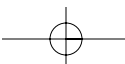
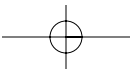
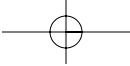


PART

3

HEAT TRANSFER





CHAPTER

16

MECHANISMS OF
HEAT TRANSFER

The science of thermodynamics deals with the *amount* of heat transfer as a system undergoes a process from one equilibrium state to another, and makes no reference to *how long* the process will take. But in engineering, we are often interested in the *rate* of heat transfer, which is the topic of the science of *heat transfer*.

In this chapter, we present an overview of the three basic mechanisms of heat transfer, which are conduction, convection, and radiation, and discuss thermal conductivity. *Conduction* is 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. *Convection* is the mode of heat 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. *Radiation* is 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. We close this chapter with a discussion of simultaneous heat transfer.

■■■■■■■
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16-1 ■ INTRODUCTION

In Chap. 2 we defined **heat** as the form of energy that can be transferred from one system to another as a result of temperature difference. A thermodynamic analysis is concerned with the *amount* of heat transfer as a system undergoes a process from one equilibrium state to another. The science that deals with the determination of the *rates* of such energy transfers is the **heat transfer**. The transfer of energy as heat is always from the higher-temperature medium to the lower-temperature one, and heat transfer stops when the two mediums reach the same temperature.

Heat can be transferred in three different modes: *conduction*, *convection*, and *radiation*. All modes of heat transfer require the existence of a temperature difference, and all modes are from the high-temperature medium to a lower-temperature one. Here we give a brief description of each mode. A detailed study of these modes is given in later chapters of this text.

16-2 ■ CONDUCTION

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

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

Consider steady heat conduction through a large plane wall of thickness $\Delta x = L$ and area A , as shown in Fig. 16-1. The temperature difference across the wall is $\Delta T = T_2 - T_1$. Experiments have shown that the rate of heat transfer \dot{Q} through the wall is *doubled* when the temperature difference ΔT across the wall or the area A normal to the direction of heat transfer is doubled, but is *halved* when the wall thickness L is doubled. Thus we conclude that *the rate of heat conduction through a plane layer is proportional to the temperature difference across the layer and the heat transfer area, but is inversely proportional to the thickness of the layer*. That is,

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

or,

$$\dot{Q}_{\text{cond}} = kA \frac{T_1 - T_2}{\Delta x} = -kA \frac{\Delta T}{\Delta x} \quad (\text{W}) \quad (16-1)$$

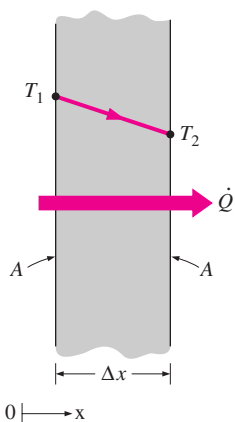
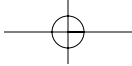


FIGURE 16-1

Heat conduction through a large plane wall of thickness Δx and area A .



where the constant of proportionality k is the **thermal conductivity** of the material, which is a *measure of the ability of a material to conduct heat* (Fig. 16–2). In the limiting case of $\Delta x \rightarrow 0$, reduces to the differential form

$$\dot{Q}_{\text{cond}} = -kA \frac{dT}{dx} \quad (\text{W}) \quad (16-2)$$

which is called **Fourier's law of heat conduction** after J. Fourier, who expressed it first in his heat transfer text in 1822. Here dT/dx is the **temperature gradient**, which is the slope of the temperature curve on a T - x diagram (the rate of change of T with x), at location x . This relation indicates that the rate of heat conduction in a direction is proportional to the temperature gradient in that direction. 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 Eq. 16–2 ensures that heat transfer in the positive x direction is a positive quantity.

The heat transfer area A is always *normal* to the direction of heat transfer. For heat loss through a 5-m-long, 3-m-high, and 25-cm-thick wall, for example, the heat transfer area is $A = 15 \text{ m}^2$. Note that the thickness of the wall has no effect on A (Fig. 16–3).

EXAMPLE 16–1 The Cost of Heat Loss through a Roof

The roof of an electrically heated home is 6 m long, 8 m wide, and 0.25 m thick, and is made of a flat layer of concrete whose thermal conductivity is $k = 0.8 \text{ W/m} \cdot ^\circ\text{C}$ (Fig. 16–4). The temperatures of the inner and the outer surfaces of the roof one night are measured to be 15°C and 4°C , respectively, for a period of 10 hours. Determine (a) the rate of heat loss through the roof that night and (b) the cost of that heat loss to the home owner if the cost of electricity is $\$0.08/\text{kWh}$.

SOLUTION The inner and outer surfaces of the flat concrete roof of an electrically heated home are maintained at specified temperatures during a night. The heat loss through the roof and its cost that night are to be determined.

Assumptions 1 Steady operating conditions exist during the entire night since the surface temperatures of the roof remain constant at the specified values. 2 Constant properties can be used for the roof.

Properties The thermal conductivity of the roof is given to be $k = 0.8 \text{ W/m} \cdot ^\circ\text{C}$.

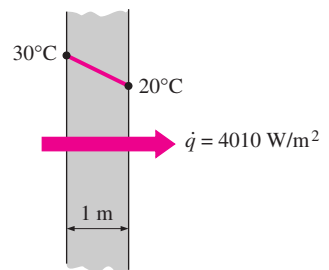
Analysis (a) Noting that heat transfer through the roof is by conduction and the area of the roof is $A = 6 \text{ m} \times 8 \text{ m} = 48 \text{ m}^2$, the steady rate of heat transfer through the roof is determined to be

$$\dot{Q} = kA \frac{T_1 - T_2}{L} = (0.8 \text{ W/m} \cdot ^\circ\text{C})(48 \text{ m}^2) \frac{(15 - 4)^\circ\text{C}}{0.25 \text{ m}} = 1690 \text{ W} = 1.69 \text{ kW}$$

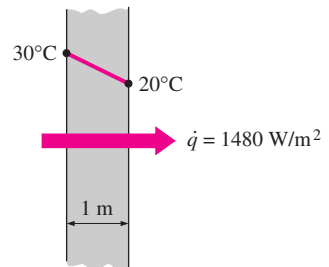
(b) The amount of heat lost through the roof during a 10-h period and its cost are determined from

$$\begin{aligned} Q &= \dot{Q} \Delta t = (1.69 \text{ kW})(10 \text{ h}) = 16.9 \text{ kWh} \\ \text{Cost} &= (\text{Amount of energy})(\text{Unit cost of energy}) \\ &= (16.9 \text{ kWh})(\$0.08/\text{kWh}) = \mathbf{\$1.35} \end{aligned}$$

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(a) Copper ($k = 401 \text{ W/m} \cdot ^\circ\text{C}$)



(b) Silicon ($k = 148 \text{ W/m} \cdot ^\circ\text{C}$)

FIGURE 16–2

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

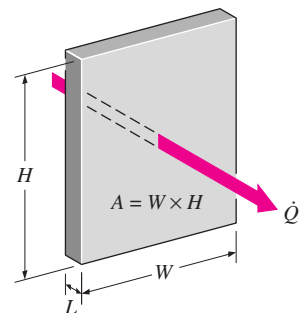


FIGURE 16–3

In heat conduction analysis, A represents the area *normal* to the direction of heat transfer.

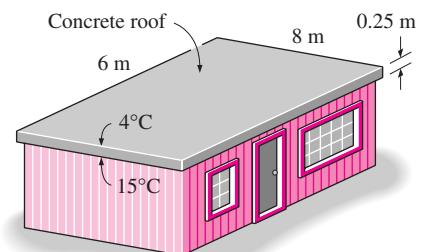


FIGURE 16–4

Schematic for Example 16–1.

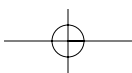


TABLE 16-1

The thermal conductivities of some materials at room temperature

Material	k , W/m · °C*
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)	0.613
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.

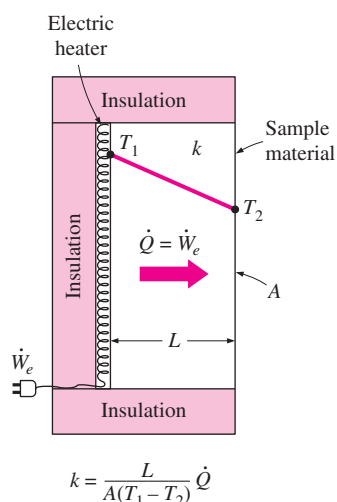


FIGURE 16-5

A simple experimental setup to determine the thermal conductivity of a material.

Discussion The cost to the home owner of the heat loss through the roof that night was \$1.35. The total heating bill of the house will be much larger since the heat losses through the walls are not considered in these calculations.

Thermal Conductivity

We have seen that different materials store heat differently, and we have defined the property specific heat C_p as a measure of a material's ability to store thermal energy. For example, $C_p = 4.18$ kJ/kg · °C for water and $C_p = 0.45$ kJ/kg · °C for iron at room temperature, which indicates that water can store almost 10 times the energy that iron can per unit mass. Likewise, the thermal conductivity k is a measure of a material's ability to conduct heat. For example, $k = 0.608$ W/m · °C for water and $k = 80.2$ W/m · °C for iron at room temperature, which indicates that iron conducts heat more than 100 times faster than water can. Thus we say that water is a poor heat conductor relative to iron, although water is an excellent medium to store thermal energy.

Equation 16-2 for the rate of conduction heat transfer under steady conditions can also be viewed as the defining equation for thermal conductivity. Thus the **thermal conductivity** of a material can be defined as *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*. The thermal conductivities of some common materials at room temperature are given in Table 16-1. The thermal conductivity of pure copper at room temperature is $k = 401$ W/m · °C, which indicates that a 1-m-thick copper wall will conduct heat at a rate of 401 W per m² area per °C temperature difference across the wall. Note that materials such as copper and silver that are good electric conductors are also good heat conductors, and have high values of thermal conductivity. Materials such as rubber, wood, and Styrofoam are poor conductors of heat and have low conductivity values.

A layer of material of known thickness and area can be heated from one side by an electric resistance heater of known output. If the outer surfaces of the heater are well insulated, all the heat generated by the resistance heater will be transferred through the material whose conductivity is to be determined. Then measuring the two surface temperatures of the material when steady heat transfer is reached and substituting them into Eq. 16-2 together with other known quantities give the thermal conductivity (Fig. 16-5).

The thermal conductivities of materials vary over a wide range, as shown in Fig. 16-6. The thermal conductivities of gases such as air vary by a factor of 10^4 from those of pure metals such as copper. Note that pure crystals and metals have the highest thermal conductivities, and gases and insulating materials the lowest.

Temperature is a measure of the kinetic energies of the particles such as the molecules or atoms of a substance. In a liquid or gas, the kinetic energy of the molecules is due to their random translational motion as well as their vibrational and rotational motions. When two molecules possessing different kinetic energies collide, part of the kinetic energy of the more energetic

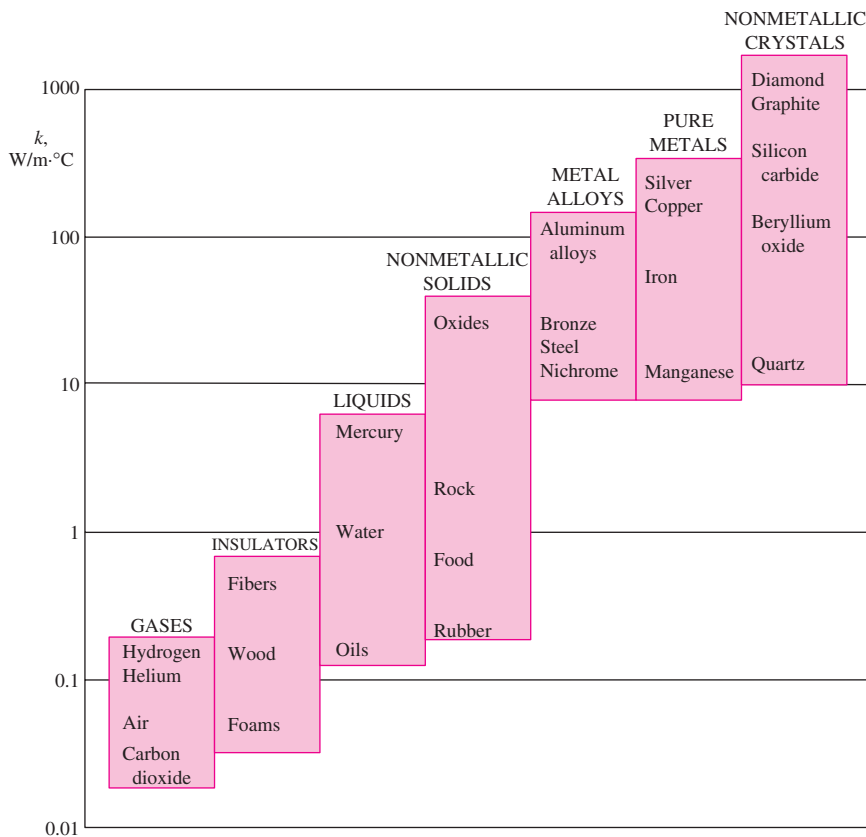


FIGURE 16-6

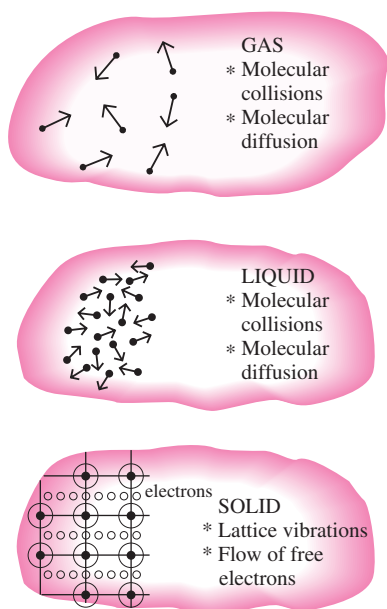
The range of thermal conductivity of various materials at room temperature.

