thermometer and steam outlet through the cork of the flask (Fig. 11.11). As water gets heated in the flask, note first that the air, which was dissolved in the water, will come out as small bubbles. Later, bubbles of steam will form at the bottom but as they rise to the cooler water near the top, they condense and disappear. Finally, as the temperature of the entire mass of the water reaches 100 °C, bubbles of steam reach the surface and boiling is said to occur. The steam in the flask may not be visible but as it comes out of the flask, it condenses as tiny droplets of water, giving a foggy appearance.

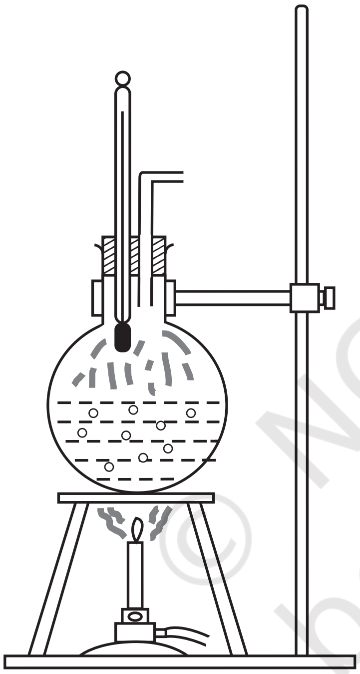

Fig. 11.11 *Boiling process.*

If now the steam outlet is closed for a few seconds to increase the pressure in the flask, you will notice that boiling stops. More heat would be required to raise the temperature (depending on the increase in pressure) before boiling begins again. Thus boiling point increases with increase in pressure.

Let us now remove the burner. Allow water to cool to about 80 °C. Remove the thermometer and steam outlet. Close the flask with the airtight cork. Keep the flask turned upside down on the stand. Pour ice-cold water on the flask. Water vapours in the flask condense reducing the pressure on the water surface inside the flask. Water begins to boil again, now at a lower temperature. Thus boiling point decreases with decrease in pressure.

This explains why cooking is difficult on hills. At high altitudes, atmospheric pressure is lower, reducing the boiling point of water as compared to that at sea level. On the other hand, boiling point is increased inside a pressure cooker by increasing the pressure. Hence cooking is faster. The boiling point of a substance at standard atmospheric pressure is called its **normal boiling point**.

However, all substances do not pass through the three states: solid-liquid-gas. There are certain substances which normally pass from the solid to the vapour state directly and vice versa. The change from solid state to vapour state without passing through the liquid state is called **sublimation**, and the substance is said to sublime. Dry ice (solid CO_2) sublimes, so also iodine. During the sublimation process both the solid and vapour states of a substance coexist in thermal equilibrium.

11.8.1 Latent Heat

In Section 11.8, we have learnt that certain amount of heat energy is transferred between a substance and its surroundings when it undergoes a change of state. The amount of heat per unit mass transferred during change of state of the substance is called latent heat of the substance for the process. For example, if heat is added to a given quantity of ice at –10 °C, the temperature of ice increases until it reaches its melting point (0 °C). At this temperature, the addition of more heat does not increase the temperature but causes the ice to melt, or changes its state. Once the entire ice melts, adding more heat will cause the temperature of the water to rise. A similar situation occurs during liquid gas change of state at the boiling point. Adding more heat to boiling water causes vaporisation, without increase in temperature.

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Table 11.5 **Temperatures of the change of state and latent heats for various substances at 1 atm pressure**

Substance	Melting Point (°C)	L_f (10^5J kg^{-1})	Boiling Point (°C)	L_v (10^5J kg^{-1})
Ethanol	–114	1.0	78	8.5
Gold	1063	0.645	2660	15.8
Lead	328	0.25	1744	8.67
Mercury	–39	0.12	357	2.7
Nitrogen	–210	0.26	–196	2.0
Oxygen	–219	0.14	–183	2.1
Water	0	3.33	100	22.6

The heat required during a change of state depends upon the heat of transformation and the mass of the substance undergoing a change of state. Thus, if mass m of a substance undergoes a change from one state to the other, then the quantity of heat required is given by

$$Q = m L$$

or $$L = Q/m \qquad (11.13)$$

where L is known as latent heat and is a characteristic of the substance. Its SI unit is J kg^{-1}. The value of L also depends on the pressure. Its value is usually quoted at standard atmospheric pressure. The latent heat for a solid-liquid state change is called the **latent heat of fusion** (L_f), and that for a liquid-gas state change is called the **latent heat of vaporisation** (L_v). These are often referred to as the heat of fusion and the heat of vaporisation. A plot of temperature versus heat for a quantity of water is shown in Fig. 11.12. The latent heats of some substances, their freezing and boiling points, are given in Table 11.5.

