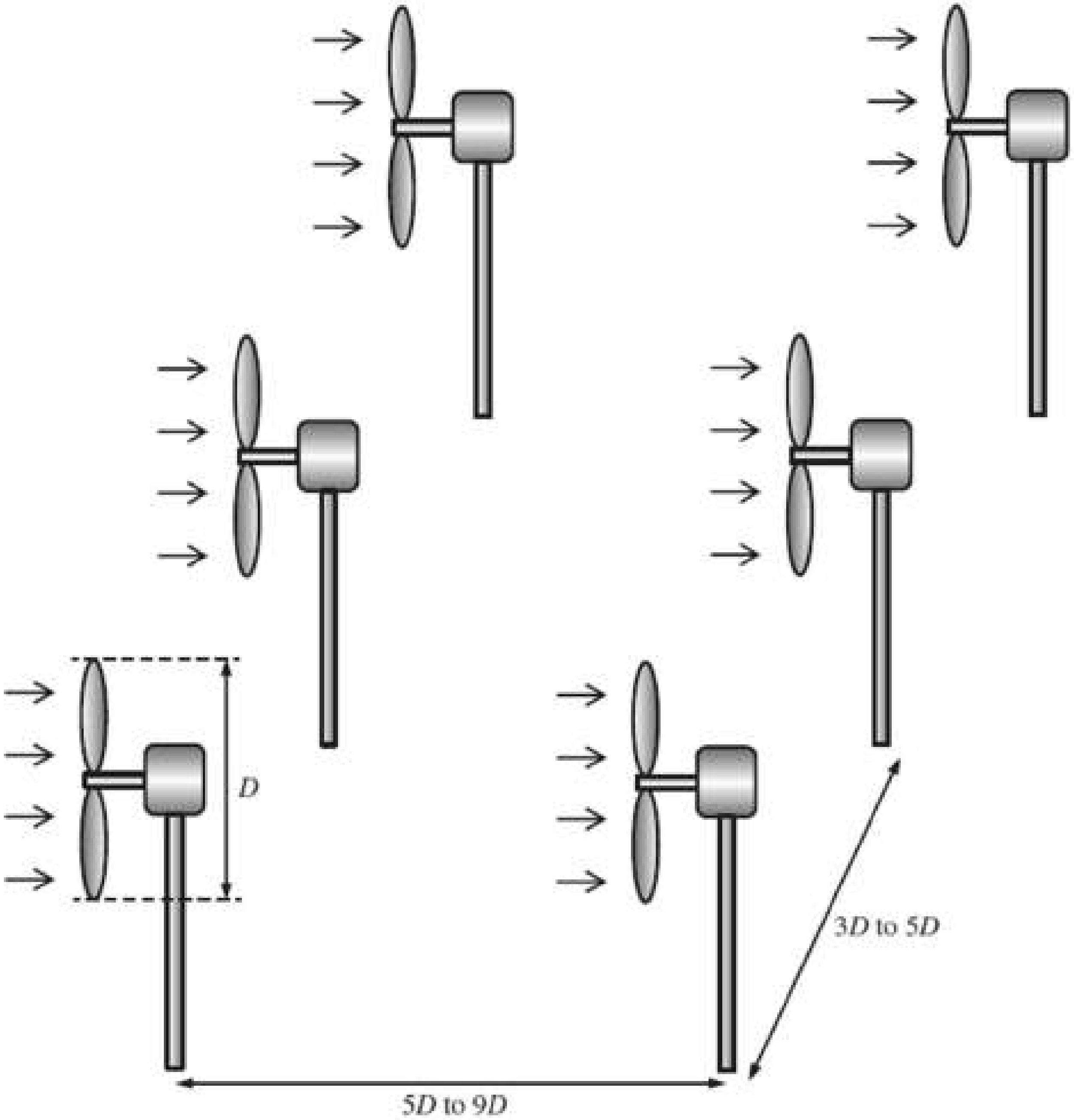


Figure 5-14 Optimum spacing of wind turbines in a wind farm.

Wind tower: The wind tower should be strong enough to support the turbine weight and withstand the forces during high wind speeds and the thrust on the wind turbine. Using tall wind towers minimizes the turbulence induced and allows flexibility in sitting.

There are several factors that need to be considered when a wind farm project is planned on a particular site.

Ground conditions: Ground conditions such as vegetation, topography, and ground roughness should be analyzed.

Access: Convenient access to the farm site, load capacity of the soil, and earthquake characteristics are some other considerations.

Traveling birds: Make sure that the planned wind farm site is not a traveling route of the birds.

Offshore wind turbines: In recent years, the number of offshore wind turbines has increased, particularly on the coasts of Denmark, Sweden, and Netherlands as well as some other European countries.

For example, in Denmark, an offshore wind farm (Horns Rev 2 project) consists of 91 turbines with a total capacity of 209 MW.

Effects of blade diameter and generator size: When the blade diameter is increased at the same generator rating, the power curve will move left. The rated power can be realized at a lower wind speed.

When a larger generator is used, the rated power increases. This is particularly advantageous at high wind speeds. Therefore, the generator size can be increased to maximize turbine power output if the turbine mostly operates at high wind speeds.

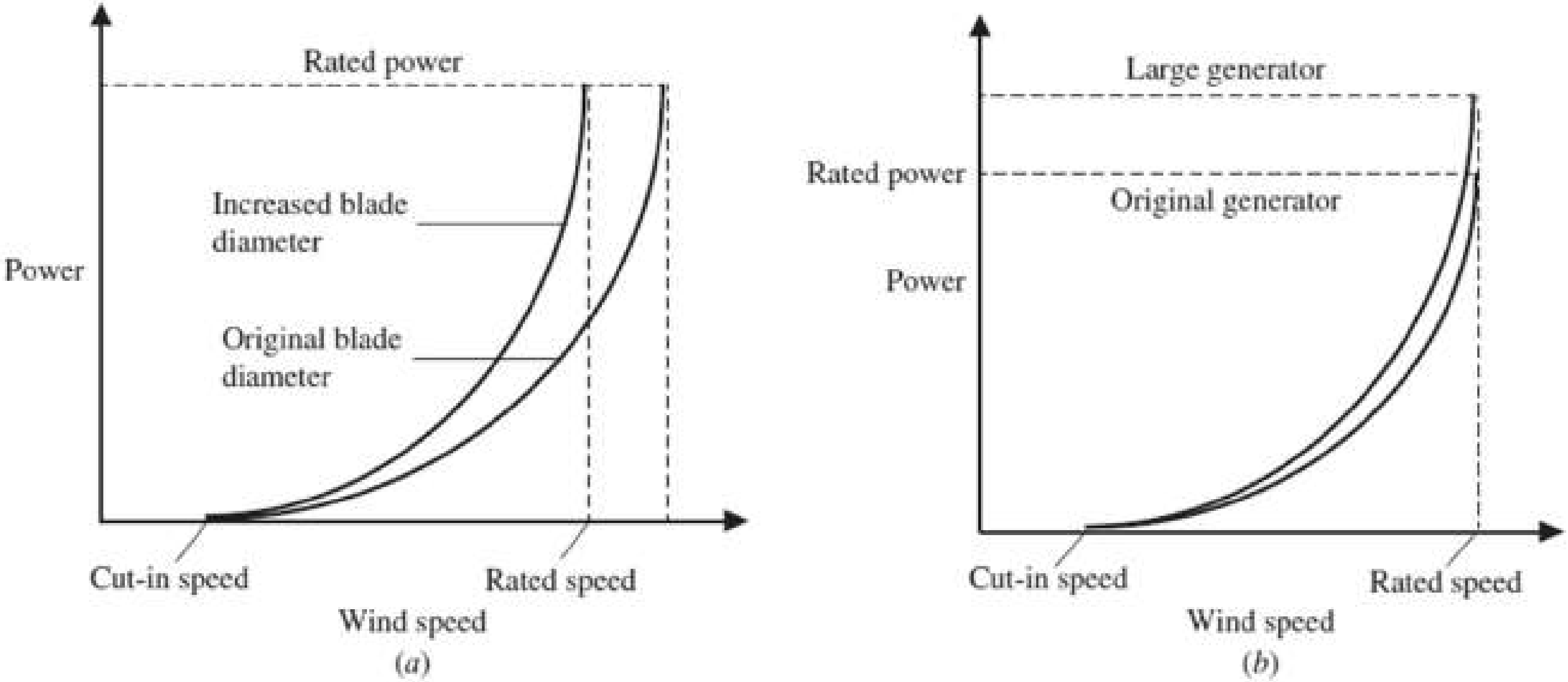


Figure 5-15 Effects of increasing blade diameter and a larger generator on power output of the wind turbine.

Grid stability: For an effective wind power generation, a reliable power grid/transmission network near the site and good grid stability is essential. The wind turbine generates power at 400 V, which is stepped up to 11 to 110 kV.

The poor grid stability may cause 10 to 20 percent power loss.

In China, some wind turbines are not connected to the grid partly because of the stability problems.

Load factor: A wind turbine generates an average of 25 to 30 percent of the rated power (load factor = 25-30%).

Power vs. Time of the day: The power changes with time of the day. For example, in early morning hours, the power output is 80 percent of average power and in the afternoon, it is 120 percent of the average power.

Such fluctuations can be reduced by using longer towers.

Tall wind towers: An important reason for using tall wind towers is that wind speed increases with tower height, and higher wind velocities translate into higher power outputs. The wind speed can be expressed as functions of tower height and the roughness of the earth's surface to be

$$\frac{V}{V_0} = \left(\frac{h}{h_0}\right)^{\alpha}$$

V	wind speed at height h
V_0	nominal wind speed at h_0
α	friction coefficient of the ground

Since the wind power is proportional to third power of wind speed, a slight increase in wind speed translates into a significant increase in power output.

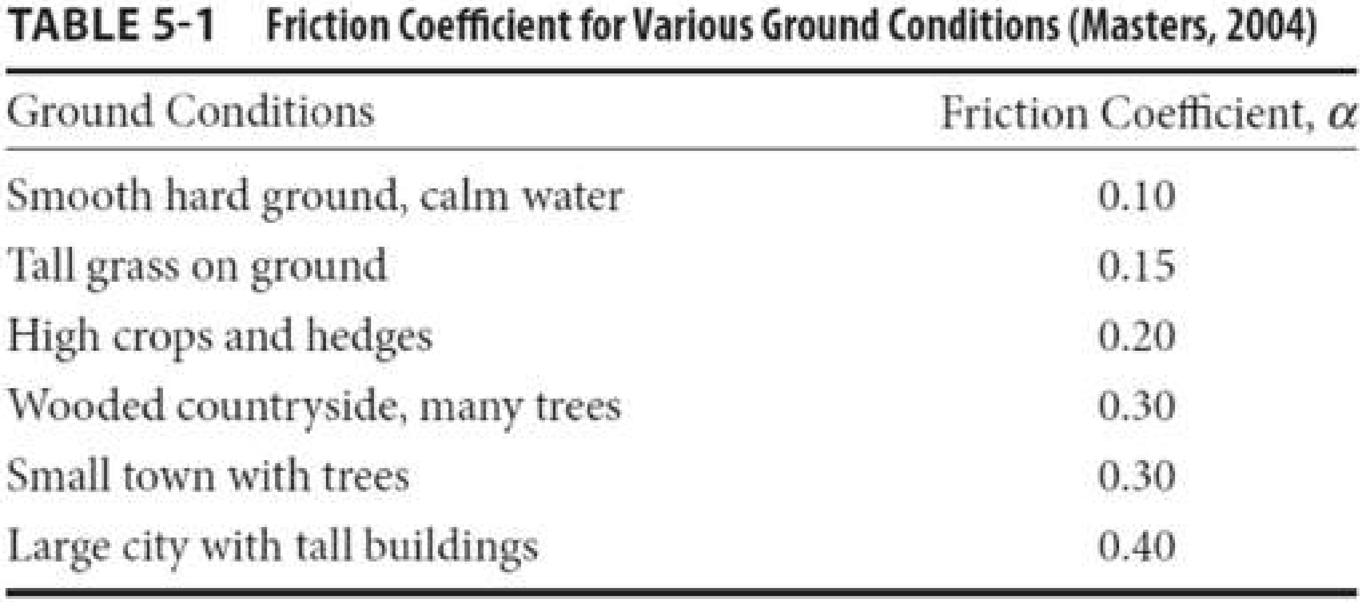


TABLE 5-1 Friction Coefficient for Various Ground Conditions (Masters, 2004)

Ground Conditions	Friction Coefficient, α
Smooth hard ground, calm water	0.10
Tall grass on ground	0.15
High crops and hedges	0.20
Wooded countryside, many trees	0.30
Small town with trees	0.30
Large city with tall buildings	0.40

No electrical grid: For the remote places on the earth, there is sometimes no connection to the electrical grid. For such places isolated power systems can be used.

Diesel engine power plants are commonly used for such autonomous power systems since diesel systems can be put in operation in a relatively short time and the units are relatively small compared to other fossil fuel based systems such as gas turbines and steam turbines.

Hybrid power system: consisting of a diesel system and a wind turbine system can be operated together in order to minimize diesel fuel consumption.

In this operation, wind power should have priority in meeting electrical needs of the users and the diesel engines should be operated to meet the demand when wind power is not sufficient.

A hybrid system for an autonomous power system can also integrate a diesel system with one or more of other renewable energy systems such as wind, photovoltaic, or a hydropower system.

The first wind turbine for electricity generation was developed at the end of 19th century.

Two important technological developments took place after 1940, which were essential for stimulating the emergence of wind turbine:

- the introduction of three-blade structure
- replacement of DC generator with AC generator

The technology for wind turbine has improved greatly over the years but there is room for more improvements.

Some of the challenges in wind power technology are

- increasing the size of the wind turbine
- designing the turbines specifically for a given site
- developing new structural dynamic concepts
- developing custom generators and power electronics
- improved manufacturing technology
- better control strategies

Cost of wind turbines: The largest cost is due to gearbox, brake, and electrical system with a contribution of 61%.

Pitch, hub, and blade account for 27% of total capital cost.

This is followed by tower system with 12%.

There are other costs associated wind turbine applications involving land, licensing, property tax, insurance, and labor, as well as operating and maintenance expenses.

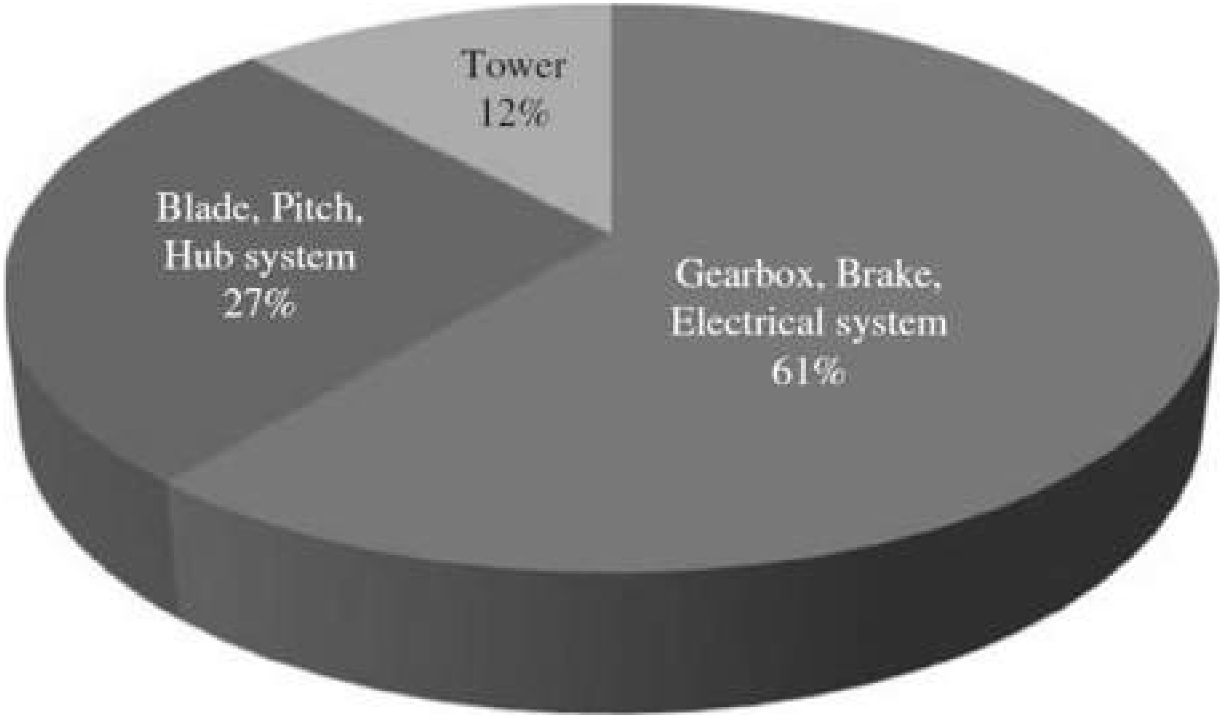
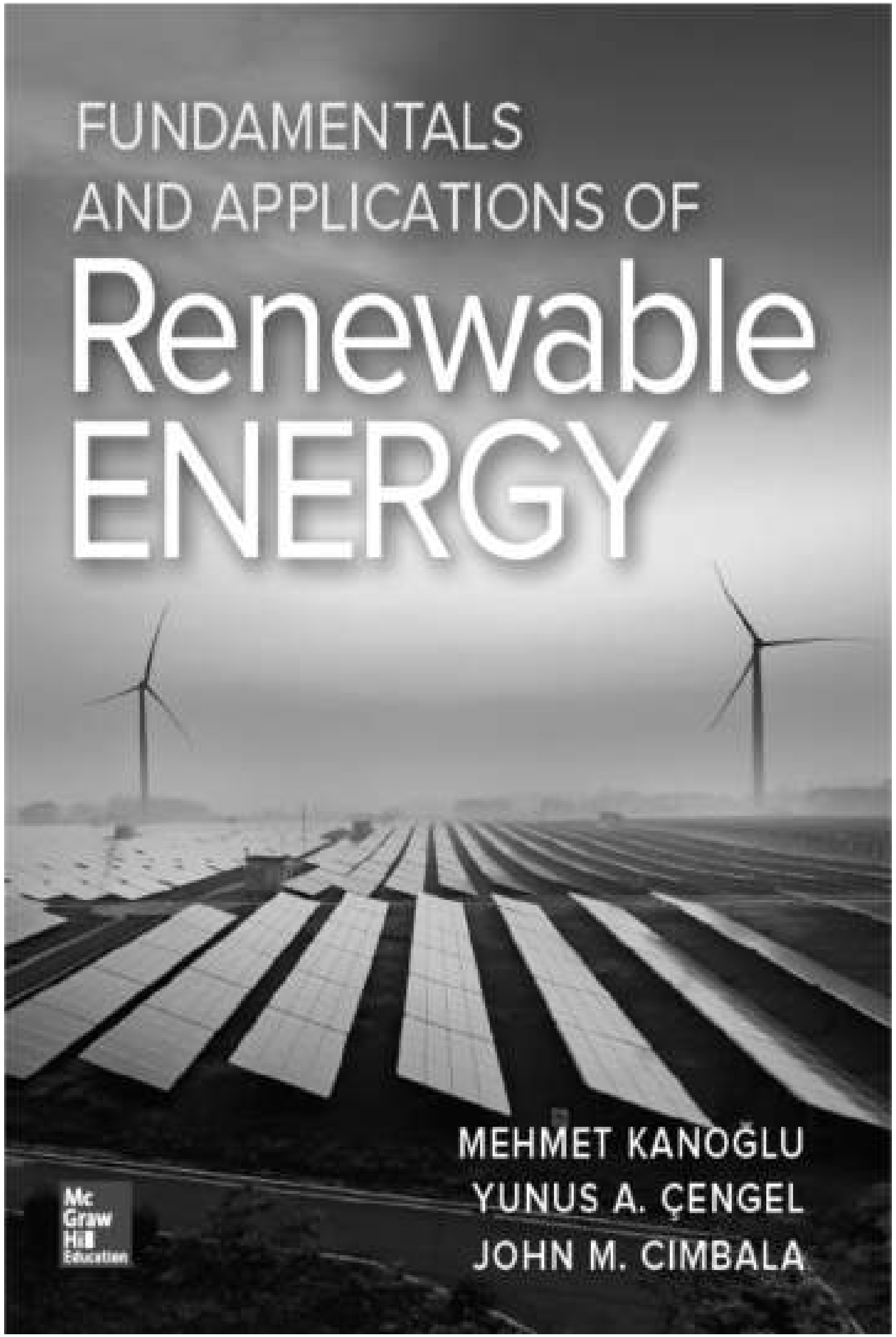


Figure 5-16 Capital cost breakdown of a wind turbine.



Chapter 6
HYDROPOWER

Fundamentals and Applications of
Renewable Energy
Mehmet Kanoglu
Yunus A. Cengel
John M. Cimbala
McGraw-Hill, 2020

6-1 INTRODUCTION

Turbines have been used for centuries to convert freely available mechanical energy from rivers and water bodies into useful mechanical work, usually through a rotating shaft.

Runner: The rotating part of a hydroturbine.

Hydraulic turbines or hydro turbines: Turbomachines producing power when the working fluid is water.

Large dams are built in the flow path of rivers to collect water.

Hydroelectric power plant: The water having potential energy is run through turbines to produce electricity in such installations.

Some dams are also used for irrigation of farms and flood control.

Cost of dam: The large dam takes a long time and a large amount of investment to build but the cost of producing electricity by hydropower is much lower than the cost of electricity production by fossil fuels.

Number of turbines: Most large hydroelectric power plants have several turbines arranged in parallel.

This offers the power company the opportunity to turn off some of the turbines during times of low power demand and for maintenance.

History: The first hydraulic turbine-generator set was developed in 1882. It used a 10-m-high water reservoir and provided a power of 6 kW to light bulbs.

This is followed by the first known hydroelectric power plant in 1883 in Northern Ireland. This plant had two turbines with a power rating of 39 kW.

An electric train was powered by this plant.

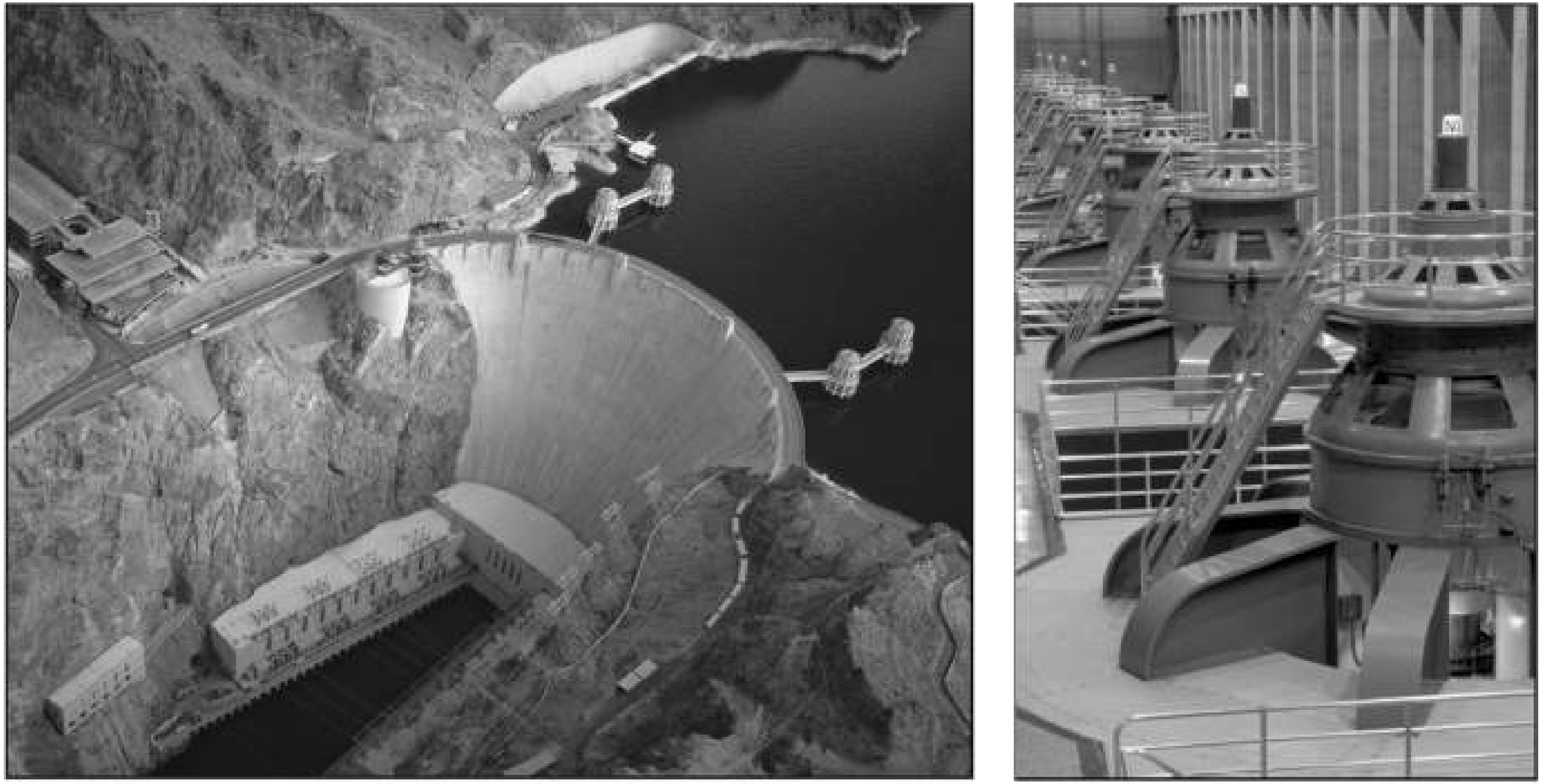
Global capacity: Most of the world’s renewable electricity production is due to hydropower with a global installed capacity of over 1250 GW as of 2017.

Percentage: Hydropower accounts for 71 percent of renewable power and it generated 17 percent of world’s electricity considering all energy sources including fossil fuels.

Countries: The installed capacity of hydropower is 341 GW in China, 103 GW in the United States, 100 GW in Brazil, and 81 GW in Canada.

USA: The United States was generating 40 percent of its electricity from hydropower in 1930. This is dropped to 6.5 percent in 2017.

Canada, Norway, Turkey, Nepal, and New Zealand produce 50 percent or more of their electricity by hydropower



(*a*) (*b*)

Figure 6-1 (*a*) An aerial view of Hoover Dam and (*b*) the top (visible) portion of several of the parallel electric generators driven by hydraulic turbines at Hoover Dam.

Hoover Dam in Boulder City, Nevada has 17 parallel turbines, 15 of which are identical large Francis turbines that can produce approximately 130 MW of electricity each. The maximum gross head is 180 m. The total peak power production of the power plant exceeds 2000 MW while about 4 billion kWh electricity is produced every year.

Considerations in building a dam with accumulation reservoir

Building a hydroelectric power plant with an accumulation reservoir is expensive and takes a long time to build.

The size of the plant including the dam is large, and environmental impacts of the plant need serious considerations and studies.

Unlike run-of-river plants, a plant with a dam can use most of the collected water for power production.

The water reservoir of a hydroelectric power plant is also used for other purposes such as irrigation, fish farming, and recreation.

For some hydroelectric installations, irrigation is more important than or as important as power production.

Components in hydroelectric power plant: The power house of a hydropower plant has hydraulic turbines and generators. A regulator, a water admission valve, an electrical command board, and an inertial flywheel are among the supplemental equipment.

Civil work: A hydroelectric power plant project involves considerable amount of civil works.

This may include the construction of a dam, water intake system for diversion of river from its normal course, a spillway to return water to its normal course, various piping, a balance chimney, and a machine house.

River plants: There is less amount of construction involved in river plants.

As a result, river plants can be built in a relatively short time; they occupy less space; they have less environmental impacts; and they involve lower initial cost compared to large hydropower plants.

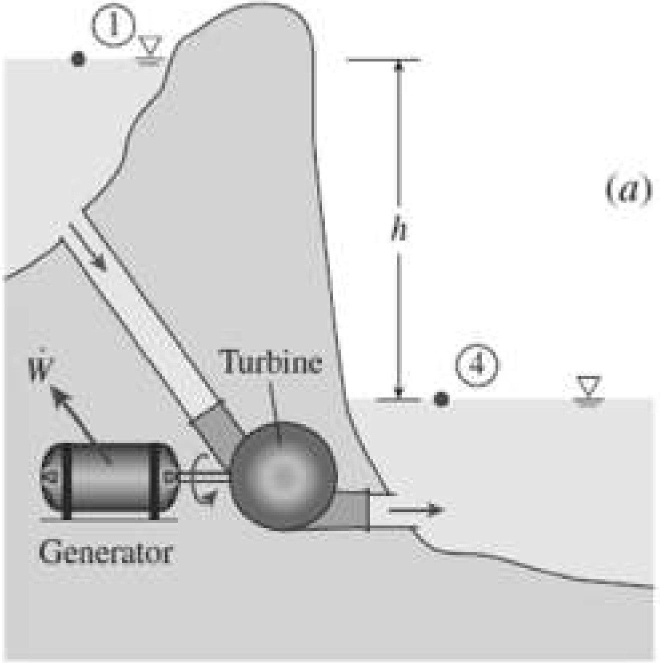
In hydroelectric power plants, large dynamic turbines are used to produce electricity.

There are two basic types of dynamic turbine:

Impulse turbines: require a higher head, but can operate with a smaller volume flow rate.

Reaction turbines: can operate with much less head, but require a higher volume flow rate.

6-2 ANALYSIS OF HYDROELECTRIC POWER PLANT



$$e_{\text{mech}} = \frac{P}{\rho} + \frac{V^2}{2} + gz$$

Mechanical energy of a flowing fluid

$$\Delta e_{\text{mech}} = \frac{P_2 - P_1}{\rho} + \frac{V_2^2 - V_1^2}{2} + g(z_2 - z_1)$$

$$\dot{W}_{\max} = \dot{m}\Delta e_{\text{mech}}$$

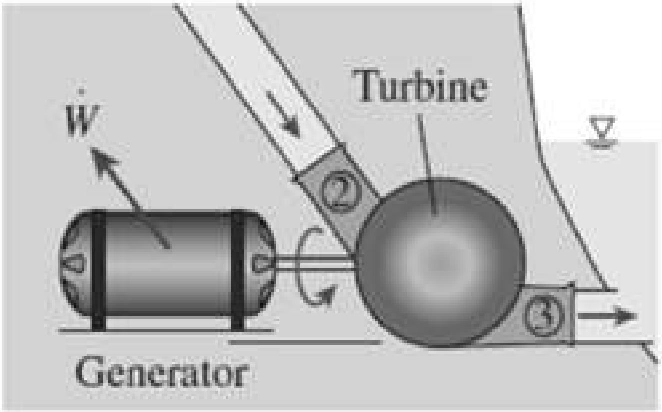
Maximum power

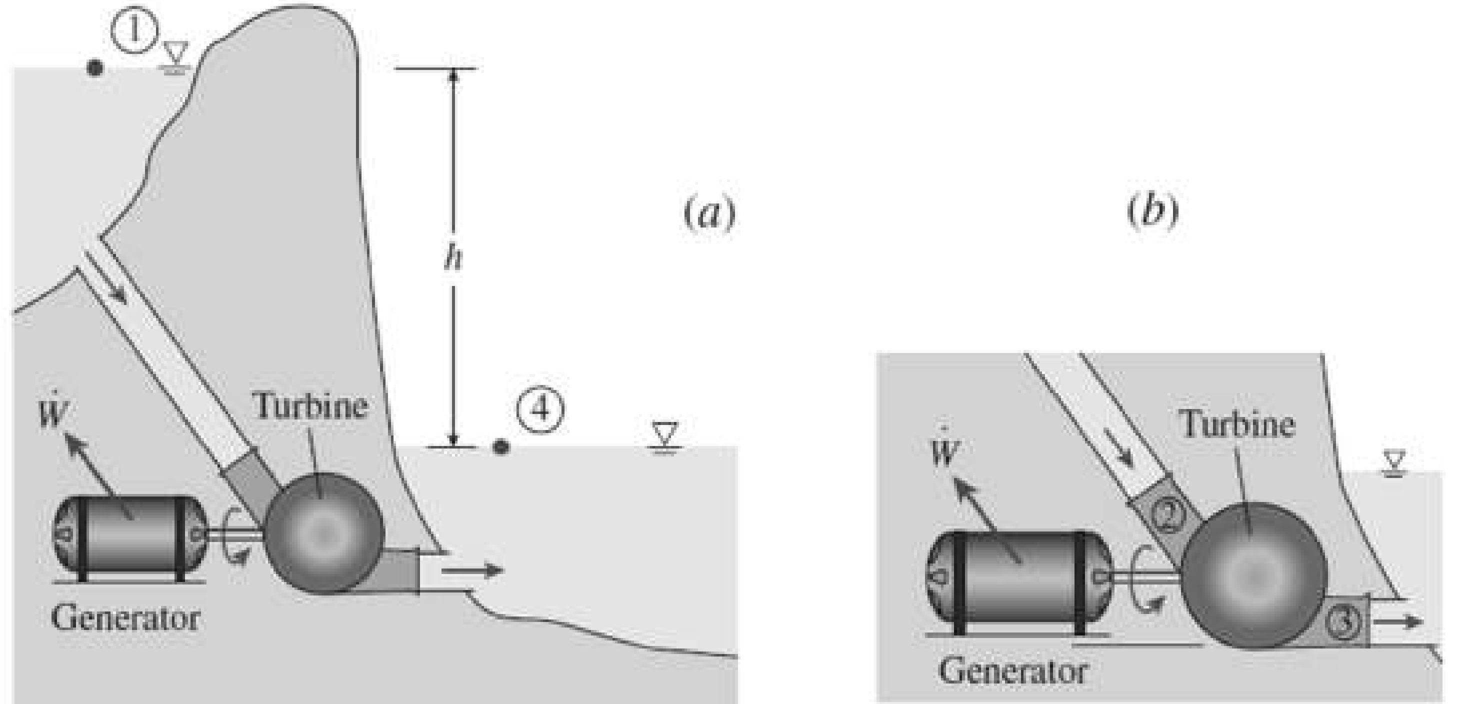
$$\dot{W}_{\max} = \dot{m}\Delta e_{\text{mech}} = \dot{m}g(z_1 - z_4) = \dot{m}gh$$

$$P_1 \approx P_4 = P_{\text{atm}} \quad \text{and} \quad V_1 = V_4 \approx 0$$

$$\dot{W}_{\max} = \dot{m}\Delta e_{\text{mech}} = \dot{m}\frac{P_2 - P_3}{\rho} = \dot{m}\frac{\Delta P}{\rho}$$

$$V_2 \approx V_3 \quad \text{and} \quad z_2 \approx z_3$$





$$\dot W_{\text{max}} = \dot m \Delta e_{\text{mech}} = \dot m g(z_1 - z_4) = \dot m g h$$
since $P_1 \approx P_4 = P_{\text{atm}}$ and $V_1 = V_4 \approx 0$

$$\dot W_{\text{max}} = \dot m \Delta e_{\text{mech}} = \dot m \frac{P_2 - P_3}{\rho} = \dot m \frac{\Delta P}{\rho}$$
since $V_2 \approx V_3$ and $z_2 \approx z_3$

Figure 6-2
Mechanical energy is illustrated by an ideal hydraulic turbine coupled with an ideal generator. In the absence of irreversible losses, the maximum produced power is proportional to (a) the change in water surface elevation from the upstream to the downstream reservoir or (b) (close-up view) the drop in water pressure from just upstream to just downstream of the turbine.

$$\eta_{\text{turbine}} = \frac{\dot{W}_{\text{shaft}}}{\Delta\dot{E}_{\text{mech,fluid}}} = \frac{\dot{W}_{\text{shaft}}}{\dot{m}\Delta e_{\text{mech}}} = \frac{\dot{W}_{\text{shaft}}}{\dot{m}gh} = \frac{\dot{W}_{\text{shaft}}}{\dot{W}_{\text{max}}}$$

Turbine efficiency

$$\eta_{\text{generator}} = \frac{\dot{W}_{\text{electric}}}{\dot{W}_{\text{shaft}}}$$

$$\eta_{\text{turbine-generator}} = \eta_{\text{turbine}}\eta_{\text{generator}} = \left(\frac{\dot{W}_{\text{shaft}}}{\dot{W}_{\text{max}}}\right)\left(\frac{\dot{W}_{\text{electric}}}{\dot{W}_{\text{shaft}}}\right) = \frac{\dot{W}_{\text{electric}}}{\dot{W}_{\text{max}}}$$

Generator efficiency

Overall efficiency

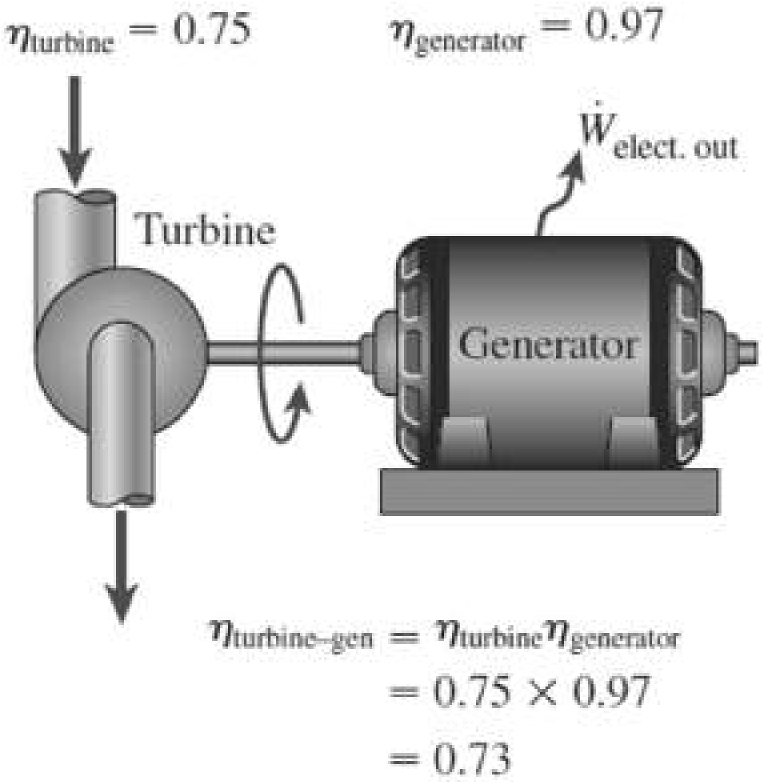


Figure 6-3
The overall efficiency of a turbine-generator is the product of the efficiency of the turbine and the efficiency of the generator, and represents the fraction of the mechanical power of the fluid converted to electrical power.

$$e_{\text{mech, in}} = e_{\text{mech, out}} + e_{\text{mech, loss}}$$

$$\frac{P_1}{\rho_1} + \frac{V_1^2}{2} + gz_1 = \frac{P_2}{\rho_2} + \frac{V_2^2}{2} + gz_2 + w_{\text{turbine}} + e_{\text{mech, loss}}$$

Steady-flow energy equation for turbine/penstock combination

$$\dot{m}\left(\frac{P_1}{\rho_1} + \frac{V_1^2}{2} + gz_1\right) = \dot{m}\left(\frac{P_2}{\rho_2} + \frac{V_2^2}{2} + gz_2\right) + \dot{W}_{\text{turbine}} + \dot{E}_{\text{mech, loss, total}}$$

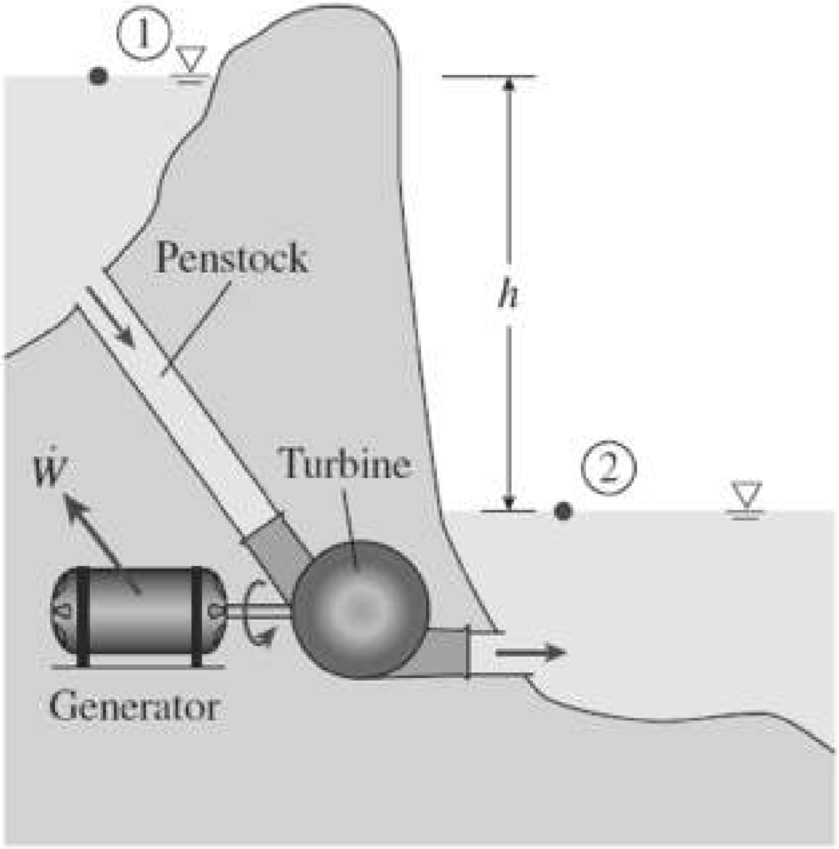


Figure 6-4
The analysis of a hydroelectric power plant involves that of the turbine and the penstock.

$$\dot{E}_{\text{mech, loss, total}} = \dot{E}_{\text{mech, loss, turbine}} + \dot{E}_{\text{mech, loss, piping}}$$

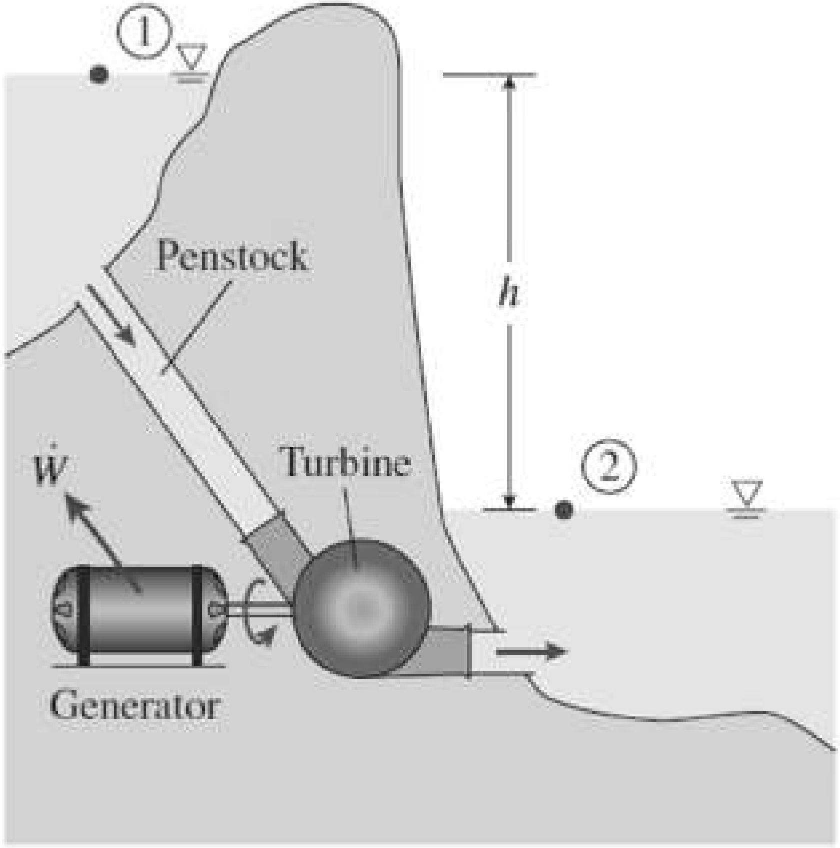
$$\frac{P_1}{\rho_1 g} + \frac{V_1^2}{2g} + z_1 = \frac{P_2}{\rho_2 g} + \frac{V_2^2}{2g} + z_2 + h_{\text{turbine},e} + h_L$$

$$h_{\text{turbine},e} = \frac{w_{\text{turbine},e}}{g} = \frac{\dot{W}_{\text{turbine},e}}{\dot{m} g} = \frac{\dot{W}_{\text{turbine}}}{\eta_{\text{turbine}} \dot{m} g}$$

Extracted head removed from the fluid by the turbine

$$h_L = \frac{e_{\text{mech, loss, piping}}}{g} = \frac{\dot{E}_{\text{mech, loss, piping}}}{\dot{m} g}$$

Irreversible head loss of piping



$$\frac{P_1}{\rho_1 g}+\frac{V_1^2}{2g}+z_1=\frac{P_2}{\rho_2 g}+\frac{V_2^2}{2g}+z_2+h_{\text{turbine},e}+h_L$$

$$h_{L,\text{total}}=h_{L,\text{major}}+h_{L,\text{minor}}=f\frac{L}{D}\frac{V^2}{2g}+\sum K_L\frac{V^2}{2g}=\left(f\frac{L}{D}+\sum K_L\right)\frac{V^2}{2g}$$

Total head loss in the penstock

where f = Darcy friction factor. It can be determined from the Moody chart (or Colebrook equation) for turbulent flow. For laminar flow, $f = 64/\text{Re}$, where Re is the Reynolds number.

L = length of the penstock

D = diameter of the penstock

V = velocity of water in the penstock

K_L = loss coefficient for minor losses in the piping system

$$H_{\text{gross}} = z_A - z_E \qquad \dot{W}_{\max} = \rho g \dot{V} H_{\text{gross}} \qquad H_{\text{net}} = \text{EGL}_{\text{in}} - \text{EGL}_{\text{out}}$$

$$\text{EGL} = \text{Pressure head} + \text{Velocity head} + \text{Elevation head} = P/\rho g + V^2/2g + z$$

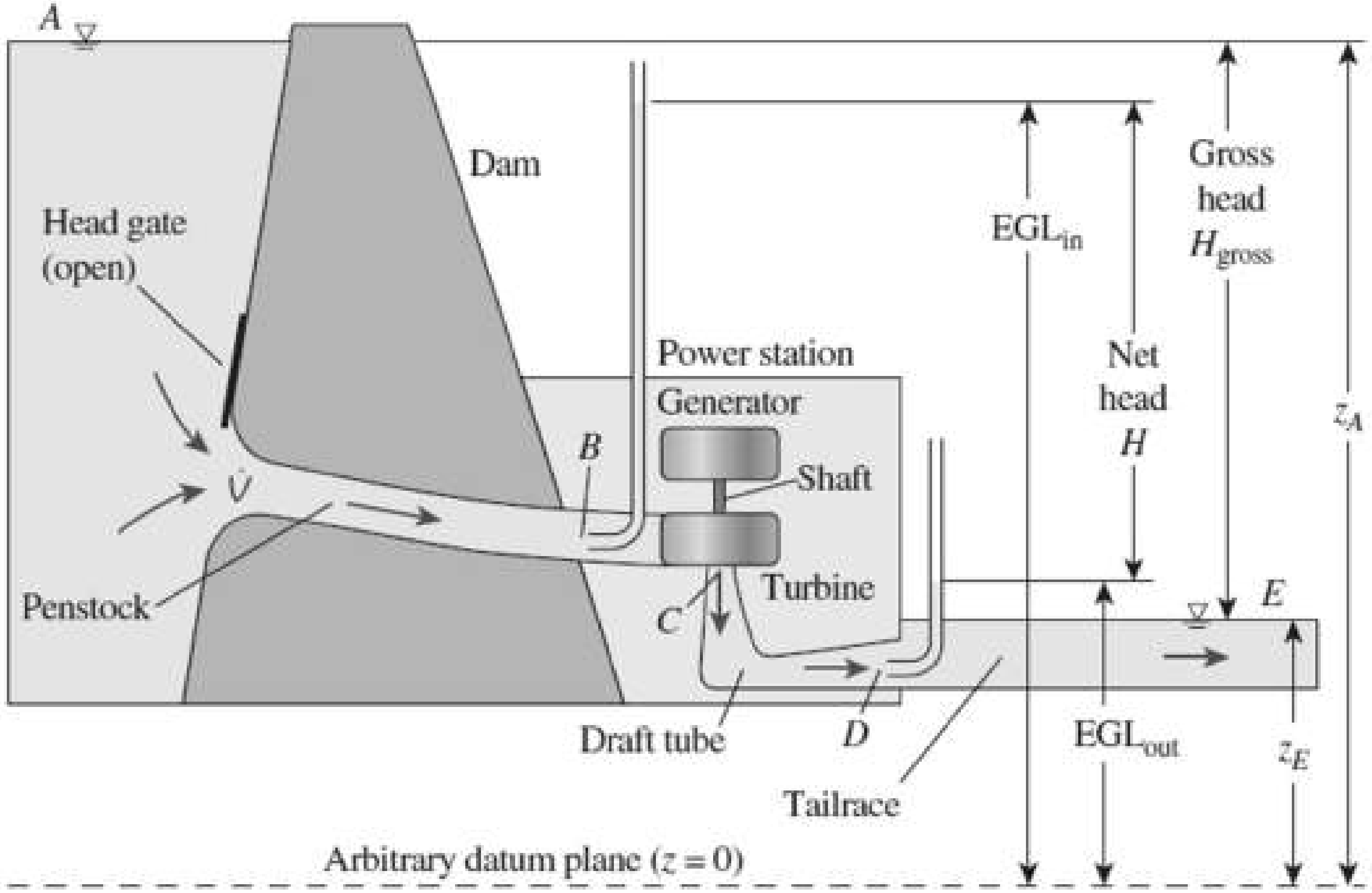


Figure 6-5 Typical setup and terminology for a hydroelectric plant that utilizes a Francis turbine to generate electricity; drawing not to scale. The pitot probes are shown for illustrative purposes only.

$$\eta_{\text{plant}} = \frac{\dot{W}_{\text{electric}}}{\dot{W}_{\text{max}}} = \frac{\dot{W}_{\text{electric}}}{\rho g \dot{V} H_{\text{gross}}}$$

Overall efficiency of the entire hydroelectric plant based on the gross head

$$\eta_{\text{turbine}} = \frac{\dot{W}_{\text{shaft}}}{\rho g \dot{V} H_{\text{net}}}$$

Turbine efficiency based on the net head

$$\dot{E}_{\text{mech,loss,piping}} = \rho g \dot{V} h_L$$

Power loss due to head loss in piping

Turbine efficiency based on the net head

$$\eta_{\text{turbine}} = \frac{\dot{W}_{\text{shaft}}}{\dot{W}_{\text{max}} - \dot{E}_{\text{mech,loss,piping}}} = \frac{\dot{W}_{\text{shaft}}}{\rho g \dot{V} H_{\text{gross}} - \rho g \dot{V} h_L} = \frac{\dot{W}_{\text{shaft}}}{\rho g \dot{V} (H_{\text{gross}} - h_L)}$$

$$\eta_{\text{piping}} = 1 - \frac{\dot{E}_{\text{mech, loss, piping}}}{\dot{W}_{\text{max}}}$$

Piping efficiency to account for irreversible head losses in the piping system

$$\eta_{\text{generator}} = \dot{W}_{\text{electric}} / \dot{W}_{\text{shaft}}$$

Generator efficiency

$$\eta_{\text{plant}} = \frac{\dot{W}_{\text{electric}}}{\dot{W}_{\text{max}}} = \frac{\dot{W}_{\text{electric}}}{\rho g \dot{V} H_{\text{gross}}} \qquad \eta_{\text{turbine}} = \frac{\dot{W}_{\text{shaft}}}{\rho g \dot{V} H_{\text{net}}} \qquad \dot{E}_{\text{mech,loss,piping}} = \rho g \dot{V} h_L$$

$$\eta_{\text{turbine}} = \frac{\dot{W}_{\text{shaft}}}{\dot{W}_{\text{max}} - \dot{E}_{\text{mech,loss,piping}}} = \frac{\dot{W}_{\text{shaft}}}{\rho g \dot{V} H_{\text{gross}} - \rho g \dot{V} h_L} = \frac{\dot{W}_{\text{shaft}}}{\rho g \dot{V} (H_{\text{gross}} - h_L)}$$

$$\eta_{\text{piping}} = 1 - \frac{\dot{E}_{\text{mech, loss, piping}}}{\dot{W}_{\text{max}}} \qquad \eta_{\text{generator}} = \dot{W}_{\text{electric}} / \dot{W}_{\text{shaft}}$$

Overall efficiency of the entire hydroelectric plant

$$\begin{aligned}
\eta_{\text{plant}} &= \eta_{\text{generator}} \eta_{\text{turbine}} \eta_{\text{piping}} \\
&= \left(\frac{\dot{W}_{\text{electric}}}{\dot{W}_{\text{shaft}}} \right) \left(\frac{\dot{W}_{\text{shaft}}}{\dot{W}_{\text{max}} - \dot{E}_{\text{mech,loss,piping}}} \right) \left(1 - \frac{\dot{E}_{\text{mech,loss,piping}}}{\dot{W}_{\text{max}}} \right) \\
&= \left(\frac{\dot{W}_{\text{electric}}}{\dot{W}_{\text{shaft}}} \right) \left[\frac{\dot{W}_{\text{shaft}}}{\dot{W}_{\text{max}} (1 - \dot{E}_{\text{mech,loss,piping}} / \dot{W}_{\text{max}})} \right] \left(1 - \frac{\dot{E}_{\text{mech,loss,piping}}}{\dot{W}_{\text{max}}} \right) \\
&= \frac{\dot{W}_{\text{electric}}}{\dot{W}_{\text{max}}}
\end{aligned}$$

6-3 IMPULSE TURBINES

In an impulse turbine, the fluid is sent through a nozzle so that most of its available mechanical energy is converted into kinetic energy.

The high-speed jet then impinges on bucket-shaped vanes that transfer energy to the turbine shaft.

The modern and most efficient type of impulse turbine is Pelton turbine and the rotating wheel is called a Pelton wheel.

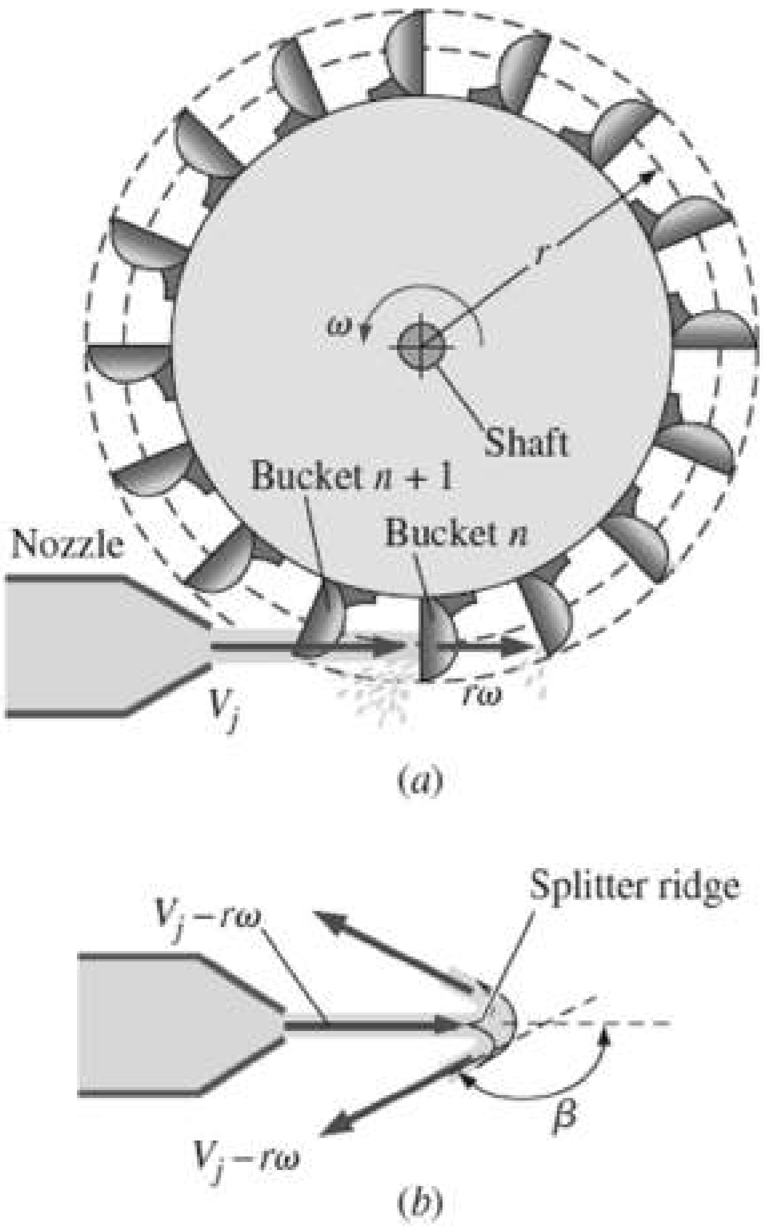


Figure 6-7
Schematic diagram of a Pelton-type *impulse turbine*; the turbine shaft is turned when high-speed fluid from one or more jets impinges on buckets mounted to the turbine shaft. (*a*) Side view, absolute reference frame, and (*b*) bottom view of a cross section of bucket *n*, rotating reference frame.

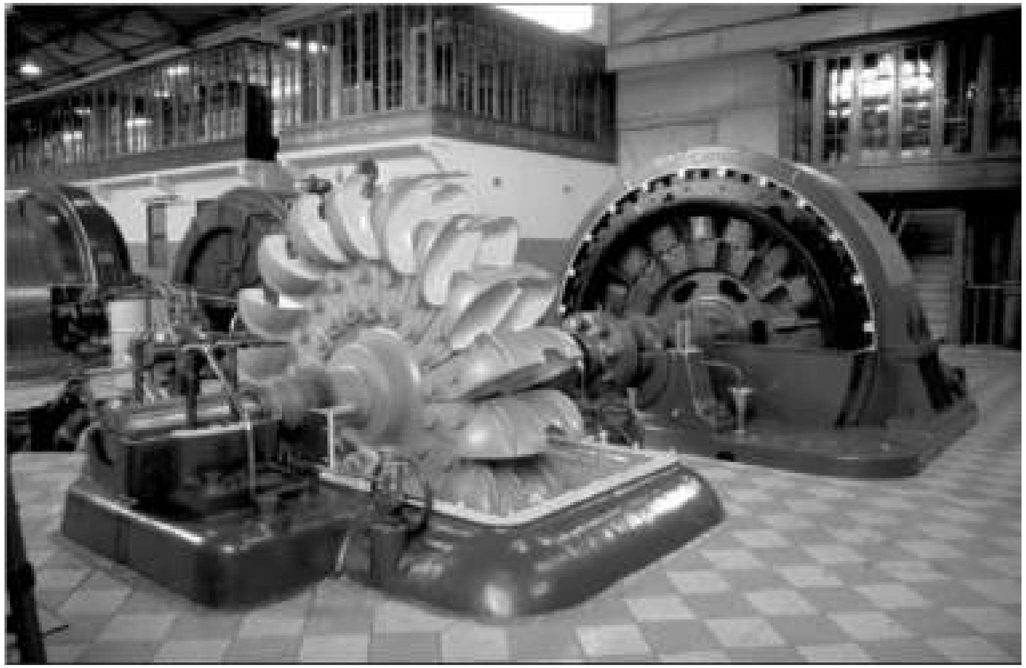


Figure 6-8
A close-up view of a Pelton wheel showing the detailed design of the buckets; the electrical generator is on the right. This Pelton wheel is on display at the Waddamana Power Station Museum near Bothwell, Tasmania.

Figure 6-9
A view from the bottom of an operating Pelton wheel illustrating the splitting and turning of the water jet in the bucket. The water jet enters from the top, and the Pelton wheel is turning to the right.

Shaft power output, Euler turbomachine equation

$$\dot{W}_{\text{shaft}} = \omega T_{\text{shaft}} = \rho\omega\dot{V}(r_2V_{2,t} - r_1V_{1,t})$$

$$V_{1,t} = r\omega + (V_j - r\omega)\cos\beta$$

$$\dot{W}_{\text{shaft}} = \rho r\omega\dot{V}\,\{V_j - [r\omega + (V_j - r\omega)\cos\beta]\}$$

Maximum power is achieved theoretically if $\beta = 180°$. Practically, the maximum power is achieved by reducing β to around 160° to 165°.

