

Thermal Radiation – Basic Relations

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11.1. INTRODUCTION

'Radiation' heat transfer is defined as "*the transfer of energy across a system boundary by means of an electromagnetic mechanism which is caused solely by a temperature difference.*" Whereas the heat transfer by conduction and convection takes place only in the presence of medium, radiation heat transfer does not require a medium. Radiation exchange, in fact, occurs most effectively in vacuum. Further, the rate of heat transfer by conduction and convection varies as the temperature difference to the first power, whereas the radiant heat exchange between two bodies depends on the difference between their temperature to the fourth power. Both the amount of radiation and the quality of radiation depend upon temperature. The dissipation from the filament of a vacuum tube or the heat leakage through the evacuated walls of a thermos flask are some familiar examples of heat transfer by radiation.

The contribution of radiation to heat transfer is very significant at high absolute temperature levels such as those prevailing in furnaces, combustion chambers, nuclear explosions and in space applications. The solar energy incident upon the earth is also governed by the laws of radiation.

The energy which a radiating surface releases is not continuous but is in the form of successive and separate (discrete) packet or quanta of energy called photons. The photons are propagated through space as rays; the movement of swarm of photons is described as electromagnetic waves. The photons travel (with speed equal to that of light) in straight paths with unchanged frequency; when they approach the receiving surface, there occurs reconversion of wave motion into thermal energy

which is partly absorbed, reflected or transmitted through the receiving surface (the magnitude of each fraction depends, upon the nature of the surface that receives the *thermal radiation*).

All types of electromagnetic waves are classified in terms of *wavelength* and are propagated at the speed of light (c) *i.e.*, 3×10^8 m/s. The electromagnetic spectrum is shown in Fig. 11.1. The distinction between one form of radiation and another lies only in its frequency (f) and wavelength (λ) which are related by

$$c = \lambda \times f \quad \dots(11.1)$$

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.

Thermal radiations exhibit characteristics similar to those of *visible light*, and follow *optical laws*. These can be *reflected*, *refracted* and are *subject to scattering and absorption* when they pass through a media. They get *polarised* and *weakened* in strength with inverse square of radial distance from the radiating surface.

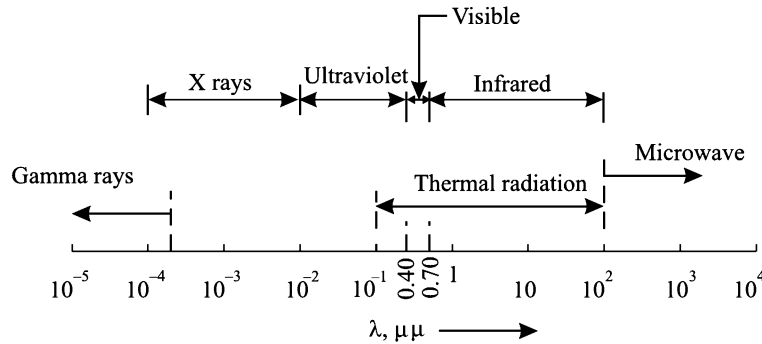


Fig. 11.1. Spectrum of electromagnetic radiation.

11.2. SURFACE EMISSION PROPERTIES

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.

The *parameters* which deal with the surface emission properties are given below :

- (i) **Total emissive power (E).** The “*emissive power*” 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 *emissive power of a black body*, according to Stefan-Boltzmann, is *proportional to absolute temperature to the fourth power*.

$$E_b = \sigma T^4 \text{ W/m}^2 \quad \dots(11.2)$$

$$E_b = \sigma A T^4 \text{ W} \quad \dots(11.2 a)$$

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

- (ii) **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,

$$E = \int_0^{\infty} E_{\lambda} d\lambda \text{ W/m}^2 \quad \dots(11.3)$$

(iii) **Emission from real surface-emissivity.** The emissive power from a real surface is given by

$$E = \epsilon \sigma AT^4 \text{ W} \quad \dots(11.4)$$

where,

ϵ = Emissivity of the material.

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., $\epsilon = \frac{E}{E_b}$)*. Its values varies for different substances ranging from 0 to 1. For a black body $\epsilon = 1$, for a white body surface $\epsilon = 0$ and for gray bodies it lies between 0 and 1. It may vary with temperature or wavelength.

(iv) **Intensity of radiation.**

(v) **Radiation density and pressure.**

(vi) **Radiosity (J).** It refers to all of the radiant energy leaving a surface.

(vii) **Interrelationship between surface emission and irradiation properties.**

11.3. ABSORPTIVITY, REFLECTIVITY AND TRANSMISSIVITY

When incident radiation (G) also called **irradiation** (defined as the *total incident radiation on a surface from all directions per unit time and per unit area of surface; expressed in W/m^2 and denoted by (G)*) impinges on a surface, three things happens; a part is *reflected back* (G_r), a part is *transmitted* through (G_t) and the remainder is *absorbed* (G_a), depending upon the characteristics of the body, as shown in Fig. 11.2.

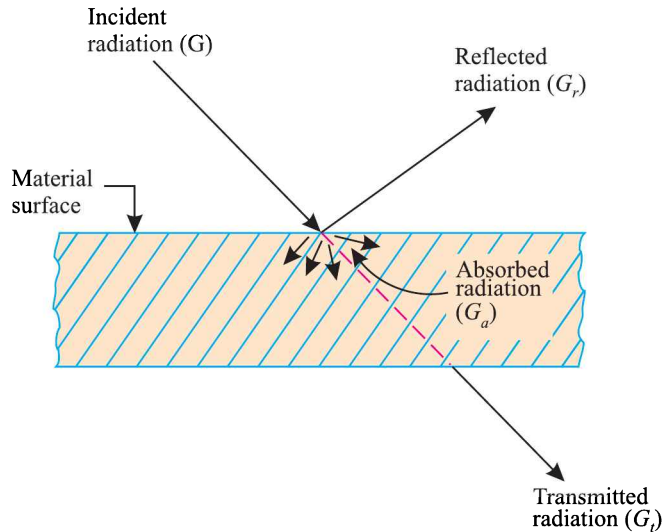


Fig. 11.2. Absorption, reflection and transmission of radiation.

By the conservation of energy principle,

$$G_a + G_r + G_t = G$$

Dividing both sides by G , we get

$$\frac{G_a}{G} + \frac{G_r}{G} + \frac{G_t}{G} = \frac{G}{G} \quad \dots(11.5)$$

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

where $\alpha = \text{absorptivity}$ (or fraction of incident radiation absorbed),
 $\rho = \text{reflectivity}$ (or fraction of incident radiation reflected), and
 $\tau = \text{transmittivity}$ (or fraction of incident radiation transmitted).

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

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.

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. (11.5) reduces to

$$\alpha + \rho = 1 \quad \dots(11.6)$$

Solids generally do not transmit unless the material is of very thin section. Metals absorb radiation within a fraction of a micrometre, and insulators within a fraction of a millimetre. Glasses and liquids are, therefore, generally considered as opaque.

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 $\tau = 0$.

Gases such as hydrogen, oxygen and nitrogen (and their mixtures such as air) have a transmissivity of practically unity.

Reflections are of two types: Refer Fig. 11.3.

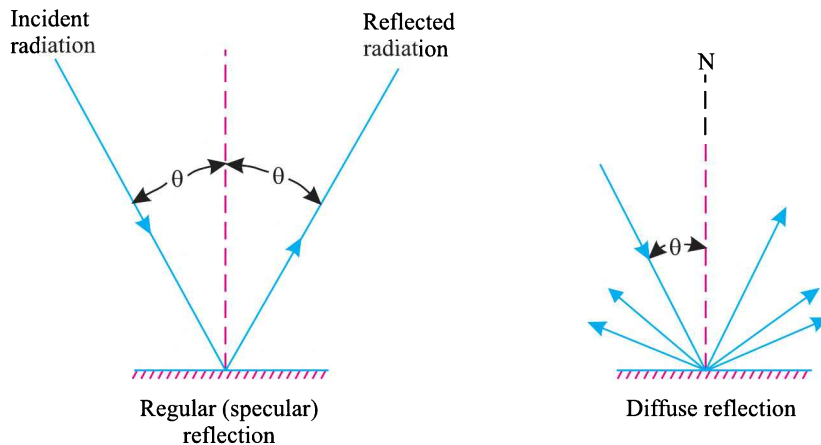
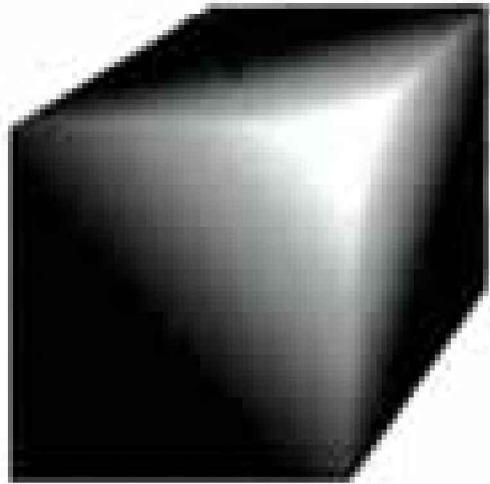


Fig. 11.3. Regular and diffuse reflections.

1. Regular (specular) reflection
2. Diffuse reflection.



A black body is theoretical perfect absorber, which absorbs radiation of all wavelength falling on it.

Regular reflection implies that angle between the reflected beam and the normal to the *surface equals* the angle made by the incident radiation with the same normal. Reflection from highly polished and smooth surfaces approaches specular characteristics.

In a *diffused reflection*, the incident beam is reflected in *all directions*. Most of the engineering materials have rough surfaces, and these rough surfaces give diffused reflections.

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 [$\alpha = (\alpha)_\lambda = \text{constant}$].

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

11.4. CONCEPT OF A BLACK BODY

A black body is an object *that absorbs all the radiant energy reaching its surface* (for a black body $\alpha = 1$, $\rho = 0$, $\tau = 0$). No actual body is perfectly black; the concept of a black body is an idealization with which the radiation characteristics of real bodies can be conveniently compared.

A *black body* has the following *properties*:

- (i) It absorbs all the incident radiation falling on it and does not transmit or reflect regardless of wavelength and direction.
- (ii) It emits maximum amount of thermal radiations at all wavelengths at any specified temperature.
- (iii) It is a *diffuse emitter* (i.e., the radiation emitted by a black body is independent of direction).

Consider a hollow enclosure with a very small hole for the passage of incident radiation as shown in Fig. 11.4. Incident radiant energy passes through the small opening; some of this energy is absorbed by the inside surface and some is reflected. However, most of this energy is absorbed on a second incidence. Again, a small fraction is reflected. After a number of such reflections the amount unabsorbed is exceedingly small and very little of the original incident energy is reflected back out of the opening. A small hole leading into a cavity (Hohlraum) thus acts very nearly as a black body because all the radiant energy entering through it gets absorbed.

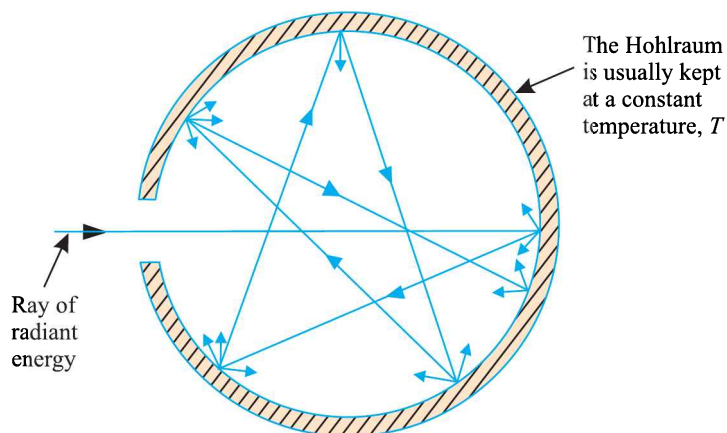


Fig. 11.4. Concept of a black body.

Isothermal furnaces, with small apertures, approximate a black body and are frequently used to *calibrate* heat flux gauges, thermometers and other radiometric devices.