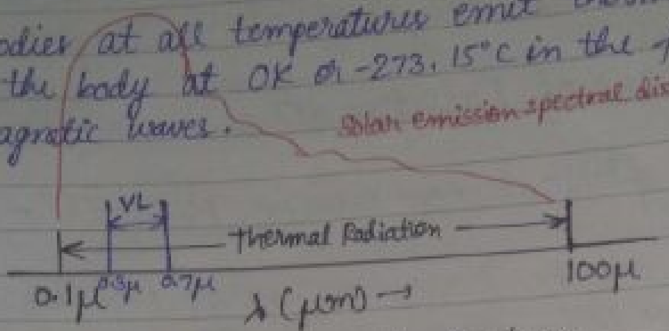
RADIATION

→ All bodies at all temperatures emit thermal radiation except the body at 0K or -273.15°C in the form of electromagnetic waves.



Electromagnetic Spectrum

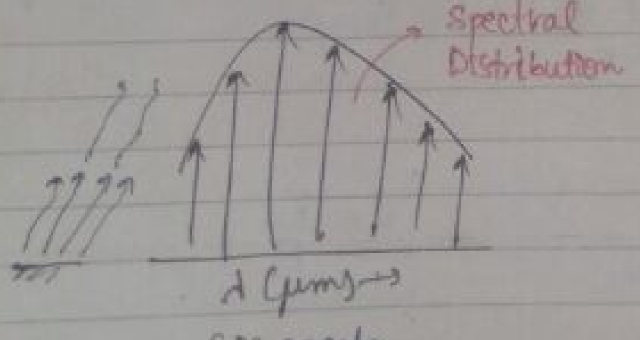
λ is the wavelength measured in Micros. $1 \mu m = 10^{-6} m$.

* All high temp. bodies like SUN, not only emits very great amount of thermal radiation but also most of the radiation occurs at short wavelengths.

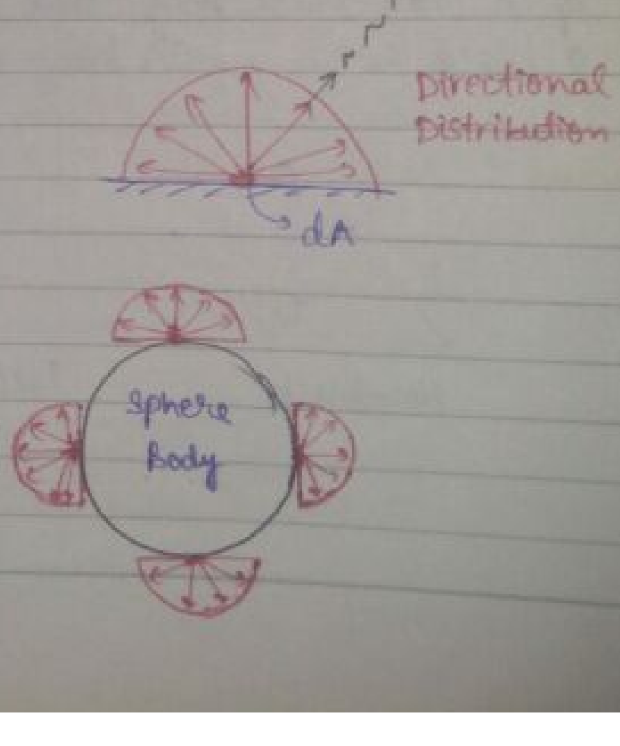
Thermal Radiation

Wavelength Module

Directional Method



EM spectrum



* Any body at any temp will emit thermal radiation in all hemispherical directions wrt differential area considered on the body and at all probable wavelengths on the electromagnetic spectrum (but in the range of 0.1 to 100 μm).

