

# chapter thirteen

## Transfer of Heat

### Conduction

If we put a poker into the fire, and hold on to it, then heat reaches us along the metal. We say the heat is *conducted*; and we soon find that some substances—metals—are good conductors, and others—such as wood or glass—are not. Good conductors feel cold to the touch on a cold day, because they rapidly conduct away the body's heat.

### Temperature Distribution along a Conductor

In order to study conduction in more detail consider Fig. 13.1 (a), which shows a metal bar AB whose ends have been soldered into the

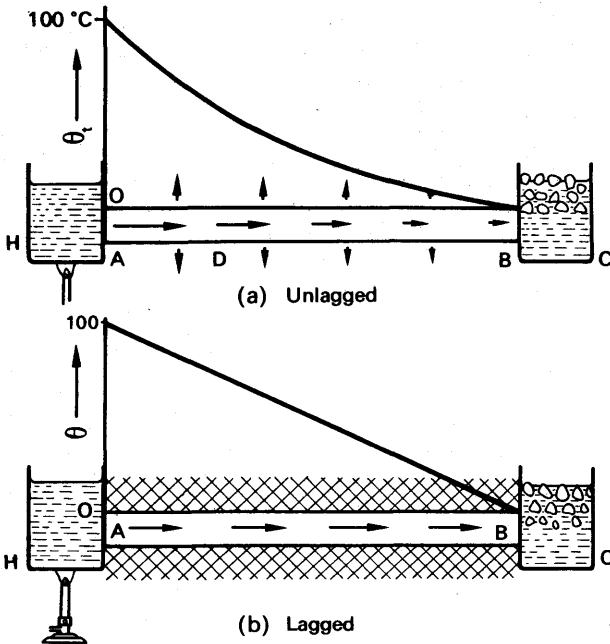


FIG. 13.1. Temperature fall along lagged and unlagged bars.

walls of two metal tanks, H, C; H contains boiling water, and C contains ice-water. Heat flows along the bar from A to B, and *when conditions are steady* the temperature  $\theta$  of the bar is measured at points along its length; the measurements may be made with thermojunctions, not shown in the figure, which have been soldered to the rod. The curve in

the upper part of the figure shows how the temperature falls along the bar, less and less steeply from the hot end to the cold.

The figure 13.1 (b) shows how the temperature varies along the bar, if the bar is *well lagged* with a bad conductor, such as asbestos wool. It now falls uniformly from hot to cold.

The difference between the temperature distributions is due to the fact that, when the bar is unlagged, heat escapes from its sides, by convection in the surrounding air. Thus the heat flowing past D per second, is less than that entering the bar at A by the amount which escapes from the surface AD. The arrows in the figure represent the heat escaping per second from the surface of the bar, and the heat flowing per second along its length. The heat flowing per second along the length decreases from the hot end to the cold. But when the bar is lagged, the heat escaping from its sides is negligible, and the flow per second is constant along the length of the bar.

We thus see that the temperature gradient along a bar is greatest where the heat flow through it is greatest. We also see that the temperature gradient is uniform only when there is a negligible loss of heat from the sides of the bar.

**Thermal Conductivity**

Let us consider a very large thick bar, of which AB in Fig. 13.2 (i) is a part, and along which heat is flowing steadily. We suppose that the

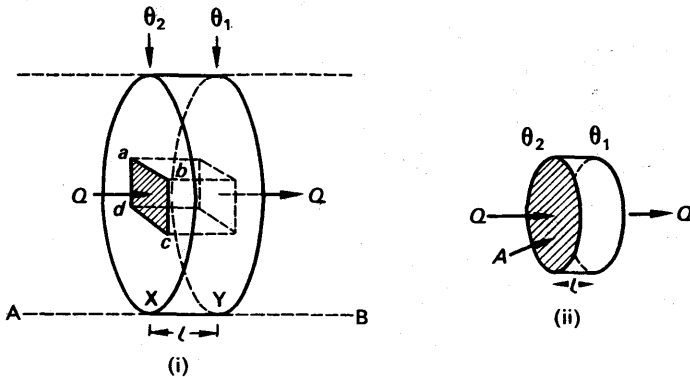


FIG. 13.2. Definition of thermal conductivity.

loss of heat from the sides of the bar is made negligible by lagging. XY is a slice of the bar, of thickness  $l$ , whose faces are at temperatures  $\theta_2$  and  $\theta_1$ . Then the *temperature gradient* over the slice is

$$\frac{\theta_2 - \theta_1}{l}$$

We now consider an element  $abcd$  of the slice of unit cross-sectional area, and we denote by  $Q$  the heat flowing through it per second. The value of  $Q$  depends on the temperature gradient, and, since some

substances are better conductors than others, it also depends on the material of the bar.

We therefore write

$$Q = k \frac{\theta_2 - \theta_1}{l}$$

where  $k$  is a factor depending on the material.

To a fair approximation the factor  $k$  is a constant for a given material; that is to say, it is independent of  $\theta_2$ ,  $\theta_1$ , and  $l$ . It is called the *thermal conductivity* of the material concerned. To put its definition into words, we let  $\theta_2 - \theta_1$  be  $1^\circ\text{C}$ , and  $l$  be  $1\text{ m}$ , so that

$$Q = k.$$

We then say:

*Consider a cube of material, whose faces are 1 m apart, and have a temperature difference of 1 deg C. If heat flows in the steady state through the cube at right angles to its faces, and none is lost from its sides, then the heat flow per unit area is numerically equal to the conductivity of the material.*

This definition leads to a general equation for the flow of heat through any parallel-sided slab of the material, when no heat is lost from the sides of the slab. As in Fig. 13.2 (ii), we denote the cross-sectional area of the slab by  $A$ , its thickness by  $l$ , and the temperature of its faces by  $\theta_1$  and  $\theta_2$ . Then the heat  $Q$  flowing through it per second is

$$Q = \frac{kA(\theta_2 - \theta_1)}{l} \quad \dots \quad (1)$$

A useful form of this equation is

$$\frac{Q}{A} = k \frac{\theta_2 - \theta_1}{l} \quad \dots \quad (2)$$

or

heat flow per  $\text{m}^2$  per second = conductivity  $\times$  temperature gradient.

(2a)

In terms of the calculus, (2) may be re-written

$$\frac{1}{A} \frac{dQ}{dt} = -k \frac{d\theta}{dl} \quad \dots \quad (3)$$

the temperature gradient being negative since  $\theta$  diminishes as  $l$  increases.

### Units and Magnitude of Conductivity

Equation (2) enables us to find the unit of thermal conductivity. We have

$$k = \frac{Q/A (\text{J m}^{-2} \text{ s}^{-1})}{(\theta_2 - \theta_1)/l (\text{K m}^{-1})}$$

Thus the unit of thermal conductivity =  $\text{J s}^{-1} \text{ m}^{-1} \text{ K}^{-1}$ , or since  $\text{joule second}^{-1} = \text{watt (W)}$ , the unit of  $k$  is  $\text{W m}^{-1} \text{ K}^{-1}$ .

## THERMAL CONDUCTIVITIES

SOLIDS  
(Mean values, c. 0–100°C)

Substance	$k$ $\text{W m}^{-1}\text{K}^{-1}$	Substance	$k$	Substance	$k$
Ag	420	Asbestos	0.13	Ice	2.1
Al	210	Brick	0.13	Marble	3.0
Cu	380	Cardboard	0.21	(white)	
Fe pure	76	Cork	0.42	Mica	0.76
wrought	59	Cotton	0.22	Paraffin wax	0.25
Hg	8	Cotton wool	0.025	Silica (fused)	1.4
Ni	87	Ebonite	0.17	Rubber (para)	0.19
Pb	35	Felt	0.038	Sand	0.054
Pt	71	Flannel	0.097	Silk	0.092
Brass	109	Glass	1.1	Slate	2.0
Duralumin	130	(window)		Wood	c. 0.21
Steel	46	Graphite	130		

## LIQUIDS AND GASES

Liquid	$k$	Gas	$k$
Alcohol (25°C)	0.18	Air (0°C)	0.024
Glycerine (20°C)	0.29	(100°C)	0.032
Olive oil (0°C)	0.17	CO <sub>2</sub> (0°C)	0.015
Paraffin oil (0°C)	0.13	H <sub>2</sub> (0°C)	0.17
Water (10°C)	0.62	N <sub>2</sub> (0°C)	0.024
(80°C)	0.67	O <sub>2</sub> (0°C)	0.024

To a rough approximation we may say that the conductivities of metals are about 1000 times as great as those of other solids, and of liquids; and they are about 10000 times as great as those of gases.

**Effect of Thin Layer of Bad Conductor**

Fig. 13.3 shows a lagged copper bar AB, whose ends are pressed against metal tanks at 0° and 100°C, but are separated from them by layers of dirt. The length of the bar is 10 cm or 0.1 m, and the dirt layers are 0.1 mm or  $0.1 \times 10^{-3}$  m thick. Assuming that the conductivity of dirt is 1/1000 that of copper, let us find the temperature of each end of the bar.

Suppose  $k$  = conductivity of copper,

$A$  = cross-section of copper,

$\theta_2, \theta_1$  = temperature of hot and cold ends.

Since the bar is lagged, the heat flow per second  $Q$  is constant from end to end. Therefore,

$$Q = \frac{k}{1000} A \frac{100 - \theta_2}{0.1 \times 10^{-3}} = k A \frac{\theta_2 - \theta_1}{0.1} = \frac{k}{1000} A \frac{\theta_1 - 0}{0.1 \times 10^{-3}}$$

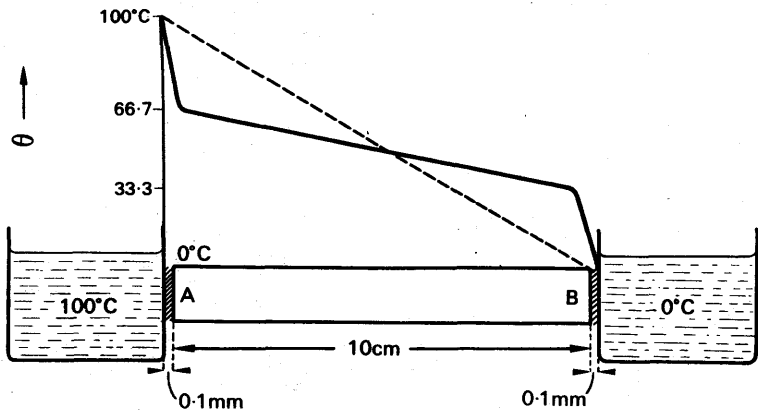


FIG. 13.3. Temperature gradients in good and bad conductors.

Dividing through  $k$ , these equations give

$$\frac{100 - \theta_2}{0.1} = \frac{\theta_2 - \theta_1}{0.1} = \frac{\theta_1}{0.1},$$

or

$$100 - \theta_2 = \theta_2 - \theta_1 = \theta_1,$$

whence

$$\theta_2 = 66.7^\circ\text{C},$$

$$\theta_1 = 33.3^\circ\text{C}.$$

Thus the total temperature drop,  $100^\circ\text{C}$ , is divided equally over the two thin layers of dirt and the long copper bar. The heavy lines in the figure show the temperature distribution; the broken line shows what it would be if there were no dirt.

### Good and Bad Conductors

The foregoing example shows what a great effect a thin layer of a bad conductor may have on thermal conditions;  $0.1$  mm of dirt causes as great a temperature fall as  $10$  cm of copper. We can generalize this result with the help of equation (2a):

$$\text{heat flow/m}^2 \text{ s} = \text{conductivity} \times \text{temperature gradient}.$$

The equation shows that, if the heat flow is uniform, the temperature gradient is inversely proportional to the conductivity. If the conductivity of dirt is  $1/1000$  that of copper, the temperature gradient in it is  $1000$  times that in copper; thus  $1$  mm of dirt sets up the same temperature fall as  $1$  m of copper. In general terms we express this result by saying that the dirt prevents a good thermal contact, or that it provides a bad one. The reader who has already studied electricity will see an obvious analogy here. The flow of heat can, in fact, be treated mathematically in the same way as the flow of electricity; we may say that a dirt layer has a high thermal resistance, and hence causes a great temperature drop.

