Radiation (Thermal Radiation).

It is the energy emission from a body in the form of electromagnetic waves as a result of its temperature.

From thermodynamics, we know that all bodies possess internal energy indicated by its absolute temp. These bodies continuously release their internal energy in the form of electromagnetic waves or energy particles (photones) called radiation.

Why the bodies release energy? (Ans. by quantum Theory)

when the temp. of a solid body is raised some atoms and molecules are raised to excited states of higher energy. There is a tendancy for these atoms or molecules to return spondaneously to lower energy states. when this occurs energy is emitted in the form of electromagnetic waves.

According to quantum Theory, the thermal radiation poropagates in the form of discrete quanta, each quanta having an energy of, $E = h\nu$, where h = planck's constant $= 6.625 \times 10^{-34}$ J.S. and ν = freqnancy of quantum.

Each quantum of photon, may be considered as a particle having, energy, mass and momentum just like the molecules of a gas. Radiation can thus be considered as a 'photon gas' flowing from one location to another with its particles governed by the following relations. $E = mC_0^2 = h\nu$ $\therefore m = \frac{h\nu}{C_0^2}$

Momentum = mass x velocity $= \frac{h\nu}{C_0^2} \times C_0 = \boxed{\frac{h\nu}{C_0}}$

Surface emission properties are: (E_b, E_λ), E, intensity of radiation, radiation density & pressure, Radiosity (J), inter relationship b/w surface emission and irradiation properties.

The rate of emission of radiation by a body depends upon the following factors: (i) The temp of the surface (ii) the nature of the surface & (3) The wavelength or frequency of surface.

Total emissive power (E)

It is the total radiant energy emitted per unit time per unit surface area of a body. The emissive power of a black body by Stefan Boltzmann is ∝ to 4th power of its absolute temp.

i.e. $E_b = \sigma T^4 \ W/m^2$ $\quad \sigma = 5.67 \times 10^{-8} \ W/m^2K^4$

$= \sigma A T^4 \ W$

Monochromatic emissive power (E_λ) or (spectral)

The energy emitted by the surface at a given wavelength in all direction is known as monochromatic emissive power (E_λ).

The total energy emitted by the surface at a given temp. is the addition of radiant energy at all wavelengths in all direction and is known as the total emissive power at that temperature.

$$E = \int_0^\infty E_\lambda d\lambda \ W/m^2$$

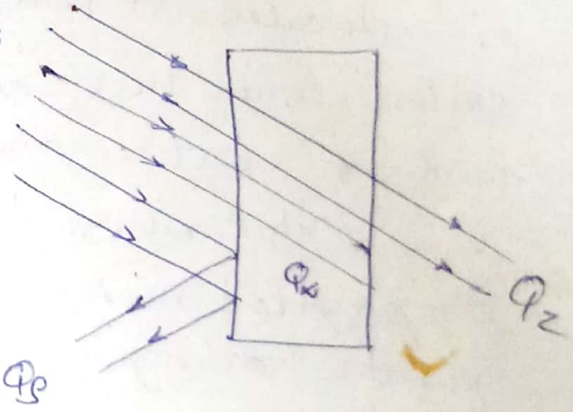
Reflection / Absorption / transmission of Radiation

Q_i - incident Radiation

Q_α - absorption fraction

Q_ρ - Reflected fraction

Q_τ - Transmitted fraction.



$Q = Q_a + Q_r + Q_t$

$Q_i = Q_\alpha + Q_\rho + Q_\tau$

For a given wavelength of incident radiation the reflected parts depends on

(1) Material (2) Surface finish (3) Angle of incidence.

But for a given body and surface finish, the reflected portion differs for different wavelength.

Ex: If thermal radiation from an electric fire falls on a slab of glass, the light waves are transmitted and heat waves are largely absorbed.

$$Q_\alpha + Q_\rho + Q_\tau = Q_i$$

Dividing by Q_i, $\quad \dfrac{Q_\alpha}{Q_i} + \dfrac{Q_\rho}{Q_i} + \dfrac{Q_\tau}{Q_i} = 1$

$$\alpha + \rho + \tau = 1$$

where α - absorptivity and is the fraction of the total incident energy which is absorbed.

ρ - reflectivity, which is the fraction of the total incident energy which is reflected.

τ - transmissivity, which is the fraction of the total incident energy which is transmitted.