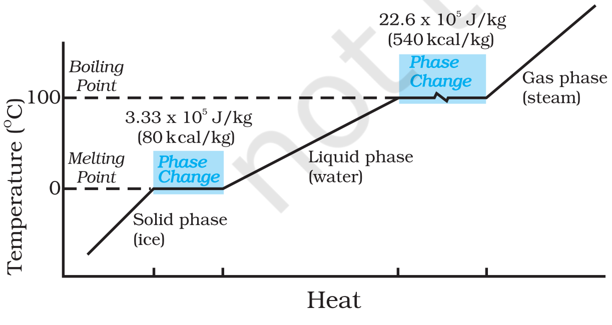

Fig. 11.12 *Temperature versus heat for water at 1 atm pressure (not to scale).*

Note that when heat is added (or removed) during a change of state, the temperature remains constant. Note in Fig. 11.12 that the slopes of the phase lines are not all the same, which indicate that specific heats of the various states are not equal. For water, the latent heat of fusion and vaporisation are $L_f = 3.33 \times 10^5$ J kg^{-1} and $L_v = 22.6 \times 10^5$ J kg^{-1}, respectively. That is, 3.33×10^5 J of heat is needed to melt 1 kg ice at 0 °C, and 22.6×10^5 J of heat is needed to convert 1 kg water into steam at 100 °C. So, steam at 100 °C carries 22.6×10^5 J kg^{-1} more heat than water at 100 °C. This is why burns from steam are usually more serious than those from boiling water.

Example 11.4 When 0.15 kg of ice at 0 °C is mixed with 0.30 kg of water at 50 °C in a container, the resulting temperature is 6.7 °C. Calculate the heat of fusion of ice. (s_{water} = 4186 J kg^{-1} K^{-1})

Answer

Heat lost by water = $ms_w (\theta_f - \theta_i)_w$

= (0.30 kg) (4186 J kg^{-1} K^{-1}) (50.0 °C – 6.7 °C)

= 54376.14 J

Heat required to melt ice = $m_2 L_f$ = (0.15 kg) L_f

Heat required to raise temperature of ice water to final temperature = $m_1 s_w (\theta_f - \theta_i)_I$

= (0.15 kg) (4186 J kg^{-1} K^{-1}) (6.7 °C – 0 °C)

= 4206.93 J

Heat lost = heat gained

54376.14 J = (0.15 kg) L_f + 4206.93 J

$L_f = 3.34 \times 10^5$ J kg^{-1}.

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▶ ***Example 11.5*** Calculate the heat required to convert 3 kg of ice at –12 °C kept in a calorimeter to steam at 100 °C at atmospheric pressure. Given specific heat capacity of ice = 2100 J kg^{-1} K^{-1}, specific heat capacity of water = 4186 J kg^{-1} K^{-1}, latent heat of fusion of ice = 3.35 × 10^5 J kg^{-1} and latent heat of steam = 2.256 ×10^6 J kg^{-1}.

Answer We have

Mass of the ice, $m = 3$ kg

specific heat capacity of ice, s_{ice}
$= 2100$ J kg^{-1} K^{-1}

specific heat capacity of water, s_{water}
$= 4186$ J kg^{-1} K^{-1}

latent heat of fusion of ice, $L_{f\,ice}$
$= 3.35 \times 10^5$ J kg^{-1}

latent heat of steam, L_{steam}
$= 2.256 \times 10^6$ J kg^{-1}

Now, Q = heat required to convert 3 kg of ice at –12 °C to steam at 100 °C,

Q_1 = heat required to convert ice at –12 °C to ice at 0 °C.

$= m\, s_{ice}\, \Delta T_1 = (3\text{ kg})\ (2100\text{ J kg}^{-1}\text{ K}^{-1})\ [0–(–12)]°\text{C} = 75600\text{ J}$

Q_2 = heat required to melt ice at 0 °C to water at 0 °C

$= m L_{f\,ice} = (3\text{ kg})\ (3.35 \times 10^5\text{ J kg}^{-1})$

$=$ 1005000 J

Q_3 = heat required to convert water at 0 °C to water at 100 °C.

$= m s_w\, \Delta T_2 = (3\text{kg})\ (4186\text{J kg}^{-1}\text{ K}^{-1})\ (100\ °\text{C})$

$=$ 1255800 J

Q_4 = heat required to convert water at 100 °C to steam at 100 °C.

$= m\ L_{steam} = (3\text{ kg})\ (2.256 \times 10^6\text{ J kg}^{-1})$

$=$ 6768000 J

So, $Q = Q_1 + Q_2 + Q_3 + Q_4$

$=$ 75600J + 1005000 J + 1255800 J + 6768000 J

$= 9.1 \times 10^6$ J ◀

11.9 HEAT TRANSFER

We have seen that heat is energy transfer from one system to another or from one part of a system to another part, arising due to temperature difference. What are the different ways by which this energy transfer takes place? There are three distinct modes of heat transfer: conduction, convection and radiation (Fig. 11.13).

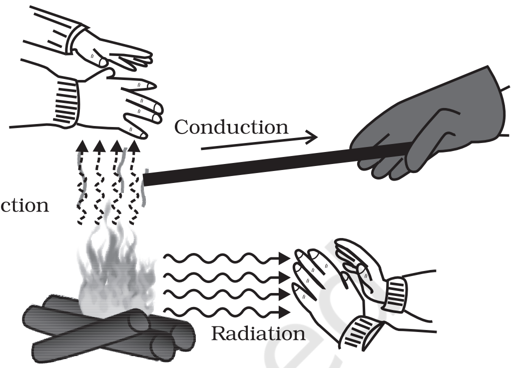

Fig. 11.13 *Heating by conduction, convection and radiation.*

11.9.1 Conduction

Conduction is the mechanism of transfer of heat between two adjacent parts of a body because of their temperature difference. Suppose, one end of a metallic rod is put in a flame, the other end of the rod will soon be so hot that you cannot hold it by your bare hands. Here, heat transfer takes place by conduction from the hot end of the rod through its different parts to the other end. Gases are poor thermal conductors, while liquids have conductivities intermediate between solids and gases.

