HEAT TRANSFER

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CONTENTS

CHAPTER 1

INTRODUCTION

Heat transfer is defined as the transfer of energy across a system boundary caused solely by a temperature difference.

The study of heat transfer has long been a basic part of engineering curricula because of the significance of energy-related applications. For example, the transfer of heat in power plants from the energy source, be it fossil, nuclear, solar, or other, to the working fluid is one of the most basic processes in such systems. Similarly, the operation of refrigeration and air-conditioning units depend on the effective transfer of heat in condensers and evaporators. Other applications pertaining to environmental control, which are of particular interest currently, include the minimization of building-heat losses by means of improved insulating techniques and the use of supplemental energy sources, such as solar radiation, heat pumps, and fireplaces. Heat transfer is also very important in the operation of electrical machinery and transformers, and is often the controlling factor in the miniaturization of electronic systems.

Today the generation of electrical energy in power plants is primarily derived from fossil fuels—coal, natural gas, and oil. The cross section of a typical large coal-fired boiler used in power stations is shown in Fig. 1–1. In this system, high-pressure preheated water flowing in the vertical tubes surrounding the combustion chamber is heated by radiation and convection heat transfer, which results from the high temperatures produced by the combustion of coal. After separating the liquid and vapor in the upper steam drum, the vapor is further heated by a series of heat exchangers (known as superheaters), which operate at higher temperatures, and is then delivered to the steam turbine. The air supplied to the combustion chamber is first forced through a steam-heated coil in order to remove excess moisture and then through an exhaust gas/air preheater.

Although traditional fossil fuels such as coal and oil will be utilized for many years to come, a new era has been brought upon us by rising costs and environmental

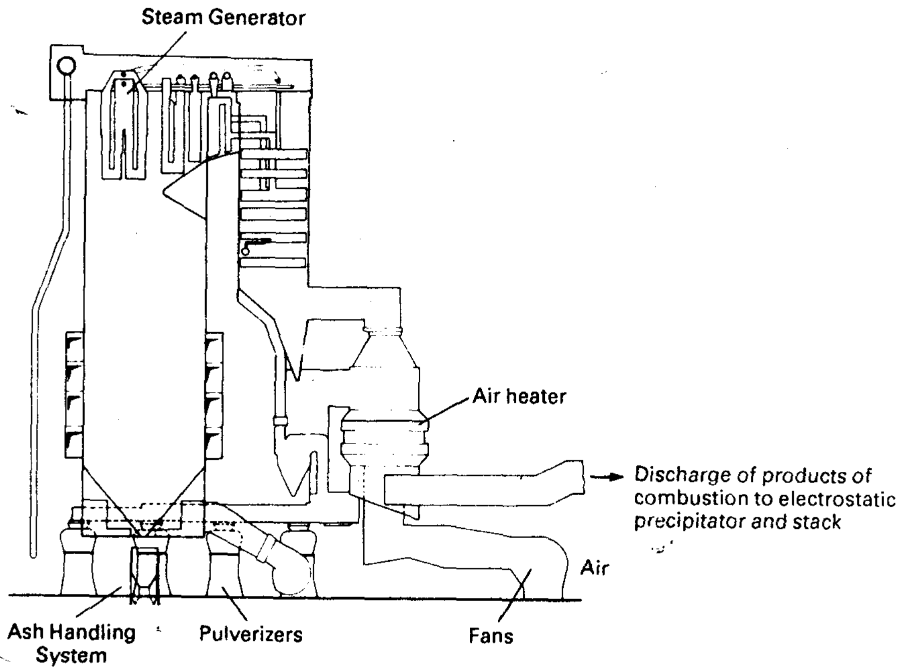
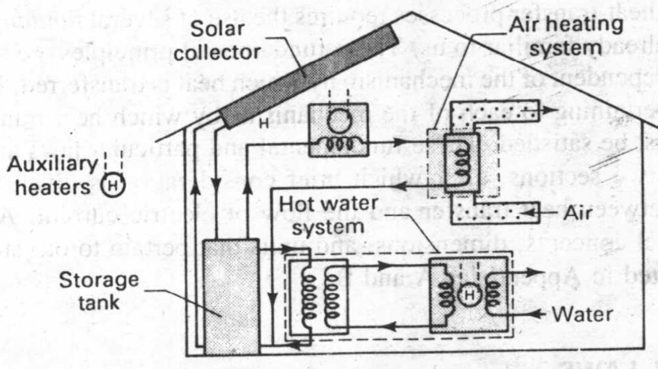