Output shaft power: $$\dot{W}_{\text{shaft}} = \rho r\omega\dot{V}(V_j - r\omega)(1 - \cos\beta)$$

Efficiency factor due to β: $$\eta_\beta = \frac{\dot{W}_{\text{shaft, actual}}}{\dot{W}_{\text{shaft, ideal}}} = \frac{1 - \cos\beta}{1 - \cos(180°)}$$

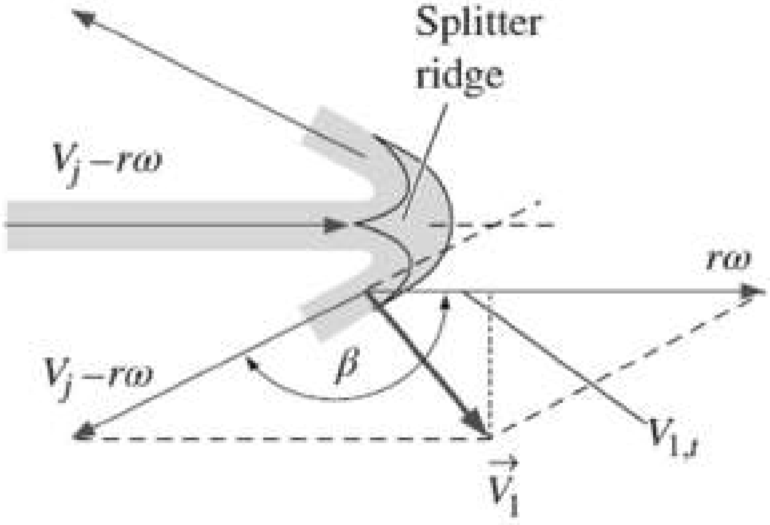


Figure 6-10
Velocity diagram of flow into and out of a Pelton wheel bucket. We translate outflow velocity from the moving reference frame to the absolute reference frame by adding the speed of the bucket ($r\omega$) *to the right.*

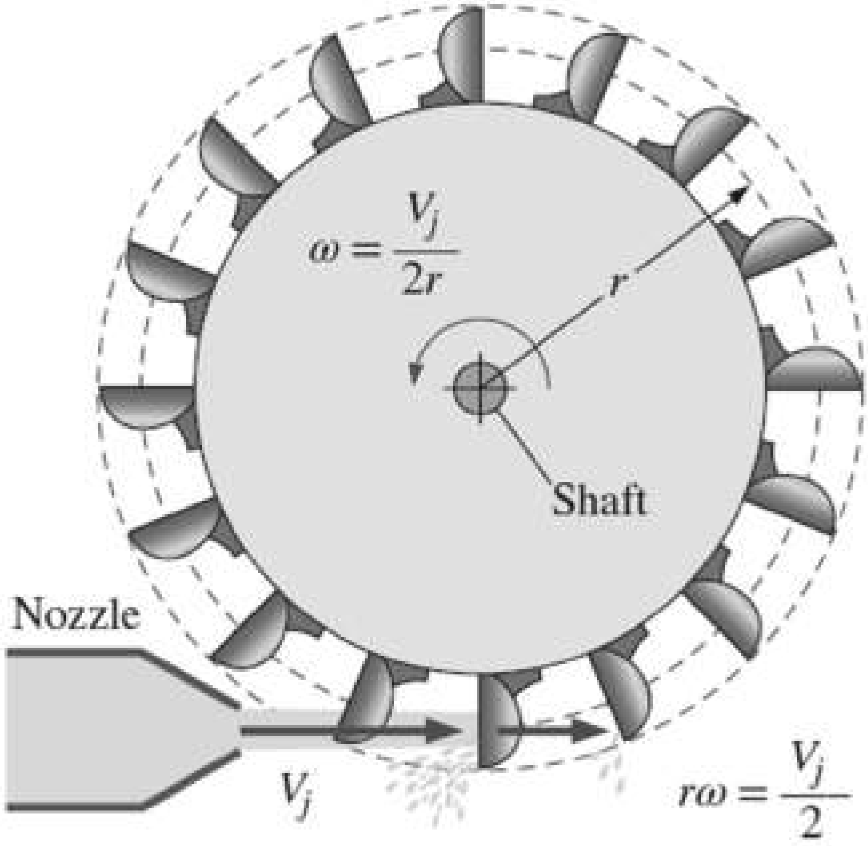


Figure 6-11
The theoretical maximum power achievable by a Pelton turbine occurs when the wheel rotates at $\omega = V_j/(2r)$, that is, when the bucket moves at half the speed of the water jet.

6-4 REACTION TURBINES

The other main type of energy-producing hydroturbine is the reaction turbine, which consists of fixed guide vanes called stay vanes, adjustable guide vanes called wicket gates, and rotating blades called runner blades.

Flow enters tangentially at high pressure, is turned toward the runner by the stay vanes as it moves along the spiral casing or volute, and then passes through the wicket gates with a large tangential velocity component.

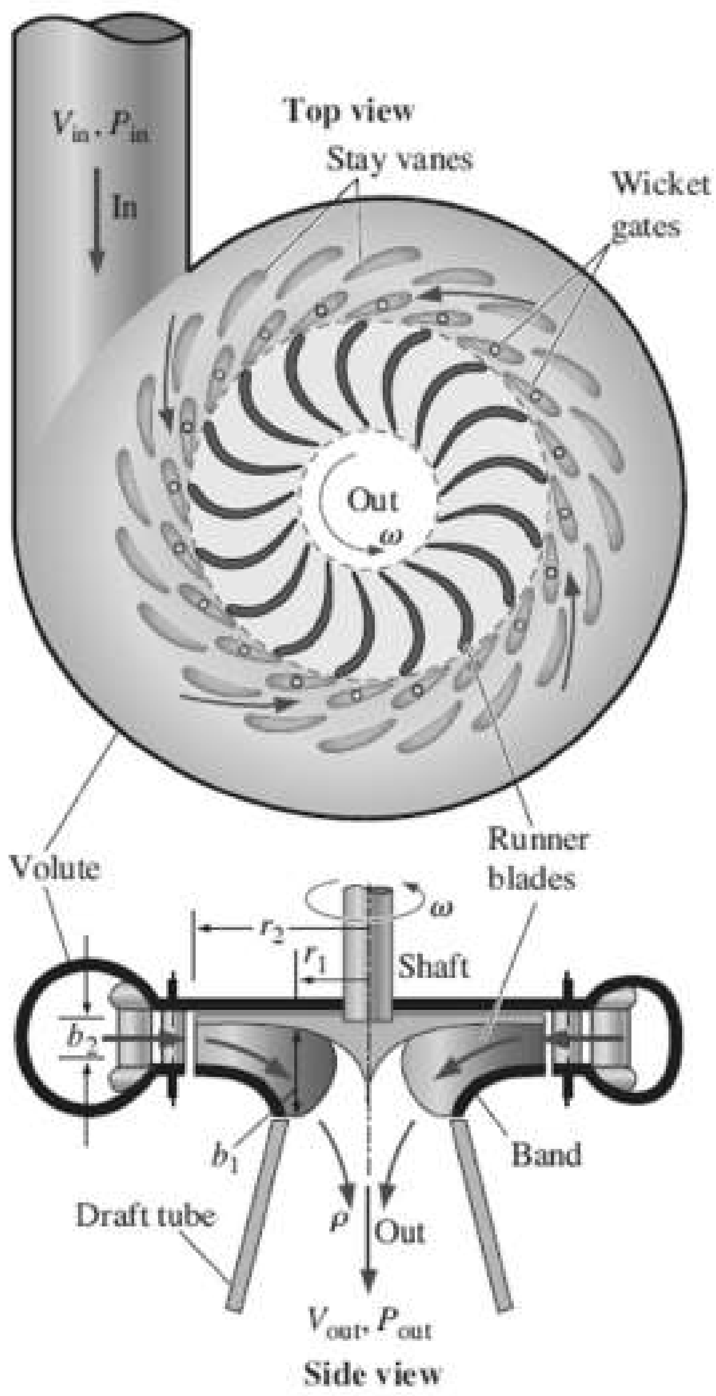


Figure 6-12
A *reaction turbine* differs significantly from an impulse turbine; instead of using water jets, a *volute* is filled with swirling water that drives the runner. For hydroturbine applications, the axis is typically vertical. Top and side views are shown, including the fixed *stay vanes* and adjustable *wicket gates*.

There are two main types of reaction turbine — *Francis* and *Kaplan*.

Francis turbine: somewhat similar in geometry to a centrifugal or mixed-flow pump, but with the flow in the opposite direction.

Kaplan turbine: somewhat like an *axial-flow* fan running backward.

We classify reaction turbines according to the angle that the flow enters the runner.

Francis radial-flow turbine: If the flow enters the runner radially.

Francis mixed-flow turbine: If the flow enters the runner at some angle between radial and axial. This design is more common.

Some hydroturbine engineers use the term "*Francis turbine*" only when there is a band on the runner.

Francis turbines are most suited for heads that lie between

- the high heads of Pelton wheel turbines
- the low heads of Kaplan turbines

A typical large Francis turbine may have 16 or more runner blades and can achieve a turbine efficiency of 90 to 95%.

Propeller mixed-flow turbine (mixed-flow turbine): If the runner has no band, and flow enters the runner partially turned.

Axial-flow turbine: if the flow is turned completely axially *before* entering the runner.

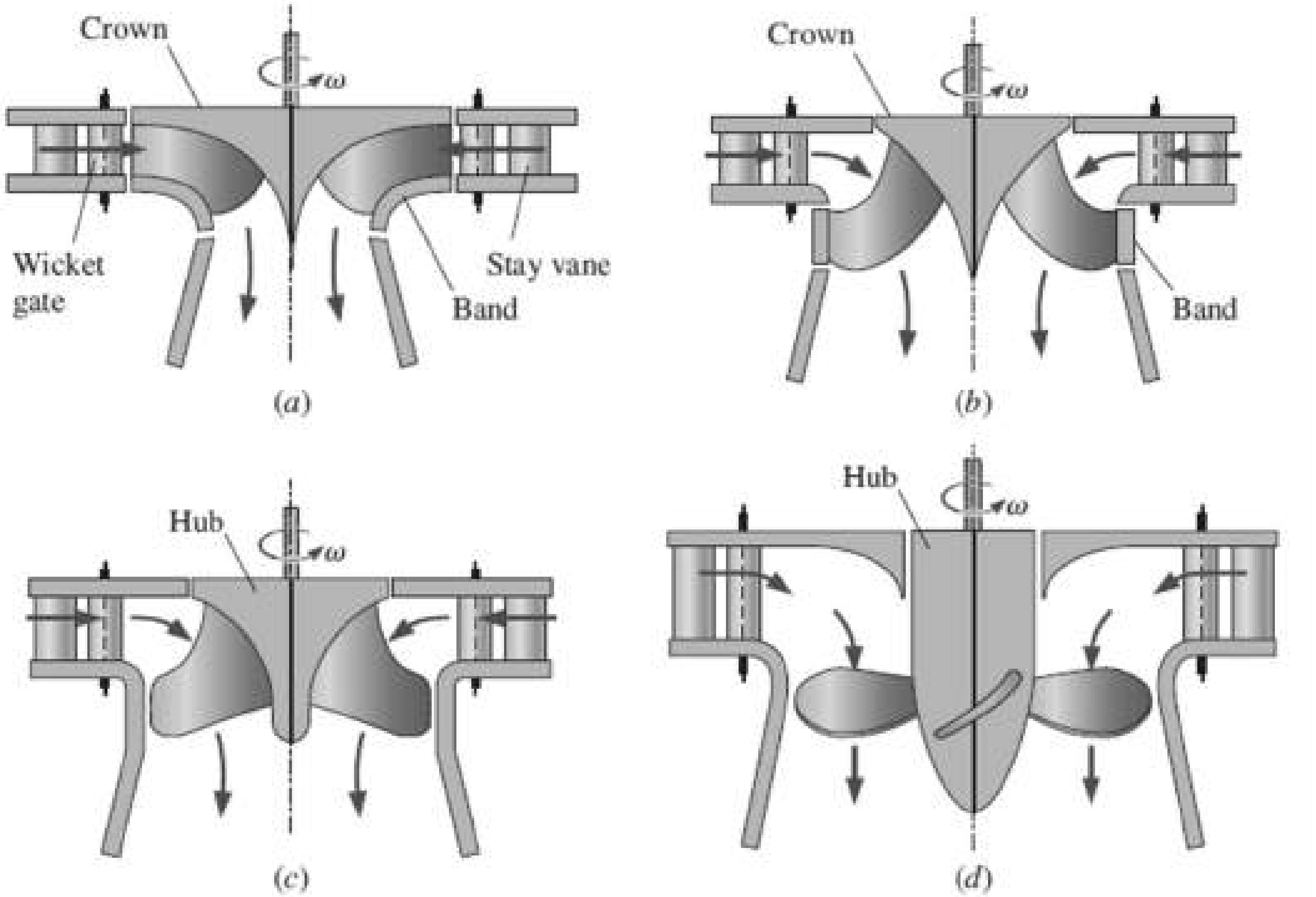


Figure 6-13 The distinguishing characteristics of the four subcategories of reaction turbines: (a) Francis radial flow, (b) Francis mixed flow, (c) propeller mixed flow, and (d) propeller axial flow. The main difference between (b) and (c) is that Francis mixed-flow runners have a band that rotates with the runner, while propeller mixed-flow runners do not. There are two types of propeller mixed-flow turbines: Kaplan turbines have adjustable pitch blades, while propeller turbines do not. Note that the terminology used here is neither universal among turbomachinery textbooks nor among hydro turbine manufacturers.

Kaplan turbines are called double regulated because the flow rate is controlled in two ways—by turning the wicket gates and by adjusting the pitch on the runner blades.

Propeller turbines: nearly identical to Kaplan turbines except that the blades are fixed (pitch is not adjustable), and the flow rate is regulated only by the wicket gates (single regulated).

Compared to the Pelton and Francis turbines, Kaplan turbines and propeller turbines are most suited for

low head, high volume flow rate conditions

Their efficiencies rival those of Francis turbines and may be as high as 94%.

Figure 6-14
The runner of a Francis radial-flow turbine used at the Boundary hydroelectric power station on the Pend Oreille River north of Spokane, WA. There are 17 runner blades of outer diameter 18.5 ft (5.6 m). The turbine rotates at 128.57 rpm and produces 230 MW of power at a volume flow rate of 335 m^3/s from a net head of 78 m.

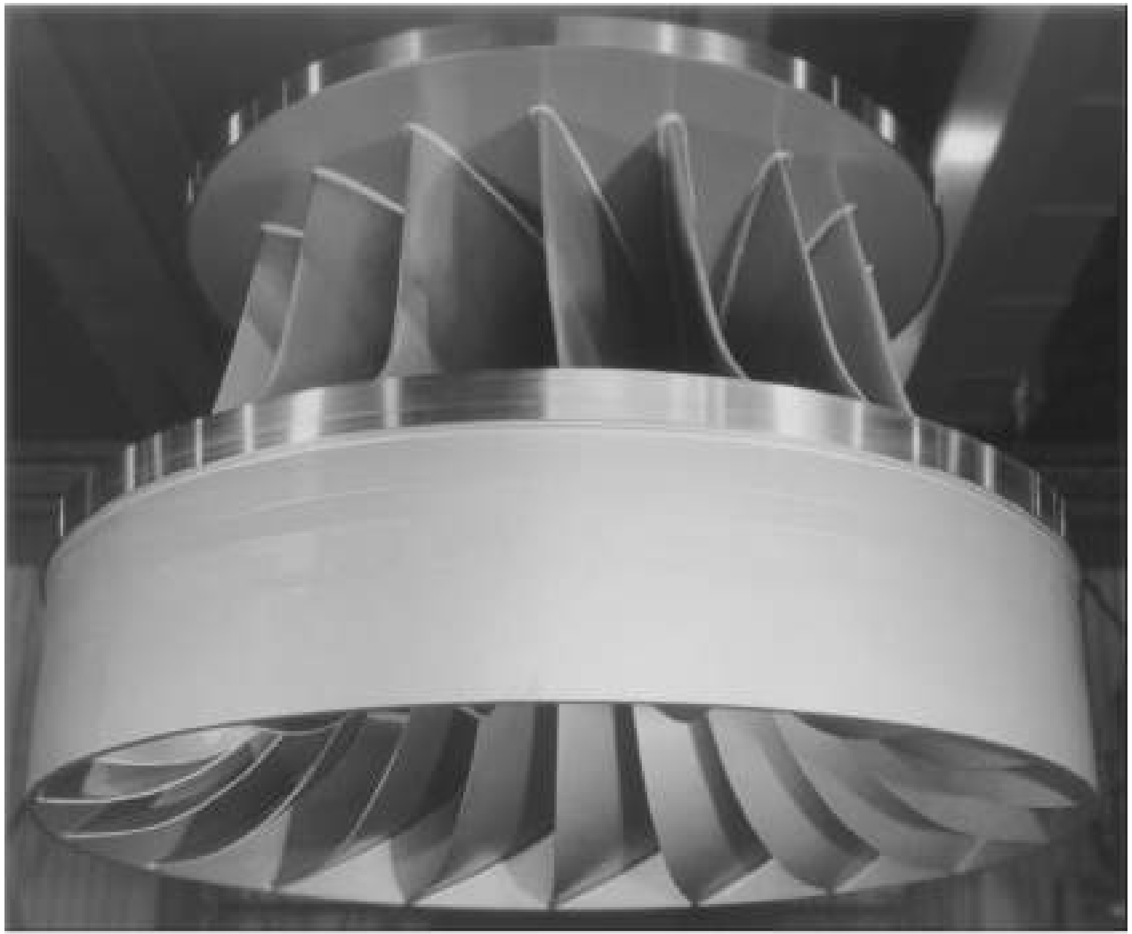


Figure 6-15
The runner of a Francis mixed-flow turbine used at the Smith Mountain hydroelectric power station in Roanoke, VA. There are 17 runner blades of outer diameter 20.3 ft (6.19 m). The turbine rotates at100 rpm and produces 194 MW of power at a volume flow rate of 375 m^3/s from a net head of 54.9 m.

Figure 6-16
The five-bladed propeller turbine used at the Warwick hydroelectric power station in Cordele, GA. There are five runner blades of outer diameter 12.7 ft (3.87 m). The turbine rotates at 100 rpm and produces 5.37 MW of power at a volume flow rate of 63.7 m^3/s from a net head of 9.75 m.

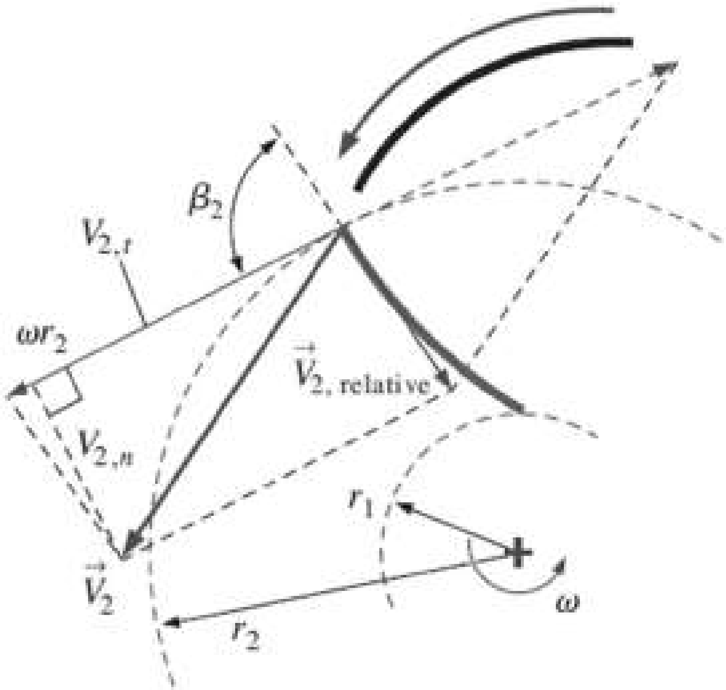


Figure 6-17
Relative and absolute velocity vectors and geometry for the outer radius of the runner of a Francis turbine. Absolute velocity vectors are bold.

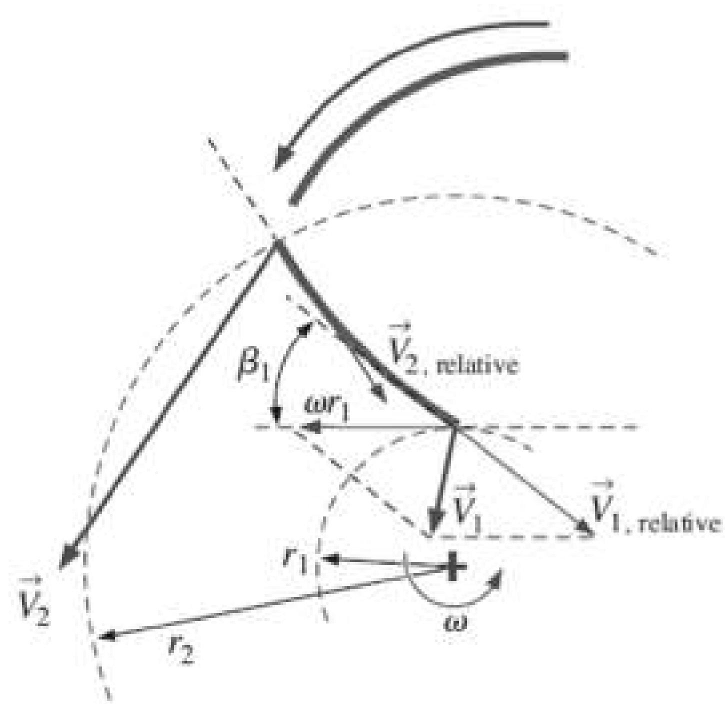


Figure 6-18
Relative and absolute velocity vectors and geometry for the inner radius of the runner of a Francis turbine. Absolute velocity vectors are bold.

Runner leading edge: $$V_{2,t} = \omega r_2 - \frac{V_{2,n}}{\tan\ \beta_2}$$

$$\dot{V} = 2\pi r_1 b_1 V_{1,n} = 2\pi r_2 b_2 V_{2,n}$$

Runner trailing edge: $$V_{1,t} = \omega r_1 - \frac{V_{1,n}}{\tan\ \beta_1}$$

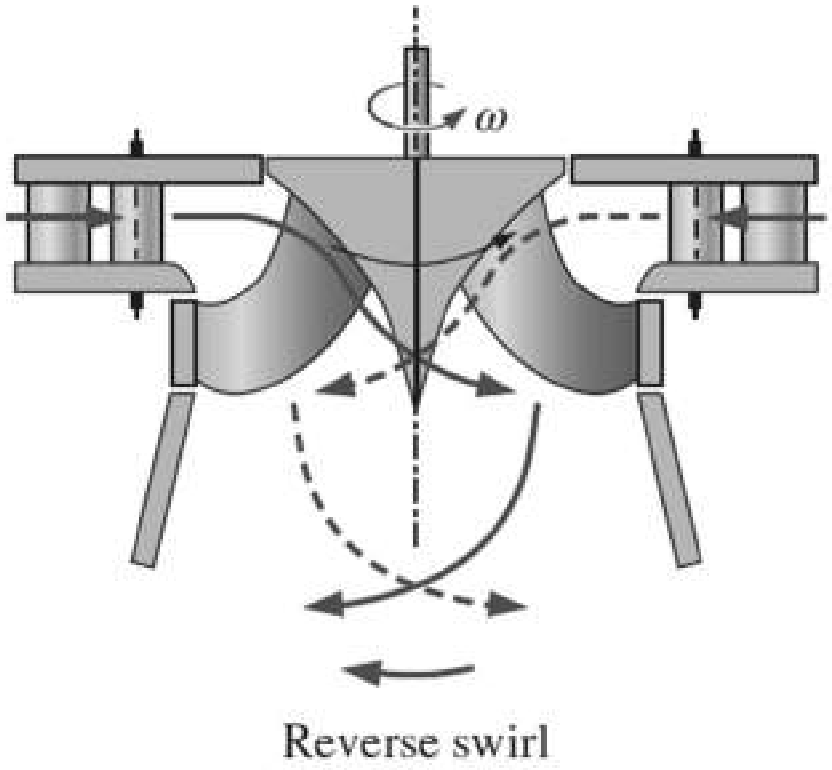


Figure 6-19
In some Francis mixed-flow turbines, high-power, high-volume flow rate conditions sometimes lead to *reverse swirl*, in which the flow exiting the runner swirls in the direction opposite to that of the runner itself, as sketched here.

6-5 TURBINE SPECIFIC SPEED

$$N_{St} = \frac{C_P^{1/2}}{C_H^{5/4}} = \frac{\left(\dfrac{\text{bhp}}{\rho\omega^3 D^5}\right)^{1/2}}{\left(\dfrac{gH}{\omega^2 D^2}\right)^{5/2}} = \frac{\omega(\text{bhp})^{1/2}}{\rho^{1/2}(gH)^{5/4}}$$

Turbine specific speed in terms of C_P and C_H

C_P Power coefficient

C_H Head coefficient

where ω is the rotational speed, bhp is brake horsepower (shaft power $\dot{W}_{\text{shaft}}$), ρ is the fluid density, and H is the net head.

$$N_{St,\,US} = \frac{(\dot{n},\,\text{rpm})(\text{bhp},\,\text{hp})^{1/2}}{(H,\,\text{ft})^{5/4}}$$

N_{St} in US units

$$N_{St,US} = 0.02301\ N_{St} \text{ or } N_{St} = 43.46\ N_{St,US}$$

Conversion between N_{St} and N_{St} in US units

Turbine specific speed is used to characterize the operation of a turbine at its optimum conditions (best efficiency point) and is useful for preliminary turbine selection.

$$N_{St,\,SI} = \frac{(\dot{n},\,\text{rpm})(\dot{V},\,\text{m}^3/\text{s})^{1/2}}{(H,\,\text{m})^{3/4}}$$

N_{St} in SI units

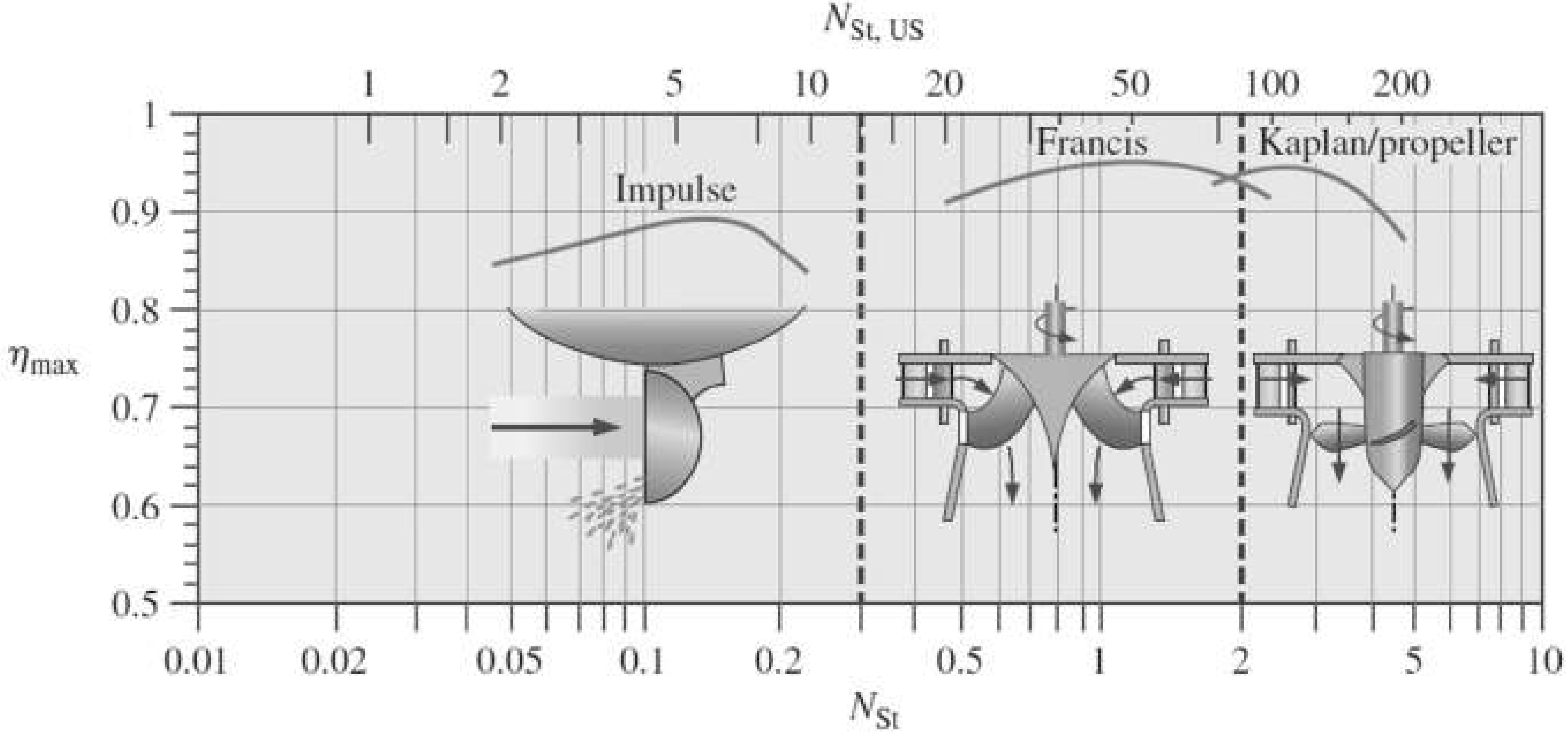


Figure 6-21
Maximum efficiency as a function of turbine specific speed for the three main types of dynamic turbine. Horizontal scales show nondimensional turbine specific speed (N_{St}) and turbine specific speed in customary U.S. units ($N_{St,US}$). Sketches of the blade types are also provided on the plot for reference.

6-6 RUN-OF-RIVER PLANTS AND WATERWHEELS

The majority of the electricity from hydroelectric power plants is produced using *accumulation reservoirs*, also called *dams*.

Run-of-river plants (also called river plants or small hydroelectric power plants) do not use water reservoirs.

Operation: They are built along a water stream such as a river. A proper portion of the water stream is diverted to a turbine-generator unit, and the used water is returned to the river.

A run-of-river plant is installed when there is sufficient velocity and flow rate for a river.

$$\dot{W}_{\text{available}} = \dot{m}\frac{V^2}{2} = \rho A V \frac{V^2}{2} = \rho A \frac{V^3}{2}$$

Power potential of water stream

Efficiency: Only about 60% of this potential is theoretically available.

The efficiency of turbine-generator units in river plants is lower than that of large hydropower plants.

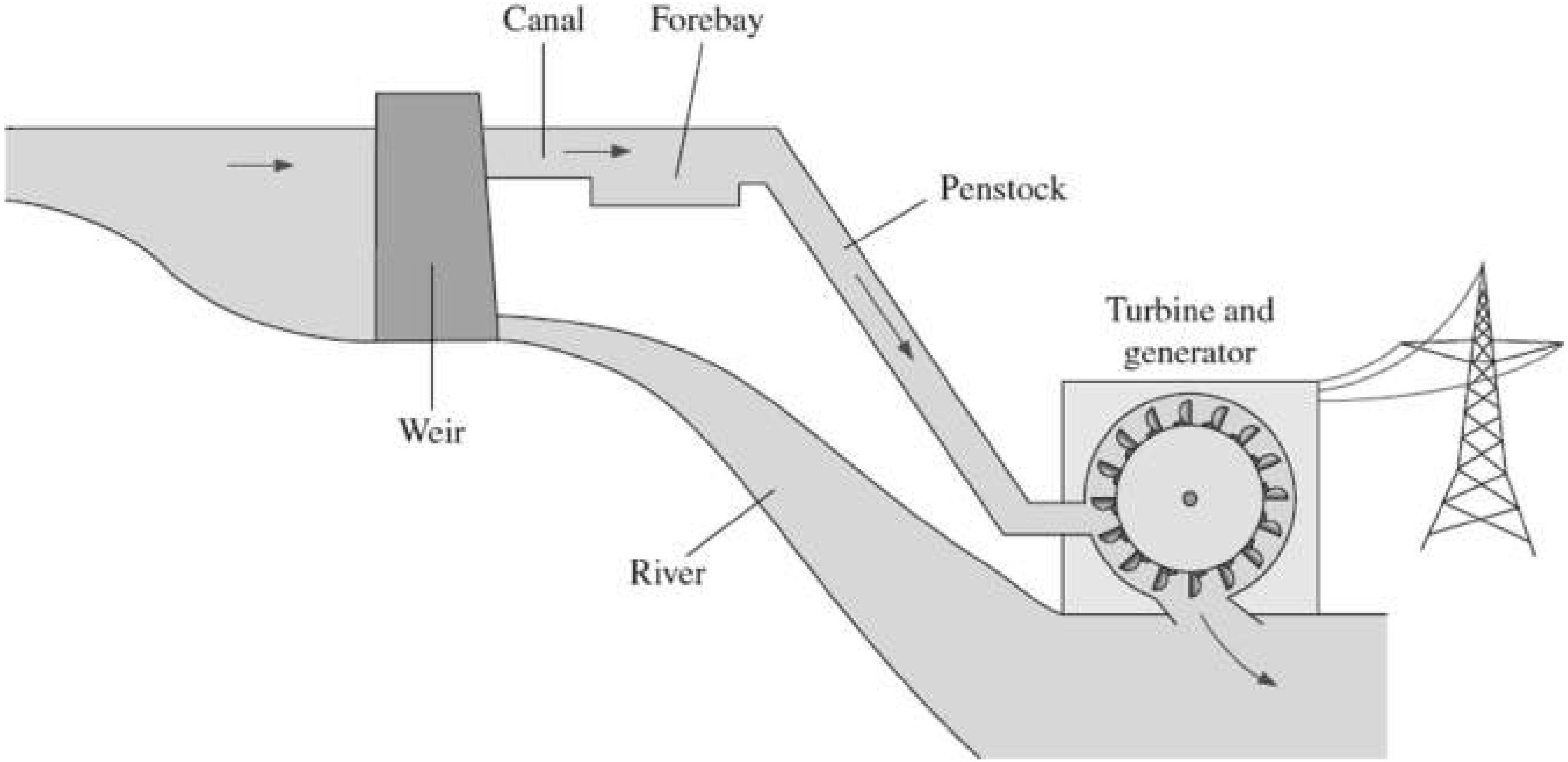


Figure 6-22
Working principle of a run-of-river plant. *Weir* is the barrier placed in river to control water discharge. *Forebay* is part of canal from which water is taken to run the turbine.

Operation of waterwheel: A waterwheel is different from a run-of-river plant in that a waterwheel is installed directly into falling or free-flowing water to convert the energy of the water into power.

For a lower bucket type of a waterwheel, water flows through the lower blades (called buckets) causing the wheel to rotate.

A more common type of a waterwheel involves upper buckets for which water flows through the upper buckets, fills them, and forces the wheel to rotate due to the weight acting on the buckets.

Waterwheels are simple devices and operation is not affected by dirty water.

Power potential from a waterwheel

$$\dot{W}_{\text{available}} = \dot{m}gH = \rho\dot{V}gH$$

m mass flow rate
V volume flow rate
ρ water density
H head of the water that is the height difference between water streams at the input and output of the water channel

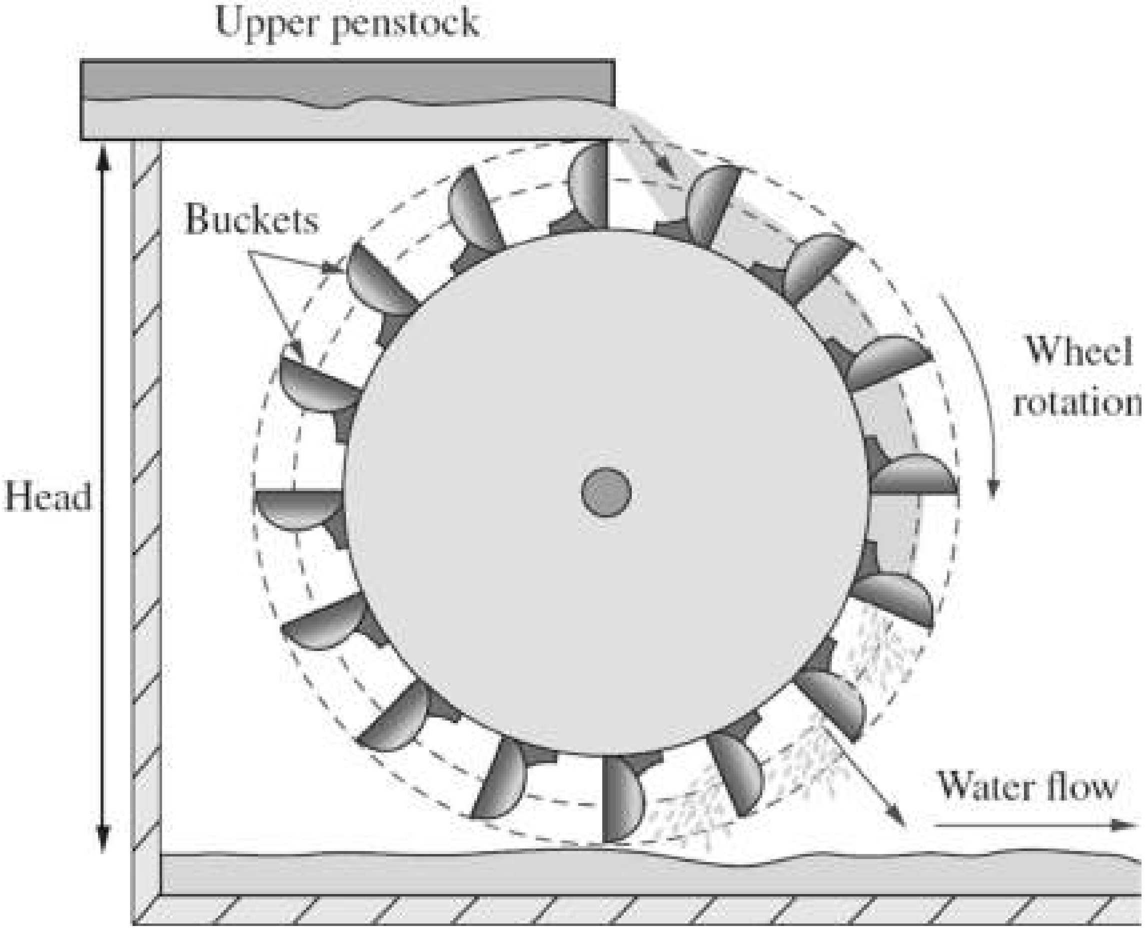


Figure 6-23
Operation of an upper bucket waterwheel.

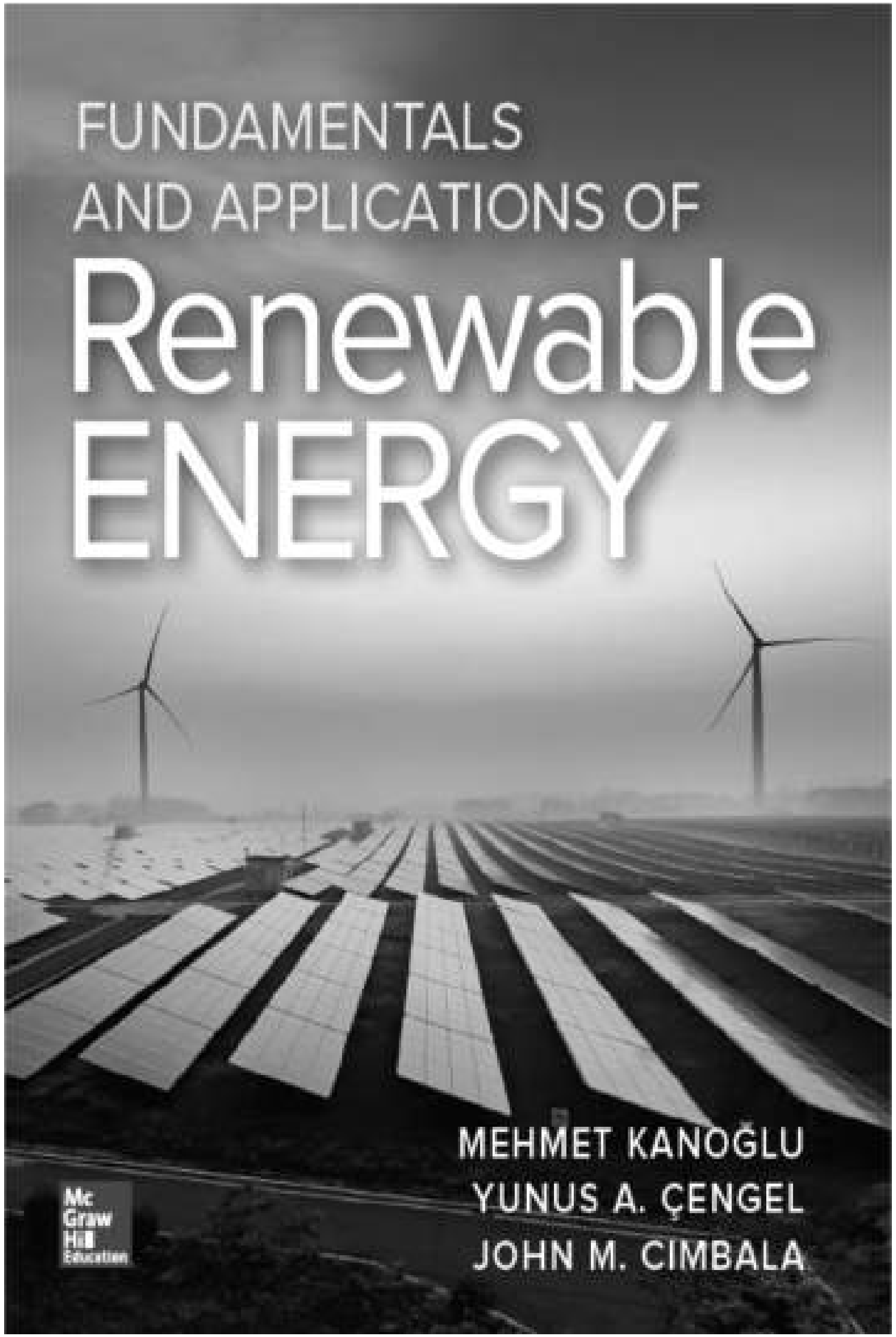
History: Waterwheels were used since ancient times for milling flour in gristmills, and they are still used in some parts of the world for this application. Previously, they were also used for water-lifting for irrigation, grinding wood into pulp for papermaking, machining, hammering wrought iron, and powering mine hoists.

Material: Usually made from wood or steel, with shovels of blades fixed regularly around their circumference.

Operation: Water pushes the shovels (or buckets) tangentially around the wheel, causing a torque to develop on the shaft.

Efficiency: The rotational speeds are typically low and these machines have low efficiencies due to losses such as friction, turbulence, and incomplete filling of the buckets. The efficiency of a waterwheel for the production of electricity is very low.

Generator: Since waterwheels have very low rotational speed, the generator requires high rates of speed multipliers for the production of electricity. This presents additional losses in the system.



Chapter 7

GEOTHERMAL ENERGY

Fundamentals and Applications of

Renewable Energy

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Yunus A. Cengel

John M. Cimbala

McGraw-Hill, 2020

7-1 INTRODUCTION

Geothermal energy: Thermal energy within the earth’s interior.

Is it really renewable? It is a renewable energy source because heat is continuously transferred from within the earth to the water recycled by rainfall or reinjected back to the ground after use.

The origin of geothermal energy is earth’s core. The core is made up of inner core (iron center) and outer core made up of very hot magma.

At some reasonable depths, the rocks and water absorb heat from magma.

These sites are characterized as geothermal resources.

By digging wells and pumping the hot water to the surface, we make use of geothermal energy.

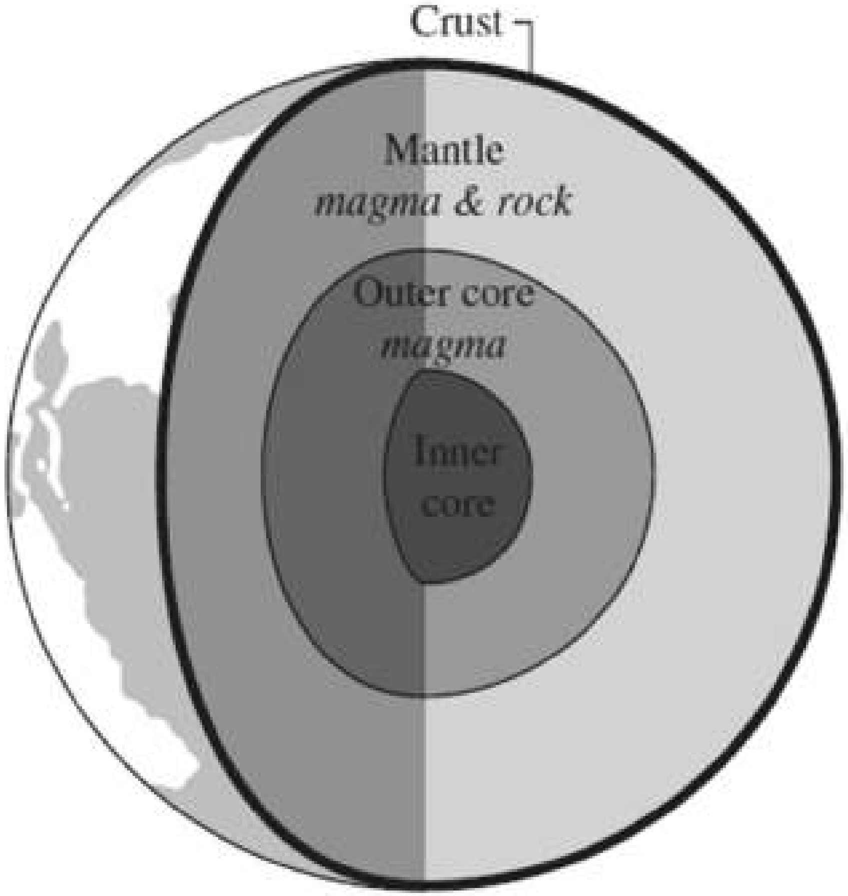


Figure 7-1 The interior of the earth.

The origin of geothermal energy is earth's core, and it is about 6500 km deep. The core is made up of inner core (iron center) and outer core made up of very hot magma.

The temperature in the magma remains very high due to decay of radioactive particles. The outer core is surrounded by the mantle whose thickness is about 3000 km. The mantle is made of magma and rock.

The layer of the earth housing continents and ocean floors is called the crust. The thickness of the crust is 25 to 55 km on the continents and 5 to 8 km under the oceans. The crust is made up of tectonic plates. Volcanoes occur near the edges of these plates due to magma getting close to it.

Classification of geothermal resources

Hydrothermal These are known geothermal fields containing high temperature water in vapor, mixture, or liquid phases.

Geopressurized These resources contain hot liquid water at 150°C to 180°C at very high pressures (up to 600 bar). The fluid in these deposit-filled reservoirs also contains methane and high levels of dissolved solids. The fluid is highly corrosive and thus very difficult to harvest and handle.

Magma They are also called molten rock, and typically contained under active volcanoes at temperatures above 650°C.

Enhanced They are also called hot, dry rock geothermal systems. These are not natural geothermal resources. The idea is injecting water into hot rock formation at high pressure and bringing the resulting hot water to the surface.

Only hydrothermal resources are being exploited. Other three are estimated to have enormous energy potentials but current technologies do not allow feasible energy production from these resources.

The quality and life of a hydrothermal resource can be prolonged by reinjecting the waste fluid back to the gorund.

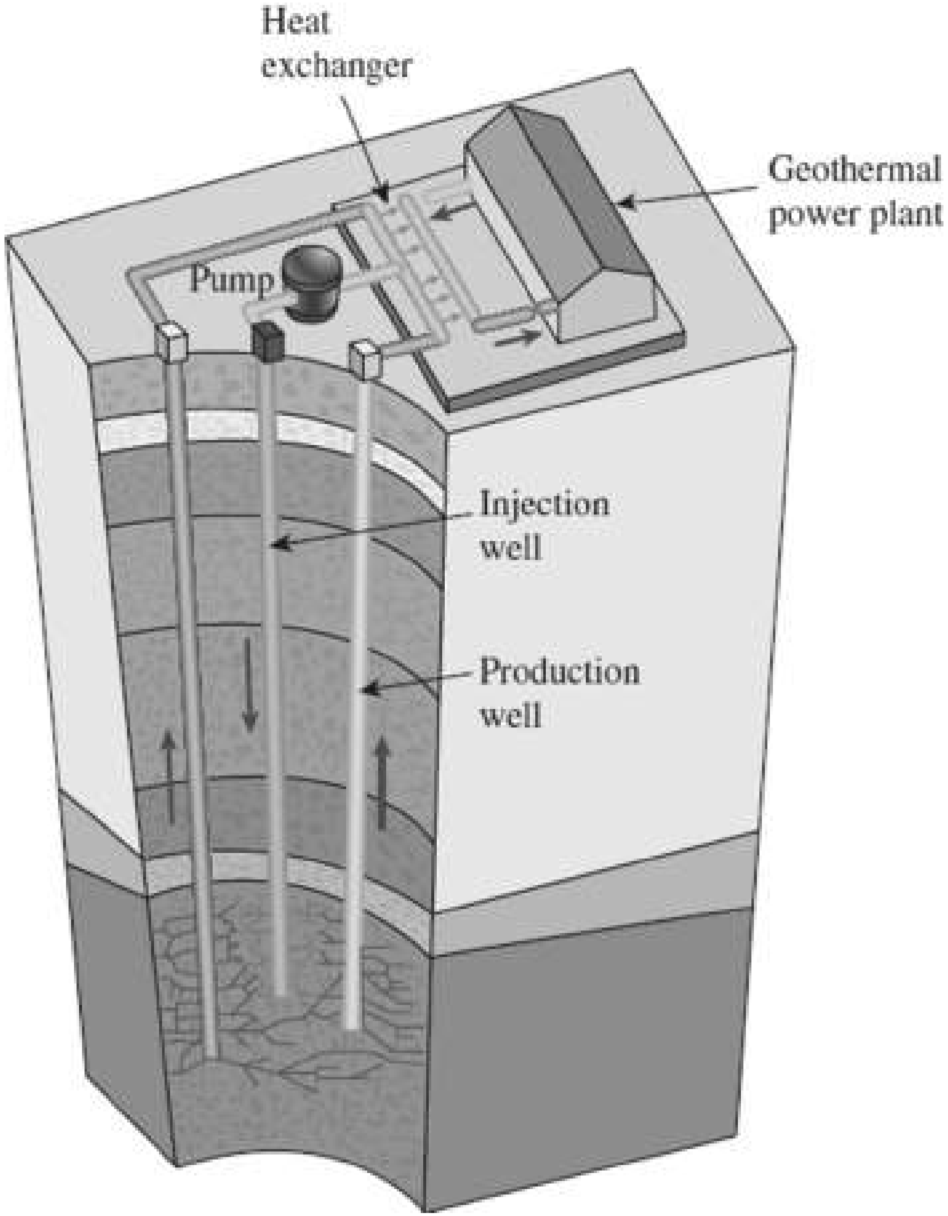


Figure 7-2
Operation of enhanced geothermal systems.

A geothermal resource contains geothermal water at a temperature higher than that of the environment. One common classification of geothermal resources is

- ✓ High temperature resource: $T > 150°\text{C}$
- ✓ Medium temperature resource:

  $90°\text{C} < T < 150°\text{C}$
- ✓ Low temperature resource: $T < 90°\text{C}$

The state of geothermal water in the reservoir may be superheated or saturated steam (dry steam), saturated steam-liquid mixture, or liquid (usually compressed liquid).

Steam-dominated resources are of the higher quality than liquid-dominated resources due to their higher enthalpy and exergy (work potential) values.

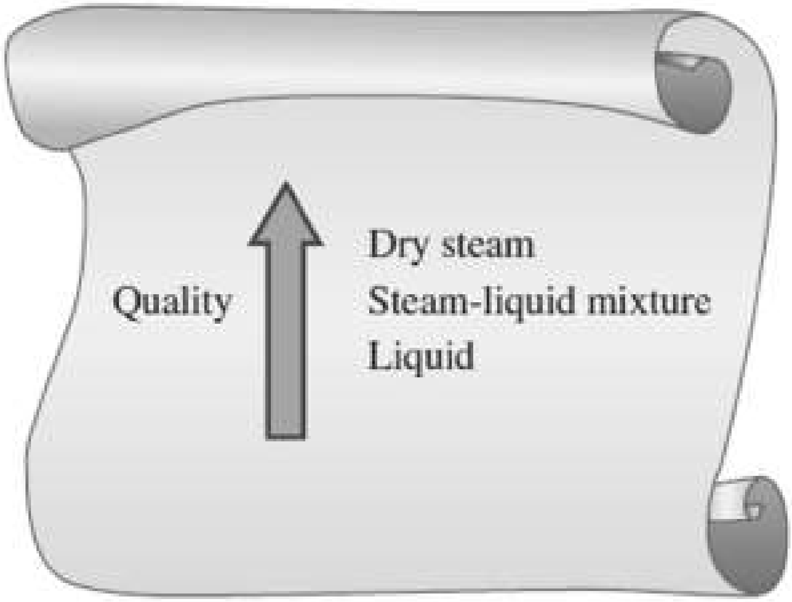


Figure 7-3
The quality of a geothermal resource depends on its phase (and temperature) in the reservoir. The higher the quality, the higher the work potential.

7-2 GEOTHERMAL APPLICATIONS

There are several options for utilizing the thermal energy produced from geothermal energy systems such as

- electricity production
- space heating
- space cooling
- cogeneration
- geothermal heat pumps

Other utilization of geothermal energy includes

growing plants and crops (greenhouses)
drying of lumber, fruits and vegetables
spas
desalination
fish farming

Most common use: Geothermal energy is most commonly used for base-load electric power generation.

Technology for geothermal power: The technology for producing power from geothermal resources is well-established and there are numerous geothermal power plants operating worldwide.

Temperature requirement: The temperature of geothermal resource should be about 120°C or higher for economic power production.

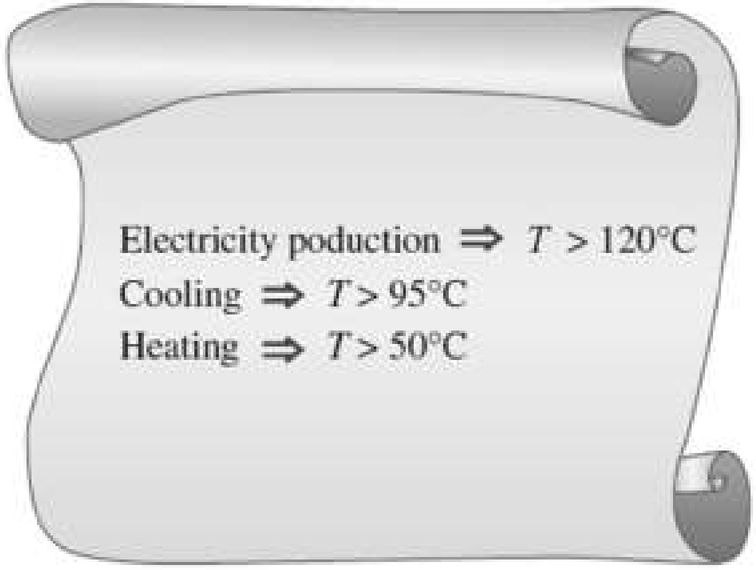


Figure 7-4
Approximate temperature requirements for geothermal applications.

Temperature for cooling: The temperature of geothermal water should be above 95°C for absorption cooling for reasonable coefficient of performance values.

Temperature for heating: A temperature above 50°C could be used.

Cogeneration: A cogeneration system utilizing geothermal energy and producing electricity and heat and/or cooling represents an enhanced use of a resource.

This is a cascaded application in which the used geothermal water leaving the power plant is used for heating/cooling before being reinjected back into the ground.

7-3 GEOTHERMAL HEATING

A number of residential and commercial districts are effectively heated in winter by low-cost geothermal heat in many parts of the world.

Examples: Some of the largest district heating installations are in China, Sweden, Iceland, Turkey, and the United States. Almost 90 percent of buildings in Iceland (a relatively small country) are heated in winter by geothermal heat.

Geothermal heat is used for space heating mostly in a district heating scheme.

Operation: Normally, hot geothermal water is not directly circulated to the district due to undesirable chemical composition and characteristics of geothermal brine.

Heat exchangers are used to transfer the heat of geothermal water to fresh water and this heated fresh water is sent to the district.

This heat is supplied to the buildings through individual heat exchangers.

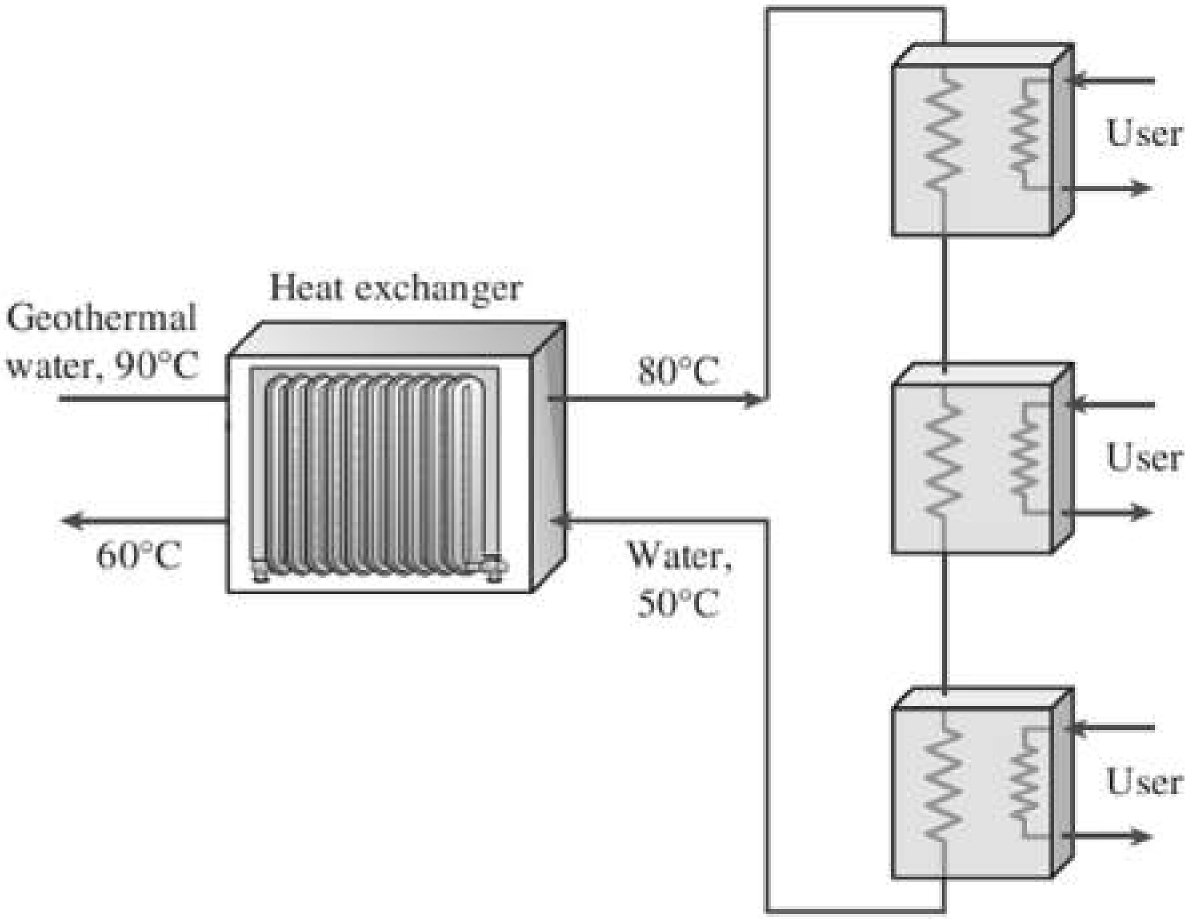


Figure 7-5
A common operating mode for geothermal district space heating systems. Temperature values are representative.

Geothermal heat can also be used for producing hot water for residences, offices, and industrial processes.

A possible process heat application of geothermal hot water can be accomplished by preheating water in steam boilers in various industries.

Carrying geothermal water over long distances for space and process heating/cooling is not cost-effective.

For space and water heating, the resource temperature should be greater than about 50°C.

$$\dot{Q}_{\text{heat,useful}} = \dot{m}c_p(T_{\text{supply}} - T_{\text{return}})$$

Rate of geothermal heat supplied to the district

$$\text{Energy consumption} = \frac{\dot{Q}_{\text{heat,useful}} \times \text{Operating hours}}{\eta_{\text{heater}}}$$

Amount of energy supplied

$$\text{Energy cost} = \text{Energy consumption} \times \text{Unit price of energy}$$

Degree-Day Method for Annual Energy Consumption

The simplest and most intuitive way of estimating the annual energy consumption of a building is the degree-day (or degree-hour) method, which is a steady-state approach.