Boiler plates are made of steel, not copper, although copper is about

eight times as good a conductor of heat. The material of the plates makes no noticeable difference to the heat flow from the furnace outside the boiler to the water inside it, because there is always a layer of gas between the flame and the boiler-plate. This layer may be very thin, but its conductivity is about  $1/10000$  that of steel; if the plate is a centimetre thick, and the gas-film  $1/1000$  centimetre, then the temperature drop across the film is ten times that across the plate. Thus the rate at which heat flows into the boiler is determined mainly by the gas.

If the water in the boiler deposits scale on the plates, the rate of heat flow is further reduced. For scale is a bad conductor, and, though it may not be as bad a conductor as gas, it can build up a much thicker layer. Scale must therefore be prevented from forming, if possible; and if not, it must from time to time be removed.

Badly conducting materials are often called *insulators*. The importance of building dwelling-places from insulating materials hardly needs to be pointed out. Window-glass is a ten-times better conductor than brick, and it is also much thinner; a room with large windows therefore requires more heating in winter than one whose walls are more modestly pierced. Wood is as bad a conductor (or as good an insulator) as brick, but it also is thinner. Wooden houses therefore have double walls, with an air-space between them; air is an excellent insulator, and the walls prevent convection. In polar climates, wooden huts must not be built with steel bolts going right through them; otherwise the inside ends of the bolts grow icicles from the moisture in the explorer's breath.

### Measurement of High Conductivity: Metals

When the thermal conductivity of a metal is to be measured, two conditions must usually be satisfied: heat must flow through the specimen at a measurable rate, and the temperature gradient along the specimen must be measurably steep. These conditions determine the form of the apparatus used.

When the conductor is a metal, it is easy to get a fast enough heat flow; the problem is to build up a temperature gradient. It is solved by

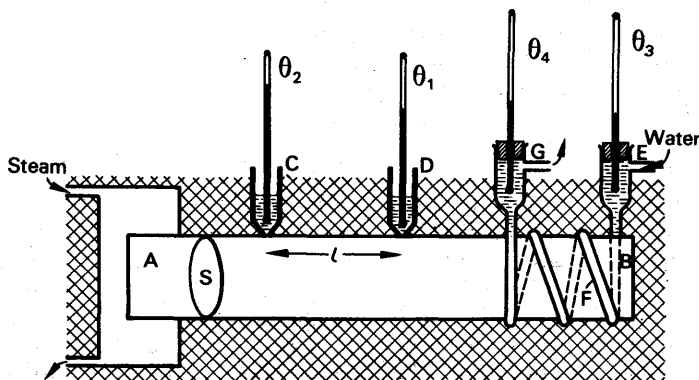


FIG. 13.4. Apparatus for thermal conductivity of a metal.

having as the specimen a bar long compared with its diameter. Fig. 13.4 shows the apparatus, which is due to Searle. AB is the specimen, about 4 cm diameter and 20 cm long. In one form of apparatus it is heated by steam at A, and cooled by circulating water at B. The whole apparatus is heavily lagged with felt. To measure the temperature gradient, thermometers are placed in the two mercury-filled cups C, D; the cups are made of copper, and are soldered to the specimen at a known distance apart. Alternatively, thermometers are placed in holes bored in the bar, which are filled with mercury. In this way errors due to bad thermal contact are avoided.

The cooling water flows in at E, round the copper coil F which is soldered to the specimen, and out at G. The water leaving at G is warmer than that coming in at E, so that the temperature falls continuously along the bar: if the water came in at G and out at E, it would tend to reverse the temperature gradient at the end of the bar, and might upset it as far back as D or C.

The whole apparatus is left running, with a steady flow of water, until all the temperatures have become constant: the temperature  $\theta_2$  and  $\theta_1$ , at C and D in the bar, and  $\theta_4$  and  $\theta_3$ , of the water leaving and entering. The steady rate of flow of the cooling water is measured with a measuring cylinder and a stop-clock.

If  $A$  is the cross-sectional area of the bar and  $k$  its conductivity, then the heat flow per second through a section such as S is

$$Q = kA \frac{\theta_2 - \theta_1}{l}.$$

This heat is carried away by the cooling water; if a mass  $m$  of specific heat capacity  $c_w$ , flows through F in 1 second, the heat carried away is  $mc_w(\theta_4 - \theta_3)$ .

Therefore

$$kA \frac{\theta_2 - \theta_1}{l} = mc_w(\theta_4 - \theta_3).$$

With this apparatus we can show that the conductivity  $k$  is a constant over small ranges of temperature. To do so we increase the flow of cooling water, and thus lower the outflow temperature  $\theta_4$ . The gradient in the bar then steepens, and  $(\theta_2 - \theta_1)$  increases. When the new steady state has been reached, the conductivity  $k$  is measured as before. Within the limits of experimental error, it is found to be unchanged.

### Measurement of Low Conductivity: Non-metallic Solids

In measuring the conductivity of a bad conductor, the difficulty is to get an adequate heat flow. The specimen is therefore made in the form of a thin disc, D, about 10 cm in diameter and a few millimetres thick (Fig. 13.5 (a)). It is heated by a steam-chest C, whose bottom is thick enough to contain a hole for a thermometer.

The specimen rests on a thick brass slab B, also containing a thermometer. The whole apparatus is hung in mid air by three strings attached to B.

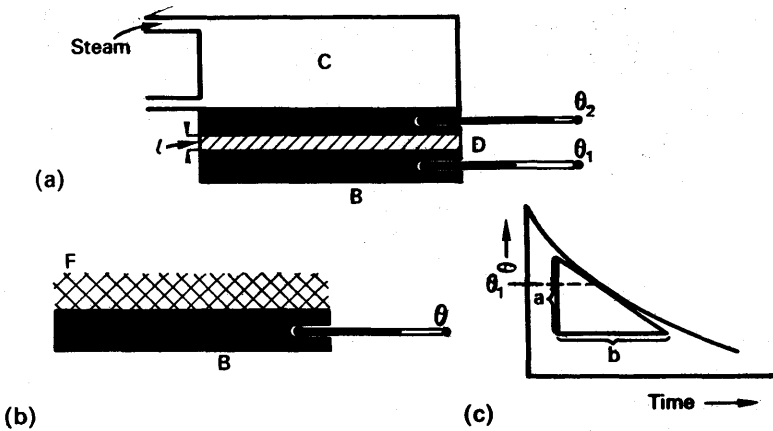


FIG. 13.5. Apparatus for thermal conductivity of a bad conductor.

To ensure good thermal contact, the adjoining faces of C, D and B must be flat and clean; those of C and B should be polished. A trace of vaseline smeared over each face improves the contact.

When the temperatures have become steady, the heat passing from C through D escapes from B by radiation and convection. Its rate of escape from B is roughly proportional to the excess temperature of B over the room (Newton's law). Thus B takes up a steady temperature  $\theta_1$  such that its rate of loss of heat to the outside is just equal to its gain through D. The rate of loss of heat from the sides of D is negligible, because their surface area is small.

This apparatus is derived from one due to Lees, and simplified for elementary work. If we use glass or ebonite for the specimen, the temperature  $\theta_1$  is generally about  $70^\circ\text{C}$ ;  $\theta_2$  is, of course, about  $100^\circ\text{C}$ . After these temperatures have become steady, and we have measured them, the problem is to find the rate of heat loss from B. To do this, we take away the specimen D and heat B directly from C until its temperature has risen by about  $10^\circ\text{C}$ . We then remove C, and cover the top part of B with a thick layer of felt F (Fig. 13.5 (b)). At intervals of a minute—or less—we measure the temperature of B, and afterwards plot it against the time (Fig. 13.5 (c)).

While the slab B is cooling it is losing heat by radiation and convection. It is doing so under the same conditions as in the first part of the experiment, because the felt prevents heat escaping from the top surface. Thus when the slab B passes through the temperature  $\theta_1$ , it is losing heat at the same rate as in the first part of the experiment. The heat which it loses is now drawn from its own heat content, whereas before it was supplied from C via D; that is why the temperature of B is now falling, whereas before it was steady. The rate at which B loses heat at the temperature  $\theta_1$  is given by:

$$\text{heat lost/second} = Mc \times \text{temperature fall/second},$$

where  $M$ ,  $c$  are respectively the mass and specific heat capacity of the slab.



To find the rate of fall of temperature at  $\theta_1$ , we draw the tangent to the cooling curve at that point. If, as shown in Fig. 13.5 (c), its gradient at  $\theta_1$  would give a fall of  $a$  deg C in  $b$  seconds, then the rate of temperature fall is  $a/b$  deg C per second.

We then have, if  $A$  is the cross-sectional area of the specimen,  $l$  its thickness, and  $k$  its conductivity,

$$kA \frac{\theta_2 - \theta_1}{l} = Mc \frac{a}{b}.$$

Thus  $k$  can be calculated.

### Liquids

In finding the conductivity of a liquid, the liquid must be heated at the top and cooled at the bottom, to prevent convection. Lees' apparatus is therefore suitable. The liquid is held in a narrow glass ring, R, Fig. 13.6, sandwiched between the plates (not shown) of the Lees' disc apparatus. Let  $k_g$ ,  $k_l$  be the conductivities of the glass and liquid

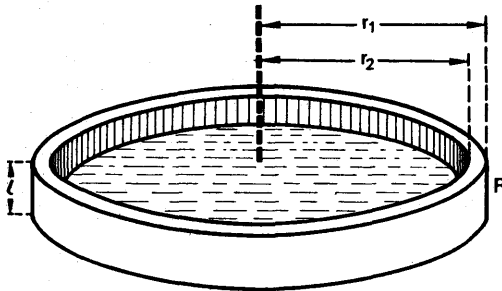


Fig. 13.6. Apparatus for finding thermal conductivity of a liquid.

respectively, and  $r_2$  and  $r_1$  the inner and outer radii of the ring. Then the downward heat flow per second is

$$Q = k_g \pi (r_1^2 - r_2^2) \frac{\theta_2 - \theta_1}{l} + k_l \pi r_2^2 \frac{\theta_2 - \theta_1}{l},$$

where  $\theta_2$  and  $\theta_1$  are the temperatures above and below the specimen and  $l$  is its thickness. The conductivity  $k_g$  need not be known; the heat flow through the ring may be determined in a preliminary experiment with the ring, but without the liquid.

### Conduction through a Tube

The conductivity of glass tubing may be measured in the laboratory with the apparatus shown in Fig. 13.7 (a). The glass tube AB is surrounded by a steam jacket J, and water flows through it from A to B at a measured rate of  $m$  g/second. Thermometers measure the inflow and outflow temperatures of the water,  $\theta_2$  and  $\theta_3$ , which eventually become steady. In the steady state, the heat flowing through the walls of the tubing is equal to the heat carried away by the water,  $mc_w(\theta_2 - \theta_3)$  joule/second.

To find the conductivity, we must know the area through which the heat flows. If  $r_1, r_2,$  are the inner and outer radii of the tube, and  $L$  is its length, then the areas of the inner and outer walls are  $2\pi r_1 L$  and  $2\pi r_2 L$  respectively (Fig. 13.7 (b)). If the tube is thin, we may take the area as constant and equal to its average value.

Thus 
$$A = 2\pi L \frac{r_1 + r_2}{2}.$$

At the entrance of the tube, the temperature gradient is  $(\theta_1 - \theta_2)/(r_2 - r_1)$ , where  $\theta_1$  is the temperature of the steam; at the exit end the gradient is  $(\theta_1 - \theta_3)/(r_2 - r_1)$ .

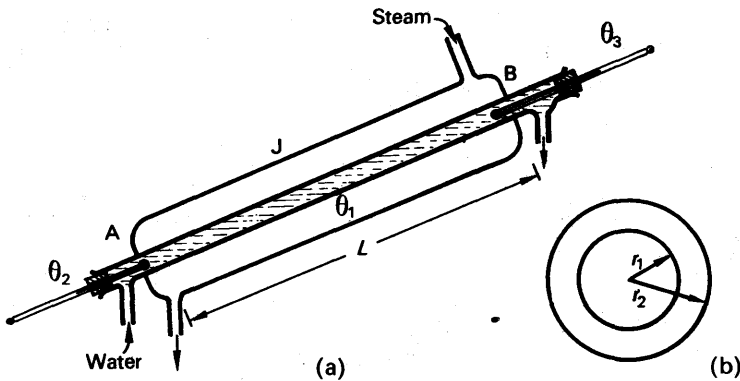


FIG. 13.7. Apparatus to measure conductivity of glass in form of tubing.

