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CHAPTER

1 Introduction

Heat transfer is the science that seeks to predict the energy transfer that may take place between material bodies as a result of a temperature difference. Thermodynamics teaches that this energy transfer is defined as heat. The science of heat transfer seeks not merely to explain how heat energy may be transferred, but also to predict the rate at which the exchange will take place under certain specified conditions. The fact that a heat-transfer *rate* is the desired objective of an analysis points out the difference between heat transfer and thermodynamics. Thermodynamics deals with systems in equilibrium; it may be used to predict the amount of energy required to change a system from one equilibrium state to another; it may not be used to predict how fast a change will take place since the system is not in equilibrium during the process. Heat transfer supplements the first and second principles of thermodynamics by providing additional experimental rules that may be used to establish energy-transfer rates. As in the science of thermodynamics, the experimental rules used as a basis of the subject of heat transfer are rather simple and easily expanded to encompass a variety of practical situations.

As an example of the different kinds of problems that are treated by thermodynamics and heat transfer, consider the cooling of a hot steel bar that is placed in a pail of water. Thermodynamics may be used to predict the final equilibrium temperature of the steel bar–water combination. Thermodynamics will not tell us how long it takes to reach this equilibrium condition or what the temperature of the bar will be after a certain length of time before the equilibrium condition is attained. Heat transfer may be used to predict the temperature of both the bar and the water as a function of time.

Most readers will be familiar with the terms used to denote the three modes of heat transfer: conduction, convection, and radiation. In this chapter we seek to explain the mechanism of these modes qualitatively so that each may be considered in its proper perspective. Subsequent chapters treat the three types of heat transfer in detail.

1-1 | CONDUCTION HEAT TRANSFER

When a temperature gradient exists in a body, experience has shown that there is an energy transfer from the high-temperature region to the low-temperature region. We say that the energy is transferred by conduction and that the heat-transfer rate per unit area is proportional to the normal temperature gradient:

$$\frac{q_x}{A} \sim \frac{\partial T}{\partial x}$$

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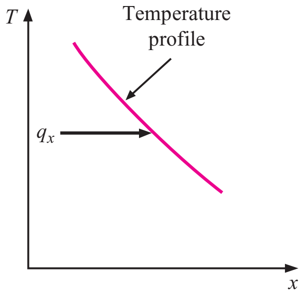
When the proportionality constant is inserted,

$$q_x = -kA\,\frac{\partial T}{\partial x} \qquad \textbf{[1-1]}$$

where q_x is the heat-transfer rate and $\partial T/\partial x$ is the temperature gradient in the direction of the heat flow. The positive constant k is called the *thermal conductivity* of the material, and the minus sign is inserted so that the second principle of thermodynamics will be satisfied; i.e., heat must flow downhill on the temperature scale, as indicated in the coordinate system of Figure 1-1. Equation (1-1) is called Fourier's law of heat conduction after the French mathematical physicist Joseph Fourier, who made very significant contributions to the analytical treatment of conduction heat transfer. It is important to note that Equation (1-1) is the defining equation for the thermal conductivity and that k has the units of watts per meter per Celsius degree in a typical system of units in which the heat flow is expressed in watts.

Figure 1-1 | Sketch showing direction of heat flow.



We now set ourselves the problem of determining the basic equation that governs the transfer of heat in a solid, using Equation (1-1) as a starting point.

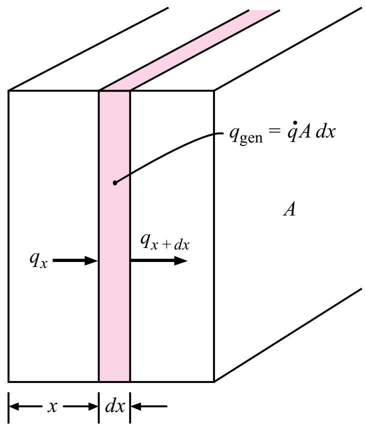
Consider the one-dimensional system shown in Figure 1-2. If the system is in a steady state, i.e., if the temperature does not change with time, then the problem is a simple one, and we need only integrate Equation (1-1) and substitute the appropriate values to solve for the desired quantity. However, if the temperature of the solid is changing with time, or if there are heat sources or sinks within the solid, the situation is more complex. We consider the general case where the temperature may be changing with time and heat sources may be present within the body. For the element of thickness dx, the following energy balance may be made:

$$\begin{aligned}&\text{Energy conducted in left face} + \text{heat generated within element}\\ &\qquad = \text{change in internal energy} + \text{energy conducted out right face}\end{aligned}$$

These energy quantities are given as follows:

$$\begin{aligned}\text{Energy in left face } &= q_x = -kA\,\frac{\partial T}{\partial x}\\ \text{Energy generated within element } &= \dot{q}A\,dx\end{aligned}$$

Figure 1-2 | Elemental volume for one-dimensional heat-conduction analysis.



$$\text{Change in internal energy } = \rho c A \frac{\partial T}{\partial \tau} dx$$

$$\text{Energy out right face } = q_{x+dx} = -kA \left.\frac{\partial T}{\partial x}\right]_{x+dx}$$

$$= -A\left[k\frac{\partial T}{\partial x} + \frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right)dx\right]$$

where

$\dot{q} =$ energy generated per unit volume, W/m^3
$c =$ specific heat of material, J/kg · °C
$\rho =$ density, kg/m^3

Combining the relations above gives

$$-kA\frac{\partial T}{\partial x} + \dot{q}A\,dx = \rho c A\frac{\partial T}{\partial \tau}dx - A\left[k\frac{\partial T}{\partial x} + \frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right)dx\right]$$

or

$$\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) + \dot{q} = \rho c\frac{\partial T}{\partial \tau} \qquad \textbf{[1-2]}$$

This is the one-dimensional heat-conduction equation. To treat more than one-dimensional heat flow, we need consider only the heat conducted in and out of a unit volume in all three coordinate directions, as shown in Figure 1-3*a*. The energy balance yields

$$q_x + q_y + q_z + q_{\text{gen}} = q_{x+dx} + q_{y+dy} + q_{z+dz} + \frac{dE}{d\tau}$$

and the energy quantities are given by

$$q_x = -k\,dy\,dz\frac{\partial T}{\partial x}$$

$$q_{x+dx} = -\left[k\frac{\partial T}{\partial x} + \frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right)dx\right]dy\,dz$$

$$q_y = -k\,dx\,dz\frac{\partial T}{\partial y}$$

$$q_{y+dy} = -\left[k\frac{\partial T}{\partial y} + \frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right)dy\right]dx\,dz$$

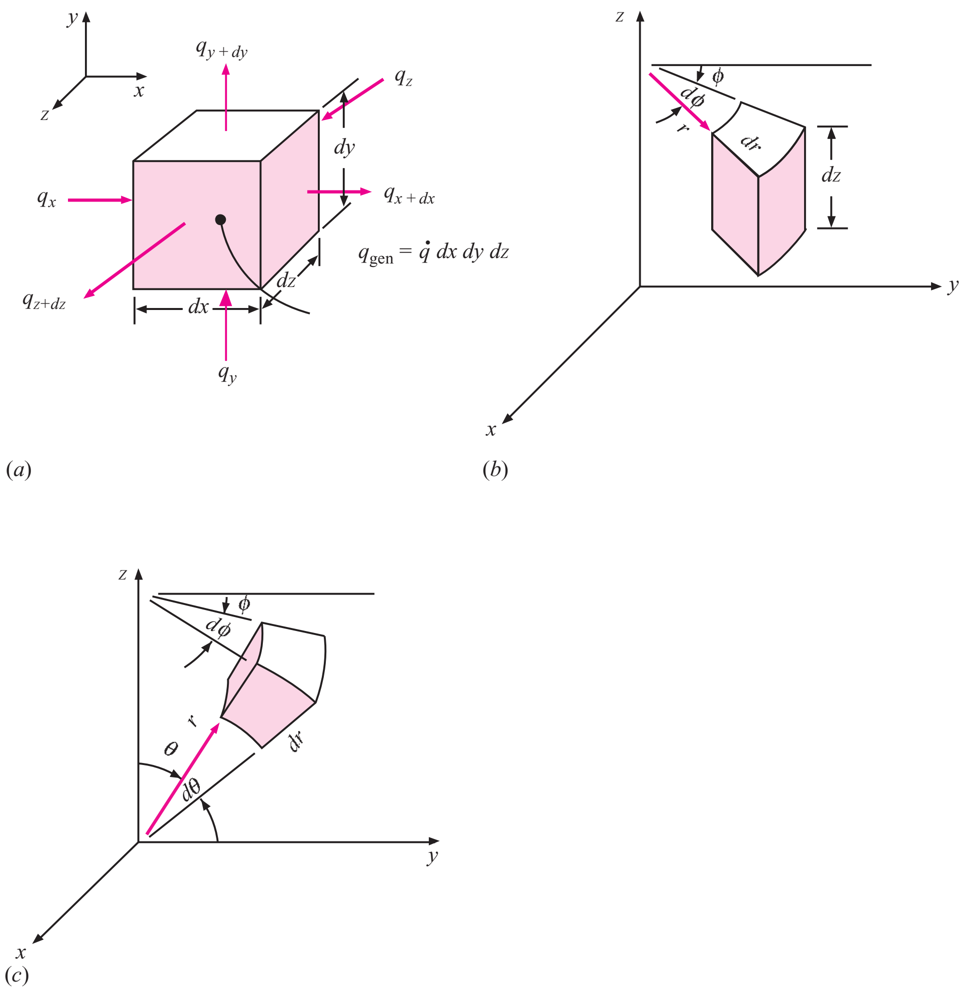
$$q_z = -k\,dx\,dy\frac{\partial T}{\partial z}$$

$$q_{z+dz} = -\left[k\frac{\partial T}{\partial z} + \frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right)dz\right]dx\,dy$$

$$q_{\text{gen}} = \dot{q}\,dx\,dy\,dz$$

$$\frac{dE}{d\tau} = \rho c\,dx\,dy\,dz\frac{\partial T}{\partial \tau}$$

Figure 1-3 | Elemental volume for three-dimensional heat-conduction analysis: (*a*) cartesian coordinates; (*b*) cylindrical coordinates; (*c*) spherical coordinates.



so that the general three-dimensional heat-conduction equation is

$$\frac{\partial}{\partial x}\left(k\,\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(k\,\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(k\,\frac{\partial T}{\partial z}\right)+\dot{q}=\rho c\,\frac{\partial T}{\partial \tau} \qquad \textbf{[1-3]}$$

For constant thermal conductivity, Equation (1-3) is written

$$\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}+\frac{\dot{q}}{k}=\frac{1}{\alpha}\frac{\partial T}{\partial \tau} \qquad \textbf{[1-3a]}$$

where the quantity $\alpha = k/\rho c$ is called the *thermal diffusivity* of the material. The larger the value of α, the faster heat will diffuse through the material. This may be seen by examining the quantities that make up α. A high value of α could result either from a high value of thermal conductivity, which would indicate a rapid energy-transfer rate, or from a low value of the thermal heat capacity ρc. A low value of the heat capacity would mean that less of the energy moving through the material would be absorbed and used to raise the temperature of

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the material; thus more energy would be available for further transfer. Thermal diffusivity α has units of square meters per second.

In the derivations above, the expression for the derivative at $x + dx$ has been written in the form of a Taylor-series expansion with only the first two terms of the series employed for the development.

Equation (1-3*a*) may be transformed into either cylindrical or spherical coordinates by standard calculus techniques. The results are as follows:

Cylindrical coordinates:

$$\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r} + \frac{1}{r^2}\frac{\partial^2 T}{\partial \phi^2} + \frac{\partial^2 T}{\partial z^2} + \frac{\dot{q}}{k} = \frac{1}{\alpha}\frac{\partial T}{\partial \tau} \qquad \textbf{[1-3}\boldsymbol{b}\textbf{]}$$

Spherical coordinates:

$$\frac{1}{r}\frac{\partial^2}{\partial r^2}(rT) + \frac{1}{r^2 \sin\theta}\frac{\partial}{\partial \theta}\left(\sin\theta \frac{\partial T}{\partial \theta}\right) + \frac{1}{r^2 \sin^2\theta}\frac{\partial^2 T}{\partial \phi^2} + \frac{\dot{q}}{k} = \frac{1}{\alpha}\frac{\partial T}{\partial \tau} \qquad \textbf{[1-3}\boldsymbol{c}\textbf{]}$$

The coordinate systems for use with Equations (1-3*b*) and (1-3*c*) are indicated in Figure 1-3*b* and *c*, respectively.

Many practical problems involve only special cases of the general equations listed above. As a guide to the developments in future chapters, it is worthwhile to show the reduced form of the general equations for several cases of practical interest.

Steady-state one-dimensional heat flow (no heat generation):

$$\frac{d^2 T}{dx^2} = 0 \qquad \textbf{[1-4]}$$

Note that this equation is the same as Equation (1-1) when $q = \text{constant}$.

Steady-state one-dimensional heat flow in cylindrical coordinates (no heat generation):

$$\frac{d^2 T}{dr^2} + \frac{1}{r}\frac{dT}{dr} = 0 \qquad \textbf{[1-5]}$$

Steady-state one-dimensional heat flow with heat sources:

$$\frac{d^2 T}{dx^2} + \frac{\dot{q}}{k} = 0 \qquad \textbf{[1-6]}$$

Two-dimensional steady-state conduction without heat sources:

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} = 0 \qquad \textbf{[1-7]}$$

1-2 | THERMAL CONDUCTIVITY

Equation (1-1) is the defining equation for thermal conductivity. On the basis of this definition, experimental measurements may be made to determine the thermal conductivity of different materials. For gases at moderately low temperatures, analytical treatments in the kinetic theory of gases may be used to predict accurately the experimentally observed values. In some cases, theories are available for the prediction of thermal conductivities in liquids and solids, but in general, many open questions and concepts still need clarification where liquids and solids are concerned.

The mechanism of thermal conduction in a gas is a simple one. We identify the kinetic energy of a molecule with its temperature; thus, in a high-temperature region, the molecules have higher velocities than in some lower-temperature region. The molecules are in continuous random motion, colliding with one another and exchanging energy and momentum. The molecules have this random motion whether or not a temperature gradient exists in the gas. If a molecule moves from a high-temperature region to a region of lower temperature, it transports kinetic energy to the lower-temperature part of the system and gives up this energy through collisions with lower-energy molecules.

Table 1-1 lists typical values of the thermal conductivities for several materials to indicate the relative orders of magnitude to be expected in practice. More complete tabular information is given in Appendix A. In general, the thermal conductivity is strongly temperature-dependent.

Table 1-1 | Thermal conductivity of various materials at 0°C.

Material	Thermal conductivity k	
	W/m · °C	Btu/h · ft · °F
Metals:		
Silver (pure)	410	237
Copper (pure)	385	223
Aluminum (pure)	202	117
Nickel (pure)	93	54
Iron (pure)	73	42
Carbon steel, 1% C	43	25
Lead (pure)	35	20.3
Chrome-nickel steel (18% Cr, 8% Ni)	16.3	9.4
Nonmetallic solids:		
Diamond	2300	1329
Quartz, parallel to axis	41.6	24
Magnesite	4.15	2.4
Marble	2.08–2.94	1.2–1.7
Sandstone	1.83	1.06
Glass, window	0.78	0.45
Maple or oak	0.17	0.096
Hard rubber	0.15	0.087
Polyvinyl chloride	0.09	0.052
Styrofoam	0.033	0.019
Sawdust	0.059	0.034
Glass wool	0.038	0.022
Ice	2.22	1.28
Liquids:		
Mercury	8.21	4.74
Water	0.556	0.327
Ammonia	0.540	0.312
Lubricating oil, SAE 50	0.147	0.085
Freon 12, CCl_2F_2	0.073	0.042
Gases:		
Hydrogen	0.175	0.101
Helium	0.141	0.081
Air	0.024	0.0139
Water vapor (saturated)	0.0206	0.0119
Carbon dioxide	0.0146	0.00844

