Heat and Mass Transfer, 3rd Edition
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Chapter 1

INTRODUCTION AND BASIC CONCEPTS

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Objectives

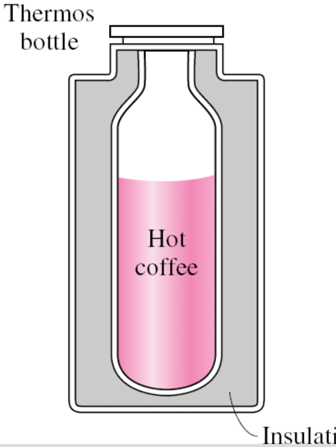
- Understand how thermodynamics and heat transfer are related to each other,
- Perform general energy balances as well as surface energy balances,
- Understand the basic mechanisms of heat transfer, which are conduction, convection, and radiation, and Fourier's law of heat conduction, Newton's law of cooling, and the Stefan–Boltzmann law of radiation
- Identify the mechanisms of heat transfer that occur simultaneously in practice
- Develop an awareness of the cost associated with heat losses
- Solve various heat transfer problems encountered in practice

INTRODUCTION

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

Thermodynamics concerned 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.

Heat Transfer deals with the determination of the *rates* of such energy transfers as well as variation of temperature.



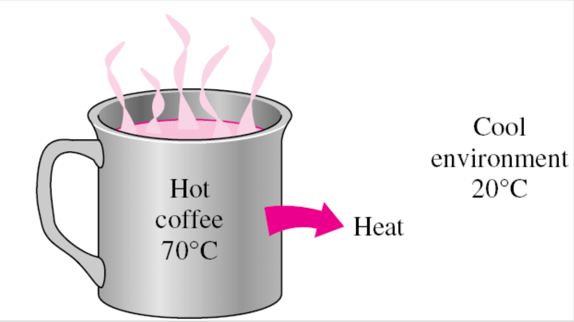
The transfer of energy as heat is always from the higher-temperature medium to the lower-temperature one.

Heat transfer stops when two mediums reach the same temperature.

Thermodynamics deals with equilibrium states and changes from one equilibrium state to another. Heat transfer deals with systems that lack thermal equilibrium, and thus it is a nonequilibrium phenomenon.

Heat Transfer

- The basic requirement for heat transfer is the presence of a temperature difference.
- The second law requires that heat be transferred in the direction of decreasing temperature.



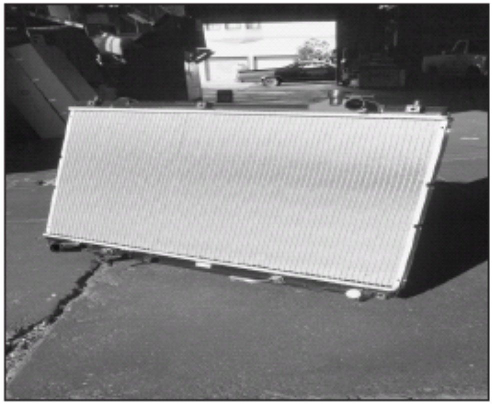
- The temperature difference is the driving force for heat transfer.
- The rate of heat transfer in a certain direction depends on the magnitude of the temperature gradient in that direction.
- The larger the temperature gradient, the higher the rate of heat transfer.

Application Areas of Heat Transfer

The human body

Air conditioning systems

Airplanes



Car radiators

Power plants

Refrigeration systems

Energy Transfer

- Energy can be transferred to or from a given mass by two mechanisms:
  - ✓ heat transfer, and
  - ✓ work.
- The amount of heat transferred during a process is denoted by Q.
- The amount of heat transferred per unit time is called **heat transfer rate**, and is denoted by $\dot{Q}$.
- The total amount of heat transfer Q during a time interval Δt can be determined from

$$Q = \int_0^{\Delta t} \dot{Q}\,dt \qquad \text{(J)}$$

- The rate of heat transfer per unit area normal to the direction of heat transfer is called **heat flux**, and the average heat flux is expressed as

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

The First Law of Thermodynamics

- The **first law of thermodynamics** states that *energy can neither be created nor destroyed during a process; it can only change forms.*

$$\left(\begin{array}{c}\textbf{Total energy}\\ \textbf{entering the}\\ \textbf{system}\end{array}\right) - \left(\begin{array}{c}\textbf{Total energy}\\ \textbf{leaving the}\\ \textbf{system}\end{array}\right) = \left(\begin{array}{c}\textbf{Change in the}\\ \textbf{total energy of}\\ \textbf{the system}\end{array}\right)$$

- The **energy balance** for any system undergoing any process can be expressed as (in the rate form)

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

- In heat transfer problems it is convenient to write a **heat balance** and to treat the conversion of nuclear, chemical, mechanical, and electrical energies into thermal energy as *heat generation.*
- The *energy balance* in that case can be expressed as

$$\underbrace{Q_{in} - Q_{out}}_{\text{Net heat transfer}} + \underbrace{E_{gen}}_{\text{Heat generation}} = \underbrace{\Delta E_{thermal,system}}_{\text{Change in thermal energy of the system}} \qquad \text{(J)}$$

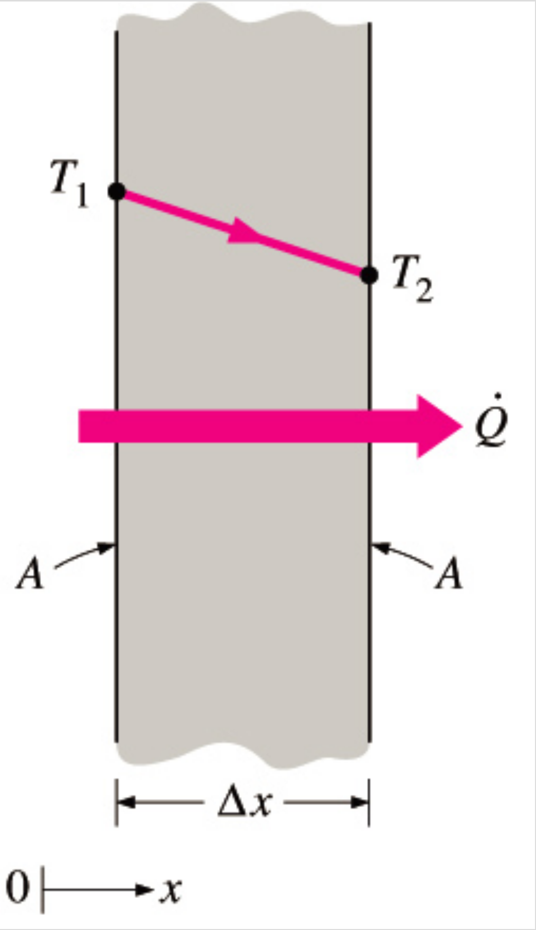
CONDUCTION

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

In gases and liquids, conduction is due to the *collisions* and *diffusion* of the molecules during their random motion.