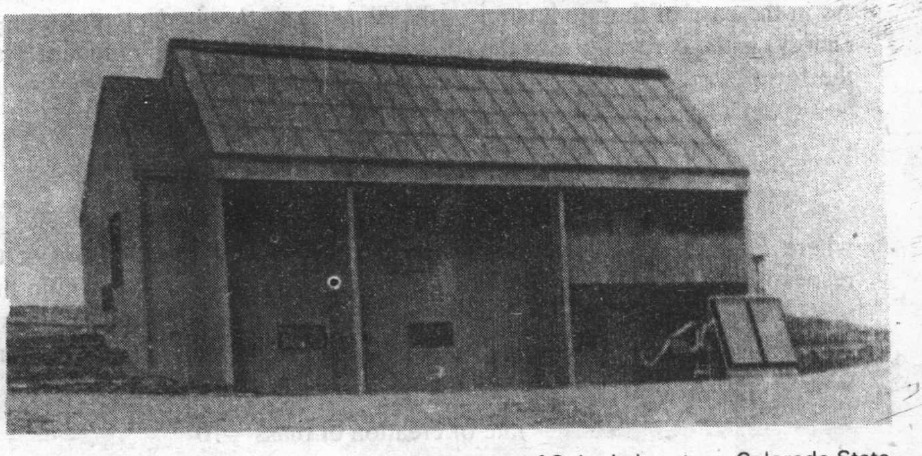
FIGURE 1–1 Coal-fired steam boiler for electric power station. (Courtesy Babcock and Wilcox.)

considerations associated with the use of these resources. As solutions are sought to our energy problems, there is no doubt that heat transfer will be a key factor. The most obvious example is the generation of power by nuclear fission, which involves (1) the transfer of heat from the reactor core to fluid circulating in a primary loop, and (2) the transfer of energy by a heat exchanger to convert secondary water to steam to power an electric generator. Although safety and environmental concerns persist, the use of nuclear power continues to increase in many countries. Another example is the use of solar energy in heating, cooling, and energy generation. The schematic of a typical solar heating system is shown in Fig. 1–2(a). This arrangement is used in the Colorado State University Solar House shown in Fig. 1–2(b). In this and other solar energy applications, thermal radiation from the sun is captured in collectors, transferred to a working fluid such as water, and stored. The stored energy is then used for direct heating of the building during both day and night. Auxiliary electrical heating is provided for periods of inclement weather. Of course, the effective use of solar energy requires that the system be carefully insulated.

The primary objective in the analysis of most heat-transfer problems is either to (1) determine the temperature distribution within the system and the rate of heat transfer for specified operating conditions (the function of evaluation), or (2) prescribe the necessary configuration (size and shape) in order to accomplish a given heat-transfer rate and/or temperatures (the function of thermal design). Although emphasis



(a) Schematic of typical solar heating system.



(b) Solar house II in CSU Solar Village. (Courtesy of Solar Laboratory, Colorado State University.)

FIGURE 1–2 Solar heating.

in our study will be placed on the evaluation function, the concepts of thermal (and hydraulic) analysis that will be developed provide the foundation for the actual design of systems involving heat transfer.

Because thermodynamics involves the study of heat and work for systems in equilibrium, a thermodynamic analysis can only provide us with predictions for the total quantity of heat transferred during a process in which a system goes from one equilibrium state (uniform temperature) to another. However, the length of time required for such processes to occur cannot be obtained by thermodynamics alone. On the other hand, the study of heat transfer involves a consideration of the mechanics of the transfer of thermal energy and is not restricted to equilibrium states. It is the science of heat transfer that enables us to perform the critical evaluation and design functions.

Analysis of heat-transfer processes requires the use of several *fundamental laws*, all of which are already familiar to us. These fundamental principles are of a general nature and are independent of the mechanism by which heat is transferred. In addition, *particular laws* pertaining to each of the mechanisms by which heat transfer can be accomplished must be satisfied. These fundamental and particular laws are reviewed in the following two sections, after which brief consideration is given to the very useful analogy between heat transfer and the flow of electric current. A review of basic mathematical concepts, dimensions, and units that pertain to our study of heat transfer is presented in Appendixes A and B.