Heat conduction may be described quantitatively as the time rate of heat flow in a material for a given temperature difference. Consider a metallic bar of length L and uniform cross-section A with its two ends maintained at different temperatures. This can be done, for example, by putting the ends in thermal contact with large reservoirs at temperatures, say, T_C and T_D, respectively (Fig. 11.14). Let us assume the ideal condition that the sides of the bar are fully insulated so that no heat is exchanged between the sides and the surroundings.

After sometime, a steady state is reached; the temperature of the bar decreases uniformly with distance from T_C to T_D; ($T_C > T_D$). The reservoir at C supplies heat at a constant rate, which transfers through the bar and is given out at the same rate to the reservoir at D. It is found

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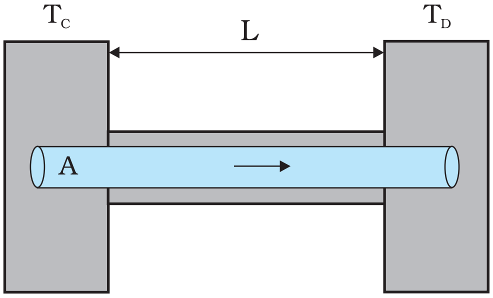

Fig. 11.14 *Steady state heat flow by conduction in a bar with its two ends maintained at temperatures T_C and T_D; ($T_C > T_D$).*

experimentally that in this steady state, the rate of flow of heat (or heat current) H is proportional to the temperature difference ($T_C - T_D$) and the area of cross-section A and is inversely proportional to the length L :

$$H = KA\frac{T_C - T_D}{L} \qquad (11.14)$$

The constant of proportionality K is called the **thermal conductivity** of the material. The greater the value of K for a material, the more rapidly will it conduct heat. The SI unit of K is J s^{-1} m^{-1} K^{-1} or W m^{-1} K^{-1}. The thermal conductivities of various substances are listed in Table 11.6. These values vary slightly with temperature, but can be considered to be constant over a normal temperature range.

Compare the relatively large thermal conductivities of good thermal conductors and, metals, with the relatively small thermal conductivities of some good thermal insulators, such as wood and glass wool. You may have noticed that some cooking pots have copper coating on the bottom. Being a good conductor of heat, copper promotes the distribution of heat over the bottom of a pot for uniform cooking. Plastic foams, on the other hand, are good insulators, mainly because they contain pockets of air. Recall that gases are poor conductors, and note the low thermal conductivity of air in the Table 11.5. Heat retention and transfer are important in many other applications. Houses made of concrete roofs get very hot during summer days because thermal conductivity of concrete (though much smaller than that of a metal) is still not small enough. Therefore, people, usually, prefer to give a layer of earth or foam insulation on the ceiling so that heat transfer is prohibited and keeps the room cooler. In some situations, heat transfer is critical. In a nuclear reactor, for example, elaborate heat transfer systems need to be installed so that the enormous energy produced by nuclear fission in the core transits out sufficiently fast, thus preventing the core from overheating.

Table 11.6 **Thermal conductivities of some material**

Material	Thermal conductivity (J s^{-1} m^{-1} K^{-1})
Metals	
Silver	406
Copper	385
Aluminium	205
Brass	109
Steel	50.2
Lead	34.7
Mercury	8.3
Non-metals	
Insulating brick	0.15
Concrete	0.8
Body fat	0.20
Felt	0.04
Glass	0.8
Ice	1.6
Glass wool	0.04
Wood	0.12
Water	0.8
Gases	
Air	0.024
Argon	0.016
Hydrogen	0.14

▶ ***Example 11.6*** What is the temperature of the steel-copper junction in the steady state of the system shown in Fig. 11.15. Length of the steel rod = 15.0 cm, length of the copper rod = 10.0 cm, temperature of the furnace = 300 °C, temperature of the other end = 0 °C. The area of cross section of the steel rod is twice that of the copper rod. (Thermal conductivity of steel = 50.2 J s^{-1} m^{-1}K^{-1}; and of copper = 385 J s^{-1}m^{-1}K^{-1}).