If  $\theta_3$  and  $\theta_2$  differ by not more than about  $10^\circ\text{C}$ , we may take the gradient as constant and equal to its average value:

$$\begin{aligned} \text{temperature-gradient} &= \frac{1}{2} \left( \frac{\theta_1 - \theta_2}{r_2 - r_1} + \frac{\theta_1 - \theta_3}{r_2 - r_1} \right) \\ &= \frac{\theta_1 - \frac{\theta_2 + \theta_3}{2}}{r_2 - r_1} \end{aligned}$$

The conductivity  $k$  therefore is given by

$$k \times 2\pi L \frac{r_1 + r_2}{2} \times \frac{\theta_1 - \frac{\theta_2 + \theta_3}{2}}{r_2 - r_1} = mc_w(\theta_3 - \theta_2) \quad (4)$$

The conductivity of *rubber tubing* can be found by a modification of this method. A measured length of the tubing is submerged in a calorimeter of water, and steam passed through for a measured time  $t$ . The rise in temperature of the water must be corrected for cooling, as in the measurement of the specific heat of a bad conductor (p. 203). The heat flow through the rubber is given by the left-hand side of equation (4) with  $\theta_2$  and  $\theta_3$  standing for the initial and final temperature of the

water. If  $m$  is the mass of water, and  $C$  the heat capacity of the calorimeter, the right-hand side of the equation is

$$(mc_w + C)(\theta_3 - \theta_2)/t.$$

### Comparison of Conductivities

Fig. 13.8 (a) shows an apparatus due to Ingenhousz for comparing the conductivities of solids. Metal, wood, glass, and other rods, of equal lengths and cross-sections, are stuck into a tank through corks. The rods are painted with the same paint, and coated with wax over

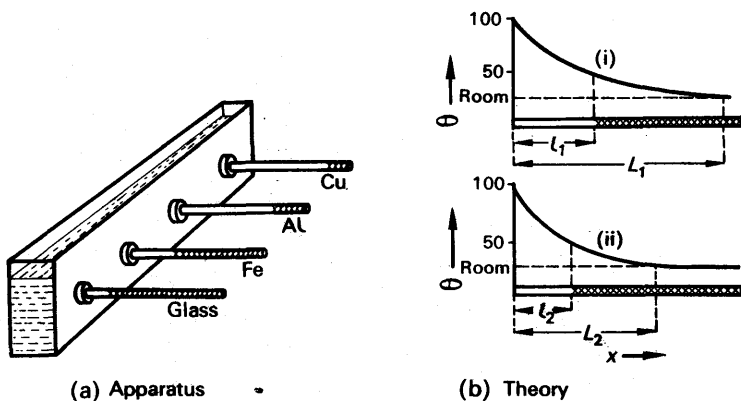


FIG. 13.8. Comparison of conductivities.

their whole projecting lengths. The tank is filled with water, leaks are stopped as well as possible, and the water is boiled. As the rods warm up, the wax melts off them. Eventually a steady state is reached, and the best conductor is the one from which wax has melted off the greatest length.

If the experiment is to give a quantitative comparison of the conductivities, the rods must be so long that the far end of each of them is at room temperature. Otherwise the following argument will not be true.

At the points where melted wax gives way to solid, each bar is at the melting-point of wax—let us call it  $50^\circ\text{C}$ . The temperature distributions along any two bars are therefore as shown in Fig. 13.8 (b); they have similar shapes, but at a given distance from the tank, (ii) is steeper than (i). If  $l_1$  is the distance along (i) to the  $50^\circ\text{C}$  point, and  $l_2$  the corresponding distance along (ii), then the curve (ii) is the same as curve (i) except that it is horizontally contracted in the ratio  $l_2/l_1$ . Therefore the gradient of (ii), at any distance  $x$ , is steeper than that of (i) in the ratio  $l_1/l_2$ . The temperature gradient at the tank end of each rod determines the rate at which heat flows into it from the hot water.

Now

$$Q \propto k \times \text{temp. grad. at hot end,}$$

where  $k$  is the conductivity of the rod. Therefore, for rods (i) and (ii)

$$\begin{aligned} \frac{Q_1}{Q_2} &= \frac{k_1}{k_2} \times \frac{\text{temp. grad. at end of (i)}}{\text{temp. grad. at end of (ii)}} \\ &= \frac{k_1}{k_2} \times \frac{l_2}{l_1} \end{aligned} \quad (5)$$

The heat passing into a rod at the hot end escapes by convection from its sides. The lengths  $l_1$  and  $l_2$  respectively, of rods (i) and (ii), have the same average temperatures;  $75^\circ\text{C}$ . Over the lengths  $l_1$  and  $l_2$ , therefore, each rod loses heat at the same rate per unit area, since each has the same surface (p. 203). The heat lost from either rod per second, *between the  $100^\circ\text{C}$  and the  $50^\circ\text{C}$  points*, is therefore proportional to the area of the rod between those points. It is therefore proportional to the distance  $l$  between them.

Since the temperature curves differ only in scale, the distance to the  $50^\circ\text{C}$  point on either rod is proportional to the distance  $L$  to the point where the rod reaches room temperature (Fig. 13.8 (b)). Beyond this point, the bar loses no heat. Therefore, by the above argument, the distance  $L$  is proportional to the *total* heat lost per second by the bar. The distance  $L$  is therefore proportional to the total heat per second lost by the bar, and this heat is the heat  $Q$  entering the bar at the hot end.

Therefore  $Q \propto L \propto l$

$$\text{or } \frac{Q_1}{Q_2} = \frac{L_1}{L_2} = \frac{l_1}{l_2}$$

$$\text{But we have seen that } \frac{Q_1}{Q_2} = \frac{k_1 l_2}{k_2 l_1} \quad (5)$$

$$\text{Therefore } \frac{k_1 l_2}{k_2 l_1} = \frac{l_1}{l_2}$$

$$\text{or } \frac{k_1}{k_2} = \frac{l_1^2}{l_2^2}$$

Thus the conductivity of a given rod is proportional to the square of the distance along it to the melting-point of the wax.

### The Cracking of Glass

Glass is a bad conductor of heat. Therefore, when a piece of glass is heated in one place, the neighbouring parts of the glass do not at first warm up with it. Consequently they resist the expansion of the heated part, and the force set up cracks the glass (p. 262). To avoid cracking the glass, care must be taken to warm the whole region around the place to be made hot. Similarly, glass which has been heated must be made to cool slowly and uniformly by playing the flame over it now and then, for shorter and shorter times as it cools.

### EXAMPLES

1. Calculate the quantity of heat conducted through  $2 \text{ m}^2$  of a brick wall 12 cm thick in 1 hour if the temperature on one side is  $8^\circ\text{C}$  and on the other side is  $28^\circ\text{C}$ . (Thermal conductivity of brick =  $0.13 \text{ W m}^{-1} \text{ K}^{-1}$ .)

$$\text{Temperature gradient} = \frac{28-8}{12 \times 10^{-2}} \text{ }^\circ\text{C m}^{-1}$$

Since 1 hour = 3600 seconds,

$$\begin{aligned} \therefore Q &= kAt \times \text{temperature gradient} \\ &= 0.13 \times 2 \times 3600 \times \frac{28-8}{12 \times 10^{-2}} \text{ joules} \\ &= 156\,000 \text{ J.} \end{aligned}$$

2. Define *thermal conductivity*. Describe and give the theory of a method of measuring the thermal conductivity of copper.

A sheet of rubber and a sheet of cardboard, each 2 mm thick, are pressed together and their outer faces are maintained respectively at 0°C and 25°C. If the thermal conductivities of rubber and cardboard are respectively 0.13 and 0.05 W m<sup>-1</sup> K<sup>-1</sup>, find the quantity of heat which flows in 1 hour across a piece of the composite sheet of area 100 cm<sup>2</sup>. (L.)

*First part.* The thermal conductivity of a substance is the quantity of heat per second flowing in the steady state through opposite faces of a unit cube of the material when a temperature difference of 1 degree is maintained across these faces. The thermal conductivity of copper can be measured by Searle's method (p. 335).

*Second part.* We must first find the temperature,  $\theta^\circ\text{C}$ , of the junction of the rubber and cardboard. The temperature gradient across the rubber =  $(\theta - 0)/2 \times 10^{-3}$ ; the temperature gradient across the cardboard =  $(25 - \theta)/2 \times 10^{-3}$ .

$$\therefore Q \text{ per second per m}^2 \text{ across rubber} = 0.13 \times (\theta - 0)/2 \times 10^{-3}$$

$$\text{and } Q \text{ per second per m}^2 \text{ across cardboard} = 0.05 \times (25 - \theta)/2 \times 10^{-3}.$$

But in the steady state the quantities of heat above are the same.

$$\therefore \frac{0.13(\theta - 0)}{2 \times 10^{-3}} = \frac{0.05(25 - \theta)}{2 \times 10^{-3}}$$

$$\therefore 13\theta = 125 - 5\theta$$

$$\therefore \theta = \frac{125}{18} = 7^\circ\text{C}.$$

Now area = 100 cm<sup>2</sup> = 100 × 10<sup>-4</sup> m<sup>2</sup>.

$\therefore Q$  through area in 1 hour (3600 seconds)

$$= \frac{0.13 \times 100 \times 10^{-4} \times 7 \times 3600}{2 \times 10^{-3}}$$

$$= 16380 \text{ J}.$$

3. Define *thermal conductivity* and explain how you would measure its value for a poorly conducting solid.

In order to minimise heat losses from a glass container, the walls of the container are made of two sheets of glass, each 2 mm thick, placed 3 mm apart, the intervening space being filled with a poorly conducting solid. Calculate the ratio of the rate of conduction of heat per unit area through this composite wall to that which would have occurred had a single sheet of the same glass been used under the same internal and external temperature conditions. (Assume that the thermal conductivity of glass and the poorly conducting solid = 0.63 and 0.049 W m<sup>-1</sup> K<sup>-1</sup> respectively. (L.)

*First part.*

*Second part.* Let  $\theta_1, \theta_4$  be the respective temperatures of the outer faces of the two glass sheets, and  $\theta_2, \theta_3$  their respective junction temperatures with the solid between them. The thickness of glass =  $2 \times 10^{-3}$  m, that of the solid =  $0.3 \times 10^{-2}$  m. In the steady state, the quantity of heat per second per metre<sup>2</sup> is the same for each. Call this  $Q_1$ . Then, for the first glass, since  $Q_1 = k \times$  temperature gradient,

$$Q_1 = 0.63 \times \frac{\theta_1 - \theta_2}{2 \times 10^{-3}}$$

$$\therefore \theta_1 - \theta_2 = Q_1 \times \frac{2 \times 10^{-3}}{0.63} = \frac{2}{630} Q_1 \quad \dots \quad (i)$$

Similarly, for the solid,

$$\theta_2 - \theta_3 = Q_1 \times \frac{3 \times 10^{-3}}{0.049} = \frac{3}{49} Q_1 \quad \dots \dots \dots \text{(ii)}$$

For the second glass,

$$\theta_3 - \theta_4 = Q_1 \times \frac{2 \times 10^{-3}}{0.63} = \frac{2}{630} Q_1 \quad \dots \dots \dots \text{(iii)}$$

Adding (i), (ii), (iii) to eliminate  $\theta_2$  and  $\theta_3$ ,

$$\therefore \theta_1 - \theta_4 = Q_1 \left( \frac{4}{630} + \frac{3}{49} \right) \quad \dots \dots \dots \text{(1)}$$

For a single sheet of glass and the same internal and external temperatures  $\theta_1$  and  $\theta_4$  respectively, the quantity of heat per second per metre<sup>2</sup>,  $Q_2$  say, is given, from (i), by

$$\theta_1 - \theta_4 = Q_2 \times \frac{2}{630} \quad \dots \dots \dots \text{(2)}$$

Hence, from (1),  $Q_1 \left( \frac{4}{630} + \frac{3}{49} \right) = Q_2 \times \frac{2}{630}$

Simplifying,  $\therefore \frac{Q_1}{Q_2} = \frac{14}{298} = 0.05$  (approx.).

**RADIATION**

**Radiation**

All heat comes to us, directly or indirectly, from the sun. The heat which comes directly travels through 150 million km of space, mostly empty, and travels in straight lines, as does the light: the shade of a tree coincides with its shadow. Both heat and light travel with the same speed because they are cut off at the same instant in an eclipse. Since light is propagated by waves of some kind we conclude that the heat from the sun is propagated by similar waves, and we say it is 'radiated'.

As we show later, radiation is more copious from a dull black body than from a transparent or polished one. Black bodies are also better absorbers of radiation than polished or transparent ones, which either allow radiation to pass through themselves, or reflect it away from themselves. If we hold a piece of white card, with a patch of black drawing ink on it, in front of the fire, the black patch soon comes to feel warmer than its white surround.

**Reflection and Refraction**

If, with either a convex lens or a concave mirror, we focus the sun's light on our skin, we feel heat at the focal spot. The heat from the sun has therefore been reflected or refracted in the same way as the light.

If we wish to show the reflection of heat unaccompanied by light, we may use two searchlight mirrors, set up as in Fig. 13.9. At the focus of

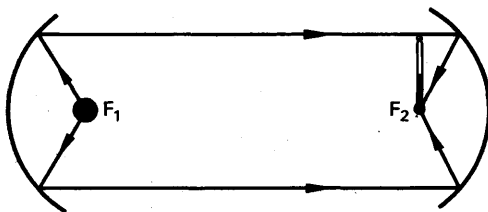


FIG. 13.9. Reflection of radiant heat.

one,  $F_1$ , we put an iron ball heated to just below redness. At the focus of the other,  $F_2$ , we put the bulb of a thermometer, which has been blackened with soot to make it a good absorber (p. 349). The mercury rises in the stem of the thermometer. If we move either the bulb or the ball away from the focus, the mercury falls back; the bulb has therefore been receiving heat from the ball, by reflection at the two mirrors. We can show that the foci of the mirrors are the same for heat as for light if we replace the ball and thermometer by a lamp and screen. (In practice we do this first, to save time in finding the foci for the main experiment.)

To show the refraction of heat apart from the refraction of light is more difficult. It was first done by the astronomer Herschel in 1800. Herschel passed a beam of sunlight through a prism, as shown diagrammatically in Fig. 13.10, and explored the spectrum with a sensitive

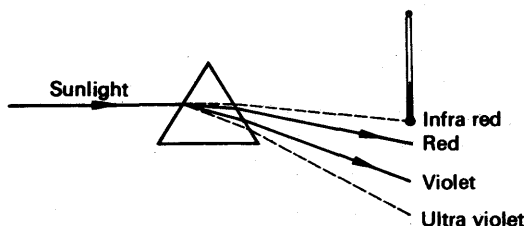


FIG. 13.10. Infra-red and ultra-violet (diagrammatic).

thermometer, whose bulb he had blackened. He found that in the visible part of the spectrum the mercury rose, showing that the light energy which it absorbed was converted into heat. But the mercury also rose when he carried the bulb into the darkened portion a little beyond the red of the visible spectrum; the sun's rays therefore carried energy which was not light.

### Ultra-violet and Infra-red

The radiant energy which Herschel found beyond the red is now called *infra-red* radiation, because it is less refracted than the red. Radiant energy is also found beyond the violet and it is called *ultra-violet* radiation, because it is refracted more than the violet.

Ultra-violet radiation is absorbed by the human skin and causes sun-burn; more importantly, it stimulates the formation of vitamin D, which is necessary for the assimilation of calcium and the prevention of rickets. It is also absorbed by green plants; in them it enables water to combine with carbon dioxide to form carbohydrates. This process is called photo-synthesis; we have already, on p. 196, discussed its importance to animals and man. Ultra-violet radiation causes the emission of electrons from metals, as in photo-electric cells; and it excites a latent image on a photographic emulsion. It is harmful to the eyes.

Ultra-violet radiation is strongly absorbed by glass—spectacle-wearers do not sunburn round the eyes—but enough of it gets through

to affect a photographic film. It is transmitted with little absorption by quartz.

Infra-red radiation is transmitted by quartz, and rock-salt, but most of it is absorbed by glass. A little, that which lies near the visible red, passes fairly easily through glass—if it did not, Herschel would not have discovered it. When infra-red radiation falls on the skin, it gives the sensation of warmth. It is what we usually have in mind when we speak of heat radiation, and it is the main component of the radiation from a hot body; but it is in no essential way different from the other components, visible and ultra-violet radiation, as we shall now see.

### Wavelengths of Radiation

In books on Optics, it is shown how the wavelength of light can be measured with a diffraction grating—a series of fine close lines ruled on glass. The wavelength ranges from  $4000 \times 10^{-10}$  m for the violet, to  $7500 \times 10^{-10}$  m for the red. The first accurate measurements of wavelength were published in 1868 by Angstrom, and in his honour a distance of  $10^{-10}$  m is called an *Angstrom unit* (A.U.). The wavelengths of infra-red radiation can be measured with a grating made from fine wires stretched between two screws of close pitch. They range from 7500 A.U. to about 1 000 000 A.U. Often they are expressed in a longer unit than the Angstrom: this unit is the micron ( $\mu\text{m}$ ), which is 1/1000 mm. Thus

$$1\mu\text{m} = 10^{-6} \text{ m} = 10^4 \text{ A.U.}$$

We denote wavelength by the symbol  $\lambda$ ; its value for visible light ranges from  $0.4 \mu\text{m}$  to  $0.75 \mu\text{m}$ , and for infra-red radiation from  $0.75 \mu\text{m}$  to about  $100 \mu\text{m}$ .

We now consider that X-rays and radio waves also have the same nature as light, and that so do the  $\gamma$ -rays from radio-active substances.

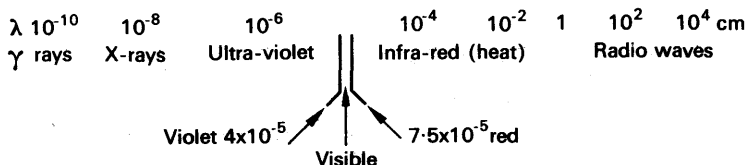


FIG. 13.11. The electromagnetic spectrum.

For reasons which we cannot here discuss, we consider all these waves to be due to oscillating electric and magnetic fields. Fig. 13.11 shows the range of their wavelengths: it is called a diagram of the *electromagnetic spectrum*.

### Detection of Heat Radiation

A thermometer with a blackened bulb is a sluggish and insensitive detector of radiant heat. More satisfactory detectors, however, are





FIG. 13.12. Bolometer strip.

less direct; they are of two main kinds, both electrical. One kind consists of a long thin strip of blackened platinum foil, arranged in a compact zigzag (Fig. 13.12). On this the radiation falls. The foil is connected in a Wheatstone bridge, to measure its electrical resistance. When the strip is heated by the radiation, its resistance increases, and the increase is measured on the bridge. The instrument

was devised by Langley in 1881; it is called a bolometer, *bole* being Greek for a ray.

The other, commoner, type of radiation detector is called a thermopile (Nobili and Melloni, c. 1830). Its action depends on the electromotive force, which appears between the junctions of two different

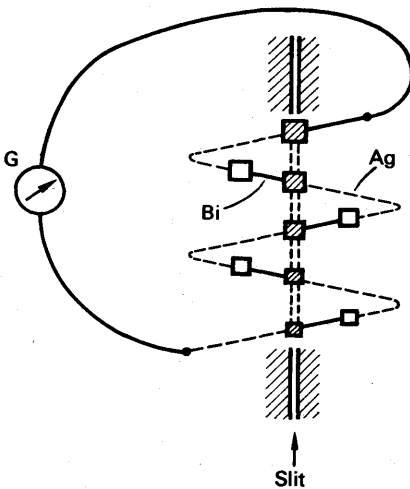


FIG. 13.13. Thermopile.

metals, when one junction is hot and the other cold. The modern thermopile is due to Coblentz (1913). It consists of many junctions between fine wires, as shown diagrammatically in Fig. 13.13; the wires are of silver and bismuth, 0.1 mm or less in diameter. Their junctions are attached to thin discs of tin, about 0.2 mm thick, and about 1 mm square. One set of discs is blackened and mounted behind a slit, through which radiation can fall on them; the junctions attached to them become the hot junctions of the thermopile. The other, cold, junctions are shielded from the radiation to

be measured; the discs attached to them help to keep them cool, by increasing their surface area.

Older types of thermopile are made from bars of metal about a millimetre thick. They are slow to warm up when radiation falls upon them, but are more rugged than the modern type.

When radiation falls on the blackened discs of a thermopile, it warms the junctions attached to them, and sets up an e.m.f. This e.m.f. can be measured with a potentiometer, or, for less accurate work, it can be used to deflect a galvanometer, G, connected directly to the ends of the thermopile (Fig. 13.13).

### Reflection and Refraction observed with Thermopile: Inverse Square Law

With a thermopile and galvanometer, we can repeat Herschel's experiment more strikingly than with a thermometer. And with the

simple apparatus of Fig. 13.13 we can show that, when heat is reflected, the angle of reflection is equal to the angle of incidence. We can also show the first law of reflection; that the incident and reflected rays are in the same plane as the normal to the reflector at the point of incidence.

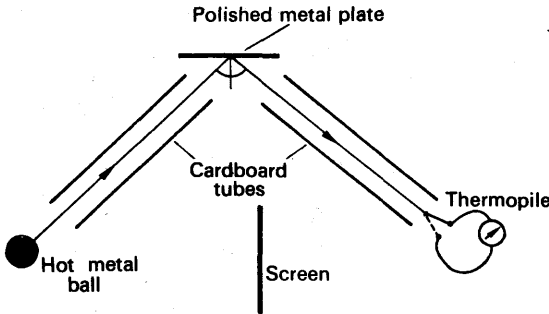


FIG. 13.14. Demonstration of reflection.

If heat is radiant energy, its intensity should fall off as the inverse square of the distance from a point source. We can check that it does so by setting up an electric lamp, with a compact filament, in a dark room preferably with black walls. When we put a thermopile at different distances from the lamp, the deflection of the galvanometer is found to be inversely proportional to the square of the distance.

If we wish to do this experiment with radiation that includes no visible light, we must modify it. Instead of the lamp, we use a large blackened tank of boiling water, A, and we fit the thermopile, B, with a conical mouthpiece, blackened on the inside. The blackening prevents any radiation from reaching the pile by reflection at the walls of the mouthpiece. We now find that the deflection of the galvanometer, G, does not vary with the distance of the pile from the tank, *provided that the tank occupies the whole field of view of the cone* (Fig. 13.15). The area  $S$  of the tank from which radiation can reach the thermopile is then proportional to the square of the distance  $d$ . And since the deflection is unchanged when the distance is altered, the total radiation from each element of  $S$  must therefore fall off as the inverse square of the distance  $d$ .

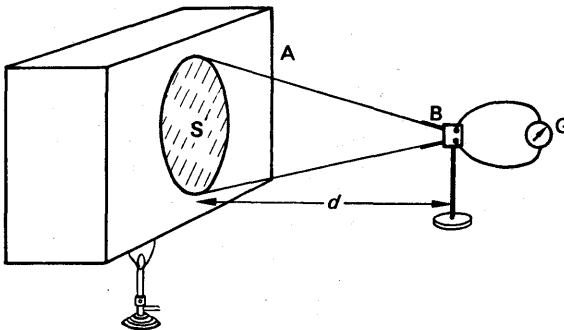


FIG. 13.15. Proof of inverse square law.

### The Infra-red Spectrometer

Infra-red spectra are important in the study of molecular structure. They are observed with an infra-red spectrometer, whose principle is shown in Fig. 13.16. Since glass is opaque to the infra-red, the radiation is focused by concave mirrors instead of lenses; the mirrors are plated with copper or gold on their front surfaces. The source of light is a Nernst filament, a metal filament coated with alkaline-earth oxides, and heated electrically. The radiation from such a filament is rich in infra-red. A carbon arc, or a gas-mantle, may be used, however.

