UNIT-4 RADIATION
Part-A

1. Define emissive power [E] and monochromatic emissive power. [$E_{b\lambda}$]

The emissive power is defined as the total amount of radiation emitted by a body per unit time and unit area. It is expressed in W/m^2.

The energy emitted by the surface at a given length per unit time per unit area in all directions is known as monochromatic emissive power.

2. What is meant by absorptivity, reflectivity and transmissivity?

Absorptivity is defined as the ratio between radiation absorbed and incident radiation.
Reflectivity is defined as the ratio of radiation reflected to the incident radiation.
Transmissivity is defined as the ratio of radiation transmitted to the incident radiation.

3. What is black body and gray body?

Black body is an ideal surface having the following properties.

A black body absorbs all incident radiation, regardless of wave length and direction. For a prescribed temperature and wave length, no surface can emit more energy than black body.

If a body absorbs a definite percentage of incident radiation irrespective of their wave length, the body is known as gray body. The emissive power of a gray body is always less than that of the black body.

4. State Planck's distribution law.

The relationship between the monochromatic emissive power of a black body and wave length of a radiation at a particular temperature is given by the following expression, by Planck.

$$E_{b\lambda} = \frac{C_1 \lambda^{-5}}{e^{\left(\frac{C_2}{\lambda T}\right)} - 1}$$

Where $E_{b\lambda}$ = Monochromatic emissive power W/m^2

λ = Wave length – m

$c_1 = 0.374 \times 10^{-15}$ W m^2

$c_2 = 14.4 \times 10^{-3}$ mK

5. State Wien's displacement law.

The Wien's law gives the relationship between temperature and wave length corresponding to the maximum spectral emissive power of the black body at that temperature.

$$\lambda_{mas} T = c_3$$

Where $c_3 = 2.9 \times 10^{-3}$ [Radiation constant]

$$\Rightarrow \quad \lambda_{mas} T = 2.9 \times 10^{-3} \text{ mK}$$

6. State Stefan – Boltzmann law. [April 2002, M.U.]

The emissive power of a black body is proportional to the fourth power of absolute temperature.

$$E_b \propto T^4$$

$$E_b = \sigma T^4$$

Where E_b = Emissive power, w/m^2

σ = Stefan. Boltzmann constant

$= 5.67 \times 10^{-8}\ W/m^2\ K^4$

T = Temperature, K

7. Define Emissivity.

It is defined as the ability of the surface of a body to radiate heat. It is also defined as the ratio of emissive power of any body to the emissive power of a black body of equal temperature.

Emissivity $\varepsilon = \frac{E}{E_b}$

8. State Kirchoff's law of radiation.

This law states that the ratio of total emissive power to the absorbtivity is constant for all surfaces which are in thermal equilibrium with the surroundings. This can be written as

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

It also states that the emissivity of the body is always equal to its absorptivity when the body remains in thermal equilibrium with its surroundings.

$\alpha_1 = E_1$; $\alpha_2 = E_2$ and so on.

9. Define intensity of radiation (I_b).

It is defined as the rate of energy leaving a space in a given direction per unit solid angle per unit area of the emitting surface normal to the mean direction in space.

$$I_n = \frac{E_b}{\pi}$$

10. State Lambert's cosine law.

It states that the total emissive power E_b from a radiating plane surface in any direction proportional to the cosine of the angle of emission

$$E_b \propto \cos\theta$$

11. What is the purpose of radiation shield?

Radiation shields constructed from low emissivity (high reflective) materials. It is used to reduce the net radiation transfer between two surfaces.

12. Define irradiation (G) and radiosity (J)

It is defined as the total radiation incident upon a surface per unit time per unit area. It is expressed in W/m^2.

It is used to indicate the total radiation leaving a surface per unit time per unit area. It is expressed in W/m^2.

13. What is meant by shape factor?

The shape factor is defined as the fraction of the radiative energy that is diffused from on surface element and strikes the other surface directly with no intervening reflections. It is represented by F_{ij}. Other names for radiation shape factor are view factor, angle factor and configuration factor.