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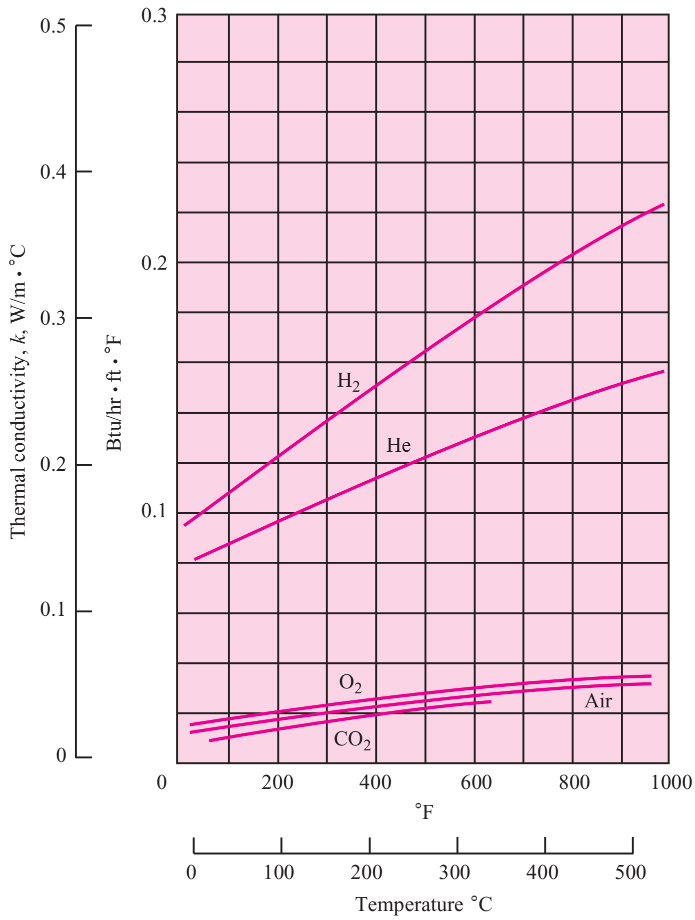
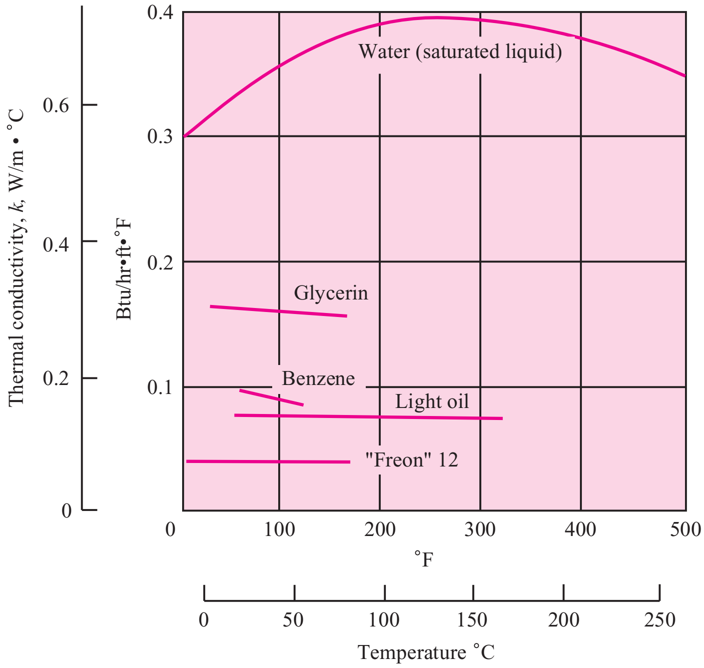
Figure 1-4 | Thermal conductivities of some typical gases
[1 W/m · °C = 0.5779 Btu/h · ft · °F].



We noted that thermal conductivity has the units of watts per meter per Celsius degree when the heat flow is expressed in watts. Note that a heat *rate* is involved, and the numerical value of the thermal conductivity indicates how fast heat will flow in a given material. How is the rate of energy transfer taken into account in the molecular model discussed above? Clearly, the faster the molecules move, the faster they will transport energy. Therefore the thermal conductivity of a gas should be dependent on temperature. A simplified analytical treatment shows the thermal conductivity of a gas to vary with the square root of the absolute temperature. (It may be recalled that the velocity of sound in a gas varies with the square root of the absolute temperature; this velocity is approximately the mean speed of the molecules.) Thermal conductivities of some typical gases are shown in Figure 1-4. For most gases at moderate pressures the thermal conductivity is a function of temperature alone. This means that the gaseous data for 1 atmosphere (atm), as given in Appendix A, may be used for a rather wide range of pressures. When the pressure of the gas becomes of the order of its critical pressure or, more generally, when nonideal-gas behavior is encountered, other sources must be consulted for thermal-conductivity data.

Figure 1-5 | Thermal conductivities of some typical liquids.



The physical mechanism of thermal-energy conduction in liquids is qualitatively the same as in gases; however, the situation is considerably more complex because the molecules are more closely spaced and molecular force fields exert a strong influence on the energy exchange in the collision process. Thermal conductivities of some typical liquids are shown in Figure 1-5.

In the English system of units, heat flow is expressed in British thermal units per hour (Btu/h), area in square feet, and temperature in degrees Fahrenheit. Thermal conductivity will then have units of Btu/h · ft · °F.

Thermal energy may be conducted in solids by two modes: lattice vibration and transport by free electrons. In good electrical conductors a rather large number of free electrons move about in the lattice structure of the material. Just as these electrons may transport electric charge, they may also carry thermal energy from a high-temperature region to a low-temperature region, as in the case of gases. In fact, these electrons are frequently referred to as the *electron gas.* Energy may also be transmitted as vibrational energy in the lattice structure of the material. In general, however, this latter mode of energy transfer is not as large as the electron transport, and for this reason good electrical conductors are almost always good heat conductors, namely, copper, aluminum, and silver, and electrical insulators are usually good heat insulators. A notable exception is diamond, which is an electrical insulator, but which can have a thermal conductivity five times as high as silver or copper. It is this fact that enables a jeweler to distinguish between genuine diamonds and fake stones. A small instrument is available that measures the response of the stones to a thermal heat pulse. A true diamond will exhibit a far more rapid response than the nongenuine stone.

Thermal conductivities of some typical solids are shown in Figure 1-6. Other data are given in Appendix A.

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Figure 1-6 | Thermal conductivities of some typical solids.

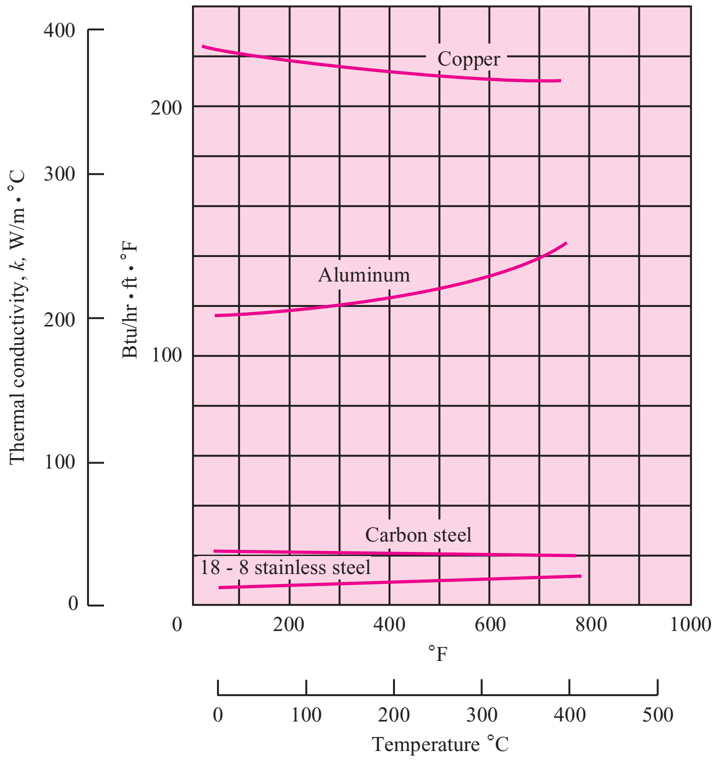


Table 1-2 | Effective thermal conductivities of cryogenic insulating materials for use in range 15°C to −195°C. Density range 30 to 80 kg/m^3.

Type of insulation	Effective k, mW/m · °C
1. Foams, powders, and fibers, unevacuated	7–36
2. Powders, evacuated	0.9–6
3. Glass fibers, evacuated	0.6–3
4. Opacified powders, evacuated	0.3–1
5. Multilayer insulations, evacuated	0.015–0.06

The thermal conductivities of various insulating materials are also given in Appendix A. Some typical values are 0.038 W/m · °C for glass wool and 0.78 W/m · °C for window glass. At high temperatures, the energy transfer through insulating materials may involve several modes: conduction through the fibrous or porous solid material; conduction through the air trapped in the void spaces; and, at sufficiently high temperatures, radiation.