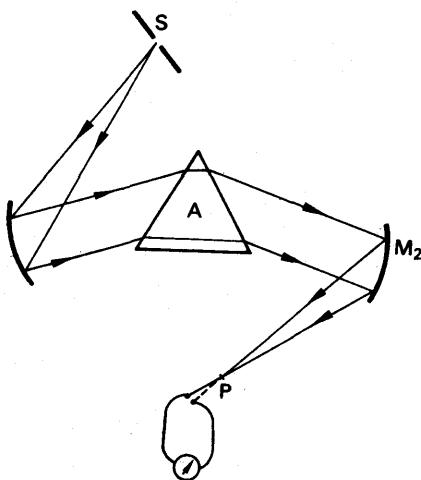


FIG. 13.16. Infra-red spectrometer.

The slit S of the spectrometer is at the focus of one mirror which acts as a collimator. After passing through the rock-salt prism, A, the radiation is focused on to the thermopile P by the mirror  $M_2$ , which re-

places the telescope of an optical spectrometer. Rotating the prism brings different wavelengths on to the slit; the position of the prism is calibrated in wavelengths with the help of a grating.

To a fair approximation, the deflection of the galvanometer is proportional to the radiant power carried in the narrow band of wavelengths which fall on the thermopile. If an absorbing body, such as a solution of an organic compound, is placed between the source and the slit, it weakens the radiation passing through the spectrometer, in the wavelengths which it absorbs. These wavelengths are therefore shown by a fall in the galvanometer deflection.

### Reflection, Transmission, Absorption

Measurements whose description is outside our scope give the amount of radiant energy approaching the earth from the sun. At the upper limit of our atmosphere, it is about  $8.0 \text{ J cm}^{-2} \text{ min}^{-1}$ .

At the surface of the earth it is always less than this because of absorption in the atmosphere. Even on a cloudless day it is less, because the ozone in the upper atmosphere absorbs much of the ultra-violet.

In Fig. 13.17, XY represents a body on which radiant energy is falling. The symbol  $I$  denotes the latter's intensity: to fix our ideas we may take

$$\begin{aligned} I &= 4.0 \text{ joule per cm}^2 \text{ per minute} \\ &= \frac{4.0}{60} \text{ joule per cm}^2 \text{ per second} \\ &= 0.067 \text{ watt per cm}^2. \end{aligned}$$

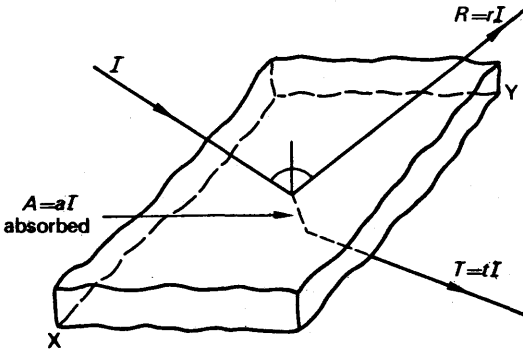


FIG. 13.17. Reflection, transmission, and absorption.

Some of this energy is reflected by the glass ( $R$ ), some is absorbed ( $A$ ), and some is transmitted ( $T$ ). The total energy transmitted, absorbed and reflected per  $\text{cm}^2$  per second is equal to the energy falling on the body over the same area and in the same time:

$$T + A + R = I.$$

If we denote by  $t$ ,  $a$ , and  $r$ , the fractions of energy which are respectively transmitted, absorbed, and reflected by the body, then

$$tI + aI + rI = I$$

or 
$$t + a + r = 1 \quad (6)$$

This equation expresses common knowledge: if a body is transparent ( $t \rightarrow 1$ ), it is not opaque, and it is not a good reflector ( $a \rightarrow 0, r \rightarrow 0$ ). But also, if the body is a good absorber of radiation ( $a \rightarrow 1$ ), it is not transparent, and its surface is dull ( $t \rightarrow 0, r \rightarrow 0$ ). And if it is a good reflector ( $r \rightarrow 1$ ), it is neither transparent nor a good absorber ( $t \rightarrow 0, a \rightarrow 0$ ). The term opaque, as commonly used, simply means not transparent; we see that it does not necessarily mean absorbent.

Equation (6), as we have written it above, is over-simplified. For a body may transmit some wavelengths (colours, if visible) and absorb or reflect others. If we now let  $I$  denote the intensity of radiation of a particular wavelength  $\lambda$ , then by repeating the argument we get

$$t_\lambda + a_\lambda + r_\lambda = 1 \quad (7)$$

where the coefficients  $t_\lambda$ , etc., all refer to the wavelength  $\lambda$ .

The truth of equation (7) is well shown by the metal gold, which reflects yellow light better than other colours. In thin films, gold is partly transparent, and the light which it transmits is green. Green is the colour complementary to yellow; gold removes the yellow from white light by reflection, and passes on the rest by transmission.

**Radiation and Absorption**

We have already pointed out that black surfaces are good absorbers and radiators of heat, and that polished surfaces are bad absorbers and radiators. This can be demonstrated by the apparatus in Fig. 13.18, in which is a cubical metal tank whose sides have a variety of finishes: dull black, dull white, highly polished. It contains boiling water, and, therefore, has a constant temperature. Facing it is a thermopile, P,

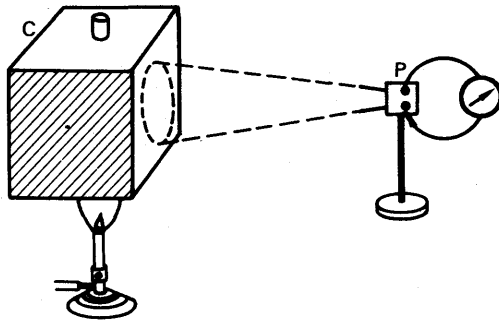


FIG. 13.18. Comparing radiators.

which is fitted with the blackened conical mouth-piece described on p. 347.

Provided that the face of the cube occupies the whole field of view of the cone, its distance from the thermopile does not matter (p. 347). The galvanometer deflection is greatest when the thermopile is facing the dull black surface of the cube, and least when it is facing the highly polished surface. The highly polished surface is therefore the worst radiator of all, and the dull black is the best.

This experiment was first done by Leslie in 1804. There were no thermopiles in those days, and Leslie detected the radiant heat with an instrument depending on the expansion of air, which we shall not describe. The tank with different surfaces is called *Leslie's cube*.

Leslie's cube can also be used in an experiment to compare the absorbing properties of surfaces, due to Ritchie (1833). A modern version of it is shown in Fig. 13.19. The cube C, full of boiling water, is

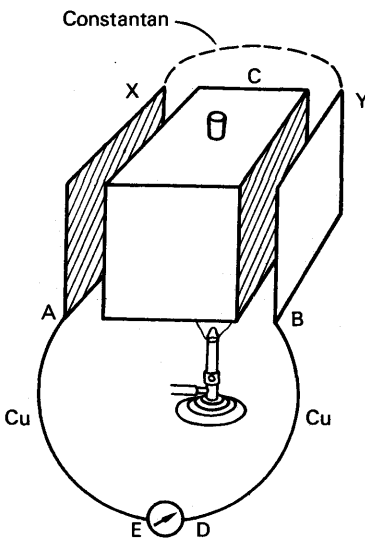


FIG. 13.19. Comparing absorbers.

placed between two copper plates, A, B, of which A is blackened and B is polished. The temperature difference between A and B is measured by making each of them one element in a thermo junction: they are joined by a constantan wire, XY, and connected to a galvanometer, by copper wires, AE, DB. If A is hotter than B, the junction, X, is hotter than the junction, Y, and a current flows through the galvanometer in one direction. If B is hotter than A, the current is reversed.

The most suitable type of Leslie's cube is one which has two opposite faces similar—say grey—and the other two opposite faces very dissimilar—one black, one polished. At first the plates A, B are set

opposite similar faces. The blackened plate, A, then becomes the hotter, showing that it is the better absorber.

The cube is now turned so that the blackened plate, A, is opposite the polished face of the cube, while the polished plate, B, is opposite the blackened face of the cube. The galvanometer then shows no deflection; the plates thus reach the same temperature. It follows that the good radiating property of the blackened face of the cube, and the bad absorbing property of the polished plate, are just compensated by the good absorbing property of the blackened plate, and the bad radiating property of the polished face of the cube.

### The Thermos Flask

A thermos flask—sometimes called a *Dewar flask* after its inventor (c. 1894)—is a device for reducing the transfer of heat to a minimum.

It consists of a double walled glass vessel, as shown in Fig. 13.20; the space between the walls is exhausted to as high a vacuum as possible, and the insides of the walls are silvered. Silvered surfaces are good reflectors, but bad absorbers and radiators. Heat therefore passes very slowly from the outer wall to the inner by radiation. If the vacuum is good, convection is almost inhibited—the goodness of the vacuum determines the goodness of the flask. Conduction through the glass is slight, because the conduction paths are long. In a good flask, the main cause of heat loss is conduction through the cork.

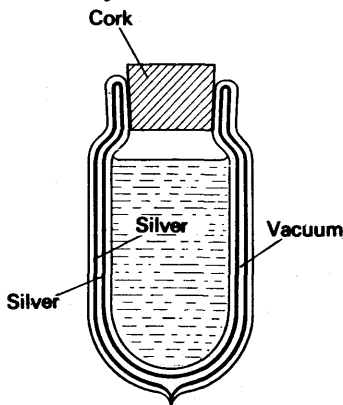


FIG. 13.20. A thermos flask.

### The Black Body

The experiments described before lead us to the idea of a perfectly black body; one which absorbs all the radiation that falls upon it, and reflects and transmits none. The experiments also lead us to suppose that such a body would be the best possible radiator.

A perfectly black body can be very nearly realized—a good one can be made in half a minute, simply by punching a small hole in the lid of an empty tin. The hole looks almost black, although the shining tin is a good reflector. The hole looks black because the light which enters through it is reflected many times round the walls of the tin, before it meets the hole again (Fig. 13.21). At each reflection, about 80 per cent of the light energy is reflected, and 20 per cent is absorbed. After two reflections, 64 per cent of the

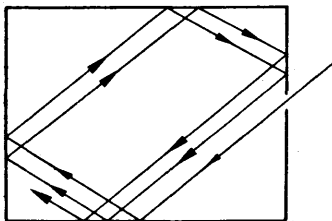


FIG. 13.21. Multiple reflections make a black body.

original light goes on to be reflected a third time; 36 per cent has been absorbed. After ten reflections, the fraction of the original energy which has been absorbed is  $0.8^{10}$ , or 0.1.

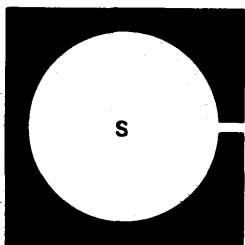


FIG. 13.22. A black body.

Any space which is almost wholly enclosed approximates to a black body. And, since a good absorber is also a good radiator, an almost closed space is the best radiator we can find.

A form of black-body which is used in radiation measurements is shown in Fig. 13.22. It consists of a porcelain sphere, S, with a small hole in it. The inside is blackened with soot to make it as good a radiator and as bad a reflector as possible. (The effect of multiple reflections is then to convert the body from nearly black to very nearly black indeed.)

The sphere is surrounded by a high-temperature bath of, for example, molten salt (the melting-point of common salt is  $801^{\circ}\text{C}$ ).

The deepest recesses of a coal or wood fire are black bodies. Anyone who has looked into a fire knows that the deepest parts of it look brightest—they are radiating most power. Anyone who has looked into a fire also knows that, in the hottest part, no detail of the coals or wood can be seen. That is to say, the radiation from an almost enclosed space is uniform; its character does not vary with the nature of the surfaces of the space. This is so because the radiation coming out from any area is made up partly of the radiation emitted by that area, and partly of the radiation from other areas, reflected at the area in question. If the surface of the area is a good radiator, it is a bad reflector, and vice-versa. And if the hole in the body is small, the radiations from every area inside it are well mixed by reflection before they can escape; the intensity and quality of the radiation escaping thus does not depend on the particular surface from which it escapes.

When we speak of the *quality* of radiation we mean the relative intensities of the different wavelengths that it comprises; the proportion of red to blue, for example. The quality of the radiation from a perfectly black body depends only on its temperature. When the body is made hotter, its radiation becomes not only more intense, but also more nearly white; the proportion of blue to red in it increases. Because its quality is determined only by its temperature, black-body radiation is sometimes called 'temperature radiation'.