1-1 FUNDAMENTAL LAWS

As in the case of thermodynamics, the *first law of thermodynamics* (conservation of energy) is the cornerstone of the science of heat transfer. This fundamental law takes the form

$$\text{rate of creation of energy} = 0$$

$$\Sigma \dot{E}_o - \Sigma \dot{E}_i + \frac{\Delta E_s}{\Delta t} = 0 \tag{1-1}$$

where $\dot{E}_i$ and $\dot{E}_o$ represent the rate of energy transfer into and out of the system, respectively, and $\Delta E_s/\Delta t$ is the rate of change in energy stored within the system.

Two other fundamental laws are required in the analysis of heat transfer in fluids that are in motion: (1) the *principle of conservation of mass* (for nonrelativistic conditions),

$$\text{rate of creation of mass} = 0$$

$$\Sigma \dot{m}_o - \Sigma \dot{m}_i + \frac{\Delta m_s}{\Delta t} = 0 \tag{1-2}$$

and (2) *Newton's second law of motion*, which is represented in terms of the x-component by

$$\text{rate of creation of momentum} = \text{sum of forces}$$

$$\Sigma \dot{M}_{o,x} - \Sigma \dot{M}_{i,x} + \frac{\Delta M_{s,x}}{\Delta t} = \Sigma F_x \tag{1-3}$$

where the momentum M_x represents the product of the x-component of velocity u and the mass m.

Three supplementary fundamental principles are required in the analysis of all heat-transfer processes: (1) *the second law of thermodynamics*, which provides us with the very critical conclusion that heat is transferred in the direction of decreasing temperature; (2) the principle of *dimensional continuity*, which requires that all equations be dimensionally consistent; and (3) *equations of state*, which provide information in equation, tabular, or graphical form pertaining to the thermodynamic properties at any state.

Concerning the thermodynamic properties, the symbols U and H ($H = U + PV$) will be used to designate the *internal energy* and *enthalpy* of a given mass m of a substance. Information pertaining to the *specific internal energy e* ($e = U/m$) and *specific enthalpy i* ($i = H/m$) is tabulated for common substances (e.g., steam tables). In addition, e and i can be expressed in terms of the *constant-volume specific heat* c_v and the *constant-pressure specific heat* c_P by

$$c_v = \left.\frac{\partial e}{\partial T}\right|_v \qquad c_P = \left.\frac{\partial i}{\partial T}\right|_P \tag{1-4,5}$$

For important practical applications involving ideal fluids (i.e., ideal gases and incompressible liquids), de and di are given by

$$de = c_v\, dT \qquad di = c_P\, dT \tag{1-6,7}$$

or, for systems with constant mass m,

$$dU = mc_v\, dT \qquad dH = mc_P\, dT \tag{1-8,9}$$

1-2 BASIC TRANSPORT MECHANISMS AND PARTICULAR LAWS

Conduction and thermal radiation represent the two fundamental mechanisms by which heat transfer is accomplished. These heat-transfer mechanisms occur in both solids and fluids. Transfer of heat by conduction (and sometimes by thermal radiation) from a solid surface to a moving fluid is known as *convection heat transfer*. These three modes of heat transfer and the particular laws that govern these phenomena are introduced in the following sections.

1-2-1 Conduction Heat Transfer

From the thermodynamic view, *temperature T* is a property that is an index of the kinetic energy possessed by the building-block particles of a substance (i.e., molecules, atoms, and electrons); the greater the agitation of these basic components of which matter is made, the higher the temperature. In this light, *conduction heat transfer* is the transfer of energy caused by physical interaction among molecular, atomic, and subatomic particles of a substance at different temperatures (level of kinetic energy). To expand upon this point, conduction in gases involves the collision and exchange of energy and momentum among molecules in continuous random motion. This same molecular transport mechanism occurs in liquids, but is complicated by the effects of molecular force fields, and can be augmented by the transport of free electrons in liquids that are good electrical conductors. On the other hand, conduction in solids occurs as a result of the movement of free electrons and vibrational energy in the atomic lattice structure of the material.