Basic Definitions of Radiation HT -

1- Total Hemispherical ~~em~~ emissive power (E) -

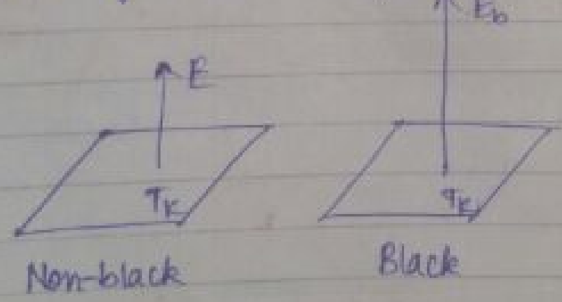
It is defined as the radiation energy emitted from the surface of your body per ~~tto~~ unit time per unit area in all possible hemispherical directions integrated over all the wavelengths.

$$E \rightarrow \text{Joule/sec-m}^2 \rightarrow W/m^2.$$

$$E = f(\underbrace{T}_{(K)\text{, Kelvin}})$$

2- Total Emissivity (ε) -

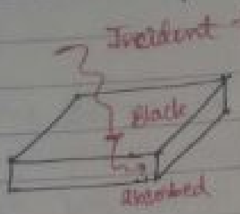
It is defined as the ratio b/w total hemispherical emissive power of a non-black body and total hemispherical emissive power of a black body, both being at the same temp.



$$\boxed{\varepsilon = \frac{E}{E_b}}.$$

Black body - It is the body which absorbs all the thermal radiation incident or falling upon the body.

→ Body is absorbing the radiation and on the same time emitting.
→ Radiation is only dependent on temp. of the body.
→ Good emitter is also a good absorber (applicable even for non-black body)



Black body → Perfect absorber
→ Ideal emitter
→ Diffusive

A narrow (or) tiny cavity in a hollow spherical container is a blackbody.

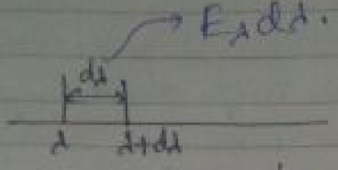
Examples- (i) A small hole in a furnace wall is black body.
(ii) In radiation analysis, sun is also treated as black body.

Note: A thermally blackbody absorbing all the incident thermal radiation may not appear black in colour to human eye.
~~Bmay~~ eg; ice and snow are thermally black.

* For any body,

$\epsilon \leq 1$, → For any body
$\epsilon_b = 1$. → For black body

3- <u>Monochromatic</u> (or) ~~Spherical~~ spectral hemispherical emissive power (E_λ) -



E-M spectrum

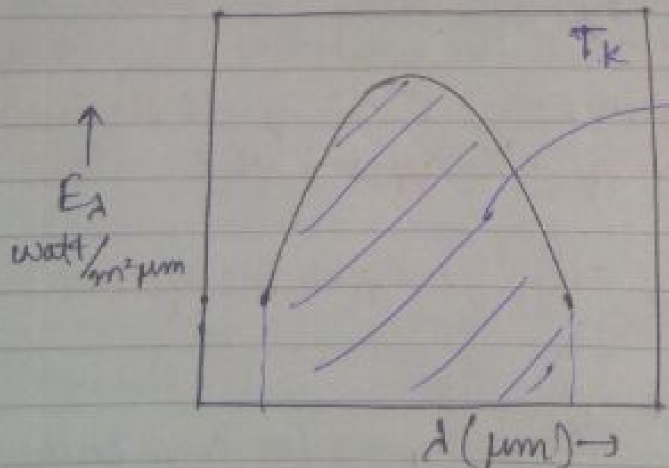
$d\lambda \rightarrow$ Differentially small increment in wavelength (λ)

E_λ at a particular wavelength λ is defined as the quantity which when multiplied by $d\lambda$ shall give the radiation energy emitted from the surface of the body per unit time per unit area in the wavelength region λ to $\lambda + d\lambda$.

$E_\lambda \rightarrow$ Joule/sec-m^2 μm $\rightarrow$ watt/m^2 μm.

$\rightarrow$ For any given body at a given temperature.

$E_\lambda = f(\lambda)$.

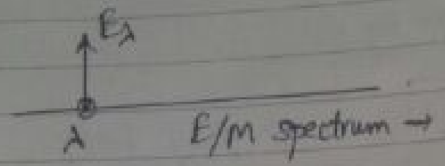


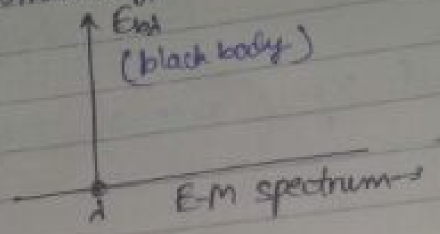
$\rightarrow$ Area $= \int_0^\infty E_\lambda d\lambda = E$

$\leftarrow$ Total hemispherical emissive power.