### Properties of Temperature Radiation

The quality of the radiation from a black body was examined by Lummer and Pringsheim in 1899. They used a black body represented by B in Fig. 13.23 and measured its temperature with a thermocouple; they took it to  $2000^{\circ}\text{C}$ . To measure the intensities of the various wavelengths, Lummer and Pringsheim used an infra-red spectrometer and a bolometer (p. 346) consisting of a single platinum strip.

The results of experiments such as these are shown in Fig. 13.24 (a). Each curve gives the relative intensities of the different wavelengths,

for a given temperature of the body. The curves show that, as the temperature rises, the intensity of every wavelength increases, but the intensities of the shorter wave lengths increase more rapidly. Thus the radiation becomes, as we have already observed, less red, that is to say, more nearly white. The curve for sunlight has its peak at about 5000 A.U., in the visible green; from the position of this peak we conclude that the surface temperature of the sun is about 6000 K. Stars which are hotter than the sun, such as Sirius and Vega, look blue, not white.

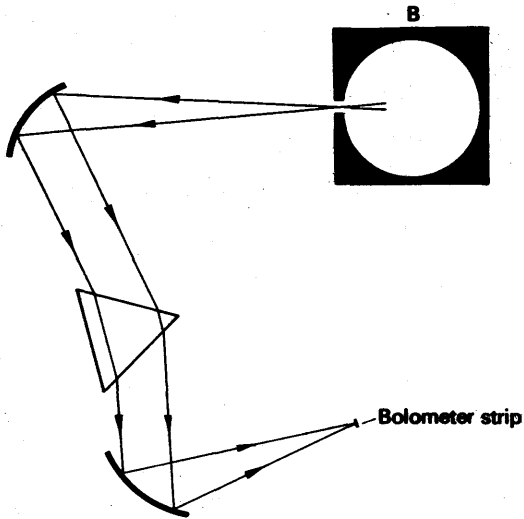


FIG. 13.23. Lummer and Pringsheim's apparatus for study of black body radiation (diagrammatic).

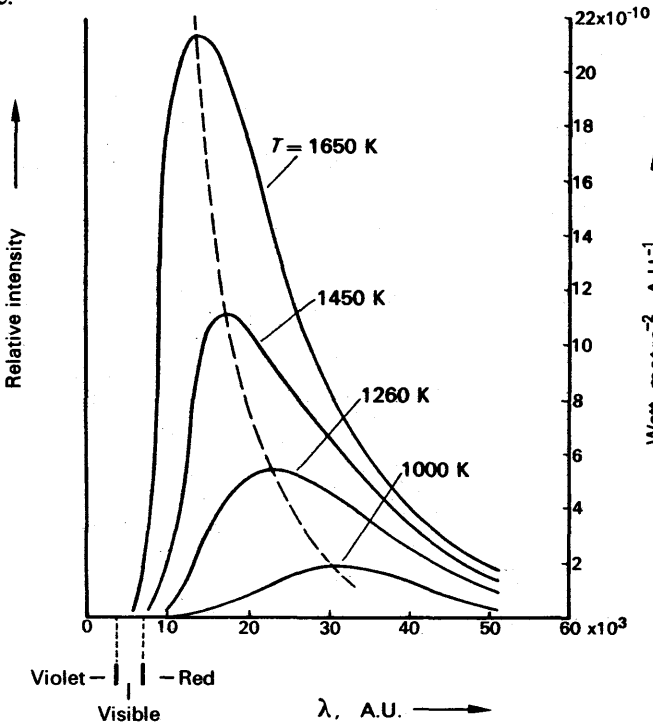


FIG. 13.24 (a). Distribution of intensity in black-body radiation.



because the peaks of their radiation curves lie further towards the visible blue than does the peak of sunlight.

The actual intensities of the radiations are shown on the right of the graph in Fig. 13.24 (a). To speak of the intensity of a single wavelength is meaningless because there is an infinite number of wavelengths, but the total intensity of the radiation is finite. The slit of the spectrometer always gathers a band of wavelengths—the narrower the slit the narrower the band—and we always speak of the intensity of a given band. We express it as follows ('s' represents 'second'):

$$\text{energy radiated } m^{-2} s^{-1}, \text{ in band } \lambda \text{ to } \lambda + \delta\lambda = E_{\lambda} \delta\lambda. \quad (8)$$

The quantity  $E_{\lambda}$  is called the *emissive power* of a black body for the wavelength  $\lambda$  and at the given temperature; its definition follows from equation (8):

$$E_{\lambda} = \frac{\text{energy radiated } m^{-2} s^{-1}, \text{ in band } \lambda \text{ to } \lambda + \delta\lambda}{\text{bandwidth, } \delta\lambda}.$$

The expression 'energy per second' can be replaced by the word 'power', whose unit is the watt. Thus

$$E_{\lambda} = \frac{\text{power radiated } m^{-2} \text{ in band } \lambda, \lambda + \delta\lambda}{\delta\lambda}.$$

In the figure  $E_{\lambda}$  is expressed in watt per  $m^2$  per Angstrom unit. SI units may be 'watt per metre<sup>2</sup> per nanometre ( $10^{-9}$  m)'.

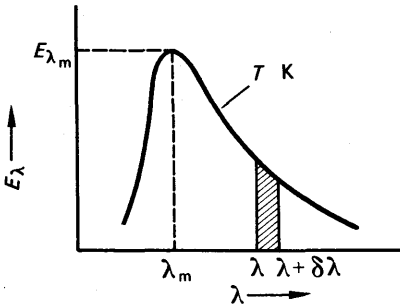


FIG. 13.24 (b). Definition of  $E_{\lambda}$ ,  $\lambda_m$ , and  $E_{\lambda_m}$ .

The quantity  $E_{\lambda} \delta\lambda$  in equation (8) is the area beneath the radiation curve between the wavelengths  $\lambda$  and  $\lambda + \delta\lambda$  (Fig. 13.24 (b)). Thus the energy radiated per  $cm^2$  per second between those wavelengths is proportional to that area. Similarly the total radiation emitted per  $cm^2$  per second over all wavelengths is proportional to the area under the whole curve.

### Laws of Black Body Radiation

The curves of Fig. 13.24 (a) can be explained only by the quantum theory of radiation, which is outside our scope. Both theory and experiment lead to three generalizations, which together describe well the properties of black-body radiation:

- (i) If  $\lambda_m$  is the wavelength of the peak of the curve for  $T$  K, then

$$\lambda_m T = \text{constant} \quad (9)$$

The value of the constant is  $2.9 \times 10^{-3}$  m K. In Fig. 13.24 (a) the dotted line is the locus of the peaks of the curves for different temperatures.

(ii) If  $E_{\lambda_m}$  is the height of the peak of the curve for the temperature  $T$  K, then

$$E_{\lambda_m} \propto T^5 \quad (10)$$

The relationships (10) and (9) are particular cases of a general law given by Wien in 1894; (9) is sometimes called *Wien's displacement law*.

(iii) If  $E$  is the total energy radiated per metre<sup>2</sup> per second at a temperature  $T$ , represented by the area under the curve, then

$$E = \sigma T^4,$$

where  $\sigma$  is a constant. This result is called **Stefan's law**, and the constant  $\sigma$  is called *Stefan's constant*. Its value is

$$\sigma = 5.7 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}.$$

### Prévost's Theory of Exchanges

In 1792 Prévost applied the idea of dynamic equilibrium to radiation. He asserted that a body radiates heat at a rate which depends only on its surface and its temperature, and that it absorbs heat at a rate depending on its surface and the temperature of its surroundings. When the temperature of a body is constant, the body is losing heat by radiation, and gaining it by absorption, at equal rates.

It is easy to think of experiments which seem to support Prévost's theory, and the reader will certainly grasp the general idea of it if he imagines hot pies and cold ice-creams put into the same cupboard. But in such experiments it is difficult to get rid of the possibility of convection. Let us rather take an old-fashioned, high vacuum, electric lamp, and put it in a can of water (Fig. 13.25 (a)). We can find the temperature of the lamp's filament by measuring its resistance. We find that, whatever the temperature of the water, the filament comes to that temperature, if we leave it long enough. When the water is cooler than the filament, the filament cools down; when the water is hotter, the filament warms up.

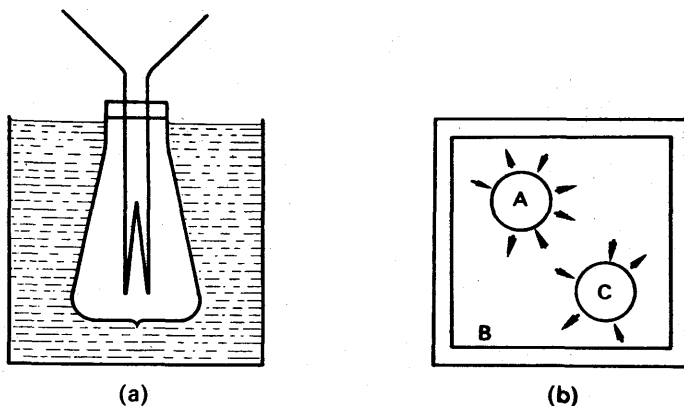


FIG. 13.25. Illustrating Prévost's theory of exchanges.

In the abstract language of theoretical physics, Prévost's theory is easy enough to discuss. If a hot body A (Fig. 13.25 (b)) is placed in an evacuated enclosure B, at a lower temperature than A, then A cools until it reaches the temperature of B. If a body C, cooler than B, is put in B, then C warms up to the temperature of B. We conclude that radiation from B falls on C, and therefore also on A, even though A

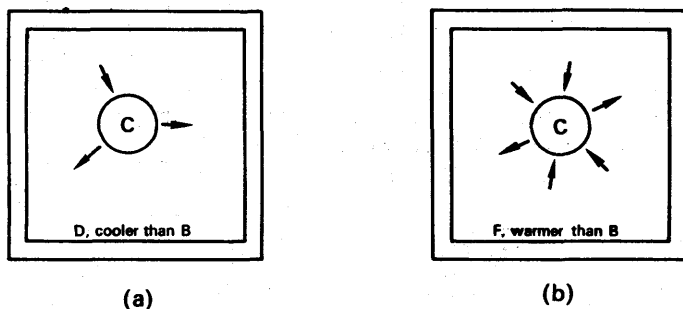


FIG. 13.26. Illustrating Prévost's theory.

is at a higher temperature. Thus A and C each come to equilibrium at the temperature of B when each is absorbing and emitting radiation at equal rates.

Now let us suppose that, after it has reached equilibrium with B, one of the bodies, say C, is transferred from B to a cooler evacuated enclosure D (Fig. 13.26 (a)). It loses heat and cools to the temperature of D. Therefore it is radiating heat. But if C is transferred from B to a warmer enclosure F, then C gains heat and warms up to the temperature of F (Fig. 13.26 (b)). It seems unreasonable to suppose that C stops radiating when it is transferred to F; it is more reasonable to suppose that it goes on radiating but, while it is cooler than F, it absorbs more than it radiates.

### Emissivity

Let us consider a body B, in equilibrium with an enclosure A, at a temperature  $T$  K (Fig. 13.27). If the body is perfectly black, it emits radiation characteristics of the temperature  $T$ ; let us write the total intensity of this radiation over all wavelengths as  $E$  watts/m<sup>2</sup>. Since the body is in equilibrium with the enclosure, it is absorbing as much as it radiates. And since it absorbs all the radiation that falls upon it, the energy falling on it per cm<sup>2</sup> per second must be equal to  $E$ . This conclusion need not surprise us, since the enclosure A is full of black body radiation characteristic of its temperature  $T$ .

Now let us consider, in the same enclosure, a body C which is not black. On each square metre of the body's surface,  $E$  watts of radiation fall (Fig. 13.27). Of this, let us suppose that the body absorbs a fraction  $a$ , that is to say, it absorbs  $aE$  watts per m<sup>2</sup>. We may call  $a$  the total absorption factor of the body C, 'total' because it refers to the total radiation. The radiation which the body does not absorb,  $(1 - a)E$ , it reflects or transmits.