Part-B

1. A black body at 3000 K emits radiation. Calculate the following:

- **i) Monochromatic emissive power at 7 μm wave length.**
- **ii) Wave length at which emission is maximum.**
- **iii) Maximum emissive power.**
- **iv) Total emissive power,**
- **v) Calculate the total emissive of the furnace if it is assumed as a real surface having emissivity equal to 0.85.**

Given: Surface temperature T = 3000K

Solution: 1. Monochromatic Emissive Power :

From Planck's distribution law, we know

$$E_{b\lambda} = \frac{C_1 \lambda^{-5}}{e^{\left(\frac{C_2}{\lambda T}\right)} - 1}$$

[From HMT data book, Page No.71]

Where

$c_1 = 0.374 \times 10^{-15}$ W m^2
$c_2 = 14.4 \times 10^{-3}$ mK
$\lambda = 1 \times 10^{-6}$ m [Given]

$$\Rightarrow \quad E_{b\lambda} = \frac{0.374 \times 10^{-15} [1 \times 10^{-6}]^{-5}}{e^{\left[\frac{144 \times 10^{-3}}{1 \times 10^{-6} \times 3000}\right]} - 1}$$

$$E_{b\lambda} = 3.10 \times 10^{12} \ W/m^2$$

2. Maximum wave length (λ_{max})

From Wien's law, we know

$$\lambda_{max} T = 2.9 \times 10^{-3} \ mK$$

$$\Rightarrow \quad \lambda_{max} = \frac{2.9 \times 10^{-3}}{3000}$$

$$\lambda_{max} = 0.966 \times 10^{-6} m$$

3. Maximum emissive power ($E_{b\lambda}$) max:

Maximum emissive power

$(E_{b\lambda})_{max} = 1.307 \times 10^{-5} T^5$
$= 1.307 \times 10^{-5} \times (3000)^5$
$(E_{b\lambda})_{max} = 3.17 \times 10^{12}$ W/m^2

4. Total emissive power (E_b):

From Stefan – Boltzmann law, we know that

$E_b = \sigma T^4$

[From HMT data book Page No.71]

Where σ = Stefan – Boltzmann constant

$= 5.67 \times 10^{-8}$ W/m^{2}K^4

$\Rightarrow E_b = (5.67 \times 10^{-8}) (3000)^4$

$E_b = 4.59 \times 10^6$ W/m^2

5. Total emissive power of a real surface:

$(E_b)_{real} = \varepsilon \sigma T^4$

Where ε = Emissivity = 0.85

$(E_b)_{real} = 0.85 \times 5.67 \times 10^{-8} \times (3000)^4$

$(E_b)_{real} = 3.90 \times 10^6$ W/m^2

2. **Assuming sun to be black body emitting radiation at 6000 K at a mean distance of 12 × 10^{10} m from the earth. The diameter of the sun is 1.5 × 10^9 m and that of the earth is 13.2 × 10^6 m. Calculation the following.**

1. **Total energy emitted by the sun.**
2. **The emission received per m^2 just outside the earth's atmosphere.**
3. **The total energy received by the earth if no radiation is blocked by the earth's atmosphere.**
4. **The energy received by a 2 × 2 m solar collector whose normal is inclined at 45° to the sun. The energy loss through the atmosphere is 50% and the diffuse radiation is 20% of direct radiation.**

Given: Surface temperature T = 6000 K

Distance between earth and sun R = 12 × 10^{10} m

Diameter on the sun $D_1 = 1.5 \times 10^9$ m

Diameter of the earth $D_2 = 13.2 \times 10^6$ m

Solution:1. Energy emitted by sun $E_b = \sigma T^4$

$\Rightarrow E_b = 5.67 \times 10^{-8} \times (6000)^4$

[$\because \sigma$ = Stefan - Boltzmann constant

$= 5.67 \times 10^{-8}$ W/m^2 K^4]

$$E_b = 73.4 \times 10^6 \ W/m^2$$

Area of sun $A_1 = 4\pi R_1^2$

$$= 4\pi \times \left(\frac{1.5 \times 10^9}{2}\right)^2$$

$$\boxed{A_1 = 7 \times 10^{18} m^2}$$

$\Rightarrow$ Energy emitted by the sun

$$E_b = 73.4 \times 10^6 \times 7 \times 10^{18}$$

$$\boxed{E_b = 5.14 \times 10^{26} \ W}$$

2. The emission received per m^2 just outside the earth's atmosphere:

The distance between earth and sun $R = 12 \times 10^{10}$ m

Area, $A = 4\pi R^2$

$$= 4 \times \pi \times (12 \times 10^{10})^2$$

$$\boxed{A = 1.80 \times 10^{23} \ m^2}$$

$\Rightarrow$ The radiation received outside the earth atmosphere per m^2

$$= \frac{E_b}{A}$$

$$= \frac{5.14 \times 10^{26}}{1.80 \times 10^{23}}$$

$$= 2855.5 \ W/m^2$$

3. Energy received by the earth:

Earth area $= \frac{\pi}{4}(D_2)^2$

$$= \frac{\pi}{4} \times [13.2 \times 10^6]^2$$

$$\boxed{\text{Earth area} = 1.36 \times 10^4 m^2}$$

Energy received by the earth

$$= 2855.5 \times 1.36 \times 10^4$$

$$= 3.88 \times 10^{17} \ W$$

4. The energy received by a 2 × 2 m solar collector;

Energy loss through the atmosphere is 50%. So energy reaching the earth.

$= 100 - 50 = 50\%$

$= 0.50$

Energy received by the earth

$= 0.50 \times 2855.5$

$= 1427.7 \ W/m^2$ ......(1)

Diffuse radiation is 20%

$\Rightarrow \ 0.20 \times 1427.7 = 285.5 \ W/m^2$

$\boxed{\text{Diffuse radiation} = 285.5 \ W/m^2}$ ....(2)

Total radiation reaching the collection

$= 142.7 + 285.5$

$= 1713.2 \ W/m^2$

$\text{Plate area} = A \times \cos\ \theta$

$= 2 \times 2 \times \cos 45°$

$= 2.82 \ m^2$

Energy received by the collector

$= 2.82 \times 1713.2$

$= 4831.2 \ W$

3. Two black square plates of size 2 by 2 m are placed parallel to each other at a distance of 0.5 m. One plate is maintained at a temperature of 1000°C and the other at 500°C. Find the heat exchange between the plates.

Given: Area A = 2 × 2 = 4 m^2

T_1 = 1000°C + 273

= 1273 K

T_2 = 500°C + 273

= 773 K

Distance = 0.5 m

To find : Heat transfer (Q)

Solution : We know Heat transfer general equation is where $Q_{12} = \dfrac{\sigma\left[T_1^4 - T_2^4\right]}{\dfrac{1-\varepsilon_1}{A_1\varepsilon_1} + \dfrac{1}{A_1F_{12}} + \dfrac{1-\varepsilon_2}{A_1\varepsilon_2}}$ [From equation No.(6)]

For black body $\varepsilon_1 = \varepsilon_2 = 1$

$$\Rightarrow \quad Q_{12} = \sigma[T_1^4 - T_2^4] \times A_1F_{12}$$

$$= 5.67 \times 10^{-8}\left[(1273)^4 - (773)^4\right] \times 4 \times F^{12}$$

$$\boxed{Q_{12} = 5.14 \times 10^5 F_{12}} \quad \ldots\ldots(1)$$

Where F_{12} – Shape factor for square plates

In order to find shape factor F_{12}, refer HMT data book, Page No.76.

$$\text{X axis} = \frac{\text{Smaller side}}{\text{Distance between planes}}$$

$$= \frac{2}{0.5}$$

$$\boxed{\text{X axis} = 4}$$

Curve $\rightarrow$ 2 [Since given is square plates]

X axis value is 4, curve is 2. So corresponding Y axis value is 0.62.

i.e., $\boxed{F_{12} = 0.62}$

$$(1) \Rightarrow \quad Q_{12} = 5.14 \times 10_5 \times 0.62$$

$$\boxed{Q_{12} = 3.18 \times 10^5 \text{ W}}$$

4. Two parallel plates of size 3 m × 2 m are placed parallel to each other at a distance of 1 m. One plate is maintained at a temperature of 550°C and the other at 250°C and the emissivities are 0.35 and 0.55 respectively. The plates are located in a large room whose walls are at 35°C. If the plates located exchange heat with each other and with the room, calculate.