Total Hemispherical Emissive power $= E = \int_0^\infty E_\lambda \, d\lambda \quad W/m^2.$

4- Monochromatic (or) Spectral emissivity ~~power~~ (ϵ_λ) -





It is defined as the ratio b/w monochromatic hemispherical emissive power of a non-black body and ~~#~~ monochromatic ~~and~~ hemispherical emissive power of a black body, both being at the same temp. and wavelength.

$$\boxed{\epsilon_\lambda = \frac{E_\lambda}{E_{b\lambda}}} \Rightarrow E_\lambda = \epsilon_\lambda E_{b\lambda}.$$

$$\epsilon = \frac{E}{E_b} = \frac{\int_0^\infty E_\lambda \, d\lambda}{\int_0^\infty E_{b\lambda} \, d\lambda} = \frac{\int_0^\infty \epsilon_\lambda E_{b\lambda} \, d\lambda}{\int_0^\infty E_{b\lambda} \, d\lambda}$$

$$\epsilon = \frac{\epsilon_\lambda \cancel{\int_0^\infty E_{b\lambda} \, d\lambda}}{\cancel{\int_0^\infty E_{b\lambda} \, d\lambda}} \Rightarrow \boxed{\epsilon = \epsilon_\lambda}.$$

If $\epsilon_\lambda \neq f(\lambda)$ or rather remaining constant.

Gray Body-

Such body whose monochromatic ϵ_λ is independent of wavelength (λ) or rather remaining constant is known as gray body or gray surface. ie for gray body

$$\boxed{\epsilon_\lambda = \text{Constant}}$$

Physical significance of gray body-

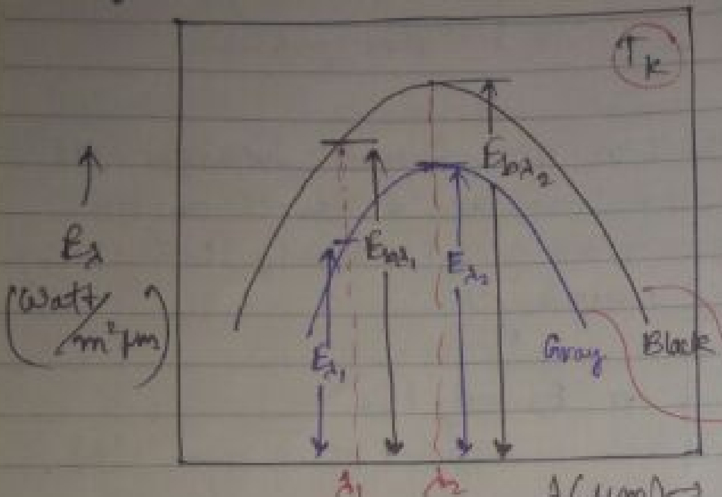
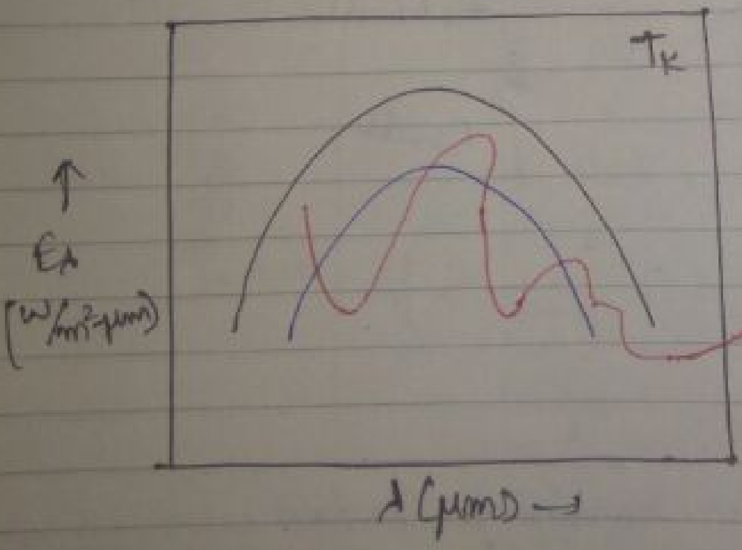


