Module IV

RADIATION

Course material Adapted from:

1. Warren. L, McCabe, Julian ,C. Smith and Peter Harriott, “Unit Operations of Chemical Engineering”, 7th Edn., McGraw Hill International Edition, NewYork 2005.

2. Holman. J.P., “Heat Transfer” , 9th Edn., Tata McGraw Hill Book Co., New Delhi, 2008.

3. R.C.Sachdeva, “Fundamentals of Engineering Heat and Mass Transfer”,

4th Edition,New Age International Publishers,2010 4. http://nptel.ac.in/courses/103103032/- Dr. Anil Verma Dept. of Chemical Engineering,IIT Guwahati

5. www.che.utexas.edu/course/che360/lecture_notes/chapter_2.ppt

CONTENTS

Concept of thermal radiation, emissive power, black body radiation, Kirchoff’s law, Stephen – Boltzman’s law, energy exchange between; two large parallel planes, two parallel planes of different emissivity. Radiation intercepted by a shield, spheres or cylinders with spherical or cylindrical enclosures, radiation energy to a completely absorbing receiver.

Introduction

Radiation is the energy emitted by matter in the form of electromagnetic waves as a result of the changes in the electronic configurations of the atoms or molecules. Unlike conduction and convection, the transfer of energy by radiation does not require the presence of an intervening medium. In fact, energy transfer by radiation is the fastest (at the speed of light) and it suffers no attenuation in a vacuum. This is exactly how the energy of the sun reaches the earth.

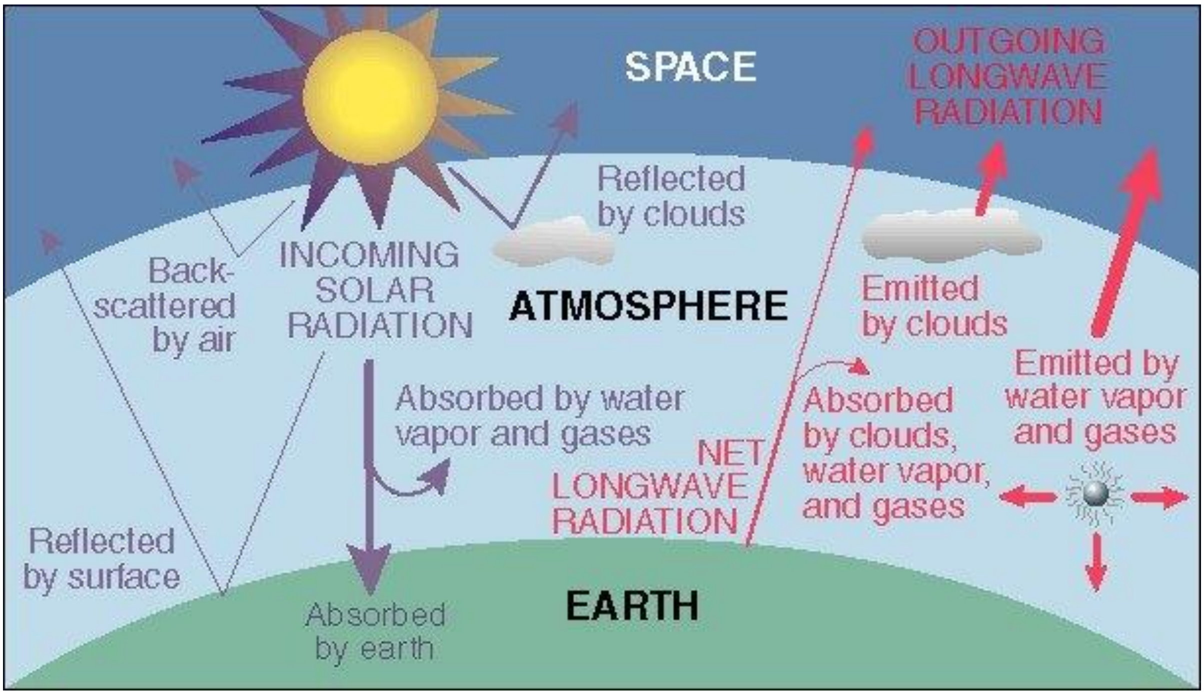


Fig:1.(a)Energy transfer from sun

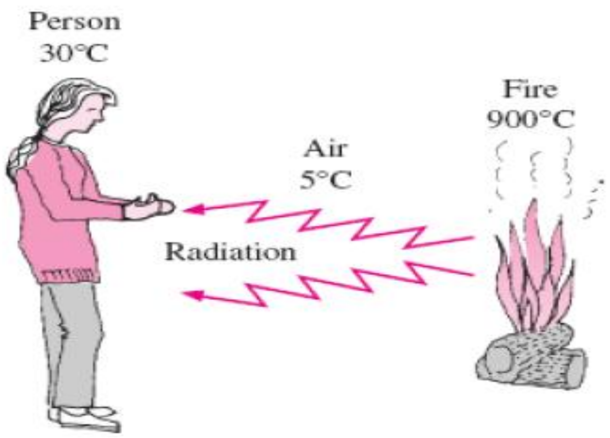
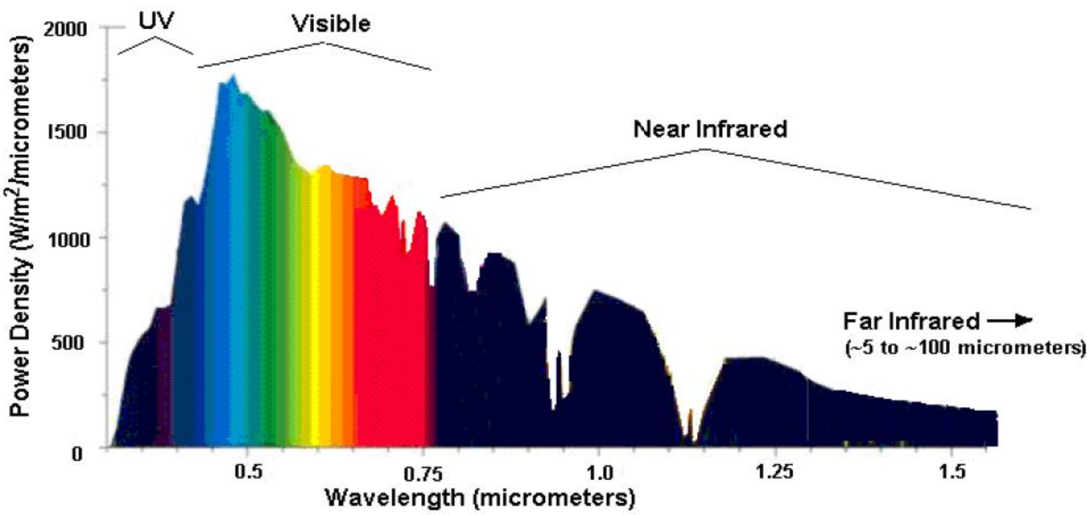


Fig.1.(b).Radiation

Thermal radiation is electromagnetic radiation generated by the thermal motion of charged particles in matter. All matter with temperature greater than absolute zero emits thermal radiation. When the temperature of the body is greater than absolute zero, interatomic collision causes the kinetic energy of the atoms or molecules to change. This results in charge – acceleration and/or dipole oscillation which



produces electromagnetic radiation.

Ex: Visible light and infra red light emitted by an incandescent light bulb.