An important technical problem is the storage and transport of cryogenic liquids like liquid hydrogen over extended periods of time. Such applications have led to the development of *superinsulations* for use at these very low temperatures (down to about −250°C). The most effective of these superinsulations consists of multiple layers of highly reflective materials separated by insulating spacers. The entire system is evacuated to minimize air conduction, and thermal conductivities as low as 0.3 m W/m · °C are possible. A convenient summary of the thermal conductivities of a few insulating materials at cryogenic temperatures is given in Table 1-2. Further information on multilayer insulation is given in References 2 and 3.

1-3 | CONVECTION HEAT TRANSFER

It is well known that a hot plate of metal will cool faster when placed in front of a fan than when exposed to still air. We say that the heat is convected away, and we call the process *convection heat transfer.* The term *convection* provides the reader with an intuitive notion concerning the heat-transfer process; however, this intuitive notion must be expanded to enable one to arrive at anything like an adequate analytical treatment of the problem. For example, we know that the velocity at which the air blows over the hot plate obviously influences the heat-transfer rate. But does it influence the cooling in a linear way; i.e., if the velocity is doubled, will the heat-transfer rate double? We should suspect that the heat-transfer rate might be different if we cooled the plate with water instead of air, but, again, how much difference would there be? These questions may be answered with the aid of some rather basic analyses presented in later chapters. For now, we sketch the physical mechanism of convection heat transfer and show its relation to the conduction process.

Consider the heated plate shown in Figure 1-7. The temperature of the plate is T_w, and the temperature of the fluid is T_∞. The velocity of the flow will appear as shown, being reduced to zero at the plate as a result of viscous action. Since the velocity of the fluid layer at the wall will be zero, the heat must be transferred only by conduction at that point. Thus we might compute the heat transfer, using Equation (1-1), with the thermal conductivity of the fluid and the fluid temperature gradient at the wall. Why, then, if the heat flows by conduction in this layer, do we speak of *convection* heat transfer and need to consider the velocity of the fluid? The answer is that the temperature gradient is dependent on the rate at which the fluid carries the heat away; a high velocity produces a large temperature gradient, and so on. Thus the temperature gradient at the wall depends on the flow field, and we must develop in our later analysis an expression relating the two quantities. Nevertheless, it must be remembered that the physical mechanism of heat transfer at the wall is a conduction process.

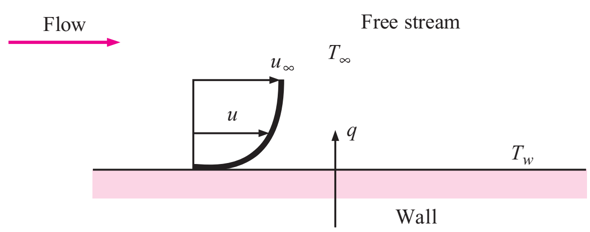
To express the overall effect of convection, we use Newton's law of cooling:

$$q = hA\,(T_w - T_\infty) \qquad \textbf{[1-8]}$$

Here the heat-transfer rate is related to the overall temperature difference between the wall and fluid and the surface area A. The quantity h is called the *convection heat-transfer coefficient,* and Equation (1-8) is the defining equation. An analytical calculation of h may be made for some systems. For complex situations it must be determined experimentally. The heat-transfer coefficient is sometimes called the *film conductance* because of its relation to the conduction process in the thin stationary layer of fluid at the wall surface. From Equation (1-8) we note that the units of h are in watts per square meter per Celsius degree when the heat flow is in watts.

In view of the foregoing discussion, one may anticipate that convection heat transfer will have a dependence on the viscosity of the fluid in addition to its dependence on the

Figure 1-7 | Convection heat transfer from a plate.



thermal properties of the fluid (thermal conductivity, specific heat, density). This is expected because viscosity influences the velocity profile and, correspondingly, the energy-transfer rate in the region near the wall.

If a heated plate were exposed to ambient room air without an external source of motion, a movement of the air would be experienced as a result of the density gradients near the plate. We call this *natural,* or *free,* convection as opposed to *forced* convection, which is experienced in the case of the fan blowing air over a plate. Boiling and condensation phenomena are also grouped under the general subject of convection heat transfer. The approximate ranges of convection heat-transfer coefficients are indicated in Table 1-3.

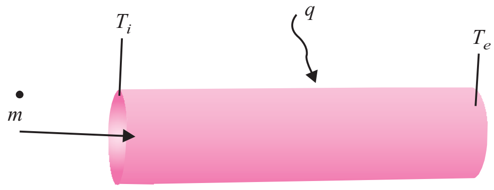
Convection Energy Balance on a Flow Channel

The energy transfer expressed by Equation (1-8) is used for evaluating the convection loss for flow over an external surface. Of equal importance is the convection gain or loss resulting from a fluid flowing inside a channel or tube as shown in Figure 1-8. In this case, the heated wall at T_w loses heat to the cooler fluid, which consequently rises in temperature as it flows

Table 1-3 | Approximate values of convection heat-transfer coefficients.

Mode	h, W/m^2 · °C	h, Btu/h · ft^2 · °F
Across 2.5-cm air gap evacuated to a pressure of 10^{-6} atm and subjected to $\Delta T = 100°C - 30°C$	0.087	0.015
Free convection, $\Delta T = 30°C$		
Vertical plate 0.3 m [1 ft] high in air	4.5	0.79
Horizontal cylinder, 5-cm diameter, in air	6.5	1.14
Horizontal cylinder, 2-cm diameter, in water	890	157
Heat transfer across 1.5-cm vertical air gap with $\Delta T = 60°C$	2.64	0.46
Fine wire in air, $d = 0.02$ mm, $\Delta T = 55°C$	490	86
Forced convection		
Airflow at 2 m/s over 0.2-m square plate	12	2.1
Airflow at 35 m/s over 0.75-m square plate	75	13.2
Airflow at Mach number = 3, $p = 1/20$ atm, $T_\infty = -40°C$, across 0.2-m square plate	56	9.9
Air at 2 atm flowing in 2.5-cm-diameter tube at 10 m/s	65	11.4
Water at 0.5 kg/s flowing in 2.5-cm-diameter tube	3500	616
Airflow *across* 5-cm-diameter cylinder with velocity of 50 m/s	180	32
Liquid bismuth at 4.5 kg/s and 420°C in 5.0-cm-diameter tube	3410	600
Airflow at 50 m/s across fine wire, $d = 0.04$ mm	3850	678
Boiling water		
In a pool or container	2500–35,000	440–6200
Flowing in a tube	5000–100,000	880–17,600
Condensation of water vapor, 1 atm		
Vertical surfaces	4000–11,300	700–2000
Outside horizontal tubes	9500–25,000	1700–4400
Dropwise condensation	170,000–290,000	30,000–50,000

Figure 1-8 | Convection in a channel.



from inlet conditions at T_i to exit conditions at T_e. Using the symbol i to designate enthalpy (to avoid confusion with h, the convection coefficient), the energy balance on the fluid is

$$q = \dot{m}(i_e - i_i)$$

where $\dot{m}$ is the fluid mass flow rate. For many single-phase liquids and gases operating over reasonable temperature ranges $\Delta i = c_p \Delta T$ and we have

$$q = \dot{m} c_p (T_e - T_i)$$

which may be equated to a convection relation like Equation (1-8)

$$q = \dot{m} c_p (T_e - T_i) = hA(T_{w,\,\text{avg}} - T_{\text{fluid, avg}}) \qquad \textbf{[1-8}\boldsymbol{a}\textbf{]}$$

In this case, the fluid temperatures T_e, T_i, and T_{fluid} are called *bulk* or *energy average* temperatures. A is the surface area of the flow channel in contact with the fluid. We shall have more to say about the notions of computing convection heat transfer for external and internal flows in Chapters 5 and 6. For now, we simply want to alert the reader to the distinction between the two types of flows.

We must be careful to distinguish between the surface area for convection that is employed in convection Equation (1-8) and the cross-sectional area that is used to calculate the flow rate from

$$\dot{m} = \rho u_{\text{mean}} A_c$$

where $A_c = \pi d^2/4$ for flow in a circular tube. The surface area for convection in this case would be πdL, where L is the tube length. The surface area for convection is always the area of the heated surface in contact with the fluid.