Fig.(i)

For gray body,
$\epsilon_\lambda = C \neq f(\lambda)$
ie. $\epsilon_{\lambda_1} = \epsilon_{\lambda_2}$,

$$\Rightarrow \frac{E_{\lambda_1}}{E_{b\lambda_1}} = \frac{E_{\lambda_2}}{E_{b\lambda_2}}.$$

→ Both the curves are in synchronous.
(ie. varying in synchronous)



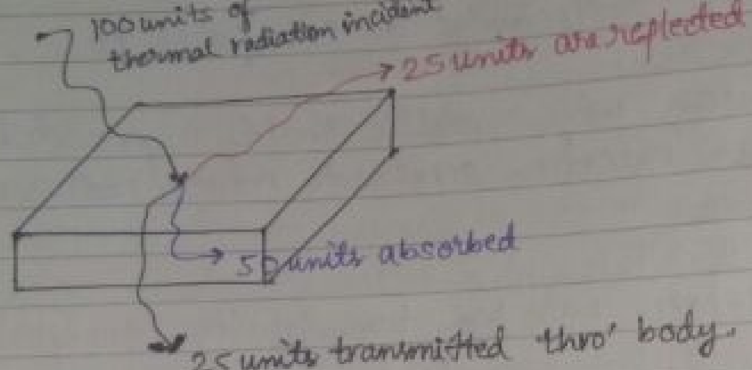
→ Non-gray surface
$\epsilon_\lambda = f(\lambda)$.

Fig (ii)

Fig.

— The ratio b/w the area under bottom curve on x-axis & the area under the top curve on x-axis will be equal to total emissivity of gray body which happens to be equal to its monochromatic emissivity.

Absorptivity (α), Reflectivity (ρ), Transmissivity (τ) -



Absorptivity (α) = $\frac{50}{100}$ = 0.5 = Fraction of radiation energy incident upon a surface which is absorbed by it.

Reflectivity (ρ) = $\frac{25}{100}$ = 0.25 = Fraction of radiation energy incident upon a surface which is reflected by it.

Transmissivity (τ) = $\frac{25}{100}$ = 0.25 = Fraction of radiation energy incident upon a surface which is ~~reflected &~~ transmitted thro' it.

* All these effects are taking into place altogether.

∴ For any surface, $\alpha + \rho + \tau = 1$.

For opaque surface, which doesn't transmit any energy, $\tau = 0$.

∴ For opaque surface, $\alpha + \rho = 1$.

→ For black body, which ~~of~~ absorbs all radiation energy incident

i.e. $\alpha_b = 1$.

and $\epsilon_b = 1$.

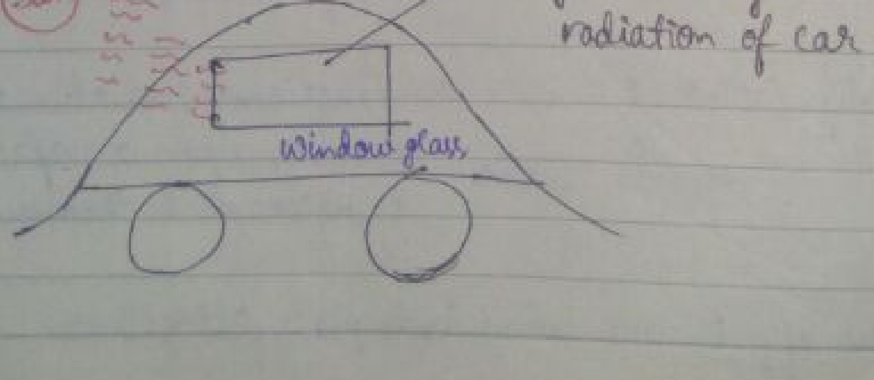
* Metals have high reflectivity as compared to ~~nom~~ non-metals.

→ This is the reason why metallic shields are provided in the furnaces as radiation screens to reduce radiation heat exchange.

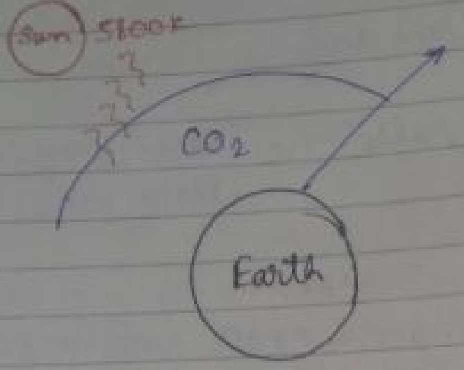
* Gases like O_2, H_2, etc. have high transmissivity (transparent to thermal radiation).

