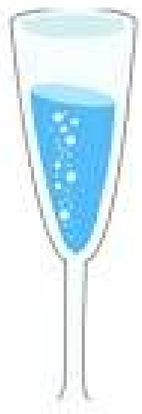
11.1. Introduction

You might have noticed that you feel hotter on a sunny afternoon as compared to a windy night. This is because of the difference in temperatures. Temperature is very high in the afternoon as compared to night. This chapter basically gives us the

Examples: information about thermal properties of matter where we will study about the properties of different substances by virtue of heat/heat transfer.

In simple terms, we can say that when the temperature is more heat is more, and when the temperature is less heat is less.

Hot Sunny day (Temperature is more)and ice-cold water (Temperature is less).



Temperature and Heat

Temperature is defined as the measure of the degree of hotness or coldness of a body.

Example:-

- A cup of hot soup or a scoop of Ice-cream.

Heat is the form of energy transferred between two (or more) systems or a system and its surroundings by virtue of temperature difference.

For eg.:- a cup of hot coffee can be considered as an object or system and anything apart from hot coffee is surroundings. Then the heat will flow from one object to another as there is a difference in temperature.

After some time we will see this hot cup of coffee will become cold as there will be a transfer of heat.

The S.I Unit of Heat is the joule (J) and some of the commonly used units are: calorie and kilocalorie

The relation between Joule and Calorie

1calorie=4.18 Joules

1kilocalorie = 1000 calories

The S.I. Unit of temperature is Kelvin (K) and some of the commonly used units are: Fahrenheit (°F) and Celsius (°C)

Measurement of Temperature

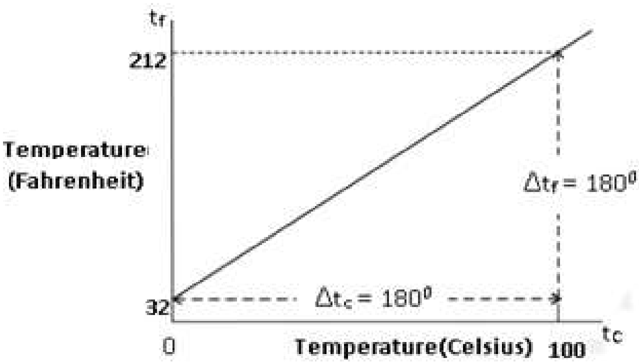
Temperature is measured with the help of a thermometer. Mercury and Alcohol are commonly used liquids in the liquid-in-glass thermometers.

- To construct a thermometer two fixed points are to be chosen as a reference point. These fixed points are known as freezing(ice point) and boiling point(steam point). The water freezes and boils at these two points under standard pressure.

- The ice and steam point in Fahrenheit Temperature scale is 32°F and 212 °F resp. It has 180 equal intervals between two reference points.
- On the Celsius Scale values are 0°C and 100°C for ice and steam point resp. It has 100 equal intervals between two reference points.

Mercury-in-Thermometer

Graphically the relation between the temperature in Celsius and Fahrenheit is given by the following graph:-



And whose equation is:

$(t_f - 32)/180 = t_c/100$

Where t_f = Fahrenheit temperature

t_c= Celsius temperature

Ideal-gas Equation and Absolute Temperature

A thermometer that uses any gas, however, gives the same readings regardless of which gas is used because all gases have the same expansion at low temperatures.

Variables that describe the behavior of gas are:-

- Quantity(mass)
- Pressure
- Volume
- Temperature i.e. (P,V,T) where (T = t + 273.15; t is the temperature in °C)

Gases which have low density obey certain laws: -

1.**Boyle's Law**– PV = constant(when temperature T is constant)

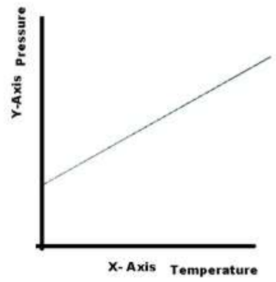
2.**Charles' Law**- V/T = constant (when pressure P is constant)

- If combine both the above laws the equation becomes PV = RT where R is called **universal gas constant** and its value = 8.31 J mol^{-1} K^{-1}.
- PV = RT is the ideal gas equation which is applicable only at low temperature.
- For any quantity of dilute gas,

PV=μRT where μ, is the number of moles in the sample of gas.

- In a constant volume gas, thermometer temperature varies with respect to pressure.

  Temperature changes linearly with an increase in pressure.

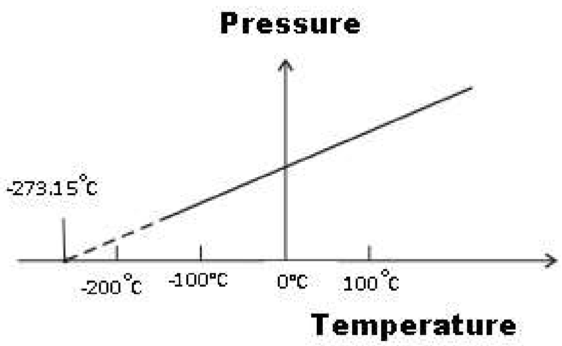


Absolute Zero

Absolute Zero is defined as the minimum absolute temperature of an ideal gas.

- If we plot pressure versus temperature we get a straight line and if we extend the line backwards to the x-axis as shown in the graph below. The minimum temperature is found to be 273.15 °C (experimentally) and this value is known as absolute zero.
- The relation between the temperature in kelvin and Celsius scale is given by

$T = t_C + 273.15$



Problem: The triple points of neon and carbon dioxide are 24.57 K and 216.55 K respectively.

Express these temperatures on the Celsius and Fahrenheit scales?

Solution: Celsius and Fahrenheit scales are related as

$T_F = (9/5)T_C + 32$ ... (ii)

For neon:

= 24.57 K

= 24.57 – 273.15 = –248.58°C

$T_F = (9/5)\ T_C + 32$

=9/5(-248.58) +32

=415.44 ºF

For carbon dioxide:

= 216.55 K

= 216.55 – 273.15 = –56.60°C

$T_F = (9/5)T_C + 32$

=9/5(-56.60) +32

= -69.88 ºC

Problem: Two absolute scales A and B have triple points of water defined to be 200 A and 350 B. What is the relation between T_A and T_B?

Solution:

The triple point of water on absolute scale A, $T_1 = 200$ A

The triple point of water on absolute scale B, $T_2 = 350$ B

The triple point of water on Kelvin scale, $T_k = 273.15$ K

The temperature of 273.15 K on the Kelvin scale is equivalent to 200 A on absolute scale A.

$T_1 = T_k$

200 A = 273.15 K

Therefore,

A = 273.15/200

The temperature of 273.15 K on the Kelvin scale is equivalent to 350 B on absolute scale B.

$T_2 = T_k$

350 B = 273.15

B= 273.15/350

T_A is the triple point of water on scale A. T_B is the triple point of water on scale B

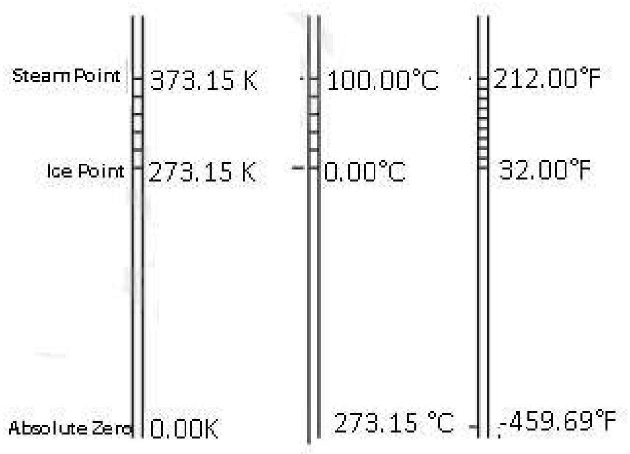
Therefore,

$$\frac{273.15}{200} \times T_A = \frac{273.15}{350} \times T_B$$

$$T_A = \frac{200}{350} T_B$$

Therefore, the ratio $T_A : T_B$ is given as 4: 7.

Comparison of Kelvin, Celsius and Fahrenheit temperature scales



WORKSHEET

1. Convert the temperature given on the Celsius scale to the Fahrenheit scale:

(i) 25° C

(ii) 45° C

(iii) 0° C

(iv) 20° C

(v) 90° C

(vi) 40.3° C

(vii) 65° C

2. Convert the temperature given on the Fahrenheit scale to the Celsius scale:

(i) 102° F

(ii) 37° F

(iii) 200° F

(iv) 175° F

(v) 185° F

(vi) 158° F

(vii) 68° F

3. What instrument is used to measure hotness or coldness or a thing?

4. What is the normal body temperature in degrees Fahrenheit?

5. What is the freezing point of water in degrees Celsius?

6. One day the minimum temperature in Bombay was recorded as 80.6° F. What was the temperature in degree Celsius of Bombay on that day?

7. In the month of June, on one day the maximum temperature in Delhi was recorded as 42.4° C. Convert it into degree Fahrenheit.

Answers for the worksheet on the conversion of temperature are given below.

Answers:

1. (i) 77° F

(ii) 113° F

(iii) 32° F

(iv) 68° F

(v) 194° F

(vi) 104.54° F

(vii) 149° F

2. (i) 38.89° C

(ii) 2.78° C

(iii) 93.33° C

(iv) 79.44° C

(v) 85° C

(vi) 70° C

(vii) 20° C

3. Thermometer

4. 98.4° F

5. 0° C

6. 27° C

7. 108.32° F

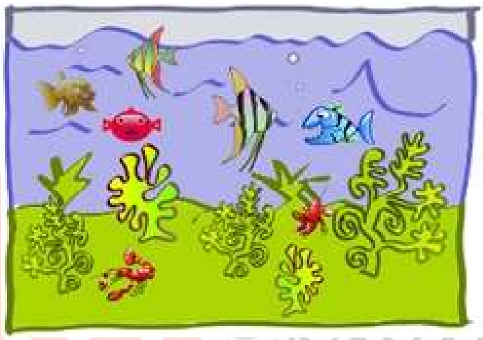
11.2 Thermal Expansion

- Thermal expansion is the phenomenon of the increase in dimensions of a body due to the increase in its temperature.

