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Physics, Chapter 18: Transfer of Heat

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Transfer of Heat

18-1 Methods of Transmitting Heat

The methods by which heat is transmitted can be classified into three distinct types known as *convection*, *conduction*, and *radiation*. In any actual case of heat transmission, a combination of these methods may be operating simultaneously, and the principal problem is to determine the rate at which heat flows from the source at higher temperature to the source at lower temperature.

We may distinguish between the three processes of heat transfer by considering whether a medium is required for the transfer of heat, and whether that medium is at rest or in motion. In the process of conduction, thermal energy is transmitted by a medium which is at rest. The process of convection requires a moving medium. In general, a fluid transports the energy. In processes of natural convection, the density differences between the heated fluid and its cooler neighborhood generate buoyant forces which cause the heated fluid to move. Heat energy is delivered to a fluid in one region of the container and becomes internal energy of the fluid. The fluid is set in motion, and the internal energy is liberated as heat in some other portion of the container. Radiation requires no medium. The energy reaching us from the sun and stars comes in the form of radiation through the vacuous space between the sun and the earth and between the stars and the earth. Radiation may be transmitted through a substance, as in the transmission of sunlight through the air or through a windowpane, and, in so doing, changes may take place in the substance and in the character of the radiation.

Thus we see that the transfer of heat by conduction and convection requires the presence of aggregates of matter. Heat energy cannot be transferred by conduction or convection from an isolated atom or molecule, but even completely isolated atoms or molecules may gain or lose energy in the process of radiation.

18-2 Conduction

The method of transferring heat by conduction can be illustrated by means of a long cylindrical copper rod which has one end placed in a gas flame while the other end is placed in a mixture of ice and water, as shown in Figure 18-1. The amount of heat which is conducted through the copper rod in any time interval, assuming that the loss of heat to the surrounding

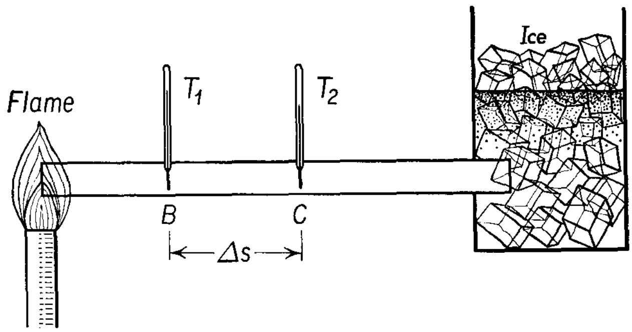

Fig. 18-1 Method of measuring the temperature gradient along a conductor of heat to determine its conductivity.

atmosphere may be neglected, can be measured by the amount of ice which is melted in this time. When a steady flow is established, the temperature of any point along the rod remains constant. Thus the quantity of heat flowing into any element of volume of the rod in a given time interval is equal to the quantity of heat flowing out of that volume element in the same time interval. If this were not so, the temperature of the volume element would be changing with time, in contradiction to the hypothesis that a steady state was established.

Any two points along the rod of Figure 18-1 are at different temperatures. Let us suppose that the points B and C have temperatures which differ in amount by ΔT, and that these two points are separated by a distance Δs along the rod. The quotient $\Delta T/\Delta s$ is called the *temperature gradient* in this region of the conductor. The greater the temperature gradient, the greater is the amount of heat which flows through this portion of the rod in any given time interval from the region at higher temperature B to the region at lower temperature C. The process of conduction may be thought of as the transfer of heat from any one part of the rod to a neighboring part, because of the difference in temperature existing between these two parts.

The rate at which heat is transferred by conduction is found to depend upon the temperature gradient and upon the cross-sectional area of the rod.