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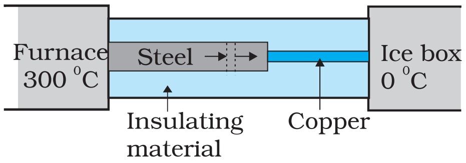

Fig. 11.15

Answer The insulating material around the rods reduces heat loss from the sides of the rods. Therefore, heat flows only along the length of the rods. Consider any cross section of the rod. In the steady state, heat flowing into the element must equal the heat flowing out of it; otherwise there would be a net gain or loss of heat by the element and its temperature would not be steady. Thus in the steady state, rate of heat flowing across a cross section of the rod is the same at every point along the length of the combined steel-copper rod. Let T be the temperature of the steel-copper junction in the steady state. Then,

$$\frac{K_1\, A_1\,(300-T)}{L_1}=\frac{K_2\, A_2\,(T-0)}{L_2}$$

where 1 and 2 refer to the steel and copper rod respectively. For $A_1 = 2\ A_2$, $L_1 = 15.0$ cm, $L_2 = 10.0$ cm, $K_1 = 50.2$ J s^{-1} m^{-1} K^{-1}, $K_2 = 385$ J s^{-1} m^{-1} K^{-1}, we have

$$\frac{50.2\times 2\,(300-T)}{15}=\frac{385T}{10}$$

which gives $T = 44.4$ °C ◀

Example 11.7 An iron bar ($L_1 = 0.1$ m, $A_1 = 0.02$ m^2, $K_1 = 79$ W m^{-1} K^{-1}) and a brass bar ($L_2 = 0.1$ m, $A_2 = 0.02$ m^2, $K_2 = 109$ W m^{-1}K^{-1}) are soldered end to end as shown in Fig. 11.16. The free ends of the iron bar and brass bar are maintained at 373 K and 273 K respectively. Obtain expressions for and hence compute (i) the temperature of the junction of the two bars, (ii) the equivalent thermal conductivity of the compound bar, and (iii) the heat current through the compound bar.

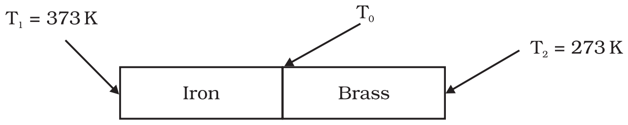

Fig 11.16

Answer

Given, $L_1 = L_2 = L = 0.1$ m, $A_1 = A_2 = A = 0.02$ m^2 $K_1 = 79$ W m^{-1} K^{-1}, $K_2 = 109$ W m^{-1} K^{-1}, $T_1 = 373$ K, and $T_2 = 273$ K.

Under steady state condition, the heat current (H_1) through iron bar is equal to the heat current (H_2) through brass bar.

So, $H = H_1 = H_2$

$$=\frac{K_1 A_1\,(T_1-T_0)}{L_1}=\frac{K_2 A_2\,(T_0-T_2)}{L_2}$$

For $A_1 = A_2 = A$ and $L_1 = L_2 = L$, this equation leads to

$K_1\ (T_1 - T_0) = K_2\ (T_0 - T_2)$

Thus, the junction temperature T_0 of the two bars is

$$T_0=\frac{(K_1T_1+K_2T_2)}{(K_1+K_2)}$$

Using this equation, the heat current H through either bar is

$$H=\frac{K_1 A\,(T_1-T_0)}{L}=\frac{K_2 A\,(T_0-T_2)}{L}$$

$$=\left(\frac{K_1K_2}{K_1+K_2}\right)\frac{A\,(T_1-T_0)}{L}=\frac{A\,(T_1-T_2)}{L\left(\frac{1}{K_1}+\frac{1}{K_2}\right)}$$

Using these equations, the heat current H' through the compound bar of length $L_1 + L_2 = 2L$ and the equivalent thermal conductivity K', of the compound bar are given by

$$H'=\frac{K'\ A\ \ (T_1-T_2)}{2\ L}=H$$

$$K'=\frac{2\ K_1\ \ K_2}{K_1+K_2}$$

(i) $$T_0=\frac{(K_1T_1+K_2T_2)}{(K_1+K_2)}$$

$$=\frac{(79\,\text{W m}^{-1}\text{K}^{-1})(373\,\text{K})+(109\,\text{W m}^{-1}\text{K}^{-1})(273\,\text{K})}{79\,\text{W m}^{-1}\text{K}^{-1}+109\ \text{W m}^{-1}\text{K}^{-1}}$$

$= 315$ K

(ii) $$K'=\frac{2K_1\ K_2}{K_1+K_2}$$

$$=\frac{2\times(79\,\text{W m}^{-1}\ \text{K}^{-1})\times(109\,\text{W m}^{-1}\ \text{K}^{-1})}{79\ \text{W m}^{-1}\ \text{K}^{-1}+109\ \text{W m}^{-1}\ \text{K}^{-1}}$$

$= 91.6$ W m^{-1} K^{-1}

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(iii) $$H' = H = \frac{K' \; A \; (T_1 - T_2)}{2 \; L}$$

$$= \frac{(91.6 \text{ W m}^{-1}\text{ K}^{-1}) \times (0.02 \text{ m}^2) \times (373\text{ K} - 273\text{ K})}{2 \times (0.1 \text{ m})}$$

