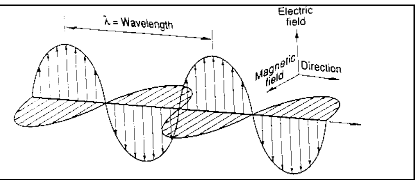
7. RADIATION

THERMAL RADIATION: Heat Transfer takes place without medium is known as Radiation. Whereas Conduction and convection requires medium of heat transfer. Radiation is the fastest mode of heat transfer. Q not linear proportional to ΔT.

Radiation is well explained by Below mentioned 2 Theory,

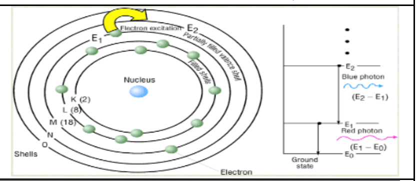
1. MAXWELL'S WAVE THEORY:

- Jame's Clerk Maxwell (Wave Theory 1864)
- Maxwell demonstrated that electric and magnetic fields travel through space as waves moving at the speed of light. He proposed that light is an undulation in the same medium that is the cause of electric and magnetic phenomena.



2. MAX PLANCK'S QUANTUM THEORY:

- The smallest amount of energy that can be emitted or absorbed in the form of electromagnetic radiation is known as quantum. The energy of the radiation absorbed or emitted is directly proportional to the frequency of the radiation.
- Radiation having dual Nature.



$\boldsymbol{E = h\vartheta}$	$h =$ Plank's Constant $= 6.6 * 10^{-34}\,J\,s$		$\vartheta =$Frequency.
$C = \lambda\vartheta$ $E = hC/\lambda$	$n = \dfrac{C_0}{C} \geq 1$	$\lambda =$Wavelength (μm) $C =$Speed of Wave in a medium	$C_0 =$Speed of Wave in Vacuum $n =$ Refractive Index

ϑ is Dependent on Source Temperature & Independent of Surrounding Medium

PREVOST'S PRINCIPLE OF EXCHANGE: Any body above 0 K can emit energy. And if the bodies are in thermal equilibrium the are absorbing and emitting same amount of energy.

ELECTROMAGNETIC SPECTRUM: (*in* μm)

10^{-4}	10^{-5}	10^{-4}	10^{-3}	10^{-2}	10^{-1}	0.4	0.77	1	10	10^{2}	10^{3}	10^{4}
			X-Ray		**UV**		**Visible**		**Infrared**		**Microwave**	
	Gamma Ray							**Thermal Radiation (In Syllabus)**				

$Q_{Radiation}$ Significant at higher temperature. But it doesn't mean radiation can be neglected at lower temperature.

PARTICIPATING V/S NON-PARTICIPATING MEDIUM:

If Refractive Index $(n) = 1$, Medium is Non-Participating Medium (Medium is not disturbing Electromagnetic wave).

For Vacuum, $n = 1$	For Gases, $n = 1.002$

VOLUMETRIC PHENOMENON	SURFACE PHENOMENON
For Gases or Semi-transparent medium, Emission of Thermal Radiation is Volumetric Phenomenon.	For Liquids and Solids, Emission of Thermal Radiation is Surface Phenomenon.

Note:

1. Radiation effect depends on direction.	2. Radiation effect depends on wavelength.

REAL BODY	DIFFUSED BODY	SPECULAR BODY
Radiation depends on direction.	Radiation is independent of direction.	$\theta_{Incident} = \theta_{Reflection}$
	Hemispherical Energy Radiation.	E.g. Still Water, Polished Surface

IRRADIATION ($\boldsymbol{G}$): It is a total rate of energy incident on the surface from all direction of any longer wavelength per unit surface area. It's because of Emission or Reflection from source.

$\begin{matrix} Hemi\ Spherical \\ Irradiation \end{matrix} = G\left(in \dfrac{W}{m^2}\right) = \iint G_{\lambda,\theta}\, d\lambda\, d\theta$	$G_\lambda =$ Monochromatic or Spectral Irradiation $G_\theta =$ Directional Irradiation

Note: G is not property of surface and it's independent of surface temperature.

