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

$$Q_{\text{emit, max}} = \sigma T_s^4 \quad (W)$$

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

$$Q_{\text{emit}} = \varepsilon \sigma T_s^4 \quad (W)$$

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

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 $\varepsilon$ and $\alpha$ 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)

$\dot{Q}_{\text{abs}} = \alpha \dot{Q}_{\text{incident}}$

$\dot{Q}_{\text{ref}} = (1 - \alpha) \dot{Q}_{\text{incident}}$
where \( Q_{\text{incident}} \) is the rate at which radiation is incident on the surface and \( \alpha \) 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 \( \varepsilon \) and surface area \( A_s \) at an absolute temperature \( T_s \) is completely enclosed by a much larger (or black) surface at absolute temperature \( T_{\text{surr}} \) 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)

\[
Q_{\text{rad}} = \varepsilon A_s \sigma (T_s^4 - T_{\text{surr}}^4) \quad \text{(W)}
\]

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 \( h_{\text{combined}} \) 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

\[
Q_{\text{total}} = h_{\text{combined}} A_s (T_s - T_a) \quad \text{(W)}
\]

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.

**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-
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 convection in a fluid can be viewed as a special case of convection in the absence of any fluid motion (Fig. 16–18).

**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

$$Q_{rad, winter} = \varepsilon \sigma A_s (T_s^4 - T_{surr, winter}^4)$$

$$= (0.95)(5.67 \times 10^{-8}\text{ W/m}^2\cdot\text{K}^4)(1.4\text{ m}^2) \times [(30 + 273)^4 - (10 + 273)^4]\text{ K}^4$$

$$= 152\text{ W}$$

and

$$Q_{rad, summer} = \varepsilon \sigma A_s (T_s^4 - T_{surr, summer}^4)$$

$$= (0.95)(5.67 \times 10^{-8}\text{ W/m}^2\cdot\text{K}^4)(1.4\text{ m}^2) \times [(30 + 273)^4 - (25 + 273)^4]\text{ K}^4$$

$$= 40.9\text{ W}$$

**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.
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

$$Q_{\text{conv}} = hA_s(T_s - T_a)$$

$$= (6 \text{ W/m}^2 \cdot \text{°C})(1.6 \text{ m}^2)(29 - 20)\text{°C}$$

$$= 86.4 \text{ W}$$

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

$$Q_{\text{rad}} = \varepsilon\sigma A_s(T_s^4 - T_{\text{air}}^4)$$

$$= \varepsilon\sigma A_s(T_s^4 - T_{\text{air}}^4)$$

$$= (0.95)(5.67 \times 10^{-8} \text{ W/m}^2 \cdot \text{K}^4)(1.6 \text{ m}^2)$$

$$\times [(29 + 273)^4 - (20 + 273)^4] \text{ K}^4$$

$$= 81.7 \text{ W}$$
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:

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

**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.

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**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 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 \( k = 0.0219 \text{ W/m · °C} \) 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

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

and

\[ \dot{Q}_{\text{rad}} = \varepsilon A \sigma (T_1^4 - T_2^4) \]

\[ = (1)(5.67 \times 10^{-8} \text{ W/m}^2 \cdot \text{K}^4)(1 \text{ m}^2)(300 \text{ K})^4 - (200 \text{ K})^4) = 368 \text{ W} \]

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

(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,

\[ Q_{\text{total}} = Q_{\text{rad}} = 368 \text{ W} \]

(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

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

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,

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

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...
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.

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**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/m² 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/m² °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 solar 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

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

**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

\[ \dot{Q}_{\text{cond}} = -k A \frac{dT}{dx} \]

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

\[ \dot{Q}_{\text{cond}} = k A \frac{\Delta T}{L} \]

where \( \Delta T \) 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

\[ \dot{Q}_{\text{conv}} = h A_s (T_s - T_\infty) \]

where \( h \) is the convection heat transfer coefficient in W/m²·°C or Btu/h·ft²·°F, \( A_s \) is the surface area through which convection heat transfer takes place, \( T_s \) is the surface temperature, and \( T_\infty \) 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 \( Q_{\text{emit, max}} = \sigma A_s T_s^4 \), where \( \sigma = 5.67 \times 10^{-8} \text{ W/m}^2 \cdot \text{K}^4 \) or 0.1714 \times 10^{-8} \text{ Btu/h · ft}^2 · \text{R}^4 \) is the Stefan–Boltzmann constant.

When a surface of emissivity \( e \) and surface area \( A_s \) at an absolute temperature \( T_s \) is completely enclosed by a much larger (or black) surface at absolute temperature \( T_{\text{surr}} \) 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

\[ \dot{Q}_{\text{rad}} = e \sigma A_s (T_s^4 - T_{\text{surr}}^4) \]

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 \( Q_{\text{absorbed}} = \alpha Q_{\text{incident}} \) where \( Q_{\text{incident}} \) is the rate at which radiation is incident on the surface and \( \alpha \) is the absorptivity of the surface.

**REFERENCES AND SUGGESTED READINGS**