Case I If $\alpha = 1$, then $\rho = 0$, $\tau = 0$ which means that incident energy is entirely absorbed by the body. Such a body is called black body.

Case II If $\rho = 1$, $\alpha = 0$ and $\tau = 0$, which means that all incident radiation is reflected. The body is called white body or: In the case of a mirror.

Case III

If $\tau = 1$, then $\alpha = 0$, $\rho = 0$, which means that all incident radiation is transmitted. The body is called transparent body.

Case - IV If $\tau = 0$, then $\alpha + \rho = 1$, the body is opaque.

Note : There are no absolute black $(\alpha = 1)$, white $(\rho = 1)$ and transparent $(\tau = 1)$ bodies in nature.

Idealization of a black body.

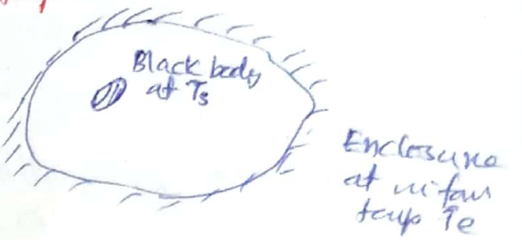
A black body is a perfect absorber of incident radiation. A black body condition can be approached in practice by forming a cavity in material as

cavity acting like a black body.

Shri Mehz.

Radiation passing through the hole into the cavity is repeatedly absorbed and reflected at the cavity walls until it is all absorbed.

A black body is a perfect emitter. ie it emits max. and of thermal radiations at all wavelengths at any specified temp.



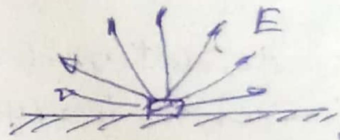
Consider a black body at a uniform temp (T_s), placed inside an arbitrarily shaped, perfectly insulated enclosure composed of another black body whose temp. is also uniform but different from that of the former. The black body and the enclosure will reach a common equilibrium temperature after a period of time. (due to heat transfer) when the black body will radiate as much energy as it absorbs.

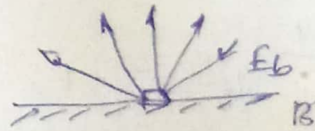
It is a diffuse emitter. ie independent of direction

Total emissivity (ε)

It is defined as the ratio of the total emissive power (E) of a real body to that of a black (E_b) surface, at the same temp.

ie $\varepsilon = \left.\dfrac{E}{E_b}\right|$ at the same temp.





The value of ε lies b/w 0 & 1

ie $0 \le \varepsilon \le 1$ by definition.

Some laws of Radiations (1) Planck's law:

The laws governing the distribution of radiant energy over wavelength for a black body at a fixed temp. were formulated by Planck. Based on extensive experimental evidence planck suggested

It states that the heat loss by radiation from a black body depends only upon its absolute temperature.

It allows us to calculate the value of the monochromatic emissive power of a black body.

$$E_{b\lambda} = \frac{2\pi C_1 \lambda^{-5}}{\exp(C_2/\lambda T) - 1}$$

$C_1 = 0.596 \times 10^{-16}\ W/m^2$

$C_2 = 0.0143877\ mK$.

C_1 & C_2 are experimental constants.

λ - wavelength, T - ab. Temp.

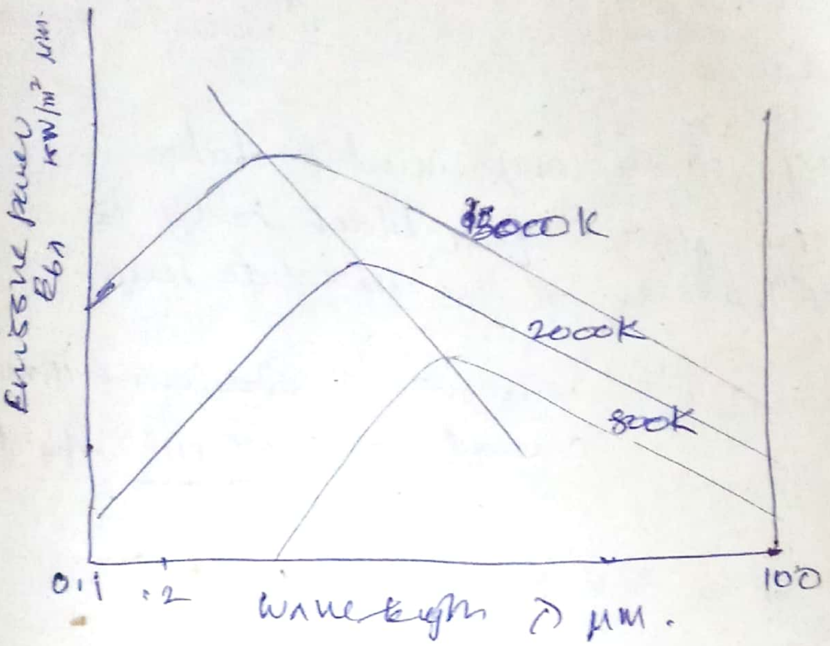
$E_{b\lambda} = \dfrac{2\pi c^2 h\, \lambda^{-5}}{\exp[ch/k\lambda T] - 1}$