Fourier Law of Conduction

On the basis of experimental observation, the rate of heat transferred by conduction in the x direction through a finite area A_x for the situation in which T is a function only of x can be expressed by

$$q_x = -kA_x \frac{dT}{dx} \qquad (1\text{–}10)$$

where A_x is normal to the direction of transfer x, and k is the *thermal conductivity*. This equation was first used to analyze conduction heat transfer in 1822 by a French mathematical physicist named J. Fourier [1] and has come to be called the *Fourier law of conduction*. An example of a one-dimensional molecular conduction-heat-transfer problem for which this equation applies is illustrated in Fig. 1–3, which shows a plate with surface temperatures T_1 and T_2. Because no temperature differences occur in the y and z directions, q_y and q_z are both zero. For this case in which T_1 is greater than T_2, the temperature gradient is negative. (As shown in Chap. 2, the temperature distribution is linear in this application because q_x, k, and A_x are all constants.)

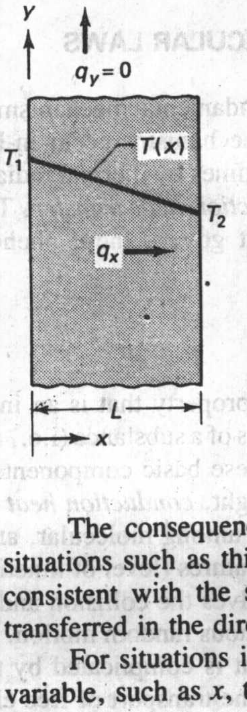


FIGURE 1–3
One-dimensional conduction heat transfer in a plate with $T_1 > T_2$; $q_y = 0$ and $q_z = 0$.

The consequence of the minus sign in Eq. (1–10) is that q_x is positive for situations such as this in which the temperature gradient is negative. This result is consistent with the second law of thermodynamics, which stipulates that heat is transferred in the direction of decreasing temperature.

For situations in which the temperature is a function of time t and one space variable, such as x, the Fourier law of conduction is written as

$$q_x = -kA_x \frac{\partial T}{\partial x} \qquad (1\text{–}11)$$

where q_x also is a function of t and x. Expressions of the form of Eqs. (1–10) and (1–11) can also be written for conduction heat transfer in the y, z, or r directions, as will be illustrated in Chap. 2. For applications in which the temperature T is a function of more than one spatial dimension, the heat transfer in each direction must be accounted for. For example, for the case in which T is a function of x and y, we must write expressions for both q_x and q_y. To accomplish this task, we utilize a more general form of the Fourier law of conduction. This general Fourier law of conduction is presented in Chap. 3, which deals with multidimensional conduction heat transfer.

Thermal Conductivity The *thermal conductivity* k is a thermophysical property of the conducting medium that represents the rate of conduction heat transfer per unit area for a temperature gradient of 1 °C/m (or 1 °F/ft). The units for k are W/(m °C) [or Btu/(h ft °F)]. (Note that °C = 1 K and °F = 1 °R.) The thermal conductivities of various common substances are listed in Table 1–1 for standard atmospheric conditions. More extensive tabulations of thermal conductivities and other properties are given in Tables A–C–1 through A–C–5 of the Appendix and in references 2 through 6.

At room temperature, k ranges from values in the hundreds for good conductors of heat such as diamond and various metals to less than 0.01 W/(m °C) for some gases. Materials with values of k less than about 1 W/(m °C) are classified as insulators. As a rule of thumb, metals with good electrical conducting properties have higher thermal conductivities than do dielectric nonmetals or semiconductors. This is because the molecular interaction in good electrical conductors is enhanced by the movement of free electrons. Exceptions to this rule include dielectric crystals, such as diamond, sapphires, and quartz, and electric semiconductors, such as silicon and germanium. A second rule is that solid phases of materials generally have higher thermal conductivities than do liquid phases. An exception to this rule is bismuth, which has a higher thermal conductivity for the liquid phase than for the solid phase.

The variation of k with temperature is shown in Fig. 1–4 for several representative substances and in Figs. A–C–1 through A–C–4 for various other common materials. The thermal conductivity of many of these substances varies by a factor of 10 or more for an order-of-magnitude change in temperature. On the other hand, the variation in k with temperature for some materials over certain temperature ranges is small enough to be neglected. We also note that exceptionally high thermal conductivities occur among the solid materials that were judged to be good conductors at room temperature. For example, the thermal conductivity of aluminum reaches a maximum value of about 20,000 W/(m °C) at 10 K. This is over 100 times as large as the value that occurs at room temperature. Substances under low-temperature conditions that have such exceedingly high thermal conductivities are known as *superconductors*.