In solids, it is due to the combination of *vibrations* of the molecules in a lattice and the energy transport by *free electrons.*

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.



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

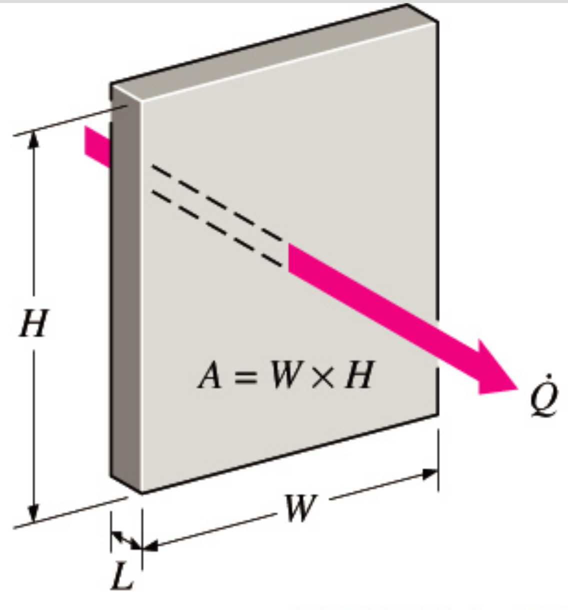
$$\dot{Q}_{\text{cond}} = kA\,\frac{T_1 - T_2}{\Delta x} = -kA\,\frac{\Delta T}{\Delta x} \qquad \text{(W)}$$

When $x \to 0$ $$\dot{Q}_{\text{cond}} = -kA\frac{dT}{dx}$$ **Fourier's law of heat conduction**

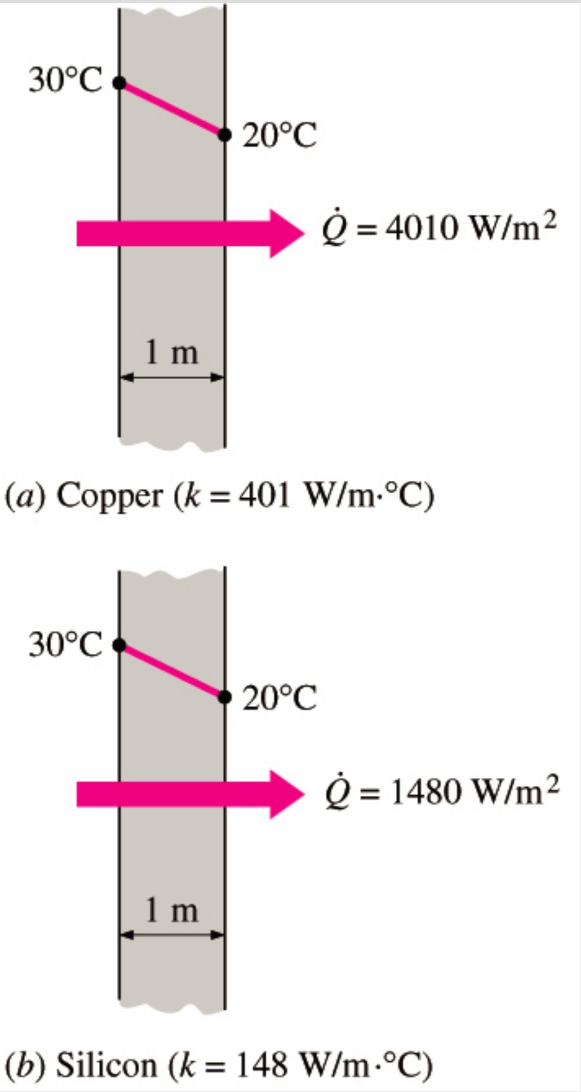
Thermal conductivity, *k* : A measure of the ability of a material to conduct heat.

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

Heat is conducted in the direction of decreasing temperature, and the temperature gradient becomes negative when temperature decreases with increasing *x*. The *negative sign* in the equation ensures that heat transfer in the positive *x* direction is a positive quantity.



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



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

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 $k = 0.8$ W/m · °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/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 $k = 0.8$ W/m · °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

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

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

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

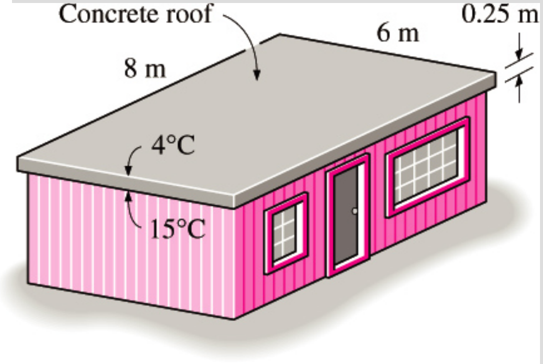


FIGURE 1–25
Schematic for Example 1–5.

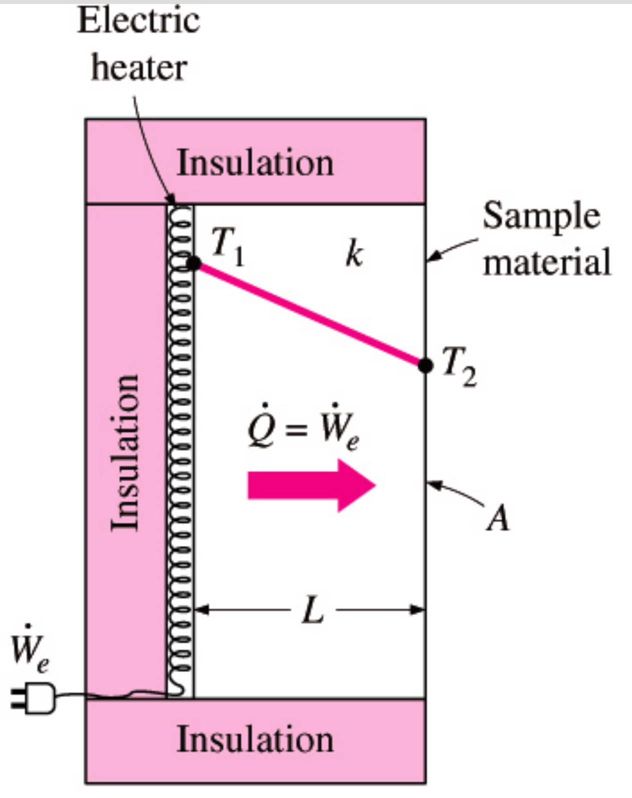
Discussion The cost to the home owner of the heat loss through the roof that night was $1.35. The total heating bill of the house will be much larger since the heat losses through the walls are not considered in these calculations.