(higher-temperature) molecule is transferred to the less energetic (lower-temperature) molecule, much the same as when two elastic balls of the same mass at different velocities collide, part of the kinetic energy of the faster ball is transferred to the slower one. The higher the temperature, the faster the molecules move and the higher the number of such collisions, and the better the heat transfer.

The *kinetic theory* of gases predicts and the experiments confirm that the thermal conductivity of gases is proportional to the *square root of the absolute temperature T* , and inversely proportional to the *square root of the molar mass M* . Therefore, the thermal conductivity of a gas increases with increasing temperature and decreasing molar mass. So it is not surprising that the thermal conductivity of helium ($M = 4$) is much higher than those of air ($M = 29$) and argon ($M = 40$).

The thermal conductivities of *gases* at 1 atm pressure are listed in Table A-23. However, they can also be used at pressures other than 1 atm, since the thermal conductivity of gases is *independent of pressure* in a wide range of pressures encountered in practice.

The mechanism of heat conduction in a *liquid* is complicated by the fact that the molecules are more closely spaced, and they exert a stronger intermolecular force field. The thermal conductivities of liquids usually lie between those of solids and gases. The thermal conductivity of a substance is normally highest in the solid phase and lowest in the gas phase. Unlike gases, the thermal

**FIGURE 16-7**

The mechanisms of heat conduction in different phases of a substance.

TABLE 16-2

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 \cdot $^{\circ}$ C, at 300 K
Copper	401
Nickel	91
Constantan (55% Cu, 45% Ni)	23
Copper	401
Aluminum	237
Commercial bronze (90% Cu, 10% Al)	52

conductivities of most liquids decrease with increasing temperature, with water being a notable exception. Like gases, the conductivity of liquids decreases with increasing molar mass. Liquid metals such as mercury and sodium have high thermal conductivities and are very suitable for use in applications where a high heat transfer rate to a liquid is desired, as in nuclear power plants.

In *solids*, heat conduction is due to two effects: the *lattice vibrational waves* induced by the vibrational motions of the molecules positioned at relatively fixed positions in a periodic manner called a lattice, and the energy transported via the *free flow of electrons* in the solid (Fig. 16-7). The thermal conductivity of a solid is obtained by adding the lattice and electronic components. The relatively high thermal conductivities of pure metals are primarily due to the electronic component. The lattice component of thermal conductivity strongly depends on the way the molecules are arranged. For example, diamond, which is a highly ordered crystalline solid, has the highest known thermal conductivity at room temperature.

Unlike metals, which are good electrical and heat conductors, *crystalline solids* such as diamond and semiconductors such as silicon are good heat conductors but poor electrical conductors. As a result, such materials find widespread use in the electronics industry. Despite their higher price, diamond heat sinks are used in the cooling of sensitive electronic components because of the excellent thermal conductivity of diamond. Silicon oils and gaskets are commonly used in the packaging of electronic components because they provide both good thermal contact and good electrical insulation.

Pure metals have high thermal conductivities, and one would think that *metal alloys* should also have high conductivities. One would expect an alloy made of two metals of thermal conductivities k_1 and k_2 to have a conductivity k between k_1 and k_2 . But this turns out not to be the case. The thermal conductivity of an alloy of two metals is usually much lower than that of either metal, as shown in Table 16-2. Even small amounts in a pure metal of “foreign” molecules that are good conductors themselves seriously disrupt the flow of heat in that metal. For example, the thermal conductivity of steel containing just 1 percent of chrome is 62 W/m \cdot $^{\circ}$ C, while the thermal conductivities of iron and chromium are 83 and 95 W/m \cdot $^{\circ}$ C, respectively.

The thermal conductivities of materials vary with temperature (Table 16-3). The variation of thermal conductivity over certain temperature ranges is negligible for some materials, but significant for others, as shown in Fig. 16-8. The thermal conductivities of certain solids exhibit dramatic increases at temperatures near absolute zero, when these solids become *superconductors*. For example, the conductivity of copper reaches a maximum value of about 20,000 W/m \cdot $^{\circ}$ C at 20 K, which is about 50 times the conductivity at room temperature. The thermal conductivities and other thermal properties of various materials are given in Tables A-15 to A-20, A-22, A-23, and A-27 to A-29.

The temperature dependence of thermal conductivity causes considerable complexity in conduction analysis. Therefore, it is common practice to evaluate the thermal conductivity k at the *average temperature* and treat it as a *constant* in calculations.

In heat transfer analysis, a material is normally assumed to be *isotropic*; that is, to have uniform properties in all directions. This assumption is realistic for most materials, except those that exhibit different structural characteristics in different directions, such as laminated composite materials and wood. The

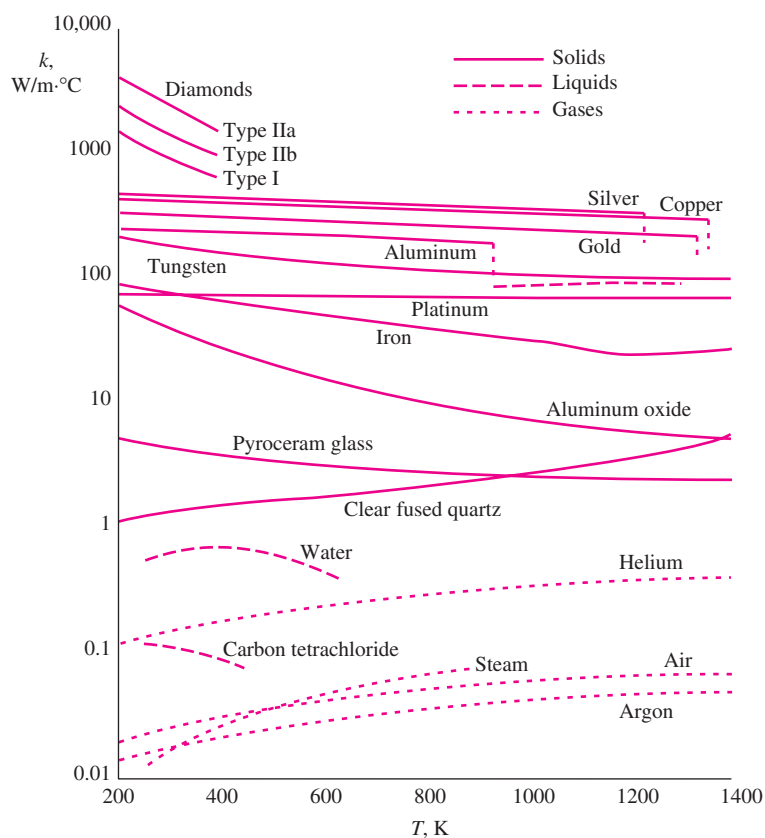


FIGURE 16-8

The variation of the thermal conductivity of various solids, liquids, and gases with temperature.

thermal conductivity of wood across the grain, for example, is different than that parallel to the grain.

Thermal Diffusivity

The product ρC_p , which is frequently encountered in heat transfer analysis, is called the **heat capacity** of a material. Both the specific heat C_p and the heat capacity ρC_p represent the heat storage capability of a material. But C_p expresses it *per unit mass* whereas ρC_p expresses it *per unit volume*, as can be noticed from their units $\text{J/kg} \cdot ^\circ\text{C}$ and $\text{J/m}^3 \cdot ^\circ\text{C}$, respectively.

Another material property that appears in the transient heat conduction analysis is the **thermal diffusivity**, which represents how fast heat diffuses through a material and is defined as

$$\alpha = \frac{\text{Heat conducted}}{\text{Heat stored}} = \frac{k}{\rho C_p} \quad (\text{m}^2/\text{s}) \quad (16-3)$$

Note that the thermal conductivity k represents how well a material conducts heat, and the heat capacity ρC_p represents how much energy a material stores per unit volume. Therefore, the thermal diffusivity of a material can be viewed as the ratio of the *heat conducted* through the material to the *heat stored* per unit volume. A material that has a high thermal conductivity or a low heat capacity will obviously have a large thermal diffusivity. The larger

TABLE 16-3

Thermal conductivities of materials vary with temperature

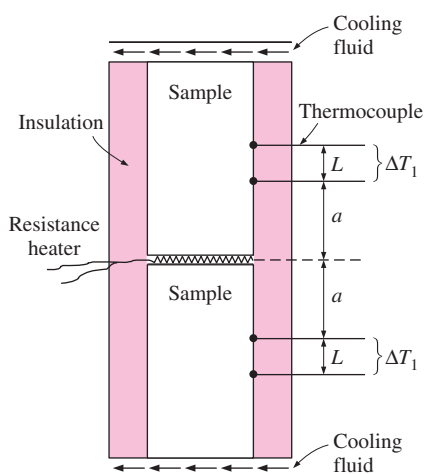
T, K	Copper	Aluminum
100	482	302
200	413	237
300	401	237
400	393	240
600	379	231
800	366	218

TABLE 16–4

The thermal diffusivities of some materials at room temperature

Material	α , m ² /s*
Silver	149×10^{-6}
Gold	127×10^{-6}
Copper	113×10^{-6}
Aluminum	97.5×10^{-6}
Iron	22.8×10^{-6}
Mercury (l)	4.7×10^{-6}
Marble	1.2×10^{-6}
Ice	1.2×10^{-6}
Concrete	0.75×10^{-6}
Brick	0.52×10^{-6}
Heavy soil (dry)	0.52×10^{-6}
Glass	0.34×10^{-6}
Glass wool	0.23×10^{-6}
Water (l)	0.14×10^{-6}
Beef	0.14×10^{-6}
Wood (oak)	0.13×10^{-6}

*Multiply by 10.76 to convert to ft²/s.

**FIGURE 16–9**

Apparatus to measure the thermal conductivity of a material using two identical samples and a thin resistance heater (Example 16–2).

the thermal diffusivity, the faster the propagation of heat into the medium. A small value of thermal diffusivity means that heat is mostly absorbed by the material and a small amount of heat will be conducted further.

The thermal diffusivities of some common materials at 20°C are given in Table 16–4. Note that the thermal diffusivity ranges from $\alpha = 0.14 \times 10^{-6}$ m²/s for water to 149×10^{-6} m²/s for silver, which is a difference of more than a thousand times. Also note that the thermal diffusivities of beef and water are the same. This is not surprising, since meat as well as fresh vegetables and fruits are mostly water, and thus they possess the thermal properties of water.

EXAMPLE 16–2 Measuring the Thermal Conductivity of a Material

A common way of measuring the thermal conductivity of a material is to sandwich an electric thermofoil heater between two identical samples of the material, as shown in Fig. 16–9. The thickness of the resistance heater, including its cover, which is made of thin silicon rubber, is usually less than 0.5 mm. A circulating fluid such as tap water keeps the exposed ends of the samples at constant temperature. The lateral surfaces of the samples are well insulated to ensure that heat transfer through the samples is one-dimensional. Two thermocouples are embedded into each sample some distance L apart, and a differential thermometer reads the temperature drop ΔT across this distance along each sample. When steady operating conditions are reached, the total rate of heat transfer through both samples becomes equal to the electric power drawn by the heater, which is determined by multiplying the electric current by the voltage.

In a certain experiment, cylindrical samples of diameter 5 cm and length 10 cm are used. The two thermocouples in each sample are placed 3 cm apart. After initial transients, the electric heater is observed to draw 0.4 A at 110 V, and both differential thermometers read a temperature difference of 15°C. Determine the thermal conductivity of the sample.