Examples of Thermal Expansion

- The water is cold at the top of the lake because it expands and becomes less dense. So when this water freezes it insulates the water below it from the outside which means cold air is like a blanket. It is because of this property many fish can survive in the winter.

(1)



Even though the top layer of water is frozen as we can see in the image (1), the plant and animal life are not getting affected as shown in the image (2).

- As soon as we turn on a hot water tap, the water comes very fast as water is still cold. But as soon as hot water starts coming, the flow of water becomes less and in some cases, it stops. This is because the hot water heats the metal valve inside the tap which expands to block off any more flow of water.

The reason why Thermal Expansion happens is:-

- When any object is heated particles start moving in random motion and thus the average distance between the molecules increases and a result the object appears to be expanded when heated. As we can see the picture below atoms is tightly packed but when we apply heat they will start moving in random motion.

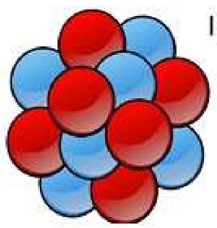


Image (a)

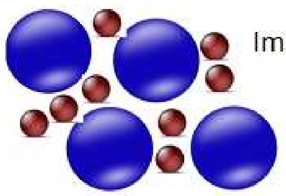


Image (b)

As we can see in the Image (a) molecules are very tightly packed but when heated the molecules start moving apart in random motion, which can be seen in Image (b).

- When an object is cooled it contracts which is referred to as negative thermal expansion.

Types of Thermal Expansion

1. Linear Expansion:- The expansion in length
2. Area Expansion:- The expansion in the area
3. Volume Expansion:- The expansion in volume

Linear Expansion

Linear Expansion means expansion in length due to the increase in temperature. The linear expansion means a fractional change in length i.e. how the length is changing with respect to the original length.

LinearExpansion $\frac{A}{A}\alpha_l T$

As we can see from the above images the length has been increased from l to l+Δl.

The coefficient of Linear Expansion is a parameter that tells us how the size of the object changes with a change in temperature. It is defined as the degree of linear expansion divided by the change in temperature.

- If the solid is in the form of a long rod, then for a small change in temperature, ΔT, the fractional change in length, Δl/l, is directly proportional to ΔT.

Mathematically can be written as:-

$$\frac{\Delta l}{l} = \alpha_1 \Delta T$$

Where α_l= the coefficient of linear expansion

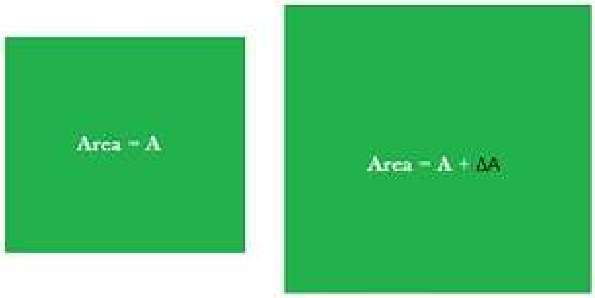
It is denoted by α_l

- It is characteristic of the material of the rod. It varies for a different substance.

Example

- The automatic hot water kettle switches off on its own when the water boils.
- Metals expand more and have a higher value of the coefficient of linear expansion.

Area Expansion



$$\frac{A}{A} 2\alpha_l T$$

Area Expansion can be defined as expansion in the area due to the increase in temperature. In the case of area expansion, there is an increase in both lengthwise and breadthwise.

As we can see from the above images the area of the cube has been increased from A to A + ΔA.

Mathematically can be written as:-

$\Delta A / A = \alpha_a \Delta T$

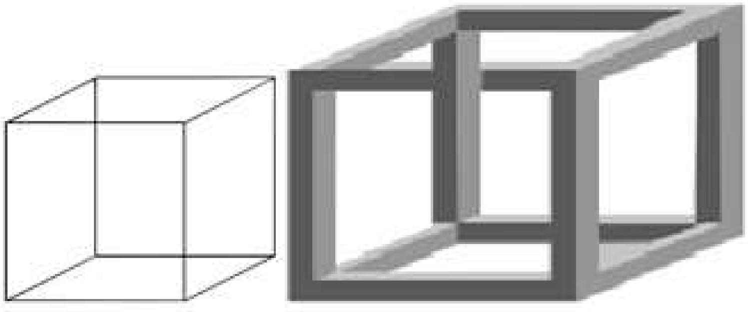
Where α_a = coefficient of area expansion.

The coefficient of Area Expansion is defined as the degree of area expansion divided by the change in temperature. This means there is an increase in the area of an object with a change in temperature.

- It is denoted by α_a
- It is characteristic of the substance and it varies with temperature.

Volume Expansion

It can be defined as expansion in volume due to an increase in temperature. This means there is an increase in the length, breadth, and height of a substance.



$$\frac{V}{V} \; 3\alpha_l T$$

- As we can see from the above images the volume of the cube has been increased from V to V + ΔV there is an increase in length, width, and height.
- The expansion in volume due to an increase in temperature. Mathematically can be written as:-

$\Delta V / V = \alpha_v \Delta T$

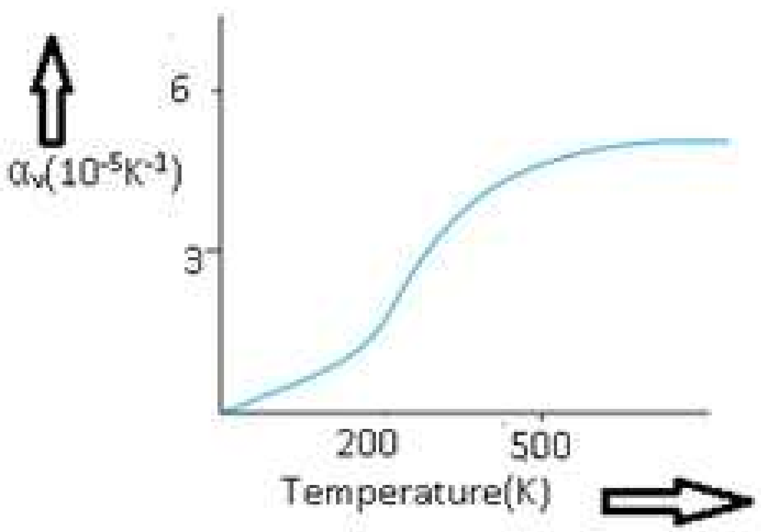
Where α_v = coefficient of volume.

The coefficient of Volume can be defined as the degree of volume expansion divided by change in temperature.

- It is denoted by α_v.
- It is characteristic of the substance
- It varies with temperature.

If the graph is plotted between α_v and temperature, then initially α_v is changing linearly then it varies non-linearly and at higher temperatures, and then it becomes constant.

Coefficient of volume expansion of copper as a function of temperature-



The thermal expansion of solids and liquids is small.

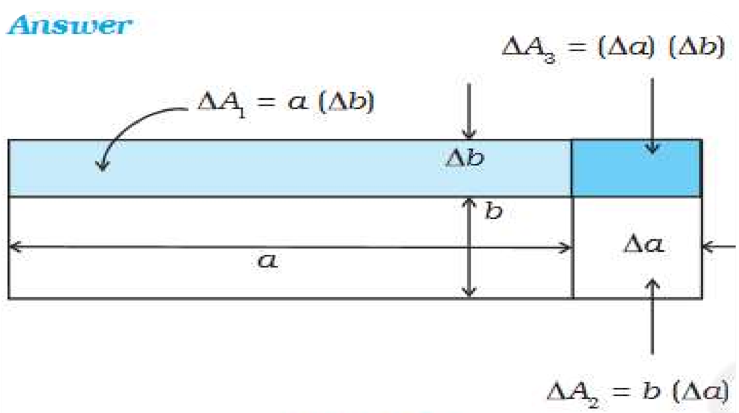


Fig. 11.8

Consider a rectangular sheet of the solid material of length a and breadth b (Fig. 11.8). When the temperature increases by ΔT, a increases by $\Delta a = \alpha_l a\Delta T$ and b increases by $\Delta b = \alpha_l b\ \Delta T$. From Fig. 11.8, the increase in area

$$\Delta A = \Delta A_1 + \Delta A_2 + \Delta A_3$$

$$\Delta A = a\ \Delta b + b\ \Delta a + (\Delta a)\ (\Delta b)$$

$$= a\ \alpha_l b\ \Delta T + b\ \alpha_l\ a\ \Delta T + (\alpha_l)^2\ ab\ (\Delta T)^2$$

$$= \alpha_l\ ab\ \Delta T\,(2 + \alpha_l\ \Delta T) = \alpha_l\ A\,\Delta T\,(2 + \alpha_l\ \Delta T)$$

Since $\alpha_l \approx 10^{-5}\ K^{-1}$, from Table 11.1, the product $\alpha_l\ \Delta T$ for fractional temperature is small in comparision with 2 and may be neglected. Hence,

$$\left(\frac{\Delta A}{A}\right)\frac{1}{\Delta T} = 2\alpha_l$$

Example 11.2 A blacksmith fixes iron ring on the rim of the wooden wheel of a bullock cart. The diameter of the rim and the iron ring are 5.243 m and 5.231 m respectively at 27 °C. To what temperature should the ring be heated so as to fit the rim of the wheel?