Thermal Conductivity

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

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

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



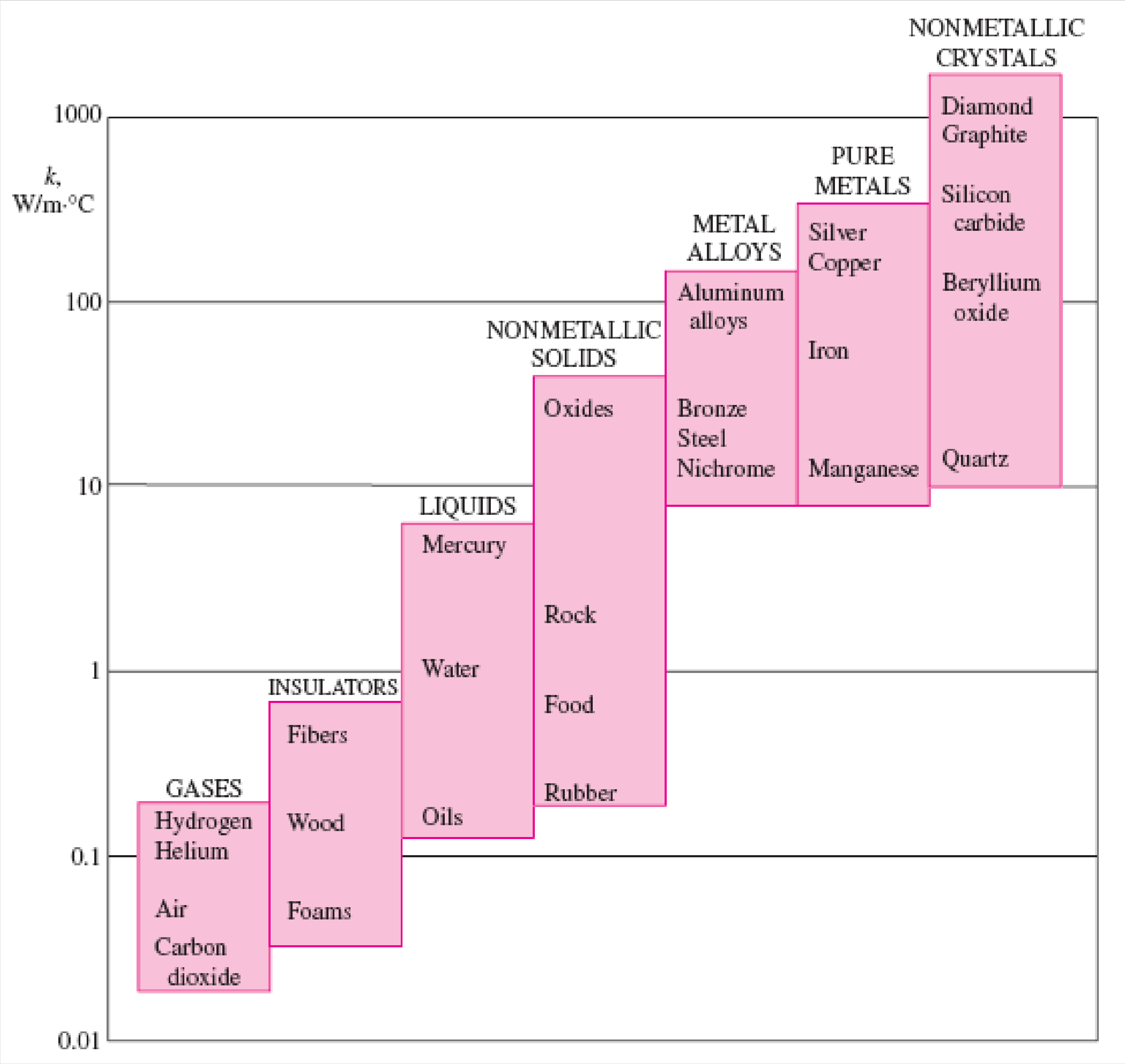
$$k = \frac{L}{A(T_1 - T_2)}\dot{Q}$$

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

TABLE 16–1

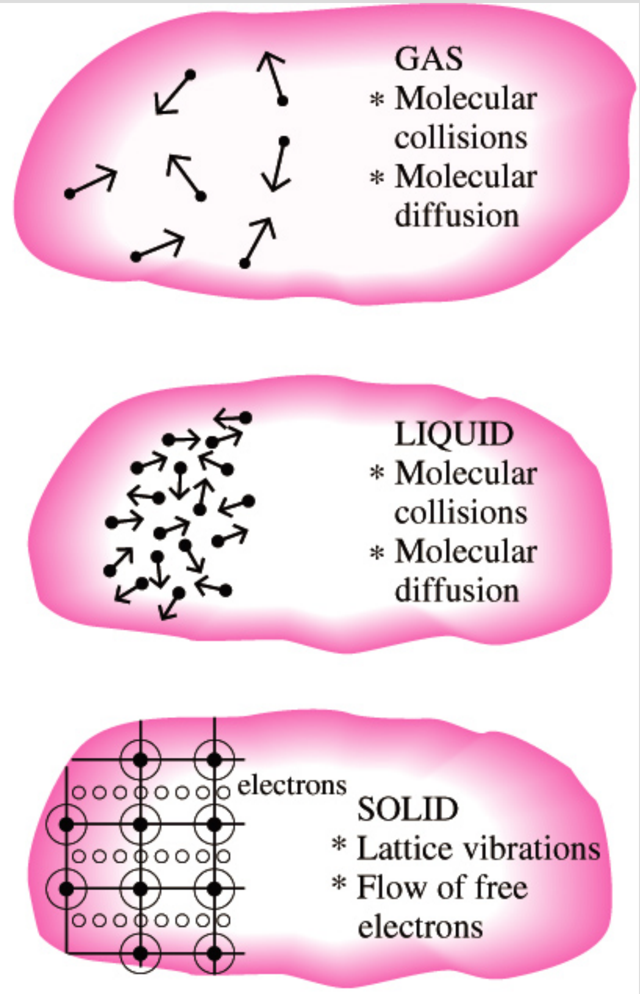
The thermal conductivities of some materials at room temperature

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)	0.607
Human skin	0.37
Wood (oak)	0.17
Helium (g)	0.152
Soft rubber	0.13
Glass fiber	0.043
Air (g)	0.026
Urethane, rigid foam	0.026



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

The thermal conductivities of gases such as air vary by a factor of 10^4 from those of pure metals such as copper. Pure crystals and metals have the highest thermal conductivities, and gases and insulating materials the lowest.