It is based on constant indoor conditions during the heating or cooling season and assumes the efficiency of the heating or cooling equipment is not affected by the variation of outdoor temperature.

These conditions will be closely approximated if all the thermostats in a building are set at the same temperature at the beginning of a heating or cooling season and are never changed, and a seasonal average efficiency is used (rather than the full-load or design efficiency) for the heaters or coolers.

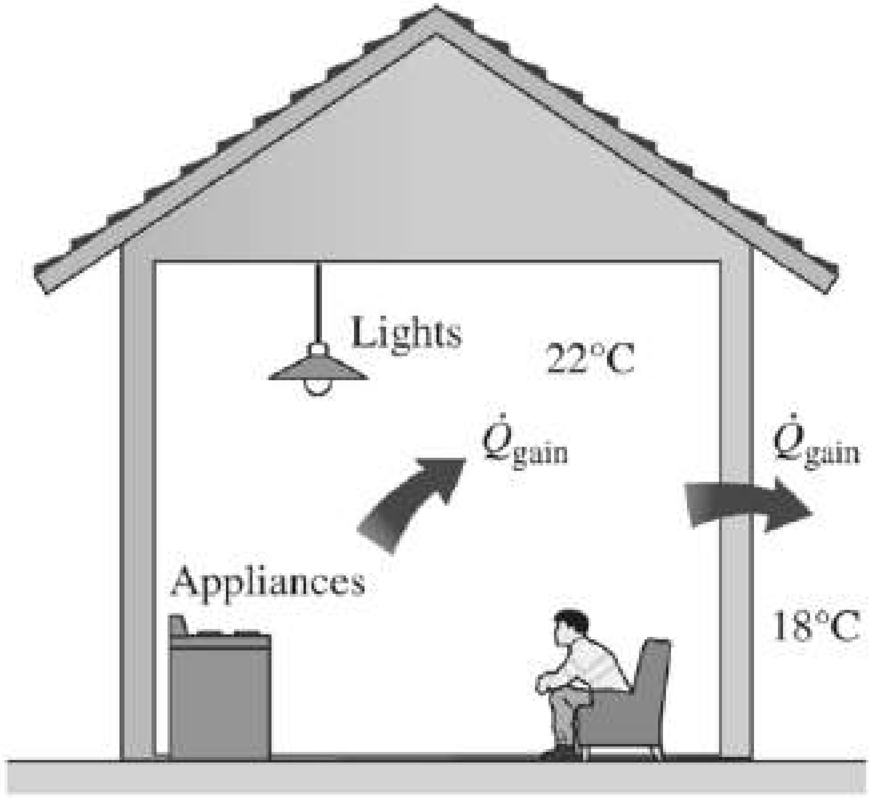


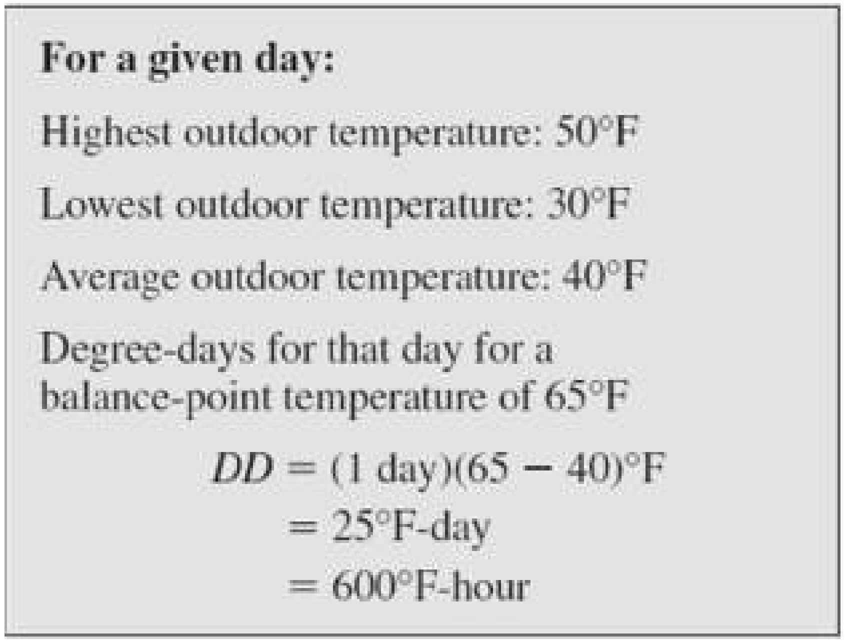
Figure 7-6
The heater of a building will not turn on as long as the internal heat gain makes up for the heat loss from a building (the balance point outdoor temperature).

T_{balance}	base temperature
T_{o}	outdoor temperature
$T_{\text{o,avg,day}}$	average outdoor temperature for each day
K_{overall}	overall heat transfer coefficient of building
η_{heater}	efficiency of heating system

$$K_{\text{overall}}(T_i - T_{\text{balance}}) = \dot{Q}_{\text{gain}} \longrightarrow T_{\text{balance}} = T_i - \frac{\dot{Q}_{\text{gain}}}{K_{\text{overall}}} \quad \dot{Q}_{\text{heating}} = \frac{K_{\text{overall}}}{\eta_{\text{heater}}}(T_{\text{balance}} - T_o)^+$$

$$Q_{\text{heating,year}} = \frac{K_{\text{overall}}}{\eta_{\text{heater}}}\int\left[T_{\text{balance}} - T_o(t)\right]^+ dt \cong \frac{K_{\text{overall}}}{\eta_{\text{heater}}} DD_{\text{heating}}$$

$$DD_{\text{heating}} = (1\text{ day})\sum_{\text{days}}(T_{\text{balance}} - T_{o,\text{avg,day}})^+ \qquad (^\circ\text{C-day})$$



For a given day:

Highest outdoor temperature: 50°F

Lowest outdoor temperature: 30°F

Average outdoor temperature: 40°F

Degree-days for that day for a balance-point temperature of 65°F

$$\begin{aligned} DD &= (1\text{ day})(65 - 40)°\text{F} \\ &= 25°\text{F-day} \\ &= 600°\text{F-hour} \end{aligned}$$

Figure 7-7
The outdoor temperatures for a day during which the heating degree-day is 25°F-day.

$$\text{Energy consumption} = \frac{K_{\text{overall}}}{\eta_{\text{heater}}} DD_{\text{heating}} \qquad \text{Fuel consumption} = \frac{\text{Energy consumption}}{\text{Heating value of fuel}}$$

$$\text{Electricity consumption} = \frac{K_{\text{overall}}}{\text{COP}_{\text{heating}}} DD_{\text{heating}}$$

$$\text{Electricity consumption} = \frac{K_{\text{overall}}}{\text{COP}_{\text{cooling}}} DD_{\text{cooling}}$$

$\boldsymbol{Q}_{\textbf{design}}$ design heating load
$\boldsymbol{T}_{\textbf{i}}$ indoor design temperature
$\boldsymbol{T}_{\textbf{o}}$ outdoor design temperature
$\boldsymbol{UA = K}_{\textbf{overall}}$ overall heat transfer coefficient of building

$$\dot{Q}_{\text{design}} = UA\Delta T_{\text{design}} = UA(T_{\text{i}} - T_{o})_{\text{design}} = K_{\text{overall}}(T_{\text{i}} - T_{o})_{\text{design}}$$

TABLE 7-1
Average Winter Temperatures and Number of Degree-Days for Selected Cities in the United States

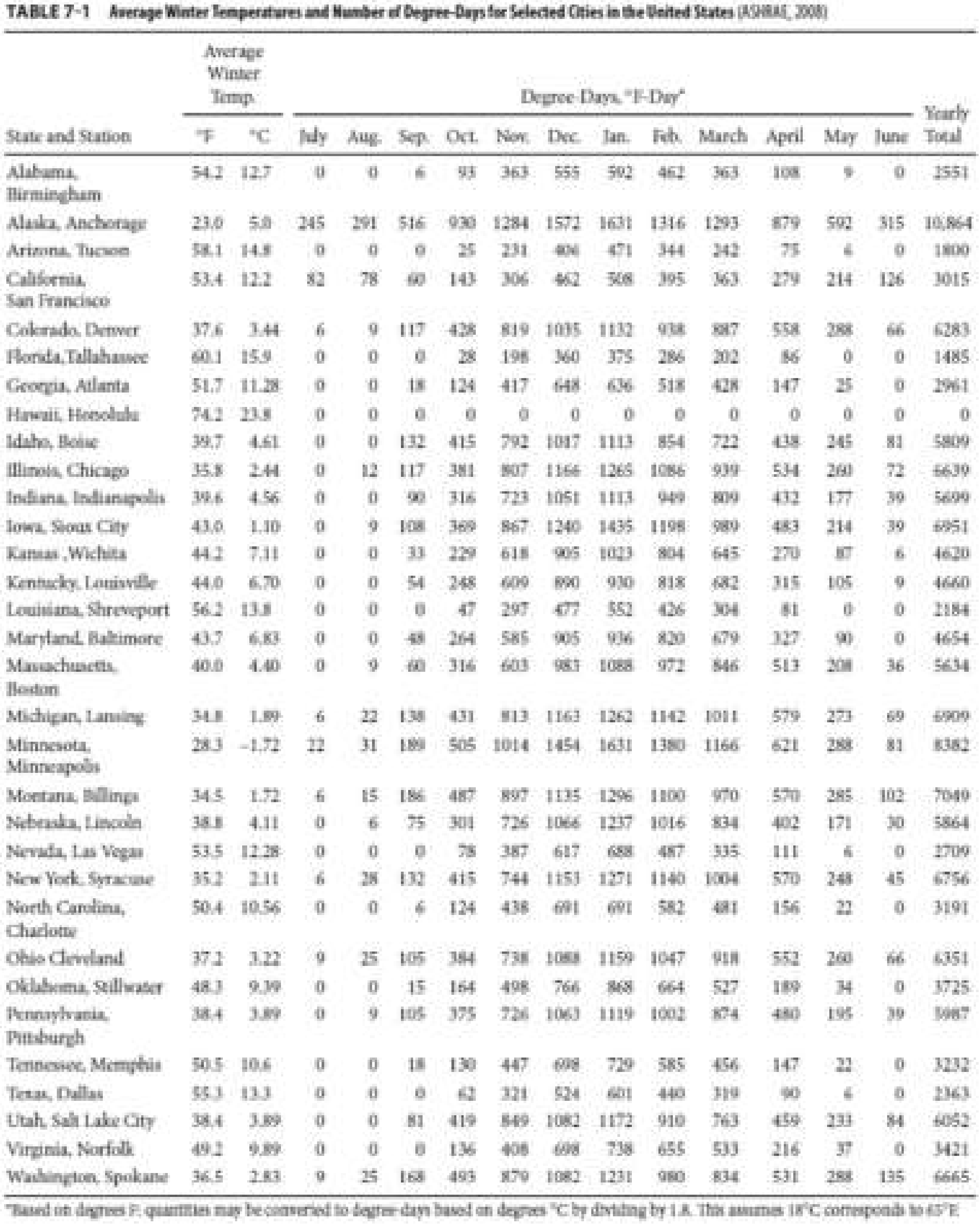


TABLE 7-1 **Average Winter Temperatures and Number of Degree-Days for Selected Cities in the United States** (ASHRAE, 2008)

	Average Winter Temp.		Degree-Days, °F-Day*												
State and Station	°F	°C	July	Aug.	Sep.	Oct.	Nov.	Dec.	Jan.	Feb.	March	April	May	June	Yearly Total
Alabama, Birmingham	54.2	12.7	0	0	6	93	363	555	592	462	363	108	9	0	2551
Alaska, Anchorage	23.0	5.0	245	291	516	930	1284	1572	1631	1316	1293	879	592	315	10,864
Arizona, Tucson	58.1	14.8	0	0	0	25	231	406	471	344	242	75	6	0	1800
California, San Francisco	53.4	12.2	82	78	60	143	306	462	508	395	363	279	214	126	3015
Colorado, Denver	37.6	3.44	6	9	117	428	819	1035	1132	938	887	558	288	66	6283
Florida,Tallahassee	60.1	15.9	0	0	0	28	198	360	375	286	202	86	0	0	1485
Georgia, Atlanta	51.7	11.28	0	0	18	124	417	648	636	518	428	147	25	0	2961
Hawaii, Honolulu	74.2	23.8	0	0	0	0	0	0	0	0	0	0	0	0	0
Idaho, Boise	39.7	4.61	0	0	132	415	792	1017	1113	854	722	438	245	81	5809
Illinois, Chicago	35.8	2.44	0	12	117	381	807	1166	1265	1086	939	534	260	72	6639
Indiana, Indianapolis	39.6	4.56	0	0	90	316	723	1051	1113	949	809	432	177	39	5699
Iowa, Sioux City	43.0	1.10	0	9	108	369	867	1240	1435	1198	989	483	214	39	6951
Kansas ,Wichita	44.2	7.11	0	0	33	229	618	905	1023	804	645	270	87	6	4620
Kentucky, Louisville	44.0	6.70	0	0	54	248	609	890	930	818	682	315	105	9	4660
Louisiana, Shreveport	56.2	13.8	0	0	0	47	297	477	552	426	304	81	0	0	2184
Maryland, Baltimore	43.7	6.83	0	0	48	264	585	905	936	820	679	327	90	0	4654
Massachusetts, Boston	40.0	4.40	0	9	60	316	603	983	1088	972	846	513	208	36	5634
Michigan, Lansing	34.8	1.89	6	22	138	431	813	1163	1262	1142	1011	579	273	69	6909
Minnesota, Minneapolis	28.3	−1.72	22	31	189	505	1014	1454	1631	1380	1166	621	288	81	8382
Montana, Billings	34.5	1.72	6	15	186	487	897	1135	1296	1100	970	570	285	102	7049
Nebraska, Lincoln	38.8	4.11	0	6	75	301	726	1066	1237	1016	834	402	171	30	5864
Nevada, Las Vegas	53.5	12.28	0	0	0	78	387	617	688	487	335	111	6	0	2709
New York, Syracuse	35.2	2.11	6	28	132	415	744	1153	1271	1140	1004	570	248	45	6756
North Carolina, Charlotte	50.4	10.56	0	0	6	124	438	691	691	582	481	156	22	0	3191
Ohio Cleveland	37.2	3.22	9	25	105	384	738	1088	1159	1047	918	552	260	66	6351
Oklahoma, Stillwater	48.3	9.39	0	0	15	164	498	766	868	664	527	189	34	0	3725
Pennsylvania, Pittsburgh	38.4	3.89	0	9	105	375	726	1063	1119	1002	874	480	195	39	5987
Tennessee, Memphis	50.5	10.6	0	0	18	130	447	698	729	585	456	147	22	0	3232
Texas, Dallas	55.3	13.3	0	0	0	62	321	524	601	440	319	90	6	0	2363
Utah, Salt Lake City	38.4	3.89	0	0	81	419	849	1082	1172	910	763	459	233	84	6052
Virginia, Norfolk	49.2	9.89	0	0	0	136	408	698	738	655	533	216	37	0	3421
Washington, Spokane	36.5	2.83	9	25	168	493	879	1082	1231	980	834	531	288	135	6665

*Based on degrees F; quantities may be converted to degree-days based on degrees °C by dividing by 1.8. This assumes 18°C corresponds to 65°F.

7-4 GEOTHERMAL COOLING

Which system: Geothermal heat may be supplied to an absorption refrigeration system for space cooling applications.

Temperature requirement: The temperature of geothermal water should be above 95°C for absorption cooling for reasonable coefficient of performance values.

A district cooling system utilizing geothermal heat may be feasible depending on the annual cooling load of the district.

Is it common? The use of geothermal heat for cooling is not common.

Example: A geothermal cooling system installed in Oregon Institute of Technology was estimated to pay for itself in about 15 years.

Absorption Cooling System

Heat-driven cooling system: A form of cooling system that becomes economically attractive when there is a source of inexpensive thermal energy at a temperature of 100 to 200°C is absorption refrigeration.

Some examples of inexpensive thermal energy sources: geothermal energy, solar energy, and waste heat from cogeneration or process steam plants, and even natural gas when it is available at a relatively low price.

Operation: These systems involve the absorption of a refrigerant by a transport medium.

The most widely used absorption refrigeration system is the ammonia–water system, where ammonia (NH_3) serves as the refrigerant and water (H_2O) as the transport medium.

Other absorption refrigeration systems include water–lithium bromide and water–lithium chloride systems, where water serves as the refrigerant.

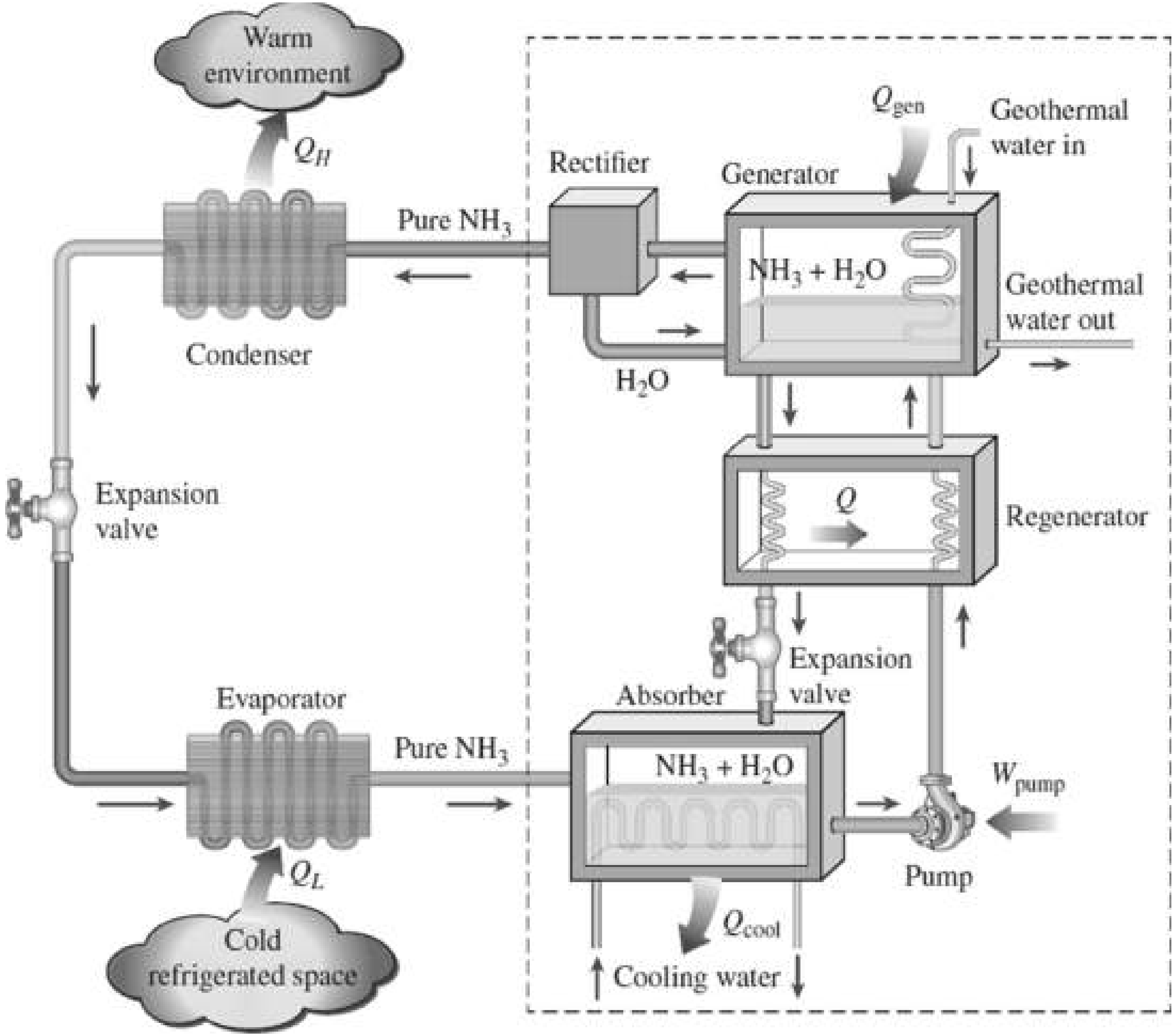


Figure 7-8 Ammonia absorption refrigeration cycle.

The operation of these systems is based on heat transfer from an external source. They are often classified as *heat-driven systems.*

Cost: The absorption refrigeration systems are much more expensive than the vapor-compression refrigeration systems.

Other issues: They are more complex and occupy more space, they are much less efficient thus requiring much larger cooling towers to reject the waste heat, and they are more difficult to service since they are less common.

When should we use these systems? Absorption refrigeration systems should be considered only when the unit cost of thermal energy is low or a free renewable energy source such as geothermal energy is available.

An ideal use of an absorption system is when it uses the waste heat of a power plant such as geothermal in a cogeneration scheme.

Common applications: Absorption refrigeration systems are primarily used in large commercial and industrial installations.

$$\mathrm{COP}_{\text{absorption}} = \frac{Q_{\text{cooling}}}{Q_{\text{gen}} + W_{\text{pump,in}}} \cong \frac{Q_{\text{cooling}}}{Q_{\text{gen}}}$$

COP of absorption refrigeration systems

7-5 GEOTHERMAL HEAT PUMP SYSTEMS

Ground-source heat pumps represent perhaps the most common use of geothermal energy in terms of the number of units installed.

These heat pumps are called geothermal heat pumps as they utilize the heat of the earth.

COP: Ground-source heat pumps provide higher values of coefficient performance (COP) compared to air-source units.

Ground temperatures: The ground at a few meters depth is at a higher temperature than the ambient air in winter and it is at a lower temperature than the ambient in summer.

Why higher COPs? These systems use higher ground temperatures in winter for heat absorption (heating mode) and cooler ground temperatures in summer for heat rejection (cooling mode), and this is the reason for higher COPs.

Heat Pump Systems

Cost: Heat pumps are generally more expensive to purchase and install than other heating systems, but they save money in the long run in some areas because they lower the heating bills.

Despite their relatively higher initial costs, the popularity of heat pumps is increasing.

The most common energy source for heat pumps is atmospheric air (air-to-air systems), although water and soil are also used.

The major problem with air-source systems is frosting, which occurs in humid climates when the temperature falls below 2 to 5°C.

$$\mathrm{COP} = \frac{Q_{\text{heating}}}{W_{\text{in}}}$$

COP of heat pump in winter

$$\mathrm{COP} = \frac{Q_{\text{cooling}}}{W_{\text{in}}}$$

COP of heat pump in summer

Water-source systems: They usually use well water from depths of up to 80 m in the temperature range of 5 to 18°C, and they do not have a frosting problem.

They typically have higher COPs but are more complex and require easy access to a large body of water such as underground water.

Ground-source systems: They are also rather involved since they require long tubing placed deep in the ground where the soil temperature is relatively constant.

COP values: The COP of heat pumps ranges between 1.5 and 4, depending on the system used and the temperature of the source.

New heat pumps that use variable-speed electric motor drives are at least twice as energy efficient as their predecessors.

Low temperature operation: Both the capacity and the efficiency of a heat pump fall significantly at low temperatures.

Most air-source heat pumps require a supplementary heating system such as electric resistance heaters or an oil or gas furnace.

Heat pumps and air conditioners have the same mechanical components. Therefore, it is not economical to have two separate systems to meet the heating and cooling requirements of a building.

One system can be used as a heat pump in winter and an air conditioner in summer, and it is just referred to as a heat pump. This is accomplished by adding a reversing valve to the cycle.

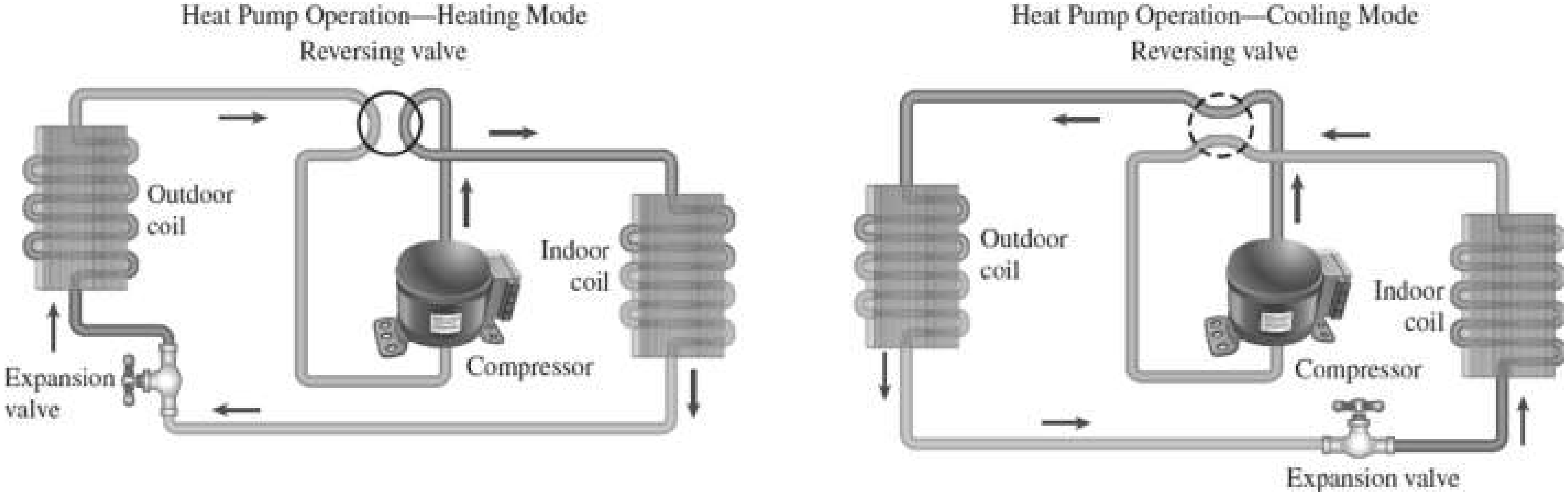


Figure 7-9 A heat pump can be used to heat a house in winter and to cool it in summer.

Where are they most competitive? Heat pumps are most competitive in areas that have a large cooling load during the cooling season and a relatively small heating load during the heating season, such as in the southern parts of the United States.

In these areas, the heat pump can meet the entire cooling and heating needs of residential or commercial buildings.

Where are they least competitive? The heat pump is least competitive in areas where the heating load is very large and the cooling load is small, such as in the northern parts of the United States.

Ground-Source Heat Pump Systems

Ground-source heat pump systems are also known as geothermal heat pumps as they use the heat of earth in its operation.

Advantages: They have higher COPs than ordinary air-source heat pumps because ground is at a higher temperature than ambient air in winter (heating mode) and at a lower temperature than ambient air in summer (cooling mode).

Ground temperature: The ground temperature increases with depth in winter and decreases with depth in summer.

It is clear that the ground temperature is more stable than air temperature throughout the year.

It is essentially constant below a certain depth of about 10 m.

It starts increasing again at a depth greater than about 60 m.

TABLE 7-2 Variation of Ground Temperature with Depth in a Location for Different Months of the Year (Schöffengrund- Schwalbach GSHP Test Plant, 1985–89)

	Ground Temperature, °C			
Depth, m	January	April	July	October
2	6	5	15	14
4	8	5	10	12
6	9	6	8	11
8	9	7	8	9
10	10	8	8	9
12	10	9	9	9
14	10	9	9	9
16	9	9	9	9

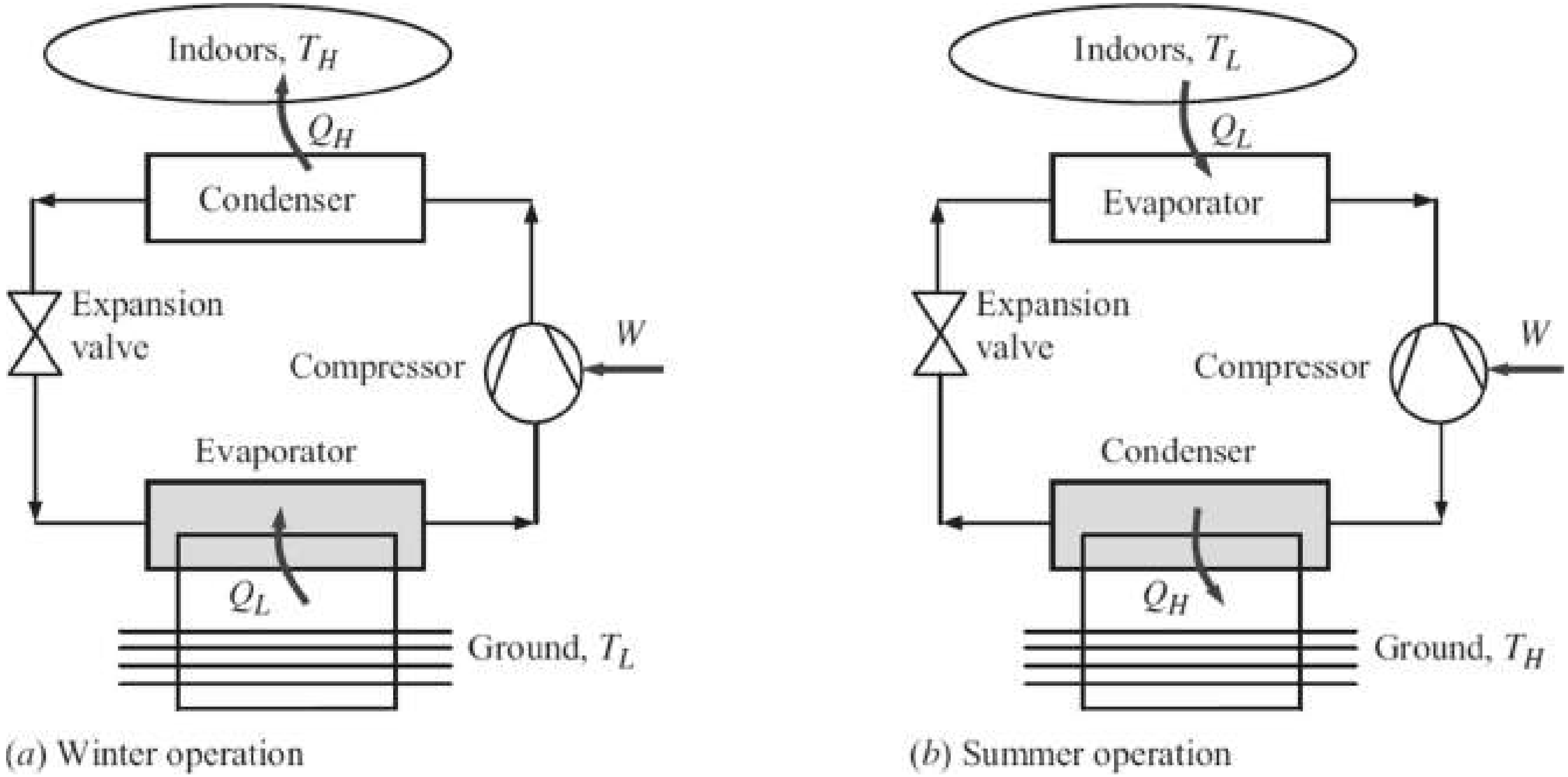


Figure 7-10
The operation of a ground-source heat pump in winter and in summer.

Comparison of performances of an air-source heat pump and a ground-source heat pump in winter

Air-source, $T_L = 0°\text{C}$, $T_H = 25°\text{C}$

Ground-source, $T_L = 10°\text{C}$, $T_H = 25°\text{C}$

Air-source: $$\text{COP}_{\text{HP,Carnot}} = \frac{T_H}{T_H - T_L} = \frac{298\ \text{K}}{298\ \text{K} - 273\ \text{K}} = 11.9$$

Ground-source: $$\text{COP}_{\text{HP,Carnot}} = \frac{T_H}{T_H - T_L} = \frac{298\ \text{K}}{298\ \text{K} - 283\ \text{K}} = 19.9$$

Horizontal loop heat pump

Depth: It involves horizontal underground piping in 1.2 to 2.0 m depths.

Location: It is suitable when there is sufficient area for pipe burial such as the relatively large backyard of a house.

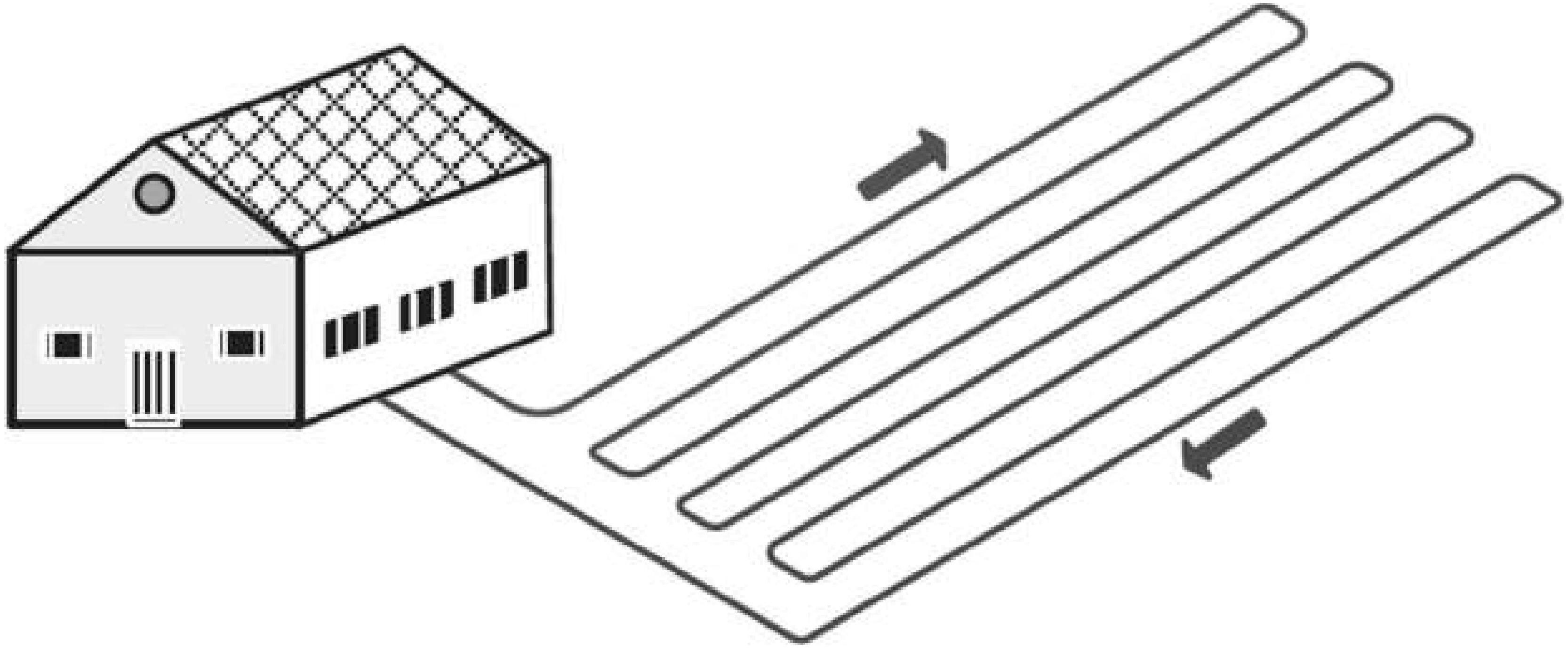


Figure 7-11
Schematic of horizontal loop ground-source heat pump.

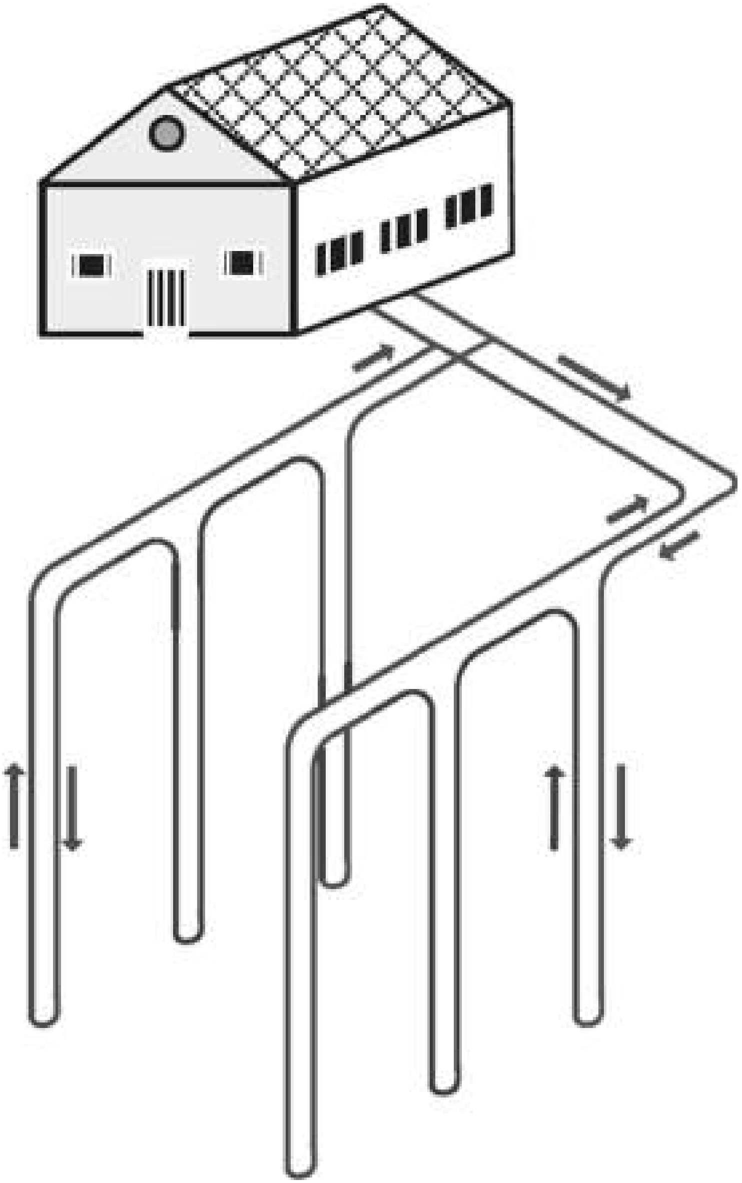


Figure 7-12
Schematic of vertical loop ground-source heat pump.

Vertical loop heat pump

Depth: It is also called borehole loop heat pump. Vertical piping in 10 to 250 m depths is used.

Location: It can be installed everywhere as a small field allowing vertical drilling is sufficient.

Cost: Vertical piping is more expensive than horizontal piping for a given heat transfer surface area.

Maintenance: These systems require virtually no regular maintenance and they are safe.

Capacity: The capacity is limited per borehole and the ground temperature is relatively low.

Example: A borehole heat pump application in Sweden involves 33 boreholes each 160-m deep, and the capacity is 225 kW.

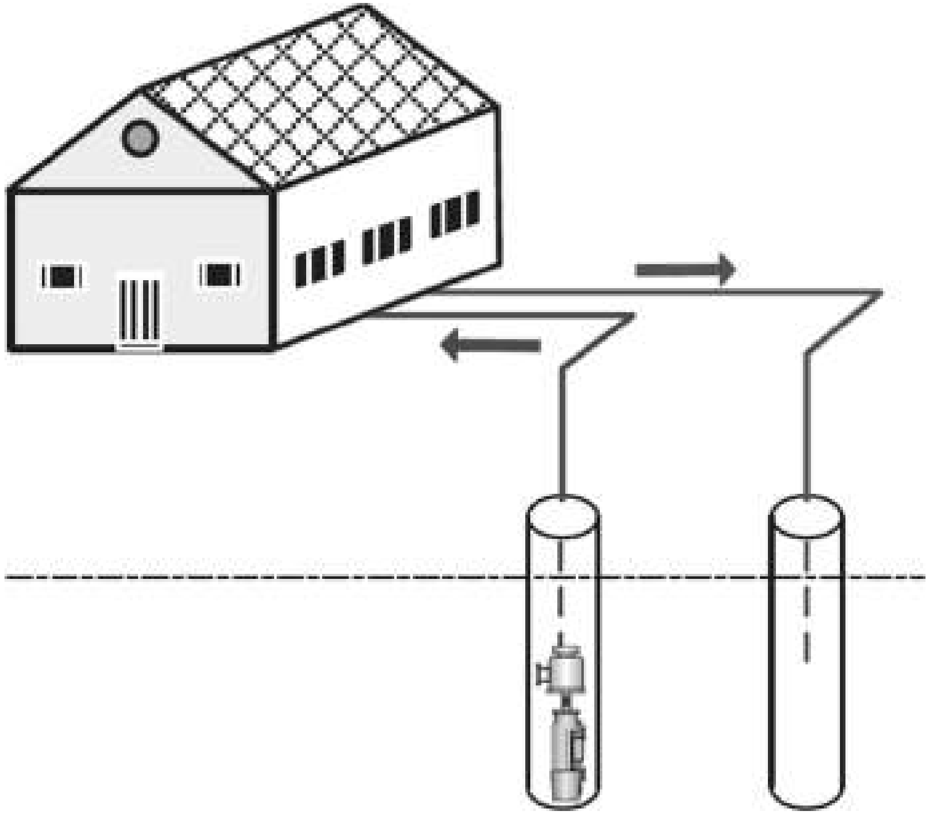


Figure 7-13
Schematic of ground water wells ground-source heat pump.

Ground water wells heat pump

Operation: Underground water is circulated through the evaporator of the heat pump unit.

Heat is transferred from the water to the refrigerant flowing in the evaporator.

The cooler water leaving the evaporator is dumped back to the ground at a different location.

Depth: The water well is located in 5 to 50 m depths.

Cost and Capacity: These systems can provide high capacities with relatively low cost.

Ground-source heat pumps can also be classified in terms of the fluid type circulating in the evaporator and the condenser.

Usually water or brine is circulated to transfer heat from the ground to the refrigerant in the evaporator by means of a horizontal-loop or borehole heat exchanger.

Water-to-air heat pump: For example, a heat pump is called water-to-air heat pump if water is circulating through the evaporator and air is circulating through the condenser.

Water-to-water heat pump: It is called a water-to-water heat pump if the heat pump is used to produce hot water by circulating water through the condenser and an underground water is circulated in the evaporator.

Europe: The number of heat pumps and ground-source ones sold in Europe has increased dramatically in recent years.

Germany: For example, the number of new geothermal heat pumps units was increased from 4000 in 2000 to 17,000 in 2015 in Germany.

Global capacity: The number of ground-source units worldwide exceeds 4.2 million (equivalent number of 12-kW units) with an installed capacity of about 50 GW.

7-6 GEOTHERMAL POWER PRODUCTION

Only a fraction of geothermal resources have relatively high temperatures making them suitable for electricity production.

Geothermal power plants have been in operation for decades in many parts of the world.

History: The first geothermal power plant was built in Italy in 1904.

In the U.S., the first plant was built in 1960 in the Geysers in northern California.

U.S. data: There are about 60 geothermal power plants in the U.S. located in California, Nevada, Utah, Montana, Idaho, and Hawaii.

Global capacity: Currently, more than 14,000 MW of geothermal electricity are produced in 24 countries.

Figure 7-15
A small-size geothermal power plant in Nevada.
The source temperature for this plant is only 120°C

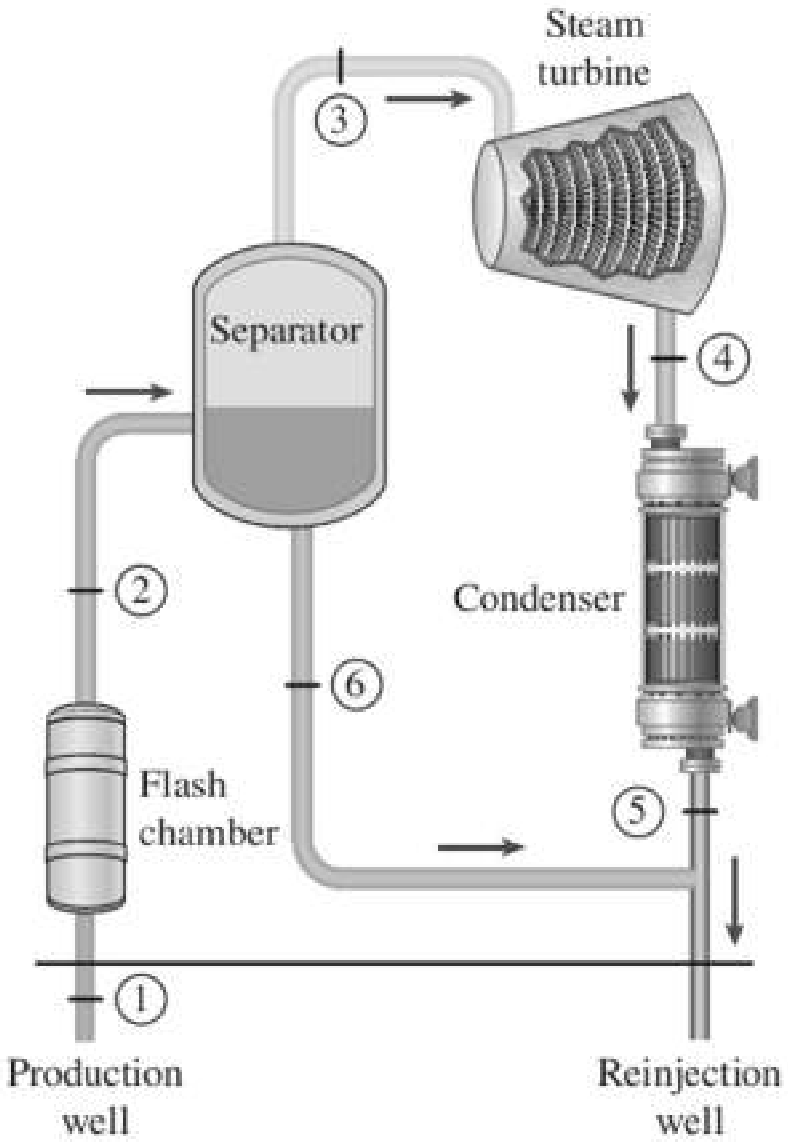
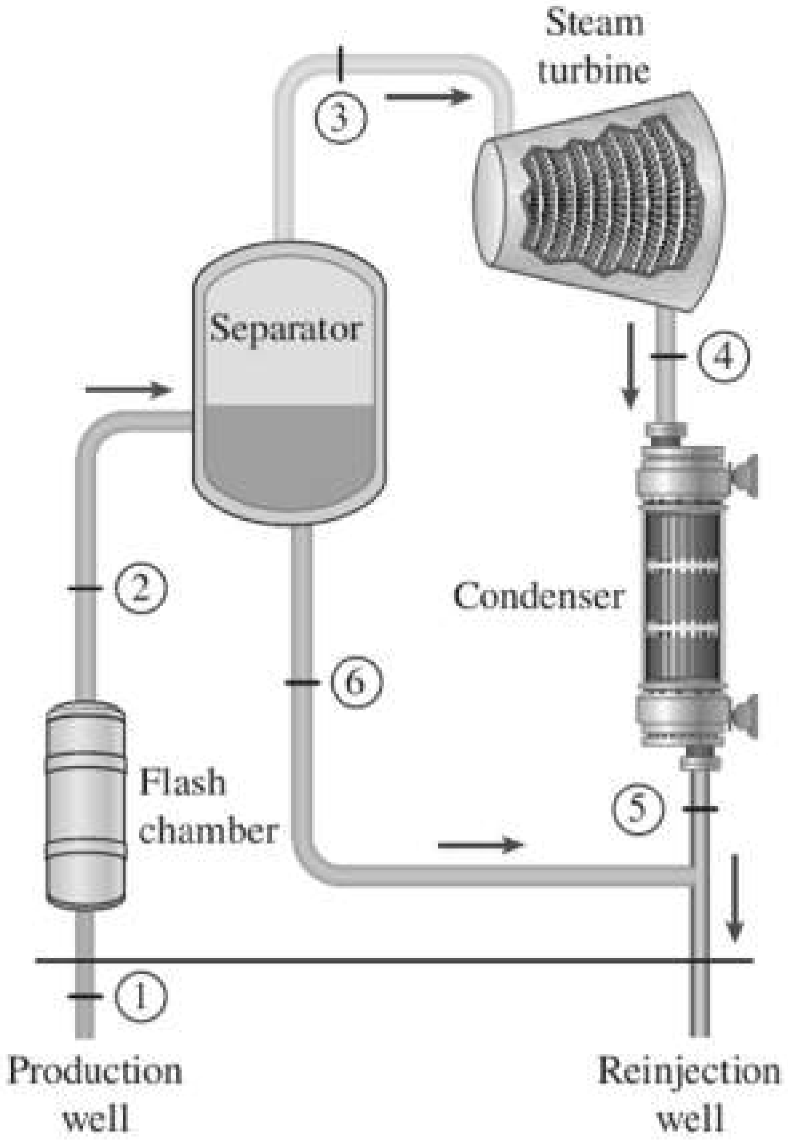


Figure 7-16
Single-flash geothermal power plant.

Direct steam cycle: The simplest geothermal cycle. Steam from the geothermal well is passed through a turbine and exhausted to the atmosphere or to a condenser.

Flash steam plants: They are used to generate power from liquid-dominated resources that are hot enough to flash a significant proportion of the water to steam in surface equipment, either at one or two pressure stages.



$$\dot{W}_{out} = \dot{m}_3(h_3 - h_4)$$ Power output from the turbine

$$\eta_{th} = \frac{\dot{W}_{out}}{\dot{E}_{in}}$$ Thermal efficiency of the plant

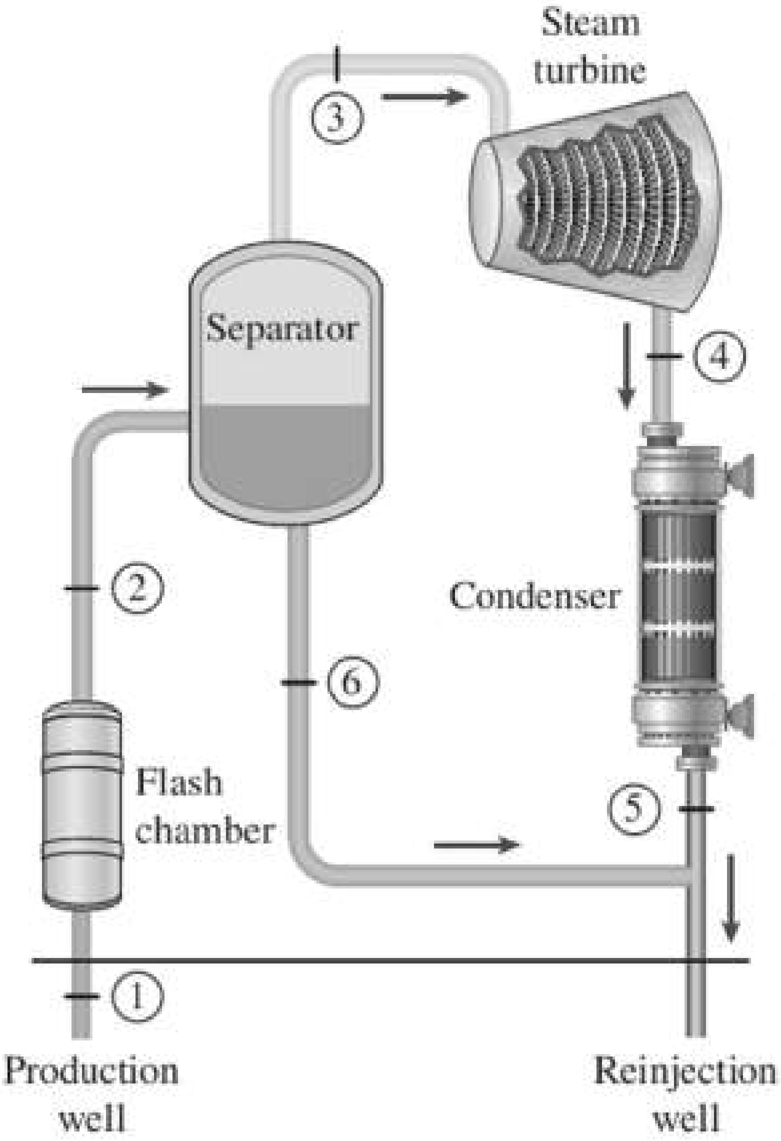
$$\dot{E}_{in} = \dot{m}_1(h_1 - h_0)$$ Energy input to the plant

$$\eta_{th} = \frac{\dot{W}_{out}}{\dot{E}_{in}} = \frac{\dot{m}_3(h_3 - h_4)}{\dot{m}_1(h_1 - h_0)}$$

$$\eta_{th} = \frac{\dot{W}_{out}}{\dot{E}_{in}} = 1 - \frac{\dot{E}_{out}}{\dot{E}_{in}}$$

$$\dot{E}_{out} = \dot{m}_6(h_6 - h_0) + \dot{m}_4(h_4 - h_0)$$

Energy output from the plant



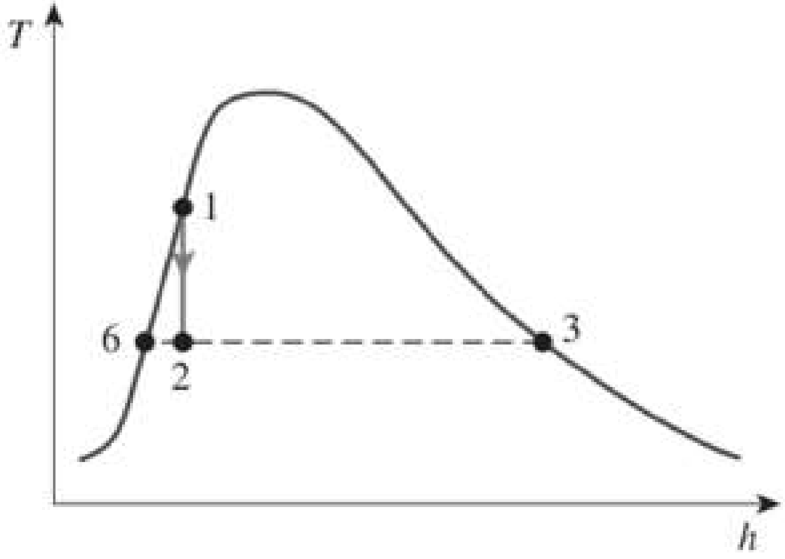


Figure 7-17
Flashing process in
temperature-enthalpy diagram.

$$\eta_{\text{th}} = \frac{\dot{W}_{\text{out}}}{\dot{E}_{\text{in}}} = \frac{\dot{m}_3(h_3 - h_4) + \dot{m}_8(h_8 - h_4)}{\dot{m}_1(h_1 - h_0)}$$

Thermal efficiency of the plant

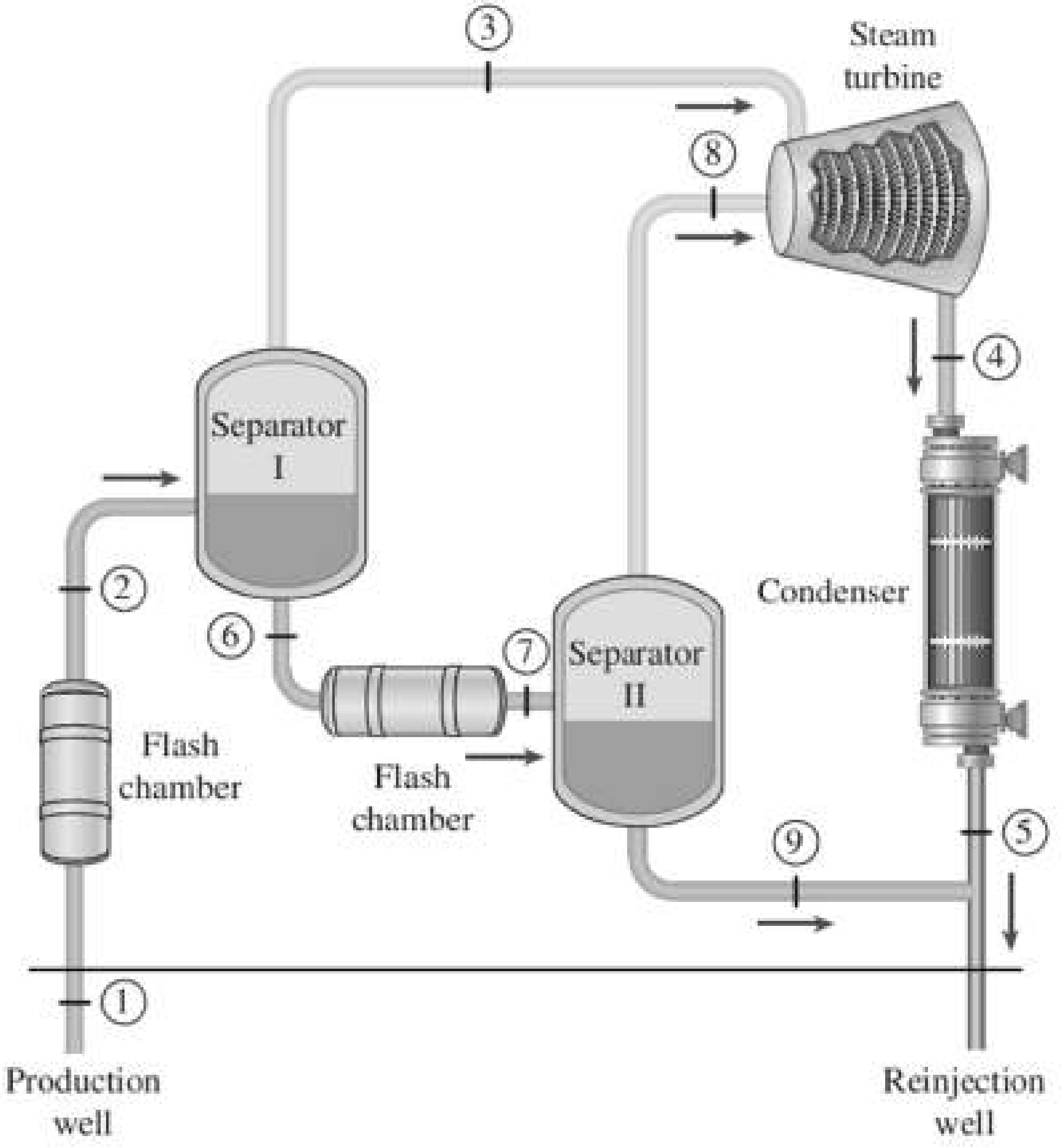


Figure 7-18 Double-flash geothermal power plant.

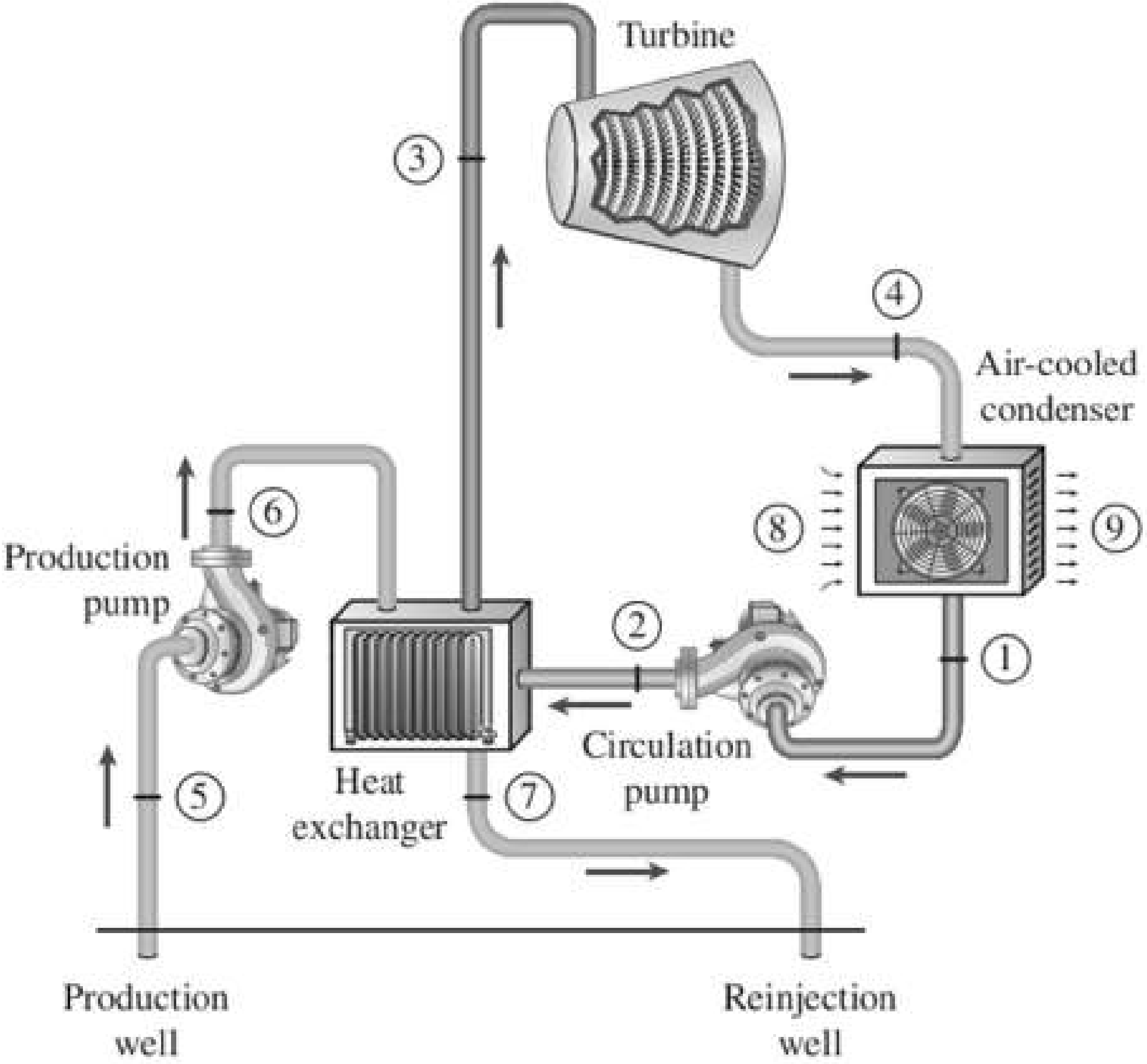


Figure 7-19
Binary cycle geothermal power plant.