→ ** The above radiation properties mentioned change with wavelength of incident thermal radiation, surface roughness of the body and also with its temp.

Example-



The window glass of a car is very much transparent (i.e. high τ) to the short wavelength solar radiation, but the same window glass almost become opaque to the long wavelength reradiation given by inside of the car thus trapping energy inside the car hence increasing its temp.



Global Warming

$\therefore$ CO_2 is called as green house gas.

→ H_2O (water vapour) is also a green house gas that's why deserts are hotter in day and cold at night.

→ As the surface roughness of the body ↓ by polishing it, the reflectivity (ρ) of the surface ↑. This is the reason why highly polished copper & aluminium sheets having very good reflectivity are generally used in the furnaces to reduce radiation heat exchange.

Laws of Thermal Radiation-

1- Kirchoff's law of thermal radiation- The law states that whenever a body is in thermal equilibrium with ~~the~~ its surroundings, its emissivity is equal to its absorptivity.

$$\boxed{\alpha = \epsilon}$$

A good absorber is always a good emitter.
eg. Black body ($\alpha = e = 1$).

→ The law is also supposed to be valid even under non-equilibrium condn.

→ For both black & non-black body.

2- Planck's law of thermal radiation- Valid only for black body.

$$E_{b\lambda} = f(\lambda, T).$$

T in Kelvin.

The law states that the monochromatic emissive power of a blackbody is dependend on both absolute temp. of black body and also on wavelength of radiation energy emitted λ (in µm).

$$E_{b\lambda} = \frac{2\pi C_1}{\lambda^5\left(e^{\frac{C_2}{\lambda T}} - 1\right)} \text{ watt}/m^2\text{-}\mu.$$

C_1 & C_2 are experimental constants.

The above functional relationship among the 3 variables can be graphically plotted as

λ_m = Wavelength at which $E_{b\lambda}$ is max. at a given absolute temp of blackbody.

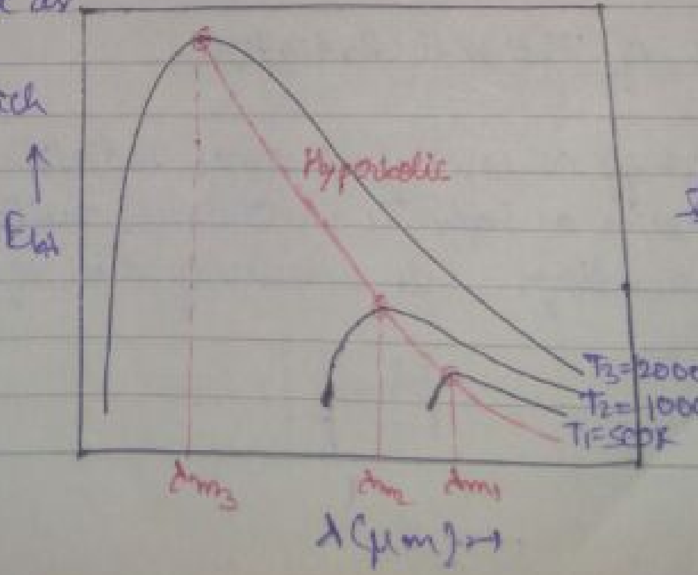


fig (i)

Note: At a given absolute temp. of a black body, as wavelength λ increases, $E_{b\lambda}$ also increases reaches a maximum & then decreases.

Also as the absolute temp. of black body ↑ (each time getting doubled) $E_{b\lambda}$ values enormously increases but now most of thermal radiation at higher temp. will be shifted to shorter (smaller) wavelength.

As T increases ⇒ λ_m decreases.

This law is used in Optical pyrometer. (Very high temp. measurement)

$\Rightarrow \lambda_m \propto \frac{1}{T}$.

$$\boxed{\lambda_m T = a = \text{Constant} = 2898 \mu m K}$$

This equation is called as Wein's Displacement Law. (3)

⇓

Valid only for black body.