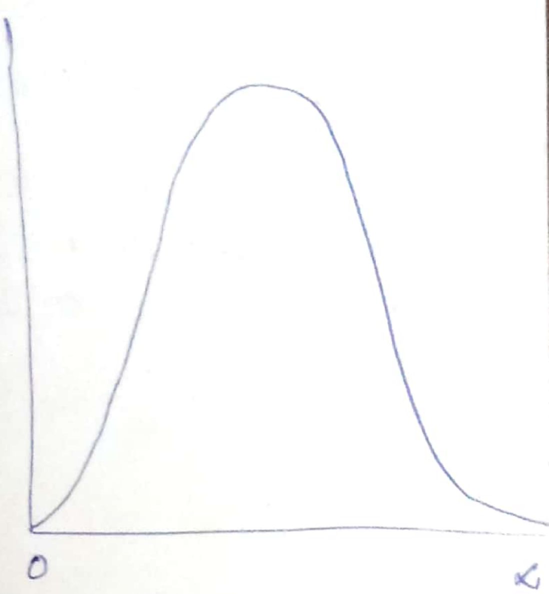
where, h = Planck's constant 6.6236×10^{-34} JS, c = Vel. of light in vacuum 2.998×10^8 m/s, k = Boltzman const, 13.802×10^{-24} J/K

For non black surface $E_\lambda = \varepsilon_\lambda E_{b\lambda}$

~~Wean~~ ② Wien's displacement Law.

If we plot the planck's equation, we get the graph as shown below for different temperatures.





All the graphs start from zero and goes to maximum and then will decrease assymptotically to zero. This will be the nature of the graph for different temps as shown.

Comments (about graphs)

1. At a particular temp $E_{b\lambda}$ increases with λ goes through a maximum and then decreases assymptotically to zero.
2. At a particular λ, $E_{b\lambda}$ increases with temperature.
3. The max. value of $E_{b\lambda}$ occurs at a smaller wavelength as Temperature increases.

To findout the location of the wavelength where the maximum $E_{b\lambda}$ occurs. Differentiate planck's law ($E_{b\lambda}$) w.r.to λ and equate to zero. ie $\frac{d}{d\lambda}(E_{b\lambda}) = 0$.
we get $\lambda_m \cdot T = 0.00290\ mK$. This is called wiens Law.
$= 2898\ \mu m K \approx 2900\ \mu m K$

ie By wien's law, the maximum value of $E_{b\lambda}$ occurs at a wavelength λ_m given by the equation $\boxed{\lambda_{max} \cdot T = 0.00290\, mK}$ or $\lambda_{m} T = 2898\ \mu mK$

Note:
Wien's displacement law states that the product of λ_{max} and T is constant, ie $\lambda_{max} \cdot T =$ constant. [≈ 2900 μmK]

(3) Stefan Boltzmann Law.

Stefan in 1879, from experimental data concluded that emissive power of a black body is proportional to the 4th power of the absolute temp.