In homogeneous materials, k can generally be assumed to be independent of direction (i.e., isotropic). However, some pure materials and laminates have thermal conductivities that are dependent upon the direction of heat flow. For example, the

TABLE 1–1 Thermal conductivity of various substances at room temperature

Substance	k W/(m °C)	k Btu/(h ft °F)
Metals		
Silver	420	240
Copper	390	230
Gold	320	180
Aluminum	200	120
Silicon	150	87
Nickel	91	53
Chromium	90	52
Iron (pure)	80	46
Germanium	60	35
Carbon steel (0.5% C)	54	31
Nonmetallic Solids		
Diamond, type 2A	2300	1300
Diamond, type 1	900	520
Sapphire (Al_2O_3)	46	27
Limestone	1.5	0.87
Glass (Pyrex 7740)	1.0	0.58
Teflon (Duroid 5600)	0.40	0.23
Brick, building	0.69	0.399
Plaster	0.13	0.075
Cork	0.040	0.023
Liquids		
Mercury	8.7	5.0
Water	0.6	0.35
Freon F-12	0.08	0.046
Gases		
Hydrogen	0.18	0.10
Air	0.026	0.015
Nitrogen	0.026	0.015
Steam	0.018	0.01
Freon F-12	0.0097	0.0056

Source: From references 2 through 5.

thermal conductivity of wood is different for heat conduction across the grain than for heat transfer parallel to the grain. Other materials with such nonisotropic characteristics include crystalline substances, laminated plastics, and laminated metals. For an introduction to the topic of conduction heat transfer in nonisotropic materials, the textbook by Eckert and Drake [7] is recommended.

Heat-transfer applications involving the more familiar metallic conductors such as copper and aluminum and insulators such as rock wool and cork are known to us

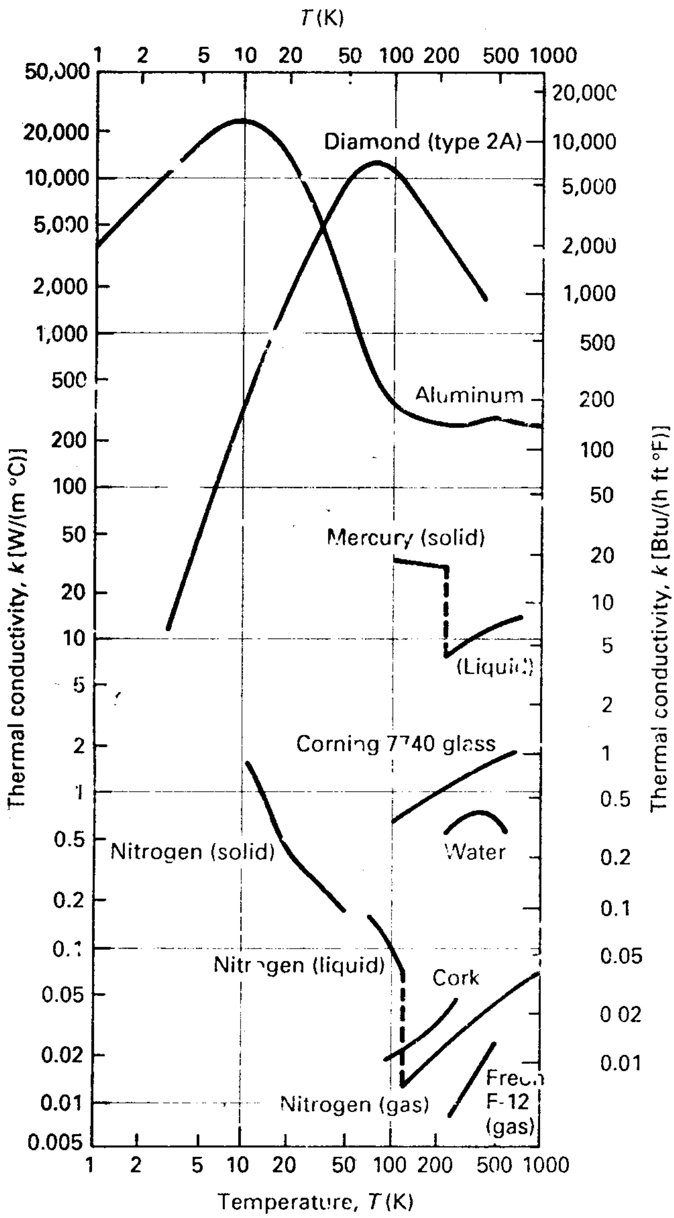


FIGURE 1-4 Variation of thermal conductivity k with temperature for representative substances (From Touloukian et al. [2]. Used with permission.)

all. To name only a few, tubes made of copper, stainless steel, aluminum, and other metals are used in boilers, evaporators, and condensers to transmit energy from one fluid to another; metal pans are used to cook food; double glass panes are used to minimize heat loss through windows; and glass fibers, bricks, and other insulative materials are used to reduce building heat losses in the winter and heat gains in the summer.