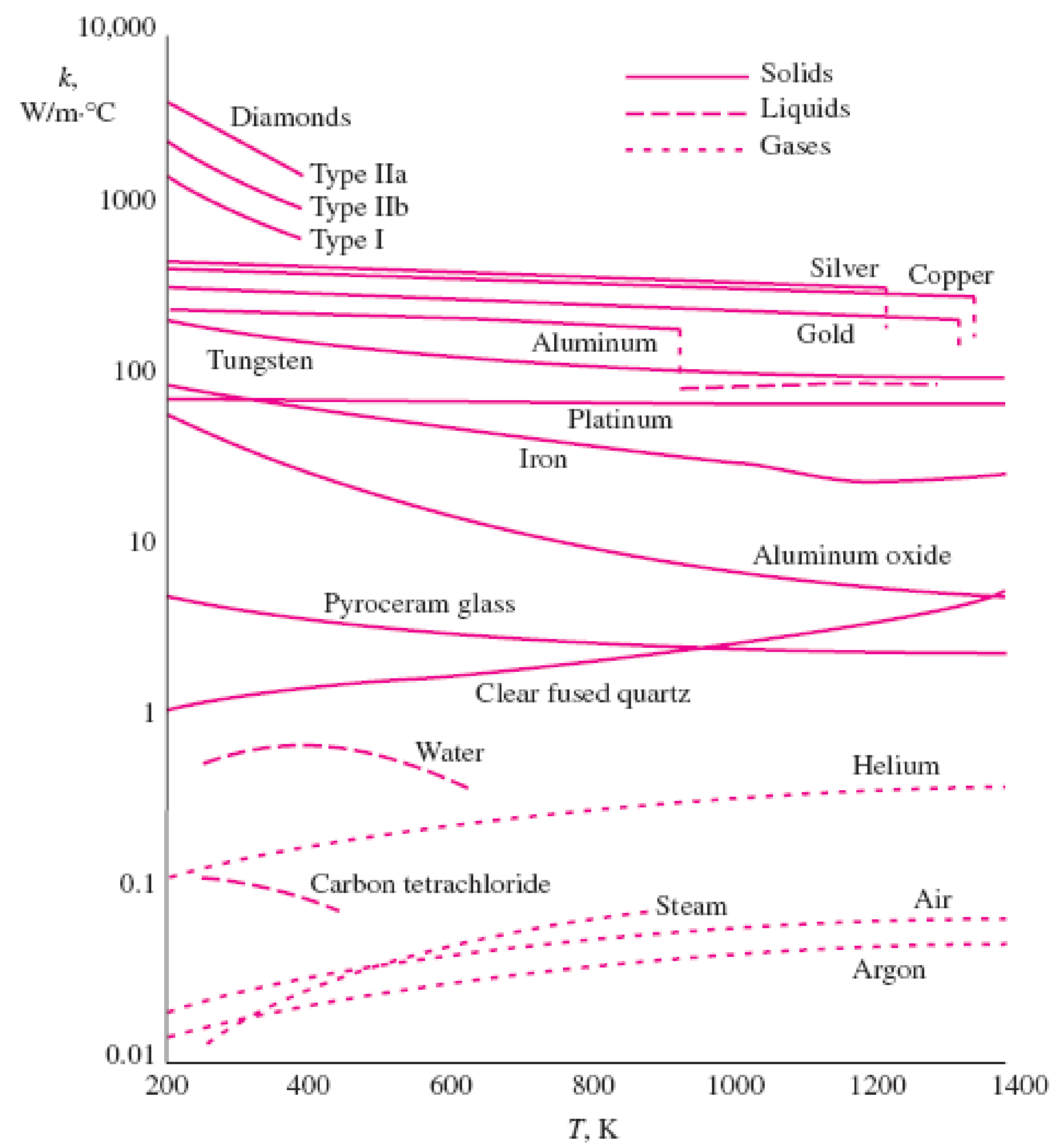


The mechanisms of heat conduction in different phases of a substance.

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 · °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



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

TABLE 16–3

Thermal conductivities of materials vary with temperature

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

Thermal Diffusivity

c_p Specific heat, J/kg · °C: Heat capacity per unit mass

ρc_p Heat capacity, J/m³ · °C: Heat capacity per unit volume

α Thermal diffusivity, m²/s: Represents how fast heat diffuses through a material

$$\alpha = \frac{\text{Heat conducted}}{\text{Heat stored}} = \frac{k}{\rho c_p} \qquad (\text{m}^2/\text{s})$$

A material that has a high thermal conductivity or a low heat capacity will obviously have a large thermal diffusivity.

The larger 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 is conducted further.