Fig.2.Solar spectrum

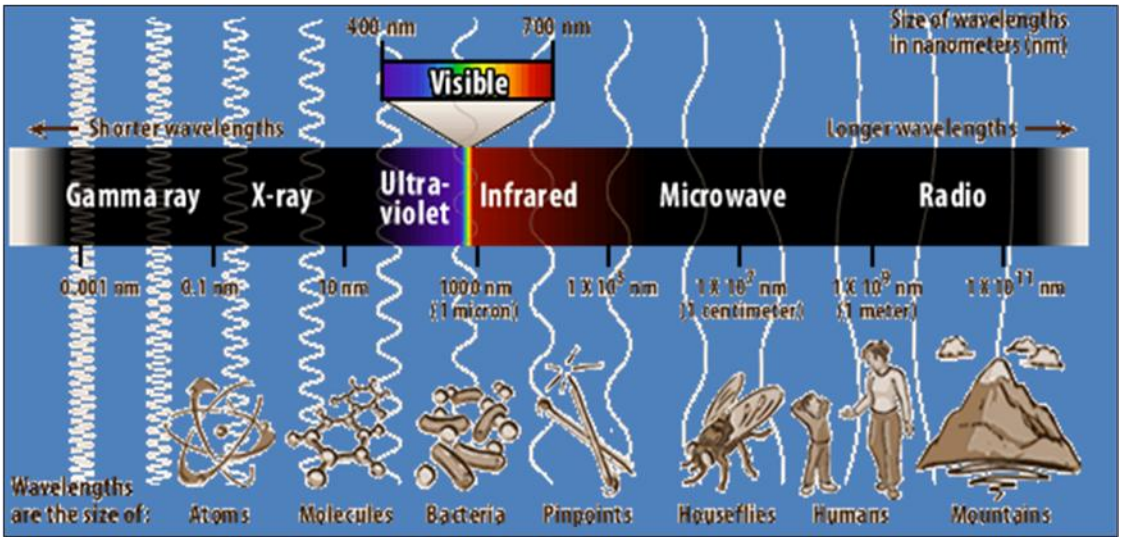
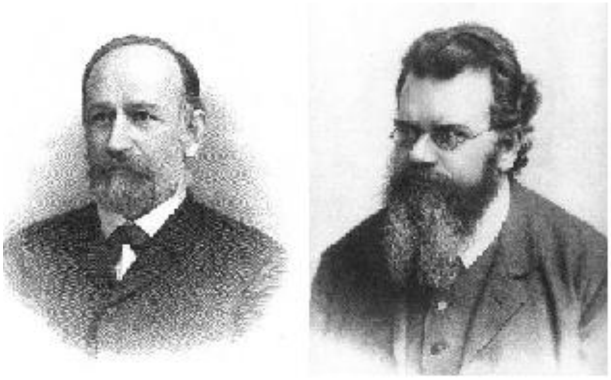


Fig.3.Wavelength spectrum

4.1.Stefan-Boltzmann law



Stefan - Boltzmann

Emissive power of a black body is proportional to fourth power of absolute temperature.

The maximum rate of radiation which can be emitted from a surface at an absolute temperature (Ts) is given by the **Stefan-Boltzmann law** as:

$E_b = \sigma T^4$

Where E_b = emissive power;

T = absolute temperature;

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

Emissive power

It is the energy emitted by the surface per unit time per unit area

When incident radiation falls on a surface, part of the energy is absorbed, part of the energy is reflected, part of the energy is transmitted.Another important radiation property of a surface is its **absorptivity** (α), which is the fraction of the radiation energy incident on a surface which is absorbed by the surface. Like emissivity, its value is in the range $0 \leq \alpha \leq 1$. A blackbody absorbs the entire radiation incident on it. That is, a black is a perfect absorber (α = 1) as well as a perfect emitter. In practice, α and ε are assumed to independent from temperature and wavelength of the radiation. The average absorptivity of a surface is taken to be equal to its average emissivity. The rate at which a surface absorbs radiation is determined from: $q_{abs} = \alpha \cdot q_{inc}$ Where q_{inc} is the rate at which radiation is incident on the surface .α = 0 for non absorbing surface; α = 1 for perfect absorber(black body)

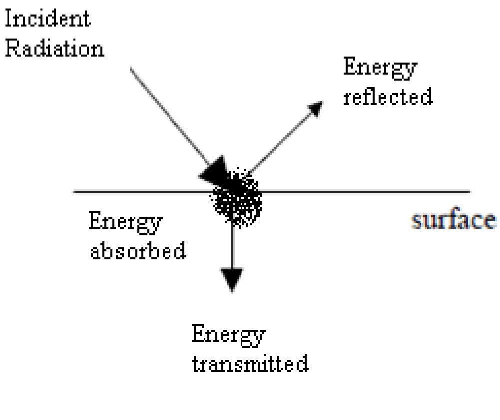


Fig.4. Incident radiation on a surface

Reflectivity (ρ), which is the fraction of the radiation energy incident on a surface which is reflected by the surface. Reflectivity and emissivity are properties of a surface that affect radiation heat transfer and how a reflective product will perform. P = 0 for non reflecting surface, ρ = 1 for perfect reflector

Transmissivity (τ), which is the fraction of the radiation energy incident on a surface which is transmitted by the surface. τ = 0 for opaque surface, τ = 1 for perfect transparent surface