SOLUTION The thermal conductivity of a material is to be determined by ensuring one-dimensional heat conduction, and by measuring temperatures when steady operating conditions are reached.

Assumptions 1 Steady operating conditions exist since the temperature readings do not change with time. 2 Heat losses through the lateral surfaces of the apparatus are negligible since those surfaces are well insulated, and thus the entire heat generated by the heater is conducted through the samples. 3 The apparatus possesses thermal symmetry.

Analysis The electrical power consumed by the resistance heater and converted to heat is

$$\dot{W}_e = VI = (110 \text{ V})(0.4 \text{ A}) = 44 \text{ W}$$

The rate of heat flow through each sample is

$$\dot{Q} = \frac{1}{2} \dot{W}_e = \frac{1}{2} \times (44 \text{ W}) = 22 \text{ W}$$

since only half of the heat generated will flow through each sample because of symmetry. Reading the same temperature difference across the same distance in each sample also confirms that the apparatus possesses thermal symmetry. The heat transfer area is the area normal to the direction of heat flow, which is the cross-sectional area of the cylinder in this case:

$$A = \frac{1}{4} \pi D^2 = \frac{1}{4} \pi (0.05 \text{ m})^2 = 0.00196 \text{ m}^2$$

Noting that the temperature drops by 15°C within 3 cm in the direction of heat flow, the thermal conductivity of the sample is determined to be

$$\dot{Q} = kA \frac{\Delta T}{L} \rightarrow k = \frac{\dot{Q}L}{A \Delta T} = \frac{(22 \text{ W})(0.03 \text{ m})}{(0.00196 \text{ m}^2)(15^\circ\text{C})} = \mathbf{22.4 \text{ W/m} \cdot ^\circ\text{C}}$$

Discussion Perhaps you are wondering if we really need to use two samples in the apparatus, since the measurements on the second sample do not give any additional information. It seems like we can replace the second sample by insulation. Indeed, we do not need the second sample; however, it enables us to verify the temperature measurements on the first sample and provides thermal symmetry, which reduces experimental error.

EXAMPLE 16–3 Conversion between SI and English Units

An engineer who is working on the heat transfer analysis of a brick building in English units needs the thermal conductivity of brick. But the only value he can find from his handbooks is 0.72 W/m · °C, which is in SI units. To make matters worse, the engineer does not have a direct conversion factor between the two unit systems for thermal conductivity. Can you help him out?

SOLUTION The situation this engineer is facing is not unique, and most engineers often find themselves in a similar position. A person must be very careful during unit conversion not to fall into some common pitfalls and to avoid some costly mistakes. Although unit conversion is a simple process, it requires utmost care and careful reasoning.

The conversion factors for W and m are straightforward and are given in conversion tables to be

$$1 \text{ W} = 3.41214 \text{ Btu/h}$$

$$1 \text{ m} = 3.2808 \text{ ft}$$

But the conversion of °C into °F is not so simple, and it can be a source of error if one is not careful. Perhaps the first thought that comes to mind is to replace °C by (°F – 32)/1.8 since $T(^{\circ}\text{C}) = [T(^{\circ}\text{F}) - 32]/1.8$. But this will be wrong since the °C in the unit W/m · °C represents *per °C change in temperature*. Noting that 1°C change in temperature corresponds to 1.8°F, the proper conversion factor to be used is

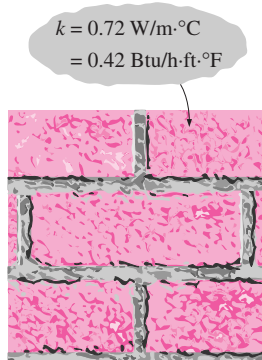
$$1^{\circ}\text{C} = 1.8^{\circ}\text{F}$$

Substituting, we get

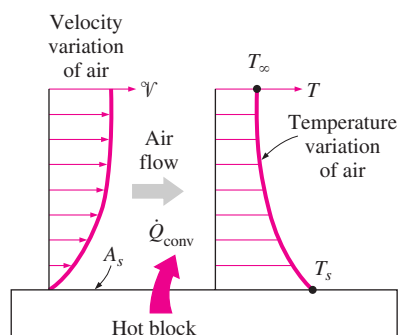
$$1 \text{ W/m} \cdot ^{\circ}\text{C} = \frac{3.41214 \text{ Btu/h}}{(3.2808 \text{ ft})(1.8^{\circ}\text{F})} = 0.5778 \text{ Btu/h} \cdot \text{ft} \cdot ^{\circ}\text{F}$$

which is the desired conversion factor. Therefore, the thermal conductivity of the brick in English units is

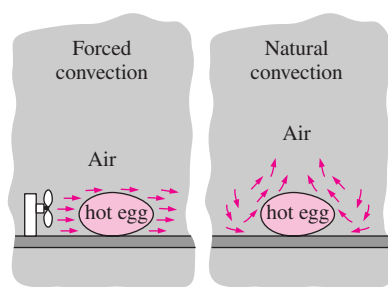
$$\begin{aligned} k_{\text{brick}} &= 0.72 \text{ W/m} \cdot ^{\circ}\text{C} \\ &= 0.72 \times (0.5778 \text{ Btu/h} \cdot \text{ft} \cdot ^{\circ}\text{F}) \\ &= \mathbf{0.42 \text{ Btu/h} \cdot \text{ft} \cdot ^{\circ}\text{F}} \end{aligned}$$

**FIGURE 16-10**

The thermal conductivity value in English units is obtained by multiplying the value in SI units by 0.5778.

**FIGURE 16-11**

Heat transfer from a hot surface to air by convection.

**FIGURE 16-12**

The cooling of a boiled egg by forced and natural convection.

Discussion Note that the thermal conductivity value of a material in English units is about half that in SI units (Fig. 16–10). Also note that we rounded the result to two significant digits (the same number in the original value) since expressing the result in more significant digits (such as 0.4160 instead of 0.42) would falsely imply a more accurate value than the original one.

16-3 ■ CONVECTION

Convection is 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. The presence of bulk motion of the fluid enhances the heat transfer between the solid surface and the fluid, but it also complicates the determination of heat transfer rates.

Consider the cooling of a hot block by blowing cool air over its top surface (Fig. 16–11). Energy is first transferred to the air layer adjacent to the block by conduction. This energy is then carried away from the surface by convection, that is, by the combined effects of conduction within the air that is due to random motion of air molecules and the bulk or macroscopic motion of the air that removes the heated air near the surface and replaces it by the cooler air.

Convection is called **forced convection** if the fluid is forced to flow over the surface by external means such as a fan, pump, or the wind. In contrast, convection is called **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 (Fig. 16–12). For example, in the absence of a fan, heat transfer from the surface of the hot block in Fig. 16–11 will be by natural convection since any motion in the air in this case will be due to the rise of the warmer (and thus lighter) air near the surface and the fall of the cooler (and thus heavier) air to fill its place. Heat transfer between the block and the surrounding air will be by conduction if the temperature difference between the air and the block is not large enough to overcome the resistance of air to movement and thus to initiate natural convection currents.

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.

Despite the complexity of convection, the rate of *convection heat transfer* is observed to be proportional to the temperature difference, and is conveniently expressed by **Newton's law of cooling** as

$$\dot{Q}_{\text{conv}} = hA_s(T_s - T_\infty) \quad (\text{W}) \quad (16-4)$$

where h is the *convection heat transfer coefficient* in $\text{W/m}^2 \cdot ^\circ\text{C}$ or $\text{Btu/h} \cdot \text{ft}^2 \cdot ^\circ\text{F}$, A_s is the surface area through which convection heat transfer takes place, T_s is the surface temperature, and T_∞ is the temperature of the fluid sufficiently far

from the surface. Note that at the surface, the fluid temperature equals the surface temperature of the solid.

The convection heat transfer coefficient h is not a property of the fluid. It is an experimentally determined parameter whose value depends on all the variables influencing convection such as the surface geometry, the nature of fluid motion, the properties of the fluid, and the bulk fluid velocity. Typical values of h are given in Table 16–5.

Some people do not consider convection to be a fundamental mechanism of heat transfer since it is essentially heat conduction in the presence of fluid motion. But we still need to give this combined phenomenon a name, unless we are willing to keep referring to it as “conduction with fluid motion.” Thus, it is practical to recognize convection as a separate heat transfer mechanism despite the valid arguments to the contrary.

EXAMPLE 16–4 Measuring Convection Heat Transfer Coefficient

A 2-m-long, 0.3-cm-diameter electrical wire extends across a room at 15°C , as shown in Fig. 16–13. Heat is generated in the wire as a result of resistance heating, and the surface temperature of the wire is measured to be 152°C in steady operation. Also, the voltage drop and electric current through the wire are measured to be 60 V and 1.5 A, respectively. Disregarding any heat transfer by radiation, determine the convection heat transfer coefficient for heat transfer between the outer surface of the wire and the air in the room.

SOLUTION The convection heat transfer coefficient for heat transfer from an electrically heated wire to air is to be determined by measuring temperatures when steady operating conditions are reached and the electric power consumed.

Assumptions 1 Steady operating conditions exist since the temperature readings do not change with time. 2 Radiation heat transfer is negligible.

Analysis When steady operating conditions are reached, the rate of heat loss from the wire will equal the rate of heat generation in the wire as a result of resistance heating. That is,

$$\dot{Q} = \dot{E}_{\text{generated}} = VI = (60 \text{ V})(1.5 \text{ A}) = 90 \text{ W}$$

The surface area of the wire is

$$A_s = \pi DL = \pi(0.003 \text{ m})(2 \text{ m}) = 0.01885 \text{ m}^2$$

Newton’s law of cooling for convection heat transfer is expressed as

$$\dot{Q}_{\text{conv}} = hA_s(T_s - T_{\infty})$$

Disregarding any heat transfer by radiation and thus assuming all the heat loss from the wire to occur by convection, the convection heat transfer coefficient is determined to be

$$h = \frac{\dot{Q}_{\text{conv}}}{A_s(T_s - T_{\infty})} = \frac{90 \text{ W}}{(0.01885 \text{ m}^2)(152 - 15)^{\circ}\text{C}} = \mathbf{34.9 \text{ W/m}^2 \cdot ^{\circ}\text{C}}$$

Discussion Note that the simple setup described above can be used to determine the average heat transfer coefficients from a variety of surfaces in air. Also, heat transfer by radiation can be eliminated by keeping the surrounding surfaces at the temperature of the wire.

TABLE 16–5

Typical values of convection heat transfer coefficient

Type of convection	h , $\text{W/m}^2 \cdot ^{\circ}\text{C}^*$
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 $\text{Btu/h} \cdot \text{ft}^2 \cdot ^{\circ}\text{F}$.

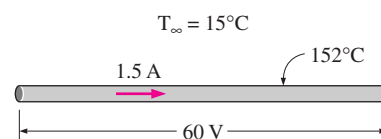
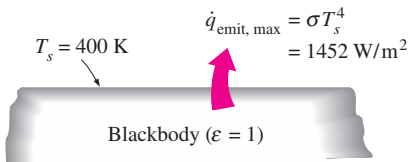


FIGURE 16–13
Schematic for Example 16–4.

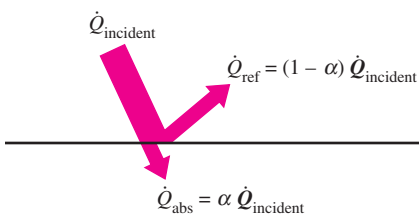
**FIGURE 16-14**

Blackbody radiation represents the *maximum amount of radiation that can be emitted from a surface at a specified temperature.*

TABLE 16-6

Emissivities of some materials at 300 K

Material	Emissivity
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

**FIGURE 16-15**

The absorption of radiation incident on an opaque surface of absorptivity α .

16-4 ■ RADIATION

Radiation is 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 energy by radiation does not require the presence of an *intervening medium*. In fact, energy 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.

In heat transfer studies we are interested in *thermal radiation*, which is the form of radiation emitted by bodies because of their temperature. It differs from other forms of electromagnetic radiation such as X-rays, gamma rays, microwaves, radio waves, and television waves that are not related to temperature. All bodies at a temperature above absolute zero emit thermal radiation.

Radiation is a *volumetric phenomenon*, and all solids, liquids, and gases emit, absorb, or transmit radiation to varying degrees. However, radiation is usually considered to be a *surface phenomenon* for solids that are opaque to thermal radiation such as metals, wood, and rocks since the radiation emitted by the interior regions of such material can never reach the surface, and the radiation incident on such bodies is usually absorbed within a few microns from the surface.