We may write

$$\Delta Q = kA \frac{\Delta T}{\Delta s} \Delta t, \tag{18-1}$$

in which ΔQ is the quantity of heat transferred through a rod of cross-sectional area A in a time interval Δt when the temperature gradient along the rod is $\Delta T/\Delta s$. The factor k is a constant of proportionality which

TABLE 18-1 THERMAL CONDUCTIVITIES

Substance	k in $\dfrac{\text{cal}}{\text{cm sec}^\circ\text{C}}$	k in $\dfrac{\text{Btu}}{\text{ft hr}^\circ\text{F}}$
Metals		
Aluminum	0.49	118
Brass	0.26	63
Copper	0.91	225
Gold	0.71	169
Iron	0.16	39
Lead	0.084	20
Nickel	0.14	34
Platinum	0.17	41
Silver	0.99	242
Tin	0.15	37
Tungsten	0.38	92
Insulators		
Aluminum foil, crumpled	($\frac{3}{8}$-in. air spaces) 0.0001	0.025
Asbestos, sheets	0.0004	0.097
Insulating brick, kaolin	0.0006	0.15
Glass, window	0.0012–0.0024	0.3–0.6
Snow	0.0011	0.27
Fluids		
Air	0.000054	0.017
Water	0.0015	0.37

depends upon the material of the rod and upon the units in which the other quantities of the equation are measured: k is called the *thermal conductivity* of the rod. Two sets of units are commonly used for expressing the thermal conductivity. In cgs units Q is expressed in calories, A in square centimeters, T in degrees centigrade, s in centimeters, and t in seconds. From Equation (18-1) we see that the appropriate units for k are $\dfrac{\text{cal}}{\text{cm sec}^\circ\text{C}}$. In

British units Q is often expressed in Btu's, A in square feet, T in degrees Fahrenheit, s in feet, and t in hours, so that the appropriate units of k are $\frac{\text{Btu}}{\text{ft hr}^\circ\text{F}}$. The thermal conductivities of metals are generally greater than those of other solids, and silver is the best conductor of all. It is also interesting to note that those substances which are good conductors of heat are also good conductors of electricity. The thermal conductivities of some more common substances are given in Table 18-1. Although conduction does take place through liquids and gases, their conductivities are very small, gases being among the poorest conductors. Many insulating materials are constructed so that they trap small quantities of air in small closed spaces and thus make use of the poor conductivity of the air for insulation, and at the same time avoid the transfer of heat through the air by convection.

Let us consider the process of conduction by a gas at rest; that is, there is no net flow of the gas, and the average velocity of the molecules of the gas in any direction is zero. If a layer of gas is at a higher temperature than an adjacent layer, the mean kinetic energy of the molecules in the high-temperature layer is greater than the mean kinetic energy of the molecules in the low-temperature layer. In the collision between a molecule from the higher-temperature region and a molecule from the lower-temperature region, energy is transferred to the slower molecule. Macroscopically, we view this process as the transfer of heat by conduction. When the gas is at very low pressure, molecules of the gas may travel from one wall of the container to the other without striking a second molecule of the gas. In a collision between a gas molecule and a wall, we assume that the molecule leaves the wall with the mean kinetic energy of the molecules of the wall. Thus a gas molecule absorbs energy at the high-temperature wall and delivers energy at the low-temperature wall. The molecules of the gas move across the apparatus without making a collision with other gas molecules. One cannot describe any region of the gas as having a temperature, for the molecules of the gas are not in equilibrium with each other, nor is it possible to have a temperature gradient within the gas.

The internal energy of a nonmetallic solid is associated with the vibrations of the atoms or molecules of the crystal about their mean positions in the crystal lattice. The molecules in a region at higher temperature may be thought to be vibrating with greater amplitude than the molecules in an adjacent region at lower temperature. These vibrations are transmitted from molecule to molecule by the forces which hold the crystal together, similar to the way in which a wave is propagated down a string. In a metallic solid the transmission of thermal energy by lattice vibrations is much smaller than the transmission of energy by a second mechanism—the transmission of energy by the free electrons of the metal. When atoms of a metal are assembled in a solid, the outermost electrons of the metal are relatively free to drift from atom to atom. These free electrons are responsible for the electrical conductivity of metals. These electrons behave like a free-electron gas, and they conduct heat in very much the same way that heat is conducted by the molecules of a gas. This relationship was first observed by Wiedemann and Franz in 1853, who noted that *the ratio of electrical to thermal conductivity was the same for all pure metals, at any given temperature*—a relationship known as the Wiedemann-Franz law.

Illustrative Example. A silver rod of circular cross section has one end immersed in a steam bath and the other end immersed in a mixture of ice and water. The distance between these two ends is 6 cm, and the diameter of the rod is 0.3 cm. Calculate the amount of heat that is conducted through the rod in 2 min.

