Lecture Eight

Thermal Radiation (Basic Relations)

1- Definitions & Properties of Radiation.

a- Radiation heat transfer:-

Is defined as the transfer of energy across a system boundary by means of an electromagnetic waves mechanism which is caused solely by a temperature difference.

b- Electromagnetic waves:-

They represent the energy emitted by matter as a result of the changes in the electronic configurations of the atoms or molecules. Electromagnetic waves transport energy just like other waves, and all electromagnetic waves travel at the speed of light in a vacuum, which is $c_0 = 2.9979 * 10^8$ m/s, and they are characterized by their *frequency (f)* or *wavelength (λ)* . The commonly used unit of wavelength is the *micrometer* (μm) or micron, where ($1\ \mu m = 10^{-6}$ m). The *frequency* (the number of oscillations per second) of an electromagnetic wave

$$c = \lambda \times f$$

The *emission of thermal radiation* (range lies between wavelength of 10^{-7} m and 10^{-4} m) *depends upon the nature, temperature and state of the emitting surface*; however, *with gases the dependence is also upon the thickness of the emitting layer and the gas pressure.*

The rate of emission of radiation by a body depends upon the following factors:

(*i*) The temperature of the surface,

(*ii*) The nature of the surface, and

(*iii*) The wavelength or frequency of radiation.

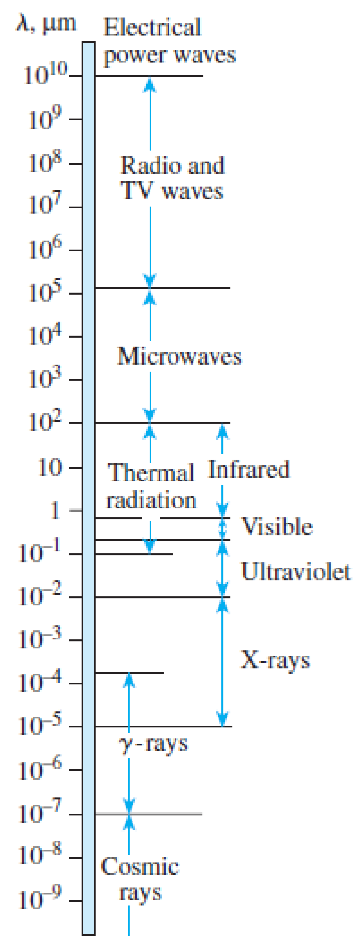


Figure (1) The electromagnetic wave spectrum.

c- **Total Emissive Power (E):-** is defined as the total amount of energy emitted by a body per unit area and time. It is expressed in (W/m^2). The emissive power of a black body, according to Stefan-Boltzmann is proportional to absolute temperature to the fourth power.

$$E_b = \sigma T^4 \text{ W/m}^2$$
$$E_b = \sigma A\, T^4 \text{ W}$$

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

d-

Monochromatic (spectral) emissive power (E_λ). It is often necessary to determine the spectral distribution of the energy radiated by a surface. At any given temperature the amount of radiation emitted per unit wavelength varies at different wavelengths. For this purpose the *monochromatic emissive power* E_λ of the surface is used. It is defined as *the rate of energy radiated per unit area of the surface per unit wavelength.*

The total emissive power is given by,

$$E = \int_0^\infty E_\lambda \, d\lambda \text{ W/m}^2$$

e-

Emission from real surface-emissivity. The emissive power from a real surface is given by

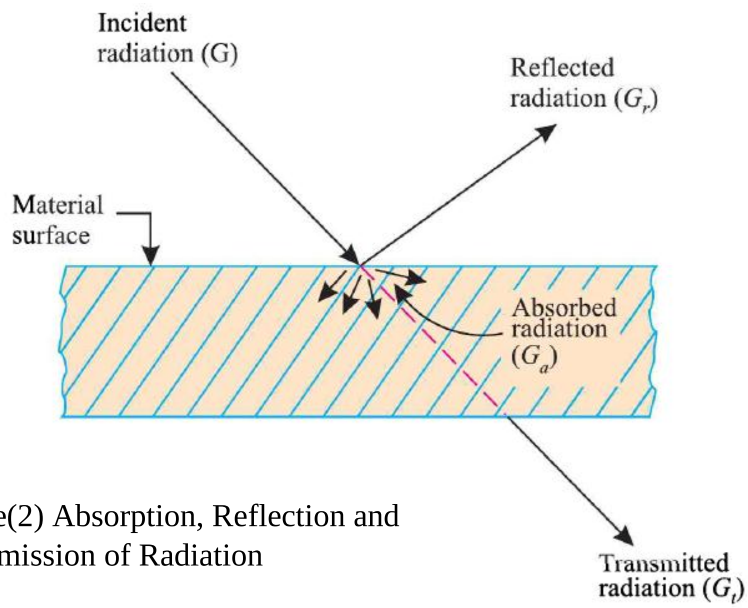
$$E = \varepsilon\, \sigma\, A T^4 \text{ W}$$

where, ε = Emissivity of the material.

f-

***Emissivity* (ε).** It is defined as the *ability of the surface of a body to radiate heat*. It is also defined as the *ratio of the emissive power of any body to the emissive power of a black body of equal temperature* (*i.e.*, $\varepsilon = \dfrac{E}{E_b}$). Its values 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.

g- **Irradiation (G) :-** is defined as the total incident radiation on a surface from all directions per unit time per unit area of surface expressed in (W/m^2), three things happens: a part is reflected back (G_r), a part is transmitted through (G_t) and the remainder is absorbed (G_a). as shown in Fig.2.