1-4 | RADIATION HEAT TRANSFER

In contrast to the mechanisms of conduction and convection, where energy transfer through a material medium is involved, heat may also be transferred through regions where a perfect vacuum exists. The mechanism in this case is electromagnetic radiation. We shall limit our discussion to electromagnetic radiation that is propagated as a result of a temperature difference; this is called *thermal radiation.*

Thermodynamic considerations show* that an ideal thermal radiator, or *blackbody,* will emit energy at a rate proportional to the fourth power of the absolute temperature of the body and directly proportional to its surface area. Thus

$$q_{\text{emitted}} = \sigma A T^4 \qquad \textbf{[1-9]}$$

*See, for example, J. P. Holman, *Thermodynamics*. 4th ed. New York: McGraw-Hill, 1988, p. 705.

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where σ is the proportionality constant and is called the Stefan-Boltzmann constant with the value of 5.669×10^{-8} W/m$^2 \cdot$ K^4. Equation (1-9) is called the Stefan-Boltzmann law of thermal radiation, and it applies only to blackbodies. It is important to note that this equation is valid only for thermal radiation; other types of electromagnetic radiation may not be treated so simply.

Equation (1-9) governs only radiation *emitted* by a blackbody. The net radiant *exchange* between two surfaces will be proportional to the difference in absolute temperatures to the fourth power; i.e.,

$$\frac{q_{\text{net exchange}}}{A} \propto \sigma(T_1^4 - T_2^4) \qquad \textbf{[1-10]}$$

We have mentioned that a blackbody is a body that radiates energy according to the T^4 law. We call such a body *black* because black surfaces, such as a piece of metal covered with carbon black, approximate this type of behavior. Other types of surfaces, such as a glossy painted surface or a polished metal plate, do not radiate as much energy as the blackbody; however, the total radiation emitted by these bodies still generally follows the T^4 proportionality. To take account of the "gray" nature of such surfaces we introduce another factor into Equation (1-9), called the emissivity ϵ, which relates the radiation of the "gray" surface to that of an ideal black surface. In addition, we must take into account the fact that not all the radiation leaving one surface will reach the other surface since electromagnetic radiation travels in straight lines and some will be lost to the surroundings. We therefore introduce two new factors in Equation (1-9) to take into account both situations, so that

$$q = F_\epsilon F_G \sigma A\,(T_1^4 - T_2^4) \qquad \textbf{[1-11]}$$

where F_ϵ is the emissivity function, and F_G is the geometric "view factor" function. The determination of the form of these functions for specific configurations is the subject of a subsequent chapter. It is important to alert the reader at this time, however, to the fact that these functions usually are not independent of one another as indicated in Equation (1-11).

Radiation in an Enclosure

A simple radiation problem is encountered when we have a heat-transfer surface at temperature T_1 completely enclosed by a much larger surface maintained at T_2. We will show in Chapter 8 that the net radiant exchange in this case can be calculated with

$$q = \epsilon_1 \sigma A_1\,(T_1^4 - T_2^4) \qquad \textbf{[1-12]}$$

Values of ϵ are given in Appendix A.

Radiation heat-transfer phenomena can be exceedingly complex, and the calculations are seldom as simple as implied by Equation (1-11). For now, we wish to emphasize the difference in physical mechanism between radiation heat-transfer and conduction-convection systems. In Chapter 8 we examine radiation in detail.

1-5 | DIMENSIONS AND UNITS

In this section we outline the systems of units that are used throughout the book. One must be careful not to confuse the meaning of the terms *units* and *dimensions*. A dimension is a physical variable used to specify the behavior or nature of a particular system. For example,

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the length of a rod is a dimension of the rod. In like manner, the temperature of a gas may be considered one of the thermodynamic dimensions of the gas. When we say the rod is so many meters long, or the gas has a temperature of so many degrees Celsius, we have given the units with which we choose to measure the dimension. In our development of heat transfer we use the dimensions

$$\begin{aligned} L &= \text{length} \\ M &= \text{mass} \\ F &= \text{force} \\ \tau &= \text{time} \\ T &= \text{temperature} \end{aligned}$$

All the physical quantities used in heat transfer may be expressed in terms of these fundamental dimensions. The units to be used for certain dimensions are selected by somewhat arbitrary definitions that usually relate to a physical phenomenon or law. For example, Newton's second law of motion may be written

$$\text{Force} \sim \text{time rate of change of momentum}$$

$$F = k\frac{d(mv)}{d\tau}$$

where k is the proportionality constant. If the mass is constant,

$$F = kma \qquad \textbf{[1-13]}$$

where the acceleration is $a = dv/d\tau$. Equation (1-11) is usually written

$$F = \frac{1}{g_c}ma \qquad \textbf{[1-14]}$$

with $1/g_c = k$. Equation (1-14) is used to define our systems of units for mass, force, length, and time. Some typical systems of units are

1. 1-pound force will accelerate a 1-lb mass 32.17 ft/s^2.
2. 1-pound force will accelerate a 1-slug mass 1 ft/s^2.
3. 1-dyne force will accelerate a 1-g mass 1 cm/s^2.
4. 1-newton force will accelerate a 1-kg mass 1 m/s^2.
5. 1-kilogram force will accelerate a 1-kg mass 9.806 m/s^2.

The 1-kg force is sometimes called a *kilopond* (kp).

Since Equation (1-14) must be dimensionally homogeneous, we shall have a different value of the constant g_c for each of the unit systems in items 1 to 5 above. These values are

1. $g_c = 32.17\ \text{lb}_m \cdot \text{ft}/\text{lb}_f \cdot \text{s}^2$
2. $g_c = 1\ \text{slug} \cdot \text{ft}/\text{lb}_f \cdot \text{s}^2$
3. $g_c = 1\ \text{g} \cdot \text{cm}/\text{dyn} \cdot \text{s}^2$
4. $g_c = 1\ \text{kg} \cdot \text{m}/\text{N} \cdot \text{s}^2$
5. $g_c = 9.806\ \text{kg}_m \cdot \text{m}/\text{kg}_f \cdot \text{s}^2$

It matters not which system of units is used so long as it is consistent with these definitions.

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Work has the dimensions of a product of force times a distance. Energy has the same dimensions. The units for work and energy may be chosen from any of the systems used on the previous page, and would be

1. $\text{lb}_f \cdot \text{ft}$
2. $\text{lb}_f \cdot \text{ft}$
3. $\text{dyn} \cdot \text{cm} = 1$ erg
4. $\text{N} \cdot \text{m} = 1$ joule (J)
5. $\text{kg}_f \cdot \text{m} = 9.806$ J

In addition, we may use the units of energy that are based on thermal phenomena:

1 Btu will raise 1 lb_m of water 1°F at 68°F.
1 cal will raise 1 g of water 1°C at 20°C.
1 kcal will raise 1 kg of water 1°C at 20°C.

Some conversion factors for the various units of work and energy are

$$\begin{aligned}
1\ \text{Btu} &= 778.16\ \text{lb}_f \cdot \text{ft} \\
1\ \text{Btu} &= 1055\ \text{J} \\
1\ \text{kcal} &= 4182\ \text{J} \\
1\ \text{lb}_f \cdot \text{ft} &= 1.356\ \text{J} \\
1\ \text{Btu} &= 252\ \text{cal}
\end{aligned}$$

Other conversion factors are given in Appendix A.

The weight of a body is defined as the force exerted on the body as a result of the acceleration of gravity. Thus

$$W = \frac{g}{g_c} m \qquad \textbf{[1-15]}$$

where W is the weight and g is the acceleration of gravity. Note that the weight of a body has the dimensions of a force. We now see why systems 1 and 5 were devised; 1 lb_m will weigh 1 lb_f at sea level, and 1 kg_m will weigh 1 kg_f.

Temperature conversions are performed with the familiar formulas

$$\begin{aligned}
{}^\circ\text{F} &= \tfrac{9}{5}{}^\circ\text{C} + 32 \\
{}^\circ\text{R} &= {}^\circ\text{F} + 459.69 \\
\text{K} &= {}^\circ\text{C} + 273.16 \\
{}^\circ\text{R} &= \tfrac{9}{5}\text{K}
\end{aligned}$$

Unfortunately, *all* of these unit systems are used in various places throughout the world. While the foot, pound force, pound mass, second, degree Fahrenheit, Btu system is still widely used in the United States, there is increasing impetus to institute the SI (Système International d'Unités) units as a worldwide standard. In this system, the fundamental units are meter, newton, kilogram mass, second, and degree Celsius; a "thermal" energy unit is not used; i.e., the joule (newton-meter) becomes the energy unit used throughout. The watt (joules per second) is the unit of power in this system. In the SI system, the standard units for thermal conductivity would become

$$k \text{ in W/m} \cdot {}^\circ\text{C}$$

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Table 1-4 | Multiplier factors for SI units.