Because of their high thermal conductivities and large electrical resistivities, silicon and diamond also find application, especially in the field of electronics. For example, silicon greases, pastes, and gaskets are often used in the construction of electronic systems in order to increase the rate of heat transfer while maintaining good electrical insulation between components. As another example, Fig. 1–5 shows a gold-plated diamond (type 2A) cube diode. Diodes such as these, ranging in size from below 0.1 mm to a few millimeters across, are used to generate high-frequency radio waves that relay telephone conversations and television broadcasts. These small diodes are characterized by very high power density operation, with operating temperatures in the range 150°C to 200°C. Because type 2A diamond has the highest thermal conductivity of all known materials in this temperature range, the diamond cube is used to remove the energy generated in the electronic semiconductor chip. Because of its effectiveness as a heat conductor, the diamond cube reduces the operating temperature of the diode, thereby increasing its lifetime and reliability.

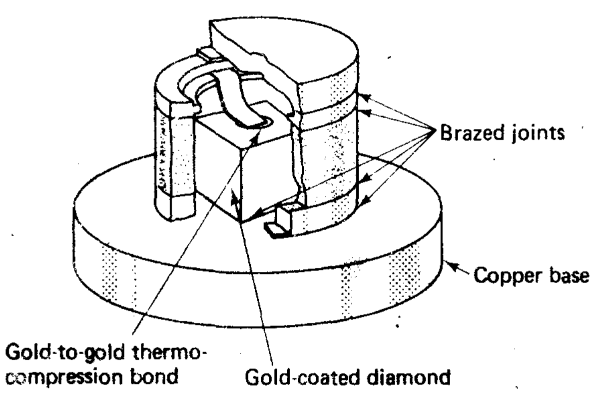


FIGURE 1–5
Microwave oscillator diode with diamond heat sink. (Courtesy of Bell Telephone Laboratories and D. Drukker & ZN. N.Y.)

Analysis of Conduction Heat Transfer

Consideration is now given to the analysis of conduction heat transfer in solids or stationary fluids. The important topic of conduction heat transfer in moving fluids will be considered separately in Sec. 1–2–3, which deals with convection.

The general theoretical analysis of conduction-heat-transfer problems involves (1) the use of (a) the fundamental first law of thermodynamics and (b) the Fourier law of conduction (particular law) in the development of a mathematical formulation that represents the energy transfer in the system; and (2) the solution of the resulting system of equations for the temperature distribution. Once the temperature distribution is known, the rate of heat transfer is obtained by use of the Fourier law of conduction. The basic concepts involved in the theoretical analysis of conduction-heat-transfer problems will be presented in Chap. 2 in the context of fairly simple one-dimensional systems. These fundamentals will then be extended to multidimensional systems in Chap. 3.

Conduction Shape Factor A simple practical approach to the analysis of basic steady-state conduction-heat-transfer problems has been developed that involves the use of an equation derived from the fundamental and particular laws. This practical equation for conduction heat transfer takes the form (for systems with uniform thermal conductivity)

$$q = kS(T_1 - T_2) \tag{1-12}$$

where q is the rate of heat transfer conducted from a surface at temperature T_1 to a surface at T_2, and S is known as the *conduction shape factor*; the unit for S is m (or ft). The conduction shape factor S is dependent upon geometry. Representative conduction shape factors are listed in Table 1-2 for several basic geometries. This practical approach to the analysis of conduction-heat-transfer problems is illustrated by several examples in this chapter. The theoretical basis for this simple method will be developed for one-dimensional systems in Chap. 2 and will be extended to more complex multidimensional systems in Chap. 3.

TABLE 1-2 Conduction shape factors S

Geometry	S
Flat plate Cross-sectional area A Thickness L	A/L
Hollow cylinder Radii r_1 and r_2 Length L	$\dfrac{2\pi L}{\ln (r_2/r_1)}$
Hollow sphere Radii r_1 and r_2	$\dfrac{4\pi r_1 r_2}{r_2 - r_1}$