The quantity of heat which is conducted across any cross section of the rod in a given time interval must be constant. Since the cross-sectional area of the rod is constant, we see, from Equation (18-1), that the temperature gradient must have the same value everywhere along the rod. Thus the temperature gradient is

$$\frac{\Delta T}{\Delta s} = \frac{100°\text{C}}{6\text{ cm}} = 16.7\,\frac{°\text{C}}{\text{cm}}\cdot$$

The thermal conductivity of silver is $0.99\,\dfrac{\text{cal}}{\text{cm sec}°\text{C}}$. We find

$$\Delta Q = kA\,\frac{\Delta T}{\Delta s}\,\Delta t = 0.99\,\frac{\text{cal}}{\text{cm sec}°\text{C}} \times 0.071\text{ cm}^2 \times 16.7\,\frac{°\text{C}}{\text{cm}} \times 120\text{ sec}.$$

Thus

$$\Delta Q = 140\text{ cal}.$$

Illustrative Example. A pipe of length l, made of material of thermal conductivity k, and having inner and outer radii r_1 and r_2, is used to heat a water bath at temperature T_2 by passing steam at temperature T_1 through the pipe. Determine the rate of flow of heat from the inside to the outside of the pipe.

From Equation (18-1) we have

$$\frac{\Delta Q}{\Delta t} = kA\,\frac{\Delta T}{\Delta s}\cdot$$

Let us consider the flow of heat through a cylindrical shell of thickness Δr at radius r. The area of the shell is

$$A = 2\pi rl,$$

and the temperature gradient across the shell is

$$\frac{\Delta T}{\Delta r},$$

so that

$$\frac{\Delta Q}{\Delta t} = 2\pi rlk\,\frac{\Delta T}{\Delta r}\cdot$$

When the pipe is in thermal equilibrium, the rate of flow of heat through each cylindrical shell must be the same as the rate of flow of heat through the pipe. Thus the quantity $\Delta Q/\Delta t$ is a constant and is independent of r. To evaluate this quantity we must apply the known conditions at the boundary of the pipe. To do this we first rewrite the above equation in a form appropriate to infinitesimally thin shells, replacing the quantity $\Delta T/\Delta r$ by dT/dr, and integrate from the inside to the outside of the pipe. Thus we obtain

$$\frac{\Delta Q}{\Delta t}\int_{r_1}^{r_2}\frac{dr}{r} = 2\pi lk\int_{T_1}^{T_2} dT.$$

Remembering that

$$\int\frac{dx}{x} = \log_\epsilon x = \ln x,$$

we find

$$\frac{\Delta Q}{\Delta t}\ln\left(\frac{r_2}{r_1}\right) = 2\pi lk(T_2 - T_1),$$

so that

$$\frac{\Delta Q}{\Delta t} = \frac{2\pi lk(T_2 - T_1)}{\ln\left(\dfrac{r_2}{r_1}\right)}.$$

If the pipe is of copper, $k = 0.91\,\dfrac{\text{cal}}{\text{cm sec}^\circ\text{C}}$. Suppose that the pipe is of inner diameter 2.5 cm and outer diameter 3 cm, and that the temperature of the steam is 120°C while the temperature of the water bath is 20°C. The rate of heat transfer through a pipe 100 cm long is

$$\frac{\Delta Q}{\Delta t} = \frac{2\pi \times 100\text{ cm} \times 0.91\,\dfrac{\text{cal}}{\text{cm sec}^\circ\text{C}} \times (20^\circ\text{C} - 120^\circ\text{C})}{\ln\left(\dfrac{3/2\text{ cm}}{2.5/2\text{ cm}}\right)},$$

$$\frac{\Delta Q}{\Delta t} = -\frac{2\pi \times 100 \times 0.91 \times 100}{0.182}\,\frac{\text{cal}}{\text{sec}} = -3.14 \times 10^5\,\frac{\text{cal}}{\text{sec}}.$$

The minus sign appearing in the expression indicates that the flow of heat is in the direction of decreasing temperature.

Problems of the type illustrated above are known as boundary-value problems; they are very common in physics and engineering. In these problems we know the applicable differential equation and certain conditions at the boundaries, and we cannot obtain a solution to the problem until we perform appropriate integrations.