Surfaces with high emissivity are also very absorptive, that is, they will readily absorb radiation striking them. These properties may vary depending on the wavelength of radiation falling on the surface. For example, the surface may reflect much of the visible radiation (i.e., light) falling on it, but not much of the ultraviolet (UV) radiation or infrared radiation falling on it

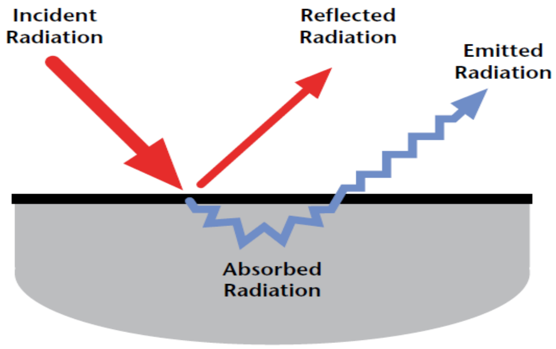


Fig.5. Incident radiation on an opaque surface

The difference between the rates of radiation emitted by the surface and the radiation absorbed is the net radiation heat transfer. If the rate of radiation absorption is greater than the rate of radiation emission, the surface is said to be gaining energy by radiation. Otherwise, the surface is said to be losing energy by radiation.

Net radiant heat transfer between two surfaces is based on the relative temperatures, the emissivity, and the view factor (portion of the surface that is on a line of sight between the surfaces) .when the surface is completely surrounded by another surface then the view factor is 1 and the net transfer equation is : $Q = \varepsilon \alpha A(T_1^4 - T_2^4)$

4.2. Blackbody

It is an ideal body that absorbs all incident energy and reflects or transmits none. It is an idealization with which the radiation characteristics of real bodies can be compared. It's a perfect absorber of incident radiation. A blackbody absorbs *all* incident radiation, regardless of wavelength and direction. A blackbody emits radiation energy uniformly in all directions per unit area normal to direction of emission. An idealized surface, which emits radiation at a maximum rate has $\varepsilon = 1$, is known as a blackbody.

Emissivity:

Emissivity of a surface is the ratio of the radiation emitted by the surface at a given temperature to the radiation emitted by a blackbody at the same temperature. The radiation emitted by actual surfaces is less than that emitted by the blackbody. The value of ε is in the range $0 \leq \varepsilon \leq 1$, is a measure of how closely a surface approximates a blackbody. The emissivity of real surfaces varies with the temperature of the surface, the wavelength, and the direction of the emitted radiation.

Surfaces with high emissivity are also very absorptive, that is, they will readily absorb radiation striking them. These properties may vary depending on the wavelength of radiation falling on the surface. For example, the surface may reflect much of the visible radiation (i.e., light) falling on it, but not much of the ultraviolet (UV) radiation or infrared radiation falling on it

Monochromatic emissivity:

It is the ratio of the monochromatic emissive power of the surface to the monochromatic emissive power of the blackbody at the same temperature and wavelength.

4.3. Gray body:

The monochromatic emissivity of the body is independent of wavelength. If the monochromatic emissivity is the same for all wavelength, it is called gray body.

4.4. Laws of Black body:

Planck's distribution law:

The spectral distribution of the radiation intensity of a black body is given by the equation

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

Where,

$I_{b\lambda}$ = radiation intensity

$C_1 = 0.595 \times 10^{-8}$ W/m^2; $C_2 = 1.4387 \times 10^{-2}$ mK

Wien's displacement law

For a black body emissive spectrum the wavelength λ_{max} giving the maximum emissive power at a particular temperature is inversely proportional to the absolute temperature

$\lambda_{max} = C / T$

where, λ_{max} = maximum wavelength; C = law constant, 0.289×10^{-2} mK; T = absolute temperature

Another form of law is given by the equation

$E_{b\,\lambda max} = C\,T^5$

Where C = law constant, 1.307×10^{-5} W/m^{2}K^5

Kirchhoff's Law

Consider a small body of surface area *As*, emissivity ε, and absorptivity α at temperature *T* contained in a large isothermal enclosure at the same temperature

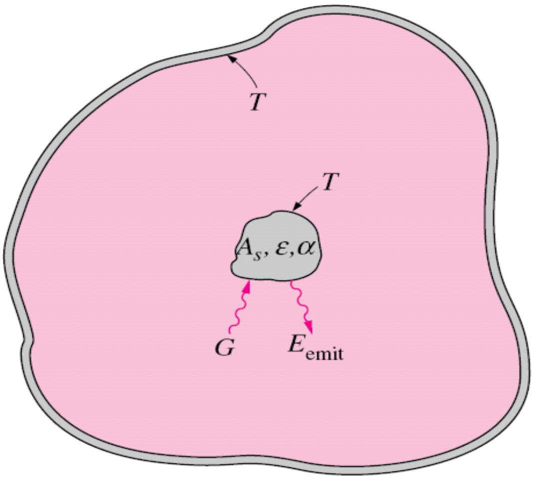


Fig.6. Small object placed in a large enclosure

A large isothermal enclosure forms a blackbody cavity regardless of the radiative properties of the enclosure surface. The body in the enclosure is too small to interfere with the blackbody nature of the cavity. Therefore, the radiation incident on any part of the surface of the small body is equal to the radiation emitted by a blackbody at temperature *T.*

$G = E_b(T) = \sigma T^4$.

The radiation absorbed by the small body per unit of its surface area is

$G_{abs} = \alpha G = \alpha\sigma T^4$

The radiation emitted by the small body is

$E_{emit} = \varepsilon\sigma T^4$

Considering that the small body is in thermal equilibrium with the enclosure, the net rate of heat transfer to the body must be zero.

$A_s \varepsilon\sigma T^4 = A_s \alpha\sigma T^4$

Thus, we conclude that

$\varepsilon(T) = \alpha(T)$

At thermal equilibrium the ratio of the total emissive power to its absorptivity is the same for all bodies. At the thermal equilibrium absorptivity and emissivity are equal.

4.5. The View Factor (also Configuration or Shape Factor)

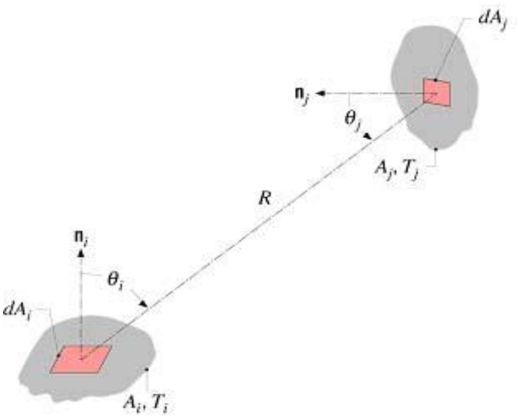


Fig.7. View Factor

The view factor, is a geometrical quantity corresponding to the fraction of the radiation leaving surface *i* that is intercepted by surface *j*.

$$F_{ij} = \frac{q_{i \to j}}{A_i J_i}$$

The view factor integral provides a general expression for F_{ij}. Consider exchange between differential areas dA_i and dA_j

$$dq_{i\to j} = I_i \cos\theta_i dA_i d\omega_{j-i} = J_i \frac{\cos\theta_i \cos\theta_j}{\pi R^2} dA_i dA_j$$

$$F_{ij} = \frac{1}{A_i} \int_{A_i} \int_{A_j} \frac{\cos\theta_i \cos\theta_j}{\pi R^2} dA_i dA_j$$

Reciprocity Relation

$$F_{ji} = \frac{1}{A_j} \int_{A_i} \int_{A_j} \frac{\cos\theta_i \cos\theta_j}{\pi R^2} dA_i dA_j$$

$$A_i F_{ij} = A_j F_{ji}$$

Summation Rule for Enclosures

$$\sum_{j=1}^{N} F_{ij} = 1$$

4.6. Heat exchange between Non-Black Bodies

4.6.1. Radiation Exchange between small gray bodies:

Consider two gray bodies 1 and 2 having emissivities ε_1 , ε_2 or absorptivities α_1, α_2. They are said to be small if their size is very small compared to the distance between them. The radiation emitted by 1 is partly absorbed by 2. The portion of radiation unabsorbed and thus reflected on the first incidence is considered to be lost in space, that is, nothing returns again to surface 1. The same can be said of surface 2 as well.

The energy emitted by body 1 = $A_1\varepsilon_1\sigma T_1^4$

The energy incident on body 2 = $F_{12}A_{12}\varepsilon_1\sigma T_1^4$

The energy absorbed by body 2 = $\alpha_2 F_{12}A_1\varepsilon_1\sigma T_1^4$

The energy transfer from 1 to 2 is

$Q_1 = \varepsilon_1\varepsilon_2 A_1 F_{12}\, \sigma T_1^4$

Similarly energy transfer from 2 to 1 is

$Q_2 = \varepsilon_1\varepsilon_2 A_2 F_{21}\, \sigma T_2^4$

Net radiant heat exchange between the two bodies is

$Q_{12} = \varepsilon_1\varepsilon_2 AF\, \sigma(T_1^4 - T_2^4)$

Where $AF = A_1F_{12} = A_2F_{21}$

4.6.2. Radiation exchange between large parallel gray planes

Consider two very large parallel gray surfaces A1 and A2,a small distance apart, and exchanging radiation. All the radiation emitted by one plane must reach and be intercepted by the other plane.

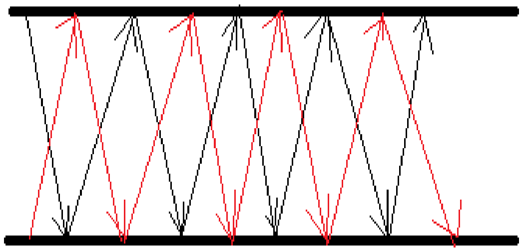


Fig.8. Heat exchange between two large parallel planes by radiation

Radiation emitted by $A_1 = \varepsilon_1\sigma T_1^4$

Radiation absorbed by $A_2 = \alpha_2\varepsilon_1\sigma T_1^4$

(on first incidence)

Radiation reflected by $A_2 = \rho_2\varepsilon_1\sigma T_1^4$

Radiation absorbed by $A_1 = \alpha_1\rho_2\varepsilon_1\sigma T_1^4 = \rho_2\varepsilon_1^2\sigma T_1^4$

Radiation reflected by $A_1 = \rho_1\rho_2\varepsilon_1\sigma T_1^4$

Radiation absorbed by $A_2 = \alpha_2\rho_1\rho_2\varepsilon_1\sigma T_1^4 = \rho_1\rho_2\varepsilon_1\varepsilon_2\sigma T_1^4$

The same applies to surface 2.The net exchange of energy for an area A is

$$Q_{12} = \frac{\varepsilon_1\varepsilon_2}{1-\rho_1\rho_2} A\sigma(T_1^4 - T_2^4) = \frac{1}{\left(\frac{1}{\varepsilon_1}\right)+\left(\frac{1}{\varepsilon_2}\right)-1} A\sigma(T_1^4 - T_2^4)$$

4.6.3. Radiation Exchange between large gray concentric cylinders or spheres

$$Q_{12} = \frac{1}{\left(\frac{1}{\varepsilon_1}\right)+\frac{A_1}{A_2}\left(\frac{1}{\varepsilon_2}-1\right)} A_1\sigma(T_1^4 - T_2^4)$$

4.6.4. Radiation Exchange between a small gray body in a large gray enclosure

When a small gray body is placed in a large gray enclosure acts like a black body. The gray surroundings are effectively black because only a negligible amount of energy is reradiated to the small gray body. Thus if the small body 1 emits a radiation of $\varepsilon_1 A_1\sigma T_1^4$, all of it will be absorbed by the enclosure. The enclosure emits

$\varepsilon_2 A_2 \sigma T_2^4$,of which $F_{21}\varepsilon_2 A_2 \sigma T_2^4$ will be incident on 1, of which $\varepsilon_1\varepsilon_2 F_{21} A_2 \sigma T_2^4$ will be absorbed by 1. The net exchange of energy is

$Q_{12} = \varepsilon_1 A_1 \sigma T_1^4 - \varepsilon_1\varepsilon_2 A_{21} \sigma T_2^4$

$Q_{12} = A_1 \varepsilon_1 \sigma (T_1^4 - T_2^4)$

4.7. Radiation shields

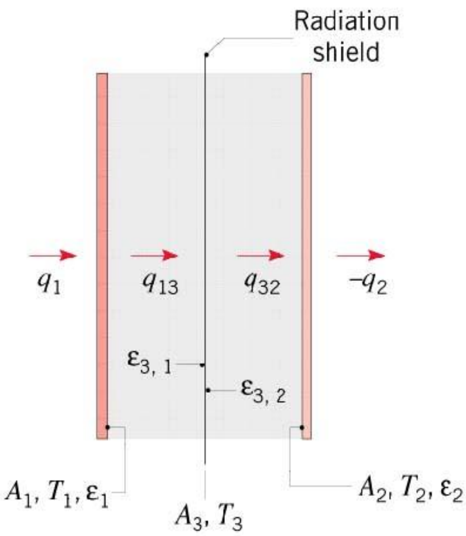
Radiation shields are often used to reduce the heat transfer by radiation between surfaces by effectively increasing the surface resistance without actually removing the heat from the overall system. A very effective insulation can be provided by using many layers of radiation reflecting films separated by a vacuum. Thin sheets of plastic coated with highly reflecting metallic films on both sides serve as very effective radiation shields. A familiar application of radiation shields is in the measurement of the temperature of a fluid by a thermometer or a thermocouple which is shielded to minimize the radiation effects.

Consider use of a single shield in a two-surface enclosure, such as that associated with large parallel plates:

$$Q_{13} = \frac{1}{\left(\frac{1}{\varepsilon_1}\right) + \left(\frac{1}{\varepsilon_3}\right) - 1} A\sigma(T_1^4 - T_3^4)$$

$$Q_{32} = \frac{1}{\left(\frac{1}{\varepsilon 3}\right) + \left(\frac{1}{\varepsilon_2}\right) - 1} A\sigma(T_3^4 - T_2^4)$$

$$Q_{12} = \frac{1}{\left(\frac{1}{\varepsilon 1}\right) + \left(\frac{1}{\varepsilon_2}\right) + 2\left(\frac{1}{\varepsilon 3}\right) - 2} A\sigma(T_1^4 - T_2^4)$$



This equation can be generalized for a system of two parallel plates separated by n screens of emissivity as

$$Q_{12} = \frac{1}{\left(\frac{1}{\varepsilon 1}\right) + \left(\frac{1}{\varepsilon_2}\right) + 2\sum_{i=1}^{n}\left(\frac{1}{\varepsilon si}\right) - (n+1)} A\sigma(T_1^4 - T_2^4)$$

Problems

P.No:1. It is observed that the intensity of the radiation emitted by the sun is max at a wave length of 0.5μ. Assuming the sun to be a black body, estimate its surface temp and emissive power.

Solution:

λ_{max} =0.5 μ

Wien's Displacement law

λ_{max} = C/T; C = 0.289 x 10^{-2} mK

T = 5780K

$E_b = \sigma T^4$

= 63284071 W/m^2

P.No: 2. Determine the radiation heat exchange /unit area between two parallel infinite walls, whose temperatures are 400^{o}C to 100^{o}C. When (i) both the black bodies (ii) both the walls are gray with emmisivity 0.8 and 0.5 respectively, σ=4.92×10^{-8} kcal/hr ^{2} K^4.

Solution:

ε_1= 0.8; ε_2 = 0.5

T_1 = 400ºC = 673K ; T_2 = 100ºC = 373K

Black body

$E_b = Q/A = \sigma(T_1^4 - T_2^4)$

= 9140.8kcal/h m^2

Gray body

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

= 4062.6 kcal/h m^2

P.No:3. The temperature of two parallel plates are at 327^{o}C and 127^{o}C. The plates are having the same emmisivity of 0.8. What will be the heat transfer between the plates? If a screen of emissivity of 0.1 on both surfaces is placed between them, what will be the reduction in heat transfer? σ=5.67×10^{-8} W/m^2K^4.

Solution:

$\varepsilon_1 = \varepsilon_2$ = 0.8; εs=0.1

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

T_1 = 327ºC = 600K ; T_2 = 127ºC = 400K

Before placing the shield:

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

= 3931.2W/m^2

After placing the shield

$$Q/A = \frac{1}{\left(\frac{1}{\varepsilon 1}\right) + \left(\frac{1}{\varepsilon_2}\right) + 2\left(\frac{1}{\varepsilon_s}\right) - 2} \sigma(T_1^4 - T_2^4)$$

= 287.65W/m^2

Assignment

1. A black body is maintained at 1000^oC. Determine the total emissive power.
2. Assuming the sun to be a black body at a temperature of $5700°C$, calculate (i) the emissive power of the surface of the sun (ii) wavelength for maximum spectral intensity. (iii) the total amount of radiant energy emitted by the sun per unit time if its diameter can be assumed to be 1.391×10^9 m.
3. A gray surface is maintained at a temperature of $827°C$. If the maximum spectral emissive power at that temperature is $1.37 \times 10^{10} W/m^2$, determine the emissivity of the surface and the wavelength corresponding to the maximum spectral intensity of radiation. Wien's displacement law constants are $1.307 \times 10^{-5}\ W/m^2K^5$, 0.289×10^{-2} mK.
4. Two large flat plates with emissivity 0.3 and 0.5 are at temperatures 800^oC and 300^oC respectively. A radiation shield (ε=0.05) is placed in between the two plates . Calculate the heat transfer rate before and after placing the shield.
5. Two circular discs of dia 20 cm each are placed 2m apart. Calculate the radiant heat exchanger for these plates if these are maintained at 800^oC and 300^oC respectively and their corresponding emissivities are 0.3 and 0.5.
6. A pipe carrying steam having an outside diameter of 20 cm runs in a large room and is exposed to air at a temperature of $30°C$. The pipe surface temperature is $200°C$. (i) Calculate the loss of heat to surroundings per metre length of pipe due to thermal radiation. The emissivity of the pipe surface is 0.8. (ii) What would be the loss of heat due to radiation if the pipe is enclosed in a 40cm diameter brick conduit of emissivity 0.9
7. The outlet header of high pressure steam super heater consist of a pipe (ε=0.8) of dia 27.5 cm. Its surface temperature is 500^oC.Calculate the loss of heat per unit length by radiation if it is placed in an enclosure at 30^oC. If the header is now enveloped in a steel screen of dia 32.5cm and ε=0.7 and the temp of the screen is 240^oC, find the reduction in heat by radiation due to the provision of screen.
8. A steam main (ε=0.79) having an O.D. of 80mm runs in a large room in which the air temp is 27^oC.The surface temp of the steam main is 300^oC. Calculate the loss of heat surroundings per meter length of pipe due to radiation.

Calculate also the reduction in heat loss if the above pipe is enclosed in brick conduit of diameter 100mm at 27^oC (ε=0.93).

9. A double walled spherical vessel used for storing liquid oxygen consists of an inner sphere of 30cm dia and outer sphere of 36cm dia. Both the surfaces are covered with a paint of emissivity 0.5. The temperature of liquid oxygen stored is -183°C whereas the temperature of the outer sphere is 20°C. Calculate the radiation heat transfer through the walls into the vessel and the rate of evaporation of liquid oxygen if its latent heat of vaporization is 213.54 kJ/kg

10. Two very large parallel-planes with emissivity 0.3 and 0.8 exchange heat by radiation. Find the % reduction in heat transfer when a polished aluminium radiation shield of ε=0.04 is placed between them.

11. A chamber for heat curing large aluminium sheets, lacquered black on both sides, operates by passing the sheets vertically between two steel plates 150mm apart. One of the plate is at 300^oC and the other exposed to the atmosphere is at 300^oC ,(A) what is the temp of the lacquered sheet ? (B) what is the heat transferred between the walls when equilibrium has been reached ? Neglect convection effects. ε_{steel} is 0.56 $\varepsilon_{lacquered}$ sheet is 1.0.

12. Two parallel gray planes which are very large have emissivities of ε_1 = 0.8 and ε_2 = 0.7 and surface one is at 867K and surface 2 is at 589K. Calculate the radiant heat exchange between the two planes.

13. Two very large parallel planes each have an emissivity of 0.7. Surface 1 is at 867K and surface 2 is at 589K.Calculate the rate of heat transfer by radiation between the planes. To reduce this loss, radiation shields having an emissivity of 0.7 are placed between the original surfaces. Calculate the reduction in rate of heat transfer.

14. A boiler furnace lagged with plate steel is lined with fireclay bricks on the inside. The temperature f the outer side of the brick setting is 127°C and the temperature of the inside of the steel plate is 50°C. Assuming the gap between plate steel and fireclay bricks to be small compared with the size of the furnace, calculate the loss of heat per unit area by radiation between lagging and setting. ε for steel = 0.6, ε for fireclay = 0.8