Binary cycle plants: They use the geothermal brine from liquid-dominated resources at relatively low temperatures.

These plants operate on a Rankine cycle with a binary working fluid (isobutane, pentane, isopentane, R-114, etc.) that has a low boiling temperature.

$$\eta_{th} = \frac{\dot{W}_{net,out}}{\dot{E}_{in}} = \frac{\dot{W}_{turbine} - \dot{W}_{pump} - \dot{W}_{fan}}{\dot{E}_{in}}$$

Thermal efficiency of the plant

$$\dot{E}_{in} = \dot{m}_5 (h_5 - h_0)$$

Energy input to the plant

$$\dot{W}_{turbine} = \dot{m}_3 (h_3 - h_4)$$

Turbine power

$$\dot{W}_{pump} = \dot{m}_1 (h_2 - h_1)$$

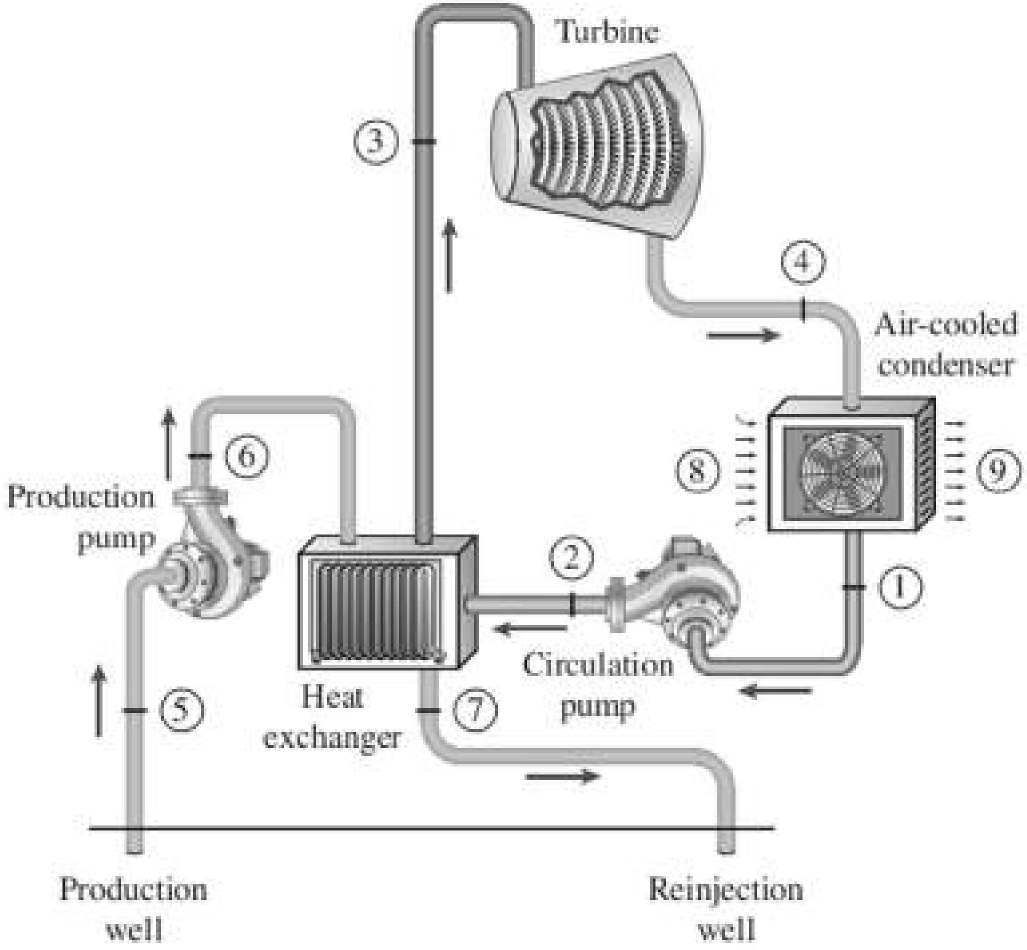
Pump power

$$\eta_{th} = \frac{\dot{W}_{net,out}}{\dot{Q}_{in}}$$

Thermal efficiency of the binary cycle

$$\dot{Q}_{in} = \dot{m}_6 (h_6 - h_7) = \dot{m}_2 (h_3 - h_2)$$

Heat input to the binary cycle



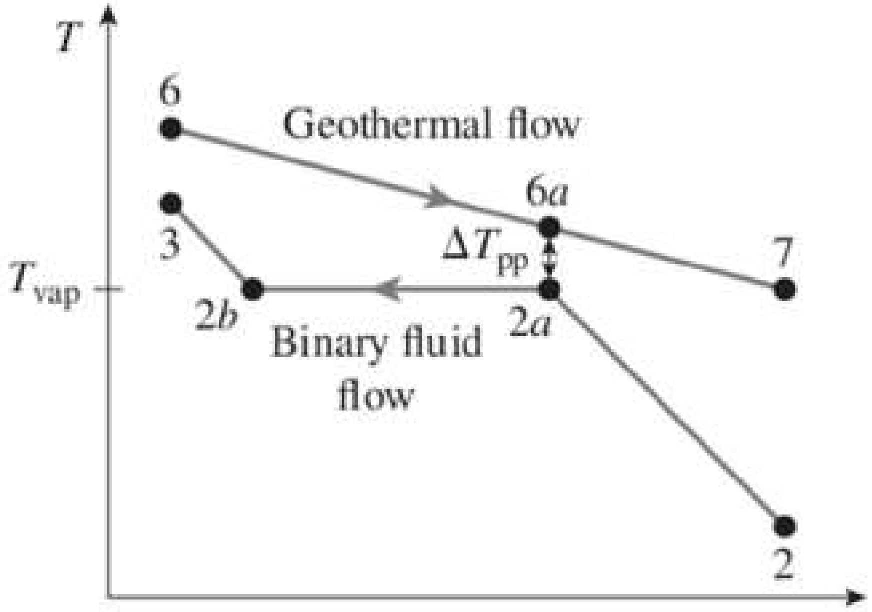


Figure 7-21
Heat exchange process between the geothermal brine and the binary working fluid in the heat exchanger of binary cycle power plant.

Energy balances in heat exchanger of binary plant

$$\dot{m}_{\text{geo}}(h_6 - h_{6a}) = \dot{m}_{\text{binary}}(h_3 - h_{2b})$$

$$\dot{m}_{\text{geo}}(h_{6a} - h_7) = \dot{m}_{\text{binary}}(h_{2a} - h_2)$$

$$h_{2a} = h_{f@T_{\text{vap}}} \qquad h_{2b} = h_{g@T_{\text{vap}}}$$

The temperature difference is called pinch-point temperature difference ΔT_{pp}.

The state 6a is called the pinch-point of geothermal water.

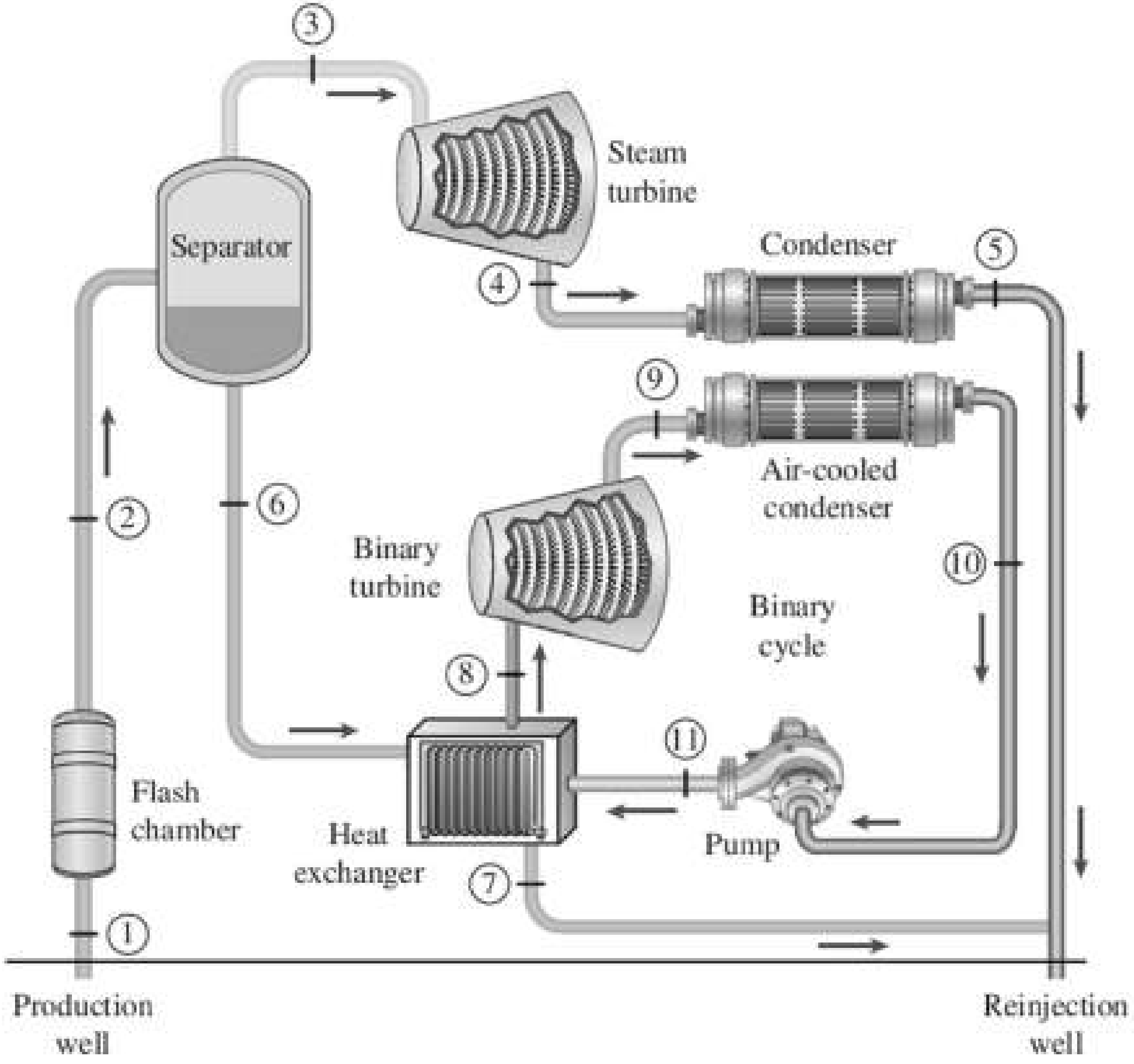


Figure 7-22
Combined flash/binary geothermal power plant.

$$\eta_{\text{th}} = \frac{\dot{W}_{\text{net,out}}}{\dot{E}_{\text{in}}} = \frac{\dot{W}_{\text{turbine}} - \dot{W}_{\text{pump}} - \dot{W}_{\text{fan}}}{\dot{E}_{\text{in}}}$$

$$= \frac{\dot{m}_3(h_3 - h_4) + \dot{m}_8(h_8 - h_9) - \dot{W}_{\text{pump}} - \dot{W}_{\text{fan}}}{\dot{m}_1(h_1 - h_0)}$$

Thermal efficiency of the plant

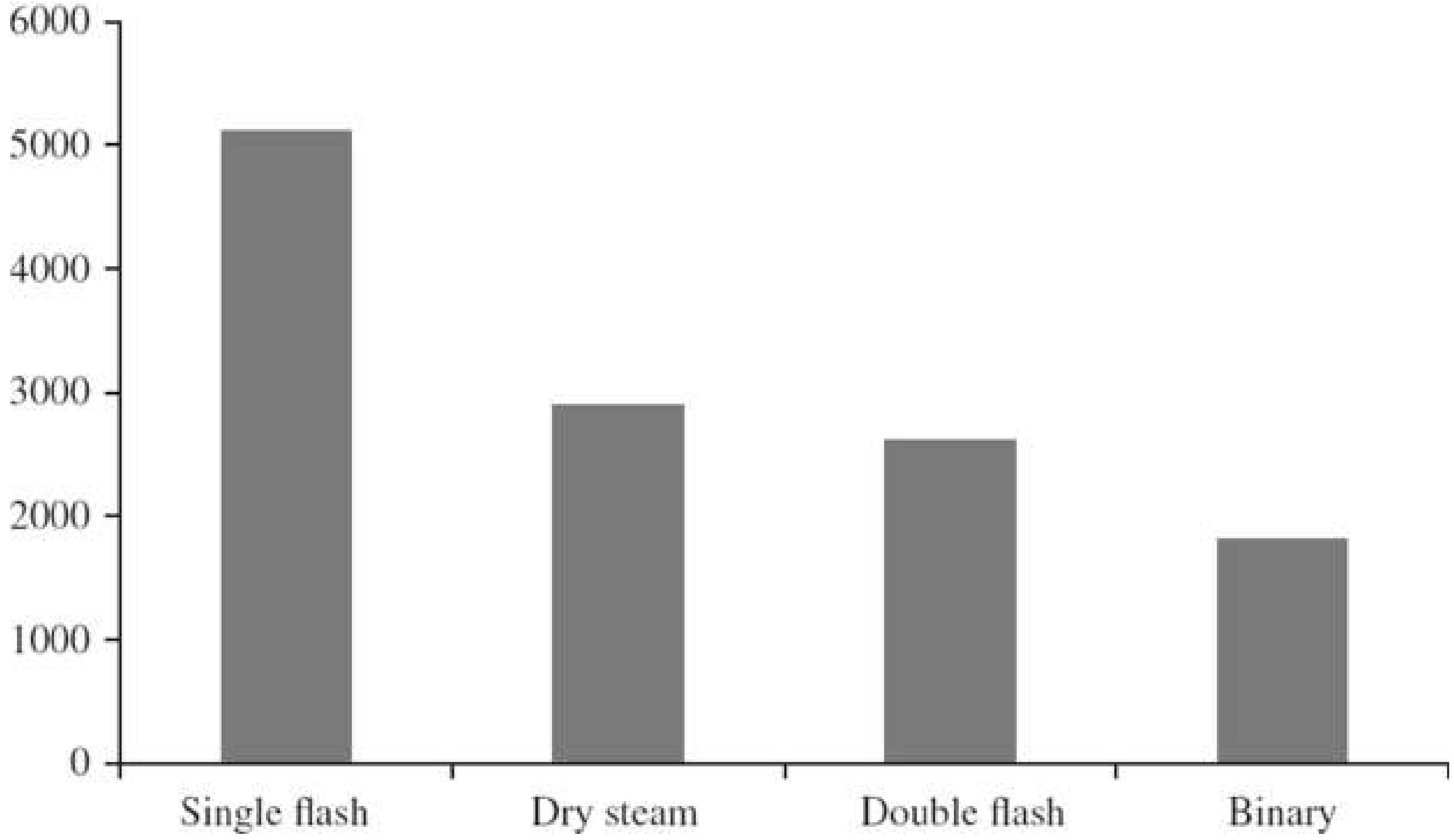


Figure 7-23
Installed capacity of different types of geothermal plants in the world as of 2015. The values are in MW.

7-7 GEOTHERMAL COGENERATION

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

A combination of power production and cooling can also be used in a cogeneration scheme.

Trigeneration: if three useful forms of energy (such as electric power, process heat, and cooling) are produced from the same energy source.

A steam-turbine (Rankine) cycle, a gas-turbine (Brayton) cycle, a combined cycle (combination of Rankine and Brayton cycles), an internal combustion engine, or any other power producing plant (such as a geothermal power plant) can be used as the power cycle in a cogeneration plant.

Cogeneration systems utilizing internal combustion engines and gas turbines in open cycle are the most utilized technologies worldwide

Cogeneration involves “cascading” of energy use from high- to low-temperature uses.

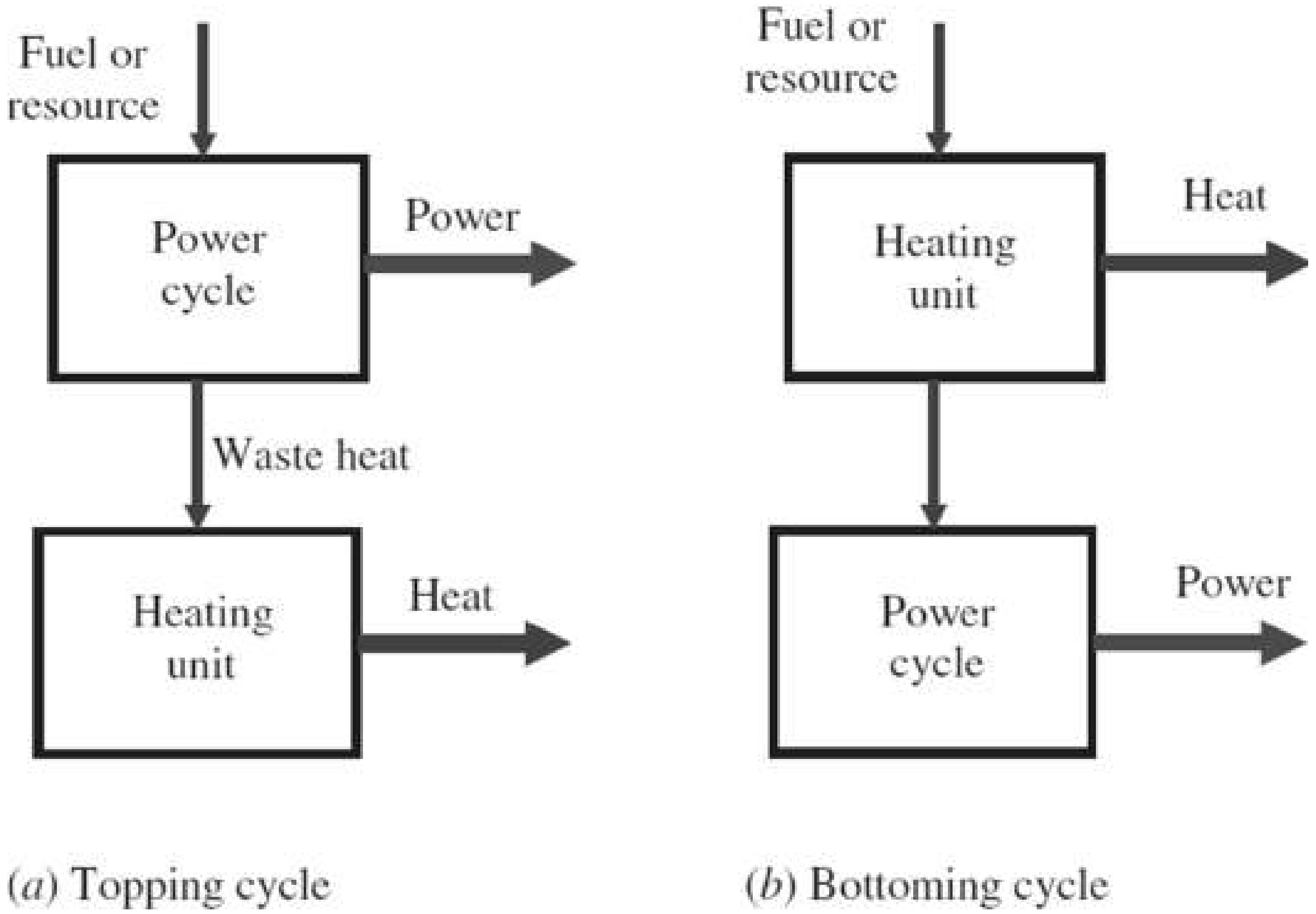
Advantages: The principal technical advantage of cogeneration systems is their ability to improve the efficiency of fuel use in the production of electrical and thermal energy.

Less fuel is required to produce a given amount of electrical and thermal energy in a single cogeneration unit than is needed to generate the same quantities of both types of energy with separate, conventional technologies.

Percent fuel savings: Energy and fuel use are reduced by up to 50%.

Cogeneration with renewables: When cogeneration is used in a renewable energy scheme, the environmental benefits are greater with respect to fossil fuel–based cogeneration units.

Renewable cogeneration systems make the most use of a resource and this translates into a greater replacement of fossil fuels.



(*a*) Topping cycle (*b*) Bottoming cycle

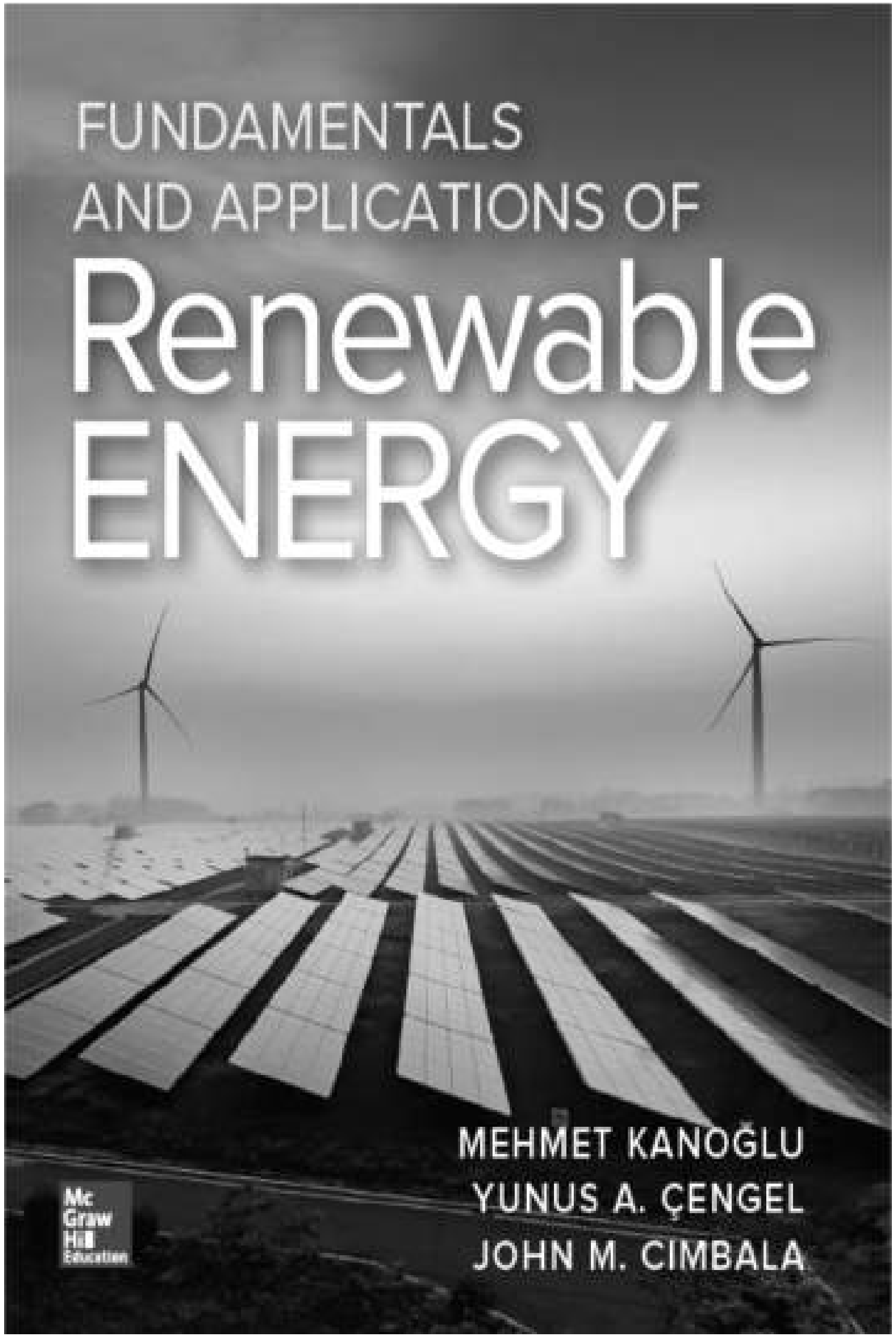
Figure 7-25
Topping and bottoming cycles.

Utilization factor of a cogeneration plant

$$\varepsilon_u = \frac{\text{Net power output} + \text{Rate of cooling delivered}}{\text{Total rate of heat input}} = \frac{\dot{W}_{\text{net}} + \dot{Q}_{\text{cooling}}}{\dot{Q}_{\text{in}}}$$

$$\varepsilon_u = \frac{\text{Net power output} + \text{Rate of heating delivered}}{\text{Total rate of heat input}} = \frac{\dot{W}_{\text{net}} + \dot{Q}_{\text{heating}}}{\dot{Q}_{\text{in}}}$$

$$\varepsilon_u = \frac{\dot{W}_{\text{net}} + \dot{Q}_{\text{heating}} + \dot{Q}_{\text{cooling}}}{\dot{Q}_{\text{in}}}$$



Chapter 8
BIOMASS ENERGY

Fundamentals and Applications of
Renewable Energy
Mehmet Kanoglu
Yunus A. Cengel
John M. Cimbala
McGraw-Hill, 2020

8-1 INTRODUCTION

Biomass : Organic renewable energy.

Biomass sources: It is mostly produced from agriculture and forest products and residues, energy crops, and algae.

Organic component of municipal and industrial wastes and the fuel produced from food processing waste such as used cooking oil are also considered biomass.

Why is biomass renewable? Despite relatively long period of times involved in growing crops and trees, they can be re-grown by planting, and therefore biomass is considered to be a renewable energy source.

Biomass in the U.S. It is estimated that about half of all renewable energy consumed in the U.S. is biomass.

Wood for space heating: Before coal, oil and natural gas replaced it as primary fuels, wood was the primary fuel for space heating in winter. Wood is still used in many parts of developing world for space heating.

Why is biomass converted to liquid and gaseous fuels? Liquid and gaseous fuels are generally more convenient forms of fuel compared to solid fuels. Therefore, crops and forest products are usually converted to liquid and gaseous fuels through some engineering processes.

Energy consumption for biomass: Growing of crops and trees as well as the conversion to liquid and gaseous fuels involve the consumption of energy in the form of electricity and fossil fuels such as coal, oil, and natural gas. The consumption of fossil fuels is accompanied by the pollutant and greenhouse emissions.

Is biomass really renewable? The renewability and cleanliness of biomass are not as good as other renewables such as solar, geothermal, or wind.

8-2 BIOMASS RESOURCES

Feedstocks: Biomass resources.

Biomass resources can be listed as follows:

Dedicated energy crops: These herbaceous energy crops are perennials that are harvested after reaching maturity. These include such grasses as switchgrass, miscanthus, bamboo, sweet sorghum, tall fescue, kochia, wheatgrass, and others.

Agricultural Crops: These include cornstarch and corn oil, soybean oil and meal, wheat starch, and vegetable oils. They generally yield sugars, oils, and extractives.

Agriculture Crop Residues: Biomass materials consisting primarily of stalks and leaves not used for commercial use such as corn stover (stalks, leaves, husks, and cobs), wheat straw, and rice straw are included in this resource. Approximately, 80 million acres of corn is planted annually.

Forestry Residues: These are biomass not harvested or used in commercial forest processes including materials from dead and dying trees.

Aquatic Crops: Aquatic biomass resources include algae, giant kelp, other seaweed, and marine microflora.

Biomass Processing Residues: Byproducts and waste streams produced by biomass processing are called residues, and they represent an additional biomass resource.

Municipal Waste: Plant based organic material generated from industrial, residential, and commercial waste represents an important biomass source. Some examples include waste paper, wood waste, yard waste, and cooking oil.

Animal Waste: Animal wastes consist of organic materials and are generated from farms and animal-processing operations. Animal waste is used as a heating fuel in some parts of the world.

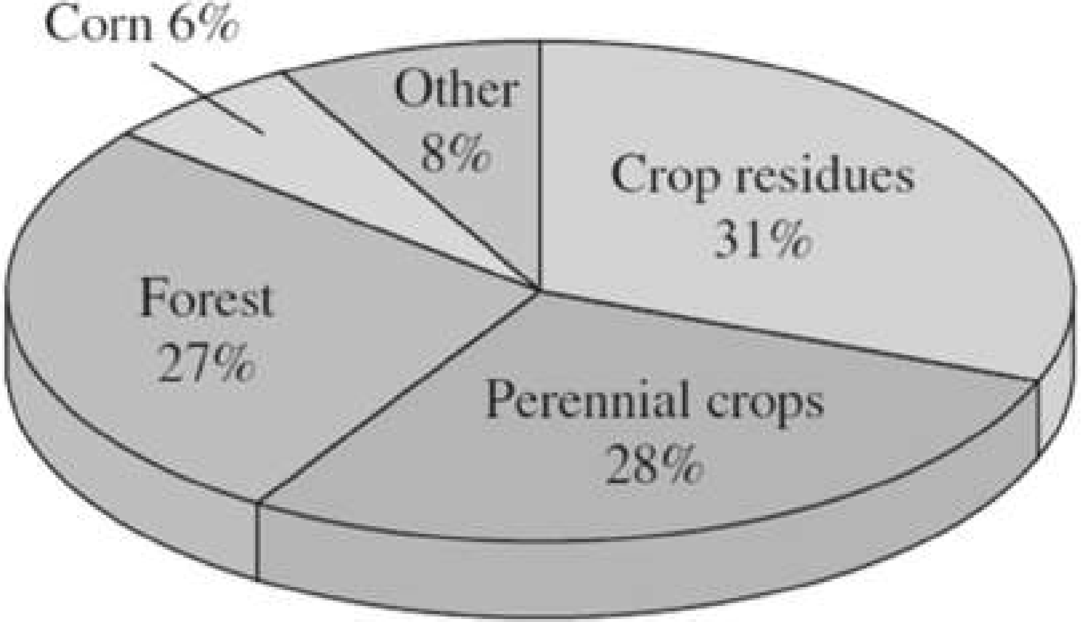


Figure 8-1
Contribution of various feedstocks to biomass production in the United States.

8-3 CONVERSION OF BIOMASS TO BIOFUEL

Biomass can be converted into liquid or gaseous fuels through various conversion processes.

Biochemical conversion processes: Enzymes and microorganisms are used as biocatalysts to convert biomass or biomass-derived compounds into desirable products.

Cellulase and hemicellulase enzymes break down the carbohydrate fractions of biomass to five- and six-carbon sugars in a process known as hydrolysis.

Yeast and bacteria then ferment the sugars into products such as ethanol.

Thermochemical conversion processes: Heat energy and chemical catalysts are used to break down biomass into intermediate compounds or products.

In **gasification**, biomass is heated in an oxygen-starved environment to produce a gas composed primarily of H_2 and CO.

Pyrolysis: Biomass is exposed to high temperatures without the presence of air, causing it to decompose.

Solvents, acids, and bases can be used to fractionate biomass into an array of products including sugars, cellulosic fibers, and lignin.

Photobiological conversion process: Research is underway for this alternative conversion process.

Photobiological conversion processes use the natural photosynthetic activity of organisms to produce biofuels directly from sunlight.

For example, the photosynthetic activities of bacteria and green algae have been used to produce hydrogen from water and sunlight.

8-4 BIOMASS PRODUCTS

Biofuels: A major product of biomass is biofuels which are a replacement for petroleum-based fuels.

Phase of biofuels: Liquid or gas

Biofuels usage: Mostly used for transportation as the engine fuel but also used for heating and electricity generation.

Most common biofuels: Ethanol and biodiesel

Other biofuels: Methanol, pyrolysis oil, biogas, producer gas, synthesis gas

Other biomass products: Antifreeze, plastics, glues, artificial sweeteners, gel for toothpaste.

Ethanol

Ethanol or ethyl alcohol (C_2H_5OH):

HHV = 29,710 kJ/kg LHV = 26,950 kJ/kg

Gasoline: HHV = 47,300 kJ/kg LHV = 43,000 kJ/kg

Mileage: A full tank of ethanol will get less mileage than that of gasoline.

Emissions: Ethanol has less hydrocarbon (HC) emissions than gasoline, and is commonly added to gasoline for improved emission from the engines.

Its use represents a renewable replacement for gasoline.

Adding ethanol to gasoline increases the octane number of gasoline allowing higher compression ratios and corresponding higher efficiencies for the engine.

Two common use of ethanol for automobiles in the U.S. include gasohol and E85.

Gasohol: a gasoline-ethanol mixture with 10 percent ethanol

E85: contains 85 percent ethanol. A 15 percent gasoline is only added to eliminate operating problems with the use of pure ethanol.

U.S. About half of the gasoline used in the U.S. includes 5 to 10% ethanol.

Brazil is the leading user of ethanol with approximately 5 million vehicles operating with 93 percent ethanol.

Ethanol sources:

Made primarily from the starch in corn grain.

Corn, sugar beets, sugar cane, cellulose (wood and paper)

Corn is the major source in the U.S. while sugar beets are primarily used in Brazil.

Process: The feedstock used for ethanol should be high in sugar content.

First, the feedstock is converted to sugar, and the sugar (glucose) is fermented into ethanol through the following reaction

$$C_6H_{12}O_6 \rightarrow 2\,C_2H_5OH + 2\,CO_2$$

Energy consumed for the production of ethanol

The cost of producing ethanol is relatively high due to growing of corn and manufacturing and processing involved.

Some studies suggest that the energy consumed during the production of ethanol (plowing, planting, harvesting, fermenting, and delivery) can be quite high per unit mass of the ethanol produced and it is sometimes comparable to energy content of ethanol itself.

Biodiesel

Process: Biodiesel is ethyl or methyl ester that is produced through a process that combines organically-derived oils with ethanol or methanol in the presence of a catalyst.

Sources: Common sources of biodiesel include

new and used vegetable oils

animal fats

recycled restaurant greases

Heating value:

HHV = 40,700 kJ/kg (17,500 Btu/lbm)

This is about 9% less than that of petroleum diesel

(HHV = 44,800 kJ/kg)

Use: Biodiesel can be used in compression ignition engines as a single fuel or can be added to conventional diesel fuel.

Common mixtures:

B20: 20% biodiesel and 80% conventional diesel

The most common biodiesel mixture used in the U.S.

B100: Biodiesel is also used as a single fuel in compression ignition engines.

Due to lower heating values, B100 provides less power from the engine.

Emissions: B100 could increase nitrogen oxides emissions while significantly reducing hydrocarbon, sulfur and carbon monoxide emissions.

Methanol

Methanol or methyl alcohol (CH_3OH)

Heating values: HHV = 22,540 kJ/kg, LHV = 20,050 kJ/kg

Pure methanol and its blend with gasoline have been extensively tested as an alternative fuel to gasoline.

Common mixtures:

M85: 85% methanol, 15% gasoline

M10: 10% methanol, 90% gasoline

Emissions: There is no noticeable emission reduction due to use of M10 in engines but M85 reduces hydrocarbon (HC) and carbon monoxide (CO) emissions significantly while also replacing more of gasoline consumption.

Sources: Fossil sources (coal, oil, natural gas) or biomass.

Natural gas is the main feedstock in the U.S. for methanol production. Synthesis gas produced from biomass can replace natural gas for this process.

Pyrolysis Oil

Process: Pyrolsis oil is produced when biomass is exposed to high temperatures without the presence of air, causing it to decompose.

A possible reaction involves heating of cellulosic feedstock in grain form for a short period (less than half a second) to a temperature of 400°C - 600°C and quenching it.

Disadvantages: The product is highly oxygenated and has considerable amounts of water. This makes these liquids corrosive and unstable with a low heating value.

Can it replace gasoline or diesel? Pyrolysis oil is not suitable as a replacement to conventional fuels such as gasoline or diesel.

Further processes are needed to make this fuel compatible with conventional hydrocarbon fuels.

Phenol: can be extracted from pyrolysis oil, and it is used to make wood adhesives, molded plastic, and foam insulation.

Biogas

Also called: swamp gas, landfill gas, digester gas

Content: 50 to 80% CH_4 and 20 to 50% CO_2 by volume

Small amounts of H_2, CO, and N_2

Heating value:

HHV of CH_4 = 55,200 kJ/kg

HHV of biogas with 50% methane by volume = 14,700 kJ/kg

HHV of biogas with 80% methane by volume = 32,700 kJ/kg

Sources: Biological waste such as animal manure, food waste, and agricultural waste

Process (Anaerobic digestion): The decomposition of organic waste into a gaseous fuel by bacteria action without the presence of oxygen.

It is possible to produce 200 to 400 m^3 of biogas from 1000 kg of organic waste with 50 to 75% methane by volume.

Heating value: Biogas is basically a gaseous fuel similar to natural gas but with a lower heating value due to significant CO_2 fraction.

Biogas uses: Biogas can be fed to a natural gas pipeline after CO_2 is removed.

It can be easily burned in a boiler for space, process, and water heating applications.

It can be used to generate steam in a steam power plant to produce electricity.

Many municipalities in different countries have solid waste treatment facilities in which they produce biogas from the waste and use the biogas for electricity generation.

Some facilities produce both electricity and heat from biogas (cogeneration).

A gas-turbine or an internal combustion engine can be used as the power producing unit.

Producer gas

Process: Producer gas is produced by thermal gasification which is the partial oxidation of a solid biomass at high temperatures into a gaseous fuel.

Steam and oxygen interacts with solid biomass such as wood during a gasification process.

Most practical gasification systems can convert 70 to 80% of the heat of the biomass into energy of producer gas.

Content: The resulting producer gas consists of

CO, H_2, CH_4, N_2, CO_2

Heating value: The composition of producer gas varies greatly. The heating value of producer gas depends on percentages of ingredient gases, and it varies between 15% and 50% of the heating value for natural gas.

Uses: Producer gas can be used as a feedstock for liquid fuels or it can be burned directly in a furnace.

Synthesis gas

Also called: biosynthesis gas, syngas

Process: Produced by thermal gasification using oxygen

Content: CO and H_2

Heating value: If a synthesis gas has 50% CO and 50% H_2 fraction by volume, its heating value is 19,000 kJ/kg.

Sources: Commonly produced from natural gas, coal, and heavy diesel.

We are more interested in its production from biomass feedstock.

Wood and other solid biomass can be used to produce syngas.

Uses: In addition to being used as the fuel for conversion to heat and electricity, synthesis gas can be used to make plastics and acids, which can then be used to make photographic films, textiles, and synthetic fabrics.

8-5 ELECTRICITY AND HEAT PRODUCTION BY BIOMASS

Biopower: The production of electricity and heat from biomass.

Capacity in the U.S.: The installed capacity of biopower in the U.S. is about 10 gigawatts.

Technologies: There are three technologies used to convert biomass energy to heat and electricity:

direct combustion, co-firing, anaerobic digestion

Direct combustion: Biomass consisting of waste wood products (i.e., wood pellet) can be burned in direct combustion in conventional boilers to generate steam or hot water.

This steam is run through a turbine coupled with a generator to produce electricity.

Co-firing: It refers to replacing only a portion of fossil fuel in coal-fired boilers with biomass.

This technology has been successfully demonstrated in most boiler technologies, including pulverized coal, cyclone, fluidized bed, and spreader stoker units.

Sulfur dioxide emissions of coal-fired power plants can be reduced considerably by co-firing biomass.

Anaerobic digestion (methane recovery): It is a common technology used to convert organic waste to methane and heat.

In this process, organic matter is decomposed by bacteria in the absence of oxygen to produce natural gas consisting primarily of methane and other byproducts such as carbon dioxide.

This gas can be used for space and water heating or electricity production.

8-6 SOLID MUNICIPALITY WASTE

Municipal solid waste (MSW):

An important class of biomass is produced by households as trash or garbage. This is referred to as MSW.

MSW content:

- Mostly organic materials such as paper, food scraps, wood, and yard trimmings
- Some fossil content such as plastic also exists.

MSW sources:

Residences (55 to 65%)

Businesses, schools, and hospitals (35 to 45%)

What is not included in MSW:

Industrial, hazardous, or construction waste.

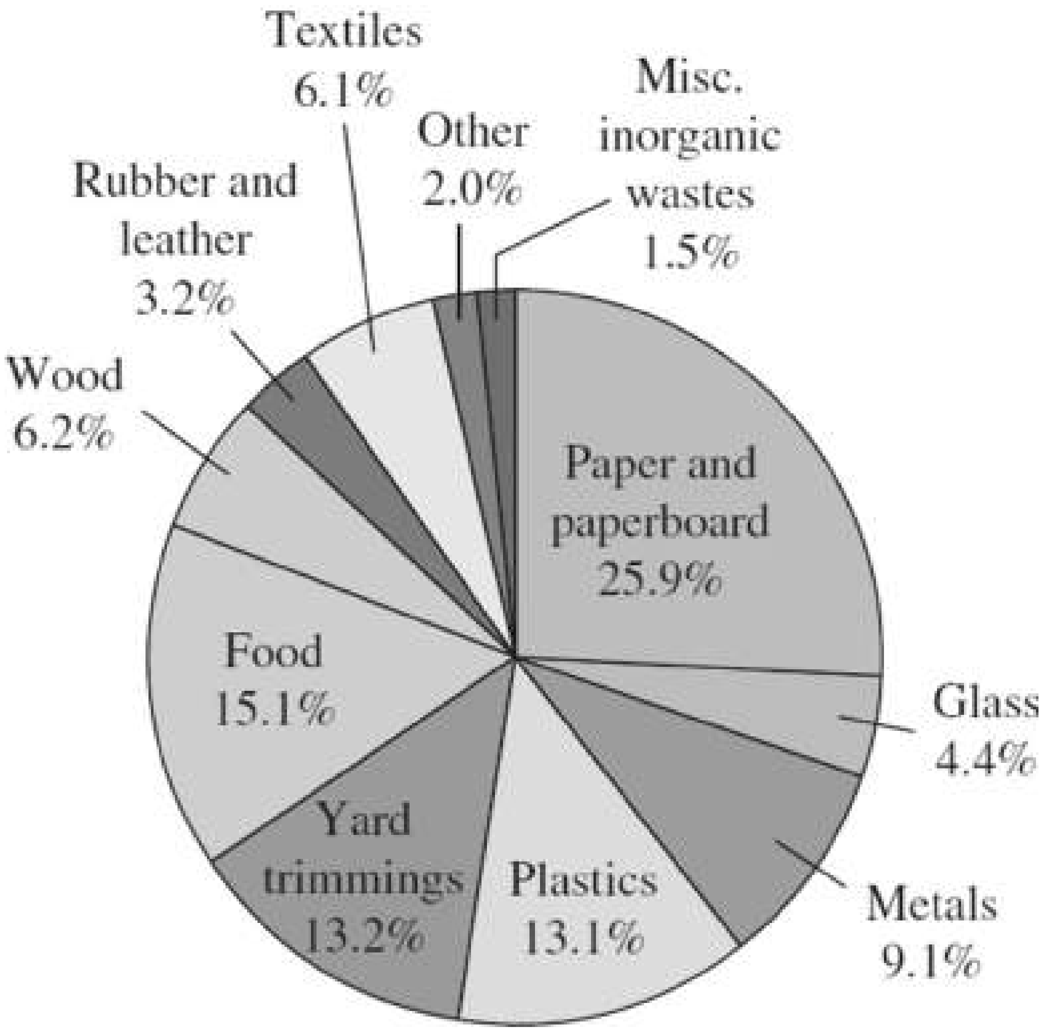


Figure 8-2
Materials in municipal solid waste and their percentages in the United States.

The U.S. Environmental Protection Agency (EPA) collects and reports data on the generation and disposal of waste in the U.S.

Why?

This data is used to measure the success of

- waste reduction

- recycling

programs across the country.

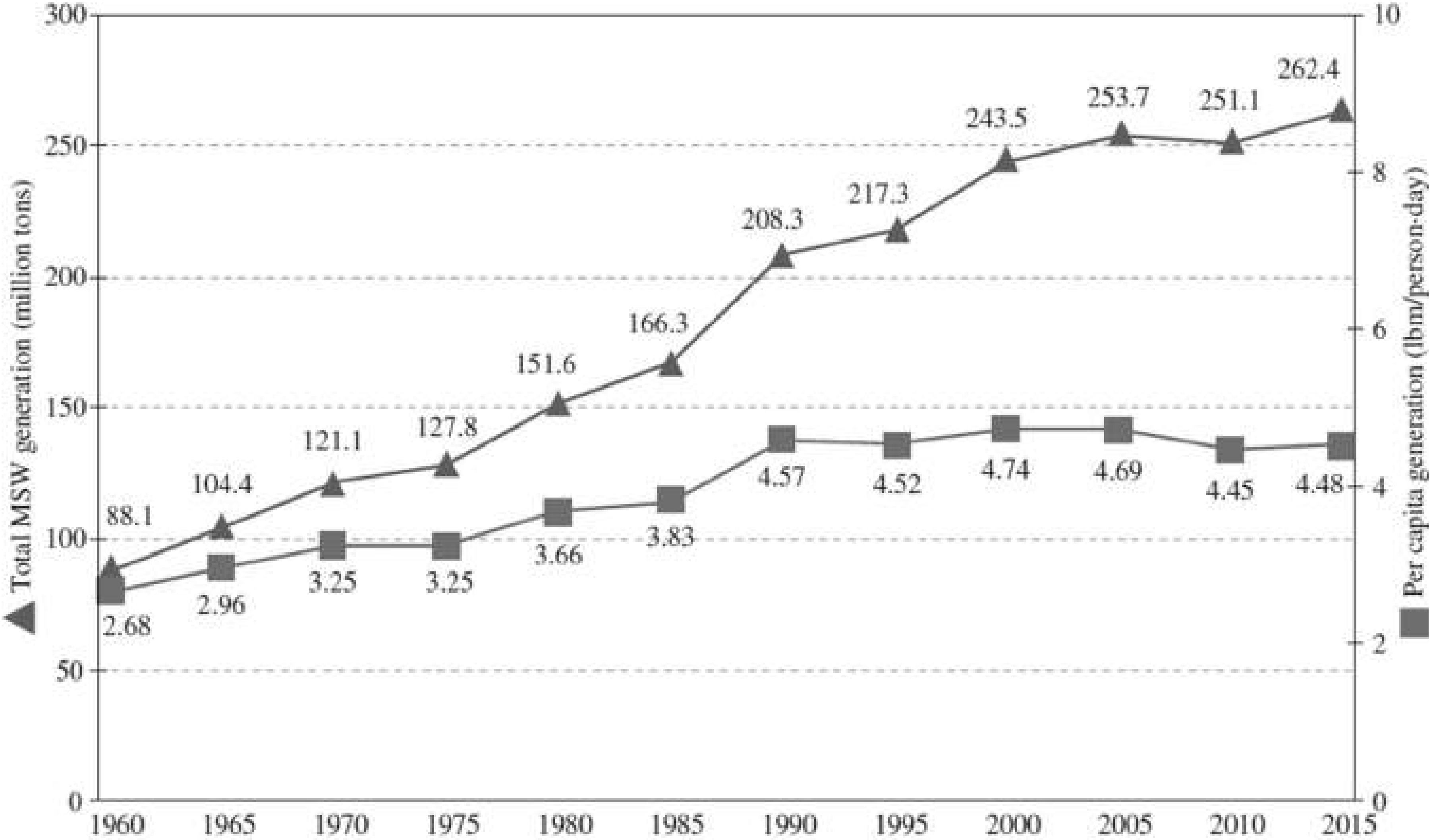


Figure 8-3
Municipal solid waste generation from 1960 to 2015 in the United States, total and per capita basis.

Total MSW generation in the U.S.: 262.4 million tons
(1 ton = 2000 lbm)

Percentage recycled or composted: 34.8%

MSW per person: 4.48 lbm (2.03 kg) of solid waste per day

Recycling and composting per person: 1.55 lbm (0.70 kg) per day

Total MSW production has increased steadily since 1960 but started to decrease between 2005 and 2010.

Per capita MWS production has increased since 1960 until 2000 when it reached the maximum value of

4.72 lbm per person per day

It has decreased slightly between 2000 and 2005 but rather significantly after 2005.

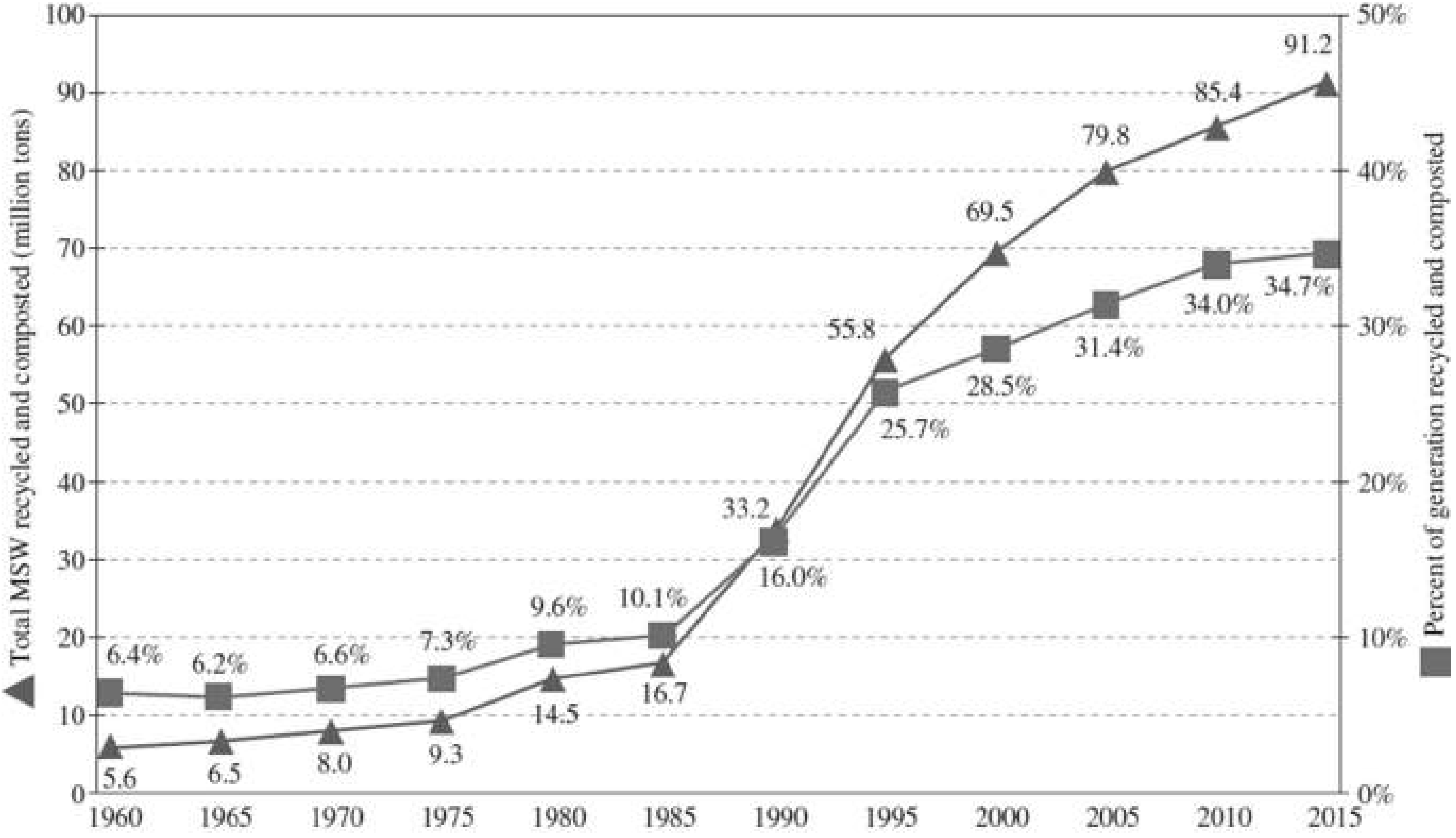


Figure 8-4

Municipal solid waste recycling from 1960 to 2015 in the U.S.

1985 recycling data: The recycling culture in the U.S. has improved significantly after 1985 when only 10.1 percent of MSW was recycled.

After dramatic increases between 1985 and 1995 in recycling rates, there is a steady increase in recycling since 1995.

2015 recycling data: 91.2 million tons of MSW were recycled or composted representing 34.8% of all MSW.

Rcycling vs. composting: About 67.8 million tons were recovered through recycling while 23.4 million tons were composted.

Recycling refers to recovery of useful materials such as paper, glass, plastic, and metals from the trash to use to make new products.

Composting refers to storing organic waste such as food scraps and yard trimmings under certain conditions to help it break down naturally. The resulting product can be used as a natural fertilizer.

What are recycled? The highest recycling rates are achieved in paper and paperboard, yard trimmings, and metals.

More than 67% of the paper and paperboard (45 million tons) and 58% of yard trimmings were recycled in 2010.

Recycling paper, paperboard, and yard trimmings alone kept almost 29% of MSW out of landfills and combustion facilities.

Advantages of recycling? Recycling reduces raw material use and associated energy consumption and greenhouse gas emissions, which cause global warming.

Air and water pollution associated with making new products are also avoided.

It is estimated that 85 million tons of MSW recycled in 2010 saved 205 million tons of CO_2 emissions.

This is equivalent to removal of 36 million cars from the roads.

Waste prevention

In addition to *recycling* and *composting*, the amount of waste can also be reduced by *waste prevention*, which is the design of products to minimize the production of waste and making the resulting waste less toxic.

Disposal of waste to a landfill: Disposal of waste to a landfill has decreased from 89% of the amount generated in 1980 to about 52.5% of MSW in 2015.

34.8% is recycled and compusted

2.8% (29 million tons) is combusted for energy recovery.

Landfills: The number of U.S. landfills has steadily declined over the years but the average landfill size has increased.

Since 1990, the total amount of MSW going to landfills dropped by almost 7 million tons, from 145 million to 138 million tons in 2015.

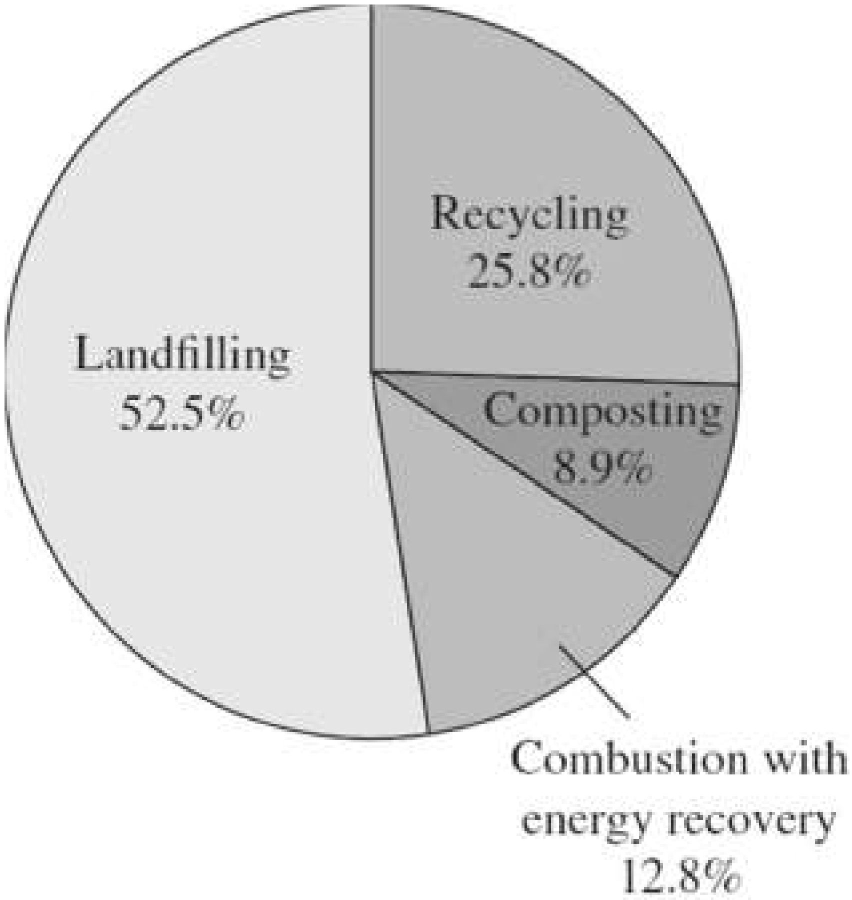


Figure 8-5
Use of municipal solid waste in the United States in 2015.

Renewable electricity from MSW: About 15% of renewable electricity generation excluding hydroelectric power comes from municipal waste facilities in the U.S.

Energy recovery options: Energy can be recovered in the form of electricity by both burying and burning options.

What is the best use of municipal solid waste?

Is it better to burn or bury waste when trying to recover energy and minimize emissions?

An EPA research compared two options for producing electricity from MSW.

The first option:

Waste to energy (WTE): Waste is burned directly for generating steam. This steam is run through a turbine to generate electricity.

The second option:

Landfill-gas-to-energy (LFGTE): It involves harvesting biogas (mostly methane) from the buried waste as it decomposes. Biogas is then used as the fuel in an internal combustion engine or gas turbine to generate electricity.

Conclusions: The research indicates that burning waste through WTE method can produce up to 10 times more electricity than burying the same amount of waste through LFGTE method.

Greenhouse gas emissions per unit electricity produced are two to six times higher in landfills than in waste burning plants

Various options are available for the treatment of MSW including recycling, composting, landfill burying, anaerobic digestion to produce methane gas, electricity production, and refused dried fuel (RDF).

RDF is the combustible portion of the MSW which is extracted by separating noncombustibles from the combustible portion of MSW.

RDF should be obtained in a form such that it can be burned directly in a boiler.

Only organic waste materials are accepted in composting facilities.