The maximum rate of radiation that can be emitted from a surface at an absolute temperature T_s (in K or R) is given by the **Stefan–Boltzmann law** as

$$\dot{Q}_{\text{emit, max}} = \sigma A_s T_s^4 \quad (\text{W}) \quad (16-5)$$

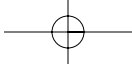
where $\sigma = 5.67 \times 10^{-8} \text{ W/m}^2 \cdot \text{K}^4$ or $0.1714 \times 10^{-8} \text{ Btu/h} \cdot \text{ft}^2 \cdot \text{R}^4$ is the *Stefan–Boltzmann constant*. The idealized surface that emits radiation at this maximum rate is called a **blackbody**, and the radiation emitted by a blackbody is called **blackbody radiation** (Fig. 16-14). The radiation emitted by all real surfaces is less than the radiation emitted by a blackbody at the same temperature, and is expressed as

$$\dot{Q}_{\text{emit}} = \epsilon \sigma A_s T_s^4 \quad (\text{W}) \quad (16-6)$$

where ϵ is the **emissivity** of the surface. The property emissivity, whose value is in the range $0 \leq \epsilon \leq 1$, is a measure of how closely a surface approximates a blackbody for which $\epsilon = 1$. The emissivities of some surfaces are given in Table 16-6.

Another important radiation property of a surface is its **absorptivity** α , which is the fraction of the radiation energy incident on a surface that is absorbed by the surface. Like emissivity, its value is in the range $0 \leq \alpha \leq 1$. A blackbody absorbs the entire radiation incident on it. That is, a blackbody is a perfect absorber ($\alpha = 1$) as it is a perfect emitter.

In general, both ϵ and α of a surface depend on the temperature and the wavelength of the radiation. **Kirchhoff's law** of radiation states that the emissivity and the absorptivity of a surface at a given temperature and wavelength are equal. In many practical applications, the surface temperature and the temperature of the source of incident radiation are of the same order of magnitude, and the average absorptivity of a surface is taken to be equal to its average emissivity. The rate at which a surface absorbs radiation is determined from (Fig. 16-15)



$$\dot{Q}_{\text{absorbed}} = \alpha \dot{Q}_{\text{incident}} \quad (\text{W}) \quad (16-7)$$

where $\dot{Q}_{\text{incident}}$ is the rate at which radiation is incident on the surface and α is the absorptivity of the surface. For opaque (nontransparent) surfaces, the portion of incident radiation not absorbed by the surface is reflected back.

The difference between the rates of radiation emitted by the surface and the radiation absorbed is the *net* radiation heat transfer. If the rate of radiation absorption is greater than the rate of radiation emission, the surface is said to be *gaining* energy by radiation. Otherwise, the surface is said to be *losing* energy by radiation. In general, 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, and the interaction of the medium between the surfaces with radiation.

When a surface of emissivity ε and surface area A_s at an *absolute temperature* T_s is *completely enclosed* by a much larger (or black) surface at absolute 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 (Fig. 16–16)

$$\dot{Q}_{\text{rad}} = \varepsilon \sigma A_s (T_s^4 - T_{\text{surr}}^4) \quad (\text{W}) \quad (16-8)$$

In this special case, the emissivity and the surface area of the surrounding surface do not have any effect on the net radiation heat transfer.

Radiation heat transfer to or from a surface surrounded by a gas such as air occurs *parallel* to conduction (or convection, if there is bulk gas motion) between the surface and the gas. Thus the total heat transfer is determined by *adding* the contributions of both heat transfer mechanisms. For simplicity and convenience, this is often done by defining a **combined heat transfer coefficient** h_{combined} that includes the effects of both convection and radiation. Then the *total* heat transfer rate to or from a surface by convection and radiation is expressed as

$$\dot{Q}_{\text{total}} = h_{\text{combined}} A_s (T_s - T_{\infty}) \quad (\text{W}) \quad (16-9)$$

Note that the combined heat transfer coefficient is essentially a convection heat transfer coefficient modified to include the effects of radiation.

Radiation is usually significant relative to conduction or natural convection, but negligible relative to forced convection. Thus radiation in forced convection applications is usually disregarded, especially when the surfaces involved have low emissivities and low to moderate temperatures.

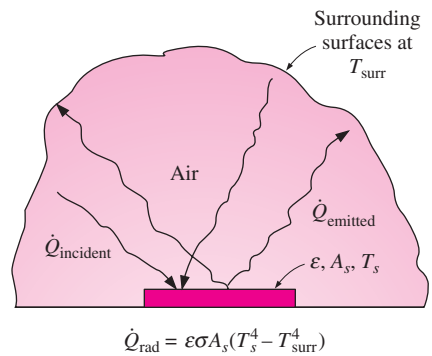


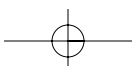
FIGURE 16–16

Radiation heat transfer between a surface and the surfaces surrounding it.

EXAMPLE 16–5 Radiation Effect on Thermal Comfort

It is a common experience to feel “chilly” in winter and “warm” in summer in our homes even when the thermostat setting is kept the same. This is due to the so called “radiation effect” resulting from radiation heat exchange between our bodies and the surrounding surfaces of the walls and the ceiling.

Consider a person standing in a room maintained at 22°C at all times. The inner surfaces of the walls, floors, and the ceiling of the house are observed to be at an average temperature of 10°C in winter and 25°C in summer. Determine the rate of radiation heat transfer between this person and the surrounding sur-



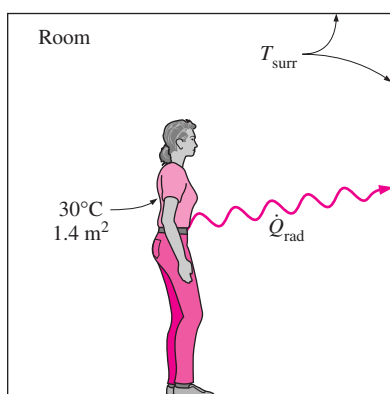


FIGURE 16-17

Schematic for Example 16-5.

faces if the exposed surface area and the average outer surface temperature of the person are 1.4 m^2 and 30°C , respectively (Fig. 16-17).

SOLUTION The rates of radiation heat transfer between a person and the surrounding surfaces at specified temperatures are to be determined in summer and winter.

Assumptions 1 Steady operating conditions exist. 2 Heat transfer by convection is not considered. 3 The person is completely surrounded by the interior surfaces of the room. 4 The surrounding surfaces are at a uniform temperature.

Properties The emissivity of a person is $\varepsilon = 0.95$ (Table 16-6).

Analysis The net rates of radiation heat transfer from the body to the surrounding walls, ceiling, and floor in winter and summer are

$$\begin{aligned}\dot{Q}_{\text{rad, winter}} &= \varepsilon \sigma A_s (T_s^4 - T_{\text{surr, winter}}^4) \\ &= (0.95)(5.67 \times 10^{-8} \text{ W/m}^2 \cdot \text{K}^4)(1.4 \text{ m}^2) \\ &\quad \times [(30 + 273)^4 - (10 + 273)^4] \text{ K}^4 \\ &= \mathbf{152 \text{ W}}\end{aligned}$$

and

$$\begin{aligned}\dot{Q}_{\text{rad, summer}} &= \varepsilon \sigma A_s (T_s^4 - T_{\text{surr, summer}}^4) \\ &= (0.95)(5.67 \times 10^{-8} \text{ W/m}^2 \cdot \text{K}^4)(1.4 \text{ m}^2) \\ &\quad \times [(30 + 273)^4 - (25 + 273)^4] \text{ K}^4 \\ &= \mathbf{40.9 \text{ W}}\end{aligned}$$

Discussion Note that we must use *absolute temperatures* in radiation calculations. Also note that the rate of heat loss from the person by radiation is almost four times as large in winter than it is in summer, which explains the “chill” we feel in winter even if the thermostat setting is kept the same.

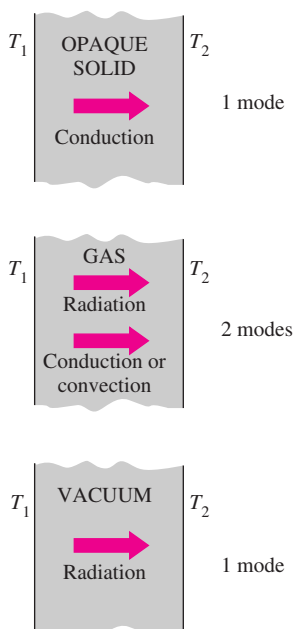


FIGURE 16-18

Although there are three mechanisms of heat transfer, a medium may involve only two of them simultaneously.

16-5 ■ SIMULTANEOUS HEAT TRANSFER MECHANISMS

We mentioned that there are three mechanisms of heat transfer, but not all three can exist simultaneously in a medium. For example, heat transfer is only by conduction in *opaque solids*, but by conduction and radiation in *semitransparent solids*. Thus, a solid may involve conduction and radiation but not convection. However, a solid may involve heat transfer by convection and/or radiation on its surfaces exposed to a fluid or other surfaces. For example, the outer surfaces of a cold piece of rock will warm up in a warmer environment as a result of heat gain by convection (from the air) and radiation (from the sun or the warmer surrounding surfaces). But the inner parts of the rock will warm up as this heat is transferred to the inner region of the rock by conduction.

Heat transfer is by conduction and possibly by radiation in a *still fluid* (no bulk fluid motion) and by convection and radiation in a *flowing fluid*. In the absence of radiation, heat transfer through a fluid is either by conduction or convection, depending on the presence of any bulk fluid motion. Convection can be viewed as combined conduction and fluid motion, and conduction in a fluid can be viewed as a special case of convection in the absence of any fluid motion (Fig. 16-18).

Thus, when we deal with heat transfer through a *fluid*, we have either *conduction* or *convection*, but not both. Also, gases are practically transparent to radiation, except that some gases are known to absorb radiation strongly at certain wavelengths. Ozone, for example, strongly absorbs ultraviolet radiation. But in most cases, a gas between two solid surfaces does not interfere with radiation and acts effectively as a vacuum. Liquids, on the other hand, are usually strong absorbers of radiation.

Finally, heat transfer through a *vacuum* is by radiation only since conduction or convection requires the presence of a material medium.

EXAMPLE 16–6 Heat Loss from a Person

Consider a person standing in a breezy room at 20°C. Determine the total rate of heat transfer from this person if the exposed surface area and the average outer surface temperature of the person are 1.6 m² and 29°C, respectively, and the convection heat transfer coefficient is 6 W/m² · °C (Fig. 16–19).

SOLUTION The total rate of heat transfer from a person by both convection and radiation to the surrounding air and surfaces at specified temperatures is to be determined.

Assumptions 1 Steady operating conditions exist. 2 The person is completely surrounded by the interior surfaces of the room. 3 The surrounding surfaces are at the same temperature as the air in the room. 4 Heat conduction to the floor through the feet is negligible.

Properties The emissivity of a person is $\varepsilon = 0.95$ (Table 16–6).

Analysis The heat transfer between the person and the air in the room will be by convection (instead of conduction) since it is conceivable that the air in the vicinity of the skin or clothing will warm up and rise as a result of heat transfer from the body, initiating natural convection currents. It appears that the experimentally determined value for the rate of convection heat transfer in this case is 6 W per unit surface area (m²) per unit temperature difference (in K or °C) between the person and the air away from the person. Thus, the rate of convection heat transfer from the person to the air in the room is

$$\begin{aligned}\dot{Q}_{\text{conv}} &= hA_s(T_s - T_\infty) \\ &= (6 \text{ W/m}^2 \cdot ^\circ\text{C})(1.6 \text{ m}^2)(29 - 20)^\circ\text{C} \\ &= 86.4 \text{ W}\end{aligned}$$

The person will also lose heat by radiation to the surrounding wall surfaces. We take the temperature of the surfaces of the walls, ceiling, and floor to be equal to the air temperature in this case for simplicity, but we recognize that this does not need to be the case. These surfaces may be at a higher or lower temperature than the average temperature of the room air, depending on the outdoor conditions and the structure of the walls. Considering that air does not intervene with radiation and the person is completely enclosed by the surrounding surfaces, the net rate of radiation heat transfer from the person to the surrounding walls, ceiling, and floor is

$$\begin{aligned}\dot{Q}_{\text{rad}} &= \varepsilon\sigma A_s(T_s^4 - T_{\text{surr}}^4) \\ &= (0.95)(5.67 \times 10^{-8} \text{ W/m}^2 \cdot \text{K}^4)(1.6 \text{ m}^2) \\ &\quad \times [(29 + 273)^4 - (20 + 273)^4] \text{ K}^4 \\ &= 81.7 \text{ W}\end{aligned}$$

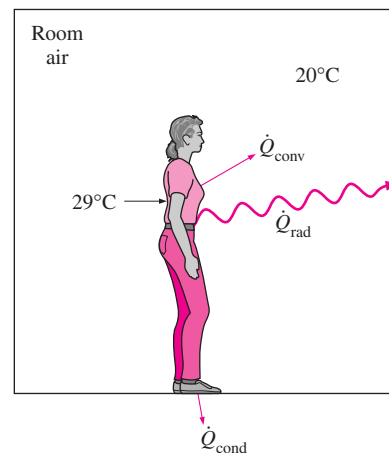


FIGURE 16–19

Heat transfer from the person described in Example 16–6.

