Chapter 4

Radiation and Heat Transfer

CHAPTER HIGHLIGHTS

- *Black Body*
- *Emissive Power*
- *Transmissibility, Absorptivity, Reflectivity*
- *Gray Body*
- *Emissivity of a Gray Surface*
- *Coloured Body*
- *Kirchoffs' Law*
- *Shape Factor*
- *Radiation Shields*
- *Quantum Theory or Planck's Theory*
- *Surface Emission Properties*
- *The Stefan–Boltzmann Law*
- *Heat Exchange Between Two Black Bodies*
- *Electrical Network Analogy for Thermal Radiation Systems*

Introduction

As the molecules and free electron transport the energy in conduction and convection, a medium is required for heat transfer. But heat transfer by radiation does not require any medium and it is more effective in vacuum rather than in a medium. When a surface radiates, then energy released by the surface is not continuous but it is in the form of packet (quanta) of energy called photons. They propagate through the space as rays. These are known as electromagnetic waves. They move with light velocity in space. When these rays strikes to any surface then, they impart their energy in the form of thermal energy which is partly absorbed, received and transmitted by the surface. According to wave theory or Maxwell theory, all type of waves carry energy and travel at different wave length λ and frequenc ν. In a medium at velocity equal to velocity of light $C = \nu h$.

Velocity of light in vacuum $C = 3 \times 10^8$ m/s.

Thermal radiation is considered in the wave length range of 0.1 μm to 100 μm.

Thermal radiation is continuously emitted by all bodies whose temperature is above absolute zero. Thermal radiations are those spectrums of rays whose wavelength vary from 0.1 μm to 100 μm.

A body that emits some radiation in the visible range is known as a light source.

The radiations emitted by bodies at room temperature fall in the infra red region of the spectrum which extends from 0.76 to 100 μm.

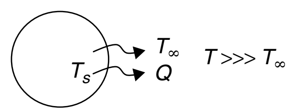
The amount of radiation emitted from a surfaces depends on

1. Material of the body
2. Surface condition
3. Surface Temperature

∴ Different bodies emit different radiation/unit area even though they are the same temperature.

Radiative Heat Transfer

Let us take a body with very high temperature kept in ambient condition.



Let A be the surface area of the body, ε is the emissitivity of the surface and σ be the Stephan Boltzman constant then the radiative heat transfer will be given as

$$Q = \varepsilon\sigma A\left[T_S^4 - T_\infty^4\right]$$

Where,

T_s = Surface temperature of body
T_∞ = Ambient temperature
$\sigma = 5.67 \times 10^{-8}$ W/m^2-K^4

Black Body

It is defined as a perfect emitter and perfect absorber of radiations. A black body absorbs all radiations falling on it. The radiation energy emitted by a black body per unit time per unit area is given by.

$$E = \sigma T^4 \text{W/m}^2$$

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

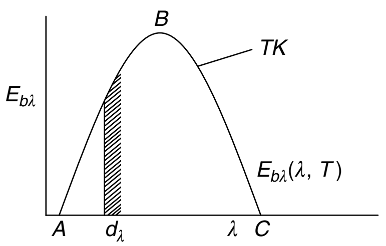
(Stefan Boltzmann constant)

Emissive Power

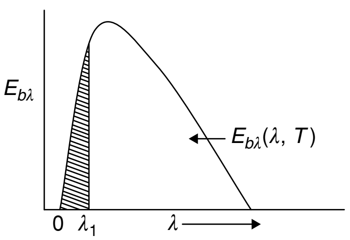
Emissive power of a black body is defined as the energy emitted by the surface per unit time per unit area (E_b).

It depends on the surface roughness and material of surface.

At a give temperature the amount of radiations emitted per unit wavelength varies at different wavelength. Hence comes the term Mono Chromatic emissive power.



Area under the curve *ABC* gives the total radiation energy of a black body at temperature *T*.



Area of the curve left of $\lambda = \lambda_1$ gives the total radiation energy emitted by the black body in the wavelength range $0 - \lambda_1$.

Mono Chromatic emissive power is the amount of radiant energy emitted by a black body at temperature TK per unit time per unit area per unit wavelength about wavelength λ is (i.e., λ to $\lambda + d\lambda$).

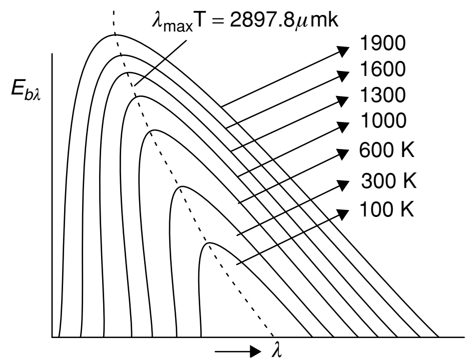
$$E_b(\lambda, T) = \frac{C_1}{\lambda^5 \left[e^{C_2/\lambda T} - 1\right]}$$

Where $C_I = 2\pi h c_0^2 = 3.74177 \times 10^8\, w\mu \dfrac{m^4}{m^2}$

$$C_2 = \frac{hc_0}{K} = 1.43878 \times 10^4\, \mu\text{mK}.$$

$$K = 1.38065 \times 10^{-23}\, \frac{\text{J}}{\text{K}};$$

Which is the Boltzmann constant.



The following points can be noted from the graph.

1. The emitted radiation is a continuous function of λ. At any specific temperature, it increases with wave length and reaches the peak and then decreases with increasing wavelength.
2. At any wavelength, the amount of emitted radiation increases with increasing temperature.
3. As temperature increases, the curve shifts to the left towards the shorter wavelength region.
4. At high temperature, larger fraction of radiation emitted is at the short wavelength region.

The hyperbolic relation between temperature and wavelength at maximum intensity of radiation is given by

$$\lambda_{\max} T = 2897.8\ \mu\text{mK}$$

$$\approx 2900\ \mu\text{mK}$$

$$\lambda_{\max}\, T = 2900\ \mu\text{mK}$$

This is known as Weins displacement law.

Radiosity (*J*)

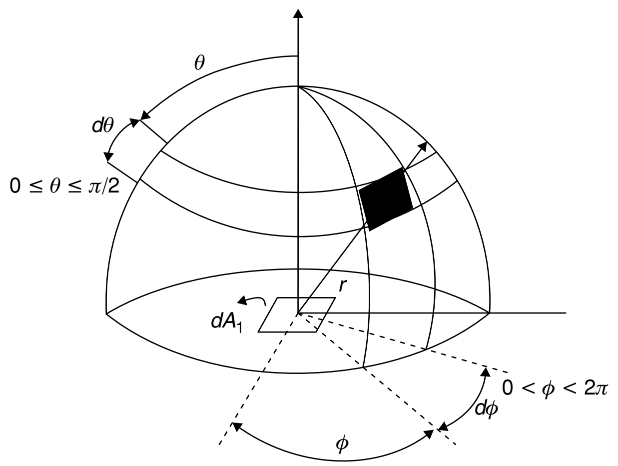
Radiosity refers to all the radiant energy (reflected portion of irradiation and direct emission) leaving a surface.

Spectral Radiosity: (J_λ)

It represents the rate at which radiation leaves a unit area of the surface at the wavelength λ per unit wavelength interval $d\lambda$ about λ.

$$J_{\lambda}(\lambda) = \int_{\theta=\pi}^{\theta=2\pi} \int_{\theta=0}^{\theta=\pi/2} I_{l,\, e+r}(\lambda,\ \theta,\ \phi) \cos\theta \sin\theta \, d\theta \, d\phi$$

Here *e* and *r* stands for emission and reflection respectively.



Total Radiosity (*J*)

It is associated with entire spectrum

$$J = \int_0^{\infty} I_{\lambda}(\lambda) d\lambda = \int_0^{\infty} \int_0^{2\pi} \int_0^{\pi/2} I_{\lambda e+r}(\lambda, \theta, \phi) \cos\theta \sin\theta \, d\theta \, d\phi$$

In the case of diffuse reflection and diffuse emitter surface. $I_{\lambda,e+r}$ will be independent of θ and ϕ and for this case

$$J_{\lambda}(\lambda) = \pi I_{\lambda,e+r}$$

or $$J = \pi I_{e+r}$$

Transmissibility, Absorptivity, Reflectivity

The radiation flux incident on a surface is known as Irradiation. It is denoted by *G*.

When radiation strikes a surface part of it is transmitted, part of it is reflected and part of it is absorbed.