SURFACE CHARACTERISTICS:

1. Absorptivity (α): The degree to which something absorbs energy. E.g. $T_{Surface} \uparrow$ 2. Reflectivity (ρ): The degree to which something reflects energy. E.g. $T_{Surface}$ Const. 3. Transmissivity (τ): The degree to which something transmits energy. E.g. $T_{Surface} = C$.	$G = G\alpha + G\rho + G\tau$ $1 = \alpha + \rho + \tau$ $0 \leq \alpha, \rho, \tau \leq 1$

$\alpha_\lambda =$ Monochromatic Absorptivity $\rho_\lambda =$ Monochromatic Reflectivity $\tau_\lambda =$ Monochromatic Transmissivity	$\alpha_\theta =$ Directional Absorptivity $\rho_\theta =$ Directional Reflectivity $\tau_\theta =$ Directional Transmissivity

SMOOTH SURFACE: When roughness is far less than incident wavelength then it is considered as smooth surface.

Note: Absorptivity (α) depends on nature of incident wavelength which is decided by source Temperature. It's not depending on surface temperature.

- For smoother surface Reflectivity is high $\rho \uparrow$.

EMISSIVE POWER (E): It is defined as rate of energy emitted by the surface to all direction of any longer wavelength per unit surface area.

$\begin{matrix} Hemi\ Spherical \\ Emissive\ Power \end{matrix} = E\left(in\frac{W}{m^2}\right) = \iint E_{\lambda,\theta}\, d\lambda\, d\theta$	E_λ = Monochromatic or Spectral Emissive Power E_θ = Directional Emissive Power

Note: Emissive Power is **only due to temperature** and it may decrease the temperature of surface. Emissive Power did not considered reflection.

RADIOSITY (J): It's total rate of energy leaving from a surface to any direction, any longer wavelength per unit surface area. It's unit is W/m^2.

$$J = E + G\rho + G\tau = E + G(1-\alpha)\ (From\ Energy\ Balance\ At\ surface)$$

If $J = E$,	1. $G = 0$ (No Irradiation)	2. $\alpha = 1$ (Completely Absorptive Body)

OPAQUE BODY: Opaque body are those body where the atoms are closely packed and the light cannot pass through.

OPAQUE BODY	**TRANSPARENT BODY**
E.g. For Solids, $1 = \alpha + \rho$ & $J = E + G\rho$ ($\because \tau = 0$)	E.g. For Solids, $0 = \alpha + \rho$($\because \tau = 1$)

Colour of any object depends on emission & reflection wavelength.

BLACK BODY: It's idealised physical solid body which can absorb all the radiation incident on it irrespective of wavelength and direction. In Absence of Colour, Appearance of the body is black so it's called as black body.

- Black body is perfect absorber and Prefect emitter of thermal Radiation. For Ideal Case, Absorptivity $(\alpha) = 1$
- Black body is a diffuse emitter (Equal emission in all direction)
- For given Wavelength & Temperature, no surface can emit more energy as thermal radiation then a black body.
- Black Body is independent of shape, size & age black body is an imaginary concept.

E.g. Ice, White Paper, some white paints having high absorptivity are treated as black body. Lamp black paint is very closed to idealised black body. Large Cavity with small opening is **experimental black body**.

TOTAL EMISSIVITY (ϵ): It's ratio of emissive power of any body at a given temperature to the emissive power of black body at a given temperature.

$\epsilon = \frac{E}{E_b} \le 1$	$\epsilon_\lambda = \frac{E_\lambda}{E_{b\lambda}} \le 1$	$\epsilon_\theta = \frac{E_\theta}{E_{b\theta}} \le 1$	$E = \iint E_{b\lambda,\theta}\, d\lambda\, d\theta$
ϵ = Total Emissivity	ϵ_λ = Monochromatic Emissivity	ϵ_θ = Directional Emissivity	E = Total emissive Pow

Total Emissivity (ϵ) Depends on the surface temperature.

GRAY BODY: In Gray Body, Properties are independent of wavelength. Gray Body emissivity & Absorptivity is less than 1.	

θ is angle measured from the normal of the surface, and thus $\theta = 0$ for radiation emitted in a direction normal to the surface. Note that emissivity nearly constant for about $\theta < 40°$ for conductors such as metals and $\theta < 70°$ for non-conductors such as plastics.

1. The emissivity of metallic surface is generally small, achieving value as low as 0.02 for highly polished Ag & Au.
2. The presence of oxide layers may significantly increase the emissivity of metallic surfaces.
3. The emissivity of non-conductors is comparatively large, generally exceeding 0.6.
4. The emissivity of conductors increases with increasing temperature; however, depending on the specific material, the emissivity of non-conductors may either increase or decreases with increasing temperature.

Diffuse Body: Independent of Direction	Gray Body: Independent of wavelength
Opaque Body: Transmissivity is Zero ($\tau = 0$)	Black Body: Absorptivity is zero ($\alpha = 1$)
White Body: Reflectivity is one ($\rho = 1$)	• Metals Are good Reflectors.
• Non-metals are good absorber.	• Gases are good Transmitter.