$E_b \propto T^4$ ie $E_b = \sigma T^4$, where σ = Stefan Boltzmann constant $= 5.67 \times 10^{-8}\ W/m^2K^4$

Proof:
Total Emissive power of a black body E_b

$$E_b = \int_0^\infty E_{b\lambda}\, d\lambda .$$

$E_{b\lambda}$ is for a particular wavelength
∴ integrating for all wavelength will give the total emissive power E_b.

but by planck's law

$$E_{b\lambda} = \frac{2\pi C_1 \lambda^{-5}}{[\exp^{C_2/\lambda T} - 1]}$$

ie
$$E_b = \int_0^\infty \frac{2\pi C_1 \lambda^{-5}}{e^{C_2/\lambda T} - 1}\, d\lambda$$

$$= 2\pi C_1 \int_0^\infty \frac{\lambda^{-5}}{e^{C_2/\lambda T} - 1}\, d\lambda .$$

Expanding the term $e^{C_2/\lambda T}$ by power series and then integrating term by term, then we get the results as a convergent series which will sum up to $\frac{\pi^4}{90}$. i.e. the net result will be of the form.

$$E_b = 2\pi C_1 \frac{\sigma T^4}{C_2^4}\left(\frac{\pi^4}{90}\right)$$

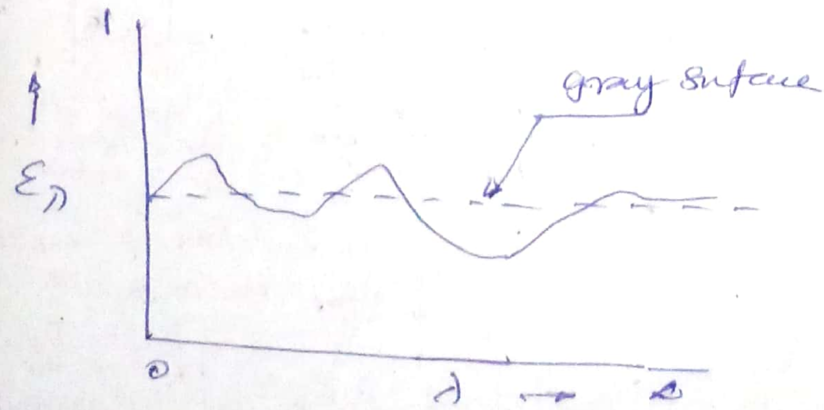
In this except T all are constant and nothing. the constant together as σ, we get.

$E_b = \sigma T^4$. where σ = Stefan Boltzmann constant = $5.67\times10^{-8}\,W/m^2K^4$

This is the Stefan Boltzmann law, it is nothing but the integration of planck's law from 0 to ∞.

Gray Surface

A surface having the same value of ε_λ at all wavelength. For a typical surface if we plot the ε_λ it varies as shown in the following figure.



Gray surface is an idealization. It turns to be a useful idealization for calculation.

Again,

If the ratio of the emissive power of a body to that of a black body at a given temp. is constant at all wavelength. Such a body is called gray body

i.e. A gray body absorbs a definite percentage of incident radiation irrespective of a wavelength.

When the absorptivity of a body varies with wavelength of radiation waves, the body is known as a colour body.

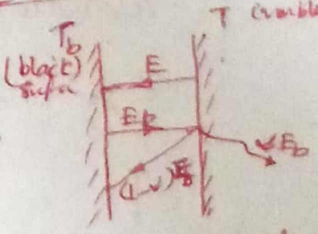
Kirchhoff Law of Radiation.

For all bodies which are in thermal equilibrium with the surroundings (i.e same temp), the ratio of the emissive power to absorptivity is the same and is equal to the emissive power of a black body at the same temperature.

It states that at thermal equilibrium, the ratio of the total emissive power to the total absorptivity is constant for all bodies.

$E = \varepsilon E_b = \varepsilon \sigma T^4$

Radiant interchange for the non-black surface equals $(E - \alpha E_b)$. If both surfaces are at the same temp., $T = T_b$, then conditions corresponds to mobile thermal equilibrium for which the resultant interchange of heat is zero.



Exchange of heat b/w a black & non black surface.

Let $E_1 = \varepsilon_1 \sigma T_0^4$

III^y $E_2 = \varepsilon_2 \sigma T_0^4$

$E_3 = \varepsilon_3 \sigma T_0^4$ etc.

$$\therefore \frac{E_1}{\alpha_1} = \frac{E_2}{\alpha_2} = \frac{E_3}{\alpha_3} = \frac{E_b}{\alpha_b}$$

$$\frac{\varepsilon_1 \sigma T_0^4}{\alpha_1} = \frac{\varepsilon_2 \sigma T_0^4}{\alpha_2} = \frac{\varepsilon_3 \sigma T_0^4}{\alpha_3} = \frac{\varepsilon_b \sigma T_0^4}{\alpha_b}$$

$$\frac{\varepsilon_1}{\alpha_1} = \frac{\varepsilon_2}{\alpha_2} = \frac{\varepsilon_3}{\alpha_3} = \frac{\varepsilon_b}{\alpha_b} = \underline{\underline{1}}$$