= 916.1 W ◀

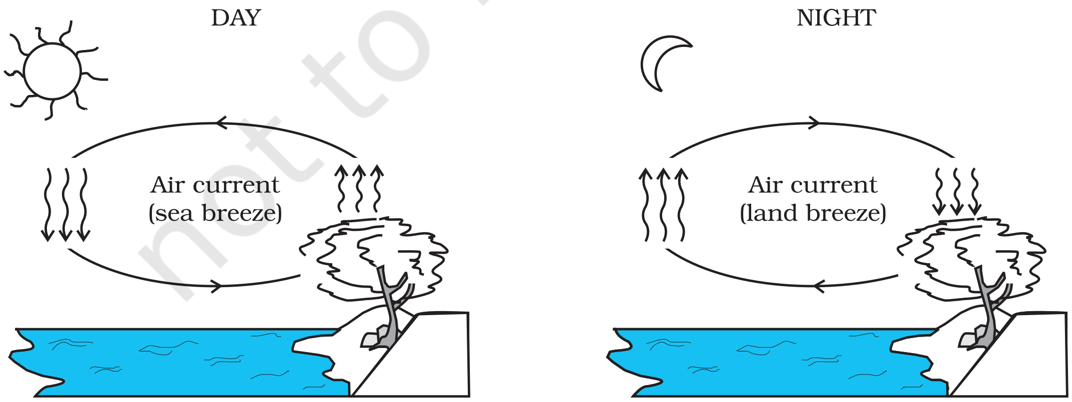
11.9.2 Convection

Convection is a mode of heat transfer by actual motion of matter. It is possible only in fluids. Convection can be natural or forced. In natural convection, gravity plays an important part. When a fluid is heated from below, the hot part expands and, therefore, becomes less dense. Because of buoyancy, it rises and the upper colder part replaces it. This again gets heated, rises up and is replaced by the relatively colder part of the fluid. The process goes on. This mode of heat transfer is evidently different from conduction. Convection involves bulk transport of different parts of the fluid.

In forced convection, material is forced to move by a pump or by some other physical means. The common examples of forced convection systems are forced-air heating systems in home, the human circulatory system, and the cooling system of an automobile engine. In the human body, the heart acts as the pump that circulates blood through different parts of the body, transferring heat by forced convection and maintaining it at a uniform temperature.

Natural convection is responsible for many familiar phenomena. During the day, the ground heats up more quickly than large bodies of water do. This occurs both because water has a greater specific heat capacity and because mixing currents disperse the absorbed heat throughout the great volume of water. The air in contact with the warm ground is heated by conduction. It expands, becoming less dense than the surrounding cooler air. As a result, the warm air rises (air currents) and the other air moves (winds) to fill the space-creating a sea breeze near a large body of water. Cooler air descends, and a thermal convection cycle is set up, which transfers heat away from the land. At night, the ground loses its heat more quickly, and the water surface is warmer than the land. As a result, the cycle is revereseed (Fig. 11.17).

The other example of natural convection is the steady surface wind on the earth blowing in from north-east towards the equator, the so-called trade wind. A resonable explanation is as follows: the equatorial and polar regions of the earth receive unequal solar heat. Air at the earth's surface near the equator is hot, while the air in the upper atmosphere of the poles is cool. In the absence of any other factor, a convection current would be set up, with the air at the equatorial surface rising and moving out towards the poles, descending and streaming in towards the equator. The rotation of the earth, however, modifies this convection current. Because of this, air close to the equator has an eastward speed of 1600 km/h, while it is zero close to the poles. As a result, the air descends not at the poles but at 30° N (North) latitude and returns to the equator. This is called **trade wind**.



Land warmer than water

Water warmer than land

Fig. 11.17 *Convection cycles.*

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11.9.3 Radiation

Conduction and convection require some material as a transport medium. These modes of heat transfer cannot operate between bodies separated by a distance in vacuum. But the earth does receive heat from the Sun across a huge distance. Similarly, we quickly feel the warmth of the fire nearby even though air conducts poorly and before convection takes some time to set in. The third mechanism for heat transfer needs no medium; it is called radiation and the energy so transferred by electromagnetic waves is called radiant energy. In an electromagnetic wave, electric and magnetic fields oscillate in space and time. Like any wave, electromagnetic waves can have different wavelengths and can travel in vacuum with the same speed, namely the speed of light i.e., 3×10^8 m s^{-1}. You will learn these matters in more detail later, but you now know why heat transfer by radiation does not need any medium and why it is so fast. This is how heat is transferred to the earth from the Sun through empty space. All bodies emit radiant energy, whether they are solid, liquid or gas. The electromagnetic radiation emitted by a body by virtue of its temperature, like radiation by a red hot iron or light from a filament lamp is called thermal radiation.

When this thermal radiation falls on other bodies, it is partly reflected and partly absorbed. The amount of heat that a body can absorb by radiation depends on the colour of the body.

We find that black bodies absorb and emit radiant energy better than bodies of lighter colours. This fact finds many applications in our daily life. We wear white or light coloured clothes in summer, so that they absorb the least heat from the Sun. However, during winter, we use dark coloured clothes, which absorb heat from the sun and keep our body warm. The bottoms of utensils for cooking food are blackened so that they absorb maximum heat from fire and transfer it to the vegetables to be cooked.

Similarly, a Dewar flask or thermos bottle is a device to minimise heat transfer between the contents of the bottle and outside. It consists of a double-walled glass vessel with the inner and outer walls coated with silver. Radiation from the inner wall is reflected back to the contents of the bottle. The outer wall similarly reflects back any incoming radiation. The space between the walls is evacuated to reduce conduction and convection losses and the flask is supported on an insulator, like cork. The device is, therefore, useful for preventing hot contents (like, milk) from getting cold, or alternatively, to store cold contents (like, ice).