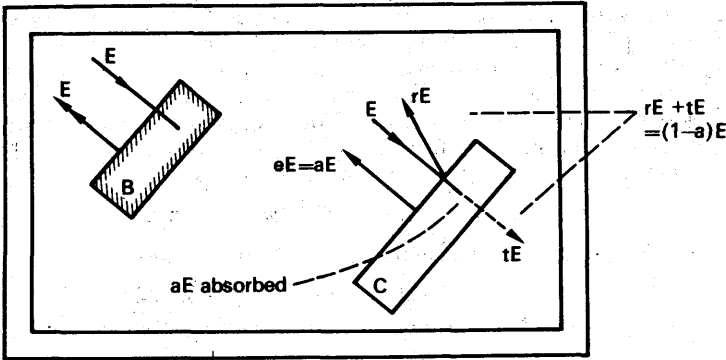


FIG. 13.27. Equilibria in an enclosure.

Thus: 
$$\left. \begin{array}{l} \text{power reflected or} \\ \text{transmitted/m}^2 \end{array} \right\} = E - aE.$$

For equilibrium, the total power leaving the body per  $m^2$  must be equal to the total power falling upon it,  $E \text{ W/m}^2$ . The power emitted by the body, which must be added to that reflected and transmitted, is therefore:

$$\text{total power radiated/m}^2 = aE \quad (12)$$

The ratio of the total power radiated per  $m^2$  by a given body, to that emitted by a black body at the same temperature, is called the *total emissivity* of the given body. Hence, by equation (12),

$$e = \frac{aE}{E} = a.$$

We have therefore shown that the total emissivity of a body is equal to its total absorption factor.

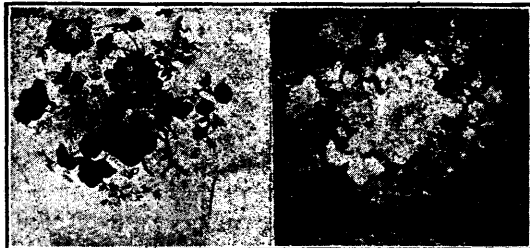
This is a formal expression of the results of Ritchie's experiment (p. 350). If we combine it with Stefan's law, we find that the total energy  $E$  radiated per  $m^2$  per second by a body of emissivity  $e$  at a temperature  $T \text{ K}$  is

$$E = eE = e\sigma T^4.$$

**Spectral Emissivity; Kirchoff's Law**

Most bodies are coloured; they transmit or reflect some wavelengths better than others. We have already seen that they must absorb these wavelengths weakly; we now see that, because they absorb them weakly, they must also

FIG. 13.28. Photographs showing how a piece of incandescent decorated crockery appears (a) by reflected light and (b) by its own emitted light.



radiate them weakly. To show this, we have only to repeat the foregoing argument, but restricting it to a narrow band of wavelengths between  $\lambda$  and  $\lambda + \delta\lambda$ . The energy falling per  $m^2$  per second on the body, in this band, is  $E_\lambda \delta\lambda$  where  $E_\lambda$  is the emissive power of a black-body in the neighbourhood of  $\lambda$ , at the temperature of the enclosure. If the body C absorbs a fraction  $a_\lambda$  of this, we call  $a_\lambda$  the spectral absorption factor of the body, for the wavelength  $\lambda$ . In equilibrium, the body emits as much radiation in the neighbourhood of  $\lambda$  as it absorbs; thus:

$$\text{energy radiated} = a_\lambda E_\lambda \delta\lambda \text{ watts per } m^2.$$

We define the spectral emissivity of the body  $e_\lambda$ , by the equation

$$\begin{aligned} e_\lambda &= \frac{\text{energy radiated by body in range } \lambda, \lambda + \delta\lambda}{\text{energy radiated in same range, by black body at same temperature}} \\ &= \frac{\text{energy radiated by body in range } \lambda, \lambda + \delta\lambda}{E_\lambda \delta\lambda} \\ &= \frac{a_\lambda E_\lambda \delta\lambda}{E_\lambda \delta\lambda} \end{aligned}$$

Thus

$$e_\lambda = a_\lambda \quad (13)$$

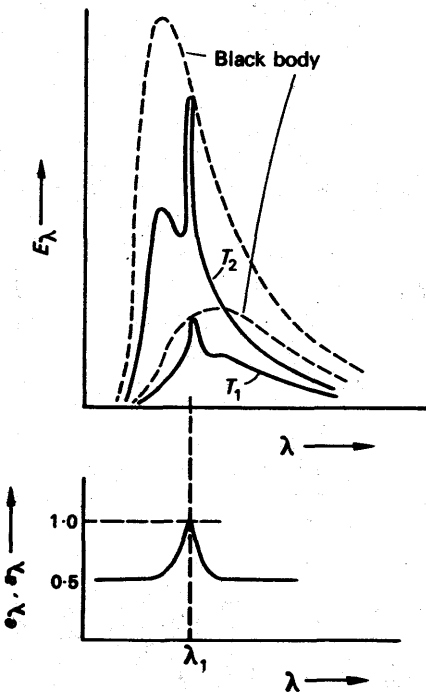


FIG. 13.29. Illustrating Kirchhoff's law of radiation.

Equation (13) expresses a law due to Kirchhoff:

*The spectral emissivity of a body, for a given wavelength, is equal to its spectral absorption factor for the same wavelength.*

Kirchhoff's law is not easy to demonstrate by experiment. One reads that a plate, which when cold shows a red pattern on a blue ground, glows blue on a red ground when heated in a furnace. But not all such plates do this, because the spectral emissivities of many coloured pigments vary with their temperature. However, Fig. 13.28 shows two photographs of a piece of pottery, one taken by reflected light at room temperature (left), the other by its own light when heated (right).

Fig. 13.29 illustrates Kirchhoff's law, by showing how the spectral emissivity and absorp-

tion factor of a coloured body may vary with wavelength, and how its emissive power  $E_\lambda$  does likewise. It is assumed that  $e_\lambda$  rises to unity at the wavelength  $\lambda_1$  (which is not likely), and that it does not vary

with the temperature. A body for which  $e_\lambda$  is the same for all wavelengths, but is less than unity, is said to be 'grey'.

### Absorption by Gases

An experiment which shows that, if a body radiates a given wavelength strongly, it also absorbs that wavelength strongly, can be made with sodium vapour. A sodium vapour lamp runs at about  $220^\circ\text{C}$ ; compared with the sun, or even an arc-lamp, it is cool. The experiment consists of passing sunlight or arc-light through a spectroscope, and observing its continuous spectrum. The sodium lamp is then placed in the path of the light, and a black line appears in the yellow. If the white light is now cut off, the line which looked black comes up brightly—it is the sodium yellow line.

The process of absorption by sodium vapour—or any other gas—is not, however, the same as the process of absorption by a solid. When a solid absorbs radiation, it turns it into heat—into the random kinetic energy of its molecules. It then re-radiates it in all wavelengths, but mostly in very long ones, because the solid is cool. When a vapour absorbs light of its characteristic wavelength, however, its atoms are excited; they then re-radiate the absorbed energy, in the same wavelength (5893 A.U. for sodium). But they re-radiate it in all directions, and therefore less of it passes on in the original direction than before (Fig. 13.30). Thus the yellow component of the original beam is weakened, but the yellow light radiated sideways by the sodium is strengthened. The sideways strengthening is hard to detect, but it was shown by R. W. Wood in 1906. He used mercury vapour instead of sodium. The phenomenon is called *optical resonance*, by analogy with resonance in sound.

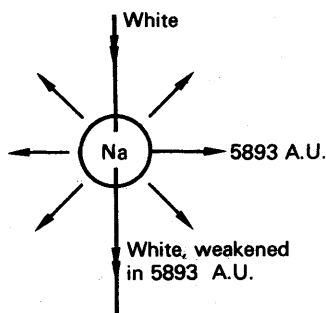


FIG. 13.30. Absorption by sodium vapour.

### CONVECTION

Liquids—except mercury, which is a molten metal—are bad conductors of heat. If we hold a test-tube full of water by the bottom, we can boil the water near the top in a Bunsen flame, without any discomfort. But if we hold the tube at the top, and heat it at the bottom, then the top becomes unbearably hot long before the water boils. The heat is brought to the top by *convection*; the warm water at the bottom expands, becomes less dense, and rises; the cold water sinks to take its place. If we heat a beaker of water at one side, and drop in a crystal of potassium permanganate, we can see the currents of hot water rising, and cold descending. Central-heating systems rely on convection to bring hot water from the boiler, in the basement, to the so-called radiators, and to take the cooler water back to the boiler.

The radiators of a central-heating system are wrongly named; they are convectors. They warm the air around them, which rises, and gives way to cooler air from cooler parts of the room. Gases are even worse conductors of heat than liquids, and for most practical purposes we can neglect conduction through them altogether. Woollen clothes keep us warm because they contain pockets of air, which hardly conduct at all, and cannot convect because they cannot move. The wool fibres themselves are much better conductors than the air they imprison.

Convection by air is important in ventilation: the fire in a room maintains a draught of hot air up the chimney, and cool fresh air from outside comes in under the door. The draught also helps to keep the fire supplied with oxygen; factory chimneys are made tall to stimulate convection and increase the draught.

### Forced and Free (Natural) Convection

A gas or a liquid may carry away heat from a hot body by convection. If the flow of liquid or gas is simply due to its being heated by the body, and hence rising, the convection is said to be *free*, or natural. But if the gas or liquid is flowing in a stream maintained by some other means, then the convection is said to be *forced*. Thus cooling one's porridge in the obvious way is an example of forced convection; it causes a more rapid loss of heat than does natural convection.

### Critical Diameter of Pipes

Hot-water and steam pipes are often lagged with asbestos to reduce the loss of heat from them. The temperature drop across the lagging makes the outside cooler than the pipe, and so, by Newton's law, tends to reduce the rate at which heat escapes from it. However, the lagging increases the outside diameter of the whole, and so increases its area of contact with the atmosphere. The increase in area tends to make convection more vigorous, by enabling the pipe to heat a greater mass of air. If the diameter of the pipe is small, the increase in area may more than offset the reduction temperature of the outside, and so increase the rate of heat loss. Thus there is a critical diameter of pipe; if the diameter is less than the critical value, the pipe should not be lagged. The critical diameter depends on many factors, but is commonly of the order of 1 cm.

### The Greenhouse

A greenhouse keeps plants warm by inhibiting convection. The glass allows radiant heat to reach the plants from the sun, but prevents the warm air in the greenhouse from escaping. In winter, when there is little sunshine, the heat is provided by hot water pipes. In summer the temperature is regulated by opening or closing the roof and windows, and so adjusting the loss of heat by convection.

## EXERCISES 13

**Conduction**

1. Define the *thermal conductivity* of a substance. Describe how the thermal conductivity of a metal may be measured, pointing out the sources of error in the experiment.

A large hot-water tank has four steel legs in the form of cylindrical rods 2.5 cm in diameter and 15 cm long. The lower ends of the legs are in good thermal contact with the floor, which is at 20°C, and their upper ends can be taken to be at the temperature of the water in the tank. The tank and the legs are well lagged so that the only heat loss is through the legs. It is found that 22 watts are needed to maintain the tank at 60°C. What is the thermal conductivity of steel? When a sheet of asbestos 1.5 mm thick is placed between the lower end of each leg and the floor only 5 watts are needed to maintain the tank at 60°C. What is the thermal conductivity of asbestos? (*O. & C.*)

2. Define *thermal conductivity* and state a unit in which it is expressed.

Explain why, in an experiment to determine the thermal conductivity of copper using a Searle's arrangement, it is necessary (*a*) that the bar should be thick, of uniform cross-section and have its sides well lagged, (*b*) that the temperatures used in the calculation should be the steady values finally registered by the thermometers.

Straight metal bars *X* and *Y* of circular section and equal in length are joined end to end. The thermal conductivity of the material of *X* is twice that of the material of *Y*, and the uniform diameter of *X* is twice that of *Y*. The exposed ends of *X* and *Y* are maintained at 100°C and 0°C, respectively and the sides of the bars are ideally lagged. Ignoring the distortion of the heat flow at the junction, sketch a graph to illustrate how the temperature varies between the ends of the composite bar when conditions are steady. Explain the features of the graph and calculate the steady temperature of the junction. (*N.*)

3. Give a critical account of an experiment to determine the thermal conductivity of a material of low thermal conductivity such as cork. Why is it that most cellular materials, such as cotton wool, felt, etc., all have approximately the same thermal conductivity?