KIRCHOFF'S LAW:

At thermal Equilibrium, $G\alpha = E \Rightarrow \alpha E_b = E \Rightarrow \boldsymbol{\alpha = \epsilon}$ It states that at thermal equilibrium, absorptivity and emissivity are equal. It's used to determine radiative properties of surface by using any one property at low temp. difference.	

PLANCK'S LAW OF DISTRIBUTION:

$E_{b\lambda}\left(in\,\frac{W}{m^2\mu m}\right) = \frac{C_1}{\lambda^5\left[e^{\frac{C_2}{\lambda T}} - 1\right]}$	$E_{b\lambda}$ = Monochromatic Emissive Power, λ = Wave length (μm) T = Temperature (K)	C_1 = 1st Radiation Constant, C_2 = 2nd Radiation Constant,

1. The monochromatic emissive power varies continuously with wave length.
2. The amount of emitted radiation at any wave length increases with increasing temperature.
3. As temperature increases, the amount of radiation emitted also increases. This is consistent with the Stefan-Boltzmann law.
4. The wave length corresponding to maximum monochromatic emissive power depends on temperature.
5. At higher temperature, the peak of the distribution shifts toward left, and respectively the more radiation emitted at short wavelength.

WEIN'S DISPLACEMENT LAW: The maximum monochromatic emissive power of a black body varies as the fifth power of the absolute temperature of the body.

$\frac{dE_{b\lambda}}{d\lambda} = 0 \Rightarrow \lambda_{max}T = C_3$	$E_{b\lambda_{max}} = \frac{C_1}{\left(\frac{C_3}{T}\right)^5\left[e^{\frac{C_2}{C_3}} - 1\right]} \propto T^5$	$C_3 = 2898\ \mu m\ K$ = 3rd Radiation Constant, λ_{max} = Wavelength at which emissive power is maximum,

STEFAN-BOLTZMANN LAW:

The Total emissive power of black body is directly proportional to forth power of absolute temperature.

$E_b = \int E_{b\lambda}\,d\lambda\ (Where, T = Const)$	$\boldsymbol{E_b \propto T^4} \Rightarrow E_b = \sigma T^4 \Rightarrow E(in\ W/m^2) = \epsilon E_b = \epsilon\sigma T^4 = \epsilon\sigma A T^4 (in\ W)$ Where, σ = Stefan-Boltzmann Constant = $5.67 * 10^{-8}\ W/m^2K^4$

Note: In radiation Calculation Temperature must be in K only.

VIEW/ GEOMETRIC/ CONFIGURATION/ ANGLE/ RADIATION/ SHAPE FACTOR:

$F_{i\to j} = F_{ij} = \frac{Q_{ij}}{Q_i}$	i = Emitter, j = Receiver,	Q_i =Amount of Energy Emitted By i Q_{ij} =Amount of Energy Received By j	$0 \le F_{ij} \le 1$	$\sum_j F_{ij} = 1$

F_{ij} = Fraction of energy leaving form i and directly sticking to j

Note: Summation Rule is only valid for closed surfaces only.

- Shape Factor is independent of Temperature of surface & Surface properties of surface.
- Shape Factor depends on orientation, Geometry of the surface.
- Shape Factor for surface is possible with itself. E.g. For Convex Profile, Flat plate, Sphere $F_{ii} = 0$

N = No. of Closed Surfaces	Total No. of shape factors = $N^2[\because n \times n\ (Matrix)]$
No. of Known Or direct Shape Factors= $N\,(N-1)/2$	No. of Unknown Shape Factors= $N\,(N+1)/2$

$$Q_{Net} = \sigma A_1 T_1^4 F_{12} - \sigma A_2 T_2^4 F_{21}$$

If $Q_{Net} = 0$ & $T_1 = T_2$, $A_1F_{12} = A_2F_{21}$	It's Reciprocity Rule (Valid only for Diffuse Emitter).

Note: A_iF_{ij} is purely Geometric Factor.

