Chapter One

Black Body Radiation

1.1 Basic Definition

Thermal Radiation: If Heat is given to any substance, the particle at atomic level can generate motion known as thermal motion. If any charged particle within the matter has thermal Motion then they generate **electromagnetic radiation** known as thermal radiation. All matter with temperature greater than absolute zero emits thermal radiation.

Consider, for example, heating iron rod to higher and higher temperatures in fire the rod assumes a dull red color then a bright red color and at very high temperature intense blue-white color. The **intensity** of a beam of **electromagnetic radiation** is the **energy** it delivers per second per unit area.

Black Body Radiation: The spectrum of the thermal radiation emitted by a hot body depends somewhat upon the composition of body .How ever experiments show that there is one class of hot body that emits thermal spectra of universal character.

A **black body** is an idealized physical body that absorbs all incident electromagnetic radiation, regardless of frequency or angle of incidence. A black body in thermal equilibrium (that is, at a constant temperature) emits electromagnetic radiation called black body radiation. When an object is heated, it radiates electromagnetic energy as result of thermal agitation of electrons in its surface.

The spectral distribution of black body radiation is specified by quantity $R \equiv R(\nu, T)$ called spectral radiancy which is defined so that $R(\nu, T)d\nu$ is equal to the energy emitted per unit time in the interval ν to $\nu + d\nu$ from unit area of surface at absolute equilibrium temperature T. The Spectral Radiancy also known as density.

Intensity of radiation depends on frequency and absolute temperature (T).

The total intensity I over the entire spectrum is given by

$$I = \int_0^\infty R(\nu, T) d\nu .$$

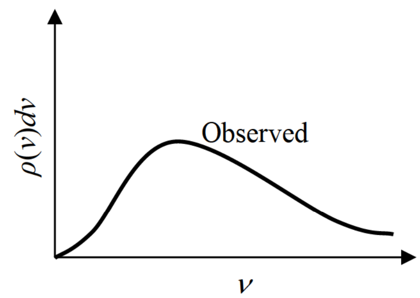

Figure 1.1

An object in thermal equilibrium with its surrounding radiates as much energy it absorbers. A black body is perfect absorber as well perfect emitter of radiation.

Observation of spectral energy density (Radiancy or Intensity) of black body radiation at different temperature as function of frequency ν.

(1) At the equilibrium the radiation emitted has a well defined **continuous** energy distribution.

(2) To each frequency there corresponds as energy density which depends neither on chemical composition of object nor on shape, but only temperature of black body.

(3) The curve shows pronounced Maximum at a given frequency, which increase with temperature, i.e. the peak of the radiation spectrum occurs at a frequency that is proportional to temperature.

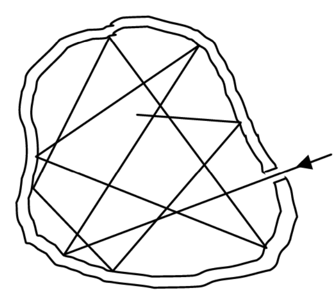
Figure 1.2

In figure the radiation incident upon the hole from the outside enters the cavity and is reflected back and forth by the walls of the cavity, eventually being absorbed on these walls. If the area of the hole is very small compared to the area of inner surface of the cavity, a negligible amount of the incident radiation will be reflected back through the hole. Essentially all the radiation upon the hole is absorbed; therefore the hole must have the properties of the surface of blackbody. Most blackbodies used in laboratory experiment are constructed along these lines.

1.2 Stefan's Law and Wien's Displacement Law

(a) Stefan's Law

The integral of the spectral radiancy $R(\nu,T)$ over all frequency ν is the total energy emitted per unit time per unit area from a black body at temperature T. It is called the radiancy $R(T)=\int_0^\infty R(T,\nu)d\nu$ or intensity I of radiated electromagnetic wave.

According to Stefan's law intensity I of radiated electromagnetic wave is proportional to fourth power of absolute temperature (T).

$I=\sigma T^4$ where σ is known as Stefan's Boltzmann constant.

The value of $\sigma=\frac{2\pi^5k^4}{15c^2h^3}$ where k is Boltzmann constant, c is speed of light and h is Plank's constant. The value of $\sigma=5.67\times10^{-8}W/m^2-{}^0K^4$

From the Stefan's law, one can calculate the Power P of radiated electromagnetic wave. So power is given by $P=\sigma AT^4$ where A is surface area of black body from which electromagnetic wave radiated.