Multiplier	Prefix	Abbreviation
10^{12}	tera	T
10^{9}	giga	G
10^{6}	mega	M
10^{3}	kilo	k
10^{2}	hecto	h
10^{-2}	centi	c
10^{-3}	milli	m
10^{-6}	micro	μ
10^{-9}	nano	n
10^{-12}	pico	p
10^{-18}	atto	a

Table 1-5 | SI quantities used in heat transfer.

Quantity	Unit abbreviation
Force	N (newton)
Mass	kg (kilogram mass)
Time	s (second)
Length	m (meter)
Temperature	$^\circ$C or K
Energy	J (joule)
Power	W (watt)
Thermal conductivity	$\text{W/m} \cdot {}^\circ\text{C}$
Heat-transfer coefficient	$\text{W/m}^2 \cdot {}^\circ\text{C}$
Specific heat	$\text{J/kg} \cdot {}^\circ\text{C}$
Heat flux	W/m^2

and the convection heat-transfer coefficient would be expressed as

$$h \text{ in W/m}^2 \cdot {}^\circ\text{C}$$

Because SI units are so straightforward we shall use them as the standard in this text, with intermediate steps and answers in examples also given parenthetically in the Btu–pound mass system. A worker in heat transfer must obtain a feel for the order of magnitudes in both systems. In the SI system the concept of g_c is not normally used, and the newton is *defined* as

$$1\text{ N} = 1\text{ kg} \cdot \text{m/s}^2 \qquad \textbf{[1-16]}$$

Even so, one should keep in mind the physical relation between force and mass as expressed by Newton's second law of motion.

The SI system also specifies standard multiples to be used to conserve space when numerical values are expressed. They are summarized in Table 1-4. Standard symbols for quantities normally encountered in heat transfer are summarized in Table 1-5. Conversion factors are given in Appendix A.

EXAMPLE 1-1 Conduction Through Copper Plate

One face of a copper plate 3 cm thick is maintained at 400°C, and the other face is maintained at 100°C. How much heat is transferred through the plate?

■ **Solution**

From Appendix A, the thermal conductivity for copper is 370 W/m · °C at 250°C. From Fourier's law

$$\frac{q}{A} = -k\frac{dT}{dx}$$

Integrating gives

$$\frac{q}{A} = -k\frac{\Delta T}{\Delta x} = \frac{-(370)(100-400)}{3\times 10^{-2}} = 3.7\ \mathrm{MW/m^2} \quad [1.173\times 10^6\ \mathrm{Btu/h\cdot ft^2}]$$

Convection Calculation — EXAMPLE 1-2

Air at 20°C blows over a hot plate 50 by 75 cm maintained at 250°C. The convection heat-transfer coefficient is 25 W/m^2 · °C. Calculate the heat transfer.

■ **Solution**

From Newton's law of cooling

$$\begin{aligned} q &= hA\,(T_w - T_\infty) \\ &= (25)(0.50)(0.75)(250-20) \\ &= 2.156\ \mathrm{kW} \quad [7356\ \mathrm{Btu/h}] \end{aligned}$$

Multimode Heat Transfer — EXAMPLE 1-3

Assuming that the plate in Example 1-2 is made of carbon steel (1%) 2 cm thick and that 300 W is lost from the plate surface by radiation, calculate the inside plate temperature.

■ **Solution**

The heat conducted through the plate must be equal to the sum of convection and radiation heat losses:

$$q_{\text{cond}} = q_{\text{conv}} + q_{\text{rad}}$$

$$-kA\frac{\Delta T}{\Delta x} = 2.156 + 0.3 = 2.456\ \mathrm{kW}$$

$$\Delta T = \frac{(-2456)(0.02)}{(0.5)(0.75)(43)} = -3.05^\circ\mathrm{C} \quad [-5.49^\circ\mathrm{F}]$$

where the value of k is taken from Table 1-1. The inside plate temperature is therefore

$$T_i = 250 + 3.05 = 253.05^\circ\mathrm{C}$$

Heat Source and Convection — EXAMPLE 1-4

An electric current is passed through a wire 1 mm in diameter and 10 cm long. The wire is submerged in liquid water at atmospheric pressure, and the current is increased until the water boils. For this situation $h = 5000\ \mathrm{W/m^2 \cdot {}^\circ C}$, and the water temperature will be 100°C. How much electric power must be supplied to the wire to maintain the wire surface at 114°C?

Solution

The total convection loss is given by Equation (1-8):

$$q = hA\,(T_w - T_\infty)$$

For this problem the surface area of the wire is

$$A = \pi dL = \pi(1\times10^{-3})(10\times10^{-2}) = 3.142\times10^{-4}\ \mathrm{m^2}$$

The heat transfer is therefore

$$q = (5000\ \mathrm{W/m^2\cdot{}^\circ C})(3.142\times10^{-4}\ \mathrm{m^2})(114-100) = 21.99\ \mathrm{W}\quad [75.03\ \mathrm{Btu/h}]$$

and this is equal to the electric power that must be applied.

EXAMPLE 1-5 Radiation Heat Transfer

Two infinite black plates at 800°C and 300°C exchange heat by radiation. Calculate the heat transfer per unit area.

Solution

Equation (1-10) may be employed for this problem, so we find immediately

$$\begin{aligned} q/A &= \sigma(T_1^4 - T_2^4) \\ &= (5.669\times10^{-8})(1073^4 - 573^4) \\ &= 69.03\ \mathrm{kW/m^2}\quad [21{,}884\ \mathrm{Btu/h\cdot ft^2}] \end{aligned}$$

EXAMPLE 1-6 Total Heat Loss by Convection and Radiation

A horizontal steel pipe having a diameter of 5 cm is maintained at a temperature of 50°C in a large room where the air and wall temperature are at 20°C. The surface emissivity of the steel may be taken as 0.8. Using the data of Table 1-3, calculate the total heat lost by the pipe per unit length.

Solution

The total heat loss is the sum of convection and radiation. From Table 1-3 we see that an estimate for the heat-transfer coefficient for *free* convection with this geometry and air is $h = 6.5\ \mathrm{W/m^2\cdot{}^\circ C}$. The surface area is πdL, so the convection loss per unit length is

$$\begin{aligned} q/L]_{\mathrm{conv}} &= h(\pi d)(T_w - T_\infty) \\ &= (6.5)(\pi)(0.05)(50-20) = 30.63\ \mathrm{W/m} \end{aligned}$$

The pipe is a body surrounded by a large enclosure so the radiation heat transfer can be calculated from Equation (1-12). With $T_1 = 50^\circ\mathrm{C} = 323^\circ\mathrm{K}$ and $T_2 = 20^\circ\mathrm{C} = 293^\circ\mathrm{K}$, we have

$$\begin{aligned} q/L]_{\mathrm{rad}} &= \epsilon_1(\pi d_1)\sigma(T_1^4 - T_2^4) \\ &= (0.8)(\pi)(0.05)(5.669\times10^{-8})(323^4 - 293^4) \\ &= 25.04\ \mathrm{W/m} \end{aligned}$$

The total heat loss is therefore

$$q/L]_{\text{tot}} = q/L]_{\text{conv}} + q/L]_{\text{rad}}$$
$$= 30.63 + 25.04 = 55.67 \text{ W/m}$$

In this example we see that the convection and radiation are about the same. To neglect either would be a serious mistake.

1-6 | SUMMARY

We may summarize our introductory remarks very simply. Heat transfer may take place by one or more of three modes: conduction, convection, and radiation. It has been noted that the physical mechanism of convection is related to the heat conduction through the thin layer of fluid adjacent to the heat-transfer surface. In both conduction and convection Fourier's law is applicable, although fluid mechanics must be brought into play in the convection problem in order to establish the temperature gradient.

Radiation heat transfer involves a different physical mechanism—that of propagation of electromagnetic energy. To study this type of energy transfer we introduce the concept of an ideal radiator, or blackbody, which radiates energy at a rate proportional to its absolute temperature to the fourth power.

It is easy to envision cases in which all three modes of heat transfer are present, as in Figure 1-9. In this case the heat conducted through the plate is removed from the plate surface by a combination of convection and radiation. An energy balance would give

$$-kA \left.\frac{dT}{dy}\right]_{\text{wall}} = hA\,(T_w - T_\infty) + F_\epsilon F_G \sigma A\,(T_w^4 - T_s^4)$$

where

T_s = temperature of surroundings
T_w = surface temperature
T_∞ = fluid temperature

To apply the science of heat transfer to practical situations, a thorough knowledge of all three modes of heat transfer must be obtained.