TABLE 16–4

The thermal diffusivities of some materials at room temperature

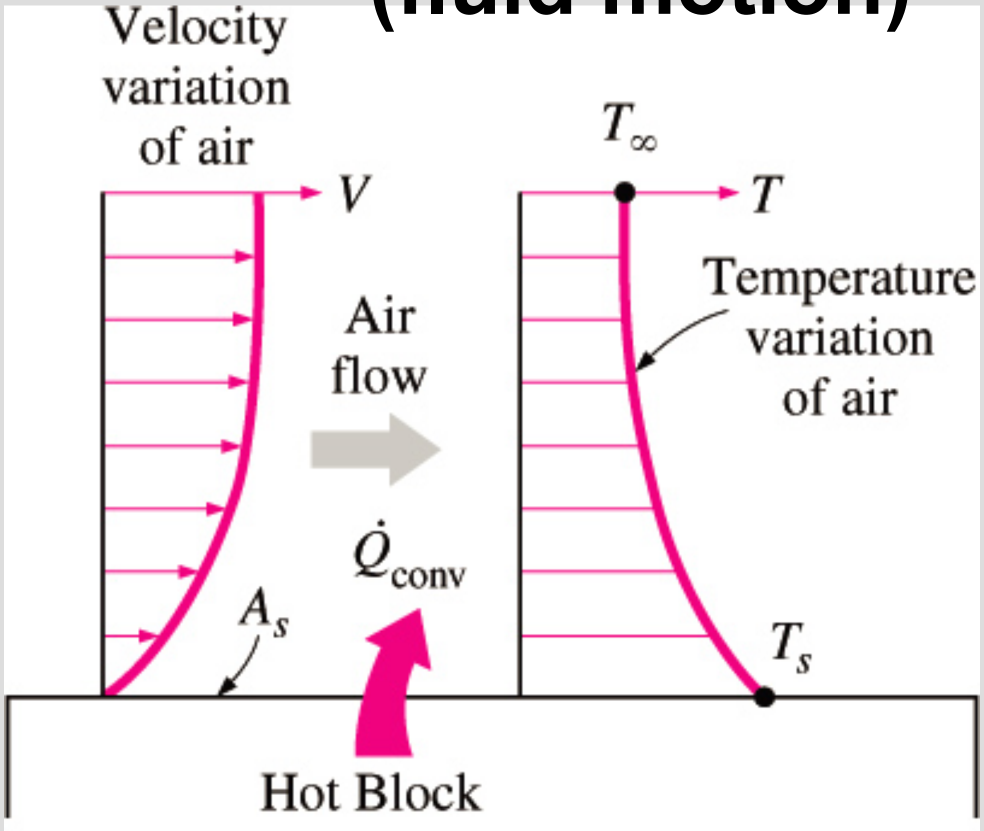
Material	α, m²/s*
Silver	149×10^{-6}
Gold	127×10^{-6}
Copper	113×10^{-6}
Aluminum	97.5×10^{-6}
Iron	22.8×10^{-6}
Mercury (l)	4.7×10^{-6}
Marble	1.2×10^{-6}
Ice	1.2×10^{-6}
Concrete	0.75×10^{-6}
Brick	0.52×10^{-6}
Heavy soil (dry)	0.52×10^{-6}
Glass	0.34×10^{-6}
Glass wool	0.23×10^{-6}
Water (l)	0.14×10^{-6}
Beef	0.14×10^{-6}
Wood (oak)	0.13×10^{-6}

CONVECTION = Conduction + Advection (fluid motion)

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

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

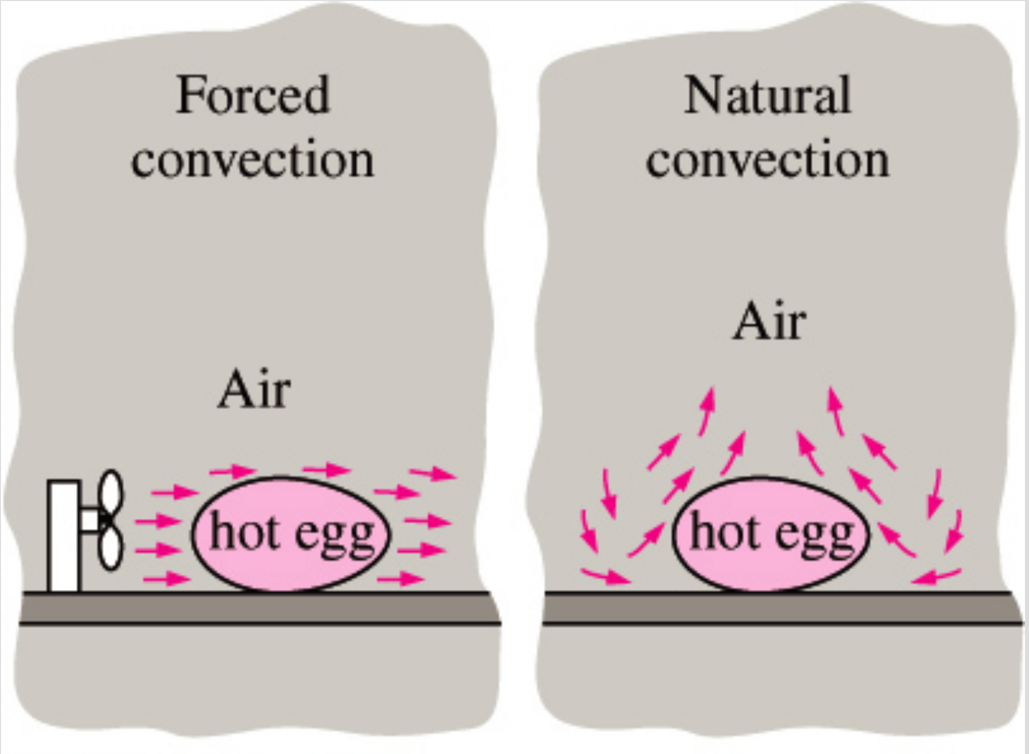
In the absence of any bulk fluid motion, heat transfer between a solid surface and the adjacent fluid is by pure conduction.



Heat transfer from a hot surface to air by convection.

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

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



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

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

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

Newton's law of cooling

h	convection heat transfer coefficient, W/m² · °C
A_s	the surface area through which convection heat transfer takes place
T_s	the surface temperature
T_∞	the temperature of the fluid sufficiently far from the surface.

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

- the bulk fluid velocity

TABLE 16–5

Typical values of convection heat transfer coefficient

Type of convection	h, W/m² · °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

EXAMPLE 1–8 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

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

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.

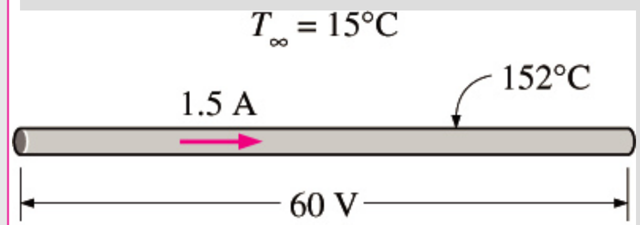


FIGURE 1–34
Schematic for Example 1–8.

RADIATION

- **Radiation:** The energy emitted by matter in the form of *electromagnetic waves* (or *photons*) as a result of the changes in the electronic configurations of the atoms or molecules.
- Unlike conduction and convection, the transfer of heat by radiation does not require the presence of an *intervening medium.*
- In fact, heat transfer by radiation is fastest (at the speed of light) and it suffers no attenuation in a vacuum. This is how the energy of the sun reaches the earth.
- In heat transfer studies we are interested in *thermal radiation,* which is the form of radiation emitted by bodies because of their temperature.
- All bodies at a temperature above absolute zero emit thermal radiation.
- 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.