18-3 Convection

Convection is the transfer of heat from one part of a fluid to another by the flow of the fluid, mixing the warmer parts of the fluid with the cooler parts.

As an example, consider the case of a jar of water which is heated by applying a flame at one side A, as shown in Figure 18-2. Heat is conducted through the glass to the water. As the water in contact with the glass is heated by conduction, its density decreases, and it floats to the top. Colder water moves down to replace it. The colder water, in turn, is heated; once hot, it rises because of its smaller density, thus setting up a circulation of the liquid. During this circulation the warmer parts of the liquid mix with the cooler parts, and in a short time a fairly uniform temperature is established throughout the liquid. This type of heat transfer is called *natural convection* because the motion of the fluid is due to differences in the density of the fluid. In the case of *forced convection*, a fan, a pump, or some other mechanical device is used for stirring and mixing the warmer and cooler parts of the fluid.

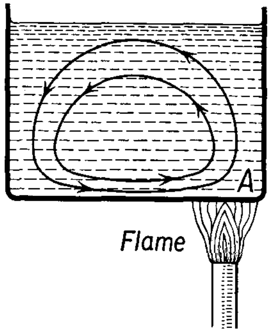

Fig. 18-2 Convection. A circulation is set up in the fluid by heating it near one end.

In almost all cases of the transfer of heat by means of fluids, both convection and conduction must be considered. The heating of a room presents several interesting illustrations of convection and conduction, and, to some extent, of radiation. If the room is heated by means of a "radiator," heat is conducted through the walls of the radiator to the air in contact with it. The warmed air rises and displaces the cooler air, thus establishing a circulation of the air in the room. The warmer air, striking the cooler walls and windows, loses heat to the outside by conduction through the walls and windows. Fortunately, there is always a film of stagnant air close to the walls and windows so that the heat which is conducted to the outside must pass through this film of air as well as through walls and windows. Since air is a very poor conductor, a thin layer of air is sufficient to form a good insulator.

The process of convection is generally much more difficult to formulate in quantitative terms than is the process of conduction. The transfer of heat by convection must be determined by experience in each particular situation. Thus one finds in handbooks typical illustrations of heat loss from vertical steampipes, from horizontal steampipes, from rough pipes, from smooth pipes, and so on, rather than a comprehensive summary of all these situations in a few simple formulas. To minimize the transfer of heat by convection, it is important that the flow of air or other fluid past the heated body be nonturbulent, that the surface be smooth rather than rough, so that a layer of stagnant fluid may be in contact with the surface, providing good insulation. Smooth pipes are often wrapped with a thin layer of asbestos tape in the mistaken notion that the insulating tape will reduce heat losses. In reality, the rough surface of the tape causes the flow of air past the pipe to be turbulent, and the more intimate contact of the flowing air with the pipe causes greater heat loss.

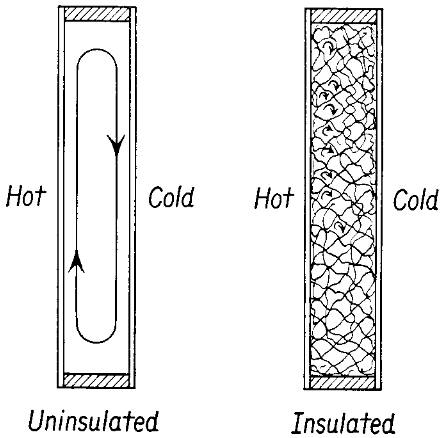

Fig. 18-3 Convection currents within the walls of a house.

There is customarily an open air space between the inner and outer walls of a house, and the transfer of heat from inside to outside in winter takes place by convection. The insulating material between the walls serves to restrict the flow of air by making many small passages in place of one large one, as shown in Figure 18-3. In the earth's atmosphere the convective flow of the air between the equator and the poles tends to equalize the temperature differential generated by the differences in solar radiation in these regions; this convective flow is largely responsible for weather and climate.

18-4 Emission and Absorption of Radiation

The radiation emitted from a warm object, which we call heat radiation, consists of *electromagnetic waves* which are identical in character with light, x-rays, radio waves, and gamma rays. These radiations travel with the speed of light, about 186,000 mi/sec, in vacuum. We shall discuss some aspects of thermal radiation more completely in the following section, while deferring discussions of other forms of electromagnetic radiation to the chapters on electronics, light, and modern physics. In this section we shall be interested in the general relationships between the process of the emission of radiation and the absorption of radiation.