11.9.4 Blackbody Radiation

We have so far not mentioned the wavelength content of thermal radiation. The important thing about thermal radiation at any temperature is that it is not of one (or a few) wavelength(s) but has a continuous spectrum from the small to the long wavelengths. The energy content of radiation, however, varies for different wavelengths. Figure 11.18 gives the experimental curves for radiation energy per unit area per unit wavelength emitted by a blackbody versus wavelength for different temperatures.

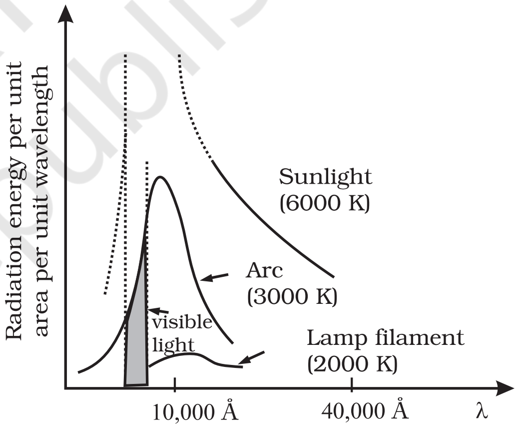

Fig. 11.18: *Energy emitted versus wavelength for a blackbody at different temperatures*

Notice that the wavelength λ_m for which energy is the maximum decreases with increasing temperature. The relation between λ_m and T is given by what is known as **Wien's Displacement Law**:

$$\lambda_m T = \text{constant} \qquad (11.15)$$

The value of the constant (Wien's constant) is 2.9×10^{-3} m K. This law explains why the colour of a piece of iron heated in a hot flame first becomes dull red, then reddish yellow, and finally white hot. Wien's law is useful for estimating the surface temperatures of celestial

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bodies like, the moon, Sun and other stars. Light from the moon is found to have a maximum intensity near the wavelength 14 μm. By Wien's law, the surface of the moon is estimated to have a temperature of 200 K. Solar radiation has a maximum at λ_m = 4753 Å. This corresponds to T = 6060 K. Remember, this is the temperature of the surface of the sun, not its interior.

The most significant feature of the blackbody radiation curves in Fig. 11.18 is that they are *universal*. They depend only on the temperature and not on the size, shape or material of the blackbody. Attempts to explain blackbody radiation theoretically, at the beginning of the twentieth century, spurred the quantum revolution in physics, as you will learn in later courses.

Energy can be transferred by radiation over large distances, without a medium (i.e., in vacuum). The total electromagnetic energy radiated by a body at absolute temperature T is proportional to its size, its ability to radiate (called emissivity) and most importantly to its temperature. For a body, which is a perfect radiator, the energy emitted per unit time (H) is given by

$$H = A\sigma T^4 \qquad (11.16)$$

where A is the area and T is the absolute temperature of the body. This relation obtained experimentally by Stefan and later proved theoretically by Boltzmann is known as **Stefan-Boltzmann law** and the constant σ is called Stefan-Boltzmann constant. Its value in SI units is 5.67×10^{-8} W m^{-2} K^{-4}. Most bodies emit only a fraction of the rate given by Eq. 11.16. A substance like lamp black comes close to the limit. One, therefore, defines a dimensionless fraction e called *emissivity* and writes,

$$H = Ae\sigma T^4 \qquad (11.17)$$

Here, e = 1 for a perfect radiator. For a tungsten lamp, for example, e is about 0.4. Thus, a tungsten lamp at a temperature of 3000 K and a surface area of 0.3 cm^2 radiates at the rate $H = 0.3 \times 10^{-4} \times 0.4 \times 5.67 \times 10^{-8} \times (3000)^4 = 60$ W.

A body at temperature T, with surroundings at temperatures T_s, emits, as well as, receives energy. For a perfect radiator, the net rate of loss of radiant energy is

$$H = \sigma A\ (T^4 - T_s^4)$$

For a body with emissivity e, the relation modifies to

$$H = e\sigma\ A\ (T^4 - T_s^4) \qquad (11.18)$$

As an example, let us estimate the heat radiated by our bodies. Suppose the surface area of a person's body is about 1.9 m^2 and the room temperature is 22°C. The internal body temperature, as we know, is about 37°C. The skin temperature may be 28°C (say). The emissivity of the skin is about 0.97 for the relevant region of electromagnetic radiation. The rate of heat loss is:

$$H = 5.67 \times 10^{-8} \times 1.9 \times 0.97 \times \{(301)^4 - (295)^4\}$$

$$= 66.4 \text{ W}$$

which is more than half the rate of energy production by the body at rest (120 W). To prevent this heat loss effectively (better than ordinary clothing), modern arctic clothing has an additional thin shiny metallic layer next to the skin, which reflects the body's radiation.

11.9.5 Greenhouse Effect

The earth's surface is a source of thermal radiation as it absorbs energy received from the Sun. The wavelength of this radiation lies in the long wavelength (infrared) region. But a large portion of this radiation is absorbed by greenhouse gases, namely, carbon dioxide (CO_2); methane (CH_4); nitrous oxide (N_2O); chlorofluorocarbon (CF_xCl_x); and tropospheric ozone (O_3). This heats up the atmosphere which, in turn, gives more energy to earth, resulting in warmer surface. This increases the intensity of radiation from the surface. The cycle of processes described above is repeated until no radiation is available for absorption. The net result is heating up of earth's surface and atmosphere. This is known as **Greenhouse Effect**. Without the Greenhouse Effect, the temperature of the earth would have been –18°C.

Concentration of greenhouse gases has enhanced due to human activities, making the earth warmer. According to an estimate, average temperature of earth has increased by 0.3 to 0.6°C, since the beginning of this century because of this enhancement. By the middle of the next century, the earth's global temperature may be 1 to 3°C higher than today. This global

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warming may cause problem for human life, plants and animals. Because of global warming, ice caps are melting faster, sea level is rising, and weather pattern is changing. Many coastal cities are at the risk of getting submerged. The enhanced Greenhouse Effect may also result in expansion of deserts. All over the world, efforts are being made to minimise the effect of global warming.

11.10 NEWTON'S LAW OF COOLING

We all know that hot water or milk when left on a table begins to cool, gradually. Ultimately it attains the temperature of the surroundings. To study how slow or fast a given body can cool on exchanging heat with its surroundings, let us perform the following activity.

Take some water, say 300 mL, in a calorimeter with a stirrer and cover it with a two-holed lid. Fix the stirrer through one hole and fix a thermometer through another hole in the lid and make sure that the bulb of thermometer is immersed in the water. Note the reading of the thermometer. This reading T_1 is the temperature of the surroundings. Heat the water kept in the calorimeter till it attains a temperature, say 40 °C above room temperature (i.e., temperature of the surroundings). Then, stop heating the water by removing the heat source. Start the stop-watch and note the reading of the thermometer after a fixed interval of time, say after every one minute of stirring gently with the stirrer. Continue to note the temperature (T_2) of water till it attains a temperature about 5 °C above that of the surroundings. Then, plot a graph by taking each value of temperature $\Delta T = T_2 - T_1$ along y-axis and the coresponding value of t along x-axis (Fig. 11.19).

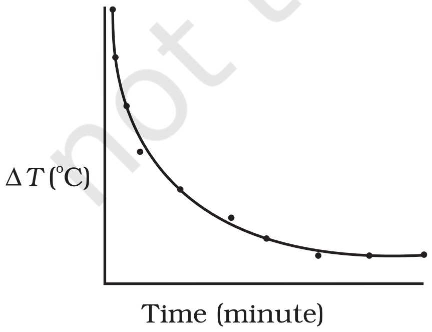

Fig. 11.19 Curve showing cooling of hot water with time.

From the graph you can infer how the cooling of hot water depends on the difference of its temperature from that of the surroundings. You will also notice that initially the rate of cooling is higher and decreases as the temperature of the body falls.

The above activity shows that a hot body loses heat to its surroundings in the form of heat radiation. The rate of loss of heat depends on the difference in temperature between the body and its surroundings. Newton was the first to study, in a systematic manner, the relation between the heat lost by a body in a given enclosure and its temperature.

According to Newton's law of cooling, the rate of loss of heat, $-\mathrm{d}Q/\mathrm{d}t$ of the body is directly proportional to the difference of temperature $\Delta T = (T_2 - T_1)$ of the body and the surroundings. The law holds good only for small difference of temperature. Also, the loss of heat by radiation depends upon the nature of the surface of the body and the area of the exposed surface. We can write

$$-\frac{dQ}{dt} = k\,(T_2 - T_1) \qquad (11.19)$$

where k is a positive constant depending upon the area and nature of the surface of the body. Suppose a body of mass m and specific heat capacity s is at temperature T_2. Let T_1 be the temperature of the surroundings. If the temperature falls by a small amount $\mathrm{d}T_2$ in time $\mathrm{d}t$, then the amount of heat lost is

$\mathrm{d}Q = ms\,\mathrm{d}T_2$

∴ Rate of loss of heat is given by

$$\frac{dQ}{dt} = ms\frac{dT_2}{dt} \qquad (11.20)$$

From Eqs. (11.15) and (11.16) we have

$$-m\,s\frac{dT_2}{dt} = k\,(T_2 - T_1)$$

$$\frac{dT_2}{T_2 - T_1} = -\frac{k}{ms}dt = -K\,dt \qquad (11.21)$$

where $K = k/m\,s$

On integrating,

$$\log_e (T_2 - T_1) = -K\,t + c \qquad (11.22)$$

$$\text{or } T_2 = T_1 + C'\,e^{-Kt}; \text{ where } C' = e^c \qquad (11.23)$$

Equation 11.23 enables you to calculate the time of cooling of a body through a particular range of temperature.