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

Stefan–Boltzmann law

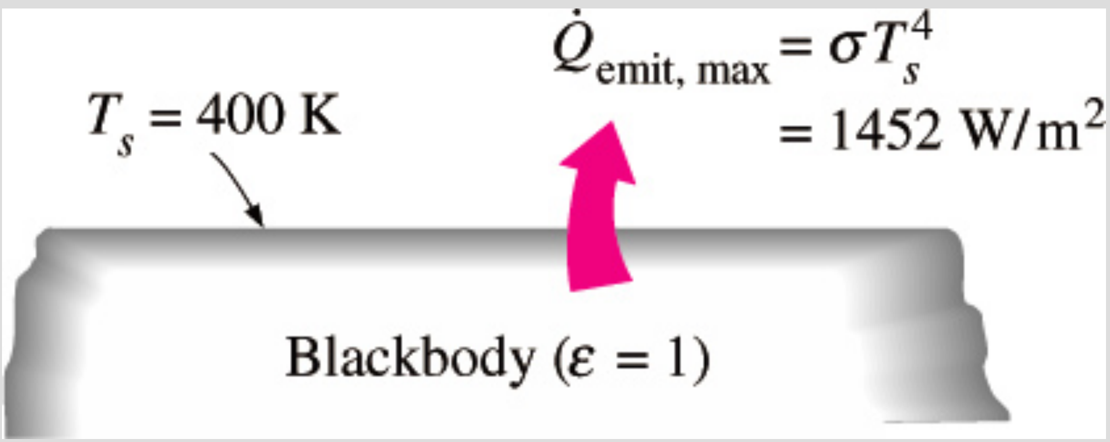
$\sigma = 5.670 \times 10^{-8}\ \text{W/m}^2 \cdot \text{K}^4$ *Stefan–Boltzmann constant*

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

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

Radiation emitted by real surfaces

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



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

TABLE 16–6

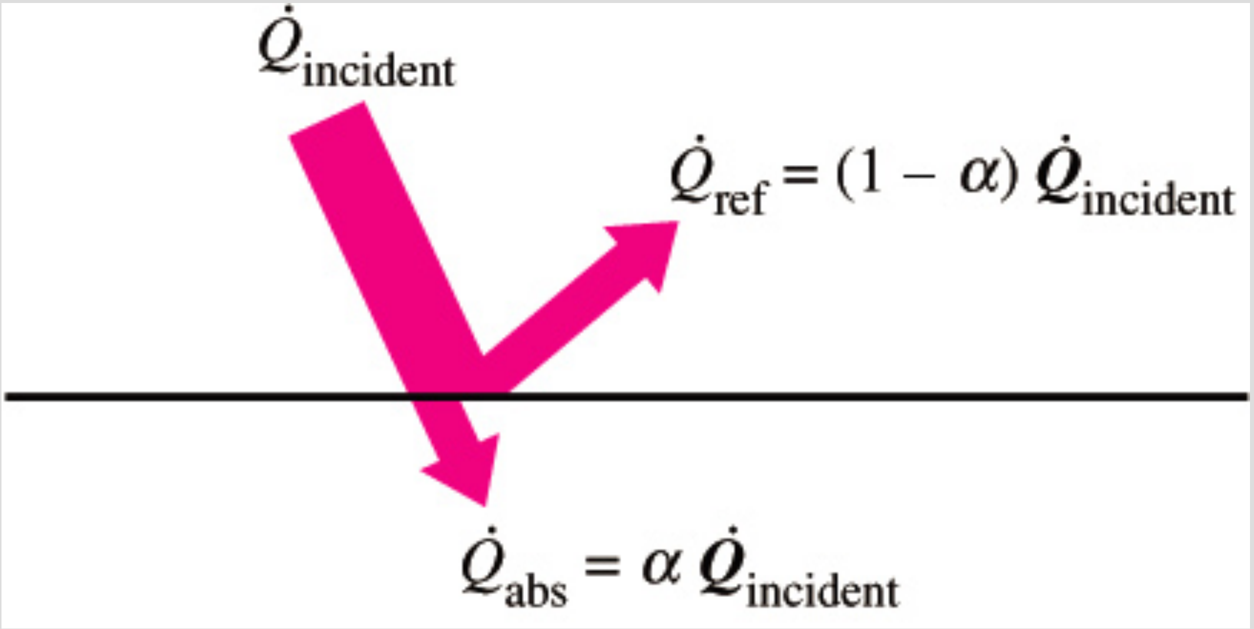
Emissivities of some materials at 300 K

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

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

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

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



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

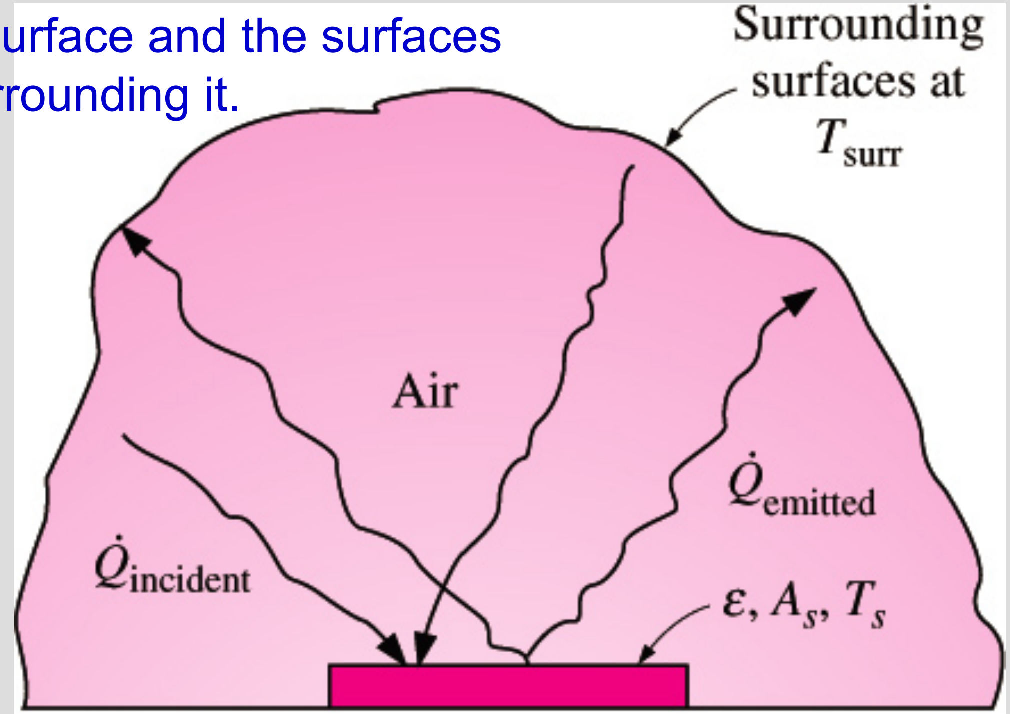
Net radiation heat transfer: The difference between the rates of radiation emitted by the surface and the radiation absorbed.