A perfect absorber of radiation is a hole in a wall, for if a hole has no matter on its opposite side, the radiation incident on the hole passes through and cannot return, for there is no matter to reflect it back. To visible light, such a hole is perfectly black; that is, it is a perfect absorber of radiation. We can approximate a perfect absorber by constructing a box, say 1 ft on a side, as shown in Figure 18-4, and by providing the box with a small hole in one face. Even though the face is painted black, the hole will look blacker. This is the case even if the inside of the box is painted white. Light incident upon the hole is reflected many times around the interior of the box before it emerges, and, though only a small fraction of the light is absorbed in each reflection, the large number of internal

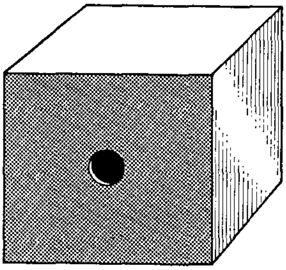

Fig. 18-4 Black body. Even though the inside of the box is painted white, and the front face is painted black, a small hole in the front face looks blacker than the black paint.

reflections greatly diminishes the intensity of the light before it emerges from the hole. The smaller the area of the hole in relation to the total surface area of the box, the more nearly the hole becomes a perfect absorber of radiation. Such a box is called a *black body* and represents a laboratory approximation to a perfect absorber. In practice, any large furnace provided with a small peephole is a good approximation to a perfect absorber, no matter what the furnace contains, and no matter what the materials of which the furnace is constructed.

When radiation is incident upon a body, some of that radiation will be absorbed and some will be reflected. The fraction of incident radiation which is absorbed by a body is called the *absorptivity* of the body. The absorptivity of a black body is unity. The absorptivity of a perfect reflector is zero. The absorptivity of any other body will have a value between zero and 1.

We can gain some insight into the relationship between the effectiveness of a body as a radiator of energy and as an absorber of radiant energy by considering a body suspended in a furnace. When equilibrium is reached, the body is at the temperature of the furnace. The body itself is radiating energy and, at the same time, is acting as an absorber of the energy radiated from the walls of the furnace. Since the body remains at constant temperature, it must radiate exactly as much energy as it absorbs. The body must be as effective in emitting radiation at a particular temperature as it is in absorbing radiation at that temperature. If the body were more effective in absorbing radiation than in emitting radiation, it would soon become hotter than the furnace, while if it were less effective an absorber of radiation than an emitter, it would continue to grow colder than the furnace. Since these effects are not observed in experience, we must conclude that a black body, which is most effective in absorbing radiation, will also be most effective in radiating energy. The effectiveness of a body in radiating energy is called its *emissivity e*. The emissivity of a body is the rate at which a body radiates energy divided by the rate at which a black body radiates energy at the same temperature. The emissivity of a black body is equal to unity. The emissivity of any other bodies lies between zero and 1 and is identical with the absorptivity of the body.

The argument we have indicated for describing the reciprocal relationship between effectiveness in radiation and absorption is a perfectly general one and does not depend upon the nature of the radiator or upon the kind of radiation. Thus *a good radiator must be a good absorber*, and vice versa. If we wish to find whether a particular radio antenna will be a good transmitting antenna and we do not have suitable instruments available to make this determination, we can study its effectiveness as a receiving antenna. An acoustical enclosure will be an effective radiator of sound if it is a good absorber of sound. One very effective type of loud-speaker baffle is called an infinite baffle, which simply consists of a hole in a wall to which a loud-speaker is bolted. In the same way a simple harmonic oscillator will absorb sound energy most effectively at those frequencies at which it radiates such energy. Similar considerations apply to atoms, molecules, and nuclei, and we can identify the presence of certain atoms in the outer atmosphere of the sun by the light they absorb in the sun's spectrum.