Figure 1-9 | Combination of conduction, convection, and radiation heat transfer.

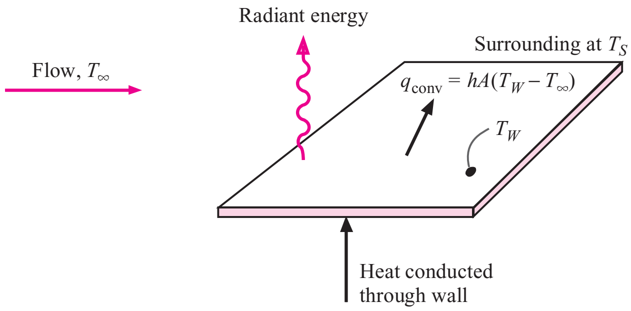

Table 1-6 | Listing of equation summary tables in text.

Table	Topic
1-3	Approximate values of convection heat-transfer coefficients
3-1	Conduction shape factors
3-2	Summary of steady-state nodal equations for $\Delta x = \Delta y$
4-1	Examples of lumped capacities
4-2	Summary of transient nodal equations for $\Delta x = \Delta y$
5-2	Forced-convection relations for flow over flat plates
6-8	Forced-convection relations for internal and external flows (nonflat plates)
7-2	Simplified relations for free convection from heated objects in room air
7-5	Summary of free-convection relations
Section 7-14 and Figure 7-15	Summary procedure for all convection calculations
8-7	Radiation formulas for diffuse, gray-body enclosures
10-3	Effectiveness relations for heat exchangers
10-4	NTU relations for heat exchangers

About Areas

The reader will note that area is an important part of the calculation for all three modes of heat transfer: The larger the area through which heat is conducted, the larger the heat transfer; the larger the surface area in contact with the fluid, the larger the potential convection heat transfer; and a larger surface will emit more thermal radiation than a small surface. For conduction, the heat transfer will almost always be directly proportional to the area. For convection, the heat transfer is a complicated function of the fluid mechanics of the problem, which in turn is a function of both the geometric configuration of the heated surface and the thermal and viscous fluid properties of the convecting medium. Radiation heat transfer also involves a complex interaction between the surface emissive properties and the geometry of the enclosure that involves the radiant transfer. Despite these remarks, the general principle is that an increased area means an increase in heat transfer.

Summary Tables Available in Text

As our discussion progresses we will present several tables which summarize equations and empirical correlations for convenience of the reader. A listing of some of these tables and/or figures along with their topical content is given in Table 1-6.

REVIEW QUESTIONS

1. Define thermal conductivity.
2. Define the convection heat-transfer coefficient.
3. Discuss the mechanism of thermal conduction in gases and solids.
4. Discuss the mechanism of heat convection.
5. What is the order of magnitude for the convection heat-transfer coefficient in free convection? Forced convection? Boiling?
6. When may one expect radiation heat transfer to be important?
7. Name some good conductors of heat; some poor conductors.

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8. What is the order of magnitude of thermal conductivity for (*a*) metals, (*b*) solid insulating materials, (*c*) liquids, (*d*) gases?

9. Suppose a person stated that heat cannot be transferred in a vacuum. How do you respond?

10. Review any standard text on thermodynamics and define: (*a*) heat, (*b*) internal energy, (*c*) work, (*d*) enthalpy.

11. Define and discuss g_c.

LIST OF WORKED EXAMPLES

1-1 Conduction through copper plate
1-2 Convection calculation
1-3 Multimode heat transfer
1-4 Heat source and convection
1-5 Radiation heat transfer
1-6 Total heat loss by convection and radiation

PROBLEMS

1-1 If 3 kW is conducted through a section of insulating material 0.6 m^2 in cross section and 2.5 cm thick and the thermal conductivity may be taken as 0.2 W/m · °C, compute the temperature difference across the material.

1-2 A temperature difference of 85°C is impressed across a fiberglass layer of 13 cm thickness. The thermal conductivity of the fiberglass is 0.035 W/m · °C. Compute the heat transferred through the material per hour per unit area.

1-3 A truncated cone 30 cm high is constructed of aluminum. The diameter at the top is 7.5 cm, and the diameter at the bottom is 12.5 cm. The lower surface is maintained at 93°C; the upper surface, at 540°C. The other surface is insulated. Assuming one-dimensional heat flow, what is the rate of heat transfer in watts?

1-4 The temperatures on the faces of a plane wall 15 cm thick are 375 and 85°C. The wall is constructed of a special glass with the following properties: $k = 0.78$ W/m · °C, $\rho = 2700$ kg/m^3, $c_P = 0.84$ kJ/kg · °C. What is the heat flow through the wall at steady-state conditions?

1-5 A certain superinsulation material having a thermal conductivity of 2×10^{-4} W/m · °C is used to insulate a tank of liquid nitrogen that is maintained at −196°C; 199 kJ is required to vaporize each kilogram mass of nitrogen at this temperature. Assuming that the tank is a sphere having an inner diameter (ID) of 0.52 m, estimate the amount of nitrogen vaporized per day for an insulation thickness of 2.5 cm and an ambient temperature of 21°C. Assume that the outer temperature of the insulation is 21°C.

1-6 Rank the following materials in order of (*a*) transient response and (*b*) steady-state conduction. Taking the material with the highest rank, give the other materials as a percentage of the maximum: aluminum, copper, silver, iron, lead, chrome steel (18% Cr, 8% Ni), magnesium. What do you conclude from this ranking?

1-7 A 50-cm-diameter pipeline in the Arctic carries hot oil at 30°C and is exposed to a surrounding temperature of −20°C. A special powder insulation 5 cm thick surrounds

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the pipe and has a thermal conductivity of 7 mW/m · °C. The convection heat-transfer coefficient on the outside of the pipe is 9 W/m^2 · °C. Estimate the energy loss from the pipe per meter of length.

1-8 Some people might recall being told to be sure to put on a hat when outside in cold weather because "you lose all the heat out the top of your head." Comment on the validity of this statement.

1-9 A 5-cm layer of loosely packed asbestos is placed between two plates at 100 and 200°C. Calculate the heat transfer across the layer.

1-10 A certain insulation has a thermal conductivity of 10 W/m · °C. What thickness is necessary to effect a temperature drop of 500°C for a heat flow of 400 W/m^2?

1-11 Assuming that the heat transfer to the sphere in Problem 1-5 occurs by free convection with a heat-transfer coefficient of 2.7 W/m^2 · °C, calculate the temperature difference between the outer surface of the sphere and the environment.

1-12 Two perfectly black surfaces are constructed so that all the radiant energy leaving a surface at 800°C reaches the other surface. The temperature of the other surface is maintained at 250°C. Calculate the heat transfer between the surfaces per hour and per unit area of the surface maintained at 800°C.

1-13 Two very large parallel planes having surface conditions that very nearly approximate those of a blackbody are maintained at 1100 and 425°C, respectively. Calculate the heat transfer by radiation between the planes per unit time and per unit surface area.

1-14 Calculate the radiation heat exchange in 1 day between two black planes having the area of the surface of a 0.7-m-diameter sphere when the planes are maintained at 70 K and 300 K.

1-15 Two infinite black plates at 500 and 100°C exchange heat by radiation. Calculate the heat-transfer rate per unit area. If another perfectly black plate is placed between the 500 and 100°C plates, by how much is the heat transfer reduced? What is the temperature of the center plate?

1-16 Water flows at the rate of 0.5 kg/s in a 2.5-cm-diameter tube having a length of 3 m. A constant heat flux is imposed at the tube wall so that the tube wall temperature is 40°C higher than the water temperature. Calculate the heat transfer and estimate the temperature rise in the water. The water is pressurized so that boiling cannot occur.

1-17 Steam at 1 atm pressure ($T_{sat} = 100$°C) is exposed to a 30-by-30-cm vertical square plate that is cooled such that 3.78 kg/h is condensed. Calculate the plate temperature. Consult steam tables for any necessary properties.

1-18 Boiling water at 1 atm may require a surface heat flux of 3×10^4 Btu/h · ft^2 for a surface temperature of 232°F. What is the value of the heat-transfer coefficient?

1-19 A small radiant heater has metal strips 6 mm wide with a total length of 3 m. The surface emissivity of the strips is 0.85. To what temperature must the strips be heated if they are to dissipate 2000 W of heat to a room at 25°C?