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

- the properties of the surfaces
- their orientation relative to each other
- the interaction of the medium between the surfaces with radiation

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

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



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

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

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

Combined heat transfer coefficient $h_{combined}$
Includes the effects of both convection and radiation

EXAMPLE 1–9 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 surfaces 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).

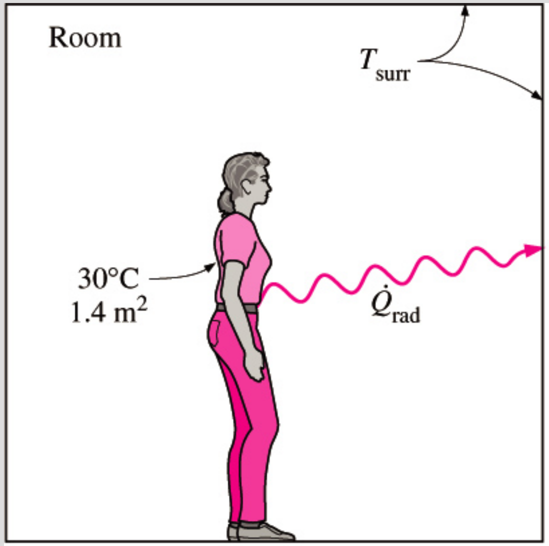


FIGURE 1–38
Schematic for Example 1–9.

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

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

and

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

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.

SIMULTANEOUS HEAT TRANSFER MECHANISMS

Heat transfer is only by conduction in *opaque solids,* but by conduction and radiation in *semitransparent solids.*

A solid may involve conduction and radiation but not convection. A solid may involve convection and/or radiation on its surfaces exposed to a fluid or other surfaces.

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.*

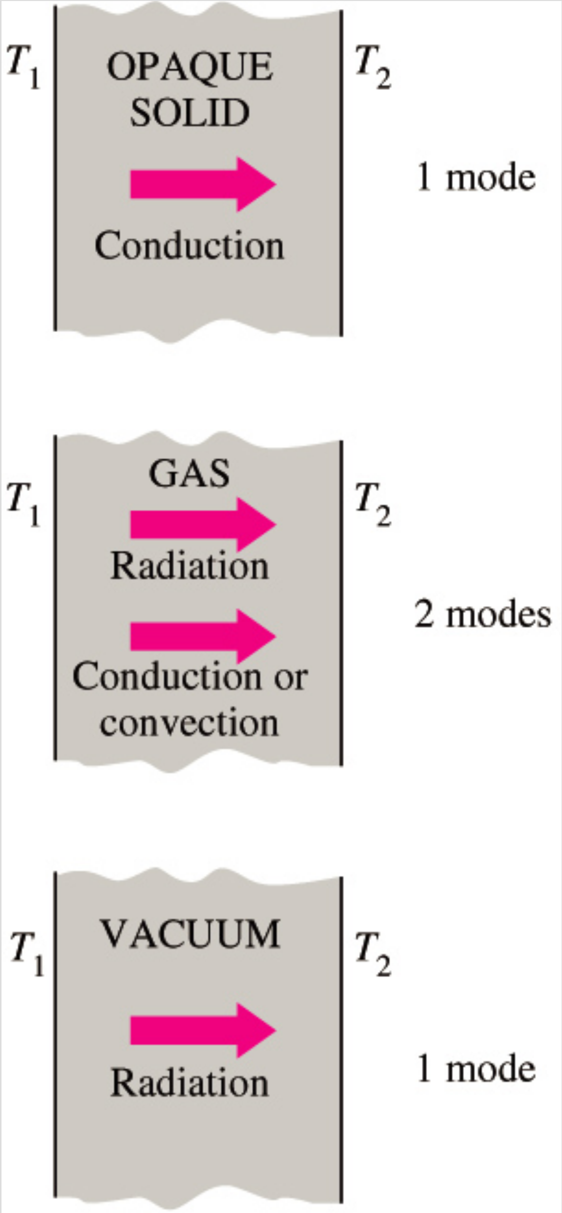
In the absence of radiation, heat transfer through a fluid is either by conduction or convection, depending on the presence of any bulk fluid motion.

Convection = Conduction + Fluid motion

Heat transfer through a *vacuum* is by radiation.

Most gases between two solid surfaces do not interfere with radiation.

Liquids are usually strong absorbers of radiation.



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

EXAMPLE 1–10 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 m^2 and 29°C, respectively, and the convection heat transfer coefficient is 6 $W/m^2 \cdot °C$ (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).

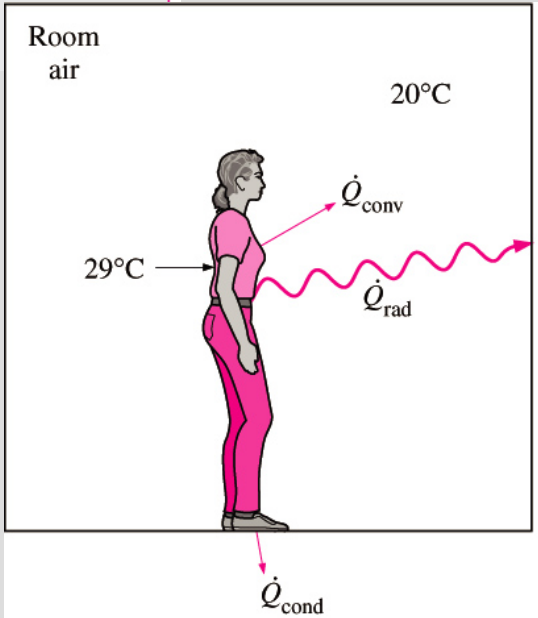


FIGURE 1–40
Heat transfer from the person described in Example 1–10.

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 (m^2) 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

$$\begin{aligned}\dot{Q}_{\text{rad}} &= \varepsilon\sigma A_s(T_s^4 - T_{\text{surr}}^4)\\ &= (0.95)(5.67\times10^{-8}\ \text{W/m}^2\cdot\text{K}^4)(1.6\ \text{m}^2)\\ &\quad\times[(29+273)^4 - (20+273)^4]\ \text{K}^4\\ &= 81.7\ \text{W}\end{aligned}$$

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:

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

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 1–11 Heat Transfer between Two Isothermal Plates

Consider steady heat transfer between two large parallel plates at constant temperatures of $T_1 = 300$ K and $T_2 = 200$ K that are $L = 1$ 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 W/m · °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 $k = 0.0219$ W/m · °C for air (Table A-22), 0.026 W/m · °C for urethane insulation (Table A-28), and 0.00002 W/m · °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

$$\begin{aligned}\dot{Q}_{\text{rad}} &= \varepsilon\sigma A(T_1^4 - T_2^4)\\ &= (1)(5.67\times10^{-8}\ \text{W/m}^2\cdot\text{K}^4)(1\ \text{m}^2)[(300\ \text{K})^4 - (200\ \text{K})^4] = 368\ \text{W}\end{aligned}$$

Therefore,

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

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.

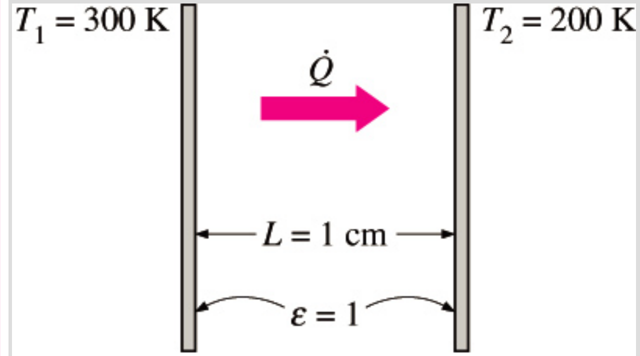


FIGURE 1–41
Schematic for Example 1–11.

(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,

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

(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

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

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,

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

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.

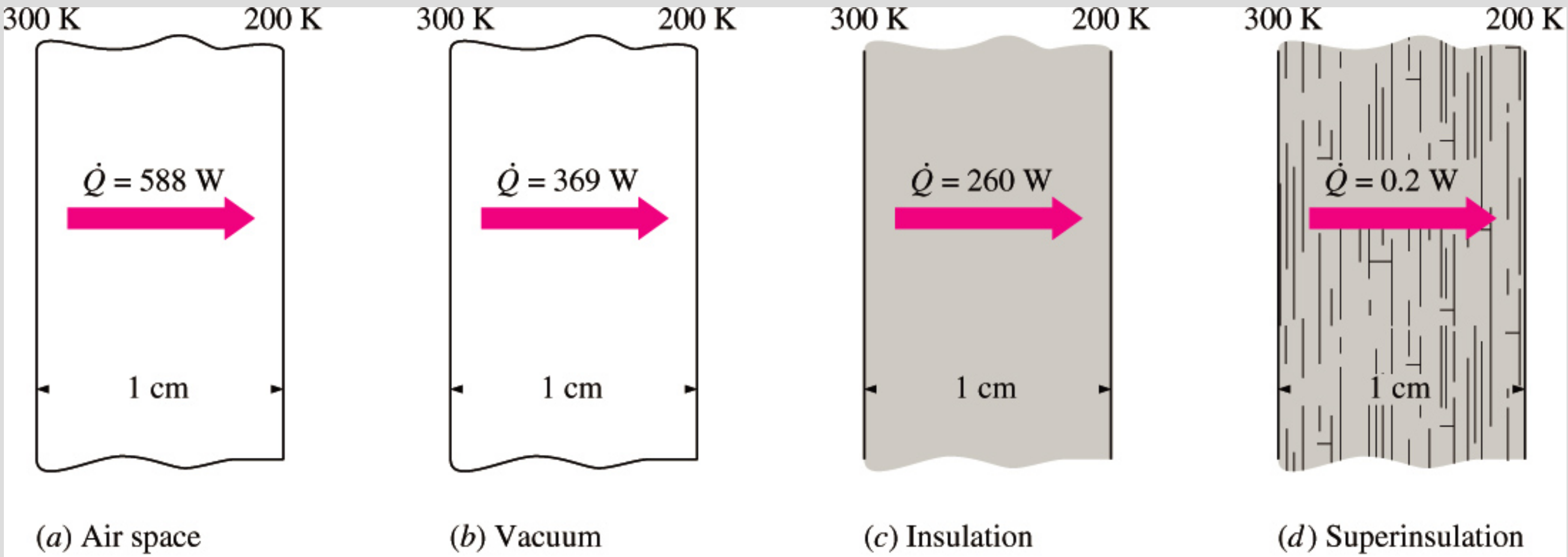


FIGURE 1–42

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

EXAMPLE 1–12 **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 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.

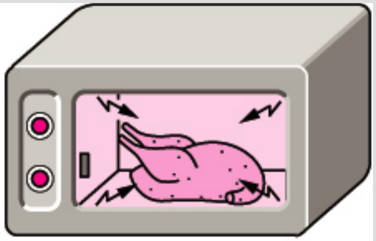


FIGURE 1–43
A chicken being cooked in a microwave oven (Example 1–12).

EXAMPLE 1–13 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 W/m^2 · °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 $\alpha = 0.6$.

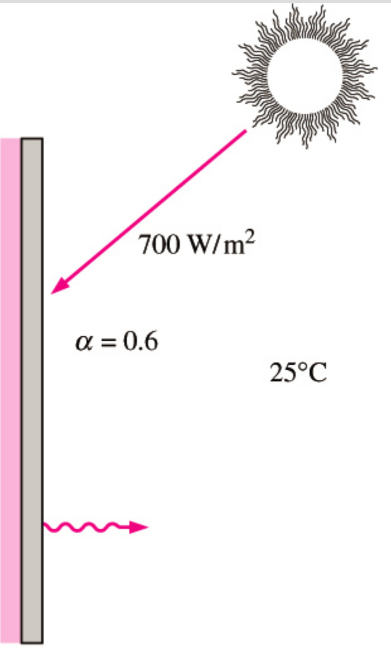


FIGURE 1–44
Schematic for Example 1–13.

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

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

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

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

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.

Concluding Points

- Differences between Thermodynamics and Heat Transfer?
- Basic Concepts of Thermodynamics
- Heat Transfer Modes?
- Fourier’s Law of Heat Conduction?
- Thermal Conductivity and Thermal Diffusivity?
- Natural (or Free) and Forced Convection?
- Convection and Newton’s Law of Cooling?
- Radiation and Stefan–Boltzman Law?
- Blackbody and Emissivity?
- Kirchhoff’s Law of Radiation?
- Combined Heat Transfer Coefficient?
- Simultaneous Heat Transfer Mechanisms?

Summary

- Introduction
- Conduction
  - ✓ Fourier’s law of heat conduction
  - ✓ Thermal Conductivity
  - ✓ Thermal Diffusivity
- Convection
  - ✓ Newton’s law of cooling
- Radiation
  - ✓ Stefan–Boltzmann law
- Simultaneous Heat Transfer Mechanisms