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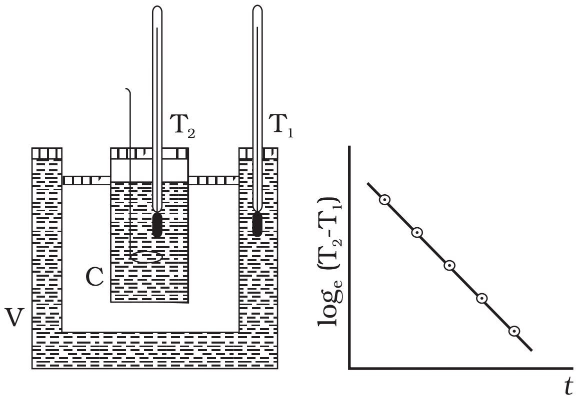
For small temperature differences, the rate of cooling, due to conduction, convection, and radiation combined, is proportional to the difference in temperature. It is a valid approximation in the transfer of heat from a radiator to a room, the loss of heat through the wall of a room, or the cooling of a cup of tea on the table.



(a) (b)

Fig. 11.20 *Verification of Newton's Law of cooling.*

Newton's law of cooling can be verified with the help of the experimental set-up shown in Fig. 11.20(a). The set-up consists of a double-walled vessel (V) containing water between the two walls. A copper calorimeter (C) containing hot water is placed inside the double-walled vessel. Two thermometers through the corks are used to note the temperatures T_2 of water in calorimeter and T_1 of hot water in between the double walls, respectively. Temperature of hot water in the calorimeter is noted after equal intervals of time. A graph is plotted between $\log_e (T_2-T_1)$ [or $\ln(T_2-T_1)$] and time (t). The nature of the graph is observed to be a straight line having a negative slope as shown in Fig. 11.20(b). This is in support of Eq. 11.22.

Example 11.8 A pan filled with hot food cools from 94 °C to 86 °C in 2 minutes when the room temperature is at 20 °C. How long will it take to cool from 71 °C to 69 °C?

Answer The average temperature of 94 °C and 86 °C is 90 °C, which is 70 °C above the room temperature. Under these conditions the pan cools 8 °C in 2 minutes.

Using Eq. (11.21), we have

$$\frac{\text{Change in temperature}}{\text{Time}} = K\Delta T$$

$$\frac{8\,°\text{C}}{2\text{ min}} = K(70\,°\text{C})$$

The average of 69 °C and 71 °C is 70 °C, which is 50 °C above room temperature. K is the same for this situation as for the original.

$$\frac{2\,°\text{C}}{\text{Time}} = K\,(50\,°\text{C})$$

When we divide above two equations, we have

$$\frac{8\,°\text{C}/2\text{ min}}{2\,°\text{C}/\text{time}} = \frac{K\,(70\,°\text{C})}{K\,(50\,°\text{C})}$$

Time = 0.7 min

= 42 s

SUMMARY

1. Heat is a form of energy that flows between a body and its surrounding medium by virtue of temperature difference between them. The degree of hotness of the body is quantitatively represented by temperature.
2. A temperature-measuring device (thermometer) makes use of some measurable property (called thermometric property) that changes with temperature. Different thermometers lead to different temperature scales. To construct a temperature scale, two fixed points are chosen and assigned some arbitrary values of temperature. The two numbers fix the origin of the scale and the size of its unit.
3. The Celsius temperature (t_C) and the Farenheit temperare (t_F)are related by

$$t_F = (9/5)\, t_C + 32$$

4. The ideal gas equation connecting pressure (P), volume (V) and absolute temperature (T) is :

$$PV = \mu RT$$

where μ is the number of moles and R is the universal gas constant.

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5. In the absolute temperature scale, the zero of the scale corresponds to the temperature where every substance in nature has the least possible molecular activity. The Kelvin absolute temperature scale (T) has the same unit size as the Celsius scale (T_c), but differs in the origin :

$$T_C = T - 273.15$$

6. The coefficient of linear expansion (α_l) and volume expansion (α_v) are defined by the relations :

$$\frac{\Delta l}{l} = \alpha_l \Delta T$$

$$\frac{\Delta V}{V} = \alpha_V \Delta T$$

where Δl and ΔV denote the change in length l and volume V for a change of temperature ΔT. The relation between them is :

$$\alpha_v = 3\,\alpha_l$$

7. The specific heat capacity of a substance is defined by

$$s = \frac{1}{m}\frac{\Delta Q}{\Delta T}$$

where m is the mass of the substance and ΔQ is the heat required to change its temperature by ΔT. The molar specific heat capacity of a substance is defined by

$$C = \frac{1}{\mu}\frac{\Delta Q}{\Delta T}$$

where μ is the number of moles of the substance.

8. The latent heat of fusion (L_f) is the heat per unit mass required to change a substance from solid into liquid at the same temperature and pressure. The latent heat of vaporisation (L_v) is the heat per unit mass required to change a substance from liquid to the vapour state without change in the temperature and pressure.

9. The three modes of heat transfer are conduction, convection and radiation.

10. In conduction, heat is transferred between neighbouring parts of a body through molecular collisions, without any flow of matter. For a bar of length L and uniform cross section A with its ends maintained at temperatures T_C and T_D, the rate of flow of heat H is :

$$H = K\,A\,\frac{T_C - T_D}{L}$$

where K is the thermal conductivity of the material of the bar.

11. Newton's Law of Cooling says that the rate of cooling of a body is proportional to the excess temperature of the body over the surroundings :

$$\frac{\mathrm{d}Q}{\mathrm{d}t} = -k\,(T_2 - T_1)$$

Where T_1 is the temperature of the surrounding medium and T_2 is the temperature of the body.

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