One face of a sheet of cork, 3 mm thick, is placed in contact with one face of a sheet of glass 5 mm thick, both sheets being 20 cm square. The outer faces of this square composite sheet are maintained at 100°C and 20°C, the glass being at the higher mean temperature. Find (*a*) the temperature of the glass-cork interface, and (*b*) the rate at which heat is conducted across the sheet, neglecting edge effects.

[Thermal conductivity of cork =  $6.3 \times 10^{-2} \text{ W m}^{-1} \text{ K}^{-1}$ , thermal conductivity of glass =  $7.14 \times 10^{-1} \text{ W m}^{-1} \text{ K}^{-1}$ .] (*O. & C.*)

4. Define *coefficient of thermal conductivity*. Describe a method of measuring this coefficient for a metal.

Assuming that the thermal insulation provided by a woollen glove is equivalent to a layer of quiescent air 3 mm thick, determine the heat loss per minute from a man's hand, surface area 200 cm<sup>2</sup> on a winter's day when the atmospheric air temperature is -3°C. The skin temperature is to be taken as 34°C and the thermal conductivity of air as  $24 \times 10^{-3} \text{ W m}^{-1} \text{ K}^{-1}$ . (*L.*)

5. Define *thermal conductivity*. Describe in detail a method of determining the thermal conductivity of cork in the form of a thin sheet.

The base and the vertical walls of an open thin-walled metal tank, filled with water maintained at 35°C, are lagged with a layer of cork of superficial area 2.00 m<sup>2</sup>



and 1.00 cm thick and the water surface is exposed. Heat is supplied electrically to the water at the rate of 250 watts. Find the mass of water that will evaporate per day, if the outside surface of the cork is at 15°C. [Assume that the thermal conductivity of cork is  $5.0 \times 10^{-2} \text{ W m}^{-1} \text{ K}^{-1}$  and that the latent heat of vaporization of water at 35°C is  $2520 \text{ J g}^{-1}$ .] (L.)

6. Explain what is meant by the *coefficient of thermal conductivity* of a metal.

One end of a long uniform metal bar is heated in a steam chest and the other is kept cool by a current of water. Draw sketch graphs to show the variation of temperature along the bar when the steady state has been attained (a) when the bar is lagged so that no heat escapes from the sides, (b) when the bar is exposed to the air. Explain the shape of the graph in each case.

The surface temperatures of the glass in a window are 20°C for the side facing the room and 5°C for the outside. Compare the rate of flow of heat through (i) a window consisting of a single sheet of glass 5.0 mm thick, and (ii) a double-glazed window of the same area consisting of two sheets of glass each 2.5 mm thick separated by a layer of still air 5.0 mm thick. It may be assumed that the steady state has been attained.

[Use the following values of coefficient of thermal conductivity: glass:  $1.0 \text{ W m}^{-1} \text{ K}^{-1}$ ; air:  $2.5 \times 10^{-2} \text{ W m}^{-1} \text{ K}^{-1}$ .] (C.)

7. Describe the construction of a Dewar (vacuum) vessel and explain the physical features which result in a reduction to a minimum of the heat exchange between the interior and exterior. Explain why such a vessel is equally suitable for thermally isolating a cold or a hot body.

A copper sphere of radius 0.5 cm is suspended in an evacuated enclosure by a copper wire of diameter 0.01 cm and length 3 cm. An insulated electrical heating coil in good thermal contact with the sphere is connected through the wall of the enclosure by two copper leads of negligible resistance each of diameter 0.02 cm and length 5 cm. What rate of heating in the coil is required to maintain the sphere at a temperature 50°C above that of the surroundings assuming that heat is lost only by conduction along the supports and along the electrical leads? When a steady state has been reached, the coil is disconnected from the electrical supply and the initial rate of fall of temperature of the sphere is found to be 0.013°C per second. Calculate the specific heat of copper, assuming that the electrical leads are still kept at the temperature of the surroundings at the points where they pass through the wall of the enclosure, that the temperature gradient in the sphere is negligible and given that the thermal capacity of the heating coil is equal to that of 1.5 g of copper. [Density of copper =  $9.0 \text{ g cm}^{-3}$ . Thermal conductivity of copper =  $380 \text{ W m}^{-1} \text{ K}^{-1}$ .] (O. & C.)

8. Define *thermal conductivity*.

A 'cold probe', i.e. an instrument to produce a low temperature at its extremity, consists of a solid copper rod 1 mm in diameter attached axially to a well-lagged

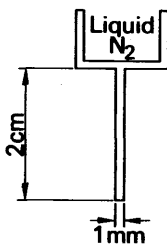


FIG. 13A.

copper reservoir which holds boiling liquid nitrogen, temperature 78 K (see Fig. 13A). The distance from the bottom of the reservoir to the tip of the probe is 2.0 cm. The curved surface of the rod is coated with a non-conducting material. Assuming that no heat can reach the copper except through its flat tip, calculate the maximum rate at which heat can be accepted there if the temperature is not to rise above  $-10^{\circ}\text{C}$ .

(Thermal conductivity of copper =  $385 \text{ W m}^{-1} \text{ K}^{-1}$ .)

If you were given such a probe and told to use it to determine the mean conductivity of copper over this temperature range, how would you proceed? Describe the kind of apparatus you would use and specify (a) the quantities you would need to measure, (b) any data you would need to know. (O. & C.)

### Radiation

9. A hot body, such as a wire heated by an electric current, can lose energy to its surroundings by various processes. Outline the nature of each of these processes.

A black body of temperature  $t$  is situated in a blackened enclosure maintained at a temperature of  $10^{\circ}\text{C}$ . When  $t = 30^{\circ}\text{C}$  the net rate of loss of energy from the body is equal to 10 watts. What will the rate become when  $t = 50^{\circ}\text{C}$  if the energy exchange takes place solely by the process of radiation? What percentage error is there in the answer obtained by basing the solution on Newton's law of cooling? (C.)

10. Explain what is meant by a *black body*. How do the total energy radiated by a black body and its distribution among the wavelengths in the spectrum depend upon the temperature of the radiator?

Describe the structure of an optical pyrometer and explain how it is used to measure the temperature of a furnace. (L.)

11. Explain what is meant by *black body radiation* and how it can be obtained in practice.

Give an account of Prévost's theory of exchanges and show how it can be used in conjunction with Stefan's law to obtain an expression for the net rate of loss of heat by a black body cooling in an evacuated enclosure.

Sketch the curves relating intensity of radiation and wavelength of radiation from a black body, for *three* different temperatures. (L.)

12. Explain what is meant by *Stefan's constant*. Defining any symbols used.

A sphere of radius 2.00 cm with a black surface is cooled and then suspended in a large evacuated enclosure the black walls of which are maintained at  $27^{\circ}\text{C}$ . If the rate of change of thermal energy of the sphere is  $1.848 \text{ J s}^{-1}$  when its temperature is  $-73^{\circ}\text{C}$ , calculate a value for *Stefan's constant*. (N.)

13. What is Prévost's Theory of Exchanges? Describe some phenomenon of theoretical or practical importance to which it applies.

A metal sphere of 1 cm diameter, whose surface acts as a black body, is placed at the focus of a concave mirror with aperture of diameter 60 cm directed towards the sun. If the solar radiation falling normally on the earth is at the rate of  $0.14 \text{ watt cm}^{-2}$ , Stefan's constant is taken as  $6 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}$  and the mean temperature of the surroundings is  $27^{\circ}\text{C}$ , calculate the maximum temperature which the sphere could theoretically attain, stating any assumptions you make. (O. & C.)

14. State Newton's law of cooling and Stefan's fourth power law. Describe an experiment to test the validity of *one* of these laws.

A sphere of copper cools at the rate of  $10 \text{ deg C min}^{-1}$  when at a temperature of  $70^{\circ}\text{C}$  in an enclosure at  $20^{\circ}\text{C}$ . Calculate its rate of cooling when its temperature

is raised to (a)  $100^{\circ}\text{C}$ , (b)  $700^{\circ}\text{C}$ , assuming the validity of Newton's law. Repeat the calculations assuming the validity of Stefan's law. Comment on your answers. (L.)

15. Explain what is meant by (a) a *black body*, (b) *black body radiation*.

State *Stefan's law* and draw a diagram to show how the energy is distributed against wavelength in the spectrum of a black body for two different temperatures. Indicate which temperature is the higher.

A roof measures  $20\text{ m} \times 50\text{ m}$  and is blackened. If the temperature of the sun's surface is  $6000\text{ K}$ , Stefan's constant  $= 5.72 \times 10^{-8}\text{ W m}^{-2}\text{ K}^{-4}$ , the radius of the sun is  $7.5 \times 10^8\text{ m}$  and the distance of the sun from the earth is  $1.5 \times 10^{11}\text{ m}$ , calculate how much solar energy is incident on the roof per minute, assuming that half is lost in passing through the earth's atmosphere, the roof being normal to the sun's rays. (O. & C.)

16. What is *black body radiation*?

Using the same axes sketch graphs, one in each instance, to illustrate the distribution of energy in the spectrum of radiation emanating from (a) a black body at  $1000\text{ K}$ , (b) a black body at  $2000\text{ K}$  and (c) a source other than a black body at  $1000\text{ K}$ . Point out any special features of the graphs.

Indicate briefly how the relative intensities needed to draw one of these graphs could be determined. (N.)

17. How can the temperature of a furnace be determined from observations on the radiation emitted?

Calculate the apparent temperature of the sun from the following information :

Sun's radius:  $7.04 \times 10^5\text{ km}$ .

Distance from earth:  $14.72 \times 10^7\text{ km}$ .

Solar constant:  $0.14\text{ watt per cm}^2$ .

Stefan's constant:  $5.7 \times 10^{-8}\text{ W m}^{-2}\text{ K}^{-4}$ . (N.)

18. Describe one experiment to show that a polished metal surface is a poor absorber of heat, and one experiment to show that such a surface reflects a high proportion of a beam of light falling on it. Briefly compare heat and light radiations from the standpoint of (a) velocity, (b) effect at a distance, (c) simple refraction, (d) transmission through material substances. (N.)

19. A block of metal is heated and (a) exposed to ordinary atmospheric conditions, or (b) placed in a high vacuum. State concisely the factors that govern the rate at which its temperature falls under conditions (a) and (b). Energy is supplied at the rate of  $165\text{ watts}$  to a closed cylindrical canister  $5\text{ cm}$  in radius and  $15\text{ cm}$  high, filled with water and exposed to the air of the room, which is at  $15^{\circ}\text{C}$ . It is found that the temperature of the water remains steady at  $80^{\circ}\text{C}$ . Find the rate of heat loss per unit area of the vessel per deg C excess temperature. Estimate also the fall of temperature in a minute, when the energy supply is shut off. Neglect the weight of the canister itself. (L.)

20. Describe an experiment to show (a) that the spectrum of an incandescent solid includes both visible and invisible radiations, (b) how the fraction of incident radiation transmitted by glass depends on the temperature of the source of the radiation.

The sun's rays are focussed by a concave mirror of diameter  $12\text{ cm}$  fixed with its axis towards the sun on to a copper calorimeter, where they are absorbed. If the thermal capacity of the calorimeter and its contents is  $247.8\text{ joules per deg C}$  and the temperature rises  $8^{\circ}\text{C}$  in  $2\text{ min}$ , calculate the heat received in  $1\text{ min}$  by a square metre of the earth's surface when the rays are incident normally. (N.)

21. Give an account of Stefan's law of radiation, explaining the character of the radiating body to which it applies and how such a body can be experimentally realized.

If each square cm of the sun's surface radiates energy at the rate of  $6.3 \times 10^3 \text{ J s}^{-1} \text{ cm}^{-2}$  and Stefan's constant is  $5.7 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}$ , calculate the temperature of the sun's surface in degrees centigrade, assuming Stefan's law applies to the radiation. (L.)

22. Explain what is meant by *black body radiation* and how it can be obtained in practice.

Give an account of Prévost's theory of exchanges and show how it can be used in conjunction with Stefan's law to obtain an expression for the net rate of loss of heat by a black body cooling in an evacuated enclosure.

Sketch the curves relating intensity of radiation and wavelength of radiation from a black body, for *three* different temperatures. (L.)