1. Heat lost by the plates.

2. Heat received by the room.

Given: Size of the plates = 3 m × 2 m

Distance between plates = 1 m

First plate temperature T_1 = 550°C + 273 = 823 K

Second plate temperature T_2 = 250°C + 273 = 523 K

Emissivity of first plate ε_1 = 0.35

Emissivity of second plate ε_2 = 0.55

Room temperature T_3 = 35°C + 273 = 308 K

To find: 1. Heat lost by the plates

2. Heat received by the room.

Solution: In this problem, heat exchange takes place between two plates and the room. So this is three surface problems and the corresponding radiation network is given below. Area $A_1 = 3 \times 2 = 6\ m^2$

$$\boxed{A_1 = A_2 = 6m^2}$$

Since the room is large $\boxed{A_3 = \infty}$

From electrical network diagram.

$$\frac{1-\varepsilon_1}{\varepsilon_1 A_1} = \frac{1-0.35}{0.35 \times 6} = 0.309$$

$$\frac{1-\varepsilon_2}{\varepsilon_2 A_2} = \frac{1-0.55}{0.55 \times 6} = 0.136$$

$$\frac{1-\varepsilon_3}{\varepsilon_3 A_3} = 0 \qquad [\because A_3 = \infty]$$

Apply $\frac{1-\varepsilon_3}{\varepsilon_3 A_3} = 0$, $\frac{1-\varepsilon_1}{\varepsilon_1 A_1} = 0.309$, $\frac{1-\varepsilon_2}{\varepsilon_2 A_2} = 0.136$ values in electrical network diagram.

To find shape factor F_{12} refer HMT data book, Page No.78.

$$X = \frac{b}{c} = \frac{3}{1} = 3$$

$$Y = \frac{a}{c} = \frac{2}{1} = 2$$

X value is 3, Y value is 2, corresponding shape factor [From table]

$F_{12} = 0.47$

$$\boxed{F_{12} = 0.47}$$

We know that,

$F_{11} + F_{12} + F_{13} = 1$ But, $F_{11} = 0$

$\Rightarrow \quad F_{13} = 1 - F_{12}$

$\Rightarrow \quad F_{13} = 1 - 0.47$

$\boxed{F_{13} = 0.53}$

Similarly, $F_{21} + F_{22} + F_{23} = 1$ We know $F_{22} = 0$

$\Rightarrow \quad F_{23} = 1 - F_{21}$

$\Rightarrow \quad F_{23} = 1 - F_{12}$

$F_{13} = 1 - 0.47$

$\boxed{F_{23} = 0.53}$

From electrical network diagram,

$$\frac{1}{A_1 F_{13}} = \frac{1}{6 \times 0.53} = 0.314 \qquad \text{....(1)}$$

$$\frac{1}{A_2 F_{23}} = \frac{1}{6 \times 0.53} = 0.314 \qquad \text{....(2)}$$

$$\frac{1}{A_1 F_{12}} = \frac{1}{6 \times 0.47} = 0.354 \qquad \text{....(3)}$$

From Stefan – Boltzmann law, we know

$E_b = \sigma T^4$

$E_{b1} = \sigma T_1^4$

$= 5.67 \times 10^{-8} [823]^4$

$$\boxed{E_{b1} = 26.01 \times 10^3 W/m^2} \qquad \text{.....(4)}$$

$E_{b2} = \sigma T_2^4$

$= 5.67 \times 10^{-8} [823]^4$

$$\boxed{E_{b2} = 4.24 \times 10^3 W/m^2} \qquad \text{.....(5)}$$

$E_{b3} = \sigma T_3^4$

$= 5.67 \times 10^{-8} [308]^4$

$$\boxed{E_{b3} = J_3 = 510.25 \ W/m^2} \qquad \text{.....(6)}$$

[From diagram]

The radiosities, J_1 and J_2 can be calculated by using Kirchoff's law.

$\Rightarrow$ The sum of current entering the node J_1 is zero.

At Node J_1:

$$\frac{E_{b1}-J_1}{0.309}+\frac{J_2-J_1}{\frac{1}{A_1F_{12}}}+\frac{E_{b3}-J_1}{\frac{1}{A_1F_{13}}}=0$$

[From diagram]

$$\Rightarrow \quad \frac{26.01\times10^3-J_1}{0.309}+\frac{J_2-J_1}{0.354}+\frac{510.25-J_1}{0.314}=0$$

$$\Rightarrow \quad 84.17\times10^3-\frac{J_1}{0.309}+\frac{J_2}{0.354}+\frac{J_1}{0.354}+1625-\frac{J_1}{0.354}=0$$

$$\Rightarrow \quad -9.24J_1+2.82J_2=-85.79\times10^3 \quad .....(7)$$

At node j_2

$$\frac{J_1-J_2}{\frac{1}{A_1F_{12}}}+\frac{E_{b3}-J_2}{\frac{1}{A_2F_{23}}}+\frac{E_{b2}-J_2}{0.136}=0 \text{ -+*}$$

$$\frac{J_1-J_2}{0.354}+\frac{510.25-J_2}{0.314}+\frac{4.24\times10^3-J_2}{0.136}=0$$

$$\frac{J_1}{0.354}-\frac{J_2}{0.354}+\frac{510.25}{0.314}-\frac{J_2}{0.314}+\frac{4.24\times10^3}{0.136}-\frac{J_2}{0.136}=0$$

$$\Rightarrow \quad 2.82J_1-13.3J_2=-32.8\times10^3 \quad ....(8)$$

Solving equation (7) and (8),

$$\Rightarrow \quad -9.24J_1+2.82J_2=-85.79\times10^3 \quad .....(7)$$

$$\Rightarrow \quad 2.82J_1-13.3J_2=-32.8\times10^3 \quad .....(8)$$

$$J_2=4.73\times10^3 W/m^2$$
$$J_1=10.73\times10^3 W/m^2$$

Heat lost by plate (1) is given by

$$Q_1=\frac{E_{b1}-J_1}{\left(\frac{1-\varepsilon_1}{\varepsilon_1A_1}\right)}$$

$$Q_1 = \frac{26.01\times10^3 - 10.73\times10^3}{\frac{1-0.35}{0.35\times6}}$$

$$\boxed{Q_1 = 49.36\times10^3 \text{ W}}$$

Heat lost by plate 2 is given by

$$Q_2 = \frac{E_{b2} - J_2}{\left(\frac{1-\varepsilon_2}{\varepsilon_2 A_2}\right)}$$

$$Q_2 = \frac{4.24\times10^3 - 4.73\times10^3}{\frac{1-0.55}{6\times0.55}}$$

$$\boxed{Q_2 = -3.59\times10^3 \text{ W}}$$

Total heat lost by the plates

$$Q = Q_1 + Q_2$$

$$= 49.36 \times 10^3 - 3.59 \times 10^3$$

$$\boxed{Q = 45.76\times10^3 \text{ W}} \qquad \text{......(9)}$$

Heat received by the room

$$Q = \frac{J_1 - J_3}{\frac{1}{A_1F_{13}}} + \frac{J_2 - J_3}{\frac{1}{A_1F_{12}}}$$

$$= \frac{10.73\times10^3 - 510.25}{0.314} = \frac{4.24\times10^3 - 510.25}{0.314}$$

$$[\because E_{b1} = J_1 = 512.9]$$

$$\boxed{Q = 45.9\times10^3 \text{ W}} \qquad \text{.....(10)}$$

From equation (9), (10), we came to know heat lost by the plates is equal to heat received by the room.

5. **A gas mixture contains 20% CO_2 and 10% H_2o by volume. The total pressure is 2 atm. The temperature of the gas is 927°C. The mean beam length is 0.3 m. Calculate the emissivity of the mixture.**

Given : Partial pressure of CO_2, P_{CO_2} = 20% = 0.20 atm

Partial pressure of H_2o, P_{H_2o} = 10% = 0.10 atm.

Total pressure P = 2 atm

Temperature T = 927°C + 273

= 1200 K

Mean beam length L_m = 0.3 m

To find: Emissivity of mixture (ε_{mix}).

Solution : To find emissivity of CO_2

$$P_{CO_2} \times L_m = 0.2 \times 0.3$$

$$\boxed{P_{CO_2} \times L_m = 0.06 \text{ m - atm}}$$

From HMT data book, Page No.90, we can find emissivity of CO_2.

From graph, Emissivity of CO_2 = 0.09

$$\boxed{\varepsilon_{CO_2} = 0.09}$$

To find correction factor for CO_2

Total pressure, P = 2 atm

$$P_{CO_2} L_m = 0.06 \text{ m - atm.}$$

From HMT data book, Page No.91, we can find correction factor for CO_2

From graph, correction factor for CO_2 is 1.25

$$\boxed{C_{CO_2} = 1.25}$$

$$\varepsilon_{CO_2} \times C_{CO_2} = 0.09 \times 1.25$$

$$\boxed{\varepsilon_{CO_2} \times C_{CO_2} = 0.1125}$$

To find emissivity of H_2o :

$$P_{H_2o} \times L_m = 0.1 \times 0.3$$

$$\boxed{P_{H_2o} L_m = 0.03 \text{ m - atm}}$$

From HMT data book, Page No.92, we can find emissivity of H_2o.

From graph Emissivity of H_2o = 0.048

$$\boxed{\varepsilon_{H_2o} = 0.048}$$

To find correction factor for H_2o :

$$\frac{P_{H_2o} + P}{2} = \frac{0.1 + 2}{2} = 1.05$$

$$\frac{P_{H_2o} + P}{2} = 1.05,$$

$$P_{H_2o} L_m = 0.03 \text{ m - atm}$$

From HMT data book, Page No.92 we can find emission of H_20

6. **Two black square plates of size 2 by 2 m are placed parallel to each other at a distance of 0.5 m. One plate is maintained at a temperature of 1000°C and the other at 500°C. Find the heat exchange between the plates.**

Given: Area A = 2 × 2 = 4 m^2

T_1 = 1000°C + 273 = 1273 K

T_2 = 500°C + 273 = 773 K

Distance = 0.5 m

To find : Heat transfer (Q)

Solution : We know Heat transfer general equation is

where $$Q_{12} = \frac{\sigma \left[T_1^4 - T_2^4\right]}{\frac{1-\varepsilon_1}{A_1\varepsilon_1} + \frac{1}{A_1 F_{12}} + \frac{1-\varepsilon_2}{A_1\varepsilon_2}}$$

[From equation No.(6)]

For black body $\varepsilon_1 = \varepsilon_2 = 1$

$\Rightarrow \quad Q_{12} = \sigma[T_1^4 - T_2^4] \times A_1F_{12}$

$= 5.67 \times 10^{-8}\left[(1273)^4 - (773)^4\right] \times 4 \times F^{12}$

$\boxed{Q_{12} = 5.14 \times 10^5 F_{12}}$ ......(1)

Where F_{12} – Shape factor for square plates

In order to find shape factor F_{12}, refer HMT data book, Page No.76.

$$\text{X axis} = \frac{\text{Smaller side}}{\text{Distance between planes}}$$

$$= \frac{2}{0.5}$$

$\boxed{\text{X axis} = 4}$

Curve $\rightarrow$ 2 [Since given is square plates]

X axis value is 4, curve is 2. So corresponding Y axis value is 0.62.

i.e., $\boxed{F_{12} = 0.62}$

(1) $\Rightarrow \quad Q_{12} = 5.14 \times 10_5 \times 0.62$

$\boxed{Q_{12} = 3.18 \times 10^5 \text{ W}}$

From graph,

Correction factor for H_2o = 1.39

$\boxed{C_{H_2O} = 1.39}$

$\varepsilon_{H_2O} \times C_{H_2O} = 0.048 \times 1.39$

$\boxed{\varepsilon_{H_2O} \times C_{H_2O} = 0.066}$

Correction factor for mixture of CO_2 and H_2O:

$$\frac{P_{H_2o}}{P_{H_2o} + P_{CO_2}} = \frac{0.1}{0.1 + 0.2} = 1.05$$

$$\boxed{\frac{P_{H_2o}}{P_{H_2o} + P_{CO_2}} = 0.333}$$

$P_{CO_2} \times L_m + P_{H_2O} \times L_m = 0.06 + 0.03$

$\boxed{P_{CO_2} \times L_m + P_{H_2O} \times L_m = 0.09}$

From HMT data book, Page No.95, we can find correction factor for mixture of CO_2 and H_2o.