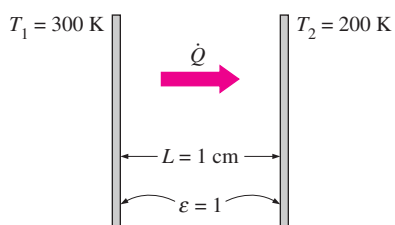


FIGURE 16–20

Schematic for Example 16–7.

Note that we must use *absolute* temperatures in radiation calculations. Also note that we used the emissivity value for the skin and clothing at room temperature since the emissivity is not expected to change significantly at a slightly higher temperature.

Then the rate of total heat transfer from the body is determined by adding these two quantities:

$$\dot{Q}_{\text{total}} = \dot{Q}_{\text{conv}} + \dot{Q}_{\text{rad}} = (86.4 + 81.7) \text{ W} = \mathbf{168.1 \text{ W}}$$

Discussion The heat transfer would be much higher if the person were not dressed since the exposed surface temperature would be higher. Thus, an important function of the clothes is to serve as a barrier against heat transfer.

In these calculations, heat transfer through the feet to the floor by conduction, which is usually very small, is neglected. Heat transfer from the skin by perspiration, which is the dominant mode of heat transfer in hot environments, is not considered here.

EXAMPLE 16–7 Heat Transfer between Two Isothermal Plates

Consider steady heat transfer between two large parallel plates at constant temperatures of $T_1 = 300 \text{ K}$ and $T_2 = 200 \text{ K}$ that are $L = 1 \text{ cm}$ apart, as shown in Fig. 16–20. Assuming the surfaces to be black (emissivity $\varepsilon = 1$), determine the rate of heat transfer between the plates per unit surface area assuming the gap between the plates is (a) filled with atmospheric air, (b) evacuated, (c) filled with urethane insulation, and (d) filled with superinsulation that has an apparent thermal conductivity of $0.00002 \text{ W/m} \cdot ^\circ\text{C}$.

SOLUTION The total rate of heat transfer between two large parallel plates at specified temperatures is to be determined for four different cases.

Assumptions 1 Steady operating conditions exist. 2 There are no natural convection currents in the air between the plates. 3 The surfaces are black and thus $\varepsilon = 1$.

Properties The thermal conductivity at the average temperature of 250 K is $k = 0.0219 \text{ W/m} \cdot ^\circ\text{C}$ for air (Table A-22), $0.026 \text{ W/m} \cdot ^\circ\text{C}$ for urethane insulation (Table A-28), and $0.00002 \text{ W/m} \cdot ^\circ\text{C}$ for the superinsulation.

Analysis (a) The rates of conduction and radiation heat transfer between the plates through the air layer are

$$\dot{Q}_{\text{cond}} = kA \frac{T_1 - T_2}{L} = (0.0219 \text{ W/m} \cdot ^\circ\text{C})(1 \text{ m}^2) \frac{(300 - 200)^\circ\text{C}}{0.01 \text{ m}} = 219 \text{ W}$$

and

$$\begin{aligned} \dot{Q}_{\text{rad}} &= \varepsilon \sigma A (T_1^4 - T_2^4) \\ &= (1)(5.67 \times 10^{-8} \text{ W/m}^2 \cdot \text{K}^4)(1 \text{ m}^2)[(300 \text{ K})^4 - (200 \text{ K})^4] = 368 \text{ W} \end{aligned}$$

Therefore,

$$\dot{Q}_{\text{total}} = \dot{Q}_{\text{cond}} + \dot{Q}_{\text{rad}} = 219 + 368 = \mathbf{587 \text{ W}}$$

The heat transfer rate in reality will be higher because of the natural convection currents that are likely to occur in the air space between the plates.

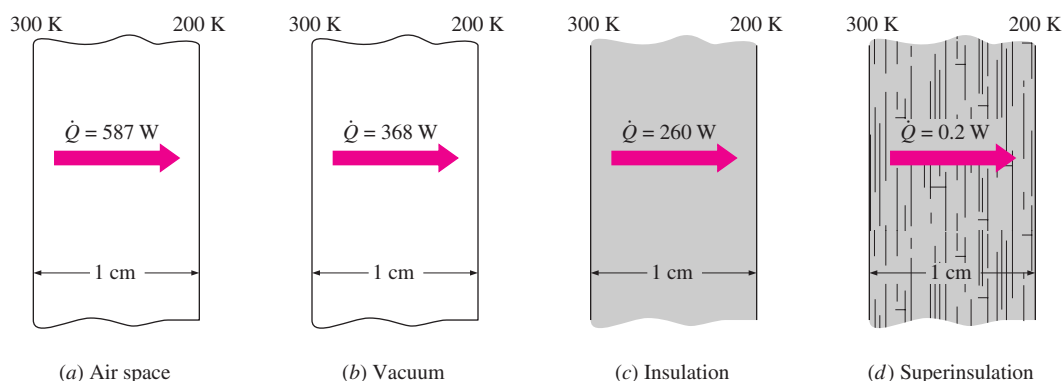


FIGURE 16-21

Different ways of reducing heat transfer between two isothermal plates, and their effectiveness.

(b) When the air space between the plates is evacuated, there will be no conduction or convection, and the only heat transfer between the plates will be by radiation. Therefore,

$$\dot{Q}_{\text{total}} = \dot{Q}_{\text{rad}} = 368 \text{ W}$$

(c) An opaque solid material placed between two plates blocks direct radiation heat transfer between the plates. Also, the thermal conductivity of an insulating material accounts for the radiation heat transfer that may be occurring through the voids in the insulating material. The rate of heat transfer through the urethane insulation is

$$\dot{Q}_{\text{total}} = \dot{Q}_{\text{cond}} = kA \frac{T_1 - T_2}{L} = (0.026 \text{ W/m} \cdot ^\circ\text{C})(1 \text{ m}^2) \frac{(300 - 200)^\circ\text{C}}{0.01 \text{ m}} = 260 \text{ W}$$

Note that heat transfer through the urethane material is less than the heat transfer through the air determined in (a), although the thermal conductivity of the insulation is higher than that of air. This is because the insulation blocks the radiation whereas air transmits it.

(d) The layers of the superinsulation prevent any direct radiation heat transfer between the plates. However, radiation heat transfer between the sheets of superinsulation does occur, and the apparent thermal conductivity of the superinsulation accounts for this effect. Therefore,

$$\dot{Q}_{\text{total}} = kA \frac{T_1 - T_2}{L} = (0.00002 \text{ W/m} \cdot ^\circ\text{C})(1 \text{ m}^2) \frac{(300 - 200)^\circ\text{C}}{0.01 \text{ m}} = 0.2 \text{ W}$$

which is $\frac{1}{1840}$ of the heat transfer through the vacuum. The results of this example are summarized in Fig. 16-21 to put them into perspective.

Discussion This example demonstrates the effectiveness of superinsulations, which are discussed in Chap. 17, and explains why they are the insulation of choice in critical applications despite their high cost.

EXAMPLE 16-8 Heat Transfer in Conventional and Microwave Ovens

The fast and efficient cooking of microwave ovens made them one of the essential appliances in modern kitchens (Fig. 16-22). Discuss the heat transfer

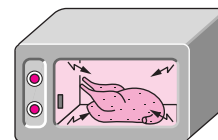


FIGURE 16-22

A chicken being cooked in a microwave oven (Example 16-8).

mechanisms associated with the cooking of a chicken in microwave and conventional ovens, and explain why cooking in a microwave oven is more efficient.

SOLUTION Food is cooked in a microwave oven by absorbing the electromagnetic radiation energy generated by the microwave tube, called the magnetron. The radiation emitted by the magnetron is not thermal radiation, since its emission is not due to the temperature of the magnetron; rather, it is due to the conversion of electrical energy into electromagnetic radiation at a specified wavelength. The wavelength of the microwave radiation is such that it is *reflected* by metal surfaces; *transmitted* by the cookware made of glass, ceramic, or plastic; and *absorbed* and converted to internal energy by food (especially the water, sugar, and fat) molecules.

In a microwave oven, the *radiation* that strikes the chicken is absorbed by the skin of the chicken and the outer parts. As a result, the temperature of the chicken at and near the skin rises. Heat is then *conducted* toward the inner parts of the chicken from its outer parts. Of course, some of the heat absorbed by the outer surface of the chicken is lost to the air in the oven by *convection*.

In a conventional oven, the air in the oven is first heated to the desired temperature by the electric or gas heating element. This preheating may take several minutes. The heat is then transferred from the air to the skin of the chicken by *natural convection* in most ovens or by *forced convection* in the newer convection ovens that utilize a fan. The air motion in convection ovens increases the convection heat transfer coefficient and thus decreases the cooking time. Heat is then *conducted* toward the inner parts of the chicken from its outer parts as in microwave ovens.

Microwave ovens replace the slow convection heat transfer process in conventional ovens by the instantaneous radiation heat transfer. As a result, microwave ovens transfer energy to the food at full capacity the moment they are turned on, and thus they cook faster while consuming less energy.

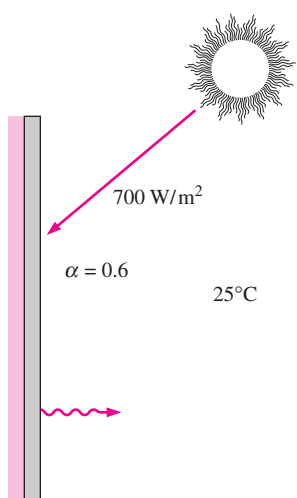


FIGURE 16–23
Schematic for Example 16–9.

EXAMPLE 16–9 Heating of a Plate by Solar Energy

A thin metal plate is insulated on the back and exposed to solar radiation at the front surface (Fig. 16–23). The exposed surface of the plate has an absorptivity of 0.6 for solar radiation. If solar radiation is incident on the plate at a rate of 700 W/m^2 and the surrounding air temperature is 25°C , determine the surface temperature of the plate when the heat loss by convection and radiation equals the solar energy absorbed by the plate. Assume the combined convection and radiation heat transfer coefficient to be $50 \text{ W/m}^2 \cdot ^\circ\text{C}$.

SOLUTION The back side of the thin metal plate is insulated and the front side is exposed to solar radiation. The surface temperature of the plate is to be determined when it stabilizes.

Assumptions 1 Steady operating conditions exist. 2 Heat transfer through the insulated side of the plate is negligible. 3 The heat transfer coefficient remains constant.

Properties The solar absorptivity of the plate is given to be $\alpha = 0.6$.

Analysis The absorptivity of the plate is 0.6, and thus 60 percent of the solar radiation incident on the plate will be absorbed continuously. As a result, the temperature of the plate will rise, and the temperature difference between the plate and the surroundings will increase. This increasing temperature difference

will cause the rate of heat loss from the plate to the surroundings to increase. At some point, the rate of heat loss from the plate will equal the rate of solar energy absorbed, and the temperature of the plate will no longer change. The temperature of the plate when steady operation is established is determined from

$$\dot{E}_{\text{gained}} = \dot{E}_{\text{lost}} \quad \text{or} \quad \alpha A_s \dot{q}_{\text{incident, solar}} = h_{\text{combined}} A_s (T_s - T_{\infty})$$

Solving for T_s and substituting, the plate surface temperature is determined to be

$$T_s = T_{\infty} + \alpha \frac{\dot{q}_{\text{incident, solar}}}{h_{\text{combined}}} = 25^{\circ}\text{C} + \frac{0.6 \times (700 \text{ W/m}^2)}{50 \text{ W/m}^2 \cdot ^{\circ}\text{C}} = \mathbf{33.4^{\circ}\text{C}}$$

Discussion Note that the heat losses will prevent the plate temperature from rising above 33.4°C . Also, the combined heat transfer coefficient accounts for the effects of both convection and radiation, and thus it is very convenient to use in heat transfer calculations when its value is known with reasonable accuracy.