Answer

Given, $T_1 = 27$ °C

$L_{T1} = 5.231$ m

$L_{T2} = 5.243$ m

So,

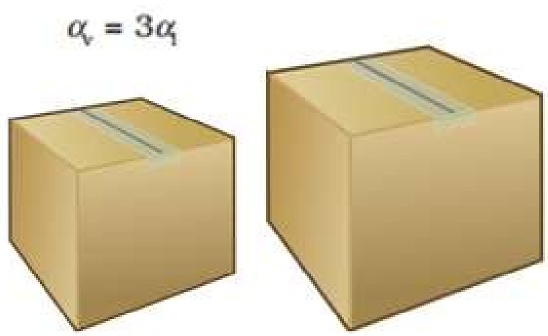
$$L_{T2} = L_{T1}\ [1 + \alpha_l\ (T_2 - T_1)]$$

$$5.243\ m = 5.231\ m\ [1 + 1.20 10^{-5}\ K^{-1}\ (T_2 - 27\ °C)]$$

or $T_2 = 218$ °C.

The relation between α_v and α_l

- The relation between the coefficient of linear expansion and coefficient of volume expansion =



To derive the above relation consider a block of cube initially its length is l, suppose temperature is increased T + ΔT as a result length will also increase from (l+Δl)

Then $\alpha_l = (\Delta l/l)/\Delta T$

Therefore, $\alpha_l l \Delta T = \Delta l$

Also as the temperature increases by ΔT, the volume increases V +ΔV

Where ΔV = change in volume which we can write as

$\Delta V = (l+\Delta l)^3 - l^3$

By solving we get $\Delta V = 3l^2 \Delta l$(we are neglecting $(\Delta l)^2$ and $(\Delta l)^3$as they are very small as to compared to l.

Therefore, $\Delta V = (3V \Delta l)/l$

$= 3V\alpha_l \Delta T$

Which gives $\alpha_v = 3\alpha_l$ the relation between the coefficient of volume expansion and coefficient of linear expansion.

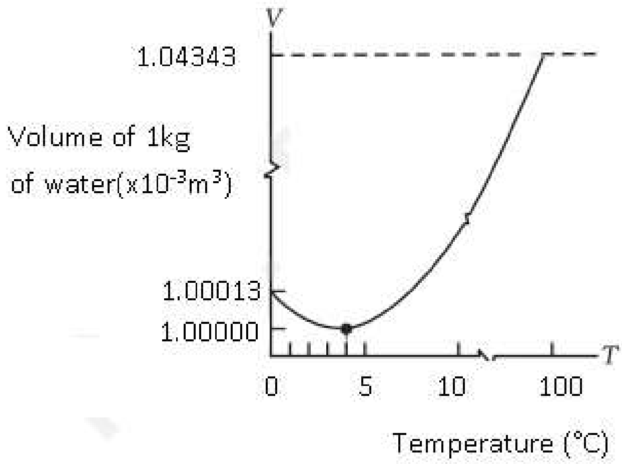
Thermal stress:

- Mechanical stress induced by a body when some or all of its parts are not free to expand or contract in response to change in temperature.
  - When an object is heated or cooled either it expands or it contracts but if for some reason if the object is not allowed to expand to contract under that case mechanical stress is induced in the body which is known as Thermal Stress.
- Example:-

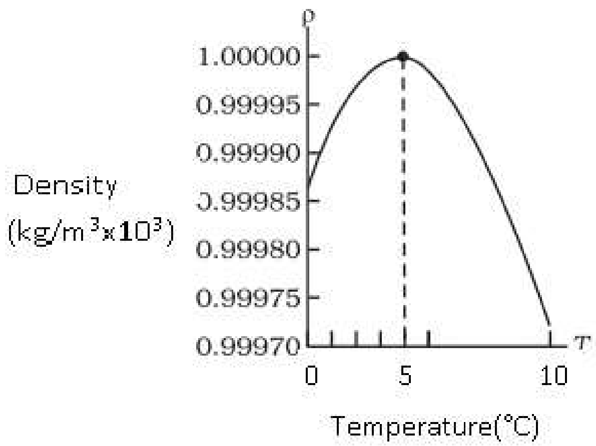
While designing structures like concrete highways gaps are left which are filled by some flexible material so that concrete is allowed to expand or contract.

11.3 Anomalous Behavior of Water

- Water shows some exceptional behavior that is when it is heated at 0°C, it contracts instead of expanding and it happens till it reaches 4 °C. The volume of a given amount of water is minimum at 4 °C, therefore, its density is maximum(Refer the Fig). After 4 °C water starts expanding. Below 4 °C, the volume increases, and therefore the density decreases. This means water has a maximum density at 4 °C.
- Advantages of Anomalous behavior of Water
- Because of this property of water in lakes and ponds freeze only at the top layer and at the bottom it does not, but if the water freezes at the bottom also then animal and plant life would not be possible.



If we plot temperature on X-axis and Density on Y-Axis we will obtain the graph as given below:-



The information we get from the above graph means that the density increases as its temperature rises from 0°C to 4 °C and density decreases after 4°C.

11.4. Heat Capacity

The change in temperature of a substance, when a given quantity of heat is absorbed or rejected by a substance is characterized by a quantity called the heat capacity of that substance.

- It is denoted by S.
- It is given as $S = \Delta Q / \Delta T$

Where ΔQ = amount of heat supplied to the substance and T to $T + \Delta T$ change in its temperature.

Specific heat capacity:

- Every substance has a unique value for the amount of heat absorbed or rejected to change the temperature of a unit mass of it by one unit. This quantity is referred to as the specific heat capacity of the substance.

Mathematically can be written as:-

$$S = \frac{\Delta Q}{\Delta T}$$

Where ΔQ = amount of heat absorbed or rejected by a substance

ΔT = temperature change

Specific Heat Capacity

- Specific heat is defined as the amount of heat per unit mass absorbed or rejected by the substance to change its temperature by one.

Mathematically can be written as:-

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

Where

- ΔQ = amount of heat absorbed or rejected by a substance
- m = mass
- ΔT = temperature change

- It depends on the nature of the substance and its temperature.
- The SI unit of specific heat capacity is J kg^{-1} K^{-1}.

Molar specific heat capacity: -

- Heat capacity per mole of the substance is defined as the amount of heat (in moles) absorbed or rejected(instead of mass m in kg) by the substance to change its temperature by one unit.

Mathematically can be written as:-

$C = S/ \mu = \Delta Q / \mu \Delta T$

Where

- μ= amount of substance in moles

- C = molar specific heat capacity of the substance.
- ΔQ = amount of heat absorbed or rejected by a substance.
- ΔT = temperature change

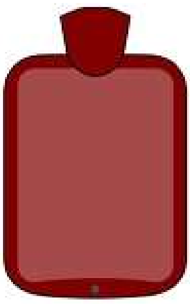
It depends on the nature of the substance and its temperature. The SI unit of molar specific heat capacity is $Jmol^{-1}\ K^{-1}$

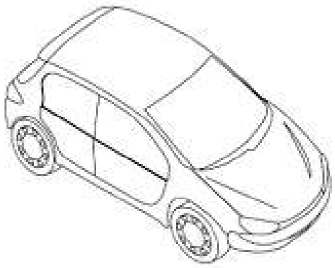
Molar specific heat capacity (Cp):-

- If the gas is held under constant pressure during the heat transfer, then the corresponding molar specific heat capacity is called molar specific heat capacity at constant pressure (Cp).

Molar specific heat capacity (C_v):-

- If the volume of the gas is maintained during the heat transfer, then the corresponding molar specific heat capacity is called molar specific heat capacity at constant volume (C_v).
- Water has the highest specific heat of capacity because of which it is used as a coolant in automobile radiators and hot water bags.





Problem:- In an experiment on the specific heat of a metal, a 0.20 kg block of the metal at 150 °C is dropped in a copper calorimeter (of water equivalent 0.025 kg) containing 150 cm^3 of water at 27 °C. The final temperature is 40 °C. Compute the specific heat of the metal. If heat losses to the surroundings are not negligible, is your Solution greater or smaller than the actual value for the specific heat of the metal?

Solution:- Mass of the metal, m = 0.20 kg = 200 g

Initial temperature of the metal, T_1 = 150°C

Final temperature of the metal, T_2 = 40°C

Calorimeter has water equivalent of mass, m' = 0.025 kg = 25 g

Volume of water, V = 150 cm^3

Mass (M) of water at temperature T = 27°C: 150 × 1 = 150 g

Fall in the temperature of the metal:

$\Delta T = T_1 - T_2 = 150 - 40 = 110°C$

Specific heat of water, C w = 4.186 J/g/°K

Specific heat of the metal = C

Heat lost by the metal, $\theta = m C\Delta T$ … (i)

Rise in the temperature of the water and calorimeter system:

$\Delta T = 40 - 27 = 13°C$

Heat gained by the water and calorimeter system:

$\Delta\theta'' = m1\ C\ w\ \Delta T'$

$= (M + m')\ C\ w\ \Delta T'$ … (ii)

Heat lost by the metal = Heat gained by the water and calorimeter system

$mC\ \Delta T = (M + m')\ Cw\ \Delta T'$

$200 \times C \times 110 = (150 + 25) \times 4.186 \times 13$

$$\frac{175 \times 4.186 \times 13}{110 \times 200} = 0.43 J g^{-1} K^{-1}$$

If some heat is lost to the surroundings, then the value of C will be smaller than the actual value.

Specific heat capacity

- Specific heat is defined as the amount of heat required to raise the temperature of a body per unit mass.
- It depends on:-
- Nature of substance
- Temperature
- Denoted by 's'

Mathematically:-

$$s = (\Delta Q / m \Delta T)$$

- where m= mass of the body
- ΔQ = amount of heat absorbed or rejected by the substance
- ΔT= temperature change
- Unit - J kg^{-1} K^{-1}
- If we are heating oil in a pan, more heat is needed when heating one cup of oil compared to just one tablespoon of oil. If the mass s is more the amount of heat required is more to increase the temperature by one degree.