(b) Wien's Displacement Law

The plot between energy density of blackbody radiation and frequency shows that maximum frequency $(\nu_{\max})$ is shifted towards right as temperature increases. Wien's displacement law stated that maximum frequency $(\nu_{\max})$ is directly proportional to absolute temperature.

$$\nu_{\max}=\frac{c}{\lambda_{\max}}=\frac{4.9663}{h}k_BT\Rightarrow\lambda_{\max}.T=\frac{hc}{4.966k_B}=2.9\times10^{-3}K.m$$

(c) Kirchhoff's Law

We have learnt that good absorbers of radiation are also good radiators. This aspect is described quantitatively by Kirchhoff's law of radiation. Before stating the law let us define certain terms.

Emissive Power

Consider a small area ΔA of a body emitting thermal radiation. Consider a small solid angle $\Delta\omega$ (see the chapter "Gauss's Law) about the normal to the radiating surface. Let the energy radiated by the area ΔA of the surface in the solid angle $\Delta\omega$ in time Δi be

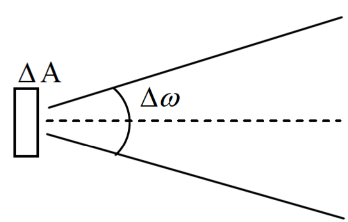

Figure 1.3

ΔU. We define emissive power of the body as

$$E = \frac{\Delta U}{(\Delta A)(\Delta \omega)(\Delta t)}$$

Thus, emissive power denotes the energy radiated per unit area per unit time per unit solid angle the normal to the area.

Absorptive power

Absorptive power of a body is defined as the fraction of the incident radiation that is absorbed by the body. If we denote the absorptive power by a,

$$a = \frac{\text{energy absorbed}}{\text{energy incident}}$$

As all the radiation incident on a blackbody is absorbed, the absorptive power of a blackbody is unity.

Note that the absorptive power is a dimensionless quantity but the emissive power is not.

The ratio of emissive power to absorptive power is the same for all bodies at a given temperature and is equal to the emissive power of a blackbody at that temperature. Thus,

$$\frac{E(\text{body})}{a(\text{body})} = E \text{ (blackbody)}$$

Kirchhoff's law tells that if a body has high emissive power, it should also have high absorptive power to have the ratio E/a same. Similarly, a body having low emissive power should have low absorptive power. Kirchhoff's law may be easily proved by a simple argument as described below.

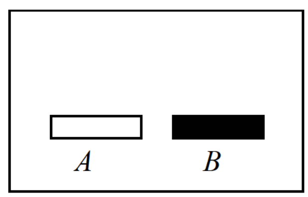

Figure 1.4

Consider two bodies A and B of identical geometrical shapes placed in an enclosure. Suppose A is an arbitrary body and B is a blackbody. In thermal equilibrium, both the bodies will have the same temperature as the temperature of the enclosure. Suppose an amount ΔU of radiation falls on the body A in a given time Δt. As A and B have the same geometrical shapes, the radiation falling on the blackbody B is also ΔU. The blackbody absorbs all of this ΔU. As the temperature of the blackbody remains constant, it also emits an amount ΔU of radiation in that time. If the emissive power of the blackbody is E_0, we have

$$\Delta U \propto E_0 \text{ or } \Delta U = kE_0 \qquad \text{(i)}$$

where k is a constant.

Let the absorptive power of A be a. Thus, it absorbs an amount $a\Delta U$ of the radiation falling on it in time Δt. As its temperature remains constant, it must also emit the amount $a\Delta U$ in that time. If the emissive power of the body A is E, we have

$$a\Delta U = kE \qquad \text{(ii)}$$

The same proportionally constant k is used in (i) and (ii) because the two bodies have identical geometrical shapes and radiation emitted in the same time Δt is considered.

From (i) and (ii) $a = \dfrac{E}{E_0}$ or, $\dfrac{E}{a} = E_0$

or, $\dfrac{E(\text{body})}{a(\text{body})} = E$ (blackbody). This proves Kirchhoff's law.