Figure(2) Absorption, Reflection and Transmission of Radiation

By the conservation of energy principle,

$$G_a + G_r + G_t = G$$

Dividing both sides by G, we get

$$\frac{G_a}{G} + \frac{G_r}{G} + \frac{G_t}{G} = \frac{G}{G}$$

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

where α = *absorptivity* (or fraction of incident radiation absorbed),
ρ = *reflectivity* (or fraction of incident radiation reflected), and
τ = *transmittivity* (or fraction of incident radiation transmitted).

When the incident radiation is absorbed, it is converted into internal energy.

h-

Black body: For perfectly absorbing body, $\alpha = 1$, $\rho = 0$, $\tau = 0$. Such a body is called a '*black body*' (i.e., a *black body is one which neither reflects nor transmits any part of the incident radiation but absorbs all of it*). In practice, a perfect black body ($\alpha = 1$) does not exist. However its concept is very important.

i- **Opaque body:** When no incident radiation is transmitted through the body, it is called an '*opaque body*'. For the opaque body $\tau = 0$, and eqn. reduces to

$$\alpha + \rho = 1 \quad ..$$

j- **White body:** If all the incident radiation falling on the body are reflected, it is called a '*white body*'.

For a white body, $\rho = 1$, $\alpha = 0$ and $\tau = 0$.

k- **Gray body:** If the radiative properties, α, ρ, τ of a body are assumed to be uniform over the entire wavelength spectrum, then such a body is called *gray body*. A *gray body* is also defined as one *whose absorptivity of a surface does not vary with temperature and wavelength of the incident radiation* [$\alpha = (\alpha)_\lambda$ = constant.].

A *coloured body* is one whose absorptivity of a surface varies with the wavelength of radiation [$\alpha \neq (\alpha)_\lambda$].

2- Kirchhoff's Law:-

Assume that a perfectly black enclosure is available, i.e., one that absorbs all the incident radiation falling upon it, as shown schematically in Figure 3. This enclosure will also emit radiation according to the T^4 law. Let the radiant flux arriving at some area in the enclosure be q_i W/m^2. Now suppose that a body is placed inside the enclosure and allowed to come into temperature equilibrium with it.

At equilibrium the energy absorbed by the body must be equal to the energy emitted; otherwise there would be an energy flow into or out of the body that would raise or lower its temperature. At equilibrium we may write

$$EA = q_i A \alpha \qquad (1)$$

If we now replace the body in the enclosure with a blackbody of the same size and shape and allow it to come to equilibrium with the enclosure *at the same temperature,*

$$E_b A = q_i A(1) \qquad (2)$$

since the absorptivity of a blackbody is unity. If Equation (1) is divided by Equation (2),

$$\frac{E}{E_b} = \alpha$$

and we find that the ratio of the emissive power of a body to the emissive power of a blackbody *at the same temperature* is equal to the absorptivity of the body. This ratio is defined as the *emissivity* of the body,

$$\epsilon = \frac{E}{E_b} \qquad (3)$$

so that

$$\epsilon = \alpha \qquad (4)$$

Equation (4) is called Kirchhoff's identity. At this point we note that the emissivities and absorptivities that have been discussed are the *total* properties of the particular material;

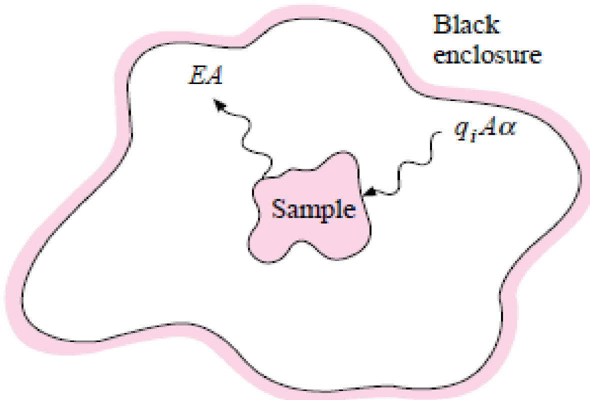


Figure 4 Sketch showing model used for deriving Kirchhoff's law.

That is, they represent the integrated behavior of the material over all wavelengths. Real substances emit less radiation than ideal black surfaces as measured by the emissivity of the material. In reality, the emissivity of a material varies with temperature and the wavelength of the radiation.

3- Planck Law.

The functional relation for $E_{b\lambda}$ was derived by Planck by introducing the quantum concept for electromagnetic energy. The derivation is now usually performed by methods of statistical thermodynamics, and $E_{b\lambda}$ is shown to be

$$E_{b\lambda} = \frac{C_1 \lambda^{-5}}{e^{C_2/\lambda T} - 1}$$

where

λ = wavelength, μm

T = temperature, K

$C_1 = 3.743 \times 10^8 \ \mathrm{W \cdot \mu m^4/m^2} \quad [1.187 \times 10^8 \ \mathrm{Btu \cdot \mu m^4/h \cdot ft^2}]$

$C_2 = 1.4387 \times 10^4 \ \mathrm{\mu m \cdot K} \quad [2.5896 \times 10^4 \ \mathrm{\mu m \cdot {}^\circ R}]$

4- Wien's displacement law.

The variation of the spectral blackbody emissive power with wavelength is plotted in Fig. (5) for selected temperatures. Several observations can be made from this figure:

1. The emitted radiation is a continuous function of *wavelength*. At any specified temperature, it increases with wavelength, reaches a 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 curves shift to the left to the shorter wavelength region. Consequently, a larger fraction of the radiation is emitted at *shorter wavelengths* at higher temperatures.

4. The radiation emitted by the *sun*, which is considered to be a blackbody at 5780 K (or roughly at 5800 K), reaches its peak in the visible region of the spectrum. Therefore, the sun is in tune with our eyes. On the other hand, surfaces at $T \leq 800$ K emit almost entirely in the infrared region and thus are not visible to the eye unless they reflect light coming from other sources.

As the temperature increases, the peak of the curve in Fig.(5) shifts toward shorter wavelengths. The wavelength at which the peak occurs for a specified temperature is given by **Wien's displacement law** as

$$(\lambda T)_{max\ power} = 2897.8\ \mu m \cdot K \quad (5)$$

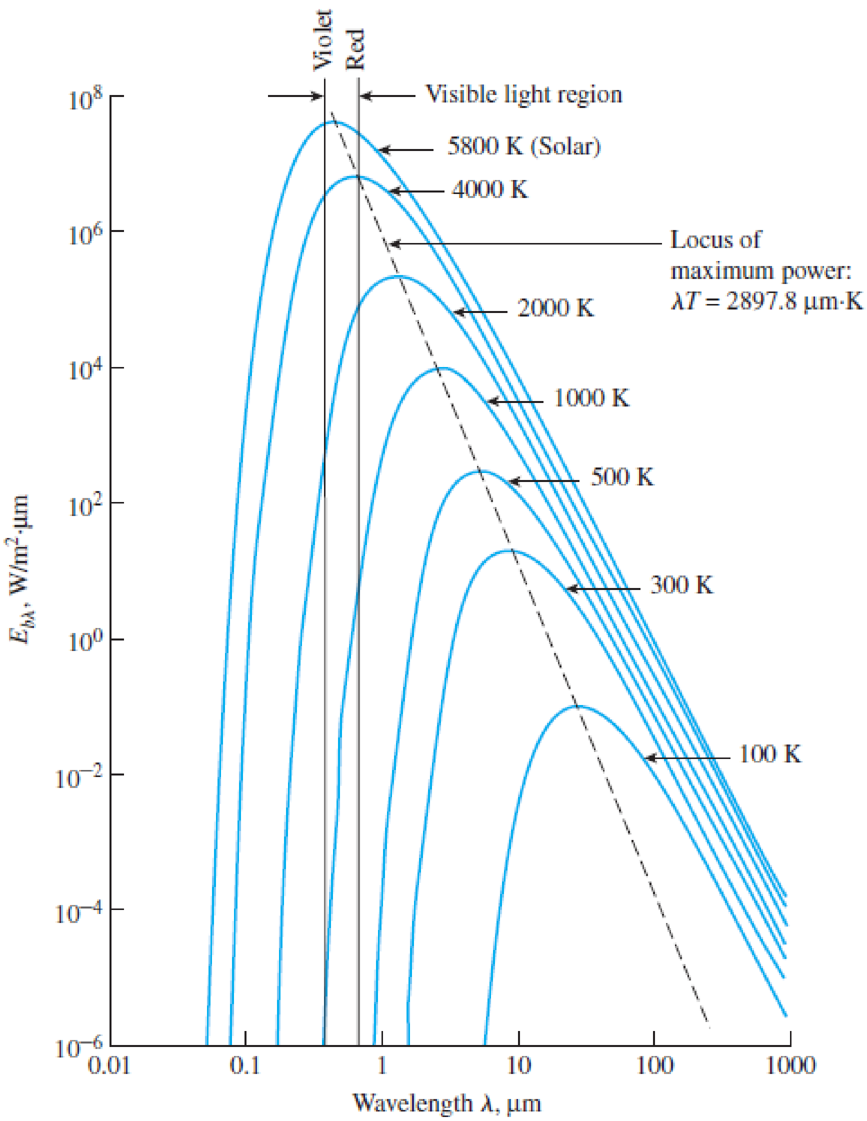


FIGURE (5) The variation of the blackbody emissive power with wavelength for several temperatures.