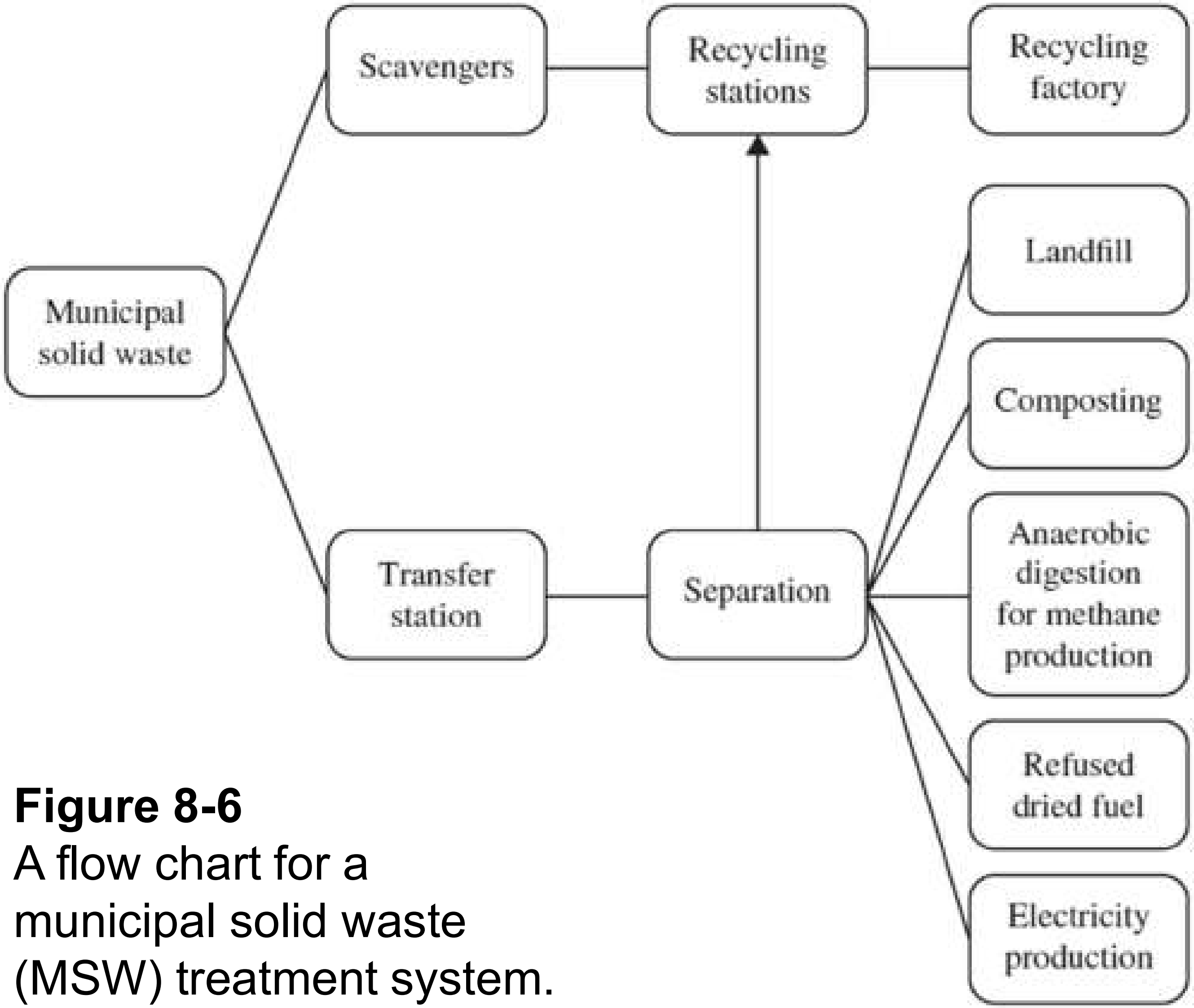
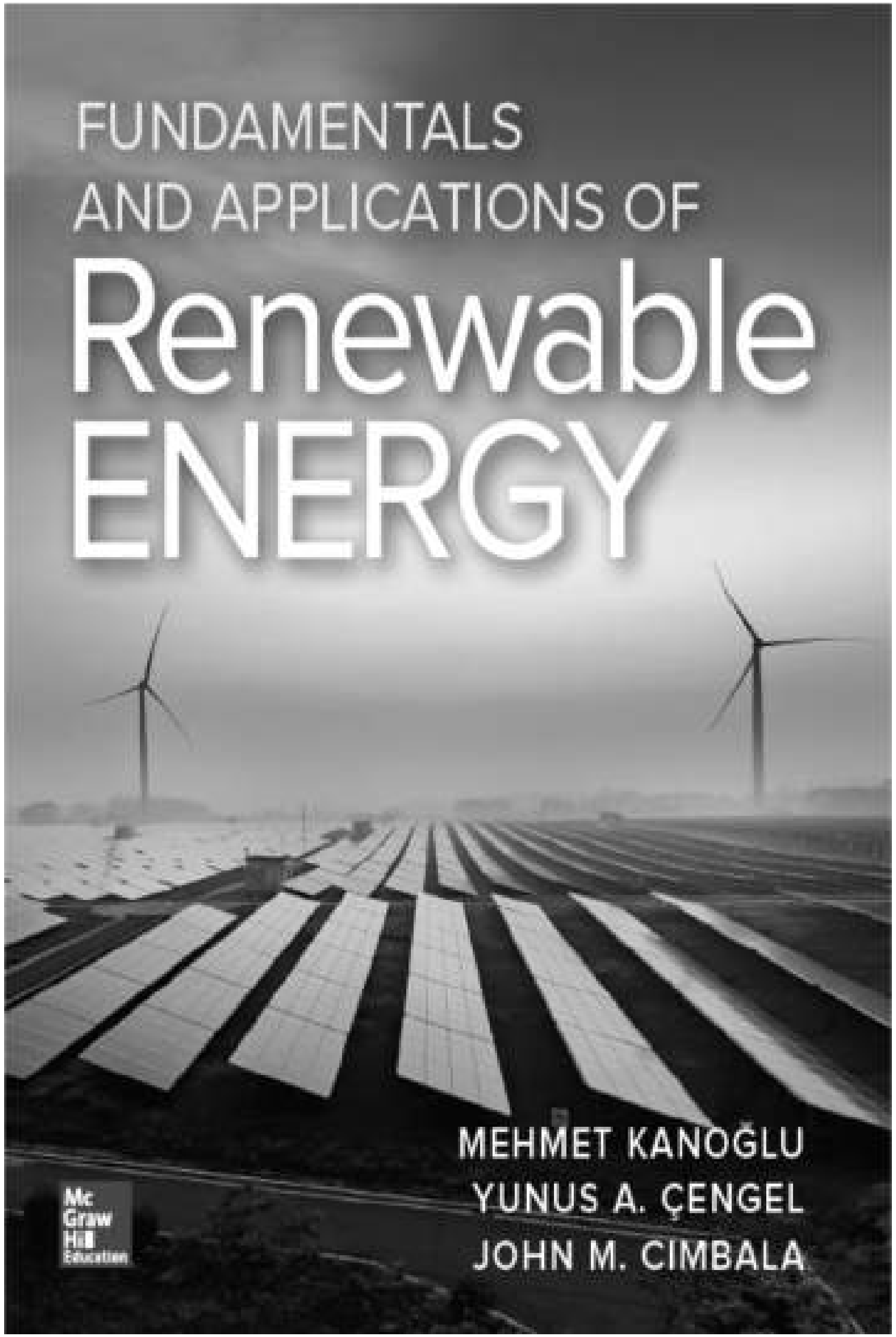


Figure 8-6
A flow chart for a municipal solid waste (MSW) treatment system.



Chapter 9
OCEAN ENERGY

Fundamentals and Applications of

Renewable Energy

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McGraw–Hill, 2020

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9-1 INTRODUCTION

Mechanical forms of ocean energy: Tremendous amounts of energy are available in oceans and seas due to *waves* and *tides*, which are mechanical form of energies as they are related to kinetic and potential energy of the ocean water.

Thermal form of ocean energy: Oceans also have thermal energy due to solar heating of ocean water.

In this chapter, we study

- ocean thermal energy conversion (OTEC)
- wave energy
- tidal energy

9-2 OCEAN THERMAL ENERGY CONVERSION

Thermal energy in ocean: Oceans have thermal energy due to solar heating of ocean water.

As a result of solar energy absorption, the water at the sea or ocean surface is warmer, and the water at a deeper location is cooler.

Temperatures: In tropical climates, surface temperatures can reach 28°C while the temperatures are as low as 4°C about 1 km below water.

Operation: The ocean can be considered to be a large heat engine with a source temperature of 28°C and a sink temperature of 4°C.

Then, a heat engine can be operated that utilizes the surface warm water as heat source and deep cold water as the heat sink for the conversion of heat to power.

This principle of power production is called *ocean thermal energy conversion* (OTEC).

Disadvantage: The main disadvantage of an OTEC plant is the low thermal efficiency.

The maximum thermal efficiency can be determined from Carnot relation using the above source and sink temperatures to be

$$\eta_{\text{th,max}} = 1 - \frac{T_L}{T_H} = 1 - \frac{(4+273)\text{ K}}{(28+273)\text{ K}} = 0.080 \text{ or } 8.0\%$$

Efficiency: Actual thermal efficiencies of OTEC systems are only around 3 percent.

OTEC applications: Experiments have been performed using the OTEC principle but the results have not been promising due to

- *large installation cost*
- *low thermal efficiency*

The equipment in OTEC systems must be very large for significant amounts of power production.

Heat exchanger size: For example, for a power output of 100 kW, the heat transfer rating of the heat exchanger of an OTEC system should be 3300 kW at a thermal efficiency of 3 percent.

This corresponds to a very large surface area for the heat exchanger and corresponding high capital and pumping costs.

The required surface area of this evaporator for a heat transfer rating of 3300 kW is

$$\dot{Q} = UA_s\Delta T_{\text{lm}} \longrightarrow A_s = \frac{\dot{Q}}{U\Delta T_{\text{lm}}} = \frac{3300\ \text{kW}}{(1.5\ \text{kW/m}^2\cdot{}^\circ\text{C})(5^\circ\text{C})} = 440\ \text{m}^2$$

Which waters are suitable? Tropical and equatorial waters are more suitable for OTEC installations due to relatively high surface temperatures.

Surface water temperatures vary with season and latitude.

In tropical waters, surface temperatures vary from 29°C in August to 24°C in February.

Hawaii, island nations in south Pacific Ocean, and Gulf nations are some of the known locations for OTEC applications.

A pilot application: A pilot OTEC plant operated between 1993 and 1998 in Hawaii with average surface and deep water temperatures of 26°C and 6°C, respectively, and a net power output of 103 kW.

About half of the power produced by the plant was used internally for pumps and parasitic work.

Two basic designs can be used for OTEC systems:

- Open systems: Claude cycle
- Closed systems: Anderson cycle

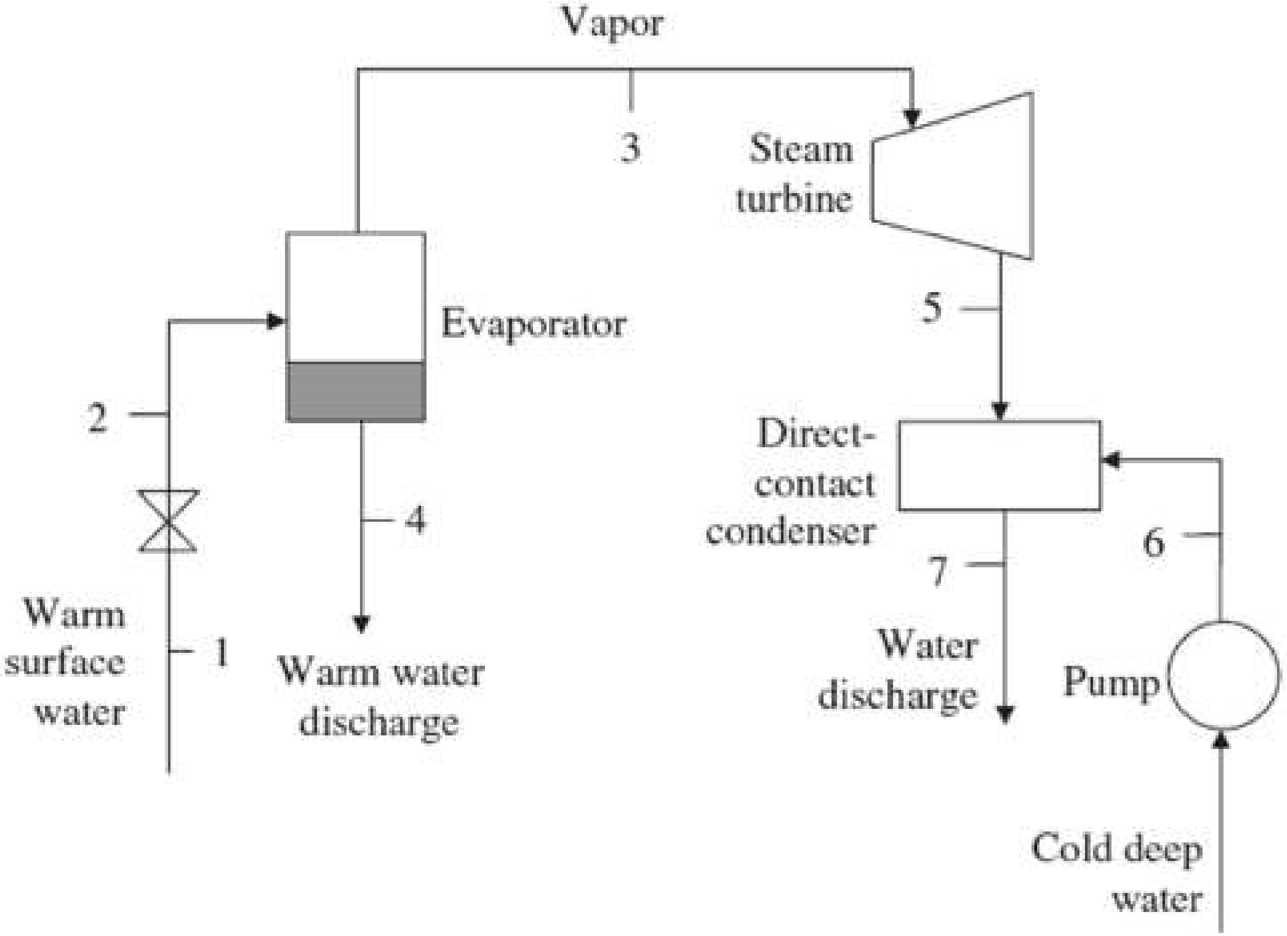
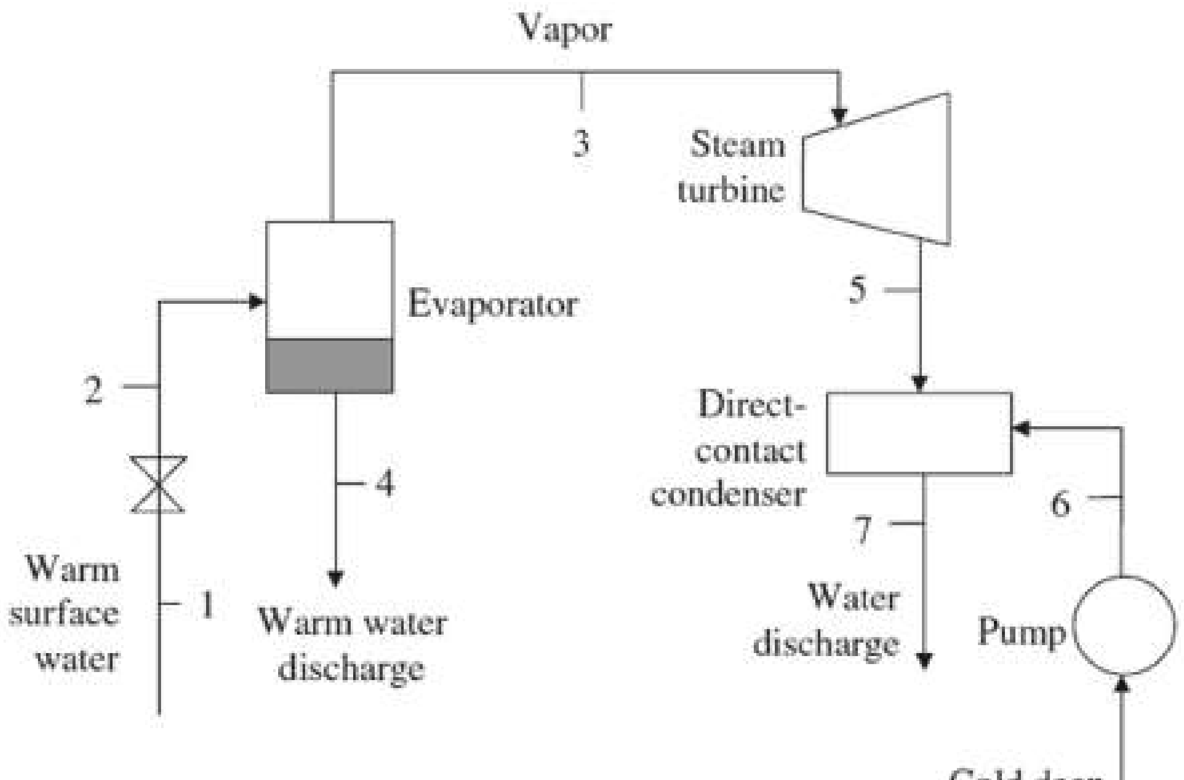


Figure 9-1 Operation of an open-system OTEC plant.



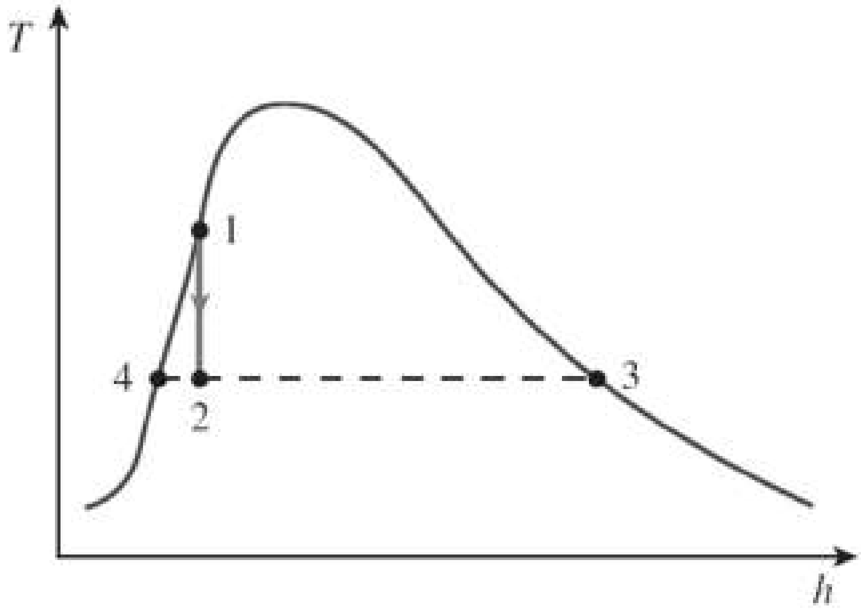


Figure 9-2
Constant-enthalpy process in the evaporator of open-system OTEC plant.

Steam turbines in OTEC systems

In Example 9-1, the specific volumes at the turbine inlet and exit are 45.65 and 85.90 m^3/kg, respectively.

These values are very high compared to those found in turbines of fossil fuel burning conventional steam power plants.

For example, the specific volume of steam is only 0.033 m^3/kg (at 10 MPa and 500°C) at the inlet of a conventional steam turbine.

Therefore, the steam turbines of OTEC systems should be very large to handle high volume flow rates and their technology needs to be somewhat different than conventional steam turbines.

Closed-cycle OTEC system, called Anderson cycle.

This is similar to binary cycle of geothermal power plants.

Closed-cycle plants operate on a Rankine cycle with a binary working fluid such as propane that has a low boiling temperature.

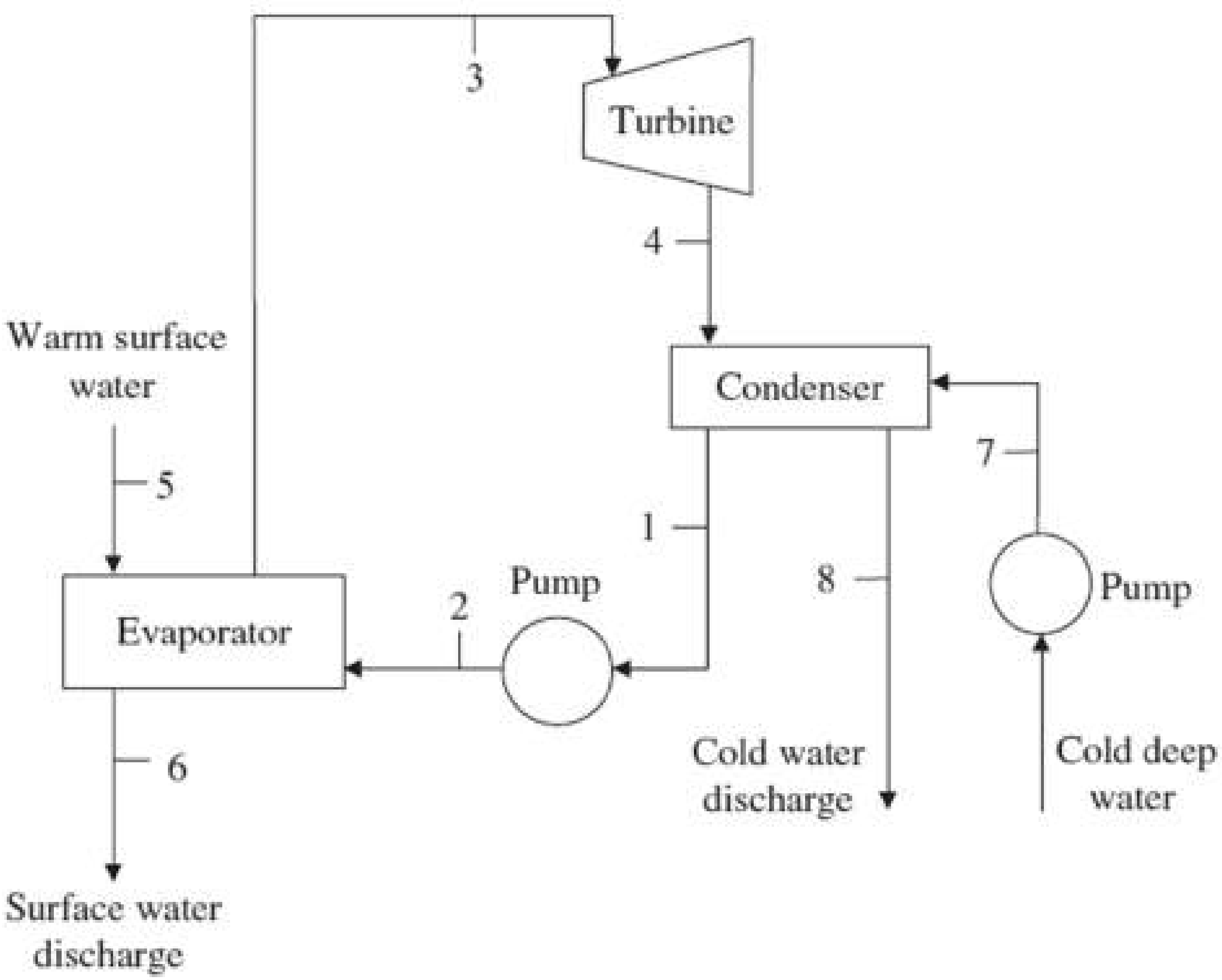


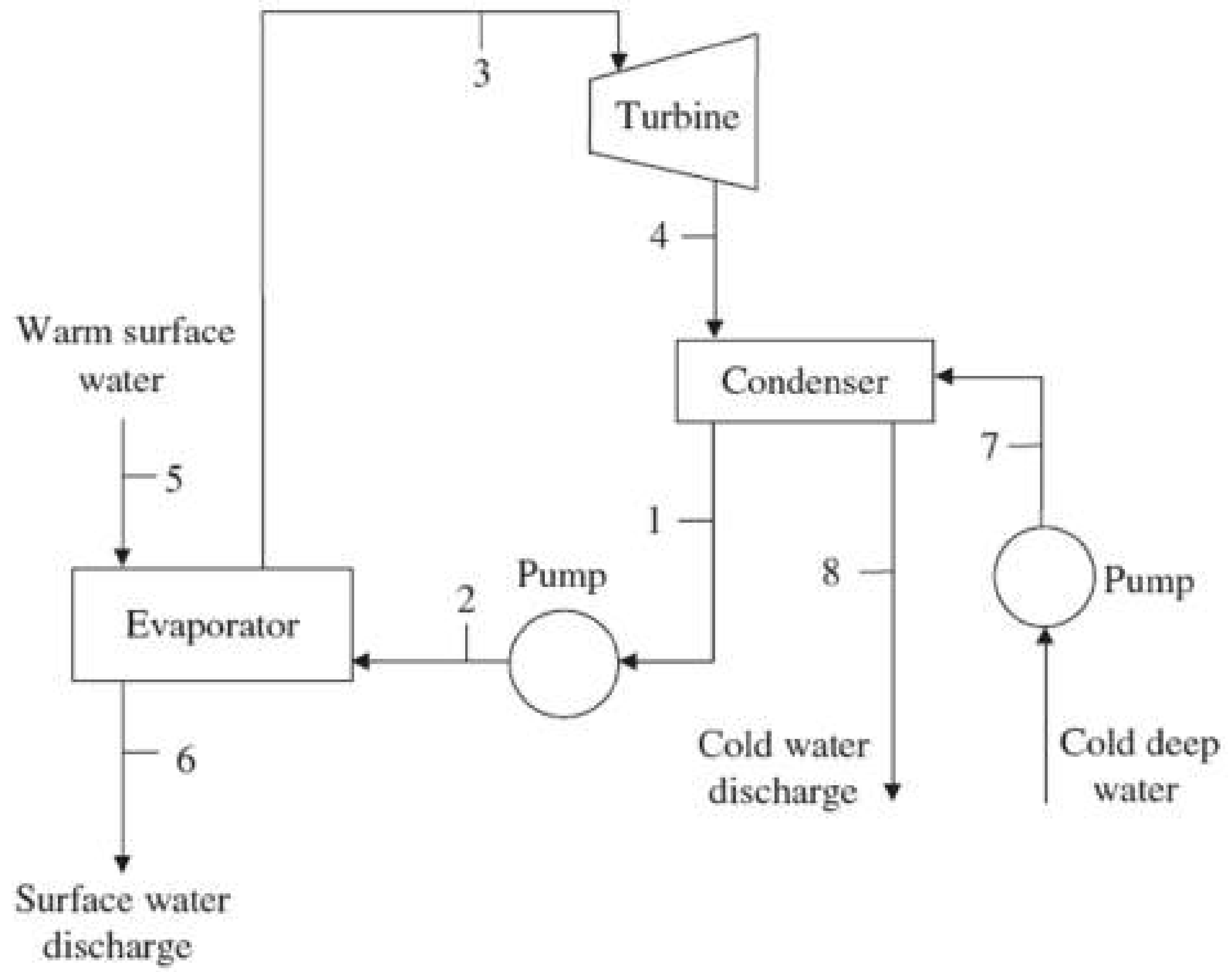
Figure 9-3 Operation of a closed-cycle OTEC plant.

$$\dot{W}_{\text{out}} = \dot{m}_{wf}(h_3 - h_4)$$ Turbine power

ww warm water
wf working fluid

$$\dot{Q}_{\text{in}} = \dot{m}_{wf}(h_3 - h_2)$$
$$\dot{Q}_{\text{in}} = \dot{m}_{ww}(h_5 - h_6)$$ Heat input

$$\eta_{\text{th}} = \frac{\dot{W}_{\text{out}}}{\dot{Q}_{\text{in}}} = \frac{\dot{m}_{wf}(h_3 - h_4)}{\dot{m}_{wf}(h_3 - h_2)} = \frac{h_3 - h_4}{h_3 - h_2}$$ Thermal efficiency



9-3 WAVE ENERGY

Reason for wave energy: Like most other renewable energy sources, wave energy is ultimately caused by solar energy.

Ocean and sea waves are caused by wind, and wind is caused by uneven solar heating of earth and water bodies and resulting temperature fluctuations.

Rotation of earth is also a contributing factor to wind and thus wave energy.

Wave energy is also referred to as *wave power* as we try to extract power from the energy of waves as a sustainable method of power generation.

Wave power potential: There is enormous potential of producing power from ocean and sea waves considering that an average of some 3 million waves break on to the coast every year.

The technologies for wave energy conversion are still in developmental stage because of technical, practical, and economical complications:

- **Access:** There are many sites of large wave activity around the world but the access to these sites is often limited.
- **Distance:** The sites of wave energy are often far from populated and industrial districts and sometimes far from power grids. This makes is difficult and expensive to transmit generated electricity.
- **Equipment:** The equipment for converting wave energy to electricity are large and complicated. They need to have high structural and mechanical strength to withstand strong motions in the sea.
- **Equipment size:** For reasonable amounts of power production, very large equipment are necessary. Hence, wave power systems involve high capital investment as well as high maintenance expenses. As a result, wave power production is not cost-competitive to conventional fossil fuel or renewable power systems.
- **Marine life:** Effect of wave power installations on marine life could be a problem.

Some ocean and sea sites involve more waves and higher wave heights compared to other sites. These locations typically attract wind surfers. Some of the known such places include

- ✓ Molakai and Alenuihaha channels in the Hawaiian islands
- ✓ Pacific coast of North America
- ✓ Arabian Sea off Pakistan and India
- ✓ North Atlantic coast of Scotland
- ✓ Coast of New England in U.S.

Wave heights: These sites involve wave heights of 1 to 5 m.

Wave time: A study of these sites reveals about half of the time more than 2-m-high waves are observed with a period of about 6 s.

Power Production from Waves

How much energy is available in ocean and sea waves?

How much power can be produced from wave energy?

$$\lambda = 1.56\tau^2$$

$$y = a\sin\left(\frac{2\pi}{\lambda}x - \frac{2\pi}{\tau}t\right)$$

$$n = 2\pi/\tau \qquad m = 2\pi/\lambda$$

$$mx - nt = 2\pi(x/\lambda - t/\tau)$$

$$V = \frac{\lambda}{\tau}$$

$$2a = h \qquad \alpha = a\frac{\cosh m\eta}{\sinh mh} \qquad \beta = a\frac{\sinh m\eta}{\sinh mh}$$

when $\eta = 0, \beta = 0$ (bottom of water)

when $\eta = h, \beta = a$ (surface of water)

for large depths, $\alpha \approx \beta \approx a$

λ	wavelength, m
τ	period, s
y	height above mean sea level, m
a	amplitude, m
t	time, s
n	phase rate, 1/s
mx-nt	phase angle
V	wave velocity, m/s
α	horizontal semi axes
β	vertical semi axes
H	water depth, m
η	Distance from bottom

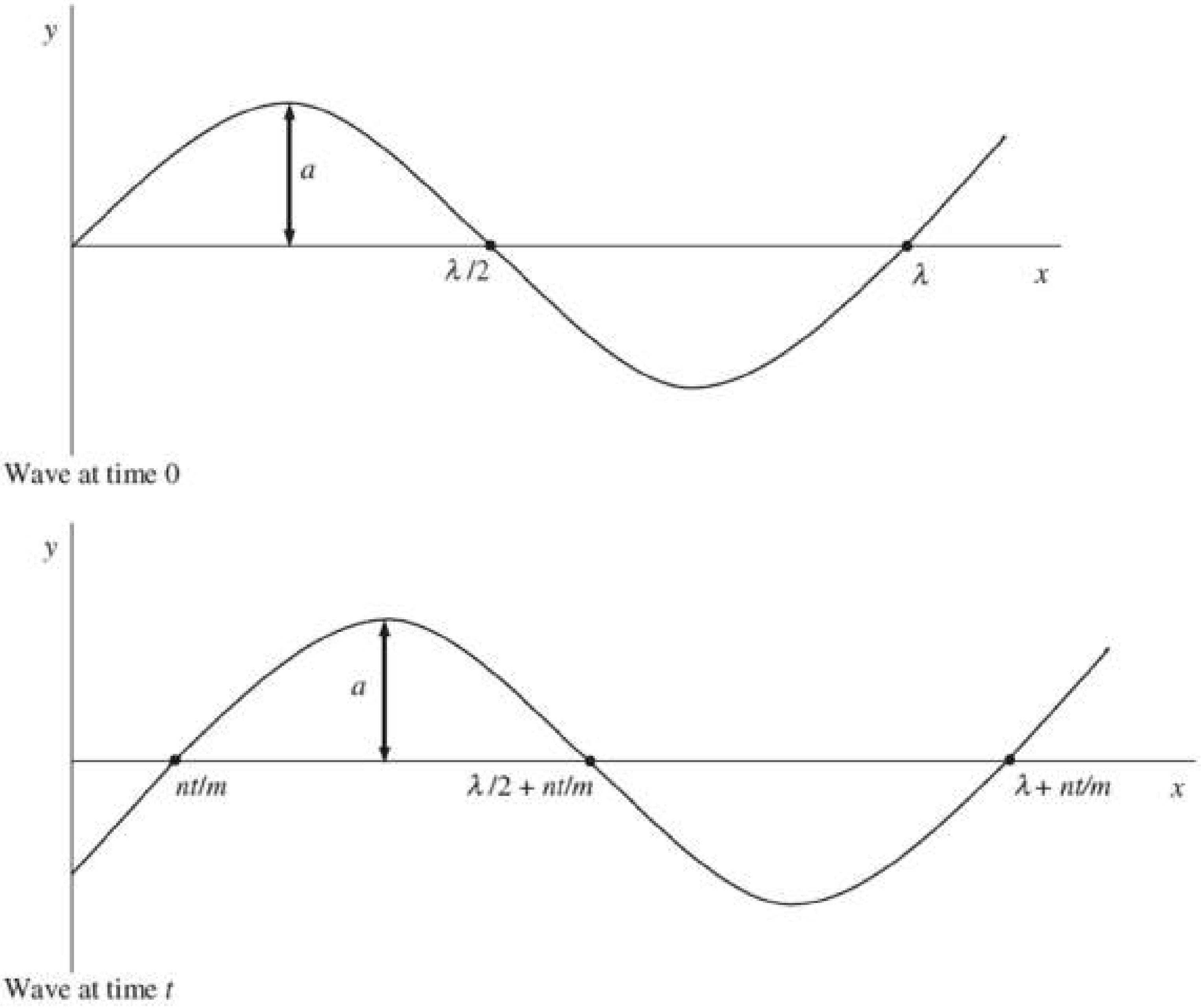


Figure 9-4 A typical traveling wave and its parameters at time 0 and time *t.*

$$dPE = m\frac{yg}{2} = (\rho y L dx)\frac{yg}{2} = \frac{\rho L}{2} y^2 g\, dx \qquad A = \lambda L$$

$$PE = \frac{1}{4}\rho a^2 \lambda L g \quad (J) \qquad pe = \frac{1}{4}\rho a^2 g \quad (J/m^2)$$

$$KE = \frac{1}{4} i \rho L g \int \omega\, d\varpi \quad (J) \qquad \omega = \frac{ac}{\sinh mh}\cos(mz - nt)$$

$$KE = \frac{1}{4}\rho a^2 \lambda L g \quad (J)$$

$$ke = \frac{1}{4}\rho a^2 g \quad (J/m^2)$$

$$e_{wave} = pe + ke = \frac{1}{2}\rho a^2 g \quad (J/m^2)$$

$$w_{available} = \frac{1}{2}\rho a^2 g \quad (J/m^2)$$

$$\dot{e}_{wave} = \frac{1}{2} f \rho a^2 g = \frac{1}{2\tau}\rho a^2 g \quad (W/m^2)$$

$$\dot{w}_{available} = \frac{1}{2\tau}\rho a^2 g \quad (W/m^2)$$

PE	potential energy, kJ
m	mass of liquid, kg
y	height above mean sea level, m
a	amplitude, m
g	acceleration due to gravity, m/s^2
ρ	density, kg/m^3
L	arbitrary width of 2-D wave, m
λ	wavelength, m
A	area, m^2
ω	complex potential
z	distance from reference point, m
e_{wave}	wave energy
$w_{available}$	available energy from a wave

Wave Power Technologies

Various systems and technologies have been proposed for wave energy conversion.

One such application involves transferring energy of wave water to air and using the compressed air to drive a turbine.

A company uses oscillating water column technology. This technology has been installed off the coast of western Scotland.

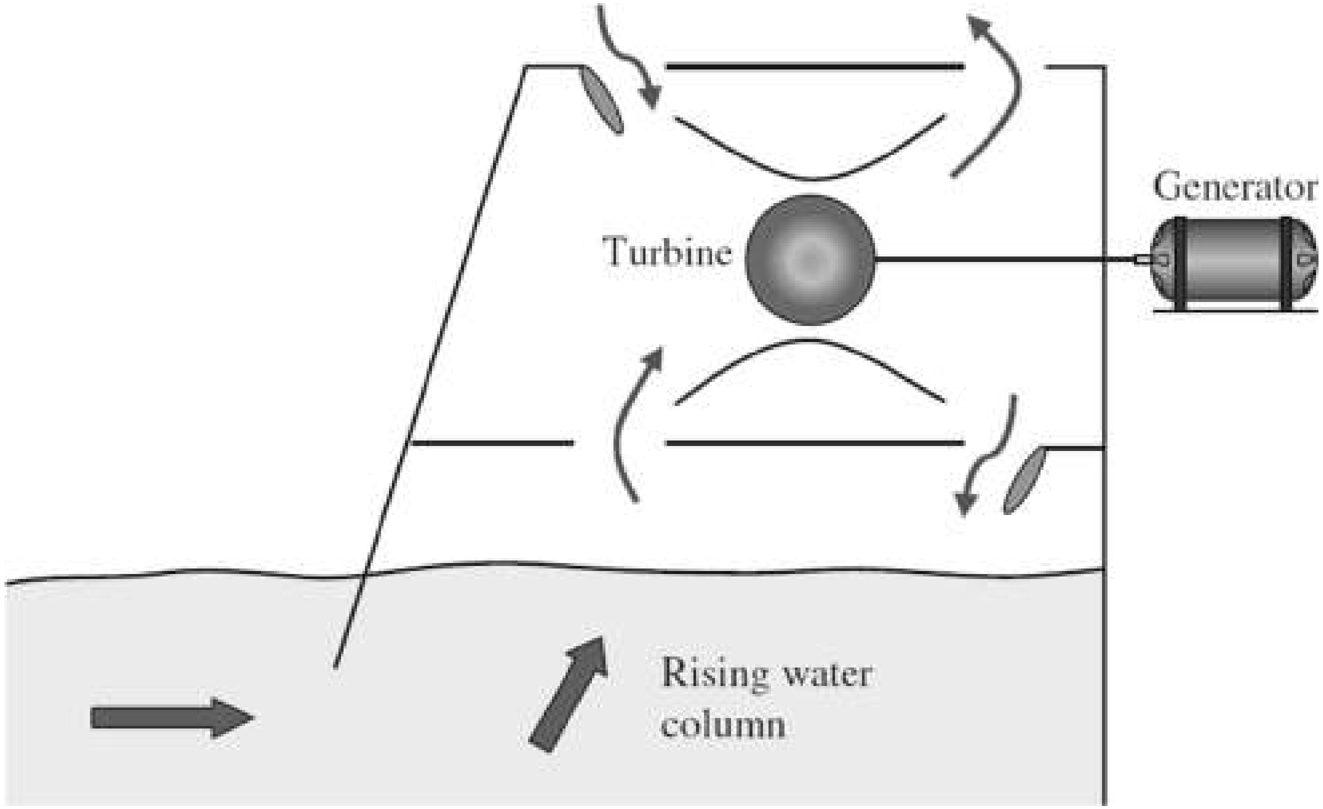
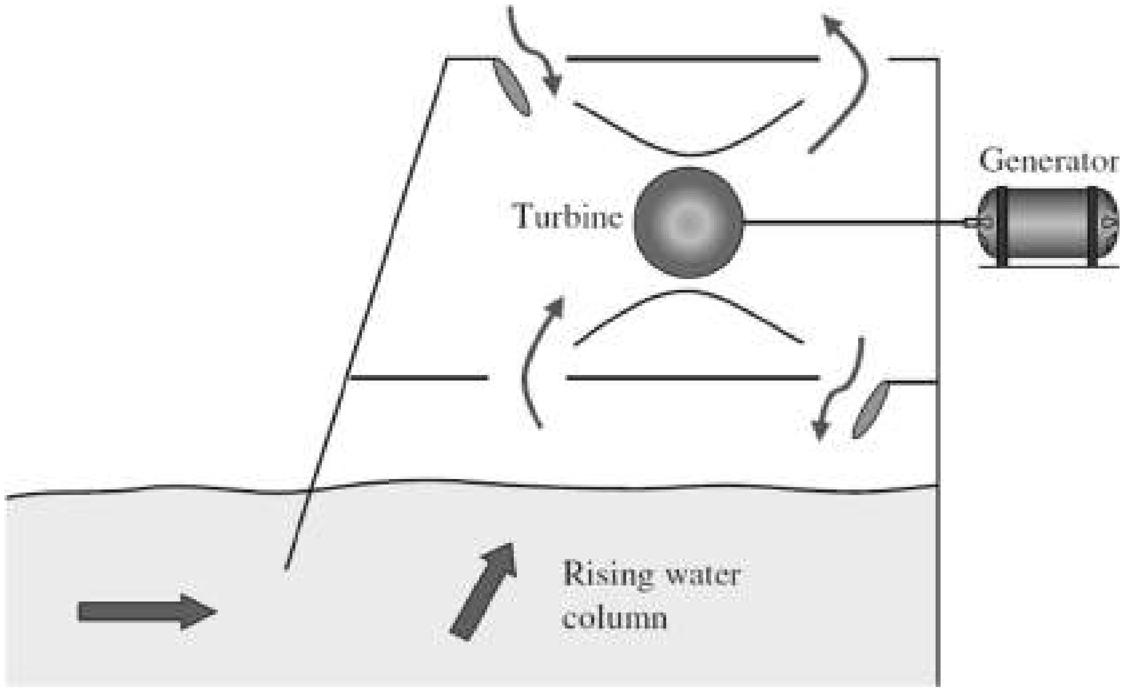


Figure 9-6 Oscillating water column technology for wave power conversion.

Operation of oscillating water column technology: Water moves into a hollow container by the wave motion. This compresses air that was in the container. The compressed air drives the turbine, which is connected to a generator where electricity is produced. When the wave moves in the opposite direction, air fills the container from the top, which is open to the atmosphere. Air flows through the turbine from both sides, depending on whether the device is “breathing” in or out. The process is repeated with the next wave. The system uses a special rotor geometry so that there is no need to change the blade angles or the direction of rotation. These systems must be large and so many of them should be installed to produce significant amounts of electricity.



Oscillating water column technology can be applied in three types of coastal wave power plants.

Shore line power plants: The plant is installed on the coast with a collector structure open to the sea. Air in the chamber is compressed and calmed by the moving and returning waves. The power outputs of shore line power plants can range from a few hundred kilowatts to a few megawatts depending on the size of the waves and the size of installments.

Near-shore power plants: In this case, the plant is installed a few hundred meters from the coastline, which is about 10 m deep. The collector is connected to the land by a dam. The power ratings range from 10 to 100 MW depending on the size of the waves and power plant. *With government incentives, these plants can operate economically.*

Breakwater power plants: In order to reduce the cost of wave power plants, the plant is integrated into a coastal structure such as a harbor breakwater or a coastal protection project. Power ratings more than 10 MW can be installed this way.

An example of breakwater power plant

The first breakwater power plant with a rating of 300 kW was installed in 2011 on the Spanish Atlantic coast at Mutriku.

The plant was built into the breakwater around the harbor.

The power plant has 16 identical turbines.

Since the cost of breakwater is handled by the local municipality the cost of the plant is relatively low.

This plant is claimed to be the only commercial wave power plant in the world.

Another commercial technology for wave energy conversion

Pelamis machine involves using wave water to drive a power machine.

Location: In this wave power technology, the machine is located about 2 to 10 km from the coast where the water is 50 m deep or more.

Capacity: A standard machine is rated at 750 kW power but the average production is about 25 to 40% of this rated power.

Machine size: This machine is 150 m long and the tube diameter is 3.5 m.

Power generation: One machine is estimated to produce 2.7 GHh of electricity per year at a capacity rate of 40 percent.

Pelamis machine was first connected to U.K. grid in 2004.

These machines were also tested in the coast of Portugal in 2009 and Scotland in 2014.

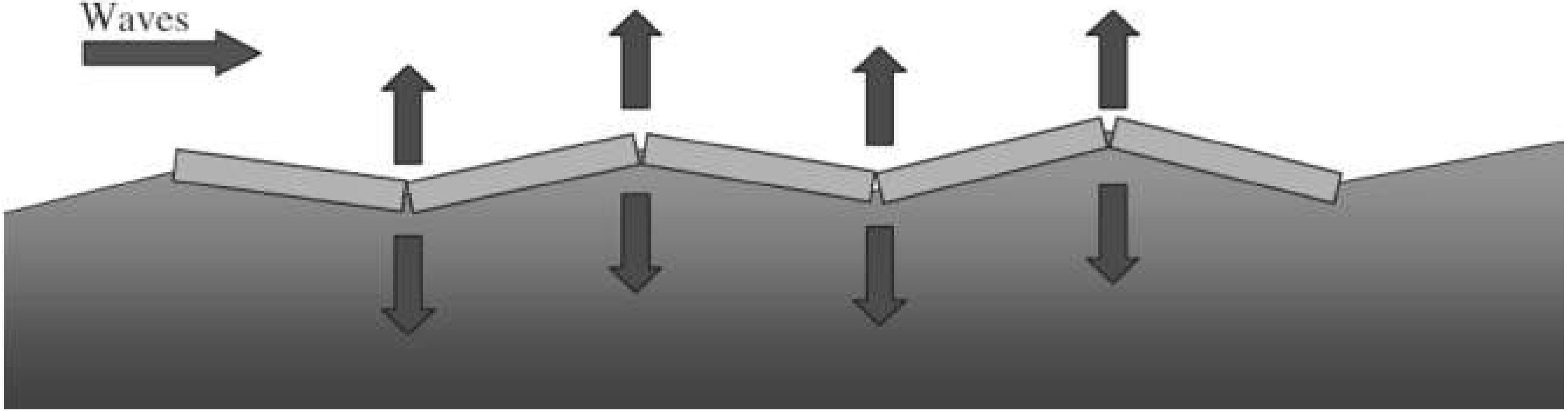


Figure 9-7
Five tube sections of a wave power machine.

Wavestar technology

Location: A large-scale test system for wave power was installed near Hanstholm at the Western coast of Denmark in 2009.

Wave time: The unit produces power from ocean waves that are 5 to 10 s apart.

Operation: A row of submerged floats which rise and fall as the wave passes the length of the machine. The up and down motion of the floats is transferred by a hydraulic system into a generator to generate electricity.

The test unit has two floats placed on one side whereas the full commercial converter will have 20 floats with 10 floats on each side.

Wave height and depth: The maximum wave height in the test site is 6 m with water depth of 5 to 8 m.

Capacity: The unit has a maximum power potential of 110 kW. In the tests, a power output of 32.4 kW is measured with a wave height of 2.6 m. The test results indicate an estimated power production of 46 MWh.

Figure 9-8

The test unit of Wavestar technology located at Western coast of Denmark. The test unit has two floats but the full commercial unit will have 20 floats.

9-4 TIDAL ENERGY

Power can be produced using the energy in tides.

Operation: A reservoir can be charged by the high tide and discharged by the low tide.

As the water flows in and out of the reservoir it runs through a hydraulic turbine to produce power.

This is similar to a hydroelectric power plant since both systems use the potential energy of water.

Tidal motion: The tidal motion of ocean and sea water is due to gravitational force of the moon and that of the sun.

These forces balance the centrifugal force on the water due to rotation of the earth.

Tide variation: The tides are not continuous and they do not have consistent patterns.

Their timings heights vary from day to day.

They vary with location of the earth.

Some coastal regions have more tidal movements with greater tide heights and some have less tidal movements.

Equipment size: As for other ocean energy systems the energy is free but the systems should be very large for significant amounts of power outputs.

Cost: This corresponds to very large capital investment.

Tidal schedule: The tidal schedule is based on moon motion around the earth which lasts 24 h and 50 min.

The tides rise and fall twice in a lunar day, and thus a full tidal cycle lasts 12 h and 25 min.

The tidal range (the difference in water elevation between high tide and low tide) varies during a lunar month, which is 29.5 days.

Spring tide: During new moon and full moon, the range is maximum, which is called *spring tide*.

Neap tide: Around first and third quarters the range is minimum, which is called *neap tide*.

An average range is about one-third of spring tide.

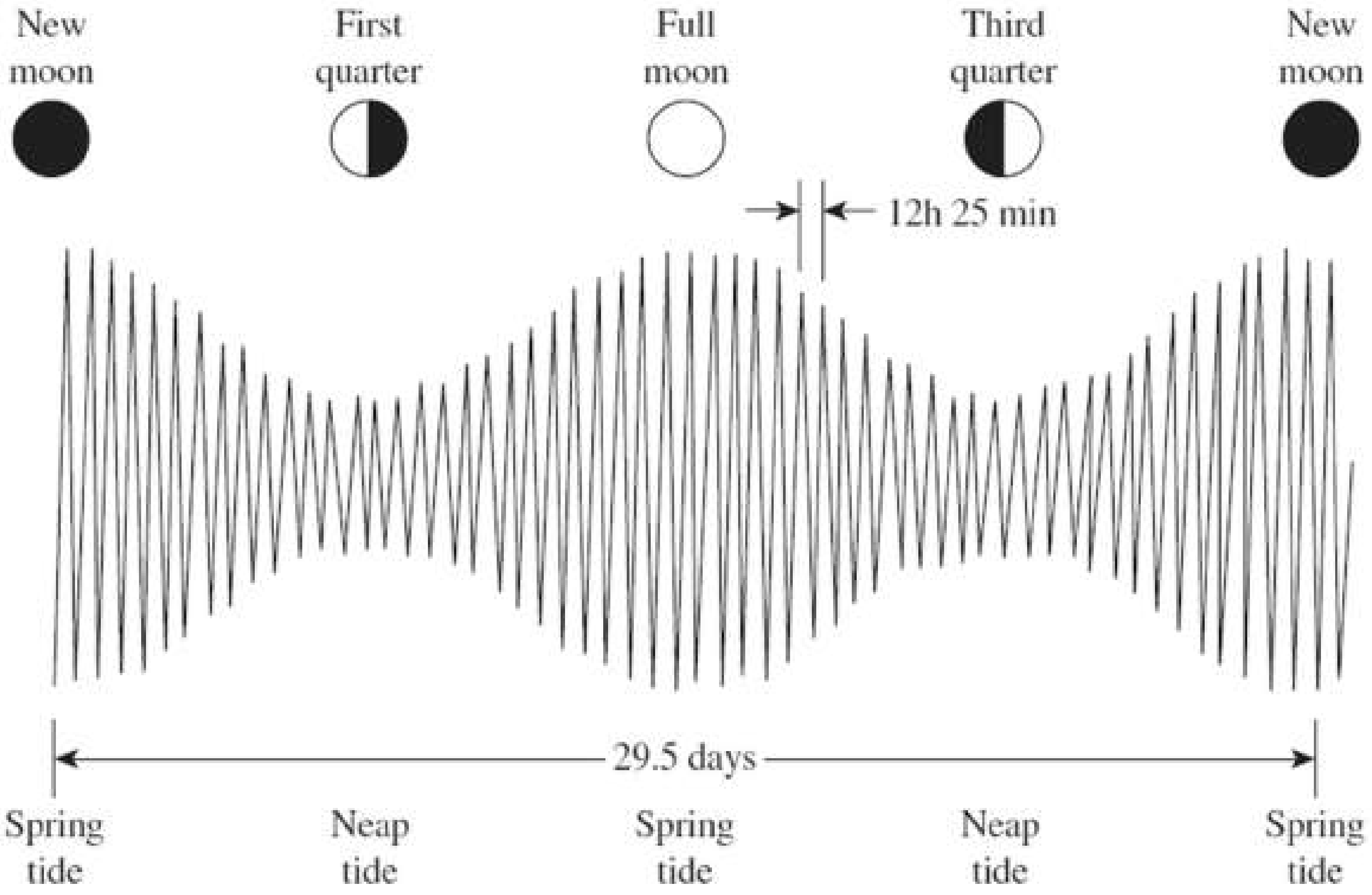


Figure 9-9 Variation of tidal range in a typical lunar month

Tidal range: Tidal ranges vary with location of the earth, profile of the shoreline and water depth.

Which locations? High range locations are more suitable for tidal power generation to better justify the installation cost.

Some of the known locations with high ride ranges are

- Bay of Fundy, Canada
- River severn estuary, UK
- Puerto Rio Gallegos, Argentina
- Bay of Mezen, Russia
- Sea of Okhotsk, Russia
- La Rance, France
- Port of Ganville, France

What is good tidal range? These coastlines have tidal ranges typically greater than 10 m.

Global tidal power potential: The recoverable tidal power potential on earth is estimated to be about 1.5 million MW.

Current capacity: Currently four tidal systems are operational with a total power rating of over 260 MW.

An example in France: The largest one is located in La Rance, France with a power rating of 240 MW and an average tide height of 8.6 m.

It has 24 identical turbines.

The plant was built in 1967, and is still operating while generating about 600 million kWh electricity per year.

This corresponds to a capacity factor of about 30 percent.

An example in Canada: The second largest one is installed in Annapolis, Canada with a power rating of 18 MW and average tide height of 6.4 m.

$$dW = gh\,dm \qquad dm = -\rho A\,dh$$

$$dW = -g\rho A h\,dh$$

$$W = \int_R^0 -g\rho A h\,dh = -g\rho A \int_R^0 h\,dh$$

$$W_{\text{available}} = \frac{1}{2} g\rho A R^2 \qquad \text{(J)}$$

h	height, m
dm	differential element, kg
ρ	density, kg/m^3
A	surface area, m^2
$W_{\text{available}}$	work potential, kJ
g	acceleration due to gravity, m/s^2
R	tidal range, m

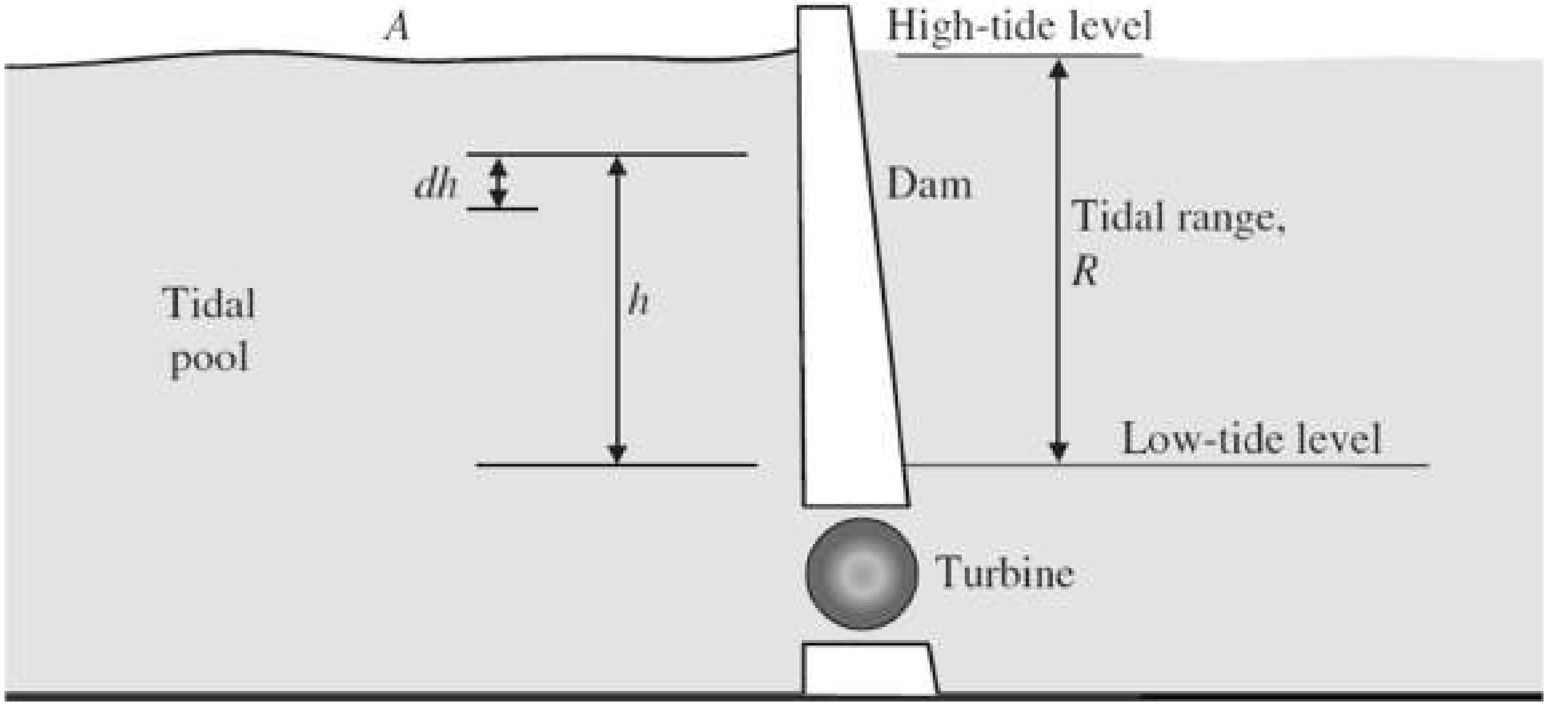


Figure 9-10 A single-pool tidal system for tidal power generation.

$$\dot{W}_{\text{available}} = \frac{W}{\Delta t} = \frac{1}{2\Delta t} g\rho A R^2 \qquad \text{(W)}$$

Full tidal cycle = 12 h, 25 min
Each emptying or filling time,
Δt = 6 h, 12.5 min = 22,350 s

$$\dot{W}_{\text{available}} = \frac{1}{2\Delta t} g\rho A R^2 = \frac{1}{2(22{,}350\ \text{s})}(9.81\ \text{m/s}^2)(1025\ \text{kg/m}^3) A R^2 \qquad \text{(W)}$$

$$\dot{W}_{\text{available}} = 0.225 A R^2 \qquad \text{(W)}$$

Surface area *A* in m^2 and range *R* in m

For a unit surface area and a tidal range of 10 m:

$$\dot{W}_{\text{available}} = 0.225 A R^2 = 0.225(1\ \text{m}^2)(10\ \text{m})^2 = 22.5\ \text{W}$$

Bay of Fundy in Canada has an area of 13,000 km^2 with an average range of 8 m:

$$\dot{W}_{\text{available}} = 0.225 A R^2 = 0.225(13{,}000 \times 10^6\ \text{m}^2)(8\ \text{m})^2 = 1.872 \times 10^{11}\ \text{W}$$

or 187,200 MW. This is a huge amount of power potential.

Because of the frictional losses, and turbine and generator inefficiencies, actual power will be less.

Assuming a conversion efficiency of 30 percent, the actual power potential becomes 56,000 MW, which is still very high.

A good strategy for emptying the pool is to do this slowly over the time.

This is called a **modulated single-pool tidal system**.

The average head in this case is less than the tidal range and the instantaneous power output is reduced in comparison to fast emptying of the pool.

This strategy reduces power fluctuations, and as a result, smaller turbine-generator units can be used with longer power generation periods.

According to this operation module, the work potential for a tidal cycle is evaluated from

$$W_{\text{available}} = g\rho A R^2 \left\{ 0.988a \left[\cos\left(\frac{\pi t_1}{6.2083}\right) - \cos\left(\frac{\pi t_2}{6.2083}\right) \right] - \frac{a^2}{2}\left(t_2^2 - t_1^2\right) \right\} \qquad \text{(J)}$$

a aconstant in 1/s and it controls the slope of the pool filling

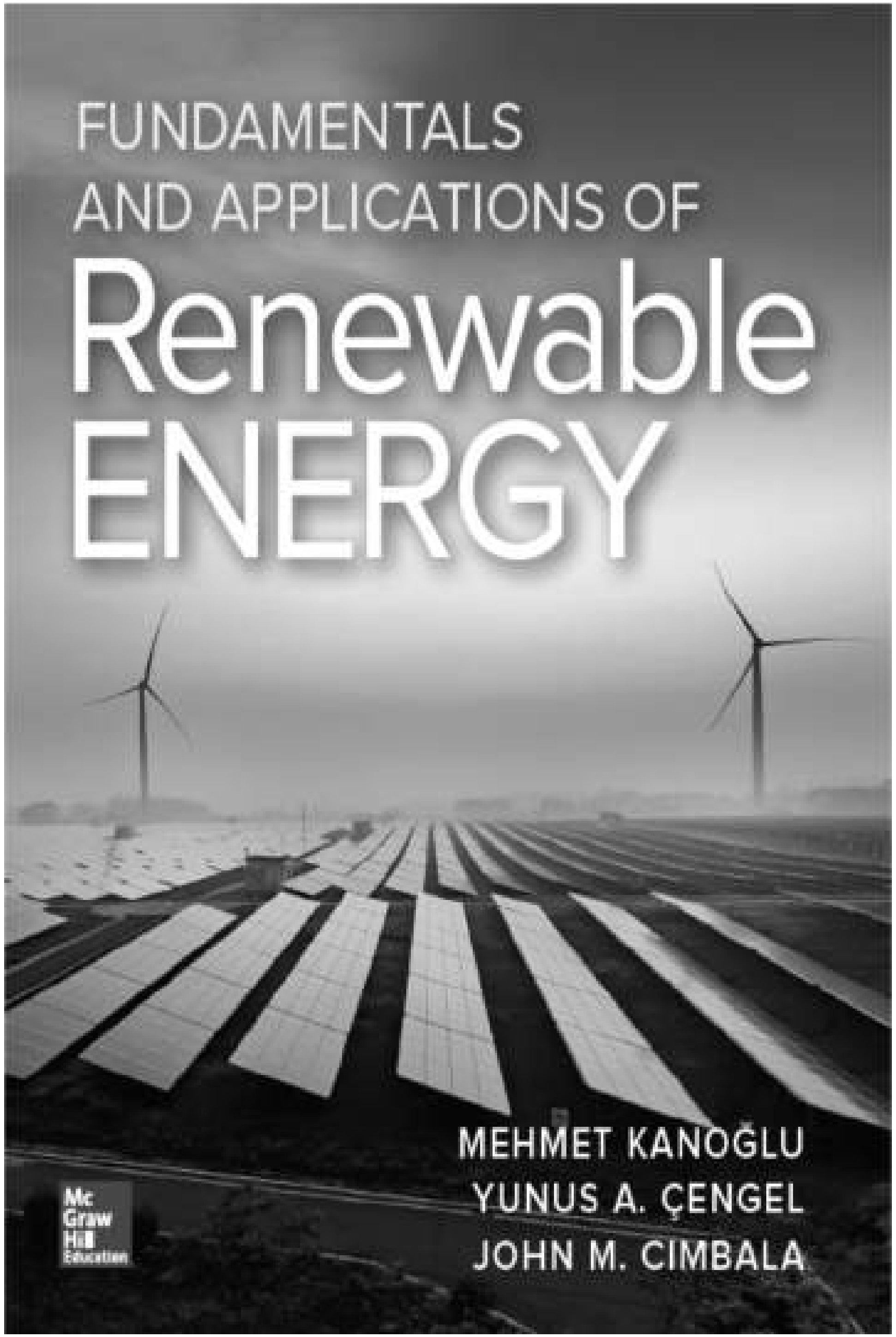
t_1 and t_2 are initial and final time of work production in hours

The value 6.2083 h represents the period of a filling or emptying process of the pool.

Efficiency of tidal power system

$$\eta_{\text{tidal}} = \frac{W_{\text{actual}}}{W_{\text{available}}}$$

Efficiency of tidal power systems can be taken to be around 30%.



Chapter 10
HYDROGEN AND FUEL CELLS

Fundamentals and Applications of
Renewable Energy
Mehmet Kanoglu
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McGraw–Hill, 2020

10-1 HYDROGEN: AN ENERGY CARRIER

Storage of renewable energy: One major problem with renewable energy sources is inability store the produced energy in a viable manner.

What about biomass? This is not a problem with biomass since the fuels produced from biomass such as ethanol and biodiesel can be stored and used anytime.

Storage of renewable electricity: The electricity produced from solar systems, hydroelectric dams, geothermal power plants and wind turbines cannot be stored for later use.

Battery? Batteries are not a viable option in today’s technology due to their very limited capacity.

Hydrogen? One possible solution to this problem is production of hydrogen from renewable electricity by the electrolysis of water.

Once produced, hydrogen can be stored and used anytime.

Hydrogen: Hydrogen is a colorless, odorless, nonmetallic, tasteless, highly flammable diatomic gas with the molecular formula H_2.

It is also the lightest element with a molecular mass of 2.016 kg/kmol.

Is H_2 a fuel? Hydrogen is a *fuel* with a higher heating value of 141,800 kJ/kg and a lower heating value of 120,000 kJ/kg.

Is H_2 an energy source? Hydrogen is not an energy source like coal, oil, and natural gas since there are no hydrogen reserves in the earth.

Although hydrogen is the most plentiful element in the universe, making up about three quarters of all matter, free hydrogen is scarce.

How is H_2 obtained? Hydrogen must be produced from other fuels such as natural gas or from water through electrolysis by consuming electricity.

Hydrogen should be called an **energy carrier** rather than an *energy source*.

Steam reforming reaction

$$CH_4 + H_2O \rightarrow CO + 3H_2$$

Water-gas shift reaction

$$CO + H_2O \rightarrow CO_2 + H_2$$

Combined reaction

$$CH_4 + 2H_2O \rightarrow CO_2 + 4H_2$$

For 1 kmol (about 16 kg) of methane used in this reaction, 4 kmol (about 8 kg) of hydrogen are produced.

Steam reforming process, endothermic, 206,000 kJ/kmol H_2 energy input

Water-gas shift reaction, exothermic, 41,000 kJ/kmol H_2 energy output

Combined reaction, 165,000 kJ/kmol H_2 energy input

This is equivalent to 81,850 kJ (or 22.73 kWh) energy input per kg of hydrogen produced.

Hydrogen is also produced from oil, coal, and biomass.

What is the problem with steam reforming?

The steam reforming is a much cheaper method of producing hydrogen compared with the water electrolysis.

However, using a fossil fuel source (natural gas) for producing hydrogen is not a sustainable path.

Why water electrolysis?

We are primarily interested in water electrolysis since it allows the use of electricity generated from renewable energies.

How about nuclear?

Nuclear electricity can also be used.

$H_2O \rightarrow H_2 + \frac{1}{2}O_2$ Water electrolysis reaction

Water electrolysis: This reaction produces 1 kmol hydrogen (about 2 kg) and 0.5 kmol of oxygen (about 16 kg) when 1 kmol (about 18 kg) of water are used.

Minimum work for water electrolysis: The minimum work required for this endothermic reaction is given by the Gibbs function of water at 25°C, which is equal to 237,180 kJ per kmol of liquid water entering the reaction.

This is equivalent to 117,650 kJ (or 32.68 kWh) per kg of hydrogen produced by the reaction.

Note that this is very close to the lower heating value of hydrogen (120,000 kJ/kg).

$H_2O \rightarrow H_2 + \frac{1}{2}O_2$ Water electrolysis reaction

An actual electrolyzer involves irreversibilities and the actual electricity consumption will be greater than the minimum value.

Efficiency of electrolysis: The efficiency of a typical electrolyzer is about 80 percent.

Therefore, there is no thermodynamic advantage of producing hydrogen through water electrolysis by consuming electricity.

The reason is that we cannot store renewable electricity effectively by other methods.

Combustion of hydrogen: Hydrogen can be used as a fuel for an internal combustion engine.

It can be burned just like gasoline or a fuel cell can be used to convert energy of hydrogen into electricity.

The exhaust of a fuel cell using hydrogen is water.

Use of hydrogen: Hydrogen is the primary fuel to power fuel cells.

Fuel cell–powered cars, bikes, stationary and portable generators, electronic devices such as computers and cell phones can all use hydrogen as the fuel.

Hydrogen can be used in variety of applications including electricity generation plants, and various industrial, commercial, and residential uses

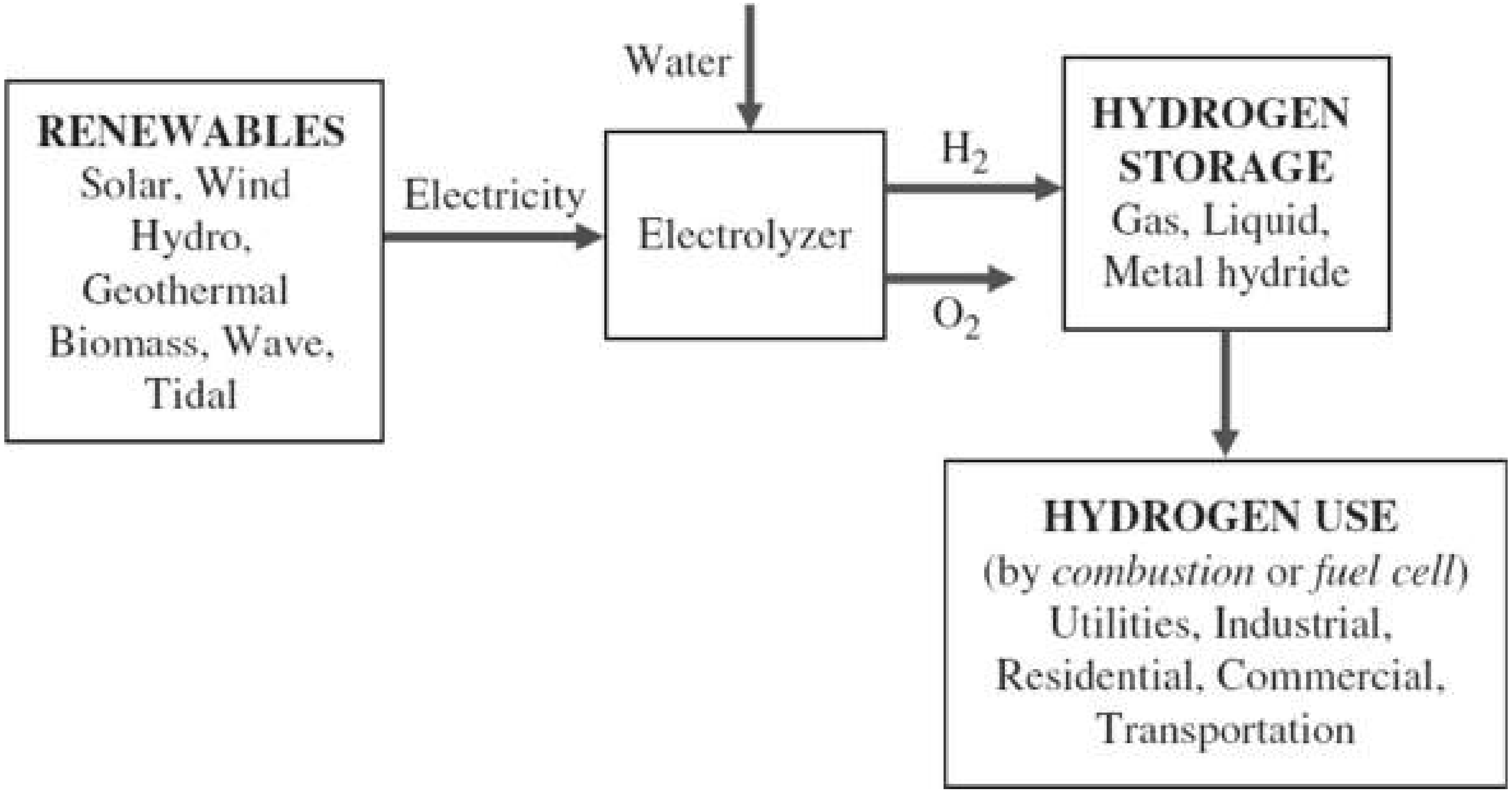


Figure 10-1 Production, storage, and utilization of hydrogen.

Problems with hydrogen: Production, storage, transportation, refueling, and use of hydrogen present a number of technical, economical, and practical problems, and a large number of research are underway to tackle these problems.

Storage as a liquid: For example, the storage of hydrogen in liquid form requires very low temperatures (about 20 K or -253°C) which are expensive to achieve and maintain.

Storage as a gas: Its storage in gas form at high pressure, on the other hand, involves low density, and a full tank will have a low range of mileage.

Extensive tests indicate that pressures as high as 70 MPa can safely be used for compressed hydrogen storage in commercial vehicles.

Storage in metal hydride: Hydrogen can also be stored in a metal hydride solid.

A hydride can absorb about 3.5 percent of its mass as hydrogen.

Cooling a hydride allows absorption of hydrogen while heating it slightly will release hydrogen as a gas.

At present, hydrogen cars used in most engineering student competitions use this technique to store hydrogen.

Hydrogen refueling stations: To power hydrogen-fueled buses, automobiles, bikes, and equipment, a number of hydrogen refueling stations are now available across Europe, Japan, and North America.

Global data: Sixty-four new public hydrogen refueling stations were opened worldwide in 2017 and the total number in the world reached 328.

Japan has 91 public hydrogen refueling stations.

Germany has 45 (plus 11 private stations), and USA has 40.

Hydrogen pipeline? A possible long-term solution to hydrogen distribution structure is formation of national hydrogen pipelines.

This can only be justified economically with a widespread use of fuel cell automobiles on the streets.

No hydrogen fuel infrastructure or fueling stations:

For locations without any hydrogen fuel infrastructure or fueling stations, local electrolysis and reformation-based technologies can be used.

Future of automobile market:

Battery, hybrid, and fuel cell technologies are all expected to play important roles in future automobile market as evidenced by the fact that major automobile companies continue to invest in all these technologies.

A widespread hydrogen distribution structure and large-scale renewable-based hydrogen production are essential if fuel cell automobiles will have a good share among other competing technologies.

10-2 FUEL CELLS

Why fuel cells? When methane (CH_4) at 25°C is burned with 50 percent excess air at 25°C adiabatically, the products will be at 1789 K.

A second-law analysis of this process reveals that the exergy of the reactants (818 MJ/kmol CH_4) decreases by 288 MJ/kmol as a result of the irreversible adiabatic combustion process alone.

That is, the exergy of the hot combustion gases at the end of the adiabatic combustion process is 818 - 288 = 530 MJ/kmol CH_4.

IWhen methane is burned, 35% of the work potential is lost before we even start using the thermal energy.

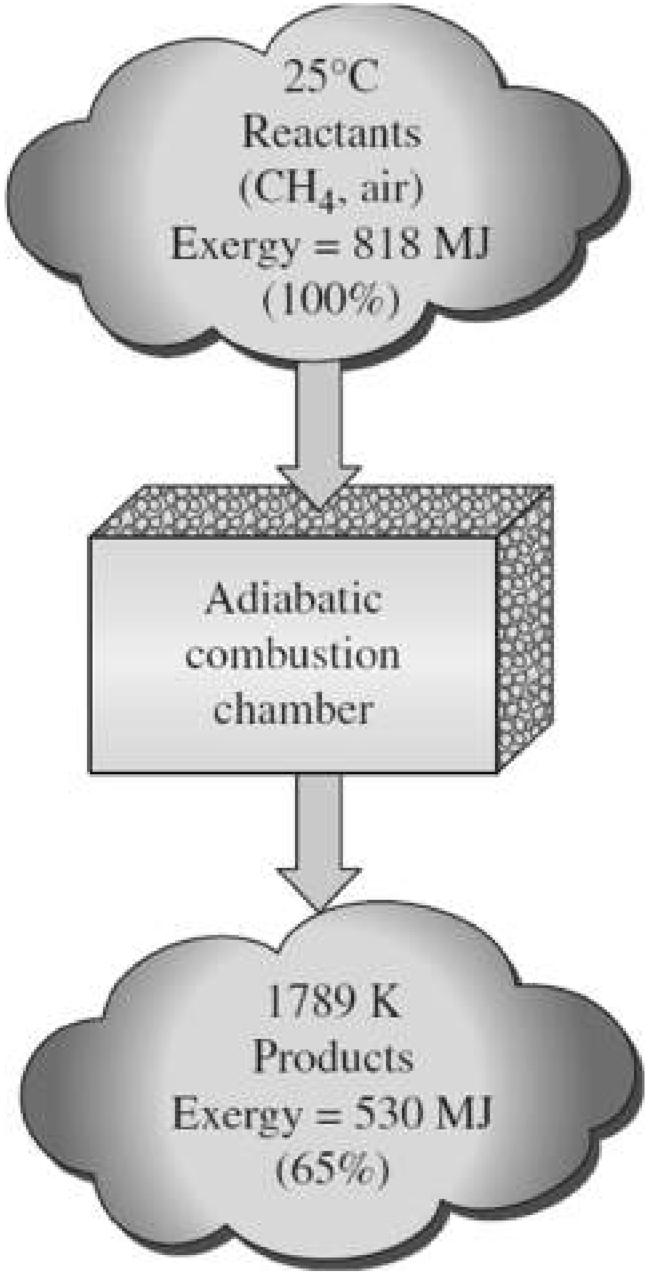


Figure 10-2 The exergy (work potential) of methane decreases by 35% as a result of irreversible combustion process.

Is there a better way of converting the chemical energy of fuel to work? The 2nd law of thermodynamics suggests that there should be a better way of converting the chemical energy to work. The better way is the less irreversible way, the best being the reversible case.

In chemical reactions, the irreversibility is due to uncontrolled electron exchange between the reacting components.

Principle of fuel cell: The electron exchange can be controlled by replacing the combustion chamber by electrolytic cells, like car batteries. In the electrolytic cells, the electrons are exchanged through conductor wires connected to a load, and the chemical energy is directly converted to electric energy. The energy conversion devices that work on this principle are called fuel cells.

Is fuel cell a heat engine? Fuel cells are not heat engines, and thus their efficiencies are not limited by the Carnot efficiency.

They convert chemical energy to electric energy essentially in an isothermal manner.

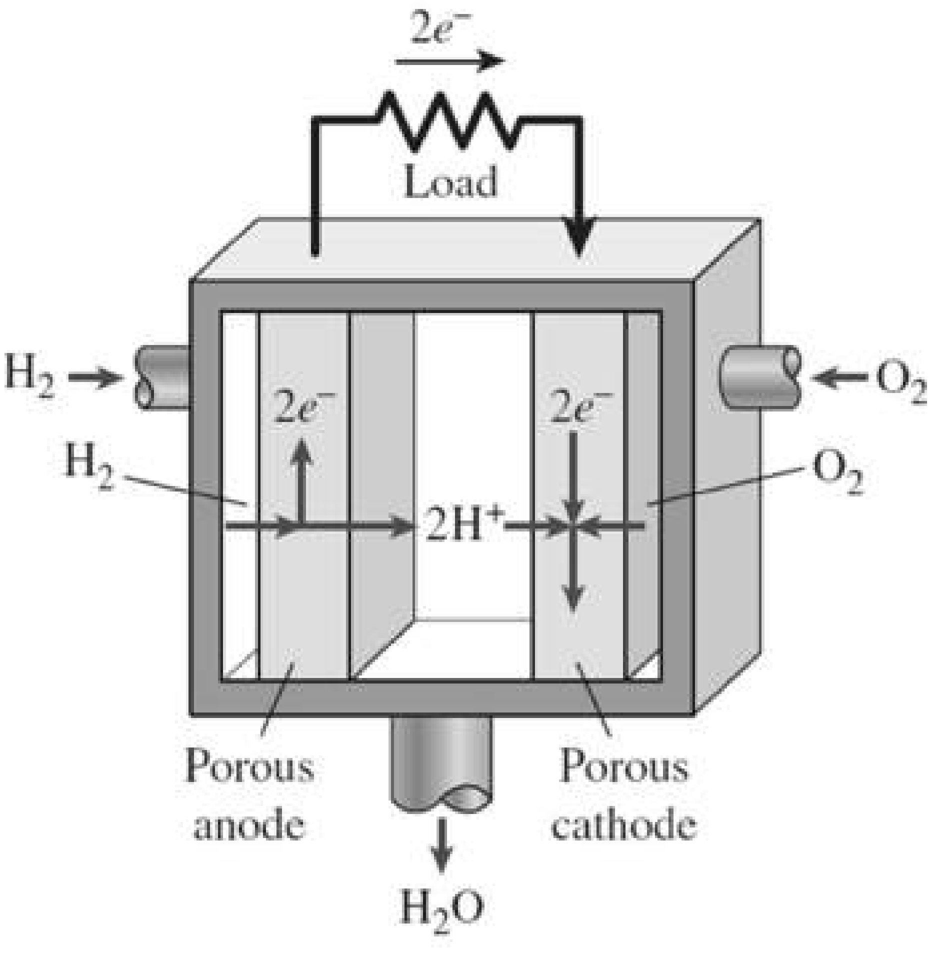


Figure 10-3a
The operation of a hydrogen-oxygen fuel cell.

Fuel cell operation: Hydrogen is ionized at the surface of the anode, and hydrogen ions flow through the electrolyte to the cathode.

There is a potential difference between the anode and the cathode, and free electrons flow from the anode to the cathode through an external circuit (such as a motor or a generator).

Hydrogen ions combine with oxygen and the free electrons at the surface of the cathode, forming water.

The fuel cell operates like an electrolysis system working in reverse.

In steady operation, hydrogen and oxygen continuously enter the fuel cell as reactants, and water leaves as the product.

A single fuel cell produces between 0.5 and 0.9 volts of electricity.

For usable voltage and reasonable power outputs, fuel cells are combined into stacks.

Example: A remote police station in Central Park in New York City is powered by a 200-kW phosphoric acid fuel cell that has an efficiency of 40% with negligible emissions (it emits 1 ppm NO_x and 5 ppm CO).

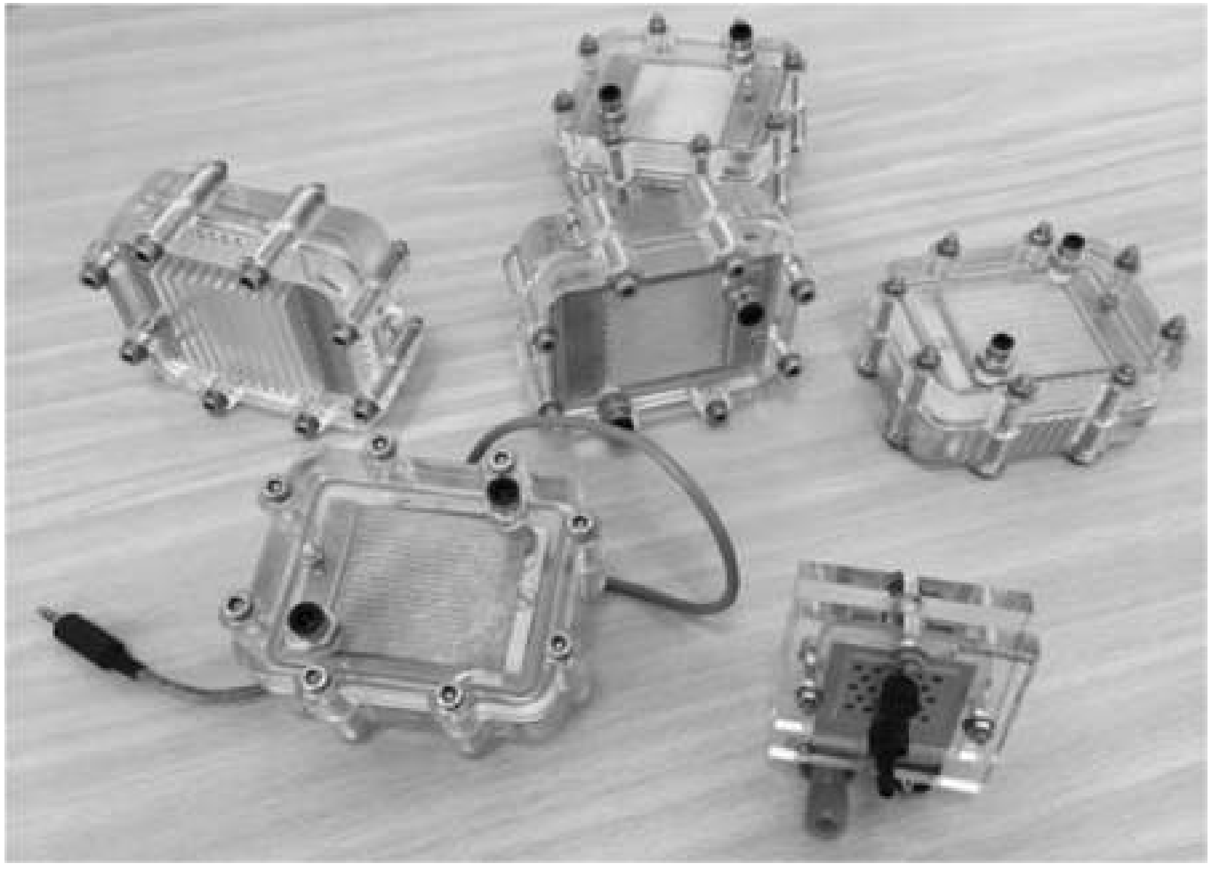


Figure 10-3b Small-size hydrogen fuel cells in a university lab.

Hybrid power systems (HPS): They combine high-temperature fuel cells and gas turbines and have the potential for very high efficiency in converting natural gas (or even coal) to electricity.

Fuel cell cogeneration: The primary objective of a fuel cell is to generate electricity but heat is also produced.

This heat can be used for space and water heating for buildings.

The efficiency of a combined heat and power plant that operates on a fuel cell can reach a utilization efficiency of 90 percent.

Fuel cell cars: Some car manufacturers are planning to introduce cars powered by fuel-cell engines, thus nearly doubling the efficiency from about 30% for the gasoline engines to up to 60% for fuel cells.

Intense research and development programs by major car manufacturers are underway to make fuel cell cars economical and commercially available in the near future.

Regenerative fuel cell

A recent technology of fuel cells involves dual operation of the system.

The fuel cell is normally used to produce electricity.

However, the operation can be reversed so that the fuel cell produces hydrogen (and oxygen) by consuming electricity.

This electricity should come from excess electricity produced from renewable energy sources such as solar or wind systems.

The hydrogen produced will be used when electricity demand is high.

The fuel cells that operate on this principle are called *regenerative fuel cell* or *reversible fuel cell.*

Fuel cells are usually classified according to the electrolyte used.

Proton exchange membrane fuel cell (PEMFC): This fuel cell contains a thin plastic polymer membrane, which is coated by platinum particles acting as the electrolyte.

Operating temperatures: Their operating temperatures are low (close to 100°C).

Advantages: An important advantage of PEMFC is its small size for a given power output.

Direct-methanol fuel cell (DMFC): This fuel cell uses a polymer membrane as the electrolyte. It uses methanol directly in the cell.

Applications: These fuel cells can be used for powering laptop computers and battery rechargers such as in cell phones.

Alkaline fuel cell (AFC): This type of fuel cells uses potassium hydroxide or an alkaline membrane as the electrolyte.

Temperatures, Efficiencies: They operate between 20°C and 250°C with efficiencies of up to 60% at low temperatures.

Advantages, Disadvantages: Alkaline fuel cells require pure hydrogen as the fuel. As a result their application is mostly limited to space applications to produce electricity and water.

Phosphoric acid fuel cell (PAFC): Phosphoric acid is used as the electrolyte while platinum is used as the catalyst, which is expensive.

Temperatures, Efficincies: The operating temperatures are about 200°C. Their current thermal efficiencies are between 35 and 45%.

Applications: Mostly used in stationary power generation with power outputs of greater than 400 kW.

Molten carbonate fuel cell (MCFC): It can use various fuels such as hydrogen, natural gas, propane, diesel, and gasified coal. When natural gas or biogas is used, the conversion from natural gas or biogas to hydrogen is accomplished within the cell.

Temperatures, Efficiencies: It can reach up to 60% efficiency with operating temperatures of about 600°C.

Applications: MCFCs are currently used in medium and large scale stationary applications at high efficiency.

Solid oxide fuel cell (SOFC): A thin layer of solid ceramic material is used as the electrolyte in SOFC allowing reliable design and high temperatures. They can use carbon monoxide, hydrogen, and gasified coal as the fuel.

Temperatures, Efficiencies: SOFC operates at temperatures are up to 1000°C with efficiencies up to 60%. The fuel cell can be combined with a gas turbine to provide efficiencies up to 75%.

Applications: Solid oxide fuel cells are good candidates for stationary power production and auxiliary power devices such as heavy-duty trucks.

Thermodynamic Analysis of Fuel Cells

$H_2 + \frac{1}{2}O_2 \rightarrow 2e^- + 2H^+ + O \rightarrow H_2O$ Hydrogen-oxygen fuel cell reaction

Anode: $H_2 \rightarrow 2e^- + 2H^+$

Cathode: $2H^+ + 2e^- + \frac{1}{2}O_2 \rightarrow H_2O$

Half cell reactions

$$\Delta\bar{H} = \sum H_r - \sum H_p = \sum N_r(\bar{h}_f^o + \bar{h} - \bar{h}^o)_r - \sum N_p(\bar{h}_f^o + \bar{h} - \bar{h}^o)_p$$

Energy or heat released during the reaction

$$\Delta\bar{H} = \sum N_r(\bar{h}_f^o)_r - \sum N_p(\bar{h}_f^o)_p$$

Energy released when reactants and products are at environment temperature

$\bar{h}_f^o$ Enthalpy of formation

$$\Delta\bar{H} = N_{H_2}(\bar{h}_f^o)_{H_2} - N_{O_2}(\bar{h}_f^o)_{O_2} - N_{H_2O}(\bar{h}_f^o)_{H_2O}$$
$$= (1)(0) - (0.5)(0) - (1\ \text{kmol})(-241{,}820\ \text{kJ/kmol})$$
$$= 241{,}820\ \text{kJ/kmol}\ H_2$$

For hydrogen-oxygen fuel cell reaction. Water is assumed vapor in the products

Dividing by molar mass of H_2 gives the lower heating value (120,000 kJ/kg)

$$W_{\max} = \sum N_r(\bar{h}_f^o + \bar{h} - \bar{h}^o - T_0\bar{s})_r - \sum N_p(\bar{h}_f^o + \bar{h} - \bar{h}^o - T_0\bar{s})_p$$

Maximum work during a chemical reaction

$$W_{\max} = \Delta\bar{G} = \sum N_r\bar{g}_{0,r} - \sum N_p\bar{g}_{0,p}$$

$$W_{\max} = \Delta\bar{G} = \sum N_r\bar{g}_{f_r}^o - \sum N_p\bar{g}_{f_p}^o$$

Maximum work when reactants and products are at environment temperature

$$\begin{aligned} W_{\max} = \Delta\bar{G} &= N_{H_2}(\bar{g}_f^o)_{H_2} - N_{O_2}(\bar{g}_f^o)_{O_2} - N_{H_2O}(\bar{g}_f^o)_{H_2O} \\ &= (1)(0) - (0.5)(0) - (1\text{ kmol})(-228{,}590\text{ kJ/kmol}) \\ &= 228{,}590\text{ kJ/kmol H}_2 \end{aligned}$$

For hydrogen-oxygen fuel cell reaction

Water is vapor in the products: $W_{\max} = \Delta\bar{G} = 228{,}590$ kJ/kmol H_2
or 113,390 kJ/kg H_2

Water is liquid in the products: $W_{\max} = \Delta\bar{G} = 237{,}180$ kJ/kmol H_2
or 117,650 kJ/kg H_2

$\bar{g}_f^o$ Gibbs function of formation

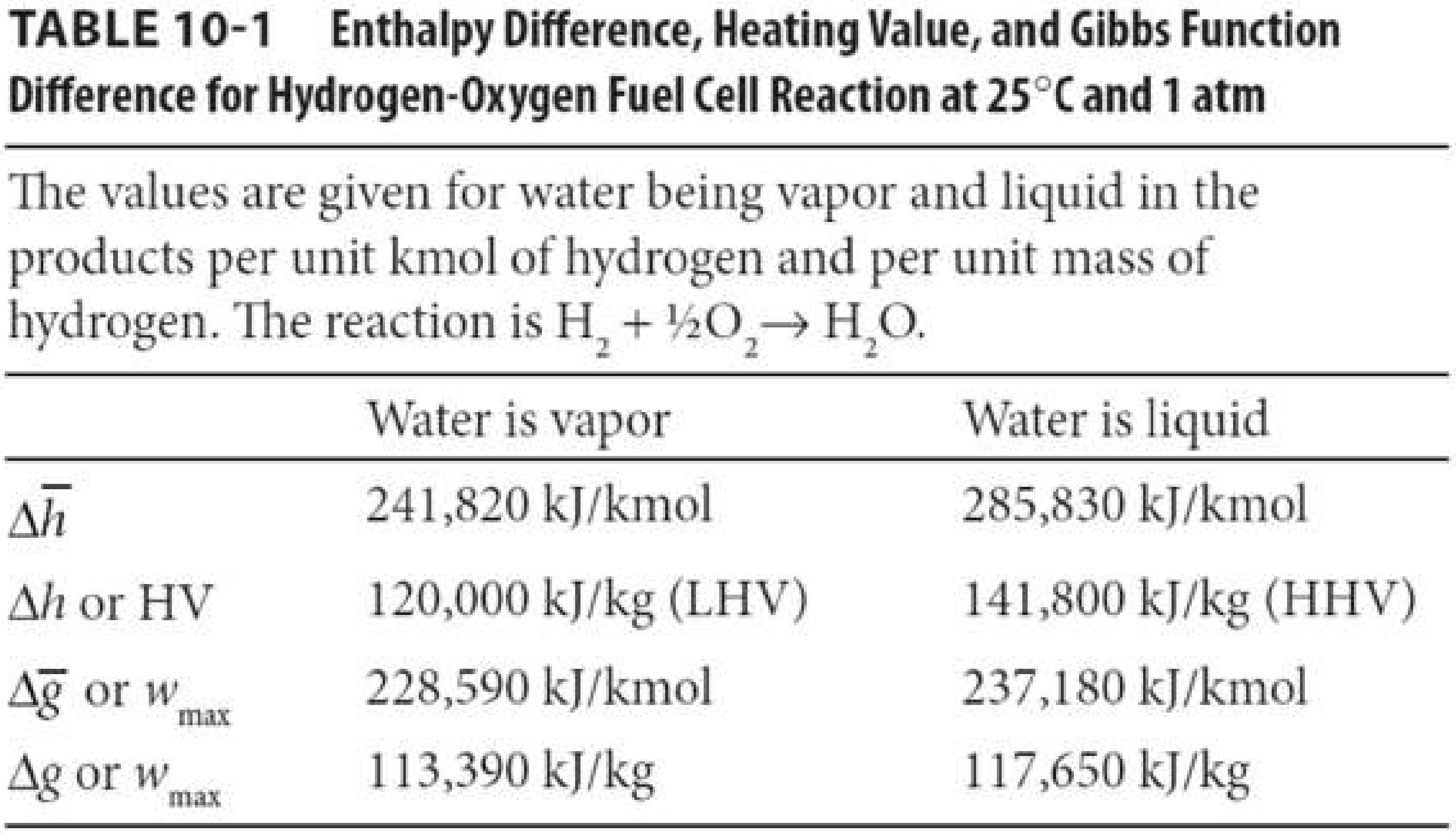


TABLE 10-1 Enthalpy Difference, Heating Value, and Gibbs Function Difference for Hydrogen-Oxygen Fuel Cell Reaction at 25°C and 1 atm

The values are given for water being vapor and liquid in the products per unit kmol of hydrogen and per unit mass of hydrogen. The reaction is $H_2 + ½O_2 \rightarrow H_2O$.

	Water is vapor	Water is liquid
$\Delta\bar{h}$	241,820 kJ/kmol	285,830 kJ/kmol
Δh or HV	120,000 kJ/kg (LHV)	141,800 kJ/kg (HHV)
$\Delta\bar{g}$ or w_{max}	228,590 kJ/kmol	237,180 kJ/kmol
Δg or w_{max}	113,390 kJ/kg	117,650 kJ/kg

$$\eta_{\text{fuel cell, II}} = \frac{w_{\text{actual}}}{w_{\text{max}}} = \frac{w_{\text{actual}}}{\Delta \bar{g}}$$ Second-law efficiency of a fuel-cell

$$\eta_{\text{fuel cell, I}} = \frac{w_{\text{actual}}}{\Delta \bar{h}}$$ First-law or thermal efficiency of a fuel-cell

$$\eta_{\text{fuel cell, I, max}} = \frac{w_{\text{max}}}{\Delta \bar{h}} = \frac{\Delta \bar{g}}{\Delta \bar{h}} = \frac{\Delta g}{\Delta h}$$ Maximum first-law efficiency of a hydrogen-oxygen fuel-cell

$$\eta_{\text{fuel cell, I, max}} = \frac{w_{\text{max}}}{\Delta \bar{h}} = \frac{\Delta \bar{g}}{\Delta \bar{h}} = \frac{\Delta g}{\text{LHV}} = \frac{113{,}390 \text{ kJ/kg}}{120{,}000 \text{ kJ/kg}} = 0.945 \text{ or } 94.5\%$$ Water in the products is vapor

$$\eta_{\text{fuel cell, I, max}} = \frac{w_{\text{max}}}{\Delta \bar{h}} = \frac{\Delta \bar{g}}{\Delta \bar{h}} = \frac{\Delta g}{\text{HHV}} = \frac{117{,}650 \text{ kJ/kg}}{141{,}800 \text{ kJ/kg}} = 0.830 \text{ or } 83.0\%$$ Water in the products is liquid

$$\eta_{\text{fuel cell, I, max}} = \frac{w_{\text{max}}}{\Delta \bar{h}} = \frac{\Delta \bar{g}}{\Delta \bar{h}} = 1 - \frac{T\Delta \bar{s}}{\Delta \bar{h}} = 1 - \frac{T\Delta s}{\Delta h} = 1 - \frac{q_{\text{rev}}}{\Delta h}$$

$\boldsymbol{q_{\text{rev}}}$ heat rejected during the isothermal heat rejection process

The high-efficiency potential is the main reason why the fuel cells are very popular.

$$T\,d\bar{s} = d\bar{h} - \bar{v}\,dP$$ Second *T ds* relation

$$\bar{g} = \bar{h} - T\bar{s}$$ Gibbs function

$$d\bar{g} = d\bar{h} - Td\bar{s} - \bar{s}\,dT = d\bar{h} - Td\bar{s}$$

$$d\bar{g} = \bar{v}\,dP$$

$$\bar{v} = R_u T/P$$ Ideal gas relation

$$d\bar{g} = R_u T \frac{dP}{P}$$

$$\bar{g} = \bar{g}_0 + R_u T \ln P$$

$$a\,A + b\,B \rightarrow c\,C + d\,D$$ A general fuel cell reaction

$$\Delta\bar{g} = \Delta\bar{g}_0 + R_u T \ln\left(\frac{P_A^a P_B^b}{P_C^c P_D^d}\right)$$

$$\Delta\bar{g} = N_e F_c V$$

N_e number of moles of electrons per kmol of reacting fuel

F_c Faraday’s constant

V cell voltage (open circuit voltage)

$$V = \frac{\Delta \bar{g}}{N_e F_c}$$

$$V = V_0 - \frac{R_u T}{N F_c} \ln\left(\frac{P_C^c P_D^d}{P_A^a P_B^b} \right)$$ Nernst equation

Ideal voltage for hydrogen-oxygen fuel cell reaction at 1 atm and 25°C. Water is liquid in the products.

$$V_0 = \frac{\Delta \bar{g}}{N_e F_c} = \frac{237{,}180 \text{ kJ/kmol}}{(2 \text{ kmol electron/kmol})(96{,}487 \text{ kJ/V} \cdot \text{kmol electron})} = 1.229 \text{ V}$$

Ideal voltage for hydrogen-oxygen fuel cell reaction at 1 atm and 25°C. Water is vapor in the products.

$$V_0 = \frac{\Delta \bar{g}}{N_e F_c} = \frac{228{,}590 \text{ kJ/kmol}}{(2 \text{ kmol electron/kmol})(96{,}487 \text{ kJ/V} \cdot \text{kmol electron})} = 1.185 \text{ V}$$

$$V = V_0 - \frac{R_u T}{N F_c} \ln\left(\frac{P_C^c P_D^d}{P_A^a P_B^b}\right)$$

$$= 1.185\ \mathrm{V} - \frac{(8.314\ \mathrm{kJ/kmol \cdot K})(298\ \mathrm{K})}{(2\ \mathrm{kmol\ electron/kmol})(96{,}487\ \mathrm{kJ/V \cdot kmol\ electron})}$$

$$\ln\left[\frac{(1\ \mathrm{atm})^1}{(1\ \mathrm{atm})^1 (0.21\ \mathrm{atm})^{0.5}}\right]$$

$$= 1.175\ \mathrm{V}$$

Cell voltage if air at 1 atm is used to provide oxygen to a fuel cell. The partial pressure of oxygen is 0.21 atm.

$$\Delta\bar{g} = \Delta\bar{g}_0 + R_u T \ln\left(\frac{P_A^a P_B^b}{P_C^c P_D^d}\right)$$

$$= 228{,}590\ \mathrm{kJ/kmol} + (8.314\ \mathrm{kJ/kmol \cdot K})(298\ \mathrm{K}) \ln\left[\frac{(1\ \mathrm{atm})^1 (0.21\ \mathrm{atm})^{0.5}}{(1\ \mathrm{atm})^1}\right]$$

$$= 226{,}660\ \mathrm{kJ/kmol}$$

Maximum work output for a hydrogen-air fuel cell. Water is vapor.

$$\Delta\bar{g} = \Delta\bar{g}_0 + R_u T \ln\left(\frac{P_A^a P_B^b}{P_C^c P_D^d}\right)$$

$$= 237{,}180\ \mathrm{kJ/kmol} + (8.314\ \mathrm{kJ/kmol \cdot K})(298\ \mathrm{K}) \ln\left[\frac{(1\ \mathrm{atm})^1 (0.21\ \mathrm{atm})^{0.5}}{(1\ \mathrm{atm})^1}\right]$$

$$= 235{,}250\ \mathrm{kJ/kmol}$$

Maximum work output for a hydrogen-air fuel cell. Water is liquid.

For a hydrogen-air fuel cell, the maximum first-law efficiency based on the lower and higher heating values are

$$\eta_{\text{fuel cell, I, max}} = \frac{w_{\text{max}}}{\Delta \bar{h}} = \frac{\Delta \bar{g}}{\Delta \bar{h}} = \frac{\Delta \bar{g} / M}{\text{LHV}} = \frac{(226{,}660 \text{ kJ/kmol})/(2.016 \text{ kg/kmol})}{120{,}000 \text{ kJ/kg}} = 0.937 \text{ or } 93.7\%$$

$$\eta_{\text{fuel cell, I, max}} = \frac{w_{\text{max}}}{\Delta \bar{h}} = \frac{\Delta \bar{g}}{\Delta \bar{h}} = \frac{\Delta \bar{g} / M}{\text{HHV}} = \frac{(235{,}250 \text{ kJ/kmol})/(2.016 \text{ kg/kmol})}{141{,}800 \text{ kJ/kg}} = 0.823 \text{ or } 82.3\%$$

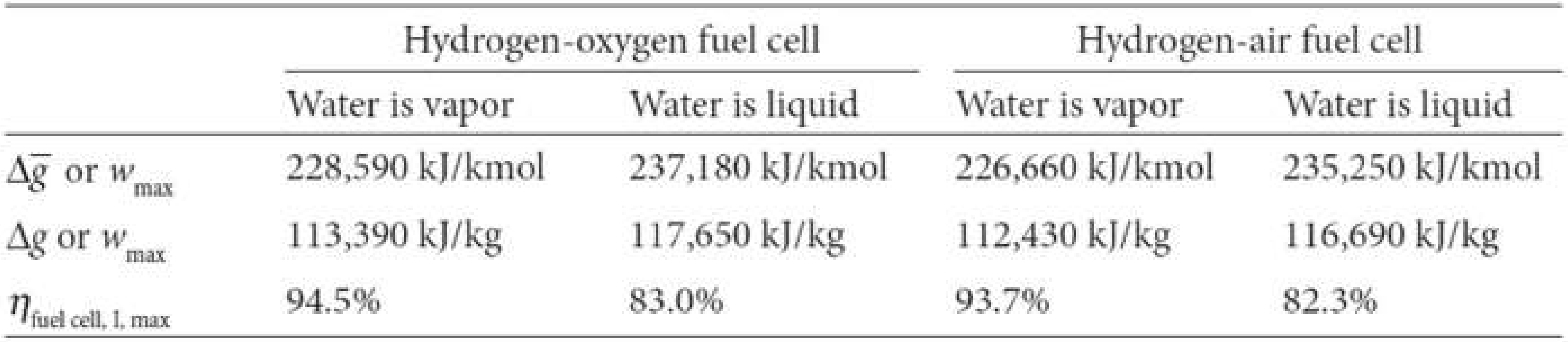


TABLE 10-2 Maximum Work and Maximum Thermal Efficiency Values for Hydrogen-Oxygen and Hydrogen-Air Fuel Cell Reactions at 25°C and 1 atm

	Hydrogen-oxygen fuel cell		Hydrogen-air fuel cell	
	Water is vapor	Water is liquid	Water is vapor	Water is liquid
$\Delta \bar{g}$ or w_{max}	228,590 kJ/kmol	237,180 kJ/kmol	226,660 kJ/kmol	235,250 kJ/kmol
Δg or w_{max}	113,390 kJ/kg	117,650 kJ/kg	112,430 kJ/kg	116,690 kJ/kg
$\eta_{\text{fuel cell, I, max}}$	94.5%	83.0%	93.7%	82.3%

Effect of temperature: The fuel cell is essentially an isothermal device and it operates ideally at the environment temperature.

The efficiency of a fuel cell decreases as the cell operating temperature increases.

The ideal cell voltage also decreases with increasing temperature.

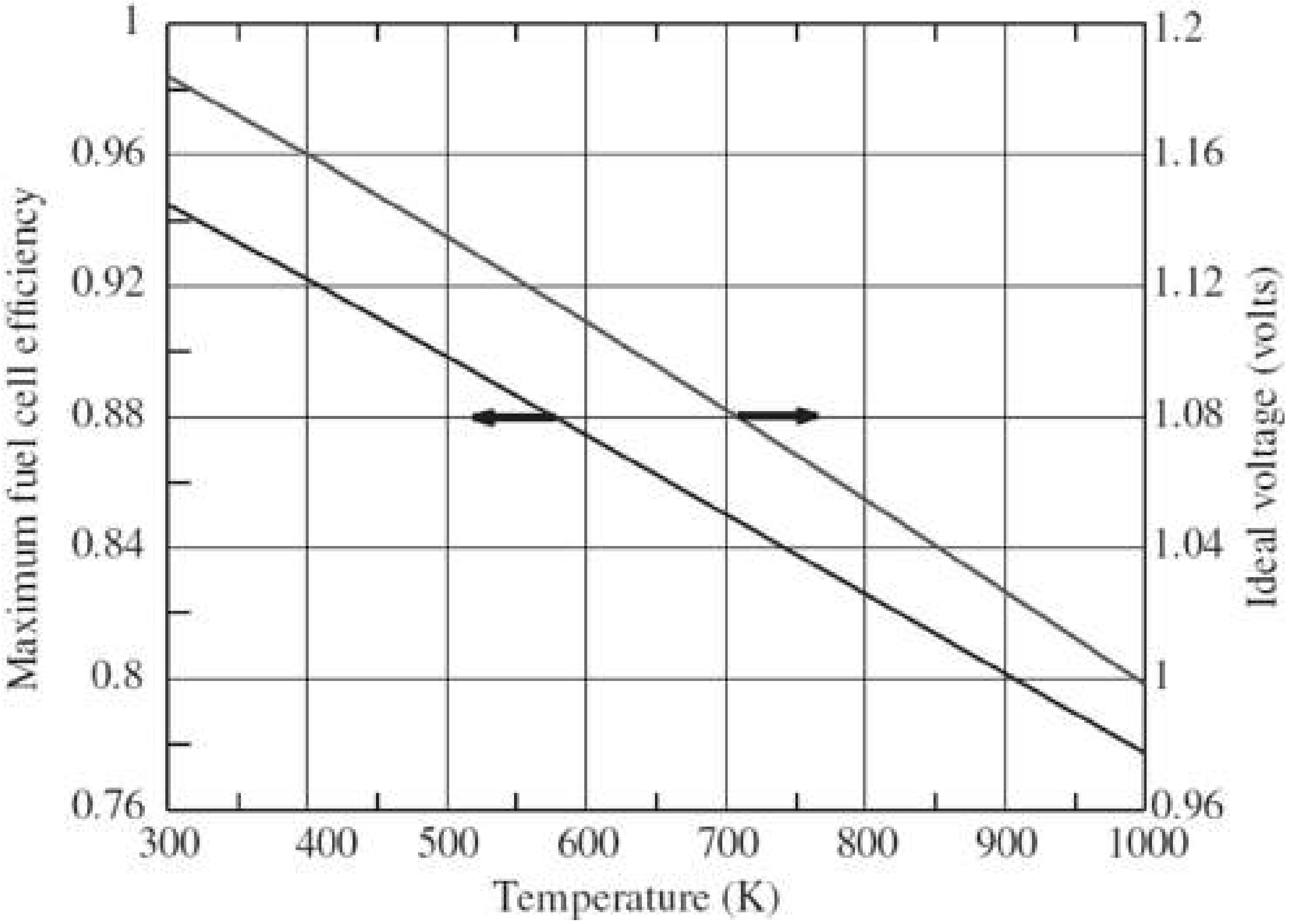
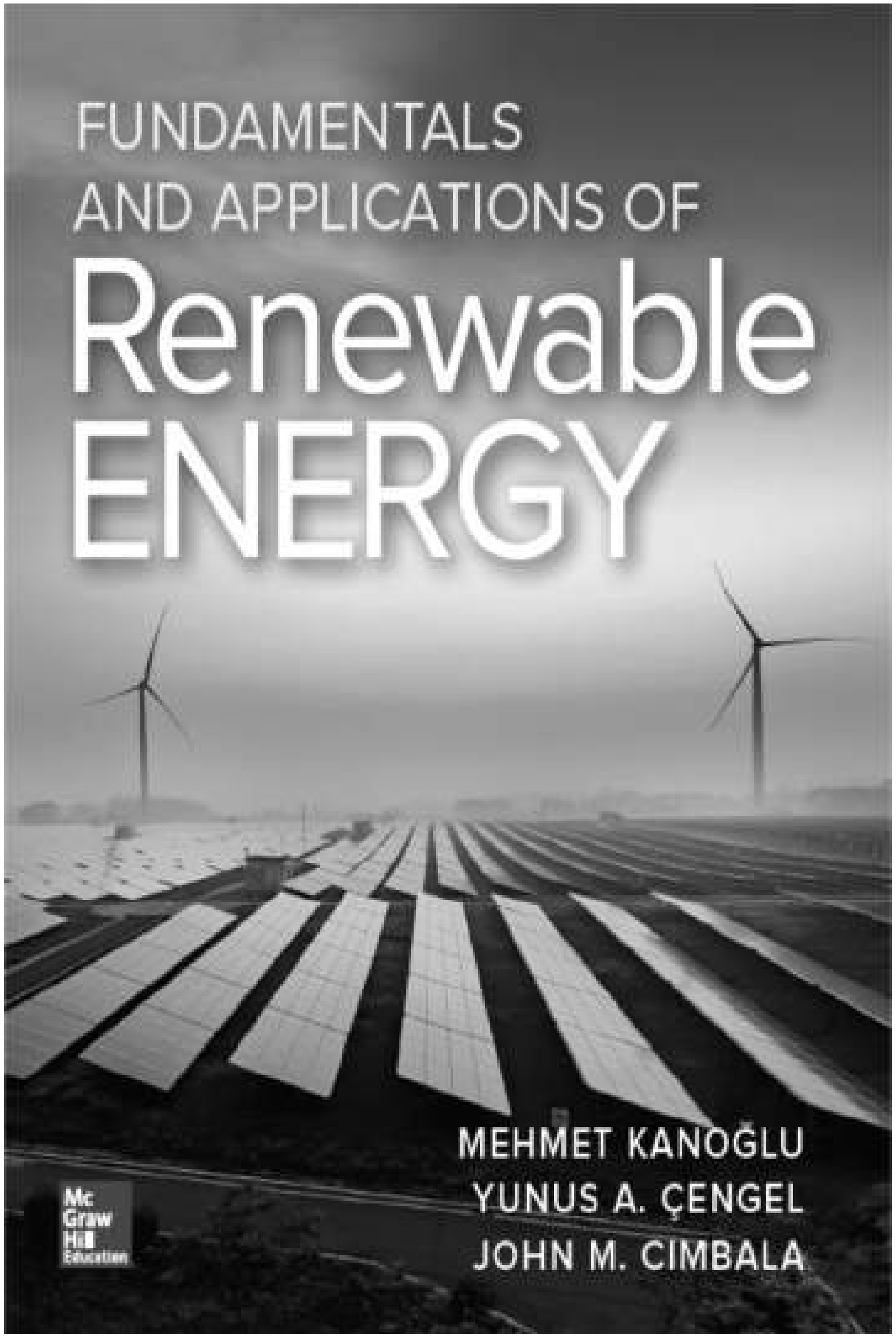


Figure 10-4
Effect of temperature on the maximum fuel cell first-law efficiency and ideal open-circuit voltage for a hydrogen-oxygen fuel cell.



Chapter 11
ECONOMICS OF RENEWABLE ENERGY

Fundamentals and Applications of
Renewable Energy
Mehmet Kanoglu
Yunus A. Cengel
John M. Cimbala
McGraw-Hill, 2020

11-1 ENGINEERING ECONOMICS

Technical vs. Economic analysis: A technical analysis for a renewable energy application is normally accompanied by an economic analysis.

Renewable energy applications replace conventional fossil fuel–based systems while providing the same desired output.

Are there always cost savings with renewable projects? A renewable energy project certainly provides savings from fossil fuel use but it may or may not provide cost savings compared to fossil fuel systems.

Calculating cost savings: A proper account of cost savings can be handled by means of ***engineering economics.***

Cost of project: An economic analysis can also provide a calculation of total cost of a project over its lifetime and it allows a cost comparison of competing projects and technologies.

Payback period: Another useful application of economic analysis is the determination of payback period for a project and specifically for a renewable energy application.

Decision criterion for renewable projects: A decision whether to implement a project is made based on the results of an economic analysis complementing a technical analysis.

A project may involve following costs

Capital cost: The capital cost is an account of the initial investment, and it may include labor and other expenses occurring at the start of the project.

Operating and maintenance costs: They are due to expenses to keep the system running in proper conditions over its lifetime.

O&M costs can be fixed (such as regular maintenance costs) or variable depending on the use of a commodity (such as electricity cost of operating an electric motor).

Salvage value: The sale value of the system at the end of its lifetime is called *salvage value* or *scrap value*.

Total cost: The total cost of a system is sum of the capital and O&M costs.

This total should be obtained considering the changes in the value of the money by time.

Expenditures: Negative (downward) arrows

Incomes: Positive (upward) arrows

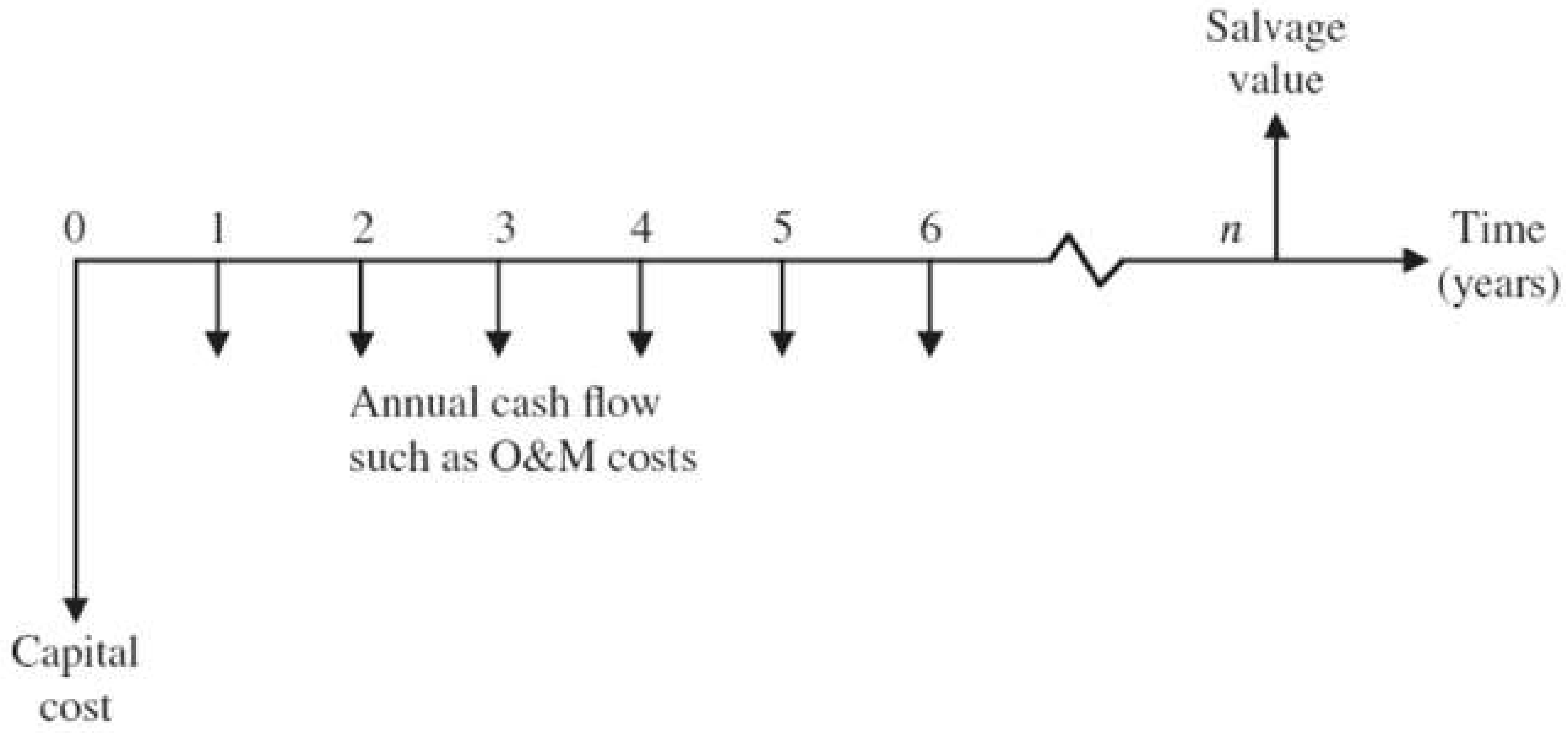


Figure 11-1
A cash flow diagram indicating various costs during the lifetime of a project.

11-2 THE TIME VALUE OF MONEY

What changes value of money by time? The value of money changes with time due to **interest** and **inflation** among other factors.

This is also due to the fact that money is always in shortage with respect to what people want to buy with money.

Which is more valuable? Having $1000 today is preferable over having $1000 in 1 year. This is because $1000 today becomes $1100 in 1 year if invested in a bank with an interest rate of 10%.

Cash flow over time: In a given energy project, the cash flow can occur at different times in the lifetime of the project.

Can we simply add incomes and subtract expenditures? No. This neglects the time value of the money.

An appropriate economic analysis considers how the value of the money changes with time.