18-5 Radiation

The thermal radiation emitted from a heated body varies in color and intensity with the temperature. According to an analysis by Joseph Stefan (1835–1893) of the radiation emitted from a heated body, the rate R at which energy is radiated from a unit area of a body at absolute temperature T is given by the equation

$$R = e\sigma T^4, \tag{18-2}$$

where σ is a constant which depends upon the units used. In cgs units the value of σ is

$$\sigma = 5.672 \times 10^{-5} \frac{\text{erg}}{\text{sec cm}^2 \text{ deg}^4},$$

while in mks units the value of σ is

$$\sigma = 5.672 \times 10^{-8} \frac{\text{joule}}{\text{sec m}^2 \text{ deg}^4}.$$

When an object of emissivity e and at temperature T_1 is placed within an enclosure at temperature T_2, the body radiates energy to the enclosure and absorbs energy from the walls of the enclosure. The rate at which energy is radiated by the body is given by Equation (18-2). To find the rate at which energy is absorbed from the walls of the enclosure, we observe that, if the body were at the temperature of the enclosure, it would be in thermal equilibrium. The energy the body absorbs is thus equal to the energy it would radiate in the same time if it were at the temperature T_2, the temperature of the enclosure. The net energy radiated by the body per unit time is the difference between the rate at which energy is radiated and the rate at which it is absorbed. Assuming that the emissivity is independent of temperature, the net rate of radiation from a body at temperature T_1 which is within an enclosure at temperature T_2 is given by

$$R = e\sigma(T_1^4 - T_2^4). \tag{18-3}$$

Equation (18-3) represents the rate at which energy, or heat, is transmitted by a body per unit area of surface. If A is the area of the surface, then the rate at which heat is radiated or absorbed is given by

$$\frac{\Delta Q}{\Delta t} = AR = Ae\sigma(T_1^4 - T_2^4). \tag{18-4}$$

In Equation (18-3) a positive value of R indicates that the body is radiating more energy than it absorbs, as would be the case when the body is hotter than its surroundings, while a negative value indicates that the body is radiating less energy than it absorbs, as would be the case if the body is cooler than its surroundings.

Illustrative Example. Calculate the rate at which energy is radiated from a tungsten ribbon filament 1 cm long and 0.2 cm wide which is maintained at a temperature of 2727°C. The emissivity of tungsten at this temperature is 0.35. Neglect the radiation absorbed by the filament from the room at 20°C.

Neglecting the contribution from the room, symbolized by T_2 in Equation (18-4), we find

$$\frac{\Delta Q}{\Delta t} = 1\text{ cm} \times 0.2\text{ cm} \times 0.35 \times 5.672 \times 10^{-5}\,\frac{\text{erg}}{\text{sec cm}^2\text{ deg}^4} \times (3000°)^4$$

$$= 64.3 \times 10^7\,\frac{\text{erg}}{\text{sec}} = 64.3\text{ watts.}$$

18-6 The Spectrum of Black-Body Radiation

The radiant energy emitted by a black body may be examined by opening a hole in the side of a furnace and letting some of the radiation emerge. It is commonly known that the color of the light emitted by a furnace changes as the temperature of the furnace rises, glowing first a deep red, then orange, and then white. These are not pure colors; they may be analyzed into their component wavelengths by means of a spectroscope (see Chapter 39). The longest wavelengths are invisible and are in the infrared region, that is, beyond the red. The wavelengths of this radiation decrease progressively

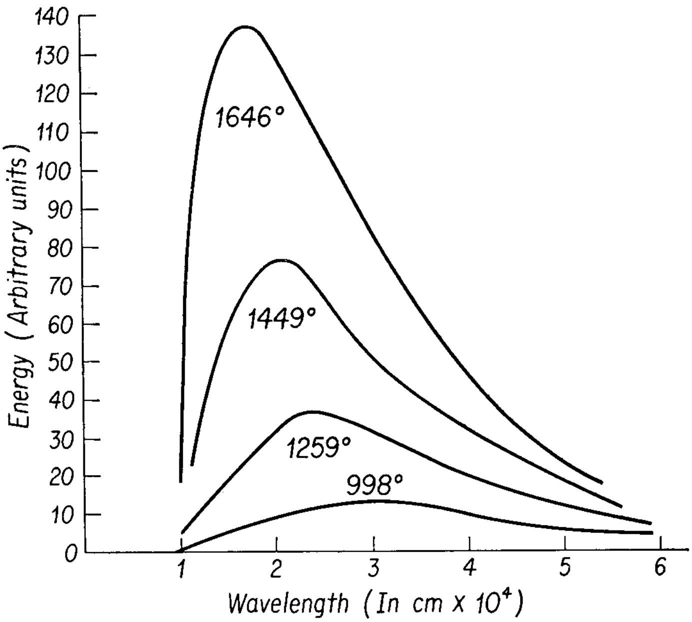

Fig. 18-5 Distribution of the energy among the wavelengths in the spectrum of a black body at different temperatures in °K.