$\alpha_b = 1$ & $\varepsilon_b = 1$

under these conditions, $E - \alpha E_b = 0$ or $\boxed{\frac{E}{\alpha} = E_b}$. Thus in general

$$\frac{E_1}{\alpha_1} = \frac{E_2}{\alpha_2} = \frac{E_3}{\alpha_3} = \frac{E_b}{\alpha_b} = \underline{\underline{E_b = f(T)}}$$

Also $\frac{E}{E_b} = \alpha = \varepsilon$

If emissivity increases, absorptivity also increases.

$$\frac{\varepsilon_1}{\alpha_1} = 1 \quad \text{ie } \underline{\varepsilon_1 = \alpha_1}$$

Kirchoff's law can also be stated as: "The emissivity ε and absorptivity α of a real surface are equal for radiation identical and temp. and wavelength

good emitters are good absorber also.

Thus the total emissivity of a surface at temp T is always equal to its total absorptivity for radiation coming from a blackbody at the same temperature. This relation simplifies the radiation ~~properties~~ analysis and is known as Kirchoffs law.

Wien's displacement law.

(Previous fig.) Fig. shows the spectral blackbody emissive power distribution over a certain range of wavelength. It is observed that, for a given temp: there is a definit peak, at a particular λ. This wavelength λ_{max} depends on the temp. T of the surface. ~~The~~

The relationship b/w the wavelength λ_{max} and absolute temp. T at which $E_{b\lambda}$ reaches a maximum value is called the wien's displacement law. It can be derived from Planck's distribution law by applying the condition of maxima.

ie differentiating $E_{b\lambda}$ w.r.to λ and setting to zero.

$$\frac{dE_{b\lambda}}{d\lambda} = \frac{d}{d\lambda}\left[\frac{c_1\lambda^{-5}}{e^{c_2/\lambda T}-1}\right] = 0$$

$$= \frac{-5 C_1 \lambda^{-5}}{e^{C_2/\lambda T}-1} - \frac{C_1 \lambda^{-5} e^{C_2/\lambda T}}{\left[e^{C_2/\lambda T}-1\right]^2} \cdot \frac{-C_2}{\lambda^2 T} = 0$$

Simplifying and rearranging we get

$$\frac{\exp\left[\frac{C_2}{\lambda T}\right]}{\exp\left[\frac{C_2}{\lambda T}\right]-1} = \frac{5\lambda T}{C_2}$$

using $x = \frac{C_2}{\lambda T}$, we get, $\frac{e^x}{e^x - 1} = \frac{5}{x}$ or $x = 5(1-e^{-x})$.

It is a transcendental equation and its solution by trial and error method converges to

$$x = \frac{C_2}{\lambda_{max} T} = 4.9651$$

substituting constant $C_2 = 1.4388 \times 10^4$ μm we get

$$\lambda_{max} T = 2897.6 \ \mu m K.$$

$$\lambda_{max} T = \underline{0.0029 \ mK}$$

Radiosity.

Radiosity J, is the total radiant energy leaving a surface per unit area per unit time. The total energy leaving a surface consists of the radiant energy leaving a surface consists of the emitted energy and reflected part of the incident energy as shown in fig.

RADIATION

Radiation heat transfer is defined as the transfer of energy across a system boundary by means of an electromagnetic mechanism which is caused solely by a temperature difference. Conduction and convection heat transfer takes place only in the presence of medium, whereas radiation heat transfer does not require a medium. Conduction and convection heat transfer varies to the first power of temp difference whereas radiative heat transfer depends on the fourth power of the temp difference. Radiation heat transfer prevails in furnaces, combustion chambers, nuclear explosions, radiation from suns.

The energy which a radiating surface releases is not continuous but is in the form of successive and separate (discrete) packet or quanta of energy called photons. These photons travel with speed equal to that of light in straight paths with unchanged frequency. All types of electromagnetic waves are classified in terms of wavelength. ~~and pro~~ Thermal radiation exhibit characteristics similar to those of visible light and follow optical laws.