$F = P(1+i)$ *n* = 1 yr

$F = P(1+i)(1+i) = P(1+i)^2$ *n* = 2 yr

i interest rate or discount rate
n number of time period
P present value of money
F future value of money

$F = P(1+i)^n$ Compound interest formula

$F = P(1+i)^n = (\$1000)(1+0.06)^4 = \$1262$ Yearly compounding *n* = 4 yr, *i* = 0.06

$i = 0.06/12 = 0.005$ Monthly interest rate

$F = P(1+i)^n = (\$1000)(1+0.005)^{48} = \$1270$ Monthly compounding *n* = 4x12 = 48

$$P = \frac{F}{(1+i)^n}$$ Relation between present and future values of money

Compounding: The money grows exponentially over the time. This is known as compounding. The compounding can be done yearly, monthly, weekly, daily or even hourly. However, in engineering calculations yearly compounding is commonly used.

$$U = P\left[\frac{i}{1-(1+i)^{-n}}\right] \qquad P = U\left[\frac{1-(1+i)^{-n}}{i}\right]$$

U uniform series amount: The periodic income or expenditure

$$U = F\left[\frac{i}{(1+i)^{n}-1}\right] \qquad F = U\left[\frac{(1+i)^{n}-1}{i}\right]$$

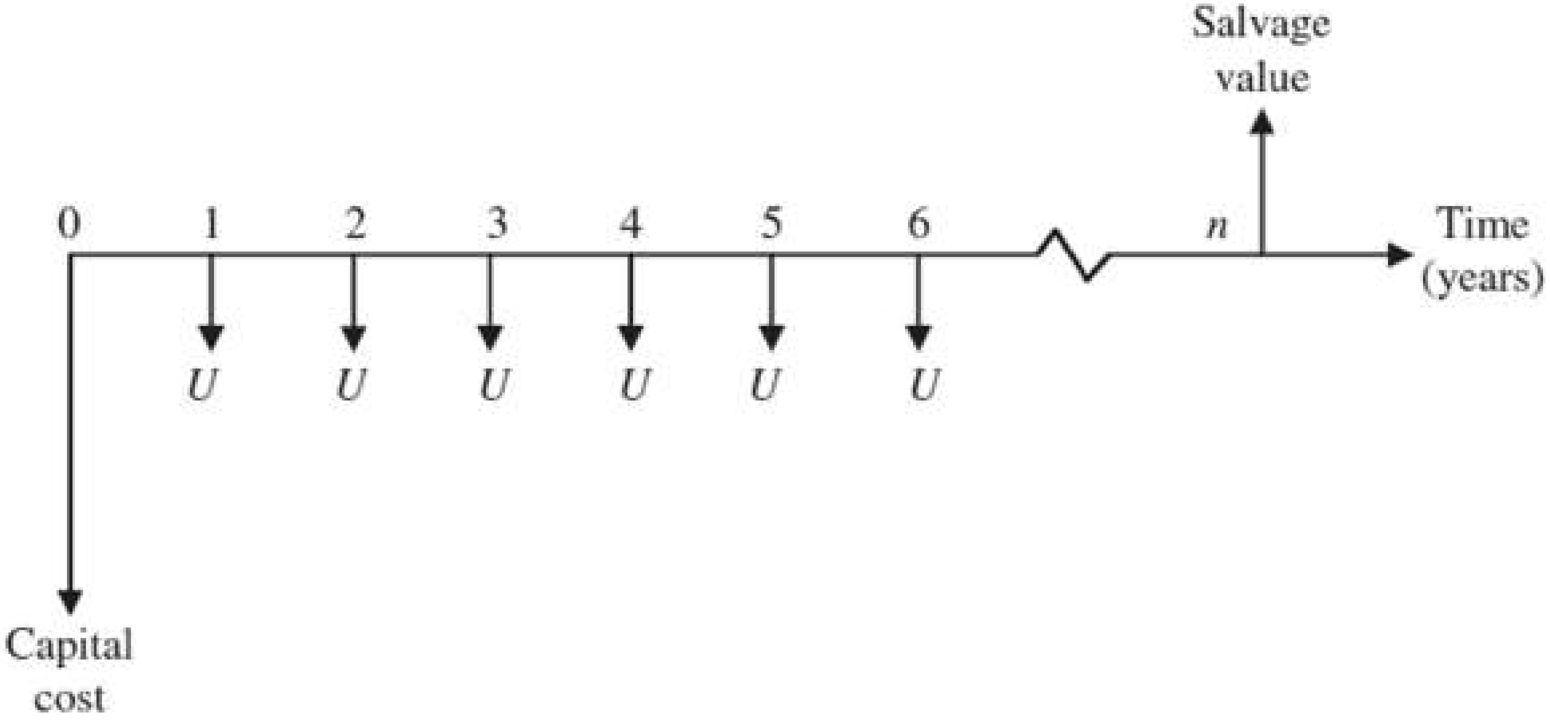


Figure 11-2 A cash flow diagram indicating uniform series amount *U.*

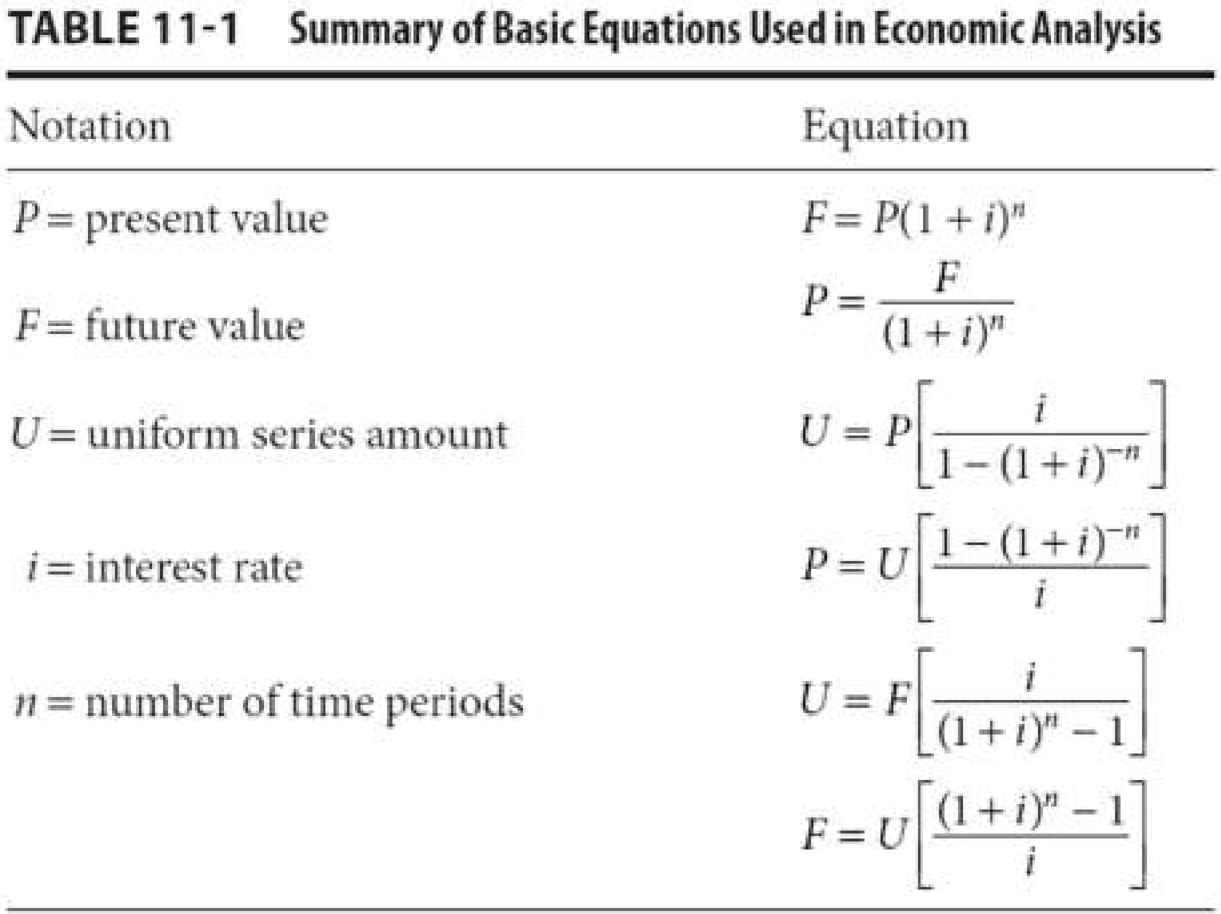


TABLE 11-1 Summary of Basic Equations Used in Economic Analysis

Notation	Equation
P = present value	$F = P(1+i)^n$
F = future value	$P = \dfrac{F}{(1+i)^n}$
U = uniform series amount	$U = P\left[\dfrac{i}{1-(1+i)^{-n}}\right]$
i = interest rate	$P = U\left[\dfrac{1-(1+i)^{-n}}{i}\right]$
n = number of time periods	$U = F\left[\dfrac{i}{(1+i)^n-1}\right]$
	$F = U\left[\dfrac{(1+i)^n-1}{i}\right]$

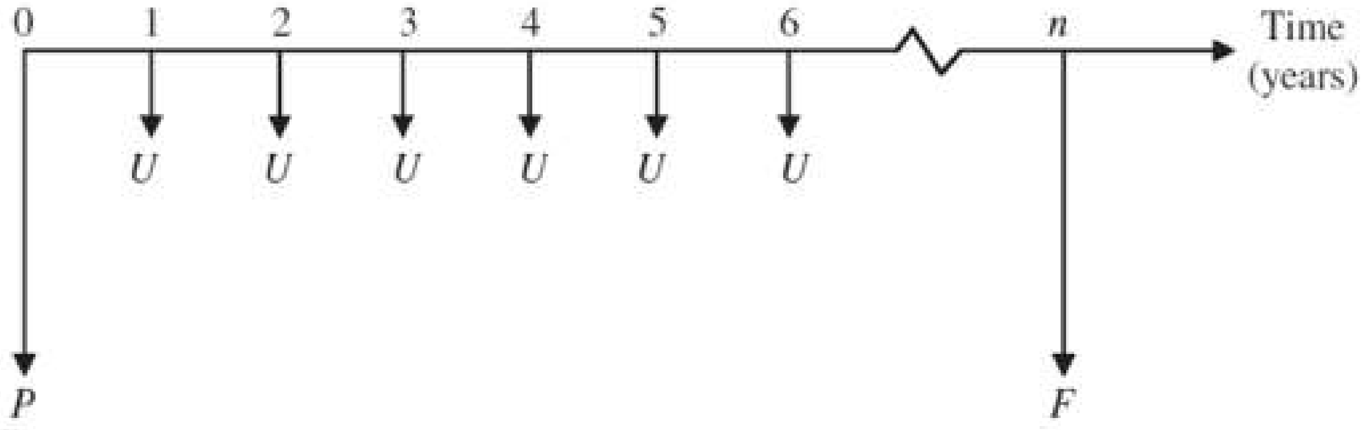


Figure 11-3
A cash flow diagram indicating present value P, future value F, and uniform series amount U.

Effect of Inflation and Taxation on Interest Rate

The time value of money is due to interest rate.

Inflation: The buying power of money also changes because the price of goods and services increases by time. This is called *inflation* and denoted by *e*.

If the interest and inflation occur at the same period at constant rates, an inflation-adjusted interest rate can be defined as

$$i_{\text{adjusted}} = \frac{i-e}{1+e} \qquad \text{(adjusted for inflation)}$$

$$i_{\text{adjusted}} = \frac{i-e}{1+e} = \frac{0.08-0.03}{1+0.03} = 0.0485$$

$i = 0.08$
$e = 0.03$

Taxation: In addition to the effect of inflation, the taxation (denoted by *t*) on an investment with interest decreases the amount of money.

Assuming that interest, inflation, and a taxation on the interest occur at the same period at constant rates, the inflation-taxation-adjusted interest rate can be expressed as

$$i_{\text{adjusted}} = \frac{(1-t)i-e}{1+e} \qquad \text{(adjusted for inflation and taxation)}$$

$$i_{\text{adjusted}} = \frac{(1-t)i-e}{1+e} = \frac{(1-0.02)0.08-0.03}{1+0.03} = 0.0470$$

$i = 0.08$

$e = 0.03$

$t = 0.02$

11-3 LIFE CYCLE COST ANALYSIS

Equations (11-1) through (11-6) are very powerful and they form basis for energy economics calculations.

One can use these equations to convert expenses occurring at different times to a desired time so that the total cost of the project can be expressed by a single value.

It also allows the comparison of competing projects and options.

Life cycle cost analysis: The comparison of projects can be done by calculating the total cost of a project. This is known as *life cycle cost analysis.*

The life cycle cost can be evaluated in different ways.

The net present value method: It is based on expressing all expenses and benefits that will occur over the *lifetime of the project* on the present time basis *P*.

The formulation given in Sec.11-2 is used to express the expenses and benefits occurring at different times.

Summing all the benefits and subtracting from the expenses on the present time gives the net present value of the project.

Which project is more desirable? The greater the positive value or the smaller the negative value represents a desirable project from an economic point of view.

Levelized annual cost (levelized annual value) method: The life cycle cost of a project can also be calculated using the levelized annual cost (or levelized annual value) method.

The net cost (or benefit) of the project is expressed by equal annual amounts over the lifetime of the project.

Each benefit/expense of the project occurring at different times is expressed by a uniform series amount U.

The net value of U is calculated by adding benefits and subtracting expenses on an annual basis.

Cost-Benefit Analysis

A project option may involve costs and benefits in economic terms.

Some projects only involve costs with no monetary benefits.

For example, the installation of an environmental control technology requires cost consumption but it may not yield any monetary benefit.

The benefits in this case are due to reduction in certain pollutants.

A life cost analysis results in the total cost of the project expressed in present term or annual cost term.

Renewable energy projects are beneficial to the environment but they are also intended to be financially attractive to the investors.

Therefore, the economic benefits are expected to outweigh the cost of the project.

A comparison of benefits and costs associated with a project can be made using a cost-benefit analysis.

The net present value calculated by adding all the benefits and subtracting from all the expenses at present time basis is used to determine whether the project is acceptable.

Net present value (NPV) = Total benefits in present time – Total costs in present time

If the net present value is greater than zero, the project yields a net benefit, and therefore, it is acceptable.

The cost-benefit method can also be expressed using *benefit-cost ratio as*

$$\text{Benefit-cost ratio} = \frac{\text{Total benefits in present time}}{\text{Total costs in present time}}$$

If this ratio is greater than unity, the project is acceptable. If it is less than unity, it is unacceptable.

In general, the projects whose benefit-cost ratio is sufficiently greater than unity receive a green light.

Unit Product Cost

In many manufacturing and other facilities, the cost of producing a unit of product is of prime interest. This may be expressed in terms of the levelized annual cost as

$$\text{Unit product cost (UPC)} = \frac{\text{Levelized annual cost}}{\text{Annual production}}$$

Unit product cost is different from specific cost (specific energy cost).

Specific cost: It refers to energy cost of a unit product.

Unit product cost: It refers to total cost (including initial cost, energy cost, O&M cost, and salvage value) expressed on levelized annual cost basis per unit product.

In the calculation of UPC, the levelized annual cost should include all costs including energy cost.

A renewable energy application may decrease the amount of energy consumption, corresponding to a reduction in the unit product cost.

Comparison of Projects Based on Life Cycle Cost Analysis

The life cycle cost analysis based on the net present value method and the levelized annual cost method can be used to compare different technology options.

If the present value method is used for the comparison: The total cost of the project over the entire lifetime of each option is calculated in present time.

The result sometimes represents the amount of investment needed today to carry out the project for its entire lifetime.

Limitation to present value method: This method requires that each option has the same lifetime.

If the levelized annual cost method is used for comparison: The total cost of the project over its entire lifetime is expressed as equal annual payments.

This method does not require that the lifetime of each option will have the same lifetime.

If an option has a shorter lifetime, it is assumed that the project will be replaced by an equivalent project at the end of its life.

Project selection criterion: In both methods, the project with the smallest total cost is selected.

If the project yields a net positive benefit instead of expenditure, the project with the highest benefit should be selected.

Are both methods equivalent? Note that both methods are equivalent and they indicate the same project as the economically viable choice.

11-4 PAYBACK PERIOD ANALYSIS

Payback period: In most renewable energy projects, it is very important to know how long it will take for the investment to pay for itself. This is called the payback period.

The payback period should be less than the life of the project but this does not guarantee a green light for the project.

Criterion for payback period: The payback period should be sufficiently shorter than the life of the project.

In today’s economic environment, it is difficult to get support for projects whose payback periods are longer than 3 or 4 years.

However, renewable energy projects also provide environmental benefits, and this may justify longer payback periods.

Consider a project that requires a total investment in the amount of *P* in present time and it provides an annual savings in the amount of *U*.

How long will it take for the investment to pay for itself from the savings it provides?

$$P = U\left[\frac{1-(1+i)^{-n}}{i}\right] \quad \Rightarrow \quad n_{dpb} = \frac{\log\left[1-\left(\frac{P}{U}\right) i\right]^{-1}}{\log(1+i)}$$

This payback period is called **discounted payback period** n_{dpb} because the time value of money is considered.

In most engineering applications, the time value of the money is neglected and a **simple payback period** is calculated from

$$n_{spb} = \frac{\text{Investment}}{\text{Annual savings}} = \frac{\text{Investment}}{U} \qquad \left(\frac{\$}{\$/\text{yr}} = \text{yr}\right)$$

$$n_{dpb} = \frac{\log\left[1-\left(\frac{P}{U}\right)i\right]^{-1}}{\log(1+i)} \qquad n_{spb} = \frac{\text{Investment}}{\text{Annual savings}} = \frac{\text{Investment}}{U} \qquad \left(\frac{\$}{\$/\text{yr}} = \text{yr}\right)$$

Investment: It represents the total cost of the project, and it is the simple sum of all the costs associated with the project over its lifetime.

Usually only initial cost is considered.

U represents annual savings.

It can be shown that the simple payback period is shorter than the discounted payback period , and thus it underestimates the actual value.

Effect of interest rate: As the interest rate gets smaller, the difference between the two payback periods also gets smaller.

Which is used most? The simple payback period is primarily used in engineering calculations, and the discounted payback period is rarely used.

Comparing projects using paybak period: The payback period analysis is sometimes used for comparing competing options. Then, the project with a shorter payback period is selected.

However, this may be misleading because an option with a longer payback period may have better net economic benefits for the entire lifetime of the project.

Example: Consider two projects with the same life periods.

Option A has a net present value (benefit) of $10,000 and a payback period of 2 years.

Option B has a net present value of $15,000 with a payback period of 3 years.

Clearly, option B provides higher monetary benefits and thus it is economically more attractive even though it has a longer payback period.

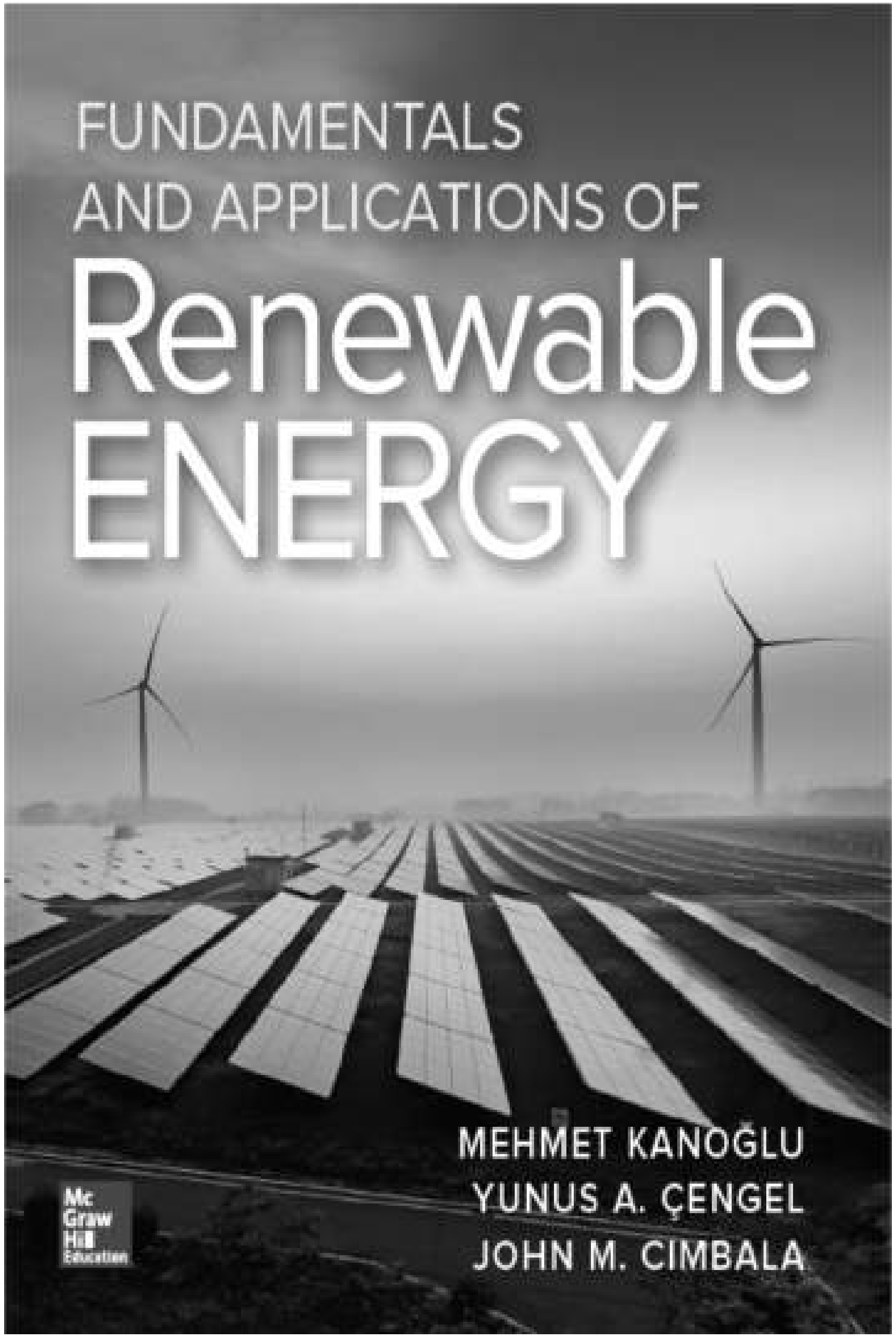
Uncertainties in economic analysis: It is difficult to quantify all of the costs and benefits associated with a project, and therefore economic analysis involves a certain degree of uncertainties.

Sometimes, some benefits of a project are difficult to be expressed in monetary terms, and their existence can be a deciding factor for a green light.

This is particularly true for renewable energy projects as they reduce or eliminate pollution and greenhouse emissions with positive consequences on humanity.

Other issues: The method of obtaining money for an investment (loan from a bank, equity, etc.) as well as tax regulations affects the outcome of an economic evaluation.

Every project has its own benefits and costs, and requires a particular analysis.



Chapter 12

ENERGY AND THE ENVIRONMENT

Fundamentals and Applications of

Renewable Energy

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McGraw-Hill, 2020

12-1 INTRODUCTION

The conversion of energy from one form to another often affects the environment and the air we breathe in many ways.

Fossil fuels such as coal, oil, and natural gas have been powering the industrial development and the amenities of modern life that we enjoy since the 1700s, but this has not been without any undesirable side effects.

From the soil we farm and the water we drink to the air we breathe, the environment has often paid a heavy toll.

Pollutants emitted during the combustion of fossil fuels contribute to smog, acid rain, and climate change.

The 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.

It is estimated that over 60,000 people in the United States alone die each year due to heart and lung diseases related to air pollution.

Considerable amounts of pollutants are emitted as the chemical energy in fossil fuels is converted to thermal, mechanical, or electrical energy via combustion, and thus power plants, industrial processes, motor vehicles, residential and commercial energy consumption, and even stoves take the blame for air pollution.

The largest sources of air pollution are

- industrial activities
- motor vehicles
- commercial and residential buildings

The pollutants released are usually grouped as

- hydrocarbons (HC)
- sulfur dioxide (SO_2)
- nitrogen oxides (NO_x)
- particulate matter (PM)
- carbon monoxide (CO)

The HC emissions are a large component of volatile organic compounds (VOCs) emissions, and the two terms are generally used interchangeably for motor vehicle emissions.

Figure 12-1
Energy conversion processes are often accompanied by air pollution and environmental effects.

Emission limits for SO_2, PM, HC, NO_x, and CO have been declining steadily since 1970.

The Clean Air Act of 1990 made the requirements on emissions even tougher, primarily for ozone, CO, nitrogen dioxide, and PM.

Emissions today vs. in the past: Today's industrial facilities and vehicles emit a fraction of the pollutants they used to emit a few decades ago.

Children: They are most susceptible to the damages caused by air pollutants since their organs are still developing.

They are also exposed to more pollution since they are more active, and thus they breathe faster.

People with heart and lung problems, especially those with asthma, are most affected by air pollutants.

This becomes apparent when the air pollution levels in their neighborhoods rise to high levels.

How can the emissions be reduced? They can be reduced by replacing fossil fuels with renewable energy sources.

Emissions with Renewables: Renewable energy systems also involve some negative environmental impacts.

Biomass energy involves ecological impacts of harvesting, transportation, and processing of plants.

Some hydroelectric power systems displace people and flood lands as well as intervene with the natural habitat of rivers for fish and other creatures.

Disposal of solar panels and collectors after their useful life is a concern for solar systems.

Geothermal systems are known to contribute to hydrogen sulfide (H_2S) emissions.

When H_2S is released as a gas into the atmosphere, it eventually changes into SO_2 and sulfuric acid.

12-2 AIR POLLUTANTS

The minimum amount of air needed for the complete combustion of a fuel is called the **stoichiometric** or theoretical air.

When a fossil fuel such as coal, oil, or natural gas is burned completely with air, the combustion products do not contain any air pollutants.

$$CH_4 + 2(O_2 + 3.76N_2) \rightarrow CO_2 + 2H_2O + 7.52N_2$$

Stoichiometric combustion of methane

$$C_8H_{18} + 12.5(O_2 + 3.76N_2) \rightarrow 8CO_2 + 9H_2O + (12.5 \times 3.76)N_2$$

Stoichiometric combustion of octane

If we consider the combustion of a particular composition or assay of coal (80 percent C, 5 percent H_2, 6 percent O_2, 2 percent N_2, 0.5 percent S, and 6.5 percent ash) with the theoretical amount of air, the complete reaction is

$$6.667C + 2.5H_2 + 0.1875O_2 + 0.07143N_2 + 0.01563S + 7.745(O_2 + 3.76N_2)$$

$$\rightarrow 6.667CO_2 + 2.5H_2O + 0.01563SO_2 + 29.19N_2$$

Why excess air? In actual combustion processes, it is common practice to use more air (called excess air) than the stoichiometric amount to increase the chances of complete combustion and/or to control the temperature of the combustion chamber.

Complete combustion: A combustion process is complete if all the carbon in the fuel burns to CO_2, all the hydrogen burns to H_2O, and all the sulfur (if any) burns to SO_2.

That is, all the combustible components of a fuel are burned to completion during a complete combustion process.

Incomplete combustion: Conversely, the combustion process is incomplete if the combustion products contain any unburned fuel or components such as C, H_2, CO, or OH.

Reasons for incomplete combustion

Insufficient oxygen is an obvious reason for incomplete combustion, but it is not the only one.

Incomplete combustion occurs even when more oxygen is present in the combustion chamber than is needed for complete combustion.

This may be attributed to insufficient mixing in the combustion chamber during the limited time that the fuel and the oxygen are in contact.

This is particularly true for internal combustion engines.

Another cause of incomplete combustion is dissociation, which becomes important at high combustion temperatures.

Main air pollutants resulting from the combustion of fossil fuels are

- Particulate matter (PM)
- Sulfur dioxide (SO_2)
- Nitrogen oxides (NO_x)
- Hydrocarbons (HC) including carbon soot particles (C)
- Carbon monoxide (CO)

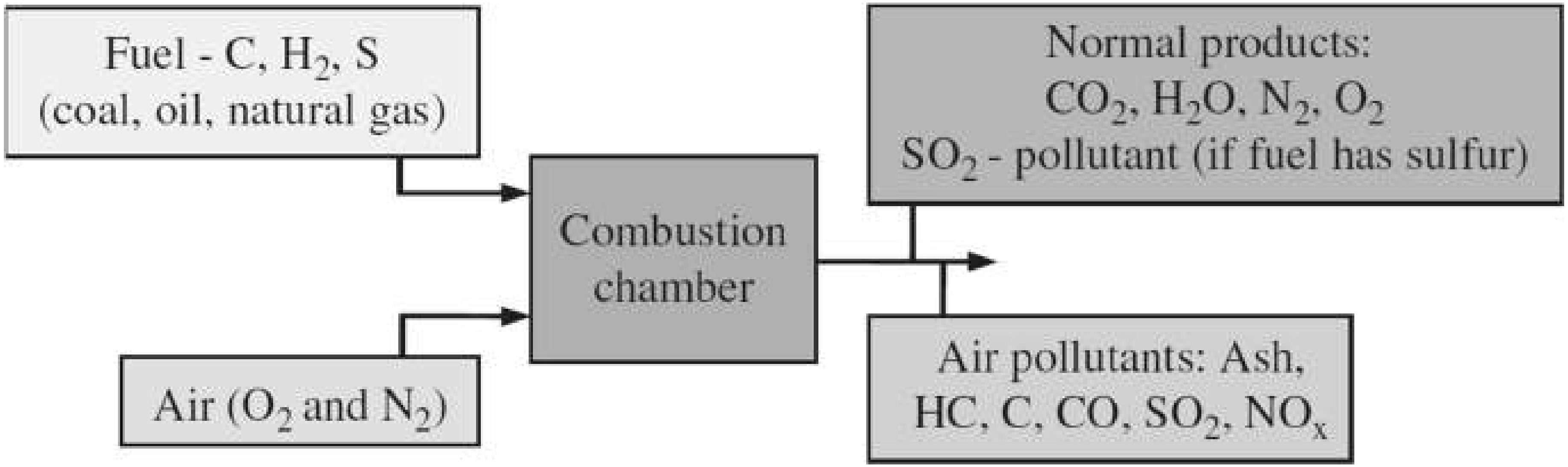


Figure 12-2 Combustion products (normal products and air pollutants) when an HC fuel burns with air.

Causes for various pollutant emissions

HC, C, and CO emissions are mainly produced due to incomplete combustion which may be due to insufficient oxygen, insufficient mixing of fuel and air, etc.

SO_2 is inevitably produced when the fuel contains sulfur.

Sulfur is a fuel which reacts with oxygen to form SO_2.

NO_x generation is due to high temperature reactions between atomic nitrogen and oxygen.

Particulate matter is commonly called ash and it is produced mostly when coal or oil is burned.

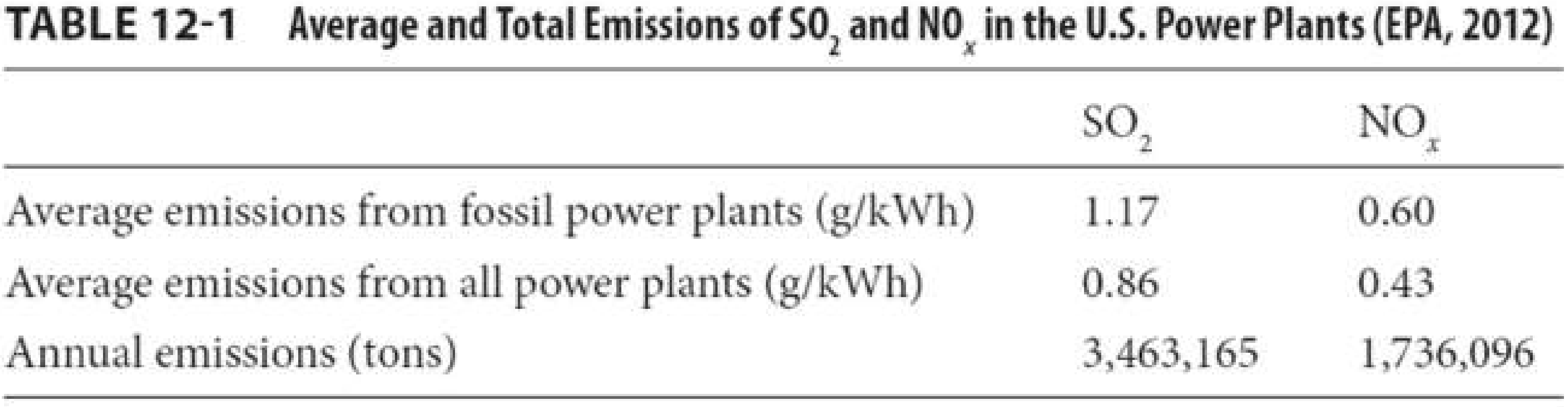


TABLE 12-1 Average and Total Emissions of SO_2 and NO_x in the U.S. Power Plants (EPA, 2012)

	SO_2	NO_x
Average emissions from fossil power plants (g/kWh)	1.17	0.60
Average emissions from all power plants (g/kWh)	0.86	0.43
Annual emissions (tons)	3,463,165	1,736,096

There are two general methods of minimizing harmful emissions from a fuel combustion system.

1. The first one is to design and optimize the combustion process such that minimum emissions are generated.

2. The second method involves after treatment.

In this method, the exhaust gases leaving the combustion chamber goes through some systems in which harmful components are treated or collected.

There are several environmental controls in a typical coal-fired power plant. These controls include

- Bottom ash collection from coal before the combustion process
- Selective catalytic reduction (SCR) for NO_x removal
- Electrostatic precipitator for flash removal
- Flue gas desulfurization for SO_2 removal
- Solid waste removal to a pond or landfill

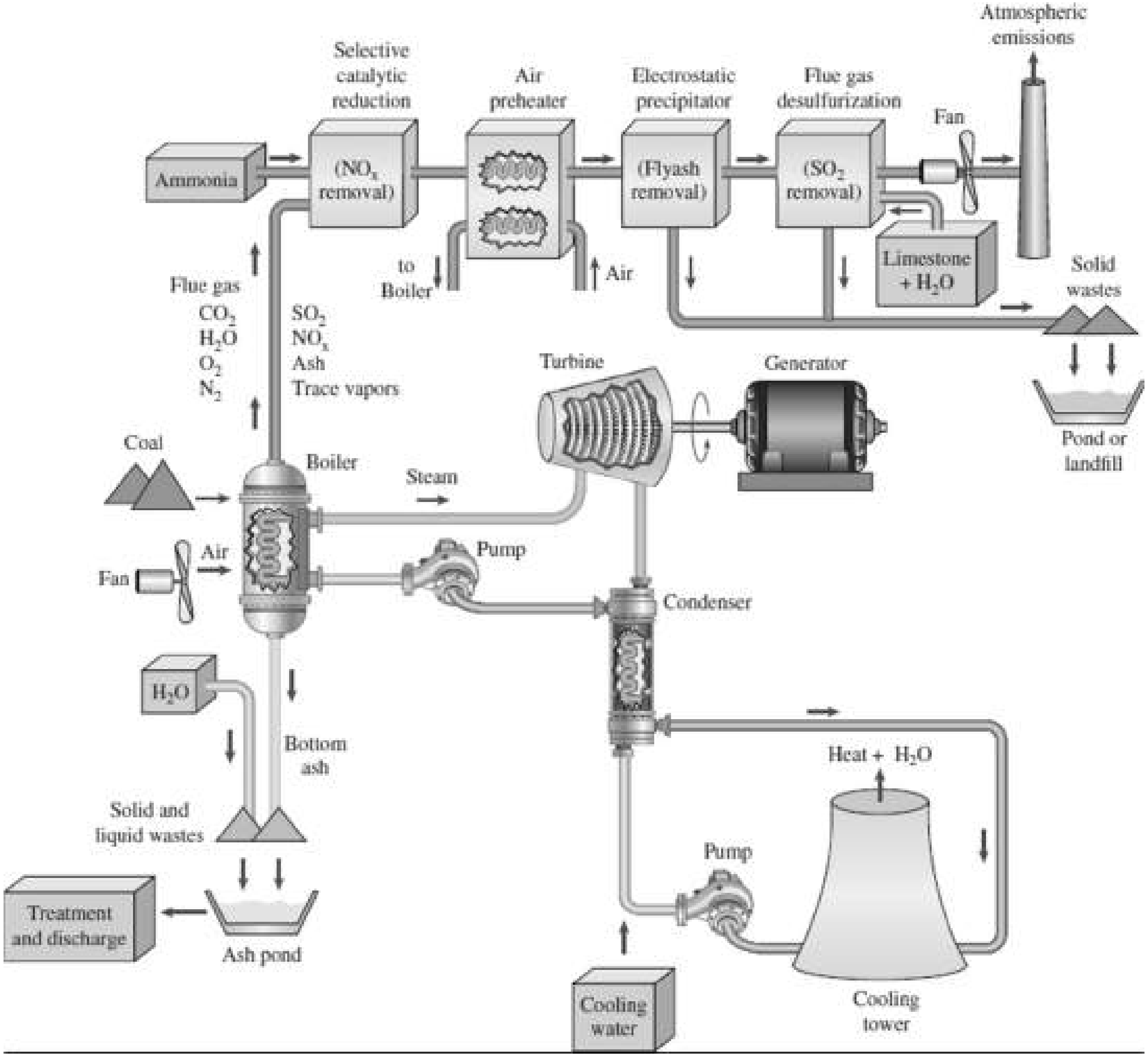


Figure 12-3
A coal-fired power plant with environmental controls for major pollutants

Particulate Matter

What is PM? Small solid and liquid particles suspended in air is generally referred to as particulate matter (PM).

Content: A primary group of PM is ash and soot particles generated from the combustion of coal and oil.

Many manufacturing and other industrial processes are responsible for the production of various PMs.

Dust particles from roads and construction and agricultural activities as well as iron, silicon, soil, and materials of earth can also be considered as part of PM.

Secondary PM: Nitrates and sulfates are formed as a result of SO_2 and NO_x emissions, and referred to as secondary PM.

PM10: When the particles are less than 10 micrometers (mm or 10^{-6} m), they are called PM10 and classified as coarse.

PM2.5: It refers to particles less than 2.5 mm, and referred to as fine.

Health effects: Particulate matter are associated with significant health effects in particular respiratory diseases such as asthma and bronchitis, cardiovascular and lung diseases, lung tissue damage, visibility impairment, and cancer.

PM2.5 can penetrate deeply into the respiratory system, and therefore it is more dangerous to health than PM10.

Ash production in coal-fired power plants: The combustion of coal produces large amounts of ash, which should be removed in a safe and effective manner. In coal-fired power plants, ash particles are carefully collected from the combustion gases. However, some ash and other particulates still remain in the combustion gases, and emitted to the atmosphere.

About 1 g of PM is released to the environment for each kWh of electricity produced from a coal-fired power plant.

In a coal-fired power plant, the flying ash particles (flash) in combustion gases can be removed and safely collected by various means such as by using a device called an electrostatic precipitator (ESP).

This prevents flash particles from being emitted to the atmosphere.

An ESP is very effective as it removes more than 99% of the ash in the combustion gases.

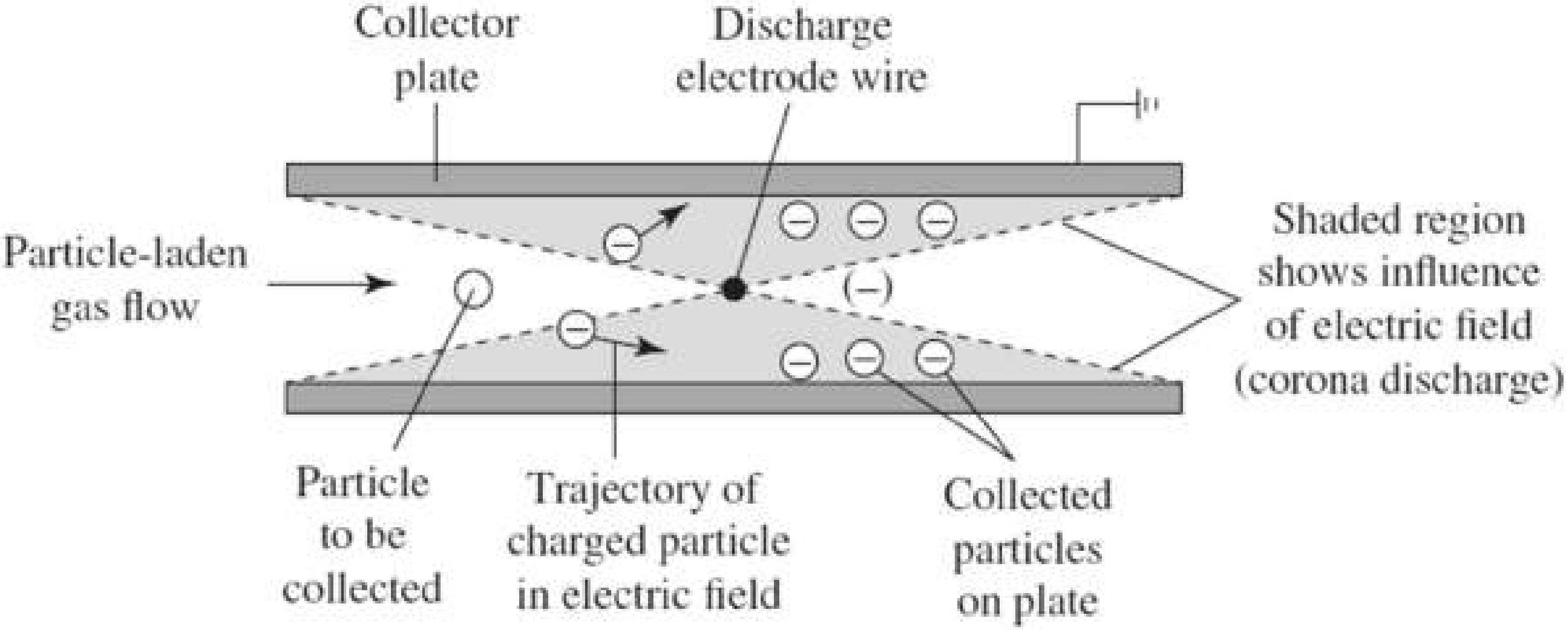


Figure 12-4 Operation of an electrostatic precipitator (ESP)

Sulfur Dioxide

How is it produced? Fossil fuels are mixtures of various chemicals, including some amounts of sulfur. The sulfur in the fuel reacts with oxygen to form sulfur dioxide (SO_2), which is an air pollutant:

$$S + O_2 \rightarrow SO_2$$

Sulfur in coal: Coal contains the most amount of sulfur among fossil fuels. Bituminous coal contains 0.5 to 4.0% sulfur by mass.

Subbituminous coal typically contains an average of 0.4% by mass.

Low-sulfur coal is more desirable and has high monetary value.

Sulfur in oil: Mass percentage of sulfur in oil may range between 0.3 and 2.3%.

Sulfur in natural gas: Natural gas also contains sulfur with varying amounts when extracted from the ground but it is removed in gas treatment plants. Therefore, natural gas combustion does not produce any SO_2.

Main source of SO_2: It is the electric power plants that burn high-sulfur coal.

SO_2 regulations: The Clean Air Act of 1970 has limited the SO_2 emissions severely, which forced the plants to install SO_2 scrubbers, to switch to low-sulfur coal, or to gasify the coal and recover the sulfur.

When coal is burned: More than 95% of sulfur is oxidized to SO_2.

About 2 to 5% of sulfur in the coal does not get burned and ends up in the solid ash particles.

Less than 1% of the SO_2 formed during combustion further reacts with O_2 to form SO_3.

The resulting SO_3 react with water vapor in the combustion gases to form sulfuric acid (H_2SO_4).

SO_2 reactions in atmosphere: SO_2 emitted from the combustion and other systems can react in the atmosphere to form sulfates which are components of acid rain.

Motor vehicles also contribute to SO_2 emissions since diesel fuel also contain small amounts of sulfur.

Regulations in sulfur content in diesel fuel:

Recent regulations have reduced the amount of sulfur in diesel fuel.

In Europe the sulfur level in diesel fuel was limited to less than 50 ppm (part per million) since 2005.

The acceptable sulfur level in diesel fuel is dropped from 50 to 10 ppm in the United States in 1990s.

Currently most diesel fuels in Europe and North America is ultra-low-sulfur diesel with a maximum of 10 ppm sulfur.

The exhaust of a diesel engine can contain up to 20 ppm of SO_2.

Most effective method of reducing SO_2 emissions: To use low-sulfur coal in electricity generation plants and heating systems.

FGD: Today, all coal-fired power plants must be equipped with flue gas desulfurization (FGD) systems, which are very effective in SO_2 removal.

In this process, a slurry of pulverized limestone (calcium carbonate—$CaCO_3$) mixed with water is used. The process takes place in a vessel called scrubber.

A mixture of limestone and water is sprayed into the combustion gas containing SO_2 according to the reaction:

$$SO_2 + (CaCO_3 + 2H_2O) + \frac{1}{2}O_2 \rightarrow CO_2 + (CaSO_4 \cdot 2H_2O)$$

The product gypsum ($CaSO_4 \cdot 2H_2O$) has commercial value as it is a main constituent in plaster, blackboard chalk, and wallboard.

FGD effectiveness: A modern flue gas desulfurization system utilizing limestone ($CaCO_3$) can remove more than 95% of SO_2 in combustion gases.

Some systems may also use lime (CaO) which is more effective, and can remove up to 99% of SO_2.

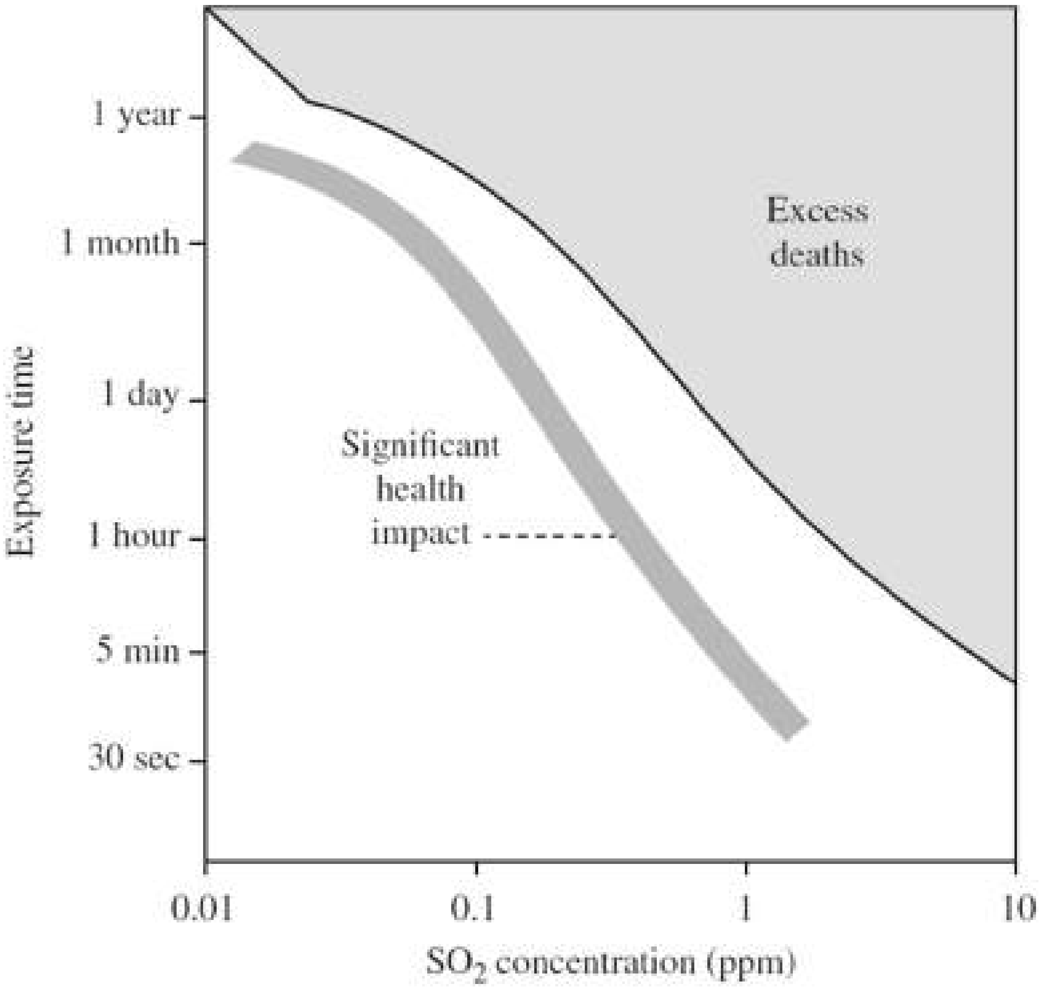


Figure 12-5
Health impact of SO_2 concentration as a function of exposure time

Health effects: SO_2 is a very toxic pollutant with serious health effects.

Longer exposures at low concentrations and shorter exposures at high concentrations may result in the similar health effects.

When SO_2 level in atmosphere is more than 1 ppm, it can lead to airway constriction.

The health effects of SO_2 include respiratory, lung, and cardiovascular illnesses.

Children and elderly with asthma and breathing problems are more sensitive to SO_2 exposure.

It also negatively affects ecosystems of rivers, lakes, and forests.

SO_2 and catalytic converter: Sulfur dioxide is not only a harmful emission but also poisons catalyst materials in catalytic converters.

SO_2 and particulate trap: Particulate traps used in reducing carbon soot particles in diesel engines are negatively affected by sulfur components in the exhaust.

H_2S formation: Another reaction of sulfur is that it combines with hydrogen at high temperatures to form hydrogen sulfide (H_2S):

$$S + H_2 \rightarrow H_2S$$

Characteristics of H_2S: H_2S is a colorless, poisonous, corrosive, flammable, and explosive gas with a rotten egg smell.

Health effects of H_2S: Long-term exposure to H_2S is associated with nervous and respiratory system and eye effects.

Nitrogen Oxides

Nitrogen oxide (NO_x) and nitrogen dioxide (NO_2) are produced during the combustion of fossil fuels such as coal, oil, and natural gas.

Electrical power plants, automobiles, and other vehicles burning fossil fuels are responsible for nitric oxide (NO) and nitrogen dioxide (NO_2) emissions, which are combined with a name of nitrogen oxides or oxides of nitrogen (NO_x).

Most of the NOx emissions from a combustion system to the atmosphere are NO but it gradually turns into NO_2 by reacting with oxygen in air.

Nitrogen oxides are produced at high combustion temperatures when a fuel is burned with oxygen in air.

A number of possible reactions can contribute the formation of NO and NO_2. Some of these reactions are as follows:

$$N_2 + O \rightarrow NO + N$$

$$N + O_2 \rightarrow NO + O$$

$$N + OH \rightarrow NO + H$$

$$NO + O_2 \rightarrow NO_2 + O$$

$$NO + H_2O \rightarrow NO_2 + H_2$$

Dissociation reactions

$$N_2 \rightarrow 2N$$

$$O_2 \rightarrow 2O$$

$$H_2O \rightarrow OH + \tfrac{1}{2}H_2$$

NO_x can also be formed by the reactions of atomic nitrogen and oxygen particles in fuel.

This is particularly the case for coal as it contains about 10% oxygen and 1% nitrogen by mass.

Natural gas also contains small amounts of nitrogen and oxygen.

For higher NO_x formation levels, the nitrogen in fuel usually has greater contribution to NO_x formation compared to that due to N_2 and O_2 in air.

In an internal combustion engine, the combustion temperatures can reach 2500 or 3000 K allowing some dissociation reactions, which result in NO_x formation.

Effect of combustion temperature: At higher combustion temperatures, more dissociation reactions cause greater amounts of NO_x production.

Very little NO_x is formed at low temperatures.

NO_x control: An effective method of NO_x control involves design and optimum operation of combustion process in combustion chambers and burners.

This includes controlling combustion temperature, combustion time, and some design characteristics of the burner.

The burners specifically designed for controlling NO_x emission are called low-NO_x burners.

NO_x control by catalytic converter: Nitrogen oxide emissions are greatly reduced in gasoline burning automobiles by the use of catalytic converters.

NO_x control in diesel engines: In diesel engines, catalytic converter is not much effective in reducing NO_x. Instead, exhaust gas recycling (EGR) is used effectively to control NO_x generation.

What is EGR? In EGR, some exhaust gases (up to 30%) are diverted back to the combustion chamber.

These gases do not react with air, but absorb heat in the chamber, thus reducing the combustion temperature.

Water injection in engines: In some large internal combustion engines such as those used in electricity production and in ships, tiny water droplets are injected into the combustion chamber.

Water evaporates absorbing heat from the surroundings.

This reduces combustion temperature and levels of NO_x formation.

Selective catalytic reduction (SCR): Another method of NO_x control involves a chemical treatment system to remove NO_x components in combustion gases. In coal-fired power plants, a SCR unit is installed into the combustion gas stream right after the boiler.

The system uses a catalyst material to promote the conversion of NO_x components into non harmful molecular nitrogen N_2.

Ammonia (NH_3) is also injected into the combustion gas stream during the following reactions

$$NO + NH_3 + \tfrac{1}{4}O_2 \rightarrow N_2 + \tfrac{3}{2}H_2O$$

$$NO_2 + 2NH_3 + \tfrac{1}{2}O_2 \rightarrow \tfrac{3}{2}N_2 + 3H_2O$$

Temperature requirement for SCR: These reactions require a temperature of about 400°C, and this is the reason the SCR system is installed right after the boiler of the power plant.

Effectiveness of SCR: The SCR systems can typically remove 70 to 90% of NO_x in the combustion gases.

Nitrogen oxides react in the atmosphere to form ground-level ozone.

It contributes to the photochemical smog and acidification of waters and soils.

The emission of NO_x causes the formation of nitrates, which are considered as PM (mostly PM2.5).

Nitrogen dioxide (NO_2) gas is toxic at high concentrations.

Health effects: The primary health effects of NO_2 are related to respiratory illnesses such as asthma and bronchitis.

Hydrocarbons

Fossil fuels (coal, oil, natural gas) are primarily made of hydrocarbons (HC).

In a combustion reaction, some of the fuel cannot find oxygen to react with during the combustion period.

As a result, some unburned or partially burned fuel particles leave the exhaust gases as HC components.

Deficiency of air: This will certainly happen when there is deficiency of air (not enough air to burn all the fuel) during combustion.

However, having stoichiometric or excess air does not guarantee that all fuel will be burned at the end of the combustion process.

Causes of HC emissions: Insufficient mixing between fuel and air, nonhomogeneous mixture, and short time of reaction are some of the causes for incomplete combustion and resulting HC emission.

The terms HC and volatile organic compounds (VOC) are usually used interchangeably.

HC emissions in vehicles: A significant portion of the VOC or HC emissions in vehicles are caused by the evaporation of fuels during refueling or spillage during spit back or by evaporation from gas tanks with faulty caps that do not close tightly.

The solvents, propellants, and household cleaning products that contain benzene, butane, or other HC products are also significant sources of HC emissions.

Other sources of HC emissions: They include venting of crankcase, petroleum refineries, chemical plants, gasoline and diesel fuel distribution and storage facilities, dry cleaners, and other processes involving chemical solvents.

When diesel fuel is burned in an internal combustion engine, combustion gases contain unburned carbon (C) soot particles, which are sometimes seen as a black smog.

Carbon soot particles are usually in the form of spheres with diameters between 10 and 80 nm (or 10×10^{-9} to 80×10^{-9} m).

The particles are essentially solid carbon with some HC on the surface.

Carbon particles are generated during combustion of an HC fuel in the fuel-rich zones with insufficient air:

$$C_mH_n + w\,(O_2 + 3.76N_2) \rightarrow a\,CO_2 + b\,H_2O + c\,CO + d\,N_2 + e\,C\ (\text{solid})$$

These soot particles may find oxygen to react with by the time the combustion is finished:

$$C\ (\text{solid}) + O_2 \rightarrow CO_2$$

Therefore, most of carbon particles generated initially in the combustion chamber will be burned into CO_2, and never get exhausted to the atmosphere.

Most diesel automotive engines are equipped with particulate traps to collect soot particles.

The traps are cleaned/regenerated periodically by burning the collected particles.

HC in gasoline engines: In a gasoline automotive engine, up to 6000 ppm of HC components exist in the exhaust after the combustion chamber. This represents 1 to 1.5% of the fuel.

About half of these are unburned fuel components while the rest are partially burned.

Most of these components are treated in the catalytic converter of the engine before exhaust gases end up in the atmosphere.

HC in diesel engines: Compared to gasoline engines, much less HC is found in the engine exhaust of a diesel engine.

The reason is that the air-fuel ratio in diesel engines (between 18 and 70) is typically much higher than those in gasoline engines (between 12 and 18).

If diesel engines did not use considerable amounts of excess air for combustion, the carbon soot particle emissions would be higher than most legal limits.

Consequences of HC emissions: Hydrocarbon components and carbon soot particles in air act as irritants and odorants.

Some of them are believed to be carcinogenic.

Nitrogen oxides and HC are two main sources for the formation of ground level ozone.

Except for CH_4, HC components react in atmosphere to form photochemical smog.

Carbon Monoxide

Carbon monoxide (CO) is a colorless, odorless, poisonous gas.

What emits CO? It is mostly emitted by industry and motor vehicles, and it can build to dangerous levels in areas with heavy congested traffic.

How is it produced? CO is produced during combustion when there is fuel-rich mixture (not enough air or oxygen in the air-fuel mixture).

$$C + \frac{1}{2}O_2 \rightarrow CO \qquad CO + \frac{1}{2}O_2 \rightarrow CO_2$$

Combustion of an HC
fuel with oxygen

Is CO a fuel? CO is also a fuel with energy content (HV = 10,100 kJ/kg).

If CO cannot find oxygen after the first reaction due to deficiency of oxygen or insufficient mixing, some CO will be part of the exhaust.

How is CO emission minimized? By avoiding fuel-rich mixtures, better mixing of fuel and air, and increasing combustion time.

CO in gasoline engines: Most CO is produced at engine start-up and acceleration during which engine runs with fuel-rich mixtures.

CO in the exhaust of a gasoline engine are between 0.1% and 5%.

CO in diesel engines: Diesel engines generate very small amounts of CO since they use excess air in fuel-air mixtures.

Health effect of CO: CO deprives the body’s organs from getting enough oxygen by binding with the red blood cells that would otherwise carry oxygen.

At low levels, CO decreases the amount of oxygen supplied to the brain and other organs and muscles, slows body reactions and reflexes, and impairs judgment.

It poses a serious threat to people with heart disease because of the fragile condition of the circulatory system and to fetuses because of the oxygen needs of the developing brain.

At high levels, it can be fatal, as evidenced by numerous deaths caused by cars that are warmed up in closed garages or by exhaust gases leaking into the cars.

Hemoglobin is the protein molecule in red blood cells that carries oxygen from the lungs to the body's tissues and returns carbon dioxide from the tissues back to the lungs. Carbon monoxide absorbed in hemoglobin is called carboxyhemoglobin (COHb). Negative physiological effects on the body are observed when the levels of COHb is above 100 ppm or 0.01%. Serious effects including coma take place after 300 ppm, and long-term exposure above 600 ppm is fatal.

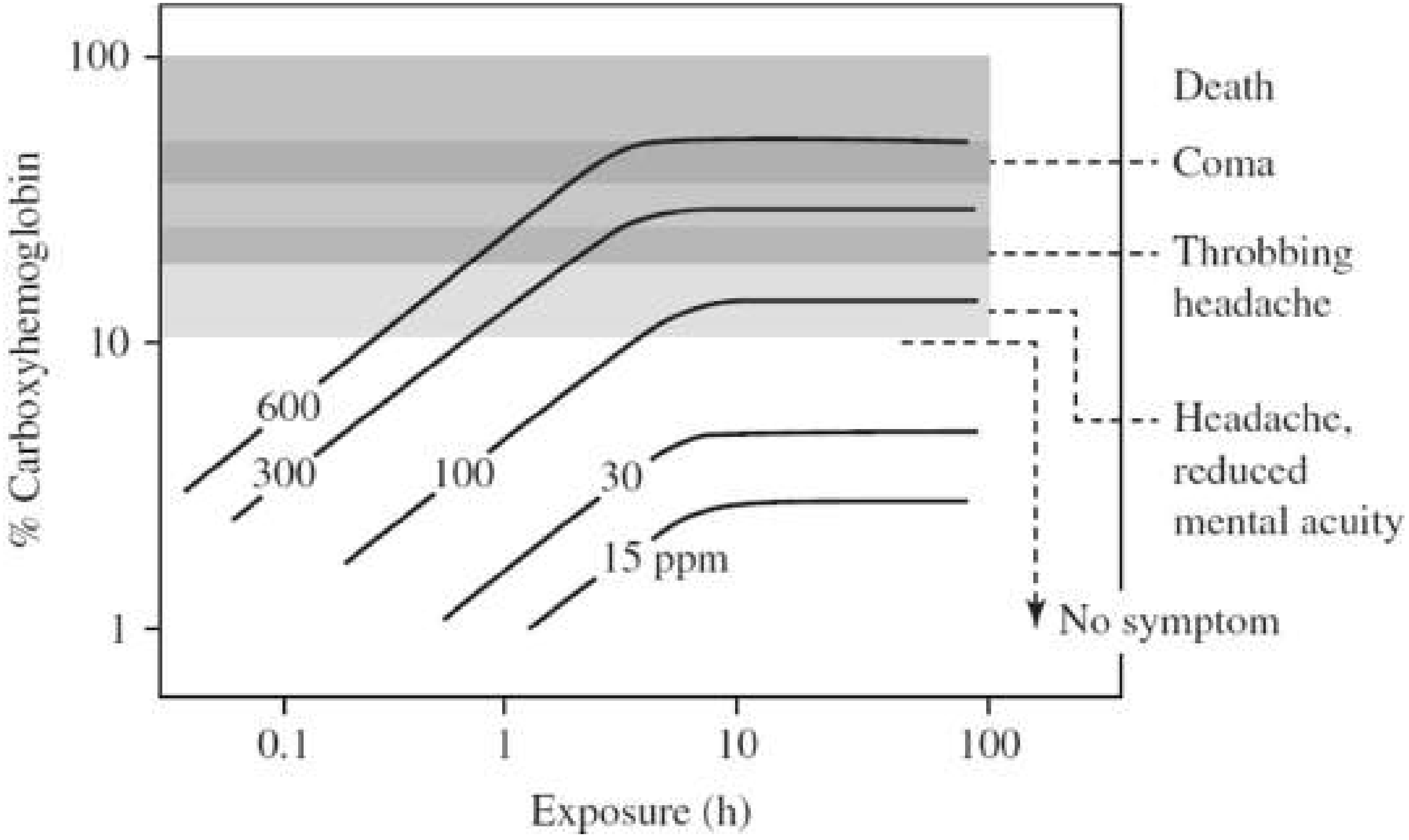


Figure 12-6 Effect of carboxyhemoglobin (COHb: CO absorbed in hemoglobin) on the human body.

Ozone, Smog, and Acid Rain

If you live in a metropolitan area such as Los Angeles, you are probably familiar with urban smog (smoke + fog = smog)—the dark yellow or brown haze that builds up in a large stagnant air mass and hangs over populated areas on calm hot summer days.

Content of smog: Smog (also called photochemical smog) is made up mostly of ground-level ozone (O_3), but it also contains numerous other chemicals, including CO, PM such as soot and dust, volatile organic compounds (VOCs) such as benzene, butane, and other HC.

Difference between ozones

The harmful ground-level ozone should not be confused with the useful ozone layer high in the stratosphere that protects the earth from the sun’s harmful ultraviolet (UV) rays.

Effects of ozone

Ozone at ground level is a pollutant with several adverse health effects.

It is harmful to lungs, other biological tissue, and trees.

It can react with rubber, plastics, and other materials with serious damage.

Agricultural crop loss due to ozone in the United States are estimated to be more than half a billion dollars per year.

Smog formation

The primary sources of NO_x and HC are motor vehicles and power plants.