SUMMARY

Heat can be transferred in three different modes: conduction, convection, and radiation. *Conduction* is 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, and is expressed by *Fourier's law of heat conduction* as

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

where k is the *thermal conductivity* of the material, A is the *area* normal to the direction of heat transfer, and dT/dx is the *temperature gradient*. The magnitude of the rate of heat conduction across a plane layer of thickness L is given by

$$\dot{Q}_{\text{cond}} = kA \frac{\Delta T}{L}$$

where ΔT is the temperature difference across the layer.

Convection is the mode of heat transfer between a solid surface and the adjacent liquid or gas that is in motion, and involves the combined effects of conduction and fluid motion. The rate of convection heat transfer is expressed by *Newton's law of cooling* as

$$\dot{Q}_{\text{convection}} = hA_s (T_s - T_{\infty})$$

where h is the *convection heat transfer coefficient* in $\text{W/m}^2 \cdot ^{\circ}\text{C}$ or $\text{Btu/h} \cdot \text{ft}^2 \cdot ^{\circ}\text{F}$, A_s is the *surface area* through which con-

vection heat transfer takes place, T_s is the *surface temperature*, and T_{∞} is the *temperature of the fluid* sufficiently far from the surface.

Radiation is 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. The maximum rate of radiation that can be emitted from a surface at an absolute temperature T_s is given by the *Stefan–Boltzmann law* as $\dot{Q}_{\text{emit, max}} = \sigma A_s T_s^4$, where $\sigma = 5.67 \times 10^{-8} \text{ W/m}^2 \cdot \text{K}^4$ or $0.1714 \times 10^{-8} \text{ Btu/h} \cdot \text{ft}^2 \cdot \text{R}^4$ is the *Stefan–Boltzmann constant*.

When a surface of emissivity ε and surface area A_s at an absolute temperature T_s is completely enclosed by a much larger (or black) surface at absolute 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

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

In this case, the emissivity and the surface area of the surrounding surface do not have any effect on the net radiation heat transfer.

The rate at which a surface absorbs radiation is determined from $\dot{Q}_{\text{absorbed}} = \alpha \dot{Q}_{\text{incident}}$ where $\dot{Q}_{\text{incident}}$ is the rate at which radiation is incident on the surface and α is the absorptivity of the surface.

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2. F. P. Incropera and D. P. DeWitt. *Introduction to Heat Transfer*. 4th ed. New York: John Wiley & Sons, 2002.

3. F. Kreith and M. S. Bohn. *Principles of Heat Transfer*. 6th ed. Pacific Grove, CA: Brooks/Cole, 2001.
4. A. F. Mills. *Basic Heat and Mass Transfer*. 2nd ed. Upper Saddle River, NJ: Prentice-Hall, 1999.
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PROBLEMS*

Heat Transfer Mechanisms

16-1C Consider two houses that are identical, except that the walls are built using bricks in one house, and wood in the other. If the walls of the brick house are twice as thick, which house do you think will be more energy efficient?

16-2C Define thermal conductivity and explain its significance in heat transfer.

16-3C What are the mechanisms of heat transfer? How are they distinguished from each other?

16-4C What is the physical mechanism of heat conduction in a solid, a liquid, and a gas?

16-5C Consider heat transfer through a windowless wall of a house on a winter day. Discuss the parameters that affect the rate of heat conduction through the wall.

16-6C Write down the expressions for the physical laws that govern each mode of heat transfer, and identify the variables involved in each relation.

16-7C How does heat conduction differ from convection?

16-8C Does any of the energy of the sun reach the earth by conduction or convection?

16-9C How does forced convection differ from natural convection?

16-10C Define emissivity and absorptivity. What is Kirchhoff's law of radiation?

16-11C What is a blackbody? How do real bodies differ from blackbodies?

16-12C Judging from its unit $\text{W/m} \cdot ^\circ\text{C}$, can we define thermal conductivity of a material as the rate of heat transfer

through the material per unit thickness per unit temperature difference? Explain.

16-13C Consider heat loss through the two walls of a house on a winter night. The walls are identical, except that one of them has a tightly fit glass window. Through which wall will the house lose more heat? Explain.

16-14C Which is a better heat conductor, diamond or silver?

16-15C Consider two walls of a house that are identical except that one is made of 10-cm-thick wood, while the other is made of 25-cm-thick brick. Through which wall will the house lose more heat in winter?

16-16C How do the thermal conductivity of gases and liquids vary with temperature?

16-17C Why is the thermal conductivity of superinsulation orders of magnitude lower than the thermal conductivity of ordinary insulation?

16-18C Why do we characterize the heat conduction ability of insulators in terms of their apparent thermal conductivity instead of the ordinary thermal conductivity?

16-19C Consider an alloy of two metals whose thermal conductivities are k_1 and k_2 . Will the thermal conductivity of the alloy be less than k_1 , greater than k_2 , or between k_1 and k_2 ?

16-20 The inner and outer surfaces of a $5\text{-m} \times 6\text{-m}$ brick wall of thickness 30 cm and thermal conductivity $0.69 \text{ W/m} \cdot ^\circ\text{C}$ are

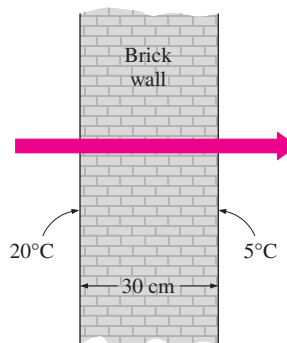




FIGURE P16-20


*Problems designated by a "C" are concept questions, and students are encouraged to answer them all. Problems designated by an "E" are in English units, and the SI users can ignore them. Problems with a CD-EES icon  are solved using EES, and complete solutions together with parametric studies are included on the enclosed CD. Problems with a computer-EES icon  are comprehensive in nature, and are intended to be solved with a computer, preferably using the EES software that accompanies this text.

maintained at temperatures of 20°C and 5°C , respectively. Determine the rate of heat transfer through the wall, in W.

Answer: 1035 W

16–21 The inner and outer surfaces of a 0.5-cm-thick 2-m \times 2-m window glass in winter are 10°C and 3°C , respectively. If the thermal conductivity of the glass is $0.78 \text{ W/m} \cdot ^{\circ}\text{C}$, determine the amount of heat loss, in kJ, through the glass over a period of 5 h. What would your answer be if the glass were 1 cm thick?

Answers: 78,624 kJ, 39,312 kJ

16–22  Reconsider Prob. 16–21. Using EES (or other) software, plot the amount of heat loss through the glass as a function of the window glass thickness in the range of 0.1 cm to 1.0 cm. Discuss the results.

16–23 An aluminum pan whose thermal conductivity is $237 \text{ W/m} \cdot ^{\circ}\text{C}$ has a flat bottom with diameter 20 cm and thickness 0.4 cm. Heat is transferred steadily to boiling water in the pan through its bottom at a rate of 800 W. If the inner surface of the bottom of the pan is at 105°C , determine the temperature of the outer surface of the bottom of the pan.

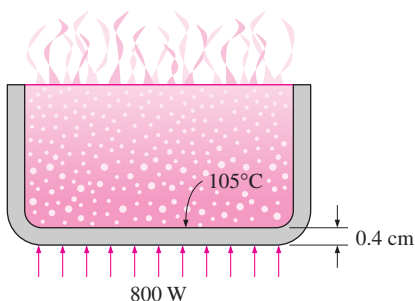


FIGURE P16–23

16–24E The north wall of an electrically heated home is 20 ft long, 10 ft high, and 1 ft thick, and is made of brick whose thermal conductivity is $k = 0.42 \text{ Btu/h} \cdot \text{ft} \cdot ^{\circ}\text{F}$. On a certain winter night, the temperatures of the inner and the outer surfaces of the wall are measured to be at about 62°F and 25°F , respectively, for a period of 8 h. Determine (a) the rate of heat loss through the wall that night and (b) the cost of that heat loss to the home owner if the cost of electricity is $\$0.07/\text{kWh}$.

16–25 In a certain experiment, cylindrical samples of diameter 4 cm and length 7 cm are used (see Fig. 16–9). The two thermocouples in each sample are placed 3 cm apart. After initial transients, the electric heater is observed to draw 0.6 A at 110 V, and both differential thermometers read a temperature difference of 10°C . Determine the thermal conductivity of the sample.

Answer: $78.8 \text{ W/m} \cdot ^{\circ}\text{C}$

16–26 One way of measuring the thermal conductivity of a material is to sandwich an electric thermofoil heater between two identical rectangular samples of the material and to heavily insulate the four outer edges, as shown in the figure. Thermocouples attached to the inner and outer surfaces of the samples record the temperatures.

During an experiment, two 0.5-cm-thick samples $10 \text{ cm} \times 10 \text{ cm}$ in size are used. When steady operation is reached, the heater is observed to draw 35 W of electric power, and the temperature of each sample is observed to drop from 82°C at the inner surface to 74°C at the outer surface. Determine the thermal conductivity of the material at the average temperature.

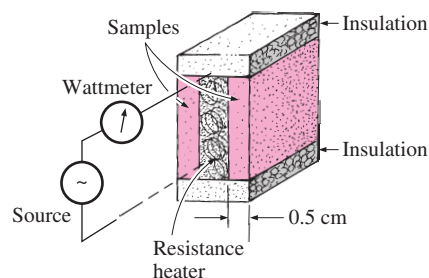



FIGURE P16–26

16–27 Repeat Prob. 16–26 for an electric power consumption of 28 W.

16–28 A heat flux meter attached to the inner surface of a 3-cm-thick refrigerator door indicates a heat flux of 25 W/m^2 through the door. Also, the temperatures of the inner and the outer surfaces of the door are measured to be 7°C and 15°C , respectively. Determine the average thermal conductivity of the refrigerator door.

Answer: $0.0938 \text{ W/m} \cdot ^{\circ}\text{C}$

16–29 Consider a person standing in a room maintained at 20°C at all times. The inner surfaces of the walls, floors, and ceiling of the house are observed to be at an average temperature of 12°C in winter and 23°C in summer. Determine the rates of radiation heat transfer between this person and the surrounding surfaces in both summer and winter if the exposed surface area, emissivity, and the average outer surface temperature of the person are 1.6 m^2 , 0.95, and 32°C , respectively.


16–30  Reconsider Prob. 16–29. Using EES (or other) software, plot the rate of radiation heat transfer in winter as a function of the temperature of the inner surface of the room in the range of 8°C to 18°C . Discuss the results.

16–31 For heat transfer purposes, a standing man can be modeled as a 30-cm-diameter, 170-cm-long vertical cylinder with both the top and bottom surfaces insulated and with the side surface at an average temperature of 34°C . For a convection heat transfer coefficient of $15 \text{ W/m}^2 \cdot ^{\circ}\text{C}$, determine the rate of heat loss from this man by convection in an environment at 20°C .

Answer: 336 W

16–32 Hot air at 80°C is blown over a 2-m \times 4-m flat surface at 30°C . If the average convection heat transfer coefficient is $55 \text{ W/m}^2 \cdot ^{\circ}\text{C}$, determine the rate of heat transfer from the air to the plate, in kW.

Answer: 22 kW

16–33  Reconsider Prob. 16–32. Using EES (or other) software, plot the rate of heat transfer

as a function of the heat transfer coefficient in the range of $20 \text{ W/m}^2 \cdot ^\circ\text{C}$ to $100 \text{ W/m}^2 \cdot ^\circ\text{C}$. Discuss the results.

16–34 The heat generated in the circuitry on the surface of a silicon chip ($k = 130 \text{ W/m} \cdot ^\circ\text{C}$) is conducted to the ceramic substrate to which it is attached. The chip is $6 \text{ mm} \times 6 \text{ mm}$ in size and 0.5 mm thick and dissipates 3 W of power. Disregarding any heat transfer through the 0.5-mm -high side surfaces, determine the temperature difference between the front and back surfaces of the chip in steady operation.

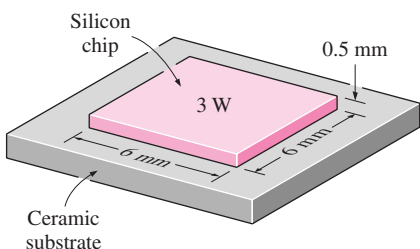


FIGURE P16–34

16–35 A 50-cm -long, 800-W electric resistance heating element with diameter 0.5 cm and surface temperature 120°C is immersed in 60 kg of water initially at 20°C . Determine how long it will take for this heater to raise the water temperature to 80°C . Also, determine the convection heat transfer coefficients at the beginning and at the end of the heating process.