1-20 Calculate the energy emitted by a blackbody at 1000°C.

1-21 If the radiant flux from the sun is 1350 W/m^2, what would be its equivalent blackbody temperature?

1-22 A 4.0-cm-diameter sphere is heated to a temperature of 200°C and is enclosed in a large room at 20°C. Calculate the radiant heat loss if the surface emissivity is 0.6.

1-23 A flat wall is exposed to an environmental temperature of 38°C. The wall is covered with a layer of insulation 2.5 cm thick whose thermal conductivity is 1.4 W/m · °C, and the temperature of the wall on the inside of the insulation is 315°C. The wall loses heat to the environment by convection. Compute the value of the convection heat-transfer coefficient that must be maintained on the outer surface of the insulation to ensure that the outer-surface temperature does not exceed 41°C.

1-24 Consider a wall heated by convection on one side and cooled by convection on the other side. Show that the heat-transfer rate through the wall is

$$q = \frac{T_1 - T_2}{1/h_1 A + \Delta x/kA + 1/h_2 A}$$

where T_1 and T_2 are the fluid temperatures on each side of the wall and h_1 and h_2 are the corresponding heat-transfer coefficients.

1-25 One side of a plane wall is maintained at 100°C, while the other side is exposed to a convection environment having $T = 10$°C and $h = 10$ W/m$^2 \cdot$ °C. The wall has $k = 1.6$ W/m $\cdot$ °C and is 40 cm thick. Calculate the heat-transfer rate through the wall.

1-26 How does the free-convection heat transfer from a vertical plate compare with pure conduction through a vertical layer of air having a thickness of 2.5 cm and a temperature difference the same at $T_w - T_\infty$? Use information from Table 1-3.

1-27 A $\frac{1}{4}$-in steel plate having a thermal conductivity of 25 Btu/h $\cdot$ ft $\cdot$ °F is exposed to a radiant heat flux of 1500 Btu/h $\cdot$ ft^2 in a vacuum space where the convection heat transfer is negligible. Assuming that the surface temperature of the steel exposed to the radiant energy is maintained at 100°F, what will be the other surface temperature if all the radiant energy striking the plate is transferred through the plate by conduction?

1-28 A solar radiant heat flux of 700 W/m^2 is absorbed in a metal plate that is perfectly insulated on the back side. The convection heat-transfer coefficient on the plate is 11 W/m$^2 \cdot$ °C, and the ambient air temperature is 30°C. Calculate the temperature of the plate under equilibrium conditions.

1-29 A 5.0-cm-diameter cylinder is heated to a temperature of 200°C, and air at 30°C is forced across it at a velocity of 50 m/s. If the surface emissivity is 0.7, calculate the total heat loss per unit length if the walls of the enclosing room are at 10°C. Comment on this calculation.

1-30 A vertical square plate, 30 cm on a side, is maintained at 50°C and exposed to room air at 20°C. The surface emissivity is 0.8. Calculate the total heat lost by both sides of the plate.

1-31 A black 20-by-20-cm plate has air forced over it at a velocity of 2 m/s and a temperature of 0°C. The plate is placed in a large room whose walls are at 30°C. The back side of the plate is perfectly insulated. Calculate the temperature of the plate resulting from the convection-radiation balance. Use information from Table 1-3. Are you surprised at the result?

1-32 Two large black plates are separated by a vacuum. On the outside of one plate is a convection environment of $T = 80$°C and $h = 100$ W/m$^2 \cdot$ °C, while the outside of the other plate is exposed to 20°C and $h = 15$ W/m$^2 \cdot$ °C. Make an energy balance on the system and determine the plate temperatures. For this problem $F_G = F_\epsilon = 1.0$.

1-33 Using the basic definitions of units and dimensions given in Section 1-5, arrive at expressions (*a*) to convert joules to British thermal units, (*b*) to convert dyne-centimeters to joules, and (*c*) to convert British thermal units to calories.

1-34 Beginning with the three-dimensional heat-conduction equation in cartesian coordinates [Equation (1-3*a*)], obtain the general heat-conduction equation in cylindrical coordinates [Equation (1-3*b*)].

1-35 Write the simplified heat-conduction equation for (*a*) steady one-dimensional heat flow in cylindrical coordinates in the *azimuth* (ϕ) direction, and (*b*) steady one-dimensional heat flow in spherical coordinates in the azimuth (ϕ) direction.

1-36 Using the approximate values of convection heat-transfer coefficients given in Table 1-3, estimate the surface temperature for which the free convection heat loss will just equal the radiation heat loss from a vertical 0.3-m-square plate or a 5-cm-diameter cylinder exposed to room air at 20°C. Assume the surfaces are blackened such that $\epsilon = 1.0$ and the radiation surrounding temperature may be taken the same as the room air temperature.

Design-Oriented Problems

1-37 A woman informs an engineer that she frequently feels cooler in the summer when standing in front of an open refrigerator. The engineer tells her that she is only "imagining things" because there is no fan in the refrigerator to blow the cool air over her. A lively argument ensues. Whose side of the argument do you take? Why?

1-38 A woman informs her engineer husband that "hot water will freeze faster than cold water." He calls this statement nonsense. She answers by saying that she has actually timed the freezing process for ice trays in the home refrigerator and found that hot water does indeed freeze faster. As a friend, you are asked to settle the argument. Is there any logical explanation for the woman's observation?

1-39 An air-conditioned classroom in Texas is maintained at 72°F in the summer. The students attend classes in shorts, sandals, and tee shirts and are quite comfortable. In the same classroom during the winter, the same students wear wool slacks, long-sleeve shirts, and sweaters, and are equally comfortable with the room temperature maintained at 75°F. Assuming that humidity is not a factor, explain this apparent anomaly in "temperature comfort."

1-40 A vertical cylinder 6 ft tall and 1 ft in diameter might be used to approximate a man for heat-transfer purposes. Suppose the surface temperature of the cylinder is 78°F, $h = 2\ \text{Btu/h} \cdot \text{ft}^2 \cdot {}^\circ\text{F}$, the surface emissivity is 0.9, and the cylinder is placed in a large room where the air temperature is 68°F and the wall temperature is 45°F. Calculate the heat lost from the cylinder. Repeat for a wall temperature of 80°F. What do you conclude from these calculations?

1-41 An ice-skating rink is located in an indoor shopping mall with an environmental air temperature of 22°C and radiation surrounding walls of about 25°C. The convection heat-transfer coefficient between the ice and air is about $10\ \text{W/m}^2 \cdot {}^\circ\text{C}$ because of air movement and the skaters' motion. The emissivity of the ice is about 0.95. Calculate the cooling required to maintain the ice at 0°C for an ice rink having dimensions of 12 by 40 m. Obtain a value for the heat of fusion of ice and estimate how long it would take to melt 3 mm of ice from the surface of the rink if no cooling is supplied and the surface is considered insulated on the back side.

1-42 In energy conservation studies, cost is usually expressed in terms of Btu of energy, or some English unit of measure such as the gallon. Some typical examples are

Overall cost: $\$/10^6$ Btu

Transportation results: passenger miles per 10^6 Btu or per gallon of fuel
ton-miles of freight per 10^6 Btu or per gallon of fuel

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Consult whatever sources are needed, and devise suitable measures for energy consumption and cost using the SI system of units. How would you price such items as

Energy content of various types of coal
Energy content of gasoline
Energy content of natural gas
Energy "content" of electricity

After devising the SI system of cost measures, construct a table of conversion factors like that given in the front inside cover of this book, to convert from SI to English and from English to SI.

1-43 Using information developed in Problem 1-42, investigate the energy cost saving that results from the installation of a layer of glass wool 15 cm thick on a steel building 12 by 12 m in size and 5 m high. Assume the building is subjected to a temperature difference of 30°C and the floor of the building does not participate in the heat lost. Assume that the outer surface of the building loses heat by convection to a surrounding temperature of $-10°\text{C}$ with a convection coefficient $h = 13\ \text{W/m}^2 \cdot °\text{C}$.

1-44 A boy-scout counselor gives the following advice to his scout troop regarding camping out in cold weather. "Be careful when setting up your cot/bunk—you may have provided for plenty of blankets to cover the top of your body, but don't forget that you can lose heat from the bottom through the thin layer of the cot/bunk. Provide a layer of insulation for your bottom side also." Investigate the validity of this statement by making suitable assumptions regarding exterior body temperature, thermal conductivity of blankets and cot/bunk materials, and the like.

REFERENCES

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