→ Since sun is a blackbody, for solar radiation

$$(\lambda_m)_{solar} \times T_{solar} = 2898$$

$$(\lambda_m)_{solar} = \frac{2898}{5800} \simeq \frac{1}{2} \mu m.$$

4- Stefan's Boltzman's Law-

The total hemispherical emissive power of a black body is directly proportional to the fourth power of the absolute temp. of the black body.

$$E_b \propto T^4$$

$$E_b = \sigma T^4 \ W/m^2.$$

σ = Stefan- Boltzman's constant.
$= 5.67 \times 10^{-8} \ W/m^2\text{-}K^4.$

Proof -

$$E_b = \int_0^\infty E_{b\lambda}\, d\lambda \quad W/m^2$$

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

$$= \sigma T^4 \ W/m^2.$$

Planck's Law

Wein's Displacement Law

Stefan- Boltzman's Law

fig. (i)

Note: The ratio b/w the area under topmost curve on x-axis and the bottom most curve on x-axis will be equal to 4^4 ie. 256.

→ For a non.- black body, whose emissivity is ϵ, its total hemispherical emissive power $= E = \epsilon E_b$.
$= \epsilon \sigma T^4 \ W/m^2$,

If 'A' is the total surface area of non-black body.

Then, radiation energy emitted from entire non-black body $= EA$ watt $= \epsilon \sigma T^4 A$ watt.

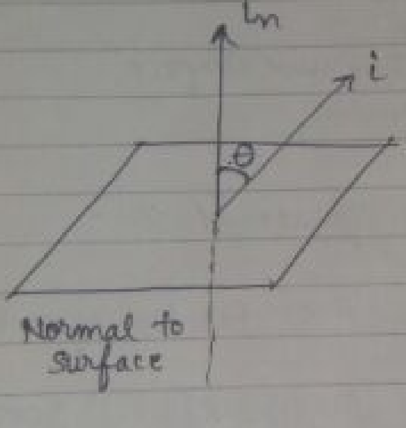
29- $E_1 = \epsilon_1 \sigma T_1^4 = 500$.
(c)
$$E_2 = \epsilon_2 \sigma T_2^4 = 1200.$$

$$\frac{T_1}{T_2} = \left(\frac{5}{12}\right)^{1/4} = 0.802.$$

31- $\cancel{E_{b\lambda} = \sigma \lambda_m T^4}$. $\lambda_m T =$ Constant.
(b)
$$0.5 \times 5800 = \lambda_{m_2} \times 1000$$

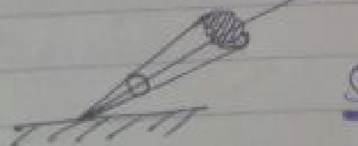
$$\boxed{\lambda_{m_2} = 2.90 \mu m}.$$

Lambert's Cosine Law -



$$\boxed{i = i_n \cos\theta}$$

i_n = Normal intensity of radiation.
i = Intensity of radiation along a dirⁿ making an angle 'θ' wrt. normal direction.



$$i \left(\frac{\text{Joule}}{\text{sec-m}^2\text{-steradian}}\right) = W/m^2\text{-steradian}.$$

Steradian is the unit of solid angle.

Intensity of radiation (i) along a given dirⁿ is defined as the radiation energy emitted from the surface of the body per unit time per unit area normal to that dirⁿ & per unit solid angle about that dir^n.

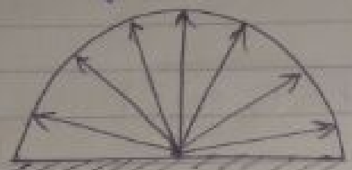
$i = \frac{dE}{d\omega}$ watt / m^2-steradian

i is a sum of all the radiations of all the wave length in one direction.

$\therefore$ Total hemispherical emissive power $= \boxed{E = \int i\,d\omega}$ W/m^2.