HCs and NO_x react in the presence of sunlight on hot calm days to form ground-level ozone, which is the primary component of smog.

Possible reactions to produce smog and ozone are

$$NO_2 + \text{energy from sunlight} \rightarrow NO + O + \text{smog}$$

$$O + O_2 \rightarrow O_3$$

The smog formation usually peaks in late afternoons when the temperatures are highest and there is plenty of sunlight.

Although ground-level smog and ozone form in urban areas with heavy traffic or industry, the prevailing winds can transport them several hundred miles to other cities.

This shows that pollution knows of no boundaries, and it is a global problem.

$$NO_2 + \text{energy from sunlight} \rightarrow NO + O + \text{smog}$$

$$O + O_2 \rightarrow O_3$$

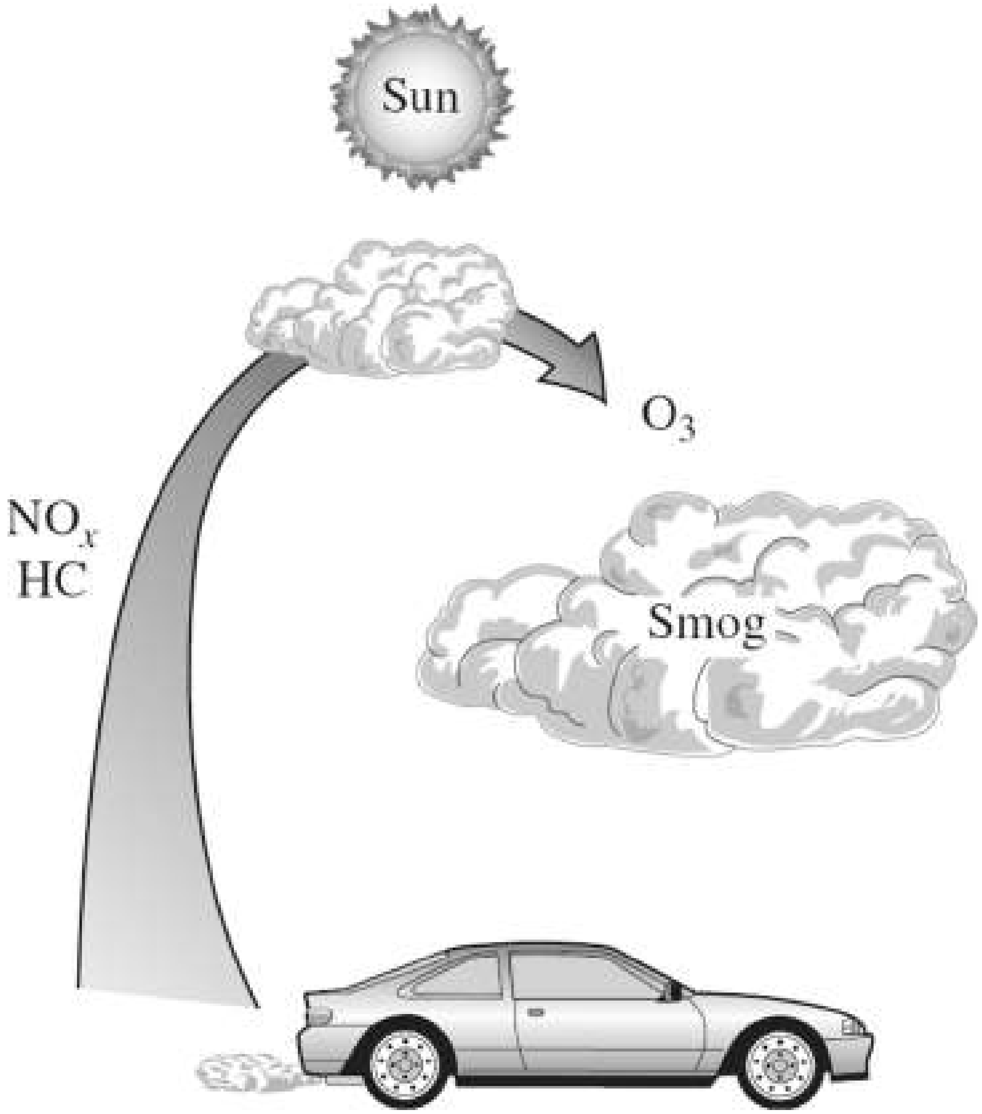


Figure 12-7
Ground-level ozone, which is the primary component of smog, forms when HC and NO_x react in the presence of sunlight in hot calm days.

Health effects of ozone: Ozone irritates eyes and damages the air sacs in the lungs where oxygen and carbon dioxide are exchanged, causing eventual hardening of this soft and spongy tissue.

It also causes shortness of breath, wheezing, fatigue, headaches, and nausea, and aggravates respiratory problems such as asthma.

Every exposure to ozone does a little damage to the lungs, just like cigarette smoke, eventually reducing the individual’s lung capacity.

Staying indoors and minimizing physical activity during heavy smog minimizes damage.

Ozone also harms vegetation by damaging leaf tissues.

Reformulated gasoline: To improve the air quality in areas with the worst ozone problems, reformulated gasoline (RFG) that contains at least 2% oxygen was introduced.

The use of RFG has resulted in significant reduction in the emission of ozone and other pollutants, and its use is mandatory in many smog-prone areas.

The most effective method of reducing ground-level ozone: Minimizing NO_x and HC emissions.

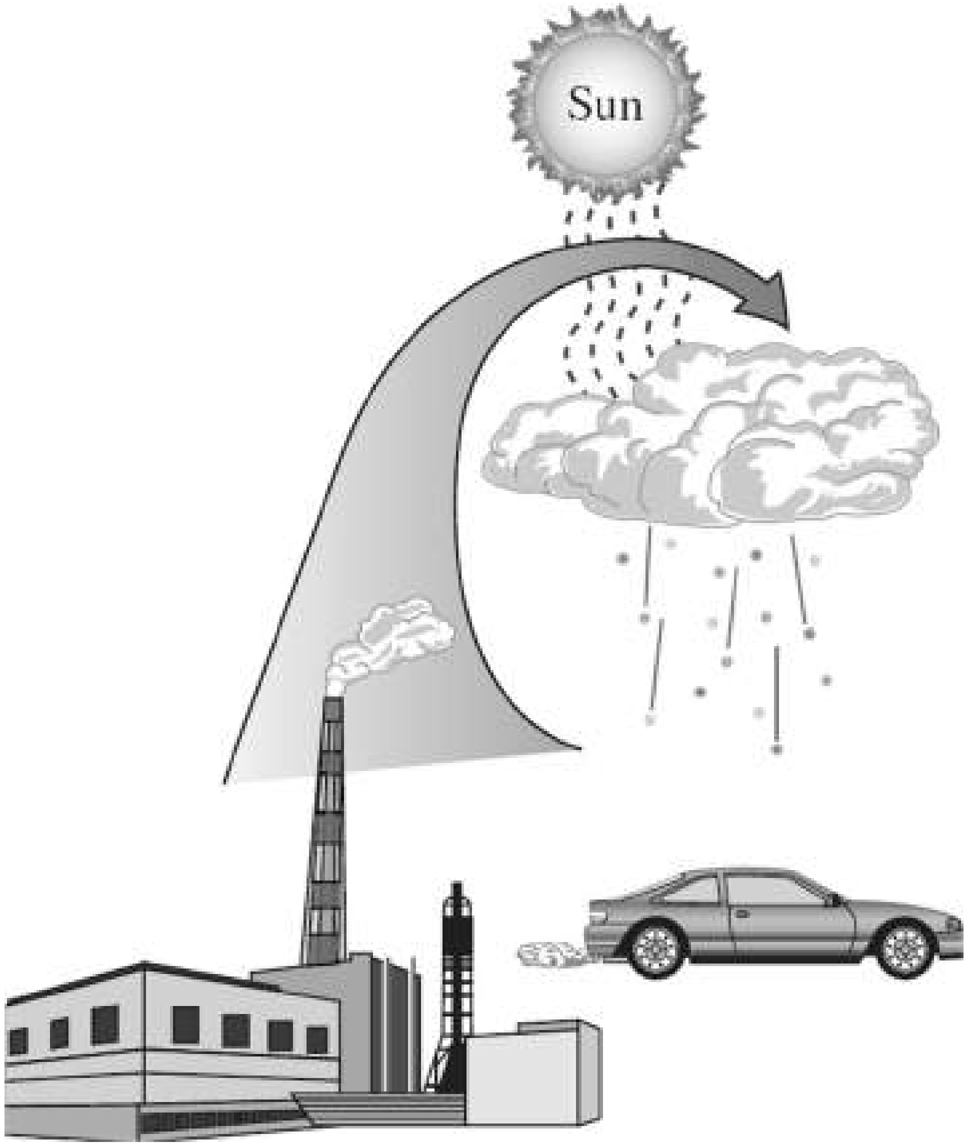
Large reductions of HC emissions from motor vehicles in recent decades contributed this cause.

However, significant reductions in NO_x and further reductions in HC emissions are needed to deal with the challenges to control ozone levels in atmosphere.

CO in smog: The other serious pollutant in smog is CO.

Dust and soot in smog: Smog also contains suspended PM such as dust and soot emitted by vehicles and industrial facilities.

Such particles irritate the eyes and the lungs since they may carry compounds such as acids and metals.



What is acid rain? The sulfur oxides and nitric oxides react with water vapor and other chemicals high in the atmosphere in the presence of sunlight to form sulfuric and nitric acids.

The acids formed usually dissolve in the suspended water droplets in clouds or fog.

These acid-laden droplets, which can be as acidic as lemon juice, are washed from the air on to the soil by rain or snow.

This is known as acid rain.

Figure 12-8 Sulfuric acid and nitric acid are formed when sulfur oxides and nitric oxides react with water vapor and other chemicals high in the atmosphere in the presence of sunlight.

Sulfur dioxide reacts with water and dissolved oxygen to produce sulfuric acid (H_2SO_4):

$$H_2O + SO_2 + \frac{1}{2}O_2 \rightarrow H_2SO_4$$

Another reaction of SO_2 produces sulfurous acid (H_2SO_3):

$$H_2O + SO_2 \rightarrow H_2SO_3$$

Both sulfuric acid and sulfurous acid are components of acid rain.

Acid droplets can penetrate deeply into lungs during respiration.

When SO_2 produced from power plants are transported through long distances due to winds, it may be transformed into sulfate particles and other acidic species.

Also, NO_x emissions cause the formation of nitrate species.

Sulfates, nitrates and other acidic species contribute acid rain.

Acid rain and rivers: The soil is capable of neutralizing a certain amount of acid, but the amounts produced by the power plants using inexpensive high-sulfur coal has exceeded this capability, and as a result many lakes and rivers in industrial areas such as New York, Pennsylvania, and Michigan have become too acidic for fish to grow.

Acid rain and forests: Forests in those areas also experience a slow death due to absorbing the acids through their leaves, needles, and roots.

Acid rain and soil: Soil is also adversely affected by acid deposition with the consequences such as soil erosion, sedimentation of waterways, and changes in animal habitat.

Even limestone and marble structures deteriorate due to acid rain.

When was the problem recognized? The magnitude of the problem was not recognized until the early 1970s, and serious measures have been taken since then to reduce the SO_2 emissions drastically by installing scrubbers in plants and by desulfurizing coal before combustion.

12-3 EMISSIONS FROM AUTOMOBILES

Automobiles are most noticeable source of air pollution and greenhouse gas emissions.

Pollutant emissions from automobiles and other internal combustion engine powered vehicles and machines have decreased by more than 90% since 1970s.

However, the number of automobiles have multiplied many times over the same period resulting in a significant increase in pollutant and greenhouse gas emissions.

Major emissions from automobile engines:

- Hydrocarbons (HC). Also called volatile organic compounds (VOC).

- Nitrogen oxides (NO_x)

- Carbon monoxide (CO)

- Carbon soot (C) particles. Primarily emitted from diesel fuel vehicles.

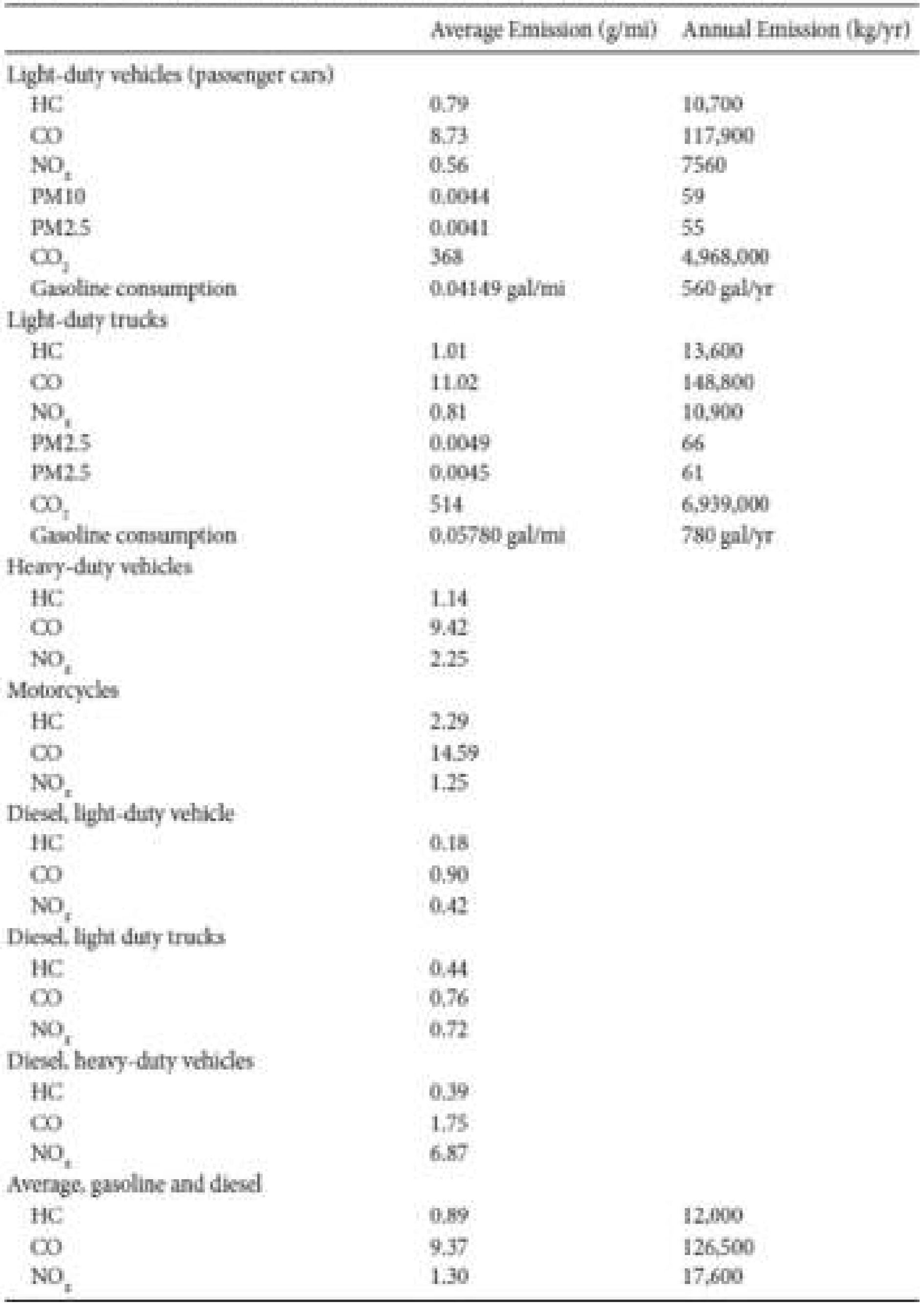


TABLE 12-2 Average Emissions from Automobiles in the United States (EPA, 2010; EPA, 2008)

	Average Emission (g/mi)	Annual Emission (kg/yr)
Light-duty vehicles (passenger cars)		
HC	0.79	10,700
CO	8.73	117,900
NO_x	0.56	7560
PM10	0.0044	59
PM2.5	0.0041	55
CO_2	368	4,968,000
Gasoline consumption	0.04149 gal/mi	560 gal/yr
Light-duty trucks		
HC	1.01	13,600
CO	11.02	148,800
NO_x	0.81	10,900
PM2.5	0.0049	66
PM2.5	0.0045	61
CO_2	514	6,939,000
Gasoline consumption	0.05780 gal/mi	780 gal/yr
Heavy-duty vehicles		
HC	1.14	
CO	9.42	
NO_x	2.25	
Motorcycles		
HC	2.29	
CO	14.59	
NO_x	1.25	
Diesel, light-duty vehicle		
HC	0.18	
CO	0.90	
NO_x	0.42	
Diesel, light duty trucks		
HC	0.44	
CO	0.76	
NO_x	0.72	
Diesel, heavy-duty vehicles		
HC	0.39	
CO	1.75	
NO_x	6.87	
Average, gasoline and diesel		
HC	0.89	12,000
CO	9.37	126,500
NO_x	1.30	17,600

$\mathrm{AF} = m_{\mathrm{air}}/m_{\mathrm{fuel}}$ air-fuel ratio

$\phi = \mathrm{AF}_a/\mathrm{AF}_s$ equivalence ratio

Lean mixture: If the air-fuel mixture has more than theoretical air (excess air), the mixture is called lean (fuel-lean), and the equivalence ratio is less than 1.

Rich mixture: If the mixture has less than theoretical air (deficiency of air), the mixture is called rich (fuel-rich), and the equivalence ratio is greater than 1.

HC and CO emissions can be minimized by using fuel-lean mixtures.

Very lean mixtures? The reason for increased HC emissions at very lean mixtures is the occurrence of misfires.

$\mathbf{NO_x}$ emissions: They are maximum at slightly lean conditions for which the combustion temperature is high and there is some extra oxygen for monatomic nitrogen with which to react.

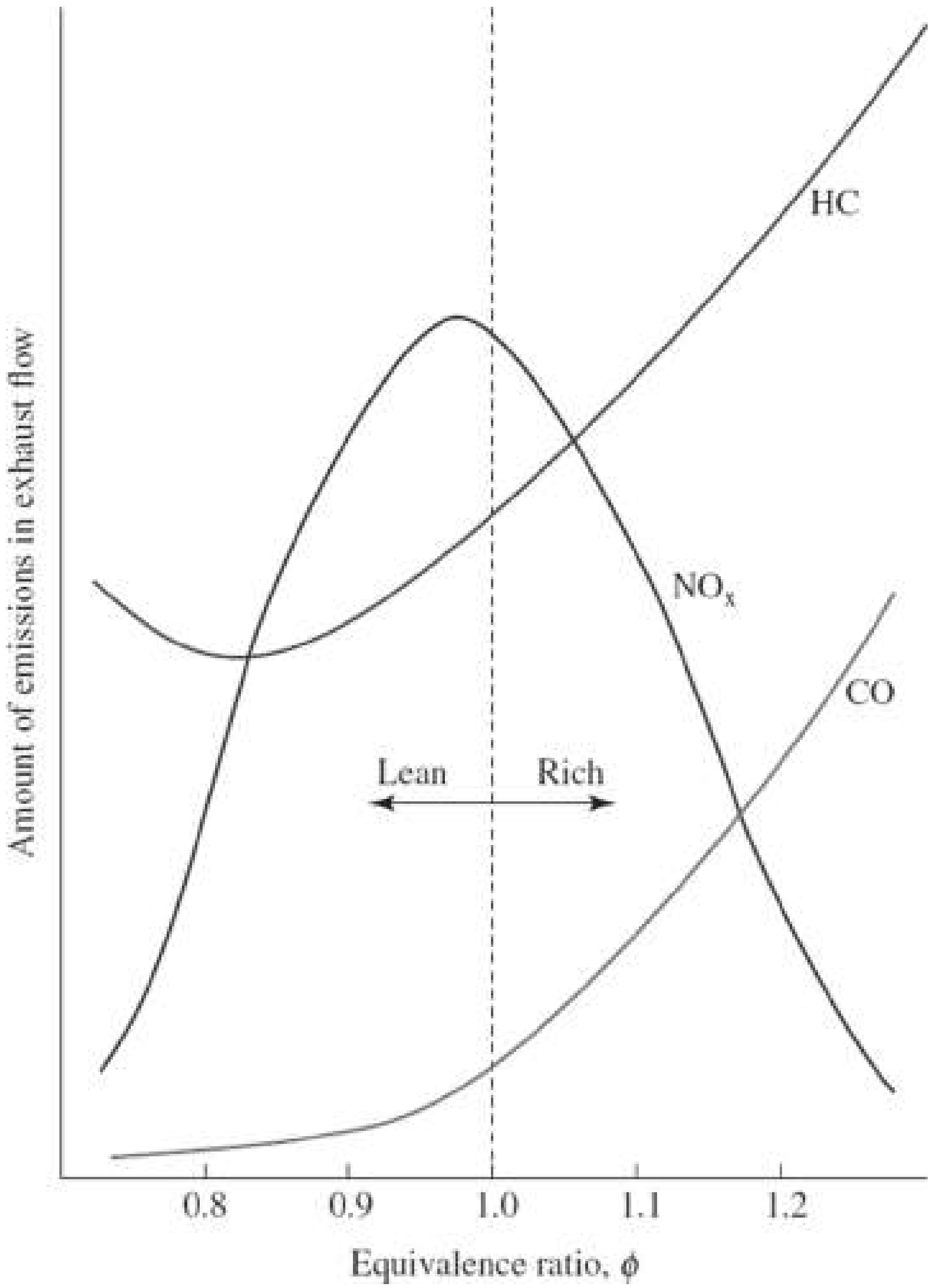


Figure 12-9
Effect of equivalence ratio (the ratio of theoretical air to actual air) on the amount of emissions in a gasoline burning internal combustion engine.

Catalytic Converters

Catalytic converters are commonly used in automobile engines for after treatment, and located in the exhaust system.

Hot exhaust gases leaving the combustion chamber are forced to flow in the converter which is a chemical chamber.

Some catalyst materials are used in the chamber to promote treatment reactions.

Reactions in catalytic converter

$$C_mH_n + w\,O_2 \rightarrow a\,H_2O + b\,CO_2$$

$$CO + \tfrac{1}{2}O_2 \rightarrow CO_2$$

$$CO + H_2O \rightarrow CO_2 + H_2$$

$$NO + CO \rightarrow \tfrac{1}{2}N_2 + CO_2$$

$$2NO + CO \rightarrow N_2O + CO_2$$

$$NO + H_2 \rightarrow \tfrac{1}{2}N_2 + H_2O$$

$$2NO + H_2 \rightarrow H_2O + H_2O$$

$$2NO + 5CO + 3H_2O \rightarrow 2NH_3 + 5CO_2$$

$$2NO + 5H_2 \rightarrow 2NH_3 + 2H_2O$$

Temperature requirements: These reactions readily take place in the converter at chamber temperatures of 600 to 700°C.

However, due to the existence of catalyst materials in the converter, these reactions can occur 250 to 300°C.

Since exhaust temperatures found in automobile and other transport engines are normally between 300 and 500°C, catalytic converters are very effective in reducing harmful emissions.

Effectiveness: A well-working catalytic converter reduces HC, CO, and NOx components by more than 90% when the converter temperature is 400°C or above.

Effect of temperature on effectiveness: Converter effectiveness reduces when the temperature goes down.

Effect of excess air on HC and CO treatment: For a converter to effectively treat HC and CO components, the air-fuel mixture should have some excess air. The converter is most effective for lean air-fuel mixtures.

Effect of rich mixture: Sometimes gasoline engines operate with rich mixtures especially during start-up and acceleration, and the catalytic converter becomes very ineffective during these periods.

Effect of excess air on treating NO_x: The converter is most effective in NO_x conversion when the mixture is close to stoichiometric (theoretical).

At lean mixtures, the converter becomes ineffective for treating NO_x components.

Catalytic converters in diesel engines: Diesel engines also use catalytic converters but their design should also include the conversion of carbon soot particles. This is done by using larger flow passages in the converter.

Diesel engines and NO_x treatment: Since diesel engines generally use lean mixtures, their converter is not effective in treating NO_x components. The solution for diesel engines is to use exhaust gas recycling (EGR).

Catalytic converters are called three-way converters as they mainly work on reducing three major automobile related pollutants:

HC, CO, and NO_x

Structure: Some catalytic converters are basically a stainless steel container mounted in the exhaust system, but close to the engine.

The inside of the container is a porous ceramic structure with packed spheres.

A more common type is a single honeycomb structure in which there are multiple flow passages for the exhaust.

Figure 12-10
Different types of catalytic converters for gasoline engines.
(a) Honeycomb structure.
(b) Packed spheres.
(c) A damaged converter showing inside structure.

Catalyst materials : They are located on the surface of ceramic passages.

Their task is to accelerate chemical reactions for the treatment of the pollutants.

The most common material used as the ceramic material of the converter is aluminum oxide (alumina).

Common catalyst materials:

- platinum
- rhodium
- palladium
- iridium

Platinum is effective in HC reaction.

Palladium is effective with CO reaction.

Rhodium is effective with NO_x reactions.

Effect of lead and sulfur on catalytic converter: Some components that may exist in fuel such as lead and sulfur can seriously harm catalytic converter by poisoning catalyst materials. Lead is particularly to be avoided as it poisons catalyst materials fast.

An engine with catalytic converter must not use leaded gasoline.

Effects of lead: Leaded gasoline has been phased out in gasoline engines since 1990s as lead is a poisonous pollutant with significant adverse effects on liver and kidney. It also accumulates in blood, bone, and soft tissues when ingested.

Amaount of lead in leaded gasoline: About 0.15 g of lead was present in leaded gasoline with 10 to 50 percent ending up in the engine exhaust.

12-4 THE GREENHOUSE EFFECT

What is greenhouse effect?

You have probably noticed that when you leave your car under direct sunlight on a sunny day, the interior of the car gets much warmer than the air outside, and you may have wondered why the car acts like a heat trap.

This is because glass at thicknesses encountered in practice transmits over 90% of radiation in the visible range and is practically opaque (nontransparent) to radiation in the longer wavelength infrared regions.

Therefore, glass allows the solar radiation to enter freely but blocks the infrared radiation emitted by the interior surfaces.

This causes a rise in the interior temperature as a result of the thermal energy buildup in the car.

This heating effect is known as the *greenhouse effect*, since it is utilized primarily in greenhouses.

Greenhouse effect on earth: The surface of the earth, which warms up during the day as a result of the absorption of solar energy, cools down at night by radiating part of its energy into deep space as infrared radiation.

Greenhouse gases: CO_2, water vapor, and trace amounts of some other gases such as methane and nitrous oxide (N_2O) act like a blanket and keep the earth warm at night by blocking the heat radiated from the earth.

They are called greenhouse gases, with CO_2 being the primary component along with water vapor.

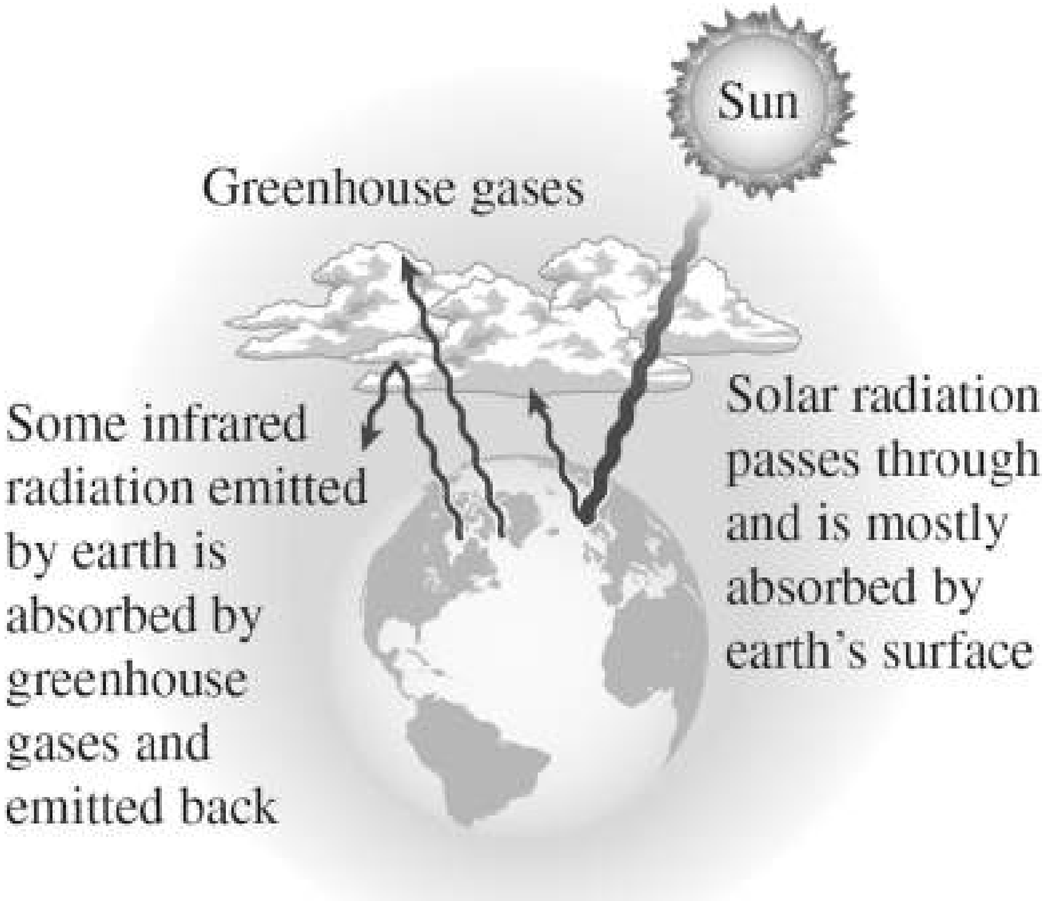


Figure 12-11
The greenhouse effect on earth.

Is greenhouse effect good or bad for earth? The greenhouse effect makes life on earth possible by keeping the earth warm (about 30°C warmer).

However, excessive amounts of greenhouse gases disturb the delicate balance by trapping too much energy, which causes the average temperature of the earth to rise and the climate at some localities to change.

What is global warming: These undesirable consequences of the greenhouse effect are referred to as global warming or global climate change.

Sources of global warming: The global climate change is due in part to the excessive use of fossil fuels such as coal, petroleum products, and natural gas in electric power generation, transportation, buildings, and manufacturing.

Amount of CO_2 in the atmosphere: As of 2019, it is about 410 ppm (or 0.41%).

This is 20% higher than the level a century ago, and it is projected to increase to over 700 ppm by the year 2100.

How can we reduce greenhouse gases? By increasing conservation efforts and improving conversion efficiencies, while meeting energy demands by the use of renewable energy rather than by fossil fuels.

A 1995 report: The world’s leading climate scientists concluded that the earth has already warmed about 0.5°C during the last century, and they estimate that the earth’s temperature will rise another 2°C by 2100.

Consequences of global warming

- 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

- Adverse side effects on human health and socioeconomic conditions in some areas

Global warming meetings

1992: A world summit in Rio de Janeiro, Brazil, attracted world attention to the problem. The agreement prepared by the committee in 1992 to control greenhouse gas emissions was signed by 162 nations.

1997: The world's industrialized countries adopted the Kyoto Protocol and committed to reduce their CO_2 and other greenhouse gas emissions by 5% below the 1990 levels by 2008 to 2012.

2011: Countries agreed in Durban, South Africa, to forge a new deal forcing the biggest polluting countries to limit greenhouse gas emissions.

2015: United Nations Climate Change Conference was held in Paris, resulting in the Paris Agreement on the reduction of climate change.

The main result of the conference was the establishment of a goal to limit global warming to less than 2°C compared to preindustrial times. Human-made (also called anthropogenic) greenhouse emissions should be eliminated during the second half of the 21st century.

CO_2 emissions in power plants and in automobiles

Major sources of greenhouse gas emissions are industrial sector and transportation.

Each kilowatt hour (kWh) of electricity produced in a fossil-fueled power plant produces 0.6 to 1 kg (1.3 to 2.2 lbm) of CO_2.

Each liter of gasoline burned by a vehicle produces about 2.5 kg of CO_2.

CO_2 and other emissions can be reduced significantly by buying an energy-efficient car that burns less fuel over the same distance, and by driving sensibly.

Saving fuel also saves money and the environment.

Figure 12-12
The average car produces several times its weight in CO_2 every year (it is driven 13,500 mi/yr, consumes 600 gal of gasoline, and produces 20 lbm of CO_2 per gallon)

CO_2 Production

$C + \frac{1}{2}O_2 \rightarrow CO$ $\quad$ $CO + \frac{1}{2}O_2 \rightarrow CO_2$

When there is a deficiency of O_2 in the combustion process, some CO cannot find O_2 to form into CO_2 and leaves the combustion chamber as CO.

CO is a very undesirable and poisonous emission.

CO_2 is not a pollutant.

It is undesirable because it is the primary greenhouse gas of concern regarding global warming.

How can CO_2 emissions be minimized? By replacing fossil fuels by renewable energy sources such as solar, wind, biomass, hydro, and geothermal. The consumption of fossil fuels can also be reduced by energy efficiency measures.

All fossil fuels (coal, oil, natural gas) contain carbon, and burning more of these fuels corresponds to more CO_2 production.

The combustion of fuels with a greater carbon percentage by mass produces a greater amount of CO_2 emission.

Combustion of octane

$$C_8H_{18} + 12.5(O_2 + 3.76N_2) \rightarrow 8CO_2 + 9H_2O + (12.5 \times 3.76)N_2$$

$$\frac{m_{CO_2}}{m_{\text{fuel}}} = \frac{N_{CO_2} M_{CO_2}}{N_{\text{fuel}} M_{\text{fuel}}}$$

Mass of CO_2 per unit mass of fuel

$$\frac{m_{CO_2}}{m_{\text{fuel}}} = \frac{N_{CO_2} M_{CO_2}}{N_{C_5H_{10}} M_{C_5H_{10}}} = \frac{(5\text{ kmol})(44\text{ kg/kmol})}{(1\text{ kmol})(70\text{ kg/kmol})} = \frac{220\text{ kg}}{70\text{ kg}} = 3.14\text{ kg }CO_2/\text{kg pentane}$$

Mass of CO_2 per kg of pentane

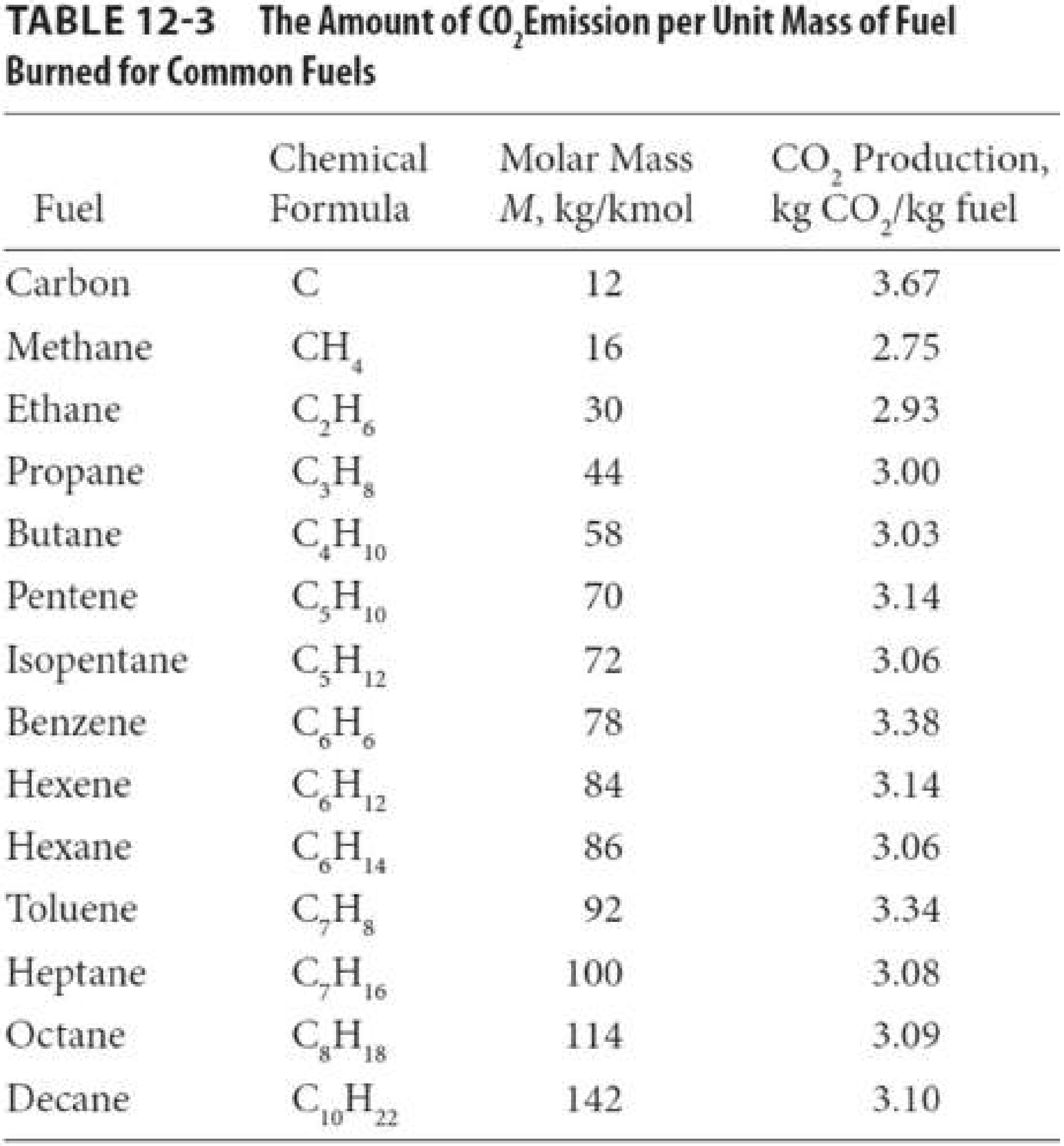


TABLE 12-3 **The Amount of CO_2 Emission per Unit Mass of Fuel Burned for Common Fuels**

Fuel	Chemical Formula	Molar Mass *M*, kg/kmol	CO_2 Production, kg CO_2/kg fuel
Carbon	C	12	3.67
Methane	CH_4	16	2.75
Ethane	C_2H_6	30	2.93
Propane	C_3H_8	44	3.00
Butane	C_4H_{10}	58	3.03
Pentene	C_5H_{10}	70	3.14
Isopentane	C_5H_{12}	72	3.06
Benzene	C_6H_6	78	3.38
Hexene	C_6H_{12}	84	3.14
Hexane	C_6H_{14}	86	3.06
Toluene	C_7H_8	92	3.34
Heptane	C_7H_{16}	100	3.08
Octane	C_8H_{18}	114	3.09
Decane	$C_{10}H_{22}$	142	3.10

CO_2 emissions by natural gas and coal

When coal, oil, and natural gas are burned in a combustion unit to provide thermal energy as in a space heating system or boiler of a power plant, the amount of CO_2 produced by natural gas is about 40 percent less than that by coal.

This is due to much higher energy content of natural gas (50,000 kJ/kg) per unit mass of the fuel compared to coal (usually between 20,000 and 30,000 kJ/kg).

Is natural gas a clean fuel?

Natural gas also emits less NO_x and PM and no SO_2 compared to coal and gasoline.

Thermal and environmental benefits of natural gas compared to coal and oil has made it an attractive fuel for electric power generation and space heating.

For these reasons, many consider natural gas as a clean fuel.

However, natural gas is still a fossil fuel and its combustion results in considerable amount of CO_2 and pollutant emissions.

CH_4 and N_2O as greenhouse gas

Methane and N_2O are other notable greenhouse gas emissions as well as air pollutants even though their emission rates are much lower than CO_2.

The energy sector (coal mining, natural gas systems, oil systems, combustion systems), agriculture, industrial activities, and waste management are major sources of CH_4 emissions.

N_2O is mostly emitted due to agricultural activities (nitrogen fertilization of soils and management of animal waste).

Energy use and industrial processes are other sources of N_2O.

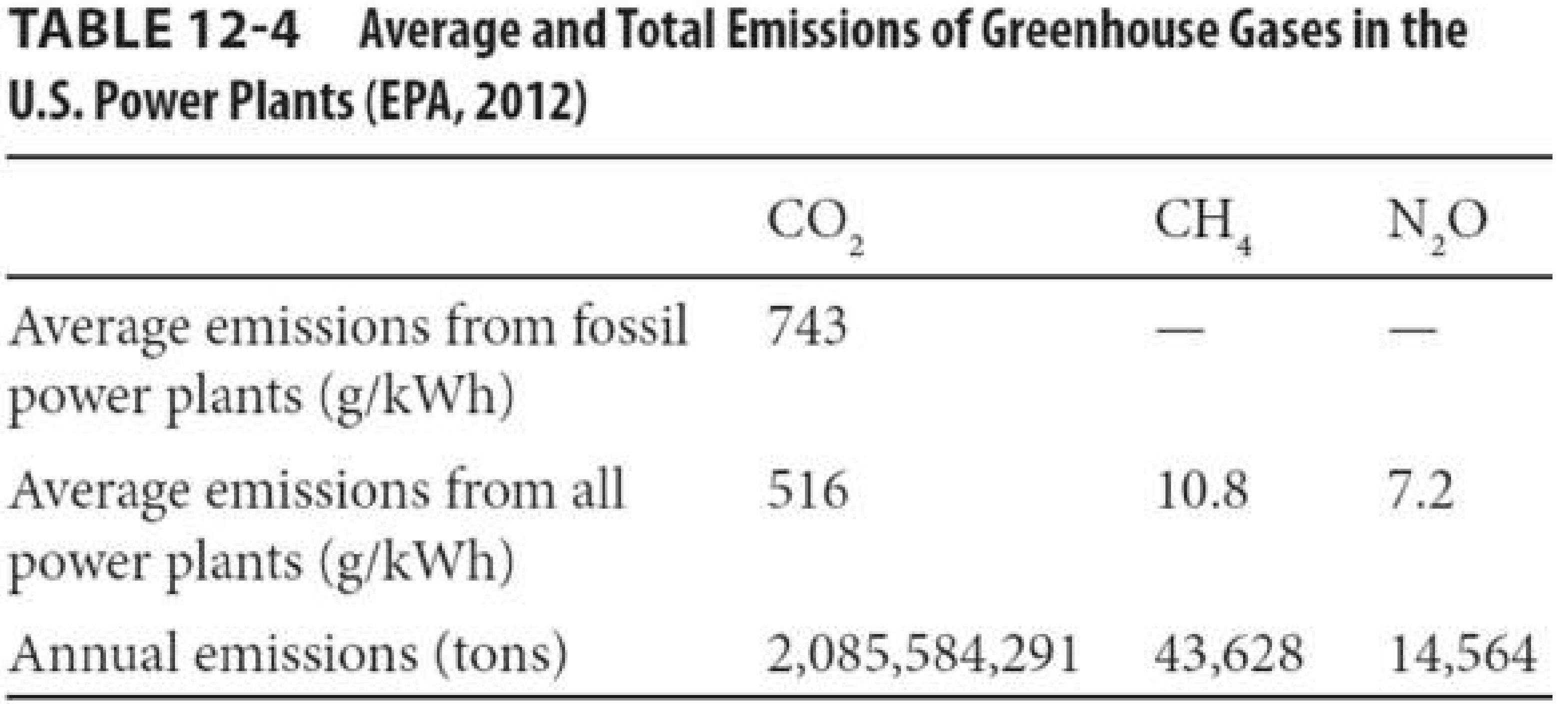


TABLE 12-4 Average and Total Emissions of Greenhouse Gases in the U.S. Power Plants (EPA, 2012)

	CO_2	CH_4	N_2O
Average emissions from fossil power plants (g/kWh)	743	—	—
Average emissions from all power plants (g/kWh)	516	10.8	7.2
Annual emissions (tons)	2,085,584,291	43,628	14,564

Global warming potential (GWP): It is defined as the ratio of the global warming effect of a given mass of a substance to that caused by the same mass of CO_2.

CO_2 is the reference gas used in measuring GWP, and, by definition, has a GWP of 1.

CH_4 is estimated to have a GWP of 28 to 36.

N_2O has a GWP of 265 to 298.

Other greenhouse gases: CFCs such as R-11, R-12, and R-113, which also cause stratospheric ozone depletion, hydrochlorofluorocarbons (such as HCFC-22), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF6).

The contribution of other greenhouse gases is much less than CO_2.

CO_2 in U.S. It is estimated that about 85 percent of the global warming emissions in the U.S. is due to CO_2.

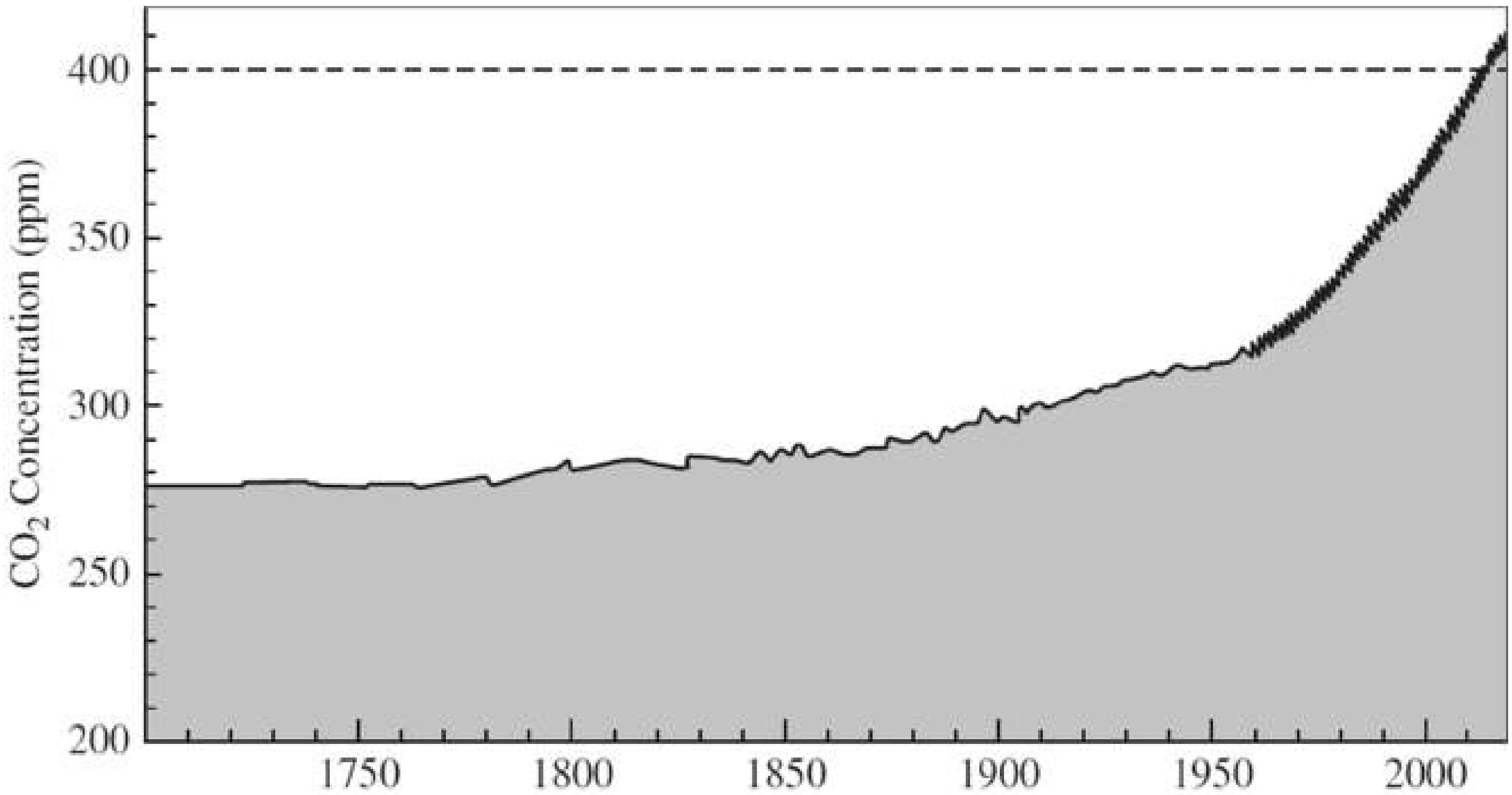


Figure 12-14
Historical trend in CO2 concentration. Measurements are from Mauna Loa Observatory in Hawaii.

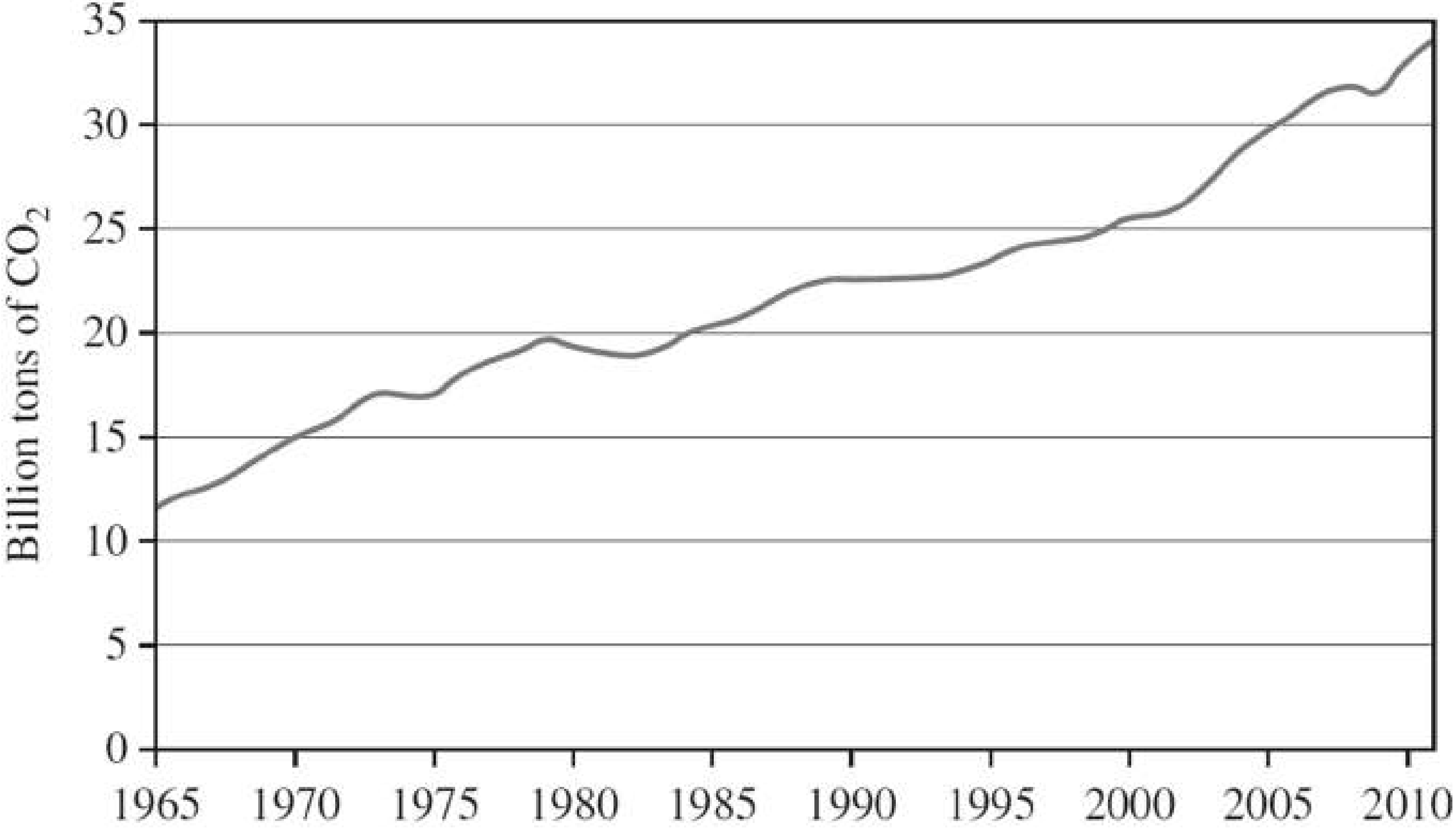


Figure 12-15

Historical trend in CO_2 emissions

Global CO_2 data

World fossil fuel related CO_2 emissions has been increasing steadily.

It reached an amount of 35.9 billion tons in 2014.

CO_2 emissions by coal, oil, and natural gas

Coal is the largest source of CO_2 emission representing 42% of total energy-related CO_2 emissions.

The share of other sources is oil (33%), natural gas (19%), cement production (6%), and gas flaring (1%).

Where do CO_2 emissions end up?

Not all CO_2 emissions end up in the atmosphere.

It is estimated that about 40% of CO_2 emissions are accumulated in the atmosphere, 30% in the oceans, and 30% on land.

The trends in CO_2 emissions are affected by the following parameters:

- Carbon intensity of energy: The amount of energy-related carbon dioxide emissions emitted per unit of energy produced

- Energy intensity of the economy: Energy consumed per dollar of gross domestic product, GDP

- Output per capita: GDP per person

- Population

Energy intensity can be decreased by energy efficiency measures.

Carbon intensity of energy can be decreased by switching to renewable energy.

Both of these will result in a decrease in CO_2 emissions.

However, the increases in output per capita and world population contribute higher rates of CO_2 emissions.

12-5 STRATOSPHERIC OZONE DEPLETION

Ground-level ozone: It is a pollutant.

Stratospheric ozone: The ozone (O_3) that exist in stratosphere.

It is 10 to 40 km above the earth’s surface.

It is desirable as it protects the earth from harmful ultraviolet (UV) radiation of the sun, mostly the most intense radiation known as ultraviolet-B (UV-B).

About 12% of solar radiation is in the UV range, and it would be devastating if it were to reach the surface of the earth.

Effects of UV

UV rays are to be avoided since they destroy protein and DNA molecules in biological tissue. They can kill microorganisms and cause serious damage to humans and other living beings.

The ozone (O_3) layer in the upper atmosphere acts as a protective blanket and absorbs most of the UV radiation.

The UV rays that remain in sunlight are still sufficient to cause serious sunburns to sun worshippers, and prolonged exposure to direct sunlight is the leading cause of skin cancer with increased risks of cataracts and blindness.

It also reduce immune function and harm algae, adversely affecting marine ecosystem.

Holes in the ozone layer: Discoveries of holes in the ozone layer in the late 1970s and 1980s have prompted the international community to ban the use of ozone-destroying chemicals such as the refrigerant Freon-12 and other CFCs in order to save the earth.

Ozone destroying reactions

The chemical reactions of CFCs in the stratosphere reacting with the ozone can be described by the following reactions

$$CCl_2F_2 + \text{solar energy} \rightarrow Cl + CClF_2$$

$$Cl + O_3 \rightarrow ClO + O_2$$

$$ClO + O \rightarrow Cl + O_2$$

In the first reaction, chlorofluoro methane is photo dissociated under the effect of intense UV radiation, yielding chlorine (Cl) atom.

Cl atom easily react with ozone to produce chlorine monoxide (ClO) and oxygen molecule (O_2), thus breaking ozone.

Stratosphere also contains atomic oxygen (O) which reacts with ClO to produce Cl and O_2 in the final reaction.

Free Cl atoms are responsible for the breakdown of ozone.

Chlorofluorocarbons (CFC)

The CFCs have been extensively used as refrigerants in refrigerators, air conditioners, and heat pumps from 1930s to 1990s.

The CFCs used in the refrigeration systems eventually end up in the atmosphere through leaking during its use or after its useful life.

Chlorine is also introduced to the atmosphere by salt (NaCl) in the ocean, volcanoes, and industrial processes.

The first member of the CFC family of refrigerants was refrigerant-11 (R-11)

Commercial production of R-11 and R-12 was started in 1931.

The versatility and low cost of CFCs made them the refrigerants of choice.

CFCs were also widely used in aerosols, foam insulations, and the electronic industry as solvents to clean computer chips.

Other refrigerants

R-11 was used primarily in large-capacity water chillers serving air-conditioning systems in buildings.

R-12 was used in domestic refrigerators and freezers, as well as automotive air conditioners.

R-22 has been used in window air conditioners, heat pumps, air conditioners of commercial buildings, and large industrial refrigeration systems.

R-502 (a blend of R-115 and R-22) has been the dominant refrigerant used in commercial refrigeration systems such as those in supermarkets.

Fully halogenated CFCs (such as R-11, R-12, and R-115) do the most damage to the ozone layer.

The nonfully halogenated refrigerants such as R-22 have about 5% of the ozone-depleting capability of R-12.

R-22 is a hydro-chlorofluorocarbon (HCFC) and its use must be discontinued by 2015.

Measures to prevent ozone depletion

The ozone crisis has caused a major stir in the refrigeration and air-conditioning industry.

It was realized in 1970s that CFCs allow more UV radiation into the earth’s atmosphere by destroying the protective ozone layer.

The use of some CFCs is banned in 1987 by Montreal Protocol.

Refrigerants that are friendly to the ozone layer that protects the earth from harmful UV rays have been developed.

The once popular refrigerant R-12 has largely been replaced by chlorine-free R-134a.

R-134a is mostly used in household refrigerators and automotive air conditioners.

The most common refrigerants for new air-conditioning and heat pump systems are R-410A and R-407C, which are also HFC refrigerants.

An HFC refrigerant does not contribute to ozone depletion.

12-6 NUCLEAR WASTE

Nuclear potential

A single nuclear power plant using fission reaction in the reactors typically produces thousands of megawatts of electricity.

1 kg of fissioned nuclear material can release 10^{11} kJ of thermal energy, which is roughly two million times the energy released when 1 kg of fossil fuel burns.

Only about 4% of the nuclear fuel is fissile uranium-235.

A unit mass of fissile nuclear fuel can provide about 80,000 times more energy than a unit mass of fossil fuel.

Fission

A nuclear fission reaction breaks nucleus of an atom which releases large amounts of energy.

In fission reaction, neutrons react with fissile isotopes of uranium and plutonium.

Uranium-233, uranium-235, and plutonium-239 are fissile isotopes.

Only uranium-235 is found in nature, but the others can be produced artificially.

Uranium-235 is used in nuclear reactors.

Is nuclear solution to pollutant and greenhouse gas emissions?

Some people may regard nuclear power plants as a potential solution to air pollution and greenhouse gas emission.

This is because the air pollutants produced by the combustion of fossil fuels such as HC, carbon soot particles, CO, sulfur oxides, and NO_x are not generated after a nuclear fission reaction.

In addition, a nuclear reaction does not generate any CO_2, which is the major greenhouse gas.

Other people, however, do not consider nuclear energy as an alternative to fossil fuels due to safety of nuclear power plants and concern over safe and permanent disposal of nuclear waste.

Nuclear accidents

Chernobyl accident that occurred in 1986 at the Chernobyl nuclear power plant in Ukraine (in former Soviet Union) was the worst nuclear power plant accident in history.

The most recent nuclear disaster occurred in Fukushima (Japan) at Fukushima I nuclear power plant in 2011.

The accident was initiated by a devastating tsunami of an earthquake.

Tsunami caused some equipment failures and as a result, reactors could not be cooled resulting in three nuclear meltdowns and large releases of radioactive materials.

Nuclear waste

Nuclear waste is generated due to fission reactor operation in nuclear power plants.

Radioactive wastes: The products of fuel rods after a fission reaction make up main radioactive wastes. Materials located or used in the reactor room absorb neutrons and become radioactive.

High-level radioactive waste consists of fission products and transuranic (elements heavier than uranium like plutonium) isotopes.

Radioactivity: When a used nuclear fuel is first discharged, intense levels of radioactivity exists. The content of the fuel changes as the time passes. However, the total radioactivity does not decrease significantly.

After 100 years, percent of total radioactivity can be as high as 99%. Therefore, once a nuclear fuel goes through a fission reaction it will be radioactive for thousands of years.

Handling nuclear wastes

Some countries recycle nuclear fuel elements.

They put high-level nuclear waste into glass or ceramic logs.

In the United States, used fuel elements are not recycled.

Instead, they are stored for several years at the reactor site until short-lived isotopes can decay and radioactive heat generation is minimized.

Later, they are taken to temporary storage locations for long-term storage.

The Yucca Mountain site in Nevada is considered as a potential deep geological repository for the used nuclear fuel.

Other wastes in nuclear plants

There are also low-level wastes produced in nuclear power plants. They include gloves, towels, lab coats, filters, and other materials that may contain small amounts of radioactive material.

These wastes are carefully handled by placing in drums and stored at some burial ground.

Effects of radioactive emissions

Radioactive emissions are harmful to living organisms.

The higher the level of radioactivity, the higher the potential health effects on humans.

Long-wave radiations with biological material causes cell damage.

Increased rate of cancer with exposure to nuclear radiation remains to be a serious concern.