The amount of radiation absorbed out of the total radiation falling on a surface is known as absorptivity.

$$\text{Absorptivity } \alpha = \frac{\text{Radiation absorbed}}{G}$$

$$\text{Reflectivity } \rho = \frac{\text{Radiation reflected}}{G}$$

$$\text{Transmissibility } \tau = \frac{\text{Radiationn transmitted}}{G}$$

$$\alpha + \ell + \tau = \frac{G}{G} = 1$$

All Radiations	Value of α, τ, ℓ	Nature of Bodies
Absorbed	$\alpha = 1$ $\rho = 0$ $\tau = 0$	Black body
Reflected	$\rho = 1$ $\alpha = 0$ $\tau - 0$	White body
Transmitted	$\tau = 1$ $\alpha = 0$ $\rho = 0$	Transparent body
Partly reflected	$\alpha + \rho = 1$ $\tau = 0$	Opaque body and absorbed

Gray Body

The emissive power of any body is less than the emissive power of the black body.

A gray body is one that absorbs a definite percentage of radiations falling on it irrespective of their wavelength.

If the ratio of the monochromatic emissive power of a body to the monochromatic emissive power of the black body over the entire wavelength spectrum is less than one then the body is said to be a gray body.

Emissivity of a Gray Surface

The emissivity of a surface is defined as the ratio of the radiation emitted by the surface at a temperature to the radiation emitted by the black body at that temperature.

Coloured Body

When the absorbitivity of a body varies with wavelength of radiation, then the body is known as a coloured body.

Kirchoffs' Law

Kirchoffs' Law states that the ratio of the total emissive power to the absorptivity is a constant for all substances which are in thermal equilibrium with the surroundings. i.e., consider bodies 1, 2, 3… which are in thermal equilibrium

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

Where E_1, E_2, E_3…are the emissive power and $\alpha_1, \alpha_2, \alpha_3, \cdots$ are the absorptive.

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

But for a black body $\alpha_b = 1$

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

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

$$\text{But } \frac{E_1}{E_b} = \varepsilon_1, \frac{E_2}{E_b} = \varepsilon_2, \frac{E_3}{E_b} = \varepsilon_3 \cdots$$

$$\therefore \quad \alpha_1 = \varepsilon_1, \ \alpha_2 = \varepsilon_2, \ \alpha_3 = \varepsilon_3 \cdots$$

$\therefore$ Absorptivity of a body is equal to emissivity when he body remains in thermal equilibrium with the surroundings.

Shape Factor

It is the function of geometry of a surface radiating heat energy.

When two bodies are radiating energy with each other the shape factor relation will be $A_1F_{12} = A_2F_{21}$

Where A_1 and A_2 are the surface areas.

If a convex surface is enclosed in another surface all the radiations from the convex surface will be intercepted by the enclosing surface.

If '1' is the convex surface and '2' the enclosing surface then $F_{11} + F_{12} = 1$

F_{11} is the fraction of radiations from the convex surface intercepted by itself and F_{12} is the fraction of radiations emitted by the convex surface intercepted by the enclosing surface.

Since it is a convex surface, no radiation from it can be intercepted by itself.

$\therefore \quad F_{11} = 0$

$F_{11} + F_{12} = 1$

Such that $F_{11} = 0, \ F_{12} = 1$

But for a concave surface then is a shape factor by itself, i.e., $F_{11} \neq 0$

Let 1 is a concave surface enclosed within another surface 2.

Surface 1 radiates heat. All radiations from 1 will not fall on 2. A portion of the radiations will fall on 1 itself. In this case $F_{11} \neq 0$

But $F_{11} + F_{12} = 1$

If there are 'n' surfaces taking part in the radiation exchange, then

$F_{11} + F_{12} + F_{13} + F_{14} + \cdots + F_{1n} = 1$

$F_{21} + F_{22} + F_{23} + F_{24} + \cdots + F_{2n} = 1$

. . .

. . .

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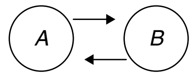
$F_{n1} + F_{n2} + F_{n3} + F_{n4} + \cdots + F_{nn} = 1$

Radiation Between Two Bodies (Surface Resistance)

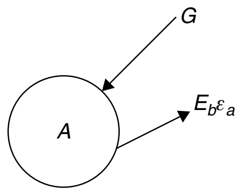
Consider two bodies radiating heat mutually in between



Take the case of body 'A'. Let its emissivity be 'ε_a'. Then the amount of energy 'A' radiates

$E_a = E_b\varepsilon_a$ (1)

because $\dfrac{E_a}{E_b} = \varepsilon_a$



If 'G' is the amount of radiation falling on A from B. Out of 'G' the energy reflection by

$A = \rho G$, where 'ρ' (2)

is the reflectivity of the surface A. Then the total energy going away from 'A' is (1) + (2).

$$J = E_b\varepsilon_a + \rho G$$

But $\rho + \varepsilon_a = 1$, neglecting τ_a

$$\therefore \quad \rho = 1 - \varepsilon_a$$

$$\therefore \quad J = E_b\varepsilon_a + (1 - \varepsilon_a)G$$

Net energy lost by A

$q = J - G$ (4)

$= E_b\varepsilon_a + (1 - \varepsilon_a)G - G$

$= E_b\varepsilon_a - G\varepsilon_a$ (5)

(3) Becomes

$J = E_b\varepsilon_a + (1 - \varepsilon_a)G.$

$J - E_b\varepsilon_b = (1 - \varepsilon_a)G$

$\therefore \quad G = \dfrac{J - E_b\varepsilon_b}{1 - \varepsilon_a}$

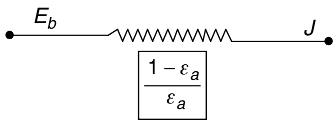
Substituting in (4) $q = J - G$

$$= J - \frac{J - E_b\varepsilon_a}{1 - \varepsilon_a}$$

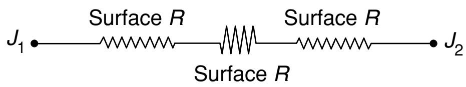
$$= \frac{J - J\varepsilon_A - J + E_b\varepsilon_a}{1 - \varepsilon_a}$$

$$= \frac{E_b\varepsilon_{a-J\varepsilon a}}{1 - \varepsilon_a}$$

$$q = \frac{E_b - J}{\frac{(1-\varepsilon_a)}{\varepsilon_a}}$$



The ratio $\frac{1-\varepsilon_a}{\varepsilon_a}$ is known as the surface resistance. In addition to the surface resistance the space resistance must also be considered.



$$q = \frac{J_1 - J_2}{\frac{1-\varepsilon_a}{\varepsilon_a} + \frac{1}{A_1F_{12}} + \frac{1-\varepsilon_b}{\varepsilon_b}}$$

$$= \frac{\ell T_1{}^4 - \ell T_2{}^4}{\frac{1-\varepsilon_a}{A_1\varepsilon_a} + \frac{1}{A_1 f_{12}} + \frac{1-\varepsilon_b}{A_2\varepsilon_b}}$$

A_1, F_{12} can be calculated from the nature of surfaces intervening.

$A_1F_{12} = A_2F_{21}$

Also

$F_{11} + F_{12} = 1$

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

Case I: Infinite plates (A + B)

$$A_1 = A_2 = A,\ F_{12} = 1$$

Then

$$q = \frac{\sigma A\left(T_1^4 - T_2^4\right)}{\frac{1-\varepsilon_a}{\varepsilon_a} + \frac{1}{F_{12}} + \frac{1-\varepsilon_b}{\varepsilon_b}}$$

But $F_{12} = 1$

$$q = \frac{\sigma A\left(T_1^4 - T_2^4\right)}{\frac{1}{\varepsilon_A} - 1 + 1 + \frac{1}{\varepsilon_b} - 1}$$

$$q = \frac{\sigma A\left(T_1^4 - T_2^4\right)}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_b} - 1}$$

Case II: Let the bodies be concentric cylinder

Here also $F_{12} = 1$

$$q = \frac{\sigma\left(T_1^4 - T_2^4\right)}{\frac{1-\varepsilon_a}{A_1\varepsilon_a} + \frac{1}{A_1F_{12}} + \frac{1-\varepsilon_b}{A_2\varepsilon_b}}$$

$$q = \frac{\sigma A_1\left(T_1^4 - T_2^4\right)}{\frac{1}{\varepsilon_a} - 1 + 1 + \frac{A_1}{A_2}\left(\frac{1}{\varepsilon_6} - 1\right)}$$

$$q = \frac{\sigma A\left(T_1^4 - T_2^4\right)}{\frac{1}{\varepsilon_a} + \frac{A_1}{A_2}\left(\frac{1}{\varepsilon_6} - 1\right)}$$

where

$$A_1 = \Pi D_1 L$$
$$A_2 = \Pi D_2 L$$

or $q = \dfrac{\sigma A_1\left(T_1^4 - T_2^4\right)}{\frac{1}{\varepsilon_a} + \frac{D_1}{D_2}\left(\frac{1}{\varepsilon_b} - 1\right)}$

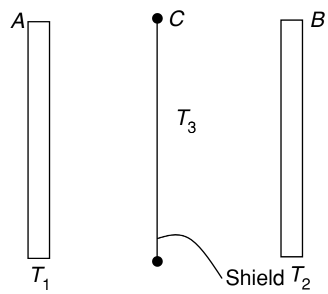
Case III: Concentric spheres

$$q = \frac{\sigma A_1\left(T_1^4 - T_2^4\right)}{\frac{1}{\varepsilon_a} + \left(\frac{1}{\varepsilon_b} - 1\right)\frac{R_1^2}{R_2^2}}$$

Radiation Shields

When we introduce a shield between two radiating surfaces, the radiation exchange is reduced.

The shields are not transferring any heat but they put a resistance in the path of heat flow. As a result the overall heat transfer is reduced.



A shield is introduced between two plates A and B.

$$Q_{A-C} = \frac{\sigma A\left(T_1^4 - T_3^4\right)}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_3} - 1}$$

$$F_{13} = 1.$$

$$Q_{C-B} = \frac{\sigma A\left(T_3^4 - T_2^4\right)}{\frac{1}{\varepsilon_3} + \frac{1}{\varepsilon_2} - 1}, \; F_{32} = 1$$

Under steady condition

$$Q_{A-C} = Q_{C-B.}$$

$$\frac{T_1^4 - T_3^4}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_3} - 1} = \frac{T_3^4 - T_2^4}{\frac{1}{\frac{1}{\varepsilon_3} + \frac{1}{\varepsilon_2} - 1}}$$

If $\varepsilon_1 = \varepsilon_2 = \varepsilon_3 = \varepsilon$

$$T_1^4 - T_3^4 = T_3^4 - T_2^4$$

$$2T_3^4 = T_1^4 + T_2$$

$$T_3^4 = \frac{T_1^4 + T_2^4}{2}$$

$$\therefore \quad Q_{A-C} = \frac{\sigma A\left(T_1^4 - \frac{T_1^4 + T_2^4}{2}\right)}{\frac{2}{\varepsilon} - 1}$$

$$= \frac{1}{2}\sigma \frac{A\left[T_1^4 - T_2^4\right]}{\frac{2}{\varepsilon} - 1}$$

If there is no shield

$$Q_{A-B} = \frac{\sigma A\left[T_1^4 - T_2^4\right]}{\frac{2}{\varepsilon} - 1}$$

$$\therefore \quad Q_{A-C} = \frac{1}{2} Q_{A-B}$$

If there are ‘n’ shields

Q with shield $= \dfrac{1}{n+1} Q$ without shield.

Thermal radiation exhibit characteriastic is similar to those of visible light and follow optical laws like reflection, refraction absorption, polarization scattering etc.

Quantum Theory or Planck’s Theory

Thermal radiation propagates in the form of quanta or photon and each photon has an energy = $h\nu$.

Where the value of h is $h = 6.625 \times 10^{-34}\ J - s$
This constant is known as Planck’s crest

Surface Emission Properties

Emission of radiation by a body depends upon the following factors.

1. The temperature of the surface.
2. The nature of the surface
3. The wave length or frequency of radiation

The parameters which deals with the surface emission properties:

Total Emission Power (E)

It is defined as the total amount of radiation emitted by a body per unit area and time. It is expressed in W/m^2. The emission power of a black body, according to Stefan–Boltzmann is proportional to absolute temperature. the 4th power of

$$E_b = \sigma \mathrm{T}^4 \ \mathrm{W/m^2}$$

$$E_b = \sigma \mathrm{AT}^4 \ \mathrm{Watt}$$

Where s = Stefan–Boltzmann constant

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

Monochromatic (spectral) Emission Power (Eλ)

It is often required to determine the spectral distribution of the energy radiated by a surface. At any temperature the amount of radiation emitted per unit wave length varies at different wave lengths. The mono-chromatic emissive power of a radiating surface is the energy emitted by the surface at a given wavelength. It is measured as W/m^2. The expression for mono-chromatic emissive power (Spectral emissive power is)

$$E_\lambda = \int_\lambda^{\lambda + d_\lambda} E_\lambda d_\lambda$$

Emission from Real Surface Emissivity

The Emissive power from a real surface is given by $E = \varepsilon \sigma AT^4$ Watt

Where (ε) = emissivity of the surface

Emissivity (ε) it is known as ability of the surface of a body to radiate heat. It is also defined as the ratio of the emissive power of anybody to the emissive power of a black body of same temperature (i.e.,) $\varepsilon = \dfrac{E}{E_b}$. Its value varies for different substances ranging from 0 to 1. For a black body $\varepsilon = 1$, for a white body surface $\varepsilon = 0$ and for gray bodies, it lies between 0 and 1. It may vary with temperature or wavelength also.

Irradiation (G)

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

Radiosity (J)

Total radiation leaving a surface per unit time per unit area.

Reflectivity

It is defined as the fraction of total incident radiation that are reflected by material

$$\text{Reflectivity } (\rho) = \frac{\text{Energy reflected(Qr)}}{\text{Total incident radiation}}$$

Absorptivity

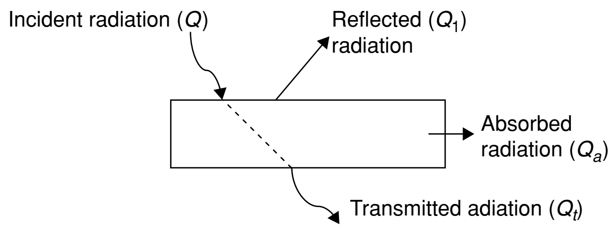
It is defined as the fraction of total incident radiation that are absorbed by material

$$\text{Absorptivity } (\alpha) = \frac{\text{Energy absorbed}}{\text{Total incident radiation}}$$

Transmissivity (τ)

It is defined as the fraction of total incident radiation that is transmitted through the material.

$$\text{Transmissivity } (\tau) = \frac{\text{Energy transmitted}}{\text{Total incident radiation}}$$



By applying the law of conservation energy

$Q = Qr + Q\tau + Q\alpha$

$$\frac{Q}{Q} = \frac{Qr}{Q} + \frac{Q_\tau}{Q} + \frac{Q\alpha}{Q}$$

$I = \rho + \tau + \alpha$

The Stefan–Boltzmann Law

This law states that the emissive power of a black body directly proportional to the fourth power of the absolute temperature

i.e., $Eb = \sigma T^4$

Where Eb = Emissive power of a black body

σ = Stefan constant – Boltzmann constant

Constant = 5.67×10^{-8} W/m^{2}K^4

Solved Examples

Example 1: A large spherical enclosure has a small opening. The rate of emission of radiative flux through this opening is 7.35 kW/m^2. The temperature at the inner surface of the sphere will be about (assume Stefan–Boltzmann constant $\sigma = 5.67 \times 10^{-8}$ W/m^2-K^4)

(A) 600°C (B) 327°C
(C) 373°K (D) 450°C

Solution:

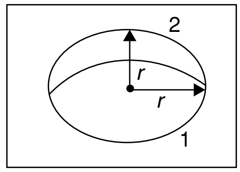
According to Stefan–Boltzmann law

$7.35 \times 10^3 = 5.67 \times 10^{-8}\, T^4$

$T = 600\ k = 327°C$

Example 2: The shape factor of a hemispherical body placed on a flat surface with respect to itself is

(A) 0 (B) 0.25
(C) 0.5 (D) 1.0



Solution:

$F_{1-1} + F_{1-2} = 1$

$F_{1-1} = 0, F_{1-2} = 1$

By reciprocity theorem

$A_1F_{1-2} = A_2\, F_{2-1}$

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

$F_{2-1} = 0.5$

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

$\therefore\quad F_{22} = 0.5$

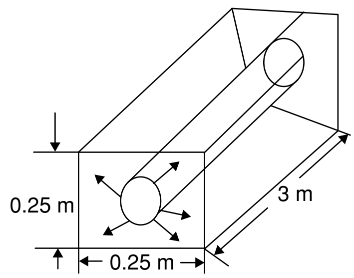
Example 3: A steel tube of outside diameter 70 mm and 3 m long at a temperature of 227°C. The tube is located within a square brick work of 0.25 m side and 27°C. Given ε (steel) = 0.79 ε (brick) = .93. The rate of heat loss by radiation is ($\sigma = 5.67 \times 10^{-8}$ W/m^{2}K)

(A) 1591.5 W (B) 1498 W
(C) 1600 W (D) 1380 W

Solution:

$A_1 = \pi d_1 L = \pi \times .07 \times 3 = 0.659\text{m}^2$

$A_2 = 4 \times a \times L = 4 \times 0.25 \times 3 = 3^2$



$$Q_{1-2} = \frac{\sigma\left(T_1^4 - T_2^4\right)}{\dfrac{1-\varepsilon_1}{A_1\varepsilon_1} + \dfrac{1}{A_1F_{1.2}} + \dfrac{1-\varepsilon_2}{A_2E_2}}$$

$= F_{12} = 1$

$$Q_{1-2} = \frac{A_1\sigma\left(T_1^4 - T_2^4\right)}{\dfrac{1}{\varepsilon_1} + \dfrac{A_1}{A_2}\left(\dfrac{1}{\varepsilon_2} - 1\right)}$$

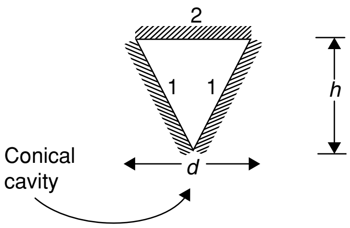
Now putting $T_1 = 227 + 273$

$= 500$ K

$T_2 = 300$ K

$Q_{1-2} = 1600$ W

Example 4: Calculate the value of shape factor F_{1-1} for below figure 2



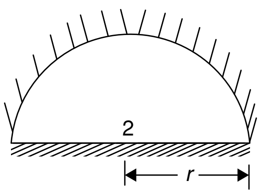
$$F_{1-1} = 1 - \frac{A_2}{A_1}$$

$$F_{1-1} = 1 - \frac{\frac{\pi}{4} d^2}{\left(\frac{\pi d \times \text{slant height}}{2}\right)}$$

$$= 1 - \frac{\frac{\pi}{4} d^2}{\frac{\pi d}{2} \times \left[\sqrt{h^2 + \left(\frac{d^2}{2}\right)^2}\right]}$$

$$I = 1 - \frac{d}{\sqrt{4h^2 + d^2}}$$

Example 5: Calculate the value of shape factor F_{1-2} for the figure below



Hemispherical Surface

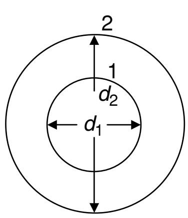
Solution:

$$F_{1-1} + F_{1-2} = 1$$
$$A_1 F_{1-2} = A_2 F_{2-1}$$
$$F_{1-2} = \frac{A_2}{A_1} F_{2-1}$$

But $\quad F_{2-1} = 1$

$$F_{1-2} = \pi r^2 / 2\pi r^2 = 0.5$$

Example 6: Calculate shape factor for outer cylinder with respect to itself



Solution:

$F_{1-1} + F_{1-2} = 1$

$F_{1-1} = 0$

As convex surface with respect to surface 2

$F_{1-2} = 1$

$F_{2-1} + F_{2-2} = 1$

By reciprocity theorem

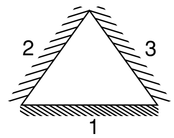
$$A_1 F_{1-2} = A_2 F_{2-1},\ \pi d_1 L \times 1 = \pi d_2 L \times F_{2-1}$$

$$F_{2-1} = \frac{d_1}{d_2}$$

From eq (1)

$$F_{2-2} = 1 - \frac{d_1}{d_2}$$

Example 7: Calculate F_{1-3} and F_{2-3} in given figure



Cross section of equilateral triangle

$F_{1-1} + F_{1-2} + F_{1-3}\ 1$

$F_{1-1} = 0$

$F_{1-2} = F_{1-3}$

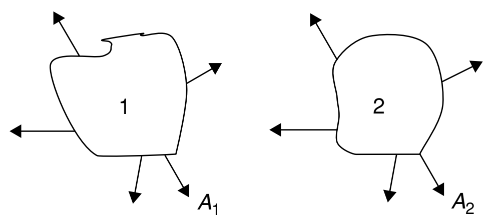
$F_{1-2} = F_{1-3} = 0.5$

$F_{2-1} + F_{2-2} + F_{2-3} = 1$

$F_{2-1} = F_{2-3} = 0.5$

Heat Exchange Bbetween Two Black Bodies

Radiation emitted by body 1 = $\sigma A_1 T_1^4$



Stefan–Boltzmann law part of this radiation on 2 = $F_{1-2}\, \sigma\, A_1\, T_1^4$

Radiation emitted by body 2 = $\sigma A_2 T_2^4$

Part of this radiation falling on 1 = $F_{2-1} \sigma A_2 T_2^4$

Heat exchange between two bodies

$= F_{1-2} \sigma A_1 T_1^4 - F_{2-1}\, \sigma A_2 T_2^4$

By reciprocity theorem

$A_1 F_{1-2} = A_2 F_{2-1}$

$\quad = A_1 F_{1-2}\, \sigma\, (T_1^4 - T_2^4)$

Electrical Network Analogy for Thermal Radiation Systems

An electrical analogy is an alternate method for analyzing heat exchange between gray or black surfaces. In this method the two terms commonly used are irradiation and radiosity. The radiosity comprises the original emittance ϕ from the surface plus the reflected portion of any radiation incident upon it.

$$J = E + PG$$
$$J = \varepsilon Eb + PG$$

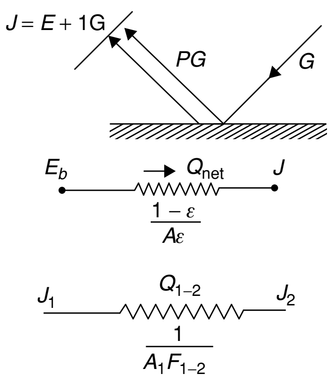
Where, Eb = emissive power of a perfect black body at the same temperature

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

$$\alpha + \rho = 1$$

$\tau = 0$; the surface being opaque

$$r = 1 - \alpha$$
$$J = \varepsilon E_b + (1 - \alpha)\, G$$
$$a = \varepsilon \text{ (by Kirchoff law)}$$
$$J = \varepsilon E_b + (1 - \varepsilon)\, G$$



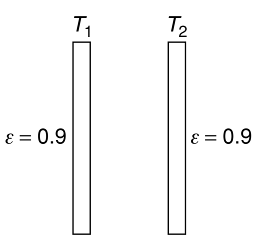
Example 8: Calculate the net radiant heat exchange per meter and for two large parallel plates at temperatures. If 427°C and 27°C respectively ε (hot plate) = 0.9 and ε (cold plate) = 0.6

Solution:

$T_1 = 427 + 2\,73 = 700$ K

$T_2 = 27 + 273$

$= 300$ K



ε_1 = hotplate = 0.9

Cold plate = 0.6

ε_3 (shield) = 0.4

Net radient heat exchange per metre^2 area. The heat flow between plates 1 and 2 is given by

$$(Q_{1-2})_{\text{net}} = \frac{\sigma\left(T_1^4 - T_2^4\right)}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1}$$

$$= 5.67 \frac{\left[\left(\frac{700}{100}\right)^4 - \left(\frac{300}{100}\right)^4\right]}{\frac{1}{0.9}{}^{+\ -1} + 0.6}$$

$$= \frac{13154.4}{1.777} = 7402.6 \text{ W}$$

Example 9: A furnace having inner size 1 m × 1 m × 1 m has a glass circular viewing window of diameter 60 cm. If the transmissibility of glass is 0.8 find the heat loss from the glass window due to radiation if the inner furnace temperature is 2000 K.

Solution: The heat flow through the window is given by $Q = (\sigma A T^4) \times \tau$ where τ is transmissivity of glass is 0.08. Find the heat loss

$$\frac{\pi}{4}\left(\frac{6}{100}\right)^2 \times 5.67\left(\frac{2000+273}{100}\right)^4 \times 0.08$$

$$= \frac{\pi}{4}(0.06)^2 \times 5.67 \times (22.73)^4 \times 0.08$$

$$= 342.34$$

Example 10: Two parallel plates of the same emissivity 0.5 are maintained at different temperatures and have radiation heat exchange between them. The radiation shield of emissivity 0.25 placed in the middle will reduce radiation heat exchange to

(A) $\frac{1}{2}$ (B) $\frac{1}{4}$

(B) $\frac{3}{10}$ (D) $\frac{3}{5}$

Solution:

Reduction in radiation heat exchange due to introduction of shield

$$= \frac{\frac{2}{\varepsilon_1} - 1}{2\left(\frac{1-\varepsilon_1}{\varepsilon_1}\right) + 2\left(\frac{1-\varepsilon_2}{\varepsilon_2}\right) + 2}$$

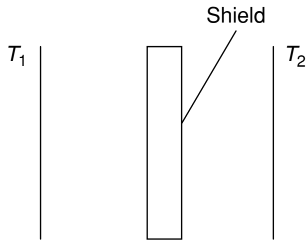
$$= \frac{\frac{2}{0.5} - 1}{2 \times \frac{05}{0.5} + 2 + \frac{0.75}{0.75} + 2} = \frac{3}{10}.$$

Example 11: Two long parallel plates of same emissivity 0.5 are maintained at different temperatures and have radiation emissivity 0.35 placed in the middle will reduce radiation heat exchange to

(A) $\dfrac{3}{7.71}$ (B) $\dfrac{1}{8}$

(C) $\dfrac{3}{4}$ (D) $\dfrac{2}{6}$

Solution:



Without shield

$$Q_1 = \frac{\sigma\left(T_1^4 - T_2^4\right)}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1} = \frac{\sigma\left(T_1^4 - T_2^4\right)}{\frac{1}{0.5} + \frac{1}{0.5} - 1}$$

$$= \sigma\frac{\left(T_1^4 - T_2^4\right)}{3}$$

Where there is inserted shield.

$$Q_2 = \frac{\sigma\left(T_1^4 - T_2^4\right)}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_s} - 1 + \frac{1}{\varepsilon_s} + \frac{1}{\varepsilon_2} - 1}$$

$$= \frac{\sigma\left(T_1^4 - T_2^4\right)}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} + \frac{2}{\varepsilon_2} - 2}$$

$$= \frac{\sigma\left(T_1^4 - T_2^4\right)}{\frac{1}{0.5} + \frac{1}{0.5} + \frac{2}{0.35} - 2} = \frac{\sigma\left(T_1^4 - T_2^4\right)}{4 + 5.71 - 2}$$

$$= \frac{\sigma\left(T_1^4 - T_2^4\right)}{7.71}$$

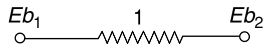
$$\frac{Q_2}{Q_1} = \frac{3}{7.71}$$

$$Q_2 = \frac{3}{7.71} Q_1$$

Example 12: Two large parallel planes are at 1000 K and 600 K. Determine the heat exchange/unit area

1. If surfaces are black
2. If the hot one has an emissivity of 0.8 and cooler one 0.5
3. If a large plate is inserted between the two, the plate having emissivity of 0.2

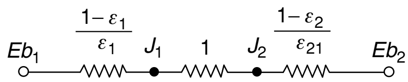
Solution:



$Q = \sigma A F_{1-2}\,(T_1^4 - T_2^4)$

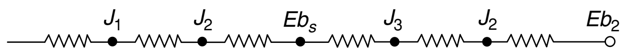
As $F_{1-2} = 1$ for large surfaces considering unit area.

$$\frac{Q}{A} = 5.67 \times 1(1000 - 100)^4 - (600/100)^4) = 49352 \text{ W/m}^2$$



$$\frac{Q}{A} = \frac{(Eb_1 - Eb_2)}{\frac{1-\varepsilon_1}{A_1\varepsilon_1} + \frac{1}{A_1 f_{1-2}} + \frac{1-\varepsilon_2}{A_2\varepsilon_2}}$$

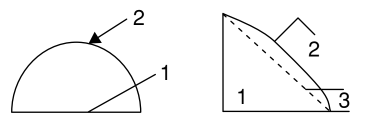
$$= \frac{56700 - 7348.32}{\frac{0.2}{1\times 0.8} + 1 + \frac{0.5}{0.5}} = 21934 \text{ W/m}^2$$



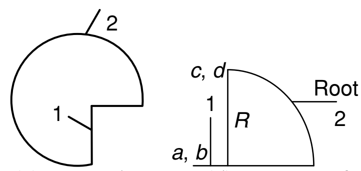
$$\frac{Q}{A} = \frac{56700 - 7348.32}{\frac{1-0.8}{0.8} + 1 + \frac{1-0.2}{0.2} + \frac{1-0.2}{0.2} + 1 + \frac{1-0.5}{0.5}}$$

$= 4387$ W/m^2

Example 13: Determine shape factor F_{12} and F_{21} for the following cases



(a) Hemisphere (b) Long Cylinder



(c) Long duct (d) Long roof

(a) Surface 1 is the base of hemisphere. All radiations from surface 1, reaches surface 2.
Hence $F_{1-2} = 1$ using reciprocity relations as surface area of hemisphere is $2\pi r^2$

$$A_1 F_{1-2} = A_2 F_{21}$$

$$\frac{\pi D^2}{4} \times 1 = 2\pi\left(\frac{D}{2^2}\right) F_{2-1}$$

$$F_{21} = 0.5$$

Considering surface 2,
$F_{2-1} + F_{22} = 1, F_{22} = 5$
Half the radiation from the hemisphere surface is intercepted by itself

(b) Quarter of a long cylinder
An imaginary surface joining edges A and B is named as surface 3.

$F_{3-2} = 1$ as all radiations from surface 3 reaches surface 2. By reciprocity rule $A_3F_{3-2} = A_2F_{2-3}$

Considering unit length:

$$\sqrt{2} \cdot R \cdot 1 = \frac{\pi}{2} RF_{2-3}$$

$F_{2-3} = 0.9003$

$F_{2-2} = 1 - 0.9003 = 0.0997$

Now considering the surface 1, and the perpendicular surface

$$2F_{2-1} + F_{22} = 1 \; F_{2-1} = 0.4502$$

Using reciprocity theorem

$$A_1F_{1-2} = A_2F_{2-1}$$

Considering unit length

$$RF_{1-2} = \frac{\pi}{2} R \times 0.4502$$

$$F_{1-2} = 0.7070$$

Shape factor to the perpendicular surface from surface

$$F_{1-4} = 1 - 0.7070 = 0.2930$$

(c) For the long duct considering the surface 1

So $F_{1-2} = 1$

By reciprocity rule

$$A_1F_{1-2} = A_2F_{2-1}$$

Considering unit length

$2R \times 1 = 1.5\pi \, RF_{2-1}$

$\therefore \quad F_{2-1} = 0.4244$

$F_{2-2} = 1 - 0.4244$

$= 0.5756$

(d) The shape factor is calculated using crossed string method ($R = 1$)

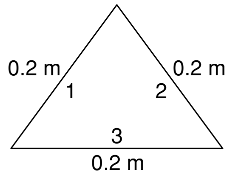
$$F_{1-2} = \frac{(ad + bc) - (ab - cd)}{24}$$

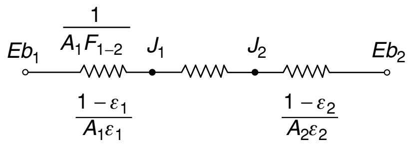
$$= \frac{(2 + \sqrt{2}) - (\sqrt{2} + 0)}{2 \times 2} = 0.5$$

Example 14: The surface A_1 and A_2 having emissivity of 0.6 and 0.4 are maintained at 800 K and 400 K. Determine the heat exchange between the surfaces per unit length considering these are long with the third side open and at 400 K. If surface 3 is well insulated; so that the surface is non absorbing determine heat exchange.

Solution: By symmetry (long duct)

(a) $F_{1-2} = F_{2-1} = F_{32} = F_{2-3} = F_{1-3} = F_{3-1} = 0.5$



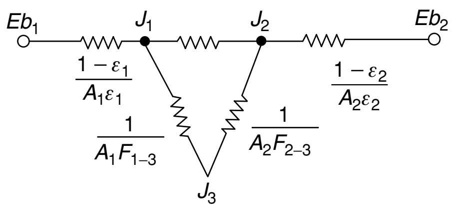


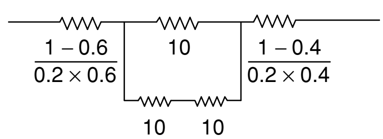
Considering the surfaces 1 and 2 the equivalent circuit can be drawn as shown in figure.

$$Q = \frac{\sigma\left(T_1^4 - T_2^4\right)}{\Sigma R}$$

$$\frac{5.67(8^4 - 4^4)}{\dfrac{1-0.6}{0.6 \times 0.2 \times 1} + \dfrac{1}{0.2 \times 1 \times 0.5} + \dfrac{1-0.4}{0.4 \times 0.2 \times 1}} = 1045 \text{ W}$$

(b) If reradiating surface is added the equivalent circuit is as shown in figure below. The equivalent resistance is 17.5





$q = 5.67\,(8^4 - 4^4)/17.5$

$= 1244.4$ W for one m length.

Exercises

Practice Problems I

Direction for questions 1 to 20: Select the correct alternative from the given choices.

1. A black body emits radiation of maximum intensity at a wavelength of 0.5 μm. Calculate its emissive power.

(A) 58.107 MW/m^2 (B) 68012 MW/m^2

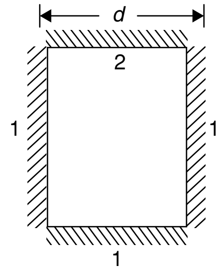
(C) 38.2 MW/m^2 (D) 48.27 MW/m^2

2. The filament of 100 W light bulb radiates energy into an enclosure at 350 K. Both the bulb and enclosure acts as black bodies. Calculate the temperature of filament of the bulb. If it is 0.12 mm in diameter and 5 cm long.

(A) 3220 K (B) 3110 K

(C) 0.4110 K (D) 4820 K

3. Calculate the value of shape factor ($F_1 - 1$) for the one given in figure



Cylindrical Cavity

(A) $\dfrac{4h+d}{d}$ (B) $\dfrac{4h+2d}{2}$

(C) $\dfrac{4h+d}{4h}$ (D) $4h/4h + d$

4. A plate having 10 cm^2 areas each side is hanging in the middle of a room of 100 m^2 total surface area. The plate temperature and emissivity are respectively 700 K and 0.6. The temperature and emissivity values for the surfaces of the room are 300 K and 0.3 respectively. Boltzmann constant $\sigma = 5.67 \times 10^{-8}$ N/m^{2}K^4. The total heat loss from the two surfaces of the plate is

(A) 13.66 (B) 27.32 W
(C) 15.784 (D) 13.66 MW

5. Two long parallel plates of same emissivity 0.5 are maintained at different temperatures and have radiation heat exchange between them. The radiation shield of emissivity 0.25 placed in the middle will reduce radiation heat exchange to

(A) 1/2 (B) 1/4
(C) 3/10 (D) 3/5

6. The net radiation from the surfaces of two parallel plates maintained at T_1 and T_2 is to be reduced 99%. Number of shields which would be placed between the two surfaces to achieve this reduction is ($\varepsilon_{\text{shield}} = 0.05$, $\varepsilon_{\text{surface}} = 0.8$)

(A) 4 (B) 3
(C) 100 (D) 99

Direction for questions 7 and 8: Two black discs of diameter 50 cm are placed parallel to each other concentrically at a distance of 1m. The discs are maintained at 527°C and 127°C respectively.

7. Determine the heat transfer between the discs/h. When no other surfaces are present except discs, consider shape factor = 0.06.

(A) 2160 kJ/h (B) 2260 kJ/h
(C) 3260 kJ/h (D) 923 kJ/h

8. Taking shape factor 0.34. Determine the heat transfer between the discs/h, when the discs are connected by cylindrical black surface.

(A) 13800 kJ/h (B) 14200 kJ/h
(C) 5230.33 kJ/h (D) 4800 kJ/h

Direction for questions 9 and 10: Radiative heat transfer is intended between the inner surfaces of two very large isothermal parallel metal plates. The upper plate (designated as plate 1) is a black surface and is the warmer one being maintained at 527°C. The lower plate (2) is a diffuse and gray surface with an emissivity of 0.7 and is kept at 127°C. Assume that the surfaces are sufficiently by large to form a two surface enclosure and steady state conditions to exit Stefan–Boltzmann constant is given as 5.67×10^{-8} W/m^{2}K^4.

9. The irradiation (in kW/m^2) for the plate (plate 1) is

(A) 1.02 (B) 3.6
(C) 17.0 (D) 7.98

10. If plate 1 is also a diffuse and gray surface with an emissivity value of 0.8, the net radiation heat exchange (in kW/m^2) between plate 1 and plate 2 is

(A) 12.97 (B) 19.51
(C) 23.0 (D) 31.72

Direction for questions 11 and 12: The sun emits maximum radiation at $\lambda = 0.52\ \mu$.

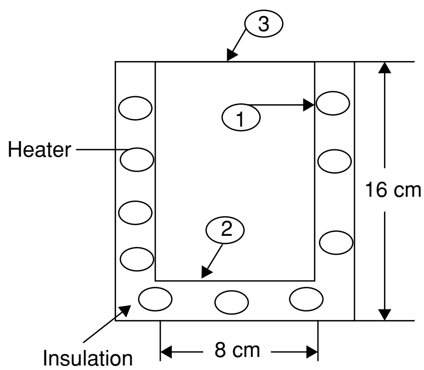
11. Calculate sun's surface temperature and emissive power of sun's surface assuming sun as a black body

(A) 5577°K, 5.485×10^7 W/m^2
(B) 6200°K, 5.88×10^7 W/m^2
(C) 4890°K, 5.485×10^7 W/m^2
(D) 7280°K, 5.88 W/m^2

12. Maximum monochromatic emissive power of sun surface is

(A) 7.8 W/m^2 (B) 6.9×10^{13} W/m^2
(C) 8.1×10^3 W/m^2 (D) 6.52×10^3 W/m^2

13. An electrically heated industrial furnace is of cylindrical form $d = 8$ cm and $H = 16$ cm and top end is open to the atmosphere. The bottom of the surface is maintained at 1627°C and cylindrical surface is maintained at 1327°C. Determine the power supplied to the furnace to maintain the conditions mentioned in the problem. The surrounding air temperature is 27°C. Assume furnace is fully insulated from outside and surfaces may be consideredas black.



(A) 2141.4 (B) 2232
(C) 2148.4 (D) 2822

14. A bed of burning coal in a furnace radiates as a plane rectangular black surface 3×2 m at 1500°C to a bank of black tubes of same projected area. The tubes are maintained at 300°C and at such a distance from the fire bed that the shape factor is 0.5. Determine the net radiant heat flow to the tube bank.
(A) 1662.5 kW (B) 1828 kW
(C) 2131 kW (D) 1322 kW

15. If both the surfaces are enclosed with an adiabatic black wall find the percentage increase in the radiant heat flow between the bed and the water wall.
(A) 3200.1 kW (B) 4433.3 kW
(C) 4100 kW (D) 2800.6 kW

Direction for questions 16 and 17: A horizontal heat pipe 2.5 cm in diameter has surface temperature of 250°C and surface $\varepsilon = 0.95$. Determine convective and radiative heat loss from the pipe for 1 m length of pipe. (given $K = 0.035$ w/mt, $\gamma = 27.8 \times 10^{-6}$ m^2/s $P_r = 0.684$)

16. If pipe is passing through still air at 30°C.
(A) 491 W (B) 223 W
(C) 320 W (D) 390 W

17. If the air is flowing perpendicular to the pipe axis at a velocity 20 m/sec. Take the following properties of air at mean temp140°C
(A) 1532 W (B) 2810 W
(C) 2201 W (D) 1490 W

18. A small sphere of 5 cm diameter at 277°C is located in another hollow sphere of 25 cm diameter whose inner surface is maintained at 7°C. Assuming both the sphere surfaces are black, find out the amount of energy falls on the outer surface of inner sphere from the inner surface of the outer sphere.
(A) 42 W (B) 38 W
(C) 60 W (D) 50 W

19. The special black body emissive power is given by
(A) Stefan–Boltzmann law (B) Kirchoff's law
(C) Weir's law (D) Plank's law

20. Thermal radiations are electromagnetic radiations whose wavelength vary
(A) Between 0.1 to 100 μm
(B) Between 0.4 to .76 μm
(C) Between 100 μm to 10^8 μm
(D) Between 150 μm to 10^5 μm

Practice Problems 2

Direction for questions 1 to 30: Select the correct alternative from the given choices.

Direction for questions 1 and 2: A gray body emits the same amount of radiation at 1200 k as black body emits at 800 k.

1. (a) Find the emissivity of the gray body.
(A) 0.189 (B) 0.122
(C) 0.197 (D) 0.20

2. If the gray body emission is 90% of black body emission at 1200 K, then find the temperature required for the gray body.
(A) 1788 K (B) 1655 K
(C) 1830 K (D) 1754 K

Direction for questions 3 and 4: A furnace emits radiation at 2100 k considering furnace as a black body.

3. Calculate total emissive power
(A) 20800 kW/m^2 (B) 13830 kW/m^2
(C) 15120 kW/m^2 (D) 1102.7 kW/m^2

4. Wavelength at which emission is maximum and corresponding heat flux
(A) 1.38 μm (B) 2.1 μm
(C) 1.91 μm (D) 1.1 μm

5. A steel plate is placed on a non-conducting opaque surface normal to incident solar radiation of 750 W/m^2. Determine the equilibrium temperature of the plate when it is
(a) Oxidized and its $\varepsilon = 0.8$
(b) Polished and its $\varepsilon = 0.07$.
Neglect effects of convection
(A) 339 K, 339 K (B) 3.14 K, 314 K
(C) 410 K, 280 K (D) 430 K, 339 K

6. A black body emits radiation of maximum intensity at a wavelength of 0.6 μm Calculate its surface temperature and emissive power.
(A) 28.02×10^6 W/m^2 (B) 32.3×10^6 W
(C) 38.3×10^6 W/m^2 (D) 40.810^6 W/m^2

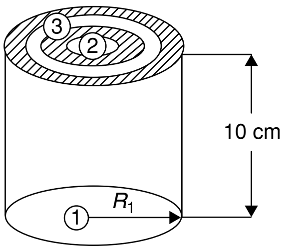
7. The filament of 100 w light bulb radiates energy into a enclosure of 350 K. Both the bulb and enclosure act as black bodies. Calculate the temperature of filament of the bulb, if it is 0.12 mm in diameter and 5 cm long.
(A) 4812.12 K (B) 5310.12 K
(C) 3110.24 K (D) 62.13 K

8. A gray opaque surface has an absorptivity 0.7. It is maintained at 200°C. It receives an irradiation of 1000 w/m^2. Its surface area is 0.2 m^2. Calculate rate of heat absorption and rate of heat emmission
(A) 100 W, 250 W (B) 150 W, 310 W
(C) 250 W, 320 W (D) 140 W, 397 W

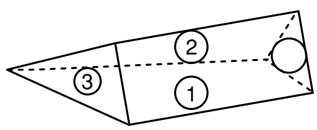
9. A small sphere of 5 cm diameter at 650 k is located in another hollow sphere of 25 cm diameter. Whose inner surface is maintained at 280 K. Assuming both the sphere surfaces are black, find at the amount of energy falls on the outer surface of inner sphere from the inner surface of the outer sphere.

(A) 81.2 W (B) 79.1 W
(C) 76.7 W (D) 38 W

10. Determine the fraction of radiation leaving the base of the cylindrical enclosure shown in fig. That escapes through a co-axial ring opening at its top surface. $F_{12} = 0.11$, $F_{13} = 0.28$
(A) 12% (B) 20%
(C) 15% (D) 17%



11. Determine the shape factor from any one side of infinitely long triangular duct whose cross section is shown in the figure. Using values 700 $a_1 = 5$ cm, $a_2 = 7$ cm and $a_3 = 10$ cm find values of F_{12}, F_{13}, F_{23}.



(A) 0.857, 0.2, 0.8 (B) .623, 0.4, 0.6
(C) 0.92, 0.3, 0.5 (D) 78, 0.4, 0.8

12. A disc of 10 cm diameter at 700 K is situated 2m below the center of another disc 2 m in diameter, which is maintained at 500 K. Find the heat lost by the smaller disc given to bigger disc.

ε_1 (for small disc) = 0.8,

ε_2 (for big disc) = 0.6
(A) 180.4 (B) 15.04
(C) 130.8 (D) 160.5

13. In a cylindrical furnace 60 cm in diameter and 100 cm high, the upper surface is maintained at 1000° K and lower surface is maintained at 700° K. If the emissivities of upper and lower surfaces are 0.8 and 07, find the net heat transfer from the upper surface to lower surface. Assume the cylindrical wall is a refractory surface.

$F_{12} = 0.1$
(A) 4876 W (B) 5820 W
(C) 3430 W (D) 8230 W

14. Three hollow cylinders of thin wall 10 cm, 20 cm and 30 cm in diameter are arranged concentrically. The temperature of the surface of 10 cm diameter cylinder and 30 cm diameter cylinder are maintained at 100° K and 300° K. Assuming the vacuum between the annular spaces find the steady state temperature attained by the surface of the cylinder whose diameter is 20 cm.

Take $\varepsilon_1 = \varepsilon_2 = \varepsilon_3 = 0.05$
(A) 692 K (B) 420 K
(C) 580 K (D) 633 K

15. The concentric spheres 20 cm and 30 cm in diameter are used to store liquid O_2 (−153°C) in a room at 300° K. The space between the spheres is evacuated. The surfaces of the spheres are highly polished as $\varepsilon = 0.04$. Find the rate of evaporation of liquid 02 per hour. Take latent heat of $O_2 = 209$ kJ/kg.
(A) 2 kg/h (B) 0.195 kJ/h
(C) 1.8 kJ/h (C) 0.108 kg/h

16. A hot water radiator of overall dimensions $2 \times 1 \times 0.2$ m is used to heat a room at 18°C. The surface temperature of the radiator is 60°C and its surface is black. Actual surface area of its the radiator is 2.5 times the area of envelope, for convection and the convection heat transfer coefficient is given by $h_e = 1.3(\theta)^{\frac{1}{3}}$ Wm^{2}K.
Calculate the rate of heat loss from radiator by convection and radiation.
(A) 10 MJ/h (B) 16.8 MJ/h
(C) 24.5 MJ/h (D) 14.3 MJ/h

Direction for questions 17 and 18: Two black discs of diameter 50 cm are placed parallel to each other concentrically at a distance of 1 m. The discs are maintained at 727°C and 227°C respectively. Calculate the heat transfer between discs per hour.

17. When no other surfaces are present except the discs,
(A) 2260 kJ/h (B) 4120 kJ/h
(C) 3180 kJ/h (D) 3880 kJ/h

18. When the discs are connected by cylindrical balance surface
(A) 12800 kJ/h (B) 13800 kJ/h
(C) 13800 kJ/h (D) 15400 kJ/h

19. A sphere having d meters OD is located eccentrically in a D meters ID sphere. Determine the shape factor between outer sphere to inner sphere.
(A) $F_{12}\left(\frac{d}{D}\right)^2$ (B) F_{12}
(C) $F_2 d^2$ (D) $F_2\left(\frac{D}{d}\right)^2$

20. The ratio of emissive power of a body to emissive power of a perfectly black body is called
(A) Absorptivity (B) Emissivity
(C) Diffusivity (D) Absorptive power

21. Thermal radiation extends over the range of
(A) $0.01 - 0.1\ \mu$ (B) $0.1 - 1.00\ \mu$
(C) 100 to 250 μ (D) 250 to 1000 μ

22. A gray body is one whose absorptivity varies
(A) Varies with temperature
(B) Varies with the wavelength of incident ray
(C) Varies with both
(D) Does not vary with temperature and wavelength of incident ray.

23. Intensity of radiation at a surface in perpendicular direction is equal to
(A) Product emissivity of surface and $\frac{1}{\pi}$.
(B) Product emissivity and π.
(C) Product emissivity and power of surface and $\frac{1}{\pi}$.
(D) Product of emissive power of surface and π.

24. Solar radiation of 1200 W/m^2 falls perpendicularly on a gray opaque surface of emissivity 0.5. If the surface temperature is 50°C and surface emissive power 600 W/m^2, the radiosity of that surface will be
(A) 600 W/m^2 (B) 1000 W/m^2
(C) 1200 W/m^2 (D) 1800 W/m^2

25. Two large parallel gray plates with a small gap exchange radiation at the rate of 1000 W/m^2. When their emissivities are 0.5 each, by coating one plate, its emissivity is reduced to 0.25.

Temperatures remain unchanged. The new rate of heat exchange shall become
(A) 500 W/m^2 (B) 600 W/m^2
(C) 700 W/m^2 (D) 800 W/m^2

26. Match the List-I (type of radiation) with List-II (characteristic).

List-I	List-II
a. Stefan-Boltman law	1. Emissive
b. Kirchoff's law	2. Monochromatic emissive ower
c. Wien's displacement law	3. Emissive power of black body
d. Lambert's law	4. $\varepsilon = \alpha$ for any body

Codes:

	a	b	c	d
(A)	3	4	2	1
(B)	1	4	2	3
(C)	3	2	4	1
(D)	2	4	3	1

Direction for questions 27, 28 and 29: An artificial spherical satellite flies around the earth. The absorptivity of the satellites surface in respect to incident solar radiation is α and the emissivity of its surface is ε. Assume that there are no inner heat sources and surface temperature is same all over it. The solar radiation reflected from earth and the radiation emitted from earth should be ignored. Take E_{in} (incident radiation from sun) = 1550 w/m^2

27. If $\alpha = 0.2$ and $\varepsilon = 0.1$ the temperature of satellites surface is
(A) 70°C (B) 75°C (C) 98 °C (D) 105°C

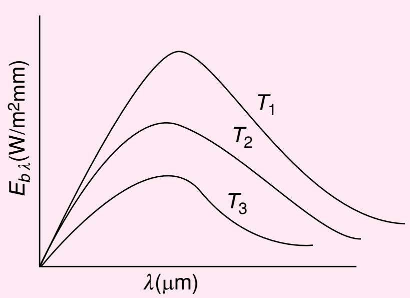
28. If the surface of satellite is considered as gray, then the surface temperature is
(A) 25°C (B) 15°C (C) 35°C (D) 30°C

29. Find the ratio of (α/ε) when the temperature of the satellite surface becomes 30°C
(A) 3.5 (B) 2.3
(C) 3.1 (D) 1.22
Take E_m incident radiator from sun = 1550 */m^2.

30. The energy of the radiation field is transported by
(A) Photons
(B) Random motion of molecules
(C) Bulk motion of molecules
(D) None of there

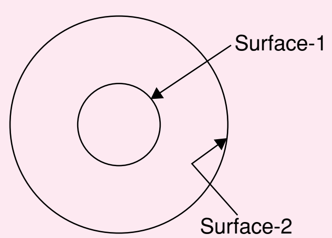
Previous Years' Questions

1. The following figure was generated from experimental data relating spectral black body emissive power to wave length at three temperatures T_1, T_2 and T_3 ($T_1 > T_2 > T_3$).



The conclusion is that the measurements are **[2005]**
(A) Correct because the maxima in $E_{b\lambda}$ show that correct trend
(B) Correct because Planck's law is satisfied
(C) Wrong because the Stefan–Boltzmann law is not satisfied
(D) Wrong because Wien's displacement law is not satisfied

2. A hollow enclosure is formed between two infinitely long concentric cylinders of radii 1 m and 2 m, respectively. Radiative heat exchange takes place between the inner surface of the larger cylinder (Surface-2) and the outer surface of the smaller cylinder (Surface-1). The radiating surfaces are diffuse and the medium in the enclosure is non-participating. The fraction of the thermal radiation leaving the larger surface and striking itself is, **[2008]**



(A) 0.25 (B) 0.5
(C) 0.75 (D) 1

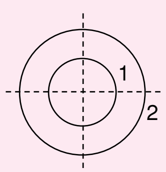
Direction for questions 3 and 4: Radiative heat transfer is intended between the inner surfaces of two very large isothermal parallel metal plates. While the upper plate (designated as plate 1) is a black surface and is the warmer one being maintained at 727°C, the lower plate (plate 2) is a diffuse and gray surface with an emissivity of 0.7 and is kept at 227°C. Assume that the surfaces are sufficiently large to form a two-surface enclosure and steady state conditions to exist. Stefan–Boltzmann constant is given as 5.67×10^{-8} W/m^{2}K^4.

3. The irradiation (in kW/m^2) for the upper plate (plate 1) is **[2009]**
(A) 2.5 (B) 3.6
(C) 17.0 (D) 19.5

4. If plate 1 is also a diffuse and gray surface with an emissivity value of 0.8, the net radiation heat exchange (in kW/m^2) between plate 1 and plate 2 is **[2009]**
(A) 17.0 (B) 19.0
(C) 23.0 (D) 31.7

5. For an opaque surface, the absorptivity (α), transmissivity (τ) and reflectivity (ρ) are related by the equation: **[2012]**
(A) $\alpha + \rho = \tau$ (B) $\rho + \alpha + \tau = 0$
(C) $\alpha + \rho = 1$ (D) $\alpha + \rho = 0$

6. Consider two infinitely long thin concentric tubes of circular cross section as shown in the figure. If D_1 and D_2 are the diameters of the inner and outer tubes respectively, then the view factor F_{22} is given by **[2012]**



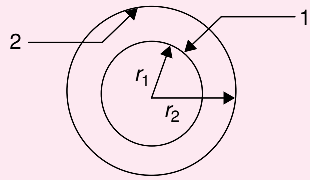
(A) $\left(\frac{D_2}{D_1}\right) - 1$ (B) Zero

(C) $\left(\frac{D_1}{D_2}\right)$ (D) $1 - \left(\frac{D_1}{D_2}\right)$

7. Two large diffuse gray parallel plates, separated by a small distance, have surface temperatures of 400 K and 300 K. If the emissivities of the surfaces are 0.8 and the Stefan–Boltzmann constant is 5.67×10^{-8} W/m^2 K^4, the net radiation heat exchange rate in kW/m^2 between the two plates is **[2013]**
(A) 0.66 (B) 0.79
(C) 0.99 (D) 3.96

8. A hemispherical furnace of 1 m radius has the inner surface (emissivity, ε = 1) of its roof maintained at 800 K, while its floor (ε = 0.5) is kept at 600 K. Stefan-Boltzmann constant is 5.668×10^{-8} W/m^2–K^4. The net radiative heat transfer (in kW) from the roof to the floor is _____. **[2014]**

9. A solid sphere of radius r_1 = 20 mm is placed concentrically inside a hollow sphere of radius r_2 = 30 mm as shown in the figure.

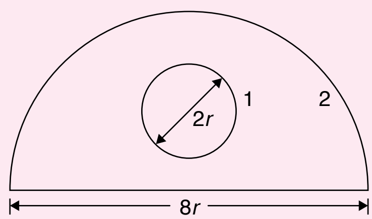


The view factor F_{21} for radiation heat transfer is **[2014]**

(A) $\frac{2}{3}$ (B) $\frac{4}{9}$ (C) $\frac{8}{27}$ (D) $\frac{9}{4}$

10. Two infinite parallel plates are placed at a certain distance apart. An infinite radiation shield is inserted between the plates without touching any of them to reduce heat exchange between the plates. Assume that the emissivities of plates and radiation shield are equal. The ratio of the net heat exchange between the plates with and without the shield is: **[2014]**
(A) 1/2 (B) 1/3 (C) 1/4 (D) 1/8

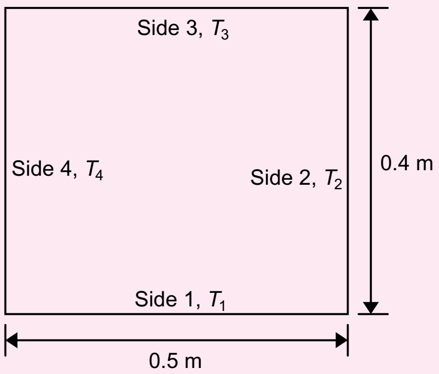
11. A solid sphere 1 of radius 'r' is placed inside a hollow, closed hemispherical surface 2 of radius '$4r$'. The shape factor F_{2-1} is: **[2015]**



(A) 1/12 (B) 1/2 (C) 2 (D) 12

12. An infinitely long furnace of 0.5 m × 0.4 m cross-section is shown in the figure below. Consider all surfaces of the furnace to be black. The top and bottom walls are maintained at temperature $T_1 = T_3$ = 927°C while the side walls are at temperature $T_2 = T_4$ = 527°C. The view factor, F_{1-2} is 0.26. The net radiation heat loss or gain on side 1 is _______ W/m. **[2016]**

Stefan-Boltzmann constant = 5.67×10^{-8} W/m^2-K^4



13. Consider the radiation heat exchange inside an annulus between two very long concentric cylinders. The radius of the outer cylinder is R_o and that of the inner cylinder is R_i. The radiation view factor of the outer cylinder onto itself is: **[2016]**

(A) $1-\sqrt{\dfrac{R_i}{R_o}}$ (B) $\sqrt{1-\dfrac{R_i}{R_o}}$

(C) $1-\left(\dfrac{R_i}{R_o}\right)^{1/3}$ (D) $1-\dfrac{R_i}{R_o}$

14. Two large parallel plates having a gap of 10 mm in between them are maintained at temperatures T_1 = 1000 K and T_2 = 400 K. Given emissivity values, $\varepsilon_1 = 0.5$, $\varepsilon_2 = 0.25$ and Stefan-Boltzmann constant $\sigma = 5.67 \times 10^{-8}$ W/m^2-K^4, the heat transfer between the plates (in kW/m^2) is ______. **[2016]**

Answer Keys

Exercises

Practice Problems 1

1. A	**2.** B	**3.** D	**4.** C	**5.** C	**6.** A	**7.** D	**8.** C	**9.** D	**10.** A
11. A	**12.** B	**13.** A	**14.** A	**15.** B	**16.** A	**17.** D	**18.** B	**19.** D	**20.** A

Practice Problems 2

1. C	**2.** D	**3.** D	**4.** A	**5.** A	**6.** A	**7.** C	**8.** D	**9.** C	**10.** D
11. A	**12.** B	**13.** A	**14.** A	**15.** D	**16.** D	**17.** A	**18.** A	**19.** A	**20.** B
21. B	**22.** D	**23.** C	**24.** C	**25.** B	**26.** B	**27.** A	**28.** B	**29.** D	**30.** A

Previous Years' Questions

1. D	**2.** B	**3.** D	**4.** D	**5.** C	**6.** D	**7.** A	**8.** 24 to 25.2	**9.** B
10. A	**11.** A	**12.** 24528 – 24532		**13.** D	**14.** 10.9–11.2			