through the colors red, orange, yellow, green, blue, and violet, and finally to the invisible ultraviolet. The distribution of energy as a function of wavelength is shown in Figure 18-5. As the temperature of the furnace increases, the wavelength of maximum intensity steadily decreases, and the intensity at every wavelength increases in such a way that the total energy radiated increases as the fourth power of the absolute temperature, according to Equation (18-2). In the figure the total energy radiated is represented by the area under a curve.

At room temperature the radiation is invisible to the eye, but even at body temperature there is sufficient infrared radiation emitted for a sensitive detector to locate the source of radiation. It has been possible to construct detectors of infrared radiation sensitive enough to locate the chimney of an industrial installation, or the engine of an airplane, and these detectors are of considerable military importance. When the temperature increases to about 700°C, the radiation becomes visible, and the body is said to be red hot. At 1500°C there is a sufficient amount of the shorter-wavelength radiation present in the spectrum for the radiation to appear nearly white. By examining the color of the light from a furnace, it is possible to determine its temperature by means of a device called an *optical pyrometer*. Through the examination of the spectrum of the sun and the stars by means of a spectroscope, it is possible to determine their temperatures. The temperature determined in this way is called the *color temperature*.

The energy emitted from a heated object appears in all parts of the electromagnetic wave spectrum. Thus radio waves have been detected in the solar spectrum as radio noise, and at the other extreme, x-rays, of very short wavelength, have been detected in solar radiation by equipment installed in rockets sent high into the earth's atmosphere. While the relative amounts of energy in these regions of the spectrum are quite small, nevertheless, recent studies of the solar spectrum have made it possible to detect these invisible radiations.

18-7 Heat Insulation

A thorough understanding of the subject of the transmission of heat will enable one to solve the very important problem of heat insulation. This involves the use of proper materials for a given job as well as the development of new insulating materials. For example, gasoline storage tanks are frequently coated with aluminum or other reflecting material to reduce the absorption of radiation from the sun. Insulating materials are constructed so that they contain many small pockets of air to make use of the very low conductivity of the air; there is practically no convection since the air is trapped in these pockets. Crumpled aluminum containing small air pockets is a very good insulator; there is practically no transfer of heat by convection. The transfer by conduction is very slight since the crumpling of the aluminum makes the conducting path very long while the cross-sectional area is very small, and very little heat is transferred by radiation.

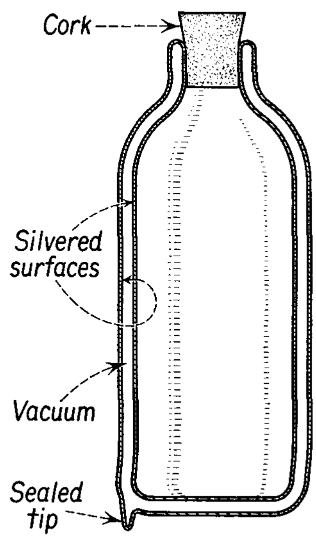

Fig. 18-6 Section of a glass thermos bottle.

The ordinary thermos bottle, sketched in Figure 18-6, is an excellent illustration of heat insulation. The thermos bottle consists of two cylindrical glass flasks sealed together at the top. The inside surface of the outer cylinder and the outside surface of the inner cylinder are silvered. Then the air between the two walls is pumped out, and the space is sealed off. If hot food is placed inside the bottle and the bottle is then corked, the food will remain hot for a long time. Very little heat will be conducted along the glass or through the cork to the outside: there is practically no convection, since there is a good vacuum between the walls, and radiation is reduced considerably by the silver coatings.

Problems

18-1. A metal rod 100 cm long and 4 cm^2 in cross-sectional area conducts 40 cal of heat per minute when the ends of the rod are maintained at a difference in temperature of 80°C. Determine the coefficient of thermal conductivity of the metal.

