PART A :

Heat transfer

Chapter 5 :

Radiation heat transfer

Introduction

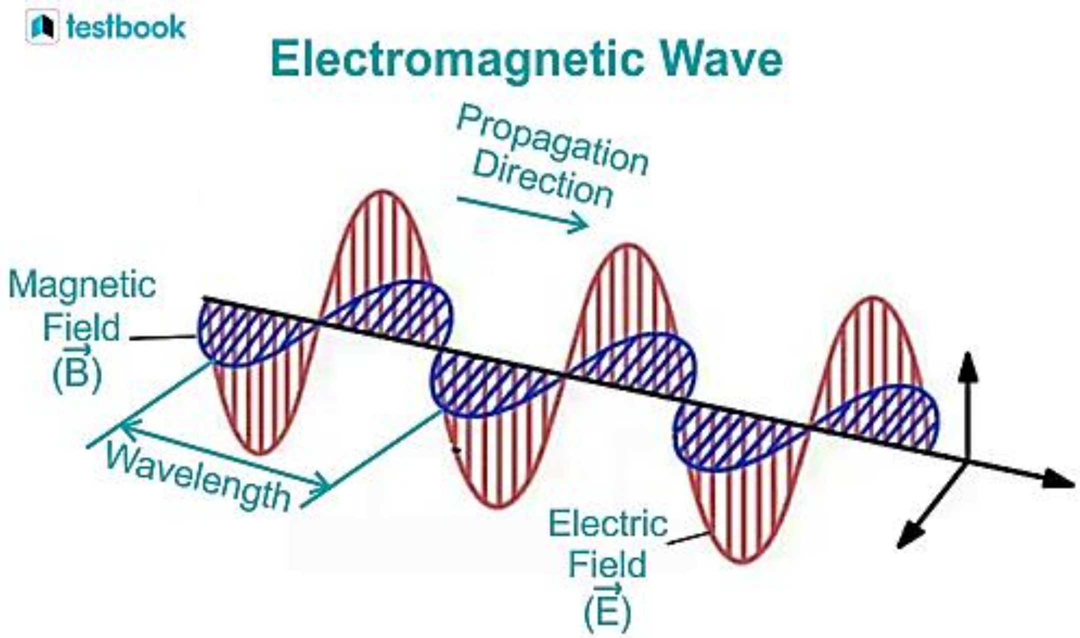
Radiation is one of the three fundamental modes of heat transfer, alongside conduction and convection. Unlike conduction and convection, which require a material medium (solid, liquid, or gas) for the transfer of heat, radiation is a form of heat transfer that occurs through electromagnetic waves.

In other words Radiation heat transfer is a process where heat waves are emitted that may be absorbed, reflected, or transmitted through a colder body. Sun heats the earth by electromagnetic waves. Hot bodies emit heat waves.

IV - 1. General information and definitions

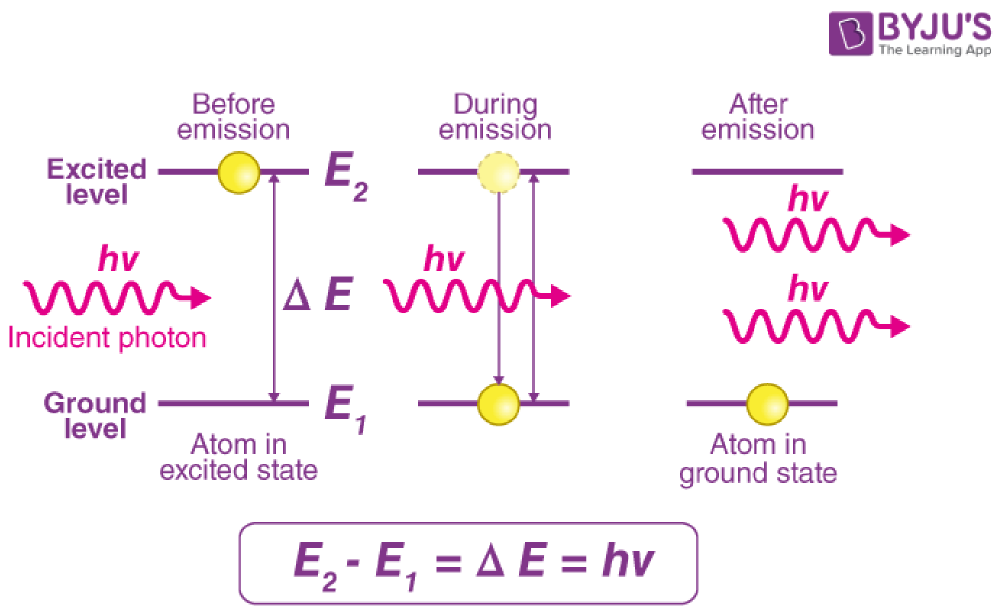
i. Electromagnetic waves:

Radiation consists of electromagnetic waves that carry energy. These waves include a range of wavelengths, from very short gamma rays to very long radio waves. In the context of thermal radiation, the relevant portion of the electromagnetic spectrum is in the infrared region.



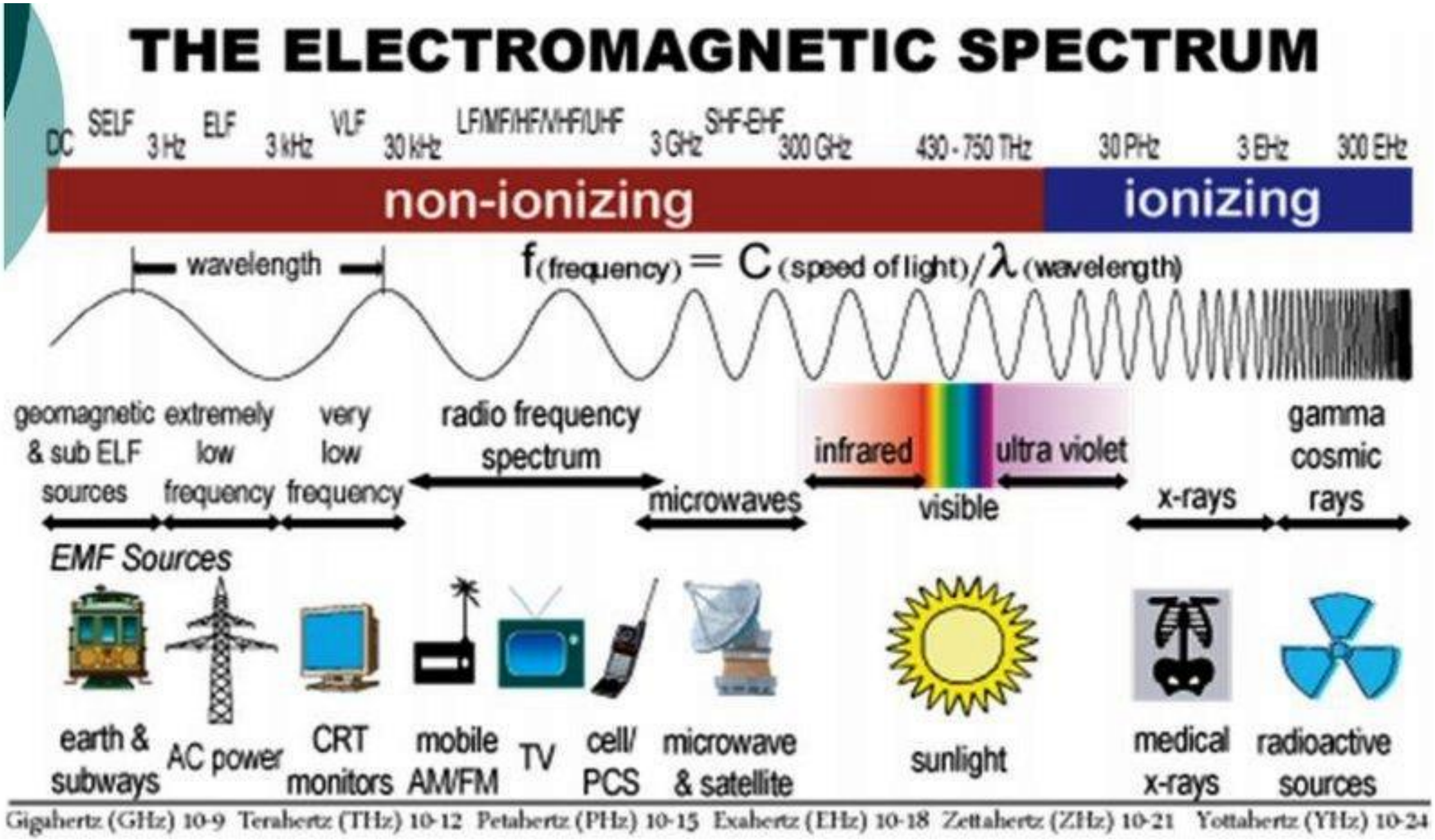
iii. Emission of Radiation

All objects with a temperature above absolute zero emit radiation. This emission occurs due to the thermal motion of atoms and molecules within the material. As these particles move, they generate electromagnetic waves.



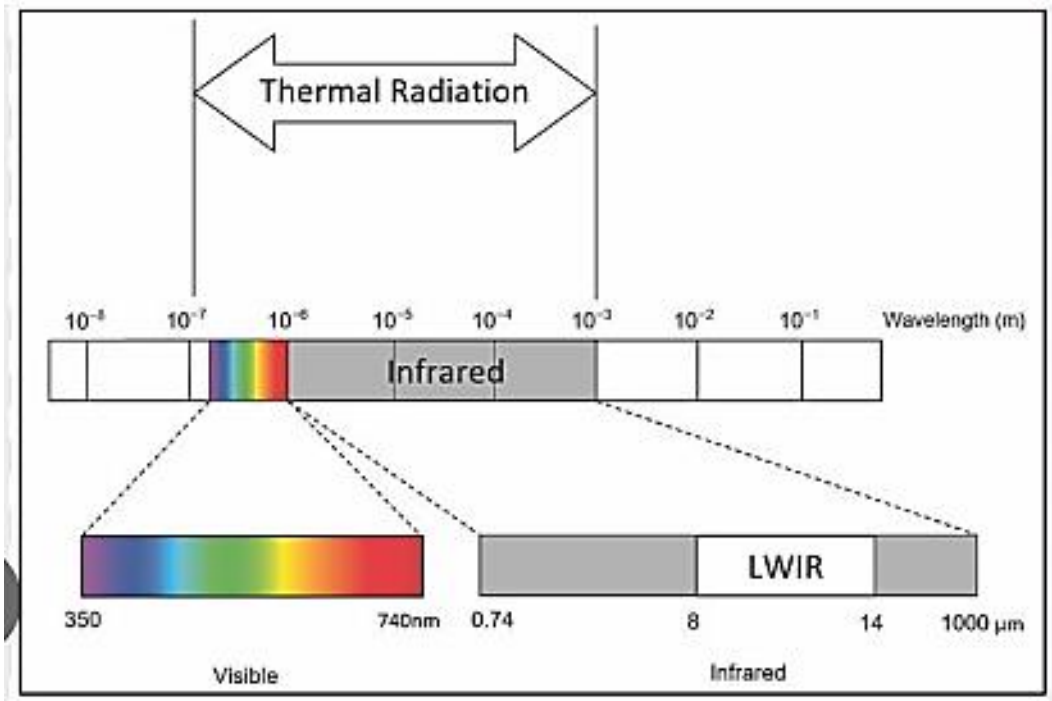
ii. Electromagnetic spectrum

The electromagnetic spectrum encompasses all types of electromagnetic radiation, including radio waves, microwaves, infrared, visible light, ultraviolet, X-rays, and gamma rays, each with distinct wavelengths and applications. It spans a continuous range from long radio waves to short gamma rays.

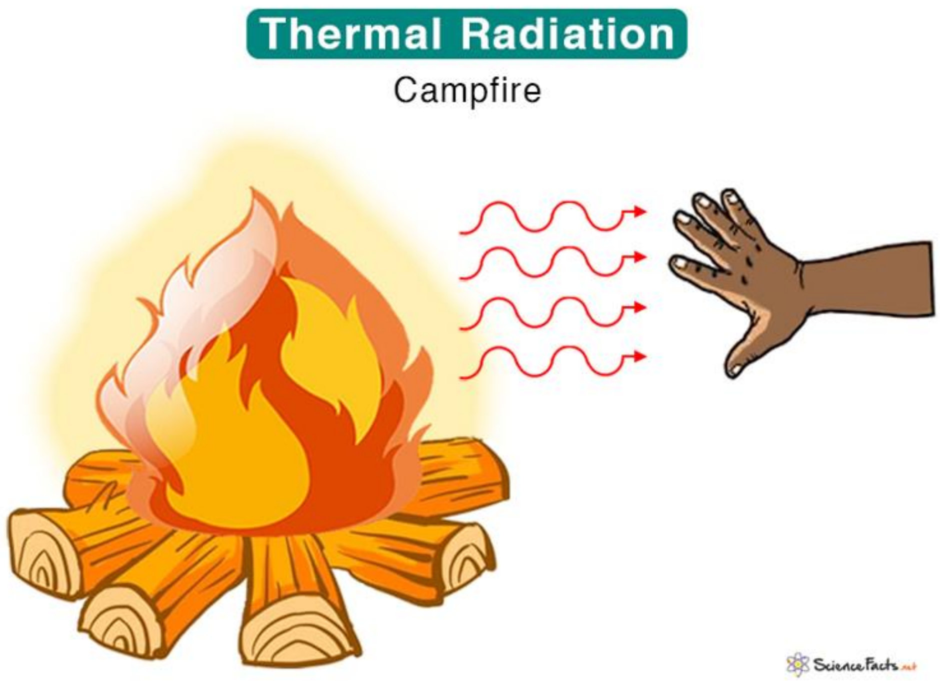

THE ELECTROMAGNETIC SPECTRUM
DC
SELF
3 Hz
ELF
3 kHz
VLF
30 kHz
LF/MF/HF/VHF/UHF
3 GHz
SHF-EHF
300 GHz
430 - 750 THz
30 PHz
3 EHz
300 EHz
non-ionizing
ionizing
wavelength
f(frequency) = C (speed of light)/λ (wavelength)
geomagnetic & sub ELF sources
extremely low frequency
very low frequency
radio frequency spectrum
microwaves
infrared
visible
ultra violet
x-rays
gamma cosmic rays
EMF Sources
earth & subways
AC power
CRT monitors
mobile AM/FM
TV
cell/ PCS
microwave & satellite
sunlight
medical x-rays
radioactive sources
Gigahertz (GHz) 10-9 Terahertz (THz) 10-12 Petahertz (PHz) 10-15 Exahertz (EHz) 10-18 Zettahertz (ZHz) 10-21 Yottahertz (YHz) 10-24

iv. Thermal radiation

Thermal radiation refers to the electromagnetic waves emitted by a material due to its temperature. This form of radiation is a key component of the radiative heat transfer process.

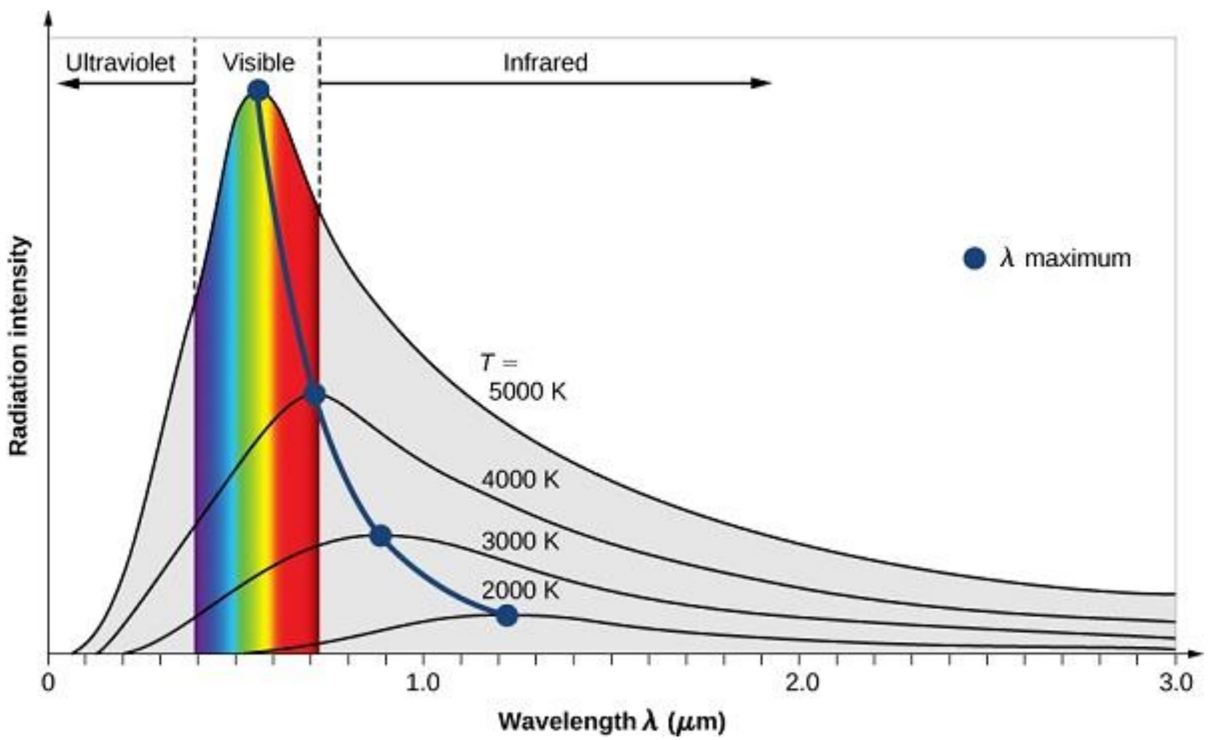


v. **Origin of Thermal Radiation** Thermal radiation is a result of the thermal motion of particles (atoms and molecules) within a material. As these particles move and vibrate due to their thermal energy, they emit electromagnetic waves.



vi. Spectral Distribution

The intensity and distribution of thermal radiation across the electromagnetic spectrum depend on the temperature of the emitting object. This relationship is described by Planck's law, which provides the spectral radiance of a blackbody.



IV - 2. Quantities for the thermal radiation range: Definitions

i. Quantities relating to emitting surfaces: what are the quatities relating to emitting surfaces?

1. Flux from a heat source

It is the thermal power radiated (emitted) by a source throughout space. It is denoted by Φ and expressed in watts (W). It is emitted at different wavelengths. Elementary monochromatic flux can be defined by :

$$\Phi_\lambda \text{ est tel que } \quad \Phi = \int_0^\infty \Phi_\lambda \, .d\lambda$$

And for a flux emitted by a source in a wavelength range

$$\Phi = \int_{\lambda_1}^{\lambda_2} \Phi_\lambda \, .d\lambda$$

2. Energy intensity (intensity of a source in one direction)

It is the flow in a given direction. It is given by :

$$I_{ox} = \frac{d\Phi_{0x}}{d\Omega} \text{ en Watt/stéradian}$$

$d\Omega$: the solid angle

And the monochromatic energy intensity, $I_{Ox,\lambda}$, can be defined as follows :

$$I_{ox} = \int_{o}^{\infty} I_{ox,\lambda}.d\lambda$$

3.Emittance of a heat source

It is the flux emitted per unit area of the source:

$$M = \frac{d\Phi}{dS} \text{ en Watt/m}^2$$

And we can define the monochromatic emittance M_λ as :

$$M = \int_0^\infty M_\lambda . d\lambda$$

4.Luminance (of a source in one direction)

The luminance L_{Ox} is the ratio of the total flux $d^2\phi_{Ox}$ emis by a surface dS′ in a solid angle dΩ. dS' is dS seen from the Ox direction which makes an angle θ.

It is given by :

$$L_{ox} = \frac{d^2\Phi_{ox}}{d\Omega\, dS \cos\theta}$$

And the monochromatic luminance $L_{Ox,\lambda}$ is given by:

$$L_{ox} = \int_{o}^{\infty} L_{ox,\lambda} . d\lambda$$

ii. Quantity relating to the reception of radiation: illuminance

The same radiating surface receives electromagnetic radiation at the same time.

The illuminance E corresponds to the total flux $d\Phi$ received by the receiving surface through surface dS and coming from all directions. It is given by :

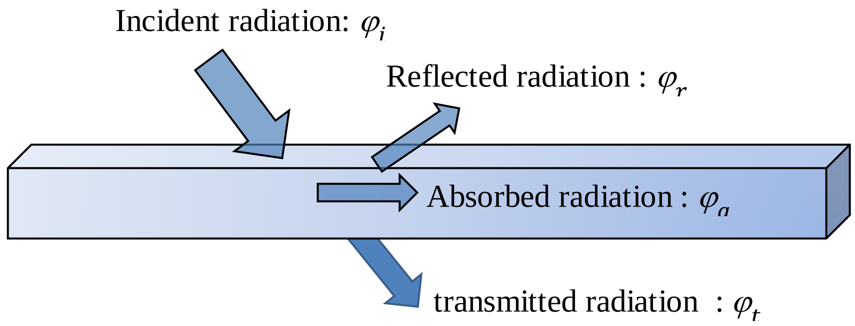
$$E = \frac{d\Phi}{dS}$$

And it is expressed in : W/m^2

iii. Total hemispherical coefficients of reflection, absorption and transmition

When radiation reaches the surface of a body, some of it is reflected, some is transmitted directly, and some is absorbed into the mass of the receiver. Only this last part corresponds to the body's energy input.

The term "total hemispherical coefficients" typically refers to coefficients associated with hemispherical radiation characteristics. These coefficients are often used in the context of radiation heat transfer.



Receiving thermal radiation on a solid

Here are a couple of related concepts:

a. The total hemispherical absorption coefficient (α)

It is defined as the ratio of the total hemispherical absorptive power of a material to the total hemispherical incident power.

Mathematically, it can be expressed as:

$$\alpha = \frac{\text{Total hemispherical absorptive power of the material}}{\text{Total hemispherical incident power}}$$

$$\boldsymbol{\alpha = \frac{\varