Thermal Properties of Matter

1. Concept of Heat and Temperature

Familiar sensations of hotness and coldness are described with adjectives such as hot , warm, cold, cool etc. When we touch an object, we use our temperature sence to ascribe to object a property called temperature. Temperature of a body determines whether it feels hot or cold to the touch. The hotter you feel on touching the body higher is its temperature.
So we can say thet Temperature is relative measurement of hotness or coldness of a body.
An observation about hot and cold bodies in contact is that, when they both are in contact temperature of cold body increases and that of hot body decreases. This happens because energy is transferred from hot body to cold body when they are in contact and this is a nonmechanical process.
This energy which is transferred from one body to another without any mechanical work involved is known as **HEAT**.
Heat is a form of energy and heat transfer from one body to another takes place by virtue of temperature difference only also heat transfer takes place from body at higher temperature to body at lower temperature.
S.I. unit of heat is Joule(J) and that of temperature is Kelvin(K).

2. Measurement of temperature

Measurement of temperature can be obtained using a thermometer.
Construction of thermometers generally require a measurable property of a substance which monotonically changes with temperature.
Examples of some common type of thermometers
(1) Mercury in a glass thermometer.The height of mercury in the tube is taken as thermometric parameter.

(2) Constant Volume gas thermometer-Gas in bulb is maintaned at constant volume.The mean pressure of gas is taken as thermomtric parameter.
(3) Constant Pressure gas thermometer-Gas in bulb is maintaned at constant pressure.Volume of gas is taken as thermomtric parameter.
(4) Resistance therometer-Electric resistance of a metal wire increases monitonically with the temperature and may be used to define temperature scale. Such thermometers are resistance theromometers.
Thermometers are calibrated to asign a numerical value to any given temperature.
Defination of any standard scale needs two fixed refrence points and these points can be corelated to physical phenomenon reproducible at the same temperature.
Two such standard points are freezing and boiling points of water at same pressure.
Two such familiar scales used for measurement of temperature are Celsius and Fahrenhite scale.
Temperature in celsius is measured in degree.
Fahrenhite scale has a smaller degree then celsius scale and a diffrent zero of temperature.
Relation between Celsius and fahrenhite scale is
$T_F=9/5\ T_C + 32°$.
where,
T_F - Fahrenhite Temperature.
T_C - Celsius Temperature.
Letters C & F are used to distinguish measurements on two scale thus
$0°\ C= 32°\ F$
this means that 0° C on celsius scale measures the same temperature as 32° F on the fahrenhite scale.
On fahrenhite scale melting point of ice and boiling point of water have values 32° F and 212° F and that on celsius scale are 0° C and 100° C.
If we now talk of Kelvin scale ,the melting point of ice and boiling point of water in the scale are 273.15 K and 373.15 K respectively.
Size of a degree in celsius and kelvin scale are same.
Relation between Celsius and kelvin scale is
$T_C = T_K - 273.15\ K$
where,
T_K - Temperature in Kelvin
T_C - Temperature in celsius

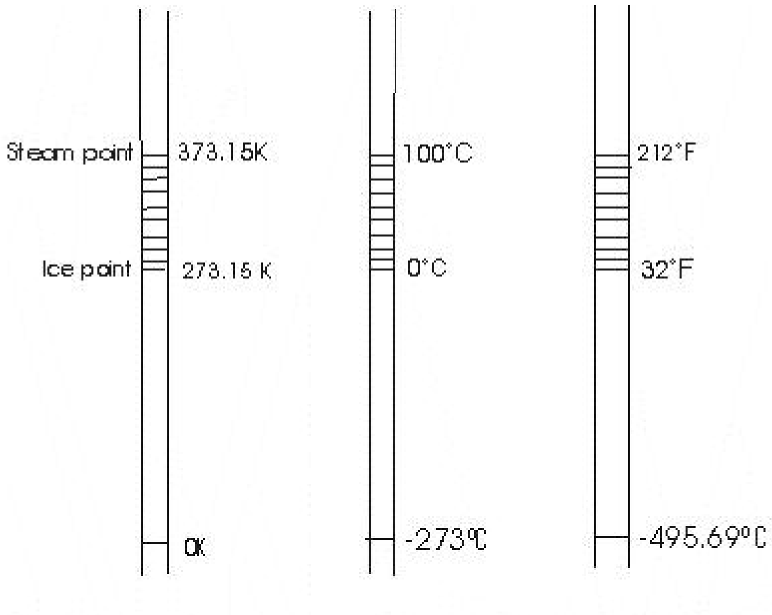

Figure 1:- Comparison between Kelvin , centigrade and fahrenhite temperature scales

Another modern fixed point of temperature is the triple point of water.

Three phases of water i.e, ice,water,water vapour co-exist at this value of temperature and pressure where

T_{tr}=273.16 K

P_{tr}= 0.46 cm of HG.

where,

T_{tr} & P_{tr} are triple point temperature and pressure.

Now if P_{tr} is pressure of an ideal gas thermometer at triple point temperature T_{tr} and if P is pressure at some other temperature T then corresponding temperature is

$T= P(T_{tr} / P_{tr})$

provided T_{tr} & P_{tr} are low.

Electric resitance of metal wire increase monitonically with temperature and may be used to define the temperature scale

If R_0 & R_{100} are resistance of metal wire at ice and steam point respectively then temperature t can be defined corresponding to resistance R_T as follows $$T=\frac{(R_{T}-R_{0})100}{(R_{100}-R_{0})}$$

A platinum wire is oftently used to construct a thermometer which is known as platinum resistance thermometer.

Gas thermometer can also define Celsius scale

If P_0 is pressure of gas at ice point and P_{1000} is pressure of gas at steam point then temperature T corresponding to a pressure P of gas is defined by $$T=\frac{(P-P_{0})100}{(P_{100}-P_{0})}$$

Question :

The surface of a body has a emissivity of .55 and area of 1.5 m^2

Find out the following

a. What rate of heat is radiated from the body if the temperature is 50°C

b. At what rate is radiation absorbed by the radiater when the surrounding temperature is 22°C

c What is the net rate of radiation from the body

Given σ=5.67 *10^{-8}

Solutions

a) Rate of radiation radiated=$e\sigma A T_b^4$=(.55)(5.67 *10^{-8})(1.5)$(323)^4$=509W

b) Rate of radiation absorbed=$e\sigma A T_s^4$=(.55)(5.67 *10^{-8})(1.5)$(295)^4$=354W

c)Net =Rate of radiation radiated-Rate of radiation absorbed=155 W

3. Absolute Temperature

In gas thermometer different gases are used for measuring high temperatures and temperature reading are found to be independent of the nature of the gas used

Graphs between pressure and temperature for different gases are plotted below

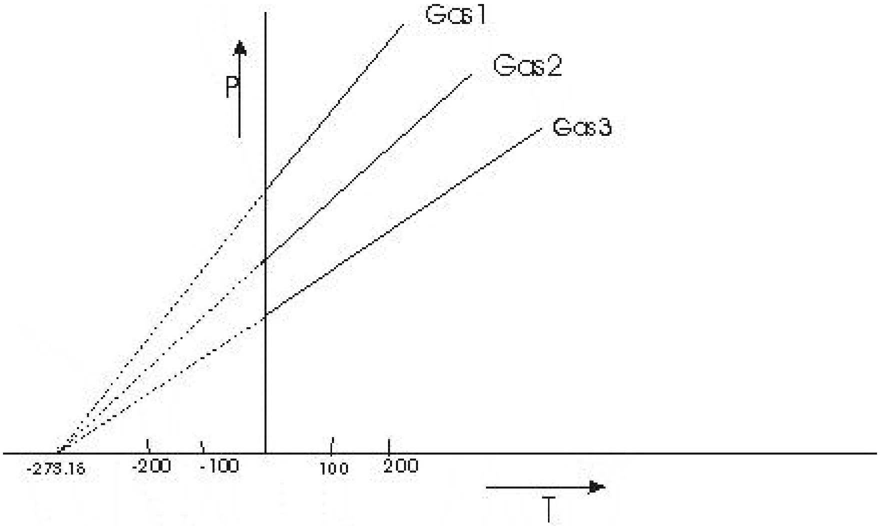

Figure 2:- P Vs T graph for different gases

It is found that when graph were extrapolated for temperature below 0° C, pressure comes out to be zero at -273° C and this is the lowest temperature.

Lord kelvin suggested that instead of 0° C which is the melting point of ice,-273° C should be regarded as the zero of the temperature scale

Such a scale of temperature is absolute scale of temperature and -273.15° C as absolute zero of this new scale and is denoted as 0K and steam point in this scale correspond to 373.15 K

4. Ideal Gas Equation

Pressure of all the gases changes with the temperature in a similar fashion for low temperature.Also many properties of gases are common at low pressure
The pressure, volume and temperature in kelvin of such gases obey the equation

$PV=nRT$ (1)

where n is amount of gas in number of moles and is given as ,
n = [Total no of molecules in given mass of gas]/[Avogadro Number(N_A)]
$N_A=6.023 \times 10^{23}$
R is universal gas constant and its value is R=8.316 J/mol-K
Equation (1) is known as ideal gas equation and a gas obeying this equation is known as ideal gas.

5. Thermal Expansion

Most of the solid material expand when heated.
Increase in dimension of a body due to increase in its temperature is called thermal expansion.
For small change in temperature ΔT of a rod of length L, the fractional change in length ΔL/L is directly propertional to ΔT(Fig 3)

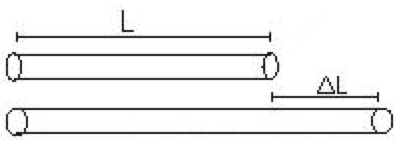

Figure 3:- linear expansion

$\Delta L/L=\alpha_L \Delta T$ (2)

or ,

$\Delta L=\alpha_L L\Delta T$ (3)

Constant α_L characterizes the thermal expansion properties of a particular material and it is known as coefficient of linear expansion.
For materials having no preferable direction, every linear dimension changes according to equation (3) and L could equally well represent the thickness of the rod, side length of the square sheet etc.
Normally metals expand more and have high value of α.
Again consider the initial surface area A of any surface and A' is the area of the solid when the temperature of the body changes by ΔT then increase in surface area is given by

$\Delta A=\alpha_A A\Delta T$ (4)

where α_A is the coefficient of area expansion.

Similarly we can define coefficient of volume expansion as fractional change in volume $\Delta V/V$ of a substance for a temperature change ΔT as

$$\alpha_{v}=\frac{\Delta V}{V\Delta T}$$

K^{-1} is the unit of these coefficients of expansions.

These three coefficient are not strictly constant for a substance and there value is depends on temperature range in which they are being measured.

As an example, fig below shows that coefficient of volume expansion increase with temperature and takes a constant value above 500K

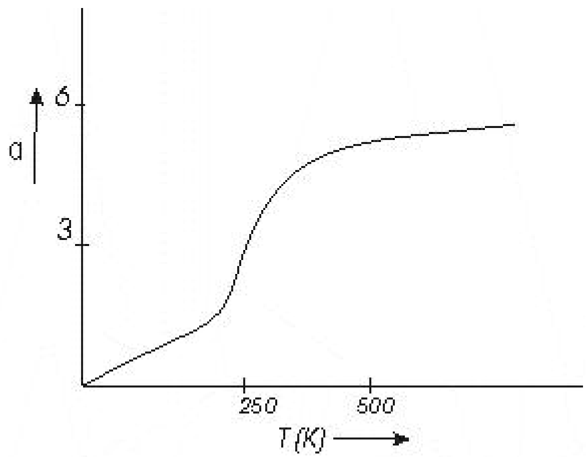

Figure 4:-Coefficient of volume expansion of copper as a function of temperature

Relation between volume and linear coefficient of expansion for solid material:

Consider a solid parallopide with dimension L_1,L_2 and L_3 then its volume is

$$V= L_1L_2L_3$$

When temperature increase by a amount ΔT then each linear dimension changes and then new volume is

$$V+\Delta V=L_1L_2L_3(1+\alpha_L\Delta T)^3$$

$$=V(1+\alpha_L\Delta T)^3$$

$$=V(1+3\alpha_L\Delta T+3\alpha_L{}^2(\Delta T)^2+\alpha_L{}^3(\Delta T)^3)$$

if ΔT is small then higher order of ΔT can be neglected.Thus we find

$$V+\Delta V=V(1+3\alpha_L\Delta T)$$

or,

$$\Delta V=3\alpha_LV_0\Delta T$$

Comparing this with equation (5) we find

$$\alpha_V=3\alpha_L$$

6. Thermal stress

If we clamp the ends of a rod rigidly to prevent expansion or contraction and then change the temperature, tensile or compressive stresses called **thermal stresses** develop.

The rod would like to expand or contract, but the clamps won't let it. The resulting stresses may become large enough to strain the rod irreversibly or even break it.

Engineers must account for thermal stress when designing structures. Concrete highways and bridge decks usually have gaps between sections, filled with a flexible material or bridged by interlocking teeth , to permit expansion and contraction of the concrete.

To calculate the thermal stress in a clamped rod, we compute the amount the rod would expand (or contract) if not held and then find the stress needed to compress (or stretch) it back to its original length. Suppose that a rod with length L and cross-sectional area A is held at constant length while the temperature is reduced (negative ΔT), causing a tensile stress. The fractional change in length if the rod were free to contract would be

$\left (\frac{\Delta L}{L} \right)_{thermal}=\alpha \Delta T$

Here both ΔL and ΔT are negative.The tension must increase by an amount F that is just enough to produce an equal and opposite fractional change in length $\left (\frac{\Delta L}{L} \right)_{tension}$. From the definition of Young's modulus,

$Y=\frac{F/A}{\Delta L /L}$

or,

$\left (\frac{\Delta L}{L} \right)_{tension}=\frac{F}{AY}$

If the length is to be constant, the total fractional change in length must be zero. This means that

$\left (\frac{\Delta L}{L} \right)_{thermal}+\left (\frac{\Delta L}{L} \right)_{tension} = \alpha \Delta T + \frac{F}{AY} = 0$

Solving for the tensile stress F/A required to keep the rod's length constant, we find

$$\begin{equation} \frac{F}{A}=-Y\alpha \Delta T \tag{7} \end{equation}$$

For a decrease in temperature, ΔT is negative, so F and F/A are positive; this means that a tensile force and stress are needed to maintain the length. If ΔT is positive, F and F/A are negative, and the required force and stress are compressive.

7. Specific Heat Capacity

If a system undergoes a change of temperature from T to T+ΔT during the transfer of ΔQ amount of heat then heat capacity c of the system is defined as the ratio of

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

Thus Heat capacity per unit mass of a substance is its specific heat capacity.

$$c=\frac{\Delta Q}{m\Delta T}$$

where,

m - mass of the substance

ΔQ - Heat absorbed or rejected by the substance

ΔT - Change in Temperature

Specific heat capacity depends on the nature of substance.

It is constant characterstics of the substance and is independent of the ammount of substance.

It also depends on the temperature of the substance

Its unit is J Kg^{-1} K^{-1}

If the amount of substance is specified in terms of no of moles n instead of mass m then the heat capacity per mole of the substance is

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

and is known as **Molar Specific Heat capacity**.

It is constant characterstics of the substance and independent of the ammount of substance

It depends on the nature of the substance ,temperature and amount of heat supplied

Its unit is J mol^{-1} K^{-1}

In case of gases , when a gas is heated, ordinarly there is change in volume as well as pressure in addition to change in temperature

For simiplicity either volume or pressure can be kept constant.Thus gas have two

specific heat capacities

1) Specific heat capacity at constant volume C_V

2) Specific heat capacity at constant pressure C_P

8. Calorimetery

Calorimetery means measurement of Heat.
Calorimeter is the device used to measure heat and it is cylinderical vessel made of copper and provided by a stirrer and a lid.
This vessel is kept in a wooden block to isolate it thermally from suroundings.A theromometer is used to measure the temperature of the content in the calorimeter.
When bodies at diffrent temperature are mixed in a calorimeter,they exchange heat with each other.
Bodies at higher temperature loose heat while bodies at low temperature gain heat.Contents of the calorimeter is continously stirred to keep temperature of contents uniform
Thus principle of calorimetery states that the total heat given by hot objects is equal to the total heat received by cold objects.

9.Change of phases:

There are three phases of matter i.e, Solid, Liquid and Gas.
Substance for example, H_2O exists in solid phase as Ice,in liquid phase as Water and in gas state as Steam.
Transtion from one phase to another phase are accompained by absorption or liberation of heat and usually by change in volume even at constant T.
Change of phase from solid to liquid is called melting , from liquid to solid is called fusion and from liquid to gas is called vaporisation
Once the temperature for phase change is reached(e,g melting or boiling temperature) no further temperature change occurs until all the substance has undergone phase change.

Question 1

A circular hole of diameter 2.00 cm is made in an aluminium plate at 0 ^{0} C .what will be the diameter at 100^0 C?

Linear expansion for aluminium = 2.3 * 10^{-3} / ^{0} C

Solution:

Diameter of circular hole in aluminium plate at 0^0 C=2.0 cm

With increase in temperature from 0^0 C to 100^0 C diameter of ring increases

using

$L=L_0(1+\alpha\Delta T)$

where L0=2.0 cm

α = 2.3 * 10^{-3} / ^{0} C

ΔT=(100 -0)=100 ^{0} C

we can find diameter at 100^0 C

L=2(1+2.3*10^{-3}*100)

=2.46 cm

Question 2

The pressure of the gas in constant volume gas thermometer are 80 cm,90cm and 100cm of mercury at the ice point,the steam point and in a heated wax bath resp.Find the temperature of the wax bath

Solution

Given that

Pressure at the ice point P_{ice}= 80 cm of Hg

Pressure at the steam point P_{steam}= 90 cm of Hg

Pressure at the wax bath P_{wax}= 100 cm of Hg

$T=(P_{wax}-P_{ice})X100/(P_{steam}-P_{ice})$

T = (100 - 80)X100/(90-80)

= 20X100/10

=200 ^{0}C

Question 3

A rod of length L having coefficent of Linear expansion a is lying freely on the floor.it is heated so that temperature changes by b. Find the longitidunal strain developed in the rod

a. 0
b. ab
c. -ab
d. none of the above

Solution

There was no restriction for it expansion.So no tensile or compressive force developed.Longitudinal strains happens only when tensile or compressive force developed in the rod.So answer is a

Question 4

.if a is coefficent of Linear expansion,b coefficent of areal expansion,c coefficent of Volume expansion.Which of the following is true

a. b=2a
b. c=3a
c. b=3a
d. a=2b

Solution

Answer is c

Question 5

.which is of them is not used as the measurable properties in thermometer?

a.Resistance of platinum wire
b.Constant volume of gas
c.Contant pressure of gas
d.None of the above

Solution

Answer is d

Question 6

.when a solid metalic sphere is heated.the largest percentage increase occurs in its

a.Diameter

b. Surface area

c. Volume

d. density

Solution

Answer is c

Question 7

.the density of the liquid depends upon

a. Nature of the liquid

b. Temperature of the liquid

c. Volume of the liquid

d. Mass of the liquid

Solution

Answer is a and b

Question 8

A metallic sphere has a cavity of diameter D at its center.If the sphere is heated,the diameter of the . cavity will

a. Decrease

b. Increase

c. Remain unchanged

d. none of the above

Solution

Answer is b

Question 9

.A metallic circular disc having a circular hole at its center rotates about it axis passing through the center and perpendicular to it plane.when the disc is heated

a. Its speed will decrease

b. Diameter will increase

c. Moment of inertia will increase

d. its speed will increase

Solution

(a),(c)

Due to thermal expansion,the diameter of the disc as well of the hole will increase.therefore the moment of inertia will increase resulting in a increase in the angular speed.

Question 10

A resistance thermometer is such that resistance varies with temperature as

$R_T=R_0(1+aT+bT^5)$

where T represent Temperature on Celsius scale And a,b,R_0 are constants.R_0 unit is ohm

Based on above data ,Find out the unit of a,b

Solution

As per dimension analysis Unit on both sides should be equal

Now since R & R_0 both unit are same

Quantity $1+aT+bT^5$ should be dimension less

so at should be dimension less

so a unit is C^{-1}

similarly bT^5 should be dimensionless

so b unit is C^{-5}

Heat Transfer

1. Introduction

We already know that heat is the energy transferred from from one systm to another or from one part of the system to its another part , arising due to temperature difference.
Heat can be transferred from one place to other by through three different modes conduction,convection & radiation.

2. Thermal Conduction

Conduction of heat takes place in a body when diffrent part of body are at diffrent temperature.
To notice conduction of heat put one end of metal rod on flame and another end on your hand. After some time you will feel hotness in your hand also.
Here heat transfer takes place from hot end on flame to cold end in your hand through conduction.
How heat transfers through conduction is given in steps below
1)Molecules at hot end of the rod begin to vibrate as there is an increase in the energy of vibration as temperature of the end of rod on flame increases.
2)These vibrating molecules then collides with the nearest neighbour sharing their energy with them and increasing their energy.
3)These neighbouring molecules further pass their energy to molecules on colder end of the rod i.e farther from the end put on flame.
4)This way energy of thermal motion is passed along from one molecule to the next keeping their original position fixed.
Metals are good conducters of electricty as well as heat.

3.Thermal Conductivity

Ability of Material to conduct heat is measured by thermal conductivity of that material.

Consider a slab of uniform crossection A and length L also one face of slab is kept at Temperature T_1 and another at T_2 and remaining surface area is covered with a non conducting material to avoid transfer of heat.

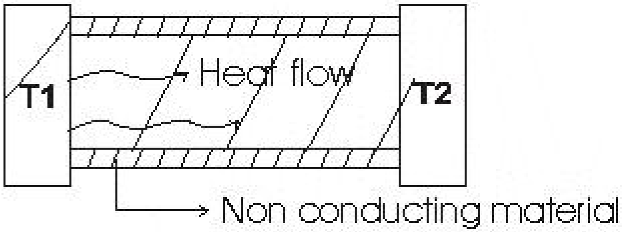

Figure 1

After sufficient time slab reaches steady state temperarure at every point will remain unchanged.

In steady state, rate of flow of the heat through any crosssection of slab is

a) directly propertional to area A

b) directly propertional to temperature diffrence (T_2-T_1)

c) inversely propertional to length

Thus if H is the quantity of heat flowing through slab per unit time then

$$H \propto \frac{A(T_2 - T_1)}{L}$$

$$H = \frac{kA(T_2 - T_1)}{L}$$

where k is a constant whose numerical value depends on the material and is called thermal conductivity of the material.

S.I. unit of thermal conductivity is $Js^{-1}m^{-1}K^{-1}$.

For small amount of heat dQ flowing between two faces of slab in small time interval dt,

$$dQ = \frac{kA(T_2 - T_1)dt}{L}$$

Materials for which K is large are good conductors of heat, while small value of K for a material implies material is poor conductor of heat.

4. Convection

Convection is transfer of heat by actual motion of matter
If material is forced to move by a blower or pump the process is called forced convection.
If the material flows due to difference in density for example that caused by thermal expansion then the process is called natural of free convection.
Meahanism of heat transfer in human body is forced convection. Here heart serves as the pump and blood as the circulating fluid.

5. Radiation

Radiation process does not need any material medium for heat transfer.
Term Radiation refers to the continous emission of energy from surface of all bodies and this energy is called radient energy.
Radiant energy is in the form of Electro Magnetic waves.
Radiant energy emitted by a sunface depends on the temperature and nature of the surface.
All bodies whether they are solid, liquid or gas emit radiant energy.
EM radiations emitted by a body by virtue of increased temperature of a body are called thermal radiation.
Thermal radiation falling on a body can partly be absorbed and partly be reflected by the body and this absorption and reflection of radiation depends on the color of body.
Thermal radiation travels through vacuum on straight line and with the velocity of light.
Thermal radiations can be reflected and refracted.

A body that absorbs all the radiation falling on it is called a black body.

Radiation emitted by black body is called Black Body radiation.

A black body is also called an ideal radiator.

For practical purpose black body can be considered as an enclosure painted black from inside and a small hole is made in the wall.

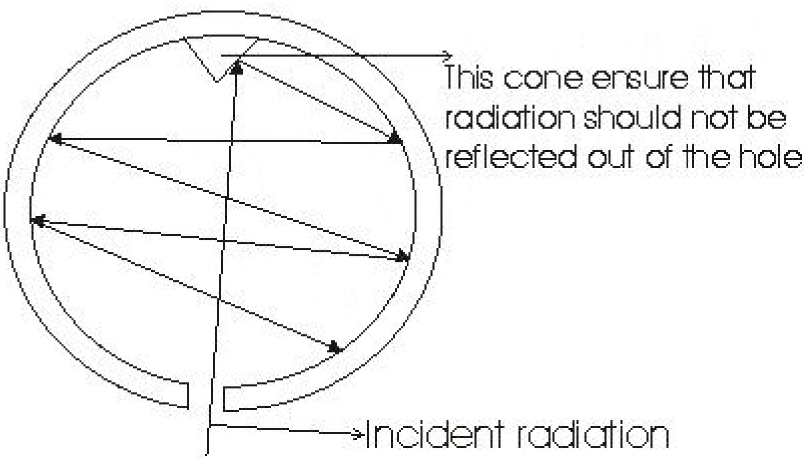

Figure 2

Once radiation enters the enclosure it has very little chance to come out of the hole and it gets absorbad after multiple refrections inside th enclosure.

Concept of a perfact black body is an ideal one.

7. Stefan Boltzmann law

The rate u_{rad} at which an object emits energy via EM radiation depends on objects surface area A and temperature T in kelvin of that area and is given by

$$u_{rad} = \sigma \varepsilon A T^4 \qquad (2)$$

Where

$$\sigma = 5.6703\times10^{-8}\ W/m^2K^4$$

is stefan boltzmann constant and ε is emissivity of object's sunface with value between 0 and 1.

Black - Body radiator has emissivity of 1.0 which is an ideal limit and does not occuer in nature.

The rate u_{abs} at which an object absorbs energy via thremal radiation from its environment with temperature T_{env} (in kelvin) is

$$u_{abs} = \sigma \varepsilon A (T_{env})^4 \qquad (3)$$

Where ε is same as in equation 2

Since an object radiate energy to the enviornment and absorbe energy from environment its net energy enchange due to thermal radiation is

$$u = u_{abs} - u_{rad}$$

$$= \sigma \varepsilon A\{(T_{env})^4 - T^4\} \qquad (4)$$

u is positive if net energy is being absorbed via radiation and negative if it is being lost via radiation.

8. Nature of thermal Radiation

Radiation emitted by a black body is a mixture of waves of different wavelengths and only a small range of wanelength has significant countribution in the total radiation.

A body is heated at different temperature and Enegy of radiation is plotted agains wavelength is plotted for different temperature we get following curves.

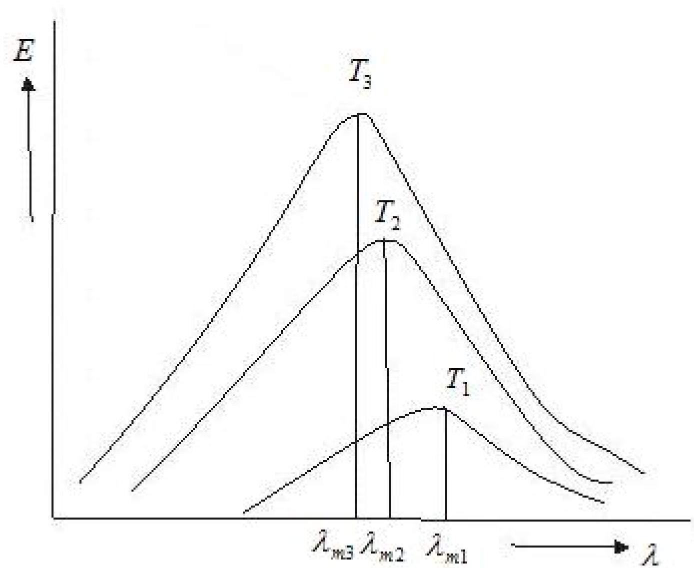

Figure 3

These curves show

(i) Energy is not uniformly distributed in the radiation spectreum of black body.

(ii) At a given temperature the intensity of radiations increases with increase in wavelength, becoms maximum at particular wavelength and further increase in wavelngth leads to decrease in intensity of heat radiation.

(iii) Increase in temperature causes increase in energy emission for all wavelengths.

(iv) Increase in temperature causes decrease in λ_m, where λ_m is wavelenght corresponding to highest intersity. This wavelength λ_m is inversily properational to the absolute temperature of the emitter.

$$\lambda_m T = b \qquad (5)$$

Where b is a constant and this equation is known as Wein's displacement law.

$b=0.2896\times10^{-2}$ mk for black body and is known as Wien's constant.

9. Kirchoff's law

Good absorbers of radiation are also good radiaters this statement is quantitatively explained by Kirchoff's law.

(i) Emissive Power -

Emissive power denotes the energy radiated per unit area per unit solid angle normal to the area.

$$E = \Delta u / [(\Delta A)(\Delta \omega)(\Delta t)]$$

where, Δu is the energy radiated by area ΔA of surface in solid angle $\Delta \omega$ in time Δt.

(ii) Absorptive Power -

Absorptive power of a body is defined as the fraction of the incident radiation that is absorbedby the body

a(absorptive power) = energy absorbed / energy incident

(iii) Kirchoff's Law

"It status that at any given temperature the ratio of emissive power to the absorptive power is constant for all bodies and this constant is equal to the emissive power of perfect B.B. at thesame temperature.

$$E/a_{body} = E_{B.B.}$$

From kirchoff's law we can say that a body having high emissive power should have high absorptive power and those having low emiesive power should have law absorptive power so as to keep the ratio E/a same.

10. Newton's Law of Cooling

Consider a hot body at temperature T_1 is placed in surrounding at temperature T_2.

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

$$dT/dt = - bA (T_1 - T_2)$$

This is known a Newton's law of cooling.

b depends on nature of surface involved and the surrounding conditions. Negative sign is to indicate that $T_1 > T_2$, dT/dt is negative and temperature decreases with time

According to this law, the rate of cooling is directly prospertional to the excess of temperature.