18-2. A copper rod 60 cm long and 8 mm in diameter has one end immersed in steam and the other end immersed in a mixture of ice and water. Determine the amount of heat which will be conducted through the rod in 5 min.

18-3. An aluminum pan has a diameter of 25 cm and is 0.5 cm thick. What is the rate of flow of heat through the bottom if the pan contains boiling water and is transmitting heat to it from a stove at a temperature of 400°C?

18-4. Water in a glass beaker is boiling away at the rate of 35 gm/min. The bottom of the beaker has an area of 200 cm^2 and is 0.2 cm thick. Calculate the temperature of the underside of the bottom of the beaker if $k = 0.002$ cal/cm sec °C.

18-5. An oven used for baking glass x-ray tubes is made of sheets of asbestos 0.75 in. thick. This oven is 4 ft high, 1 ft wide, and 1 ft deep. At what rate must heat be supplied to this oven to maintain the temperature inside at 400°C if the temperature of the air just outside the asbestos is 100°C?

18-6. Calculate the rate at which energy is radiated from a black body whose temperature is 1500° abs if its surface area is 1 cm^2.

18-7. Calculate the rate at which energy is radiated from a tungsten filament which is maintained at the temperature of 2500° abs if its surface area is 0.30 cm^2 and its emissivity at this temperature is 0.30.

18-8. The operating temperature of a 50-watt incandescent bulb is 2500° abs. The emissivity of the filament is 0.30. Find the surface area of the filament.

18-9. If the incandescent bulb of Problem 18-8 is placed within an enclosure at a temperature of 500° abs, what power must be supplied to the bulb to keep it at its normal operating temperature? Neglect convection losses from the surface of the glass bulb.

18-10. A blackened copper sphere initially at a temperature of 0°C is placed within an evacuated furnace which is held at a temperature of 500°C. If the sphere is 1 cm in diameter, what will be the initial rate of change of temperature of the sphere?

18-11. A copper rod 1 m long has been "turned" so that the first 60 cm of its length is 2 cm in diameter, while the last 40 cm of its length is 1 cm in diameter.

The thick end is maintained at a temperature of 100°C, while the thin end is maintained at a temperature of 0°C. Find (a) the temperature at the junction between the thick and thin ends and (b) the rate of heat flow. [HINT: When equilibrium has been reached, the same rate of flow must exist at all points within the rod. If this were not so, some part of the rod would be absorbing heat, and its temperature would rise.]

18-12. A cubical ice chest is to be constructed of sheet asbestos 1 in. thick. The chest is to have an inside volume of 1 ft^3 and is to hold 25 lb of ice. How long will the block of ice last if the outside temperature is 100°F?

18-13. A uniform sheet of concrete of thickness 8 in. separates a reservoir at 40°F from a reservoir at 160°F. The thermal conductivity of the concrete is $k = 12 \dfrac{\text{Btu in.}}{\text{hr ft}^2\ {}^\circ\text{F}}$. Find (a) the temperature gradient and (b) the heat flow through the concrete in Btu/ft^2-hr. (c) A 4-in.-thick slab of glass of conductivity $k = 6 \dfrac{\text{Btu in.}}{\text{hr ft}^2\ {}^\circ\text{F}}$ is introduced on the low-temperature side of the concrete. Find the temperature of the interface between the concrete and the glass.

18-14. A cube of copper 1 cm on a side and of mass 7 gms is heated to a temperature of 727°C. The cube is in an evacuated box whose walls are held at a constant temperature of 27°C. The cube cools by radiation alone. (a) How much heat has been lost when the temperature of the cube has dropped by 1°C? (b) How long does it take for the temperature to drop by 2°C? The specific heat of copper is 0.1 cal/gm °C, and its emissivity is 0.3.

18-15. The earth receives energy from the sun at the rate of 1.94 calories per minute per cm^2, called the *solar constant.* The radius of the earth's orbit is 149×10^6 km and the diameter of the sun is 1.39×10^6 km. Assuming the sun to be a black body, find the surface temperature of the sun. (See Figure 36-2.)

18-16. Using the data in the second illustrative example of Section 18-2, find the temperature gradient (a) at the inner surface and (b) at the outer surface of the pipe.