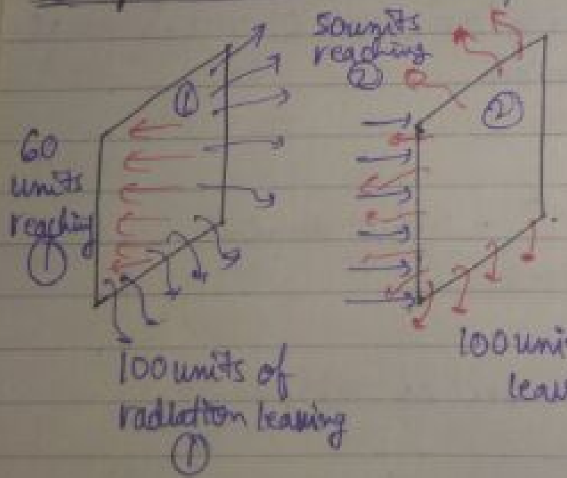
→ A diffuse surface has the same intensity of radiation along all the direction i.e. for diffuse surface 'i' is independent of dir^n. eg. blackbody

For blackbody, $E_b = \pi i_n$ W/m^2.



A Diffusive Surface

Shape Factor or View factor or Configuration Factor-



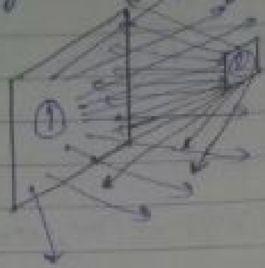
$F_{12} = \frac{50}{100} = 0.5 =$ Fraction of radiation energy leaving surface ① that reaches surface ②.

$F_{21} = 0.6 =$ Energy leaving ② reaches ①.

In general, F_{mn} = Fraction of radiation energy leaving surface ⓜ that reaches surface ⓝ.

$0 \le F_{mn} \le 1$.

→ The shape factor b/w 2 surfaces is independent of their temp., emissivity, wavelengths of emission but depends only on ~~how closely~~ their sizes, their shapes and how closely the two surfaces are kept wrt each other.



$\boxed{F_{21} > F_{12}.}$

→ $F_{11} = 0$.

① Flat surface.

→ $F_{11} \geq 0$

① Concave surface

→ $F_{11} = 0$.

① Convex surface

When one body or a surface is completely surrounded by another body or a surface, the shape factor of inner body wrt. the outer is equal to <u>One</u>.

<u>Examples</u> -

(1)

Hemispherical Dome

Circular plate

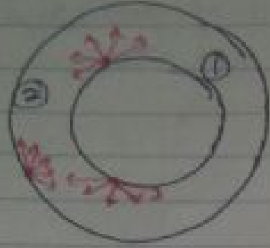
$F_{12} = 1.$

$F_{21} < 1$

$F_{22} < 1$

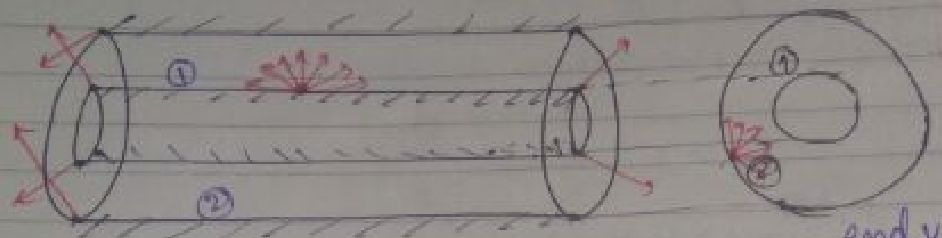
$F_{21} + F_{22} = 1.$

② Two concentric spherical ~~sphere~~ surfaces-



$F_{12} = 1$
$F_{21} < 1$
$F_{22} < 1$
Here also, $F_{21} + F_{22} = 1$.

③ Two infinitely long concentric cylindrical surfaces-



end view

$F_{12} = 1$ (Neglecting end effects), as long cylinder

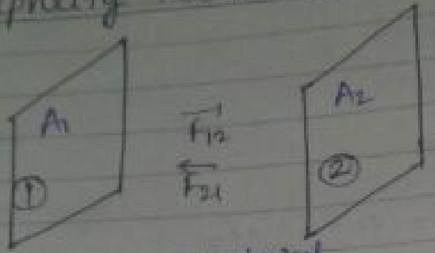
$F_{21} < 1$ (see in end view).

$F_{22} < 1$ $\quad$ $F_{21} + F_{22} = 1$ (Neglect end effects).

④ A body kept in an enclosure-

$F_{12} = 1$.
$F_{21} < 1$
$F_{22} < 1$
$F_{21} + F_{22} = 1$.

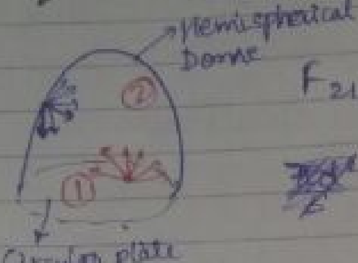
Reciprocity Relation b/w shape factors –



$$\boxed{A_1 F_{12} = A_2 F_{21}}$$

↓ Reciprocity theorem.

*



$F_{21} + F_{22} = 1.$

$\pi r^2 \times \cancel{F_{12}}^{1} = 2\pi r^2 \times F_{21}$

$F_{21} = \frac{1}{2}.$

$$\boxed{F_{22} = 0.5}$$

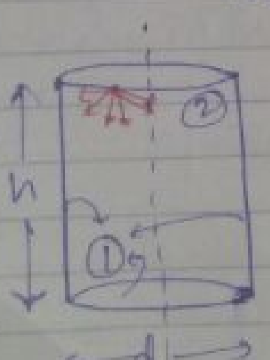
34 – $\cancel{F_{12}}^{1} \times 4\pi r_1^2 = 4\pi r_2^2 \times F_{21}.$

$F_{21} = \frac{4}{9} \overset{0.44}{} = 0.44.$

28 – (d) $4 \frac{\pi}{4_2} D^2 \times \cancel{F_{12}}^{1} = 6D^2 \, F_{21}$

$F_{21} = \frac{\pi}{6}.$

16 – (b)

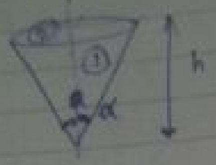


$F_{21} = 1$

① → Circular Base + Cylindrical Surface.

$F_{12} = \frac{A_2}{A_1} = \frac{d}{d + 4h}.$

19
(b)



$F_{21} = 1.$

$\pi r^2 \times 1 = \pi r l \times F_{12}$

$F_{12} = \frac{r}{l}.$

$\cos\alpha = \frac{h}{l}.$

$l = \sqrt{r^2+h^2}. \quad l = \frac{h}{\cos\alpha}$

$= \sqrt{h^2\sin^2\alpha + h^2}$

$= \frac{h\tan\alpha \times \cos\alpha}{h}$

$\tan\alpha = \frac{r}{h}$

$\boxed{F_{12} = \sin\alpha}$

$r = h\tan\alpha$

22
(b)

$F_{21} = 0.004.$

$0.6 \times 1 = A_{21} \times 0.004$

$A_{21} = \frac{600}{4} = 150 = 150\,m^2.$

25

$6a^2 = 150$

$\boxed{a = 5\,m}.$

Summation Rule among Shape Factors -

If there are 'n' no. of surfaces involved in any radiation heat exchange then

$F_{11} + F_{12} + F_{13} + \dots + F_{1n} = 1.$

$F_{21} + F_{22} + F_{23} + \dots F_{2n} = 1.$

$\vdots$

$F_{n1} + F_{n2} + \dots F_{nn} = 1.$

If any particular surface is either flat or convex surface, then its self shape factor becomes zero.

Note: Even now reciprocity rel^n is valid b/w any 2 surfaces.
eg., $A_2 F_{23} = A_3 F_{32}$.
$A_1 F_{1m} = A_m F_{m1}$.

2-(d) $\overset{0}{F_{11}} + F_{12} + F_{13} = 1$.
$F_{12} = 1 - 0.17 = 0.83$.

$F_{12} \times \frac{\pi D^2}{4} = \frac{\pi D}{2} t \times F_{21}$

$F_{21} = 0.2075$.

$\boxed{\text{From symmetry of fig. } F_{21} = F_{23}}$

$\therefore F_{23} = 0.2075$.

~~$F_{22} = 1 - 0.2075 = 0.7985$~~

$F_{22} = 1 - 0.2075 - 0.2075$
$= 1 - 0.4150$
$\boxed{F_{22} = 0.585}$

*

Very long Duct.

From symmetry of fig.
$F_{12} = F_{13}$.

Since, duct is very long,
(Neglecting end effects)

$\overset{0}{F_{11}} + F_{12} + F_{13} = 1$
$F_{12} = F_{13} = \frac{1}{2}$.