CONCEPT OF SURFACE RESISTANCE & SPACE RESISTANCE:

Assumption:

1. Surfaces are diffuse, opaque, Gray isothermal.
2. Uniform Irradiation & uniform radiosity.

For Solids, $\tau = 0 \Rightarrow \rho = 1 - \alpha$ $\alpha = \epsilon\ (From\ Kirchoff's\ Law)$	$J = E + G\rho = \epsilon E_b + G\rho\ (\because \tau = 0)$ $\therefore G = (J - \epsilon E_b)/\rho$	$\frac{Q_{Surface}}{A} = J - G$
From Above 3 Equations, $\frac{Q_{Surface}}{A} = \frac{E_b - J}{(1-\epsilon)/\epsilon}$	$Voltage = E_b - J$ $Surface\ Resistance = \frac{1-\epsilon}{\epsilon A}$	For Black Body, $\alpha = \epsilon = 1, \rho = 0$ $\therefore J = E_b$ $\therefore R_{Surface} = 0$

For 2 Plates, $Q_{Space} = J_1A_1F_{12} - J_2A_2F_{21}$

$Q_{Space} = \frac{J_1 - J_2}{1/A_2F_{21}} = \frac{J_2 - J_1}{1/A_1F_{12}}$	$R_{Space} = \frac{1}{A_1F_{12}} = \frac{1}{A_2F_{21}}$

NET HEAT EXCHANGE BETWEEN TWO GRAY SURFACE:

			E_{b1}	$R_{Surface}$	J_1	R_{Space}	J_2	$R_{Surface}$	E_{b2}
$Q_{Net} = \frac{E_{b1} - E_{b2}}{R_{Eq}}$	$R_{Eq} = \frac{1-\epsilon_1}{\epsilon_1 A_1} + \frac{1}{A_1 F_{12}} + \frac{1-\epsilon_2}{\epsilon_2 A_2}$			$\frac{1-\epsilon_1}{\epsilon_1 A_1}$		$\frac{1}{A_1 F_{12}}$		$\frac{1-\epsilon_2}{\epsilon_2 A_2}$	
$E_{b1} - E_{b2} = \sigma(T_1^4 - T_2^4)$									

NET HEAT EXCHANGE BETWEEN TWO BLACK SURFACE: $Q_{Net} = \sigma A_1 F_{12}(T_1^4 - T_2^4)(\because \epsilon_1 = \epsilon_2 = 1)$

SPECIAL CASES:

$Q_{Net} = \bar{\epsilon}\,\sigma A_1(T_1^4 - T_2^4)$	Equivalent Emissivity ($\bar{\epsilon}$)
CASE-I: Two Infinite Parallel Plates ($A_1 = A_2$) Here, $F_{12} = F_{21} = 1$	$\bar{\epsilon} = \frac{1}{\epsilon_1} + \frac{1}{\epsilon_2} - 1$
CASE-II: Two Hollow Concentric Cylinder. ($A_1 : A_2 = D_1 : D_2$) Here, $F_{12} = F_{21} = 1$	$\bar{\epsilon} = \frac{1}{\epsilon_1} + \frac{D_1}{D_2}\left(\frac{1}{\epsilon_2} - 1\right)$
CASE-III: Two Hollow Concentric Sphere. ($A_1 : A_2 = D_1^2 : D_2^2$) Here, $F_{12} = F_{21} = 1$	$\bar{\epsilon} = \frac{1}{\epsilon_1} + \frac{D_1^2}{D_2^2}\left(\frac{1}{\epsilon_2} - 1\right)$
CASE-IV: Small Body Kept in a large enclosure ($A_1 : A_2 \approx 0$) Here, $F_{12} = F_{21} = 1$	$\bar{\epsilon} = \epsilon_1$

RADIATION HEAT TRANSFER COEFFICIENT:

Surrounding is very large can be treat like a black body for easy analysis. To Treat surrounding as black body some imaginary temperature of surrounding is calculated, this imaginary temperature is called effective sky temperature.

$Q_{Conv} = h_c A(T_S - T_\infty)$	$Q_{rad} = h_r A(T_S - T_{Sky}) = \epsilon A\sigma(T_S^4 - T_{Sky}^4)$
Radiation heat transfer Coefficient, $h_r = \epsilon A\sigma(T_S^2 + T_{Sky}^2)(T_S + T_{Sky})$	

Note: If T_{Sky} is not given in the problem, Consider $T_{Sky} = T_{amb}$.

RADIATION EFFECT ON TEMPERATURE MEASUREMENT:

T_f = Actual Temperature of Fluid in K	T_{th} = Temperature value measured by the thermometer
T_w = Temperature of surrounding surface in K	h = Convection heat transfer coefficient.
ϵ = Emissivity of sensor of the thermometer	

At equilibrium Condition of thermocouple, $q_{Conv} = q_{rad}$

$$h(T_f - T_{th}) = \epsilon\sigma(T_{th}^4 - T_w^4) \Rightarrow T_f = T_{th} + Radiation\ Correction = T_{th} + (\epsilon\sigma/h)(T_{th}^4 - T_w^4)$$

RADIATION SHIELD/ SCREEN: It's thin plate made up of very high reflectivity.

For Solids, $\tau = 0 \Rightarrow \rho = 1 - \alpha$ $\alpha = \epsilon$ $(From\ Kirchoff's\ Law)$ $\rho \uparrow \Rightarrow \alpha \downarrow \Rightarrow \epsilon \downarrow \Rightarrow R_{Surface} \uparrow$ $Q_{Net} = \frac{E_{b1} - E_{b2}}{R_{Eq}}$ $E_{b1} - E_{b2} = \sigma(T_1^4 - T_2^4)$	ϵ_3, ϵ_4 = Emissivity of surfaces on both the side of shield

E_{b1}	Q_{S1}			ϵ_3, ϵ_4	Q_{S2}			E_{b2}
	$\frac{1-\epsilon_1}{\epsilon_1 A_1}$	$\frac{1}{A_1 F_{13}}$	$\frac{1-\epsilon_3}{\epsilon_3 A_3}$	**Shield**	$\frac{1-\epsilon_4}{\epsilon_4 A_4}$	$\frac{1}{A_4 F_{42}}$	$\frac{1-\epsilon_2}{\epsilon_2 A_2}$	

$$R_{Eq} = \frac{1-\epsilon_1}{\epsilon_1 A_1} + \frac{1}{A_1 F_{13}} + \frac{1-\epsilon_3}{\epsilon_3 A_3} + \frac{1-\epsilon_4}{\epsilon_4 A_4} + \frac{1}{A_4 F_{42}} + \frac{1-\epsilon_2}{\epsilon_2 A_2}$$

Here, $A_1 = A_2 = A_3 = A_4$ N = No. Of Shields ϵ_s = Emissivity of Shield	$Q_{withShield} = \frac{A_1\sigma(T_1^4 - T_2^4)}{\left(\frac{1}{\epsilon_1} + \frac{1}{\epsilon_2} - 1\right) + \left(\frac{1}{\epsilon_3} + \frac{1}{\epsilon_4} - 1\right)} = \frac{A_1\sigma(T_1^4 - T_2^4)}{\frac{1}{\epsilon_1} + \frac{1}{\epsilon_2} + \frac{2N}{\epsilon_s} - (N+1)}$
$\frac{Q_{withShield}}{Q_{withoutShield}} = \frac{\frac{1}{\epsilon_1} + \frac{1}{\epsilon_2} - 1}{\frac{1}{\epsilon_1} + \frac{1}{\epsilon_2} + \frac{2N}{\epsilon_s} - (N+1)}$	If $\epsilon_1 = \epsilon_2 = \epsilon_3 = \epsilon_4 = \epsilon_s = \epsilon$ (All have equal emissivity), $\frac{Q_{withShield}}{Q_{withoutShield}} = \frac{1}{N+1}$
At Steady State, $Q_{S1} = Q_{S2}$ Here, $A_1 = A_2 = A_3 = A_4$ T_S =Shield Temperature.	$\frac{T_1^4 - T_s^4}{T_s^4 - T_2^4} = \left(\frac{1}{\epsilon_1} + \frac{1}{\epsilon_s} - 1\right) \Big/ \left(\frac{1}{\epsilon_s} + \frac{1}{\epsilon_2} - 1\right)$ At $\epsilon_1 = \epsilon_2$, $T_s^4 = (T_1^4 + T_2^4)/2$

SOLID ANGLE ($\boldsymbol{\omega}$): Solid angle is defined as the region of sphere which is enclosed by conical surface with the vertex of cone at the centre of sphere. Solid Angle is ratio of area to the square of distance between them.

For Hemisphere, $\omega = 2\pi$ Steradian. For Sphere, $\omega = 4\pi$ Steradian.	$\omega = \iint \frac{dA_n}{r^2} = \iint \sin\theta\, d\theta\, d\emptyset$	θ = Zenith Angle, $\emptyset$ = Azimuth Angle,

INTENSITY OF RADIATION: It's defined as the rate of energy radiated per unit projected area normal to the line of vie of receiver from the radiating surface per unit solid angle.

$I = \frac{dQ}{dA\cos\theta\, d\omega} = \frac{dE}{\cos\theta\sin\theta\, d\theta\, d\emptyset}$	I is based on Projected area, E is based on Surface Area,	For Diffused Emitter (Black Body), $I = Constant \Rightarrow \boldsymbol{E = \pi I}$