Specific heat capacity of water

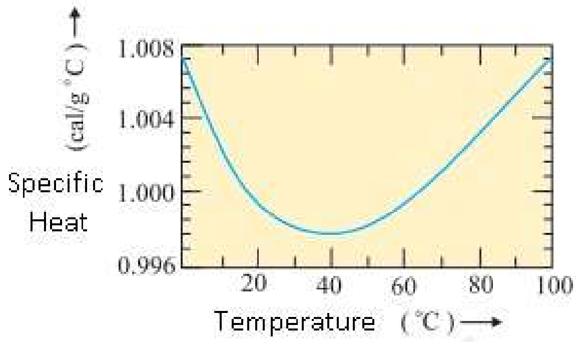
Calorie: - One calorie is defined to be the amount of heat required to raise the

the temperature of 1g of water from 14.5 °C to 15.5 °C.

- In SI units, the specific heat capacity of water is 4186 J kg^{-1} K^{-1}e.

4.186 J g^{-1} K^{-1}.

- The specific heat capacity depends on the process or the conditions under which heat capacity transfer takes place.



Variation of specific heat capacity of water with temperature

- Water has the highest specific heat of capacity because of which it is used as a coolant in automobile radiators and hot water bags.

Problem: A geyser heats water flowing at the rate of 3.0 liters per minute from 27 °C to 77 °C. If the geyser operates on a gas burner, what is the rate of consumption of the fuel if its heat of combustion is 4.0 × 104 J/g?

Answer:

Water is flowing at a rate of 3.0 liter/min.

The geyser heats the water, raising the temperature from 27°C to 77°C.

Initial temperature, T_1 = 27°C

Final temperature, T_2 = 77°C

∴Rise in temperature, $\Delta T = T_2 - T_1$

$= 77 – 27= 50°C$

Heat of combustion = 4×10^4 J/g°C

Specific heat of water, c = 4.2 $J^{-1}\ g^{-1}°C^{-1}$

Mass of flowing water, m = 3.0 litre/min = 3000 g/min

Total heat used, $\Delta Q = mc\ \Delta T$

$= 3000 \times 4.2 \times 50$

$= 6.3 \times 10^5$ J/min

∴Rate of consumption = $(6.3x10^5)/(4x10^4)$= 15.75g/min

Molar Specific Heat Capacity

- Heat capacity per mole of the substance is defined as the amount of heat (in moles) absorbed or rejected (instead of mass m in kg) by the substance to change its temperature by one unit.

$C = S/ \mu= \Delta Q / \mu\ \Delta T$

Where

- μ= amount of substance in moles
- C = molar specific heat capacity of the substance.

- ΔQ = amount of heat absorbed or rejected by a substance.
- ΔT = temperature change
- Depends on :
- nature of substance
- Temperature
- Conditions under which heat is supplied
- SI Unit: J/mol/K

Examples: - All the cooking vessels are made by the material which has less specific heat and their bottom is polished so that they can be heated quickly by applying a small amount of heat. Vessels made of copper, aluminum.

Molar Specific heat capacity at constant pressure (Cp)

- If the gas is held under constant pressure during the heat transfer, then the corresponding molar specific heat capacity is called molar specific heat capacity at constant pressure (Cp).

Problem: - What amount of heat must be supplied to 2.0×10^{-2} kg of nitrogen (at room temperature) to raise its temperature by 45 °C at constant pressure?

(Molecular mass of N_2 = 28; R = 8.3 J mol^{-1} K^{-1}.)

Answer:-

Mass of nitrogen, m = 2.0×10^{-2} kg = 20 g

Rise in temperature, ΔT = 45°C

Molecular mass of N_2, M = 28

Universal gas constant, R = 8.3 J mol^{-1} K^{-1}

Number of moles, n =m/M

$=2.0x10^{-2}x10^{3}/28 = 0.714$

Molar specific heat at constant pressure for nitrogen = C_p =7/2R

=7/2x8.3 = 29.05 J mol^{-1} K^{-1}

The total amount of heat to be supplied is given by the relation:

$\Delta Q = nC_P\,\Delta T$

$= 0.714 \times 29.05 \times 45$

$= 933.38$ J

Therefore, the amount of heat to be supplied is 933.38 J.

Molar Specific heat capacity at constant volume (C_v):-

- If the volume of the gas is maintained during the heat transfer, then the corresponding molar specific heat capacity is called molar specific heat capacity at constant volume (C_v).

To Prove: - C_p-C_v = R for an ideal gas

From First Law: - $\Delta Q = \Delta U + \Delta W$.

- Consider the case gas is enclosed in a cylinder fitted with a piston. Then the work is done changes to
- $\Delta Q = \Delta U + P\Delta V$
- At constant volume $\Delta Q = \Delta U$ (where $\Delta V=0$)

Therefore

$$C_v = (\Delta Q/ \Delta T)_v = (\Delta U/ \Delta T)_v = \Delta U/ \Delta T$$

- At constant pressure:- $C_p=(\Delta Q/ \Delta T)_p = (\Delta U + P\Delta V)/ \Delta T$

By solving and doing all calculations:

$C_p - C_v = R$

Hence proved.

Specific Heat Ratio: -

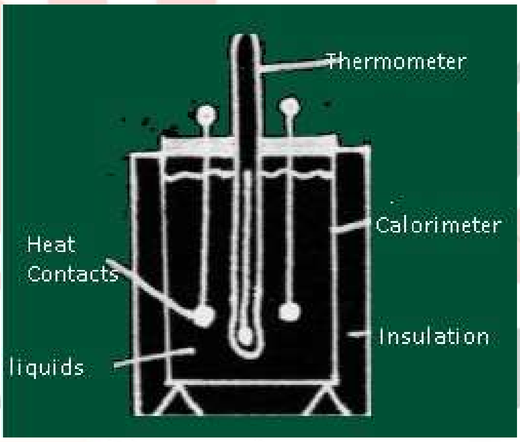
- It is denoted by γ.
- $\gamma = C_p/C_v$
- For Monoatomic gas:-
- $C_v = 3/2R$
- $C_p = 5/2R$
- $\gamma = 1.67$
- For Diatomic gas: -
- $C_v = 5/2\ R$
- $C_p = 7/2R$
- $\gamma = 1.4$

11.5. Calorimeter

The calorimeter is made up of 2 words:-

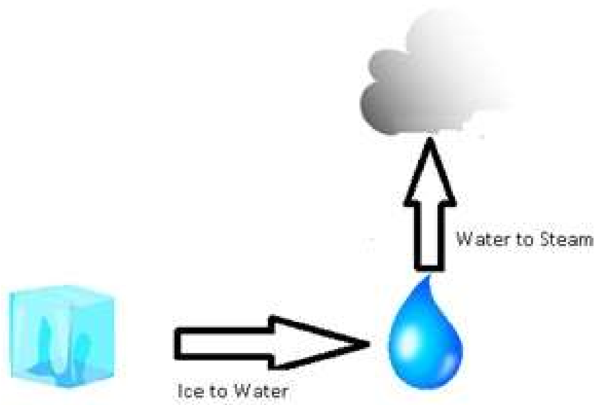
- Calorie which means heat and metry means measurement. Therefore Calorimetry means the measurement of heat.
- Calorimetry is defined as heat transfers from a body at a higher temperature to a body at a lower temperature provided there is no loss of heat to the atmosphere.

- The principle of Calorimetry is heat lost by one body is equal to the heat gained by another body.
- The Device which measures Calorimetry is known as **Calorimeter.**
- Description of Calorimeter
- A calorimeter consists of the metallic vessel and a stirrer both are made of the same material (copper or aluminum) and the vessel is kept in a wooden jacket so that there is no heat loss. A mercury thermometer can be inserted through a small opening in the outer jacket.



Change of State

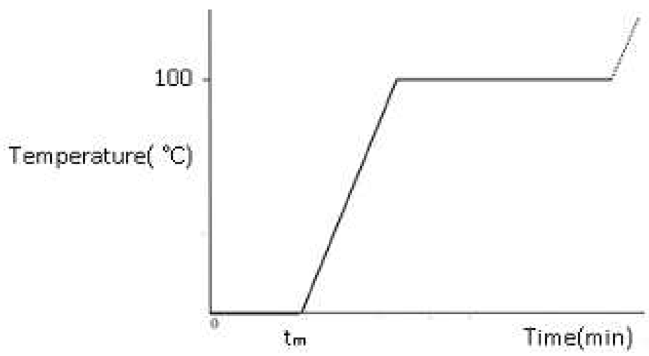
The transition from either solid to liquid or gas and gas to either liquid or solid is termed as a **change of state.**

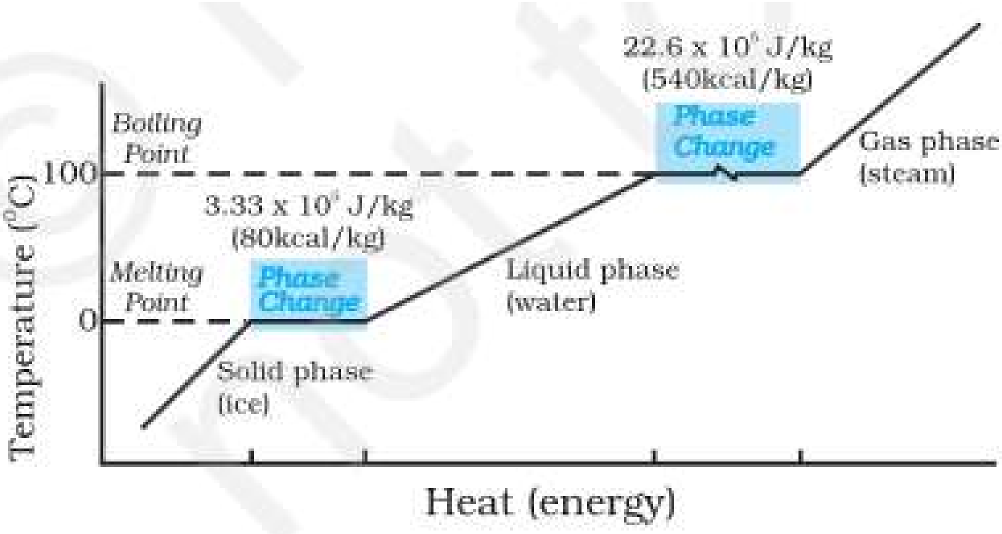


We can form the above image solid (ice) changes to liquid (water) and liquid changes to vapor (gas).

Change from solid (ice) to liquid (water) is known as **Melting.**

Change from liquid (water) to solid (ice) is known as **Fusion**.

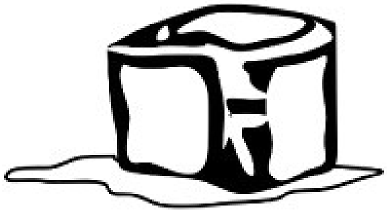




Note that when the heat is added (or removed) during a change of state, the temperature remains constant. Note in Fig. 11.12 that the lopes of the phase lines are not all the same, which indicates that specific heats of the various states are not equal. For water, the latent heat of fusion and vaporization is Lf = 3.33 105 J kg–1and Lv = 22.6 105 J kg–1 respectively. That is3.33 105 J of heat is needed to melt 1 kg of ice at 0 °C, and 22.6 105 J of heat is needed to convert 1 kg of water to steam at 100°C. So, steam at 100°C carries 22.6 105 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.

Thermal Equilibrium: - At this stage, there is no loss or gain of heat takes place.

The temperature at which the solid and the liquid states of the substance are in thermal equilibrium with each other is called its **melting point**.



It depends on the

- substance
- Pressure.

The melting point of a substance at standard atmospheric pressure is called its **normal melting point.**

Example 11.4 When 0.15 kg of ice of 0 °C 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_2L_f = (0.15 kg) L_f
Heat required to raise temperature of ice water to final temperature = $m_1s_w (\theta_f - \theta_i)_I$
= (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 = 3.3410^5 J kg^{-1}.

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 10^5 J kg^{-1}

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

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 kg) (2100 J kg^{-1} K^{-1}) [0–(–12)]°C = 75600 J

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

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

= 1005000 J

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

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

= 1255800 J

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

= $m\, L_{steam}$ = (3 kg) (2.25610^6 J kg^{-1})

= 6768000 J

Q = $Q_1 + Q_2 + Q_3 + Q_4$

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

= 9.110^6 J

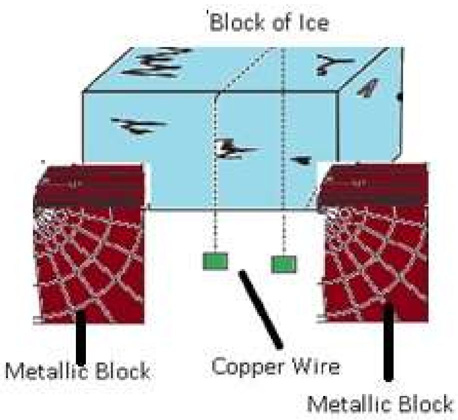
Regelation:-

- Regelation can be defined as a phenomenon in which the freezing point of water is lowered by the application of pressure.

Example:-

Cause of regelation:-

- If we have a block of ice and a copper wire pulled by two masses if we will observe that copper wire can pass through the ice block this is because copper is a good conductor of heat so as it passes through the ice it gets refreeze as the copper will generate heat and this heat will pass quickly to the ice below and it starts melting because there is the increase in pressure which lowers the temperature, as a result, the wire will move through the ice. This happens because of regelation.



The image above explains how a copper wire can pass through the block of ice.

Vaporisation: - Transition from liquid to vapour.

- The change of state from liquid to vapor (or gas) is called vaporization.

- The temperature at which the liquid and the vapor states of the substance coexist is called its boiling point.
- The boiling point at standard atmospheric pressure is known as a **normal boiling point**.

- It depends on the nature of substance & pressure
- It increases with an increase in pressure and vice versa.

Example: As altitude increases, the density of the air becomes thinner, and thus exerts less pressure. At high altitudes, external pressure on water is therefore decreased and will hence take less energy to break the water. If less energy is required it means less heat and less temperature which means that water will boil at a lower temperature.

Sublimation: - Transition from Solid to Vapour.

During the sublimation (solid changes to vapor without going through liquid state) process both the solid and vapor states of a substance coexist in thermal equilibrium.

Example:-

- Dry ice (solid CO_2) sublimes iodine.
- Naphthalene balls sublime to the gaseous state.

Example 11.3 A sphere of aluminium of 0.047 kg placed for sufficient time in a vessel containing boiling water, so that the sphere is at 100 °C. It is then immediately transfered to 0.14 kg copper calorimeter containing 0.25 kg of water at 20 °C. The temperature of water rises and attains a steady state at 23 °C. Calculate the specific heat capacity of aluminium.

Answer In solving this example we shall use he fact that at a steady state, heat given by an luminium sphere will be equal to the heat bsorbed by the water and calorimeter.

Mass of aluminium sphere (m_1) = 0.047 kg
Initial temp. of aluminium sphere = 100 °C
Final temp. = 23 °C
Change in temp (ΔT) =(100 °C - 23 °C) = 77 °C
Let specific heat capacity of aluminium be s_{Al}.

The amount of heat lost by the aluminium sphere = $m_1 s_{Al} \Delta T = 0.047 kg \times s_{Al} \times 77$ °C

Mass of water (m_2) = 0.25 kg

Mass of calorimeter (m_3) = 0.14 kg

Initial temp. of water and calorimeter = 20 °C

Final temp. of the mixture = 23 °C

Change in temp. (ΔT_2) = 23 °C – 20 °C = 3 °C

Specific heat capacity of water (s_w)

= 4.18 10^3 J kg^{-1} K^{-1}

Specific heat capacity of copper calorimeter

= 0.386 10^3 J kg^{-1} K^{-1}

The amount of heat gained by water and calorimeter = $m_2 s_w \Delta T_2 + m_3 s_{cu} \Delta T_2$

= $(m_2 s_w + m_3 s_{cu})(\Delta T_2)$

= 0.25 kg 4.18 10^3 J kg^{-1} K^{-1} + 0.14 kg 0.386 10^3 J kg^{-1} K^{-1}) (23 °C – 20 °C)

In the steady state heat lost by the aluminium sphere = heat gained by water + heat gained by calorimeter.

So, 0.047 kg s_{Al} 77 °C

= (0.25 kg 4.18 10^3 J kg^{-1} K^{-1}+ 0.14 kg 0.386 10^3 J kg^{-1} K^{-1})(3 °C)

s_{Al} = 0.911 kJ kg^{-1} K^{-1}

11.6. Heat Transfer - Radiation, Convection, And Conduction

Any matter which is made up of atoms and molecules has the ability to transfer heat. The atoms are in different types of motion at any time. The motion of molecules and atoms is responsible for heat or thermal energy and every matter has this thermal energy. The more the motion of molecules, the more will be the heat energy. However, talking about heat transfer, it is nothing but the process of transfer of heat from the high-temperature body to a low temperature one.

11.6. What is Heat Transfer?

According to thermodynamic systems, heat transfer is defined as

The movement of heat across the border of the system due to a difference in temperature between the system and its surroundings.

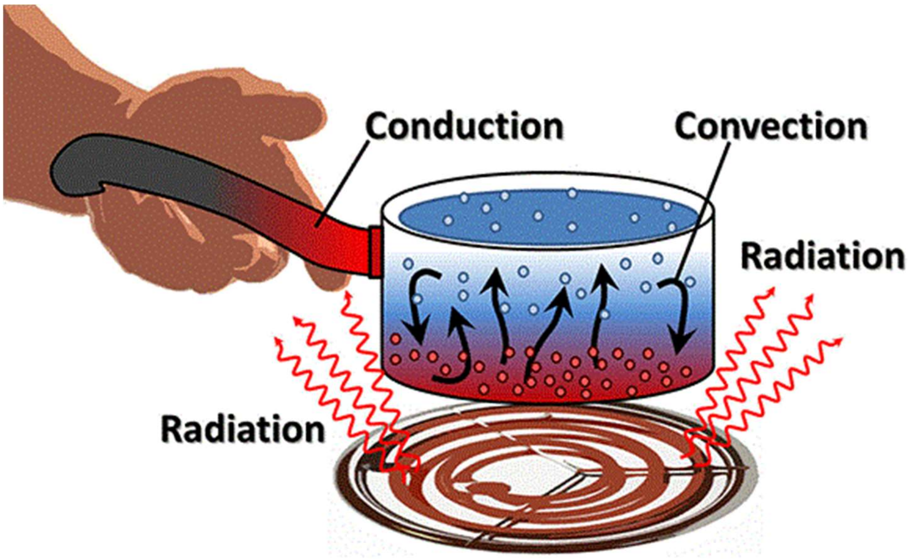
Interestingly, the difference in temperature is said to be a 'potential' that causes the transfer of heat from one point to another. Besides, heat is also known as flux.

How is Heat Transferred?

Heat can travel shift from one place to another in several ways. The ***different modes of heat transfer include***:

- Conduction
- Convection
- Radiation

Meanwhile, if the temperature difference exists between the two systems, heat will find a way to transfer from the higher to the lower system.



What is Conduction?

Conduction is defined as the process in which heat flows from objects with a higher temperature to objects with lower temperatures.

An area of higher kinetic energy transfers thermal energy towards the lower kinetic energy area. High-speed particles clash with particles moving at a slow speed, as a result, slow speed particles increase their kinetic energy. This is a typical form of heat transfer and takes place through physical contact. Conduction is also known as there.

- Whenever a utensil is kept on flame it becomes hot and the heat travels from the base of the utensil to its handle. This is due to the transfer of heat from the hotter base of the utensil to the cold handle. When this pan is removed from the flame and kept aside soon the utensil cools down. This is again due to the transfer of heat from the hot utensil to the cold surrounding.

- Generally, the heat is transferred in solids by the process of conduction. It is the most important mode of heat transfer in solids than in liquids and gases.
- But it is not necessary that all solids will conduct heat because there are many solids that are poor conductors of heat.
- Materials that allow heat to pass through them easily are known as conductors of heat. For instance, all metals like aluminum, iron, and copper are conductors of heat.
- Whereas those materials which do not allow heat to pass through them easily are known as poor conductors of heat. For instance, plastic, wood, water, and air. They are also termed as insulators.

Therefore the concept of conduction is applicable to solids and that to only those solids which are good conductors of heat.

There is another term called thermal conductivity which refers to the ability of conducting heat. It is maximum in solids that are good conductors than liquids which in turn has greater thermal conductivity than gases. i.e. solids > liquids > gases.

Here temperature at side A is T_A and the temperature at side B is T_B.

- There is a temperature difference as $T_A > T_B$.
- So in this heat transfer will take place from A to B because we already learned that heat transfers from the higher temperature to lower temperature.
- Heat From side A starts losing heat and side B will gain heat.
- So temperature at side A will decrease and that on side B will increase because it is gaining heat. But after some time the temperature will become equal on both sides.
- This situation is called steady-state and after this, no transfer of heat will take place because conduction comes into act only if there is a temperature difference.

mal conduction or heat conduction.

Conduction Equation

The coefficient of thermal conductivity shows that a metal body conducts heat better when it comes to conduction.

. ***The rate of conduction can be calculated by the following equation:***

Q = [K.A.(T hot−T cold)] d

Where,

- Q is the transfer of heat per unit time
- K is the thermal conductivity of the body
- A is the area of heat transfer
- T_{hot} is the temperature of the hot region
- T_{cold} is the temperature of the cold region
- d is the thickness of the body

Conduction Examples

Following are the examples of conduction:

- Ironing of clothes is an example of conduction where the heat is conducted from the iron to the clothes.
- Heat is transferred from hands to ice cube resulting in the melting of an ice cube when held in hands.
- Heat conduction through the sand at the beaches. This can be experienced during summers. Sand is a good conductor of heat.

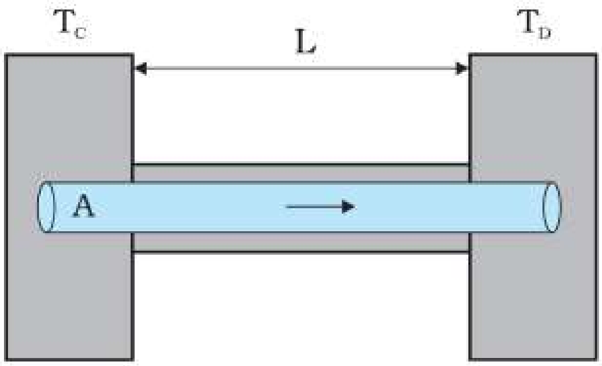
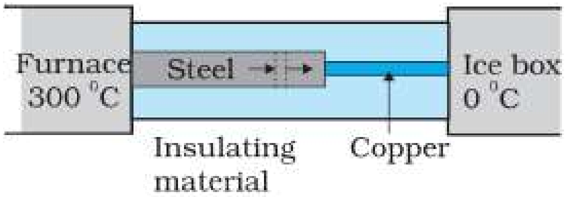


Fig. 11.14 *Steady state heat flow by conduction in a bar with its two ends maintained at temperatures T_C and T_D; ($T_C > T_D$).*

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 :

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

▶ ***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 $s^{-1}m^{-1}K^{-1}$).



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,

$$\frac{K_1 A_1 \; 300 \quad T}{L_1} = \frac{K_2 A_2 \; T - 0}{L_2}$$

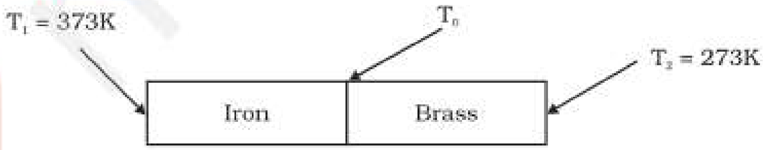
where 1 and 2 refer to the steel and copper rod respectively. For $A_1 = 2\ A_2$, $L_1 = 15.0$ cm, $L_2 = 10.0$ cm, $K_1 = 50.2$ J s^{-1} m^{-1} K^{-1}, $K_2 = 385$ J s^{-1} m^{-1} K^{-1}, we have

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

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.

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, $H = H_1 = H_2$

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

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

$$T_0 = \frac{K_1 T_1 \quad K_2 T_2}{K_1 \quad K_2}$$

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

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

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

$$H \quad \frac{K \; A \; T_1 - T_2}{2 \; L} \quad H$$

$$K \quad \frac{2 \; K_1 \; K_2}{K_1 \quad K_2}$$

(i) $$T_0 \quad \frac{K_1 T_1 \quad K_2 T_2}{K_1 \quad K_2}$$

$$\frac{79\,W\,m^{-1}K^{-1} \quad 373\,K \quad 109\,W\,m^{-1}K^{-1} \quad 273\,K}{79\,W\,m^{-1}K^{-1} \quad 109\,W\,m^{-1}K^{-1}}$$

$= 315\ K$

(ii) $$K = \frac{2K_1 \; K_2}{K_1 \quad K_2}$$

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

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

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

$$\frac{91.6\,W\,m^{-1}\,K^{-1} \times 0.02\,m^2 \times 373\,K{-}273\,K}{2\times 0.1\,m}$$

$= 916.1\ W$

Solved problems on thermal conductivity

Question 1

A slab of stone of area $0.36 m^2$

and thickness $0.1 m$ is exposed on the lower surface to steam at $100^\circ C$. A block of ice at $0^\circ C$, rests on the upper surface of the slab. If in one hour, $4.8 kg$ of ice is melted, calculate the thermal conductivity of the stone.

Answer 1

The amount of heat flowing through the slab is

$Q = kA(T_1 - T_2)tx$ According to the conditions of the problem, $Q = mL$.

$mL = kA(T_1 - T_2)tx$ Here it is given that

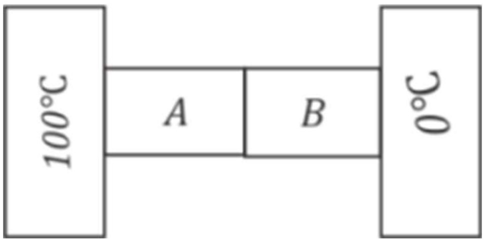
$m = 4.8 kg$; $L = 80 kcal/kg$; $A = 0.36 m^2$; $T_1 - T_2 = 100 - 0 = 100^\circ C$

Now $t = 1 hour = 3600 s, x = 0.1 m k = ?$

Therefore, $4.8 \times 80 = k \times 0.36 \times 100 \times 36000.1$ Or, thermal conductivity $k = 3 \times 10^{-4} kcal s^{-1} m - 1^\circ C^{-1}$

Question

Two metal cubes A and B of the same size are arranged as shown in the figure. The extreme ends of the combination are maintained at the indicated temperatures. The arrangement is thermally insulated. The coefficient of thermal conductivity of A and B is $300 W/m^\circ C$ and $200 W/m^\circ C$, respectively. After a steady-state is reached, what will be the temperature T of the interface? (IIT 1996)



Answer In the steady-state, Rate of flow of heat through cube A = Rate of flow of heat through cube B

$K_1A(100-T)x=K_2A(T-0)x300A(100-T)x=200A(T-0)x$ or,

$300-3T=2T$ or, $5T=300T=60{\circ}C$

Question The two ends of a rod of length L and uniform cross-sectional area A are kept at temperatures T_1 and T_2 where $(T_1>T_2)$. The rate of heat transfer, dQdt through the rod in a steady state is given by

(a) $dQdt=K(T_1-T_2)LA$

(b) $dQdt=KLA(T_1-T_2)$

(c) $dQdt=KA(T_1-T_2)L$

(d) $dQdt=KL(T_1-T_2)A$

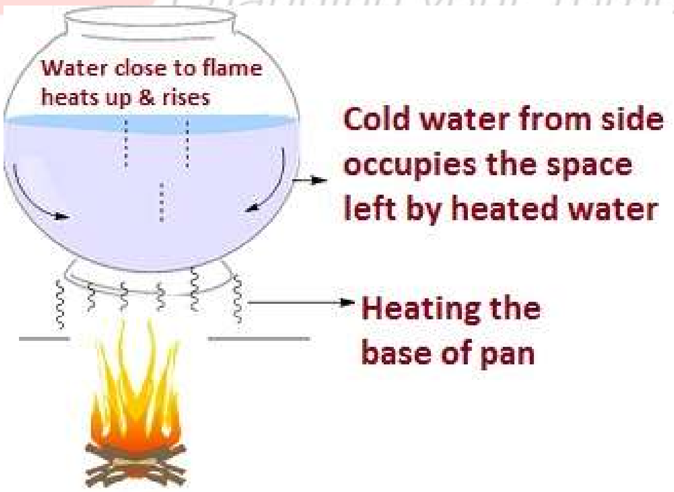
Answer is c

What is Convection?

Convection is defined as

The movement of fluid molecules from higher tempera **Convection**

- The method of transferring heat by the movement of the particles of substance away from the source of heat is known as convection. It takes place only in liquids and gases.
- On heating, the water, the part of it near the flame gets heated up and expands due to which it becomes less dense and consequently rises up.
- This creates a vacuum and the cold water from the sides slides down to occupy the space near the flame.
- This water also gets heated up and rises.
- Again the cold water slides down. So it is like a cycle that continues again and again until and unless the entire water is heated up.
- This process continues unless the whole water present in the beaker gets heated up.
- The air too gets heated up by this process. The air near the heat source gets heated up and rises. The cold air from the sides slides to occupy the space. In this way, the air gets heated.



- Due to this reason, the air just above the flame of the candle is hotter than the air at the side.
- **Sea Breeze and Land Breeze**
- The land gets heated up by the heat radiated by the sun, much faster than the water during the daytime. This heats up the air over the land and it expands and hence the hot air rises up and creates a vacuum. The cool air from the sea occupies the space left by the hot air. The warm air from the land moves towards the sea to complete the cycle. The air from the sea is called the sea breeze.
- But the reverse process takes place at night. The land cools down quickly and seawater remains hot. This heats up the air over the sea and it expands and hence the hot air rises up and creates a vacuum. The cool air from the land occupies the space left by the hot air. And hence the cool air moves from the land to the sea and is known as the land breeze.
- 

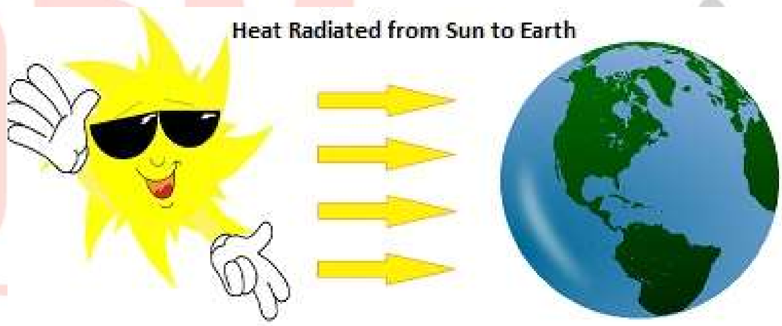
Day time

- 

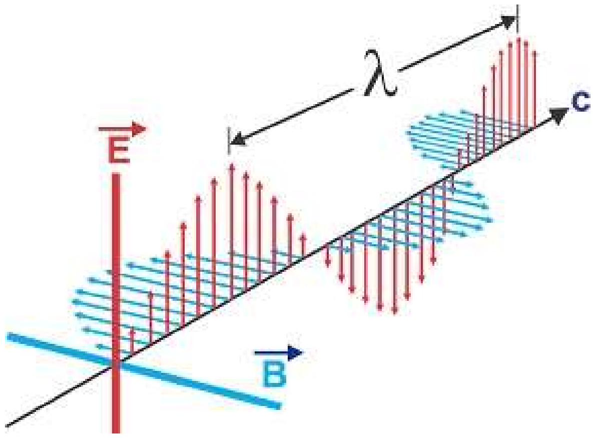
- Nighttime

Radiation

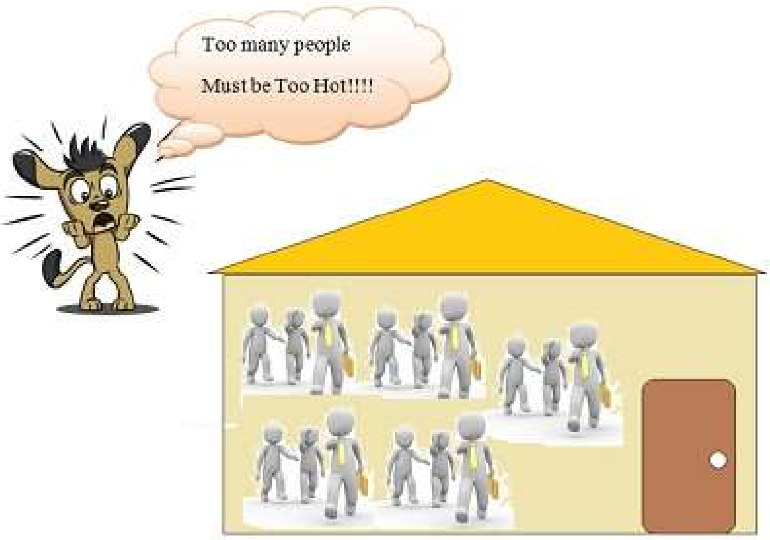
- The heat given off from the sun cannot reach us by the process of conduction or convection because both the processes require a medium to transfer the heat but due to the absence of a medium such as air in maximum layers of space between the earth and the sun, these processes cannot transfer the heat to the earth.



- At this moment another process called radiation comes into act to transfer the heat radiated by the sun to the earth.
- This heat transferring process doesn't require any medium.
- These are the form of electromagnetic waves. Their characteristic is that they can travel through a vacuum and travel with the speed of light ($3X10^8$ m/s). This propagation of heat from the sun to earth involves both the electric field represented by E and the magnetic field represented by B.



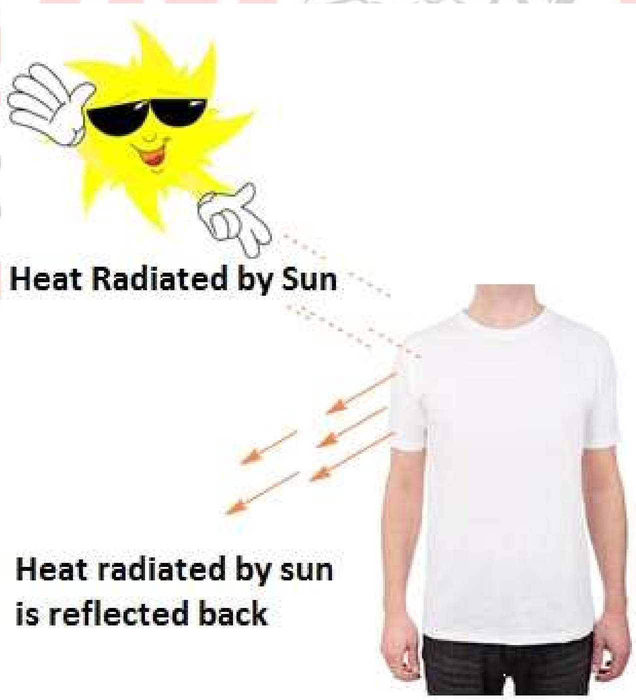
- Not only the sun but all hot bodies radiate heat. That can propagate through a medium or even in a vacuum. Heating of room by a room heater, heating up of utensils kept over the flame, and then cooling down when kept away from heat are all due to radiation.
- The human body releases heat to the surroundings and receives heat from it by the process of radiation. This can be proved using a simple example. You feel quite comfortable in a room with one person but if the same room has many people you feel hot due to the radiation of heat from the human body.



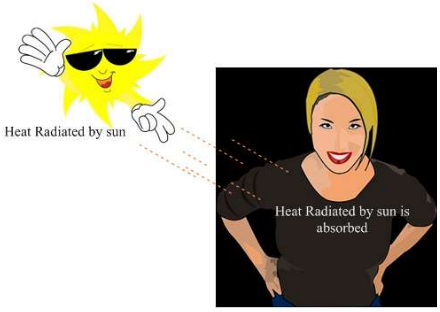
- All hot bodies radiate heat which falls on the nearby objects.

The objects absorb some part of heat, reflect some part of the heat, and transmit some part of the heat falling on them. The temperature of the object increases due to the absorbed part of the heat.**Reasons to wear white or light-colored clothes in summer and dark-colored and woolen clothes in winter**

Light colors are the best reflectors of heat falling and as a result, light-colored clothes reflect the maximum amount of heat they receive and make us feel cool to some extent and hence we feel more comfortable wearing them in the summer.



But on the other hand, dark colors are good absorbers of heat falling on them and as a result, the dark-colored clothes absorb the maximum amount of heat they receive and make us feel warm and comfortable during winter.



Winter seasons are also accompanied with woolen clothes. This is due to the reason that wool being a poor conductor of heat traps the air in between the woolen fibers. The trapped air prevents the flow of heat from our body to the cold surroundings and vice versa thereby making us feel warm.

11.8 What is Newton's Law of Cooling?

Newton's law of cooling describes the rate at which an exposed body changes temperature through radiation which is approximately proportional to the difference between the object's temperature and its surroundings, provided the difference is small.

Definition: According to Newton's law of cooling, the rate of loss of heat from a body is directly proportional to the difference in the temperature of the body, and its surroundings.

Newton's law of cooling is given by, $dT/dt = k(T_t - T_s)$

Where,

- T_t = temperature at time t and
- T_s = temperature of the surrounding,
- k = Positive constant that depends on the area and nature of the surface of the body under consideration.

Newton's Law of Cooling Formula

The greater the difference in temperature between the system and surrounding, the more rapidly the heat is transferred i.e. the body temperature of body changes. Newton's law of cooling formula is expressed by,

$T(t) = T_s + (T_o - T_s)\, e^{-kt}$

Where,

- t = time,
- T(t) = temperature of the given body at time t,
- T_s = surrounding temperature,
- T_o = initial temperature of the body,
- k = constant.

Newton's Law of Cooling Derivation

For small temperature differences between a body and its surrounding, the rate of cooling of the body is directly proportional to the temperature difference and the surface area exposed.

$dQ/dt \propto (q - q_s)$], where q and q_s are temperature corresponding to object and surroundings.

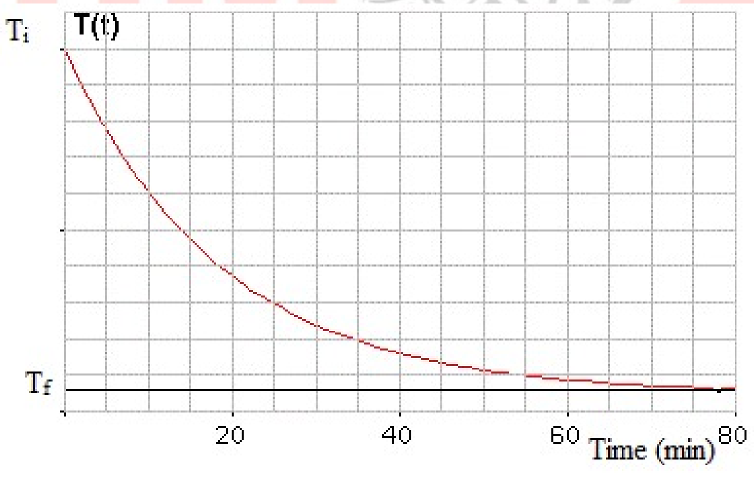
From above expression , $dQ/dt = -k[q - q_s)]$ . . . . (1)

This expression represents Newton's law of cooling. It can be derived directly from Stefan's law, which gives,

$k = [4e\sigma \times \theta^3_o/mc]$ A . . . . . (2)

Now, $d\theta/dt = -k[\theta - \theta_o]$

⇒∫θ1θ2dθ(θ−θo)=∫01−kdt\int_{\theta_1}^{\theta_2}\frac{d\theta}{(\theta-\theta_o)} = \int_{0}^{1}-k dt∫θ1θ2(θ−θo)dθ=∫01−kdt



Newton's Law of Cooling – Temperature vs Time

where,

q_i = initial temperature of object,

q_f = final temperature of object.

$\ln (q_f - q_0)/(q_i - q_0) = kt$

$(q_f - q_0) = (q_i - q_0)\, e^{-kt}$

$q_f = q_0 + (q_i - q_0)\, e^{-kt}$ . . . . . . (3).

⇒ **Check:** Heat transfer by conduction

Methods to Apply Newton's Law of Cooling

Sometime when we need only approximate values from Newton's law, we can assume a constant rate of cooling, which is equal to the rate of cooling corresponding to the average temperature of the body during the interval.

i.e. $d\theta \backslash dt = k(<q> - q_0)$ . . . . (4)

If q_i and q_f be the initial and final temperature of the body then,

$<q> = (q_i + q_f)/2$ . . . . . (5)

Remember equation (5) is only an approximation and equation (1) must be used for exact values.

Limitations of Newtons Law of Cooling

- The difference in temperature between the body and surroundings must be small,
- The loss of heat from the body should be by radiation only,

- The major limitation of Newton's law of cooling is that the temperature of surroundings must remain constant during the cooling of the body.

Solved Examples

Example 1: A body at temperature 40ºC is kept in a surrounding of constant temperature 20ºC. It is observed that its temperature falls to 35ºC in 10 minutes. Find how much more time will it take for the body to attain a temperature of 30ºC.

Solution:

From Newton's law of cooling, $q_f = q_i\ e^{-kt}$

Now, for the interval in which temperature falls from 40 to 35ºC.

$(35 – 20) = (40 – 20)\ e^{-k.10}$

$e^{-10k} = 3/4$

$k = [\ln 4/3]/10$ . . . . (a)

Now, for the next interval;

$(30 – 20) = (35 – 20)e^{-kt}$

$e^{-kt} = 2/3$

$kt = \ln 3/2$ . . . . (b)

From equation (a) and (b);

$t = 10 \times [\ln(3/2)/\ln(4/3)] = 14.096$ min.

Aliter : (by approximate method)

For the interval in which temperature falls from 40 to 35ºC

$<q> = (40 + 35)/2 = 37.5^{o}C$

From equation (4);

$d\theta/dt = k(<q> - q_0)$

$(35 - 40)/10 = k(37.5 - 20)$

$k = 1/32 \text{ min}^{-1}$

Now, for the interval in which temperature falls from 35ºC to 30ºC

$<q> = (35 + 30)/2 = 32.5^{o}C$

From equation (4);

$(30 - 35)/t = (32.5 - 20)$

Therefore, the required time t = 5/12.5 × 35 = 14 min.

Example 2: The oil is heated to 70ºC. It cools to 50ºC after 6 minutes. Calculate the time taken by the oil to cool from 50ºC to 40ºC given the surrounding temperature $T_s = 25^{o}C$.

Solution:

Given:

Temperature of oil after 10 min = 50ºC,

- T_s = 25°C,
- T_o = 70°C,
- t = 6 min

On substituting the given data in Newton's law of cooling formula, we get;

$T(t) = T_s + (T_s – T_o)\ e^{-kt}$

$[T(t) – T_s]/[T_o – T_s] = e^{-kt}$

$-kt \ln = [\ln T(t) – T_s]/T_o – T_s$

-kt = [ln 50 – 25]/70 – 25 = ln 0.555

k = – (-0.555/6) = 0.092

If T(t) = 45ºC (average temperature as the temperature decreases from 50ºC to 40ºC)

Time taken is $-kt \ln e = [\ln T(t) – T_s]/[T_o – T_s]$

-(0.092) t = ln 45 – 25/[70 – 25]

-0.092 t = -0.597

t = -0.597/-0.092 = 6.489 min.

Example 3: Water is heated to 80ºC for 10 min. How much would be the temperature if k = 0.056 per min and the surrounding temperature is 25ºC?

Solution:

Given:

- T_s = 25ºC,
- T_o = 80ºC,
- t = 10 min,
- k = 0.056

Now, substituting the above data in Newton's law of cooling formula,

$T(t) = T_s + (T_o – T_s) \times e^{-kt}$

$= 25 + (80 – 25) \times e^{-0.56} = 25 + [55 \times 0.57] = 45.6$ ºC

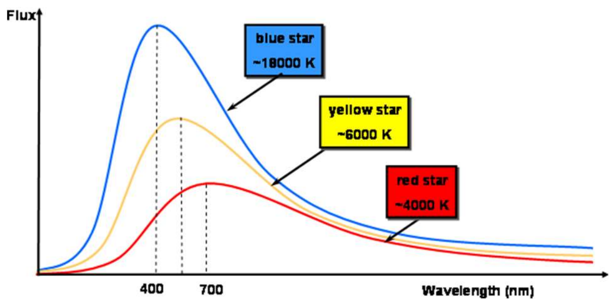
Temperature cools down from 80ºC to 45.6ºC after 10 min.

11. 9. Blackbody Radiation

All objects with a temperature above absolute zero (0 K, -273.15 ºC) emit energy in the form of electromagnetic radiation.

A blackbody is a theoretical or model body that absorbs all radiation falling on it, reflecting or transmitting none. It is a hypothetical object which is a "perfect" absorber and a "perfect" emitter of radiation over all wavelengths.

The spectral distribution of the thermal energy radiated by a blackbody (i.e. the pattern of the intensity of the radiation over a range of wavelengths or frequencies) depends ***only on its temperature***.



Blackbody radiation curves at several different temperatures.

Credit: Swinburne

The characteristics of blackbody radiation can be described in terms of several laws:

1. **Planck's Law** of blackbody radiation, a formula to determine the spectral energy density of the emission at each wavelength *(E_λ)* at a particular absolute temperature (T).

$$E_\lambda = \frac{8\pi hc}{\lambda^5 (e^{(hc/\lambda\kappa T)} - 1)}$$

2. **Wien's Displacement Law**, which states that the frequency of the peak of the emission (f_{max}) increases linearly with absolute temperature (T). Conversely, as the temperature of the body *increases*, the wavelength at the emission peak *decreases*.

$$f_{max} \propto T$$

3. **Stefan–Boltzmann Law**, which relates the *total* energy emitted *(E)* to the absolute temperature (T).

$$E \propto T^4$$

In the image above, notice that:

- The blackbody radiation curves have quite a complex shape (described by Planck's Law).
- The spectral profile (or curve) at a specific temperature corresponds to a specific peak wavelength, and vice versa.
- As the temperature of the blackbody increases, the peak wavelength decreases (Wien's Law).
- The intensity (or flux) at all wavelengths increases as the temperature of the blackbody increases.
- The total energy being radiated (the area under the curve) increases rapidly as the temperature increases (Stefan–Boltzmann Law).
- Although the intensity may be very low at very short or long wavelengths, at any temperature above absolute zero energy is theoretically emitted at *all* wavelengths (the blackbody radiation curves never reach zero).

In astronomy, stars are often modeled as blackbodies, although it is not always a good approximation. The temperature of a star can be deduced from the wavelength of the peak of its radiation curve.

In 1965, the cosmic microwave background radiation (CMBR) was discovered by Penzias and Wilson, who later won the Nobel Prize for their work. The radiation spectrum was measured by the COBE satellite and found to be a remarkable fit to a blackbody curve with a temperature of 2.725 K and is interpreted as evidence that the universe has been expanding and cooling for about 13.7 billion years. A more recent mission, WMAP, has measured the spectral details to much higher resolution, finding tiny temperature fluctuations in the early Universe which ultimately led to the large-scale structures we see today.

Greenhouse effect

The greenhouse effect is a natural process that warms the Earth's surface. When the Sun's energy reaches the Earth's atmosphere, some of it is reflected back to space and the rest is absorbed and re-radiated by greenhouse gases.

Greenhouse gases include water vapor, carbon dioxide, methane, nitrous oxide, ozone, and some artificial chemicals such as chlorofluorocarbons (CFCs).

The absorbed energy warms the atmosphere and the surface of the Earth. This process maintains the Earth's temperature at around 33 degrees Celsius warmer than it would otherwise be, allowing life on Earth to exist.

Enhanced greenhouse effect

The problem we now face is that human activities – particularly burning fossil fuels (coal, oil, and natural gas), agriculture, and land clearing – are increasing the concentrations of greenhouse gases. This is the enhanced greenhouse effect, which is contributing to the warming of the Earth.

Greenhouse effect

Step 1: Solar radiation reaches the Earth's atmosphere - some of this is reflected back into space.

Step 2: The rest of the sun's energy is absorbed by the land and the oceans, heating the Earth.

Step 3: Heat radiates from Earth towards space.

Step 4: Some of this heat is trapped by greenhouse gases in the atmosphere, keeping the Earth warm enough to sustain life.

Step 5: Human activities such as burning fossil fuels, agriculture, and land clearing are increasing the amount of greenhouse gases released into the atmosphere.

Step 6: This is trapping extra heat, and causing the Earth's temperature to rise.