16–36 A 5-cm -external-diameter, 10-m -long hot-water pipe at 80°C is losing heat to the surrounding air at 5°C by natural convection with a heat transfer coefficient of $25 \text{ W/m}^2 \cdot ^\circ\text{C}$. Determine the rate of heat loss from the pipe by natural convection, in W . *Answer: 2945 W*

16–37 A hollow spherical iron container with outer diameter 20 cm and thickness 0.4 cm is filled with iced water at 0°C . If the outer surface temperature is 5°C , determine the approximate rate of heat loss from the sphere, in kW , and the rate at which ice melts in the container. The heat from fusion of water is 333.7 kJ/kg .

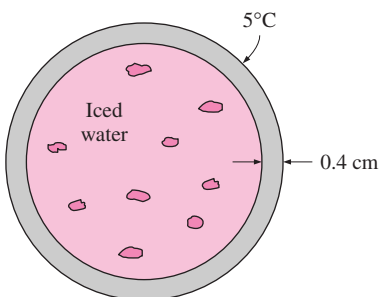



FIGURE P16–37

16–38  Reconsider Prob. 16–37. Using EES (or other) software, plot the rate at which ice melts as a

function of the container thickness in the range of 0.2 cm to 2.0 cm . Discuss the results.

16–39E The inner and outer glasses of a $6\text{-ft} \times 6\text{-ft}$ double-pane window are at 60°F and 42°F , respectively. If the 0.25-in. space between the two glasses is filled with still air, determine the rate of heat transfer through the window.

Answer: 439 Btu/h

16–40 Two surfaces of a 2-cm -thick plate are maintained at 0°C and 80°C , respectively. If it is determined that heat is transferred through the plate at a rate of 500 W/m^2 , determine its thermal conductivity.

16–41 Four power transistors, each dissipating 15 W , are mounted on a thin vertical aluminum plate $22 \text{ cm} \times 22 \text{ cm}$ in size. The heat generated by the transistors is to be dissipated by both surfaces of the plate to the surrounding air at 25°C , which is blown over the plate by a fan. The entire plate can be assumed to be nearly isothermal, and the exposed surface area of the transistor can be taken to be equal to its base area. If the average convection heat transfer coefficient is $25 \text{ W/m}^2 \cdot ^\circ\text{C}$, determine the temperature of the aluminum plate. Disregard any radiation effects.

16–42 An ice chest whose outer dimensions are $30 \text{ cm} \times 40 \text{ cm} \times 40 \text{ cm}$ is made of 3-cm -thick Styrofoam ($k = 0.033 \text{ W/m} \cdot ^\circ\text{C}$). Initially, the chest is filled with 40 kg of ice at 0°C , and the inner surface temperature of the ice chest can be taken to be 0°C at all times. The heat of fusion of ice at 0°C is 333.7 kJ/kg , and the surrounding ambient air is at 30°C . Disregarding any heat transfer from the $40\text{-cm} \times 40\text{-cm}$ base of the ice chest, determine how long it will take for the ice in the chest to melt completely if the outer surfaces of the ice chest are at 8°C .

Answer: 32.7 days

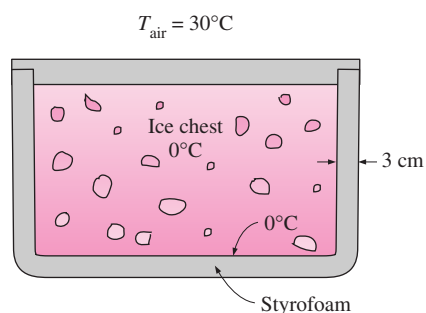


FIGURE P16–42

16–43 A transistor with a height of 0.4 cm and a diameter of 0.6 cm is mounted on a circuit board. The transistor is cooled by air flowing over it with an average heat transfer coefficient of $30 \text{ W/m}^2 \cdot ^\circ\text{C}$. If the air temperature is 55°C and the transistor case temperature is not to exceed 70°C , determine the amount of power this transistor can dissipate safely. Disregard any heat transfer from the transistor base.

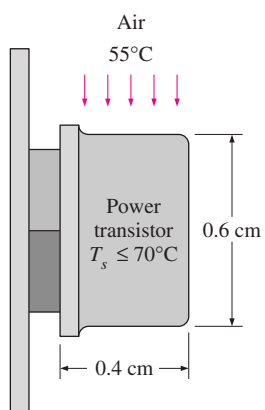



FIGURE P16-43

16-44  Reconsider Prob. 16-43. Using EES (or other) software, plot the amount of power the transistor can dissipate safely as a function of the maximum case temperature in the range of 60°C to 90°C. Discuss the results.

16-45E A 200-ft-long section of a steam pipe whose outer diameter is 4 in passes through an open space at 50°F. The average temperature of the outer surface of the pipe is measured to be 280°F, and the average heat transfer coefficient on that surface is determined to be 6 Btu/h · ft² · °F. Determine (a) the rate of heat loss from the steam pipe and (b) the annual cost of this energy loss if steam is generated in a natural gas furnace having an efficiency of 86 percent, and the price of natural gas is \$0.58/therm (1 therm = 100,000 Btu).

Answers: (a) 289,000 Btu/h, (b) \$17,074/yr

16-46 The boiling temperature of nitrogen at atmospheric pressure at sea level (1 atm) is −196°C. Therefore, nitrogen is commonly used in low temperature scientific studies since the temperature of liquid nitrogen in a tank open to the atmosphere will remain constant at −196°C until the liquid nitrogen in

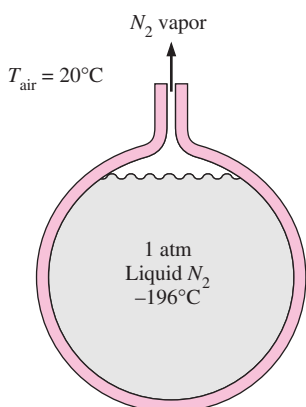



FIGURE P16-46

the tank is depleted. Any heat transfer to the tank will result in the evaporation of some liquid nitrogen, which has a heat of vaporization of 198 kJ/kg and a density of 810 kg/m³ at 1 atm.

Consider a 4-m-diameter spherical tank initially filled with liquid nitrogen at 1 atm and −196°C. The tank is exposed to 20°C ambient air with a heat transfer coefficient of 25 W/m² · °C. The temperature of the thin-shelled spherical tank is observed to be almost the same as the temperature of the nitrogen inside. Disregarding any radiation heat exchange, determine the rate of evaporation of the liquid nitrogen in the tank as a result of the heat transfer from the ambient air.

16-47 Repeat Prob. 16-46 for liquid oxygen, which has a boiling temperature of −183°C, a heat of vaporization of 213 kJ/kg, and a density of 1140 kg/m³ at 1 atm pressure.

16-48  Reconsider Prob. 16-46. Using EES (or other) software, plot the rate of evaporation of liquid nitrogen as a function of the ambient air temperature in the range of 0°C to 35°C. Discuss the results.

16-49 Consider a person whose exposed surface area is 1.7 m², emissivity is 0.7, and surface temperature is 32°C. Determine the rate of heat loss from that person by radiation in a large room having walls at a temperature of (a) 300 K and (b) 280 K. *Answers: (a) 37.4 W, (b) 169.2 W*

16-50 A 0.3-cm-thick, 12-cm-high, and 18-cm-long circuit board houses 80 closely spaced logic chips on one side, each dissipating 0.06 W. The board is impregnated with copper fillings and has an effective thermal conductivity of 16 W/m · °C. All the heat generated in the chips is conducted across the circuit board and is dissipated from the back side of the board to the ambient air. Determine the temperature difference between the two sides of the circuit board. *Answer: 0.042°C*

16-51 Consider a sealed 20-cm-high electronic box whose base dimensions are 40 cm × 40 cm placed in a vacuum chamber. The emissivity of the outer surface of the box is 0.95. If the electronic components in the box dissipate a total of 100 W of power and the outer surface temperature of the box is not to exceed 55°C, determine the temperature at which the surrounding surfaces must be kept if this box is to be cooled by radiation

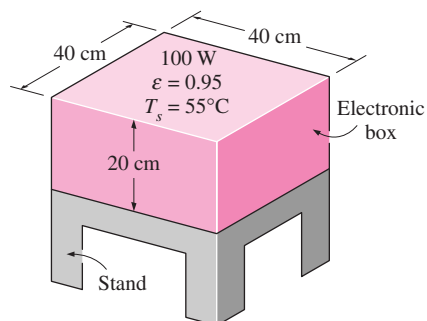


FIGURE P16-51

alone. Assume the heat transfer from the bottom surface of the box to the stand to be negligible.

16-52 Using the conversion factors between W and Btu/h, m and ft, and K and R, express the Stefan–Boltzmann constant $\sigma = 5.67 \times 10^{-8} \text{ W/m}^2 \cdot \text{K}^4$ in the English unit $\text{Btu/h} \cdot \text{ft}^2 \cdot \text{R}^4$.

16-53 An engineer who is working on the heat transfer analysis of a house in English units needs the convection heat transfer coefficient on the outer surface of the house. But the only value he can find from his handbooks is $20 \text{ W/m}^2 \cdot ^\circ\text{C}$, which is in SI units. The engineer does not have a direct conversion factor between the two unit systems for the convection heat transfer coefficient. Using the conversion factors between W and Btu/h, m and ft, and $^\circ\text{C}$ and $^\circ\text{F}$, express the given convection heat transfer coefficient in $\text{Btu/h} \cdot \text{ft}^2 \cdot ^\circ\text{F}$.

Answer: $3.52 \text{ Btu/h} \cdot \text{ft}^2 \cdot ^\circ\text{F}$

Simultaneous Heat Transfer Mechanisms

16-54C Can all three modes of heat transfer occur simultaneously (in parallel) in a medium?

16-55C Can a medium involve (a) conduction and convection, (b) conduction and radiation, or (c) convection and radiation simultaneously? Give examples for the “yes” answers.

16-56C The deep human body temperature of a healthy person remains constant at 37°C while the temperature and the humidity of the environment change with time. Discuss the heat transfer mechanisms between the human body and the environment both in summer and winter, and explain how a person can keep cooler in summer and warmer in winter.

16-57C We often turn the fan on in summer to help us cool. Explain how a fan makes us feel cooler in the summer. Also explain why some people use ceiling fans also in winter.

16-58 Consider a person standing in a room at 23°C . Determine the total rate of heat transfer from this person if the exposed surface area and the skin temperature of the person are 1.7 m^2 and 32°C , respectively, and the convection heat transfer coefficient is $5 \text{ W/m}^2 \cdot ^\circ\text{C}$. Take the emissivity of the skin and the clothes to be 0.9, and assume the temperature of the inner surfaces of the room to be the same as the air temperature.

Answer: 161 W

16-59 Consider steady heat transfer between two large parallel plates at constant temperatures of $T_1 = 290 \text{ K}$ and $T_2 = 150 \text{ K}$ that are $L = 2 \text{ cm}$ apart. Assuming the surfaces to be black (emissivity $\varepsilon = 1$), determine the rate of heat transfer between the plates per unit surface area assuming the gap between the plates is (a) filled with atmospheric air, (b) evacuated, (c) filled with fiberglass insulation, and (d) filled with superinsulation having an apparent thermal conductivity of $0.00015 \text{ W/m} \cdot ^\circ\text{C}$.

16-60 A 1.4-m-long, 0.2-cm-diameter electrical wire extends across a room that is maintained at 20°C . Heat is generated in the wire as a result of resistance heating, and the surface temperature of the wire is measured to be 240°C in steady op-

eration. Also, the voltage drop and electric current through the wire are measured to be 110 V and 3 A, respectively. Disregarding any heat transfer by radiation, determine the convection heat transfer coefficient for heat transfer between the outer surface of the wire and the air in the room.

Answer: $170.5 \text{ W/m}^2 \cdot ^\circ\text{C}$

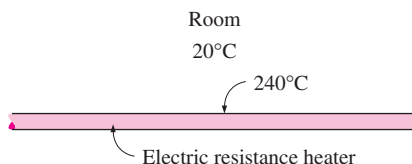




FIGURE P16-60

16-61  Reconsider Prob. 16-60. Using EES (or other) software, plot the convection heat transfer coefficient as a function of the wire surface temperature in the range of 100°C to 300°C . Discuss the results.

16-62E A 2-in-diameter spherical ball whose surface is maintained at a temperature of 170°F is suspended in the middle of a room at 70°F . If the convection heat transfer coefficient is $12 \text{ Btu/h} \cdot \text{ft}^2 \cdot ^\circ\text{F}$ and the emissivity of the surface is 0.8, determine the total rate of heat transfer from the ball.

16-63  A 1000-W iron is left on the iron board with its base exposed to the air at 20°C . The convection heat transfer coefficient between the base surface and the surrounding air is $35 \text{ W/m}^2 \cdot ^\circ\text{C}$. If the base has an emissivity of 0.6 and a surface area of 0.02 m^2 , determine the temperature of the base of the iron. *Answer: 674°C*

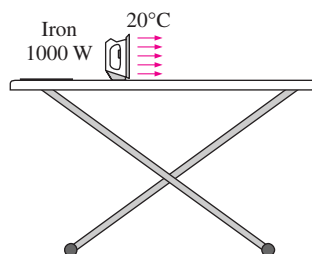



FIGURE P16-63

16-64 The outer surface of a spacecraft in space has an emissivity of 0.8 and a solar absorptivity of 0.3. If solar radiation is incident on the spacecraft at a rate of 950 W/m^2 , determine the surface temperature of the spacecraft when the radiation emitted equals the solar energy absorbed.

16-65 A 3-m-internal-diameter spherical tank made of 1-cm-thick stainless steel is used to store iced water at 0°C . The tank is located outdoors at 25°C . Assuming the entire steel tank to be at 0°C and thus the thermal resistance of the tank to be negligible, determine (a) the rate of heat transfer to the iced water in the tank and (b) the amount of ice at 0°C that melts during a 24-h period. The heat of fusion of water at atmospheric pressure

is $h_{ij} = 333.7 \text{ kJ/kg}$. The emissivity of the outer surface of the tank is 0.6, and the convection heat transfer coefficient on the outer surface can be taken to be $30 \text{ W/m}^2 \cdot ^\circ\text{C}$. Assume the average surrounding surface temperature for radiation exchange to be 15°C . **Answer:** 5898 kg

16–66  The roof of a house consists of a 15-cm-thick concrete slab ($k = 2 \text{ W/m} \cdot ^\circ\text{C}$) that is 15 m wide and 20 m long. The emissivity of the outer surface of the roof is 0.9, and the convection heat transfer coefficient on that surface is estimated to be $15 \text{ W/m}^2 \cdot ^\circ\text{C}$. The inner surface of the roof is maintained at 15°C . On a clear winter night, the ambient air is reported to be at 10°C while the night sky temperature for radiation heat transfer is 255 K. Considering both radiation and convection heat transfer, determine the outer surface temperature and the rate of heat transfer through the roof.

If the house is heated by a furnace burning natural gas with an efficiency of 85 percent, and the unit cost of natural gas is $\$0.60/\text{therm}$ (1 therm = 105,500 kJ of energy content), determine the money lost through the roof that night during a 14-h period.

16–67E Consider a flat plate solar collector placed horizontally on the flat roof of a house. The collector is 5 ft wide and 15 ft long, and the average temperature of the exposed surface of the collector is 100°F . The emissivity of the exposed surface of the collector is 0.9. Determine the rate of heat loss from the collector by convection and radiation during a calm day when the ambient air temperature is 70°F and the effective sky temperature for radiation exchange is 50°F . Take the convection heat transfer coefficient on the exposed surface to be $2.5 \text{ Btu/h} \cdot \text{ft}^2 \cdot ^\circ\text{F}$.

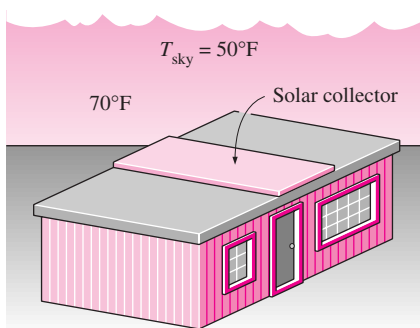


FIGURE P16–67E

Review Problems

16–68 It is well known that wind makes the cold air feel much colder as a result of the *windchill* effect that is due to the increase in the convection heat transfer coefficient with increasing air velocity. The windchill effect is usually expressed in terms of the *windchill factor*, which is the difference between the actual air temperature and the equivalent calm-air temperature. For example, a windchill factor of 20°C for an

actual air temperature of 5°C means that the windy air at 5°C feels as cold as the still air at -15°C . In other words, a person will lose as much heat to air at 5°C with a windchill factor of 20°C as he or she would in calm air at -15°C .

For heat transfer purposes, a standing man can be modeled as a 30-cm-diameter, 170-cm-long vertical cylinder with both the top and bottom surfaces insulated and with the side surface at an average temperature of 34°C . For a convection heat transfer coefficient of $15 \text{ W/m}^2 \cdot ^\circ\text{C}$, determine the rate of heat loss from this man by convection in still air at 20°C . What would your answer be if the convection heat transfer coefficient is increased to $50 \text{ W/m}^2 \cdot ^\circ\text{C}$ as a result of winds? What is the windchill factor in this case? **Answers:** 336 W, 1120 W, 32.7°C

16–69 A thin metal plate is insulated on the back and exposed to solar radiation on the front surface. The exposed surface of the plate has an absorptivity of 0.7 for solar radiation. If solar radiation is incident on the plate at a rate of 700 W/m^2 and the surrounding air temperature is 10°C , determine the surface temperature of the plate when the heat loss by convection equals the solar energy absorbed by the plate. Take the convection heat transfer coefficient to be $30 \text{ W/m}^2 \cdot ^\circ\text{C}$, and disregard any heat loss by radiation.

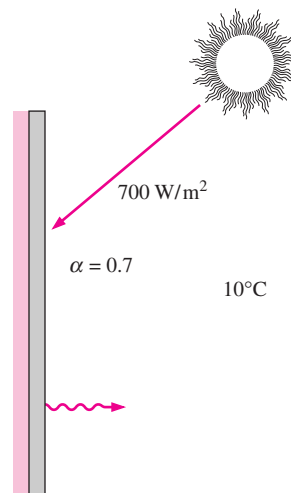


FIGURE P16–69

16–70 A $4\text{-m} \times 5\text{-m} \times 6\text{-m}$ room is to be heated by one ton (1000 kg) of liquid water contained in a tank placed in the room. The room is losing heat to the outside at an average rate of 10,000 kJ/h. The room is initially at 20°C and 100 kPa, and is maintained at an average temperature of 20°C at all times. If the hot water is to meet the heating requirements of this room for a 24-h period, determine the minimum temperature of the water when it is first brought into the room. Assume constant specific heats for both air and water at room temperature. **Answer:** 77.4°C

16–71 Consider a $3\text{-m} \times 3\text{-m} \times 3\text{-m}$ cubical furnace whose top and side surfaces closely approximate black surfaces at a

temperature of 1200 K. The base surface has an emissivity of $\varepsilon = 0.7$, and is maintained at 800 K. Determine the net rate of radiation heat transfer to the base surface from the top and side surfaces. **Answer: 594,400 W**

16-72 Consider a refrigerator whose dimensions are $1.8 \text{ m} \times 1.2 \text{ m} \times 0.8 \text{ m}$ and whose walls are 3 cm thick. The refrigerator consumes 600 W of power when operating and has a COP of 2.5. It is observed that the motor of the refrigerator remains on for 5 min in and then is off for 15 min in periodically. If the average temperatures at the inner and outer surfaces of the refrigerator are 6°C and 17°C , respectively, determine the average thermal conductivity of the refrigerator walls. Also, determine the annual cost of operating this refrigerator if the unit cost of electricity is $\$0.08/\text{kWh}$.

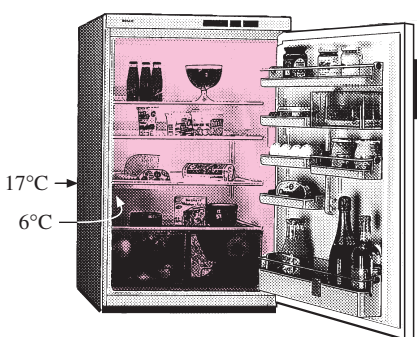


FIGURE P16-72

16-73 Engine valves ($C_p = 440 \text{ J/kg} \cdot ^\circ\text{C}$ and $\rho = 7840 \text{ kg/m}^3$) are to be heated from 40°C to 800°C in 5 min in the heat treatment section of a valve manufacturing facility. The valves have a cylindrical stem with a diameter of 8 mm and a length of 10 cm. The valve head and the stem may be assumed to be of equal surface area, with a total mass of 0.0788 kg. For a single valve, determine (a) the amount of heat transfer, (b) the average rate of heat transfer, and (c) the average heat flux, (d) the number of valves that can be heat treated per day if the heating section can hold 25 valves, and it is used 10 h per day.

16-74 Consider a flat plate solar collector placed at the roof of a house. The temperatures at the inner and outer surfaces of the glass cover are measured to be 28°C and 25°C , respectively. The glass cover has a surface area of 2.2 m^2 and a thickness of 0.6 cm and a thermal conductivity of $0.7 \text{ W/m} \cdot ^\circ\text{C}$. Heat is lost from the outer surface of the cover by convection and radiation with a convection heat transfer coefficient of $10 \text{ W/m}^2 \cdot ^\circ\text{C}$ and an ambient temperature of 15°C . Determine the fraction of heat lost from the glass cover by radiation.

16-75 The rate of heat loss through a unit surface area of a window per unit temperature difference between the indoors and the outdoors is called the U -factor. The value of the U -factor ranges from about $1.25 \text{ W/m}^2 \cdot ^\circ\text{C}$ (or $0.22 \text{ Btu/h} \cdot \text{ft}^2 \cdot ^\circ\text{F}$) for low- e coated, argon-filled, quadruple-pane windows to $6.25 \text{ W/m}^2 \cdot ^\circ\text{C}$ (or $1.1 \text{ Btu/h} \cdot \text{ft}^2 \cdot ^\circ\text{F}$) for a single-

pane window with aluminum frames. Determine the range for the rate of heat loss through a $1.2\text{-m} \times 1.8\text{-m}$ window of a house that is maintained at 20°C when the outdoor air temperature is -8°C .

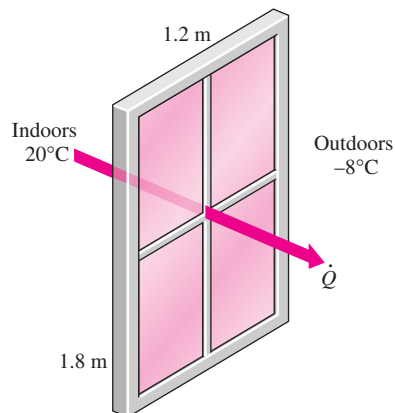



FIGURE P16-75

16-76  Reconsider Prob. 16-75. Using EES (or other) software, plot the rate of heat loss through the window as a function of the U -factor. Discuss the results.

16-77 Consider a house in Atlanta, Georgia, that is maintained at 22°C and has a total of 20 m^2 of window area. The windows are double-door type with wood frames and metal spacers and have a U -factor of $2.5 \text{ W/m}^2 \cdot ^\circ\text{C}$ (see Prob. 16-75 for the definition of U -factor). The winter average temperature of Atlanta is 11.3°C . Determine the average rate of heat loss through the windows in winter.

16-78 A 50-cm-long, 2-mm-diameter electric resistance wire submerged in water is used to determine the boiling heat transfer coefficient in water at 1 atm experimentally. The wire temperature is measured to be 130°C when a wattmeter indicates the electric power consumed to be 4.1 kW. Using Newton's law of cooling, determine the boiling heat transfer coefficient.

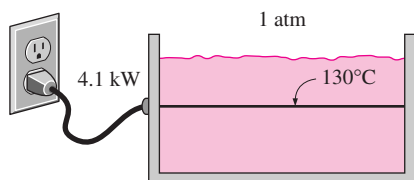
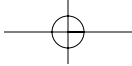


FIGURE P16-78

Design and Essay Problems

16-79 Write an essay on how microwave ovens work, and explain how they cook much faster than conventional ovens. Discuss whether conventional electric or microwave ovens consume more electricity for the same task.

16-80 Using information from the utility bills for the coldest month last year, estimate the average rate of heat loss from



your house for that month. In your analysis, consider the contribution of the internal heat sources such as people, lights, and appliances. Identify the primary sources of heat loss from your house and propose ways of improving the energy efficiency of your house.

16-81 Conduct this experiment to determine the heat transfer coefficient between an incandescent lightbulb and the surrounding air using a 60-W lightbulb. You will need an indoor-outdoor thermometer, which can be purchased for about \$10 in

a hardware store, and a metal glue. You will also need a piece of string and a ruler to calculate the surface area of the lightbulb. First, measure the air temperature in the room, and then glue the tip of the thermocouple wire of the thermometer to the glass of the lightbulb. Turn the light on and wait until the temperature reading stabilizes. The temperature reading will give the surface temperature of the lightbulb. Assuming 10 percent of the rated power of the bulb is converted to light, calculate the heat transfer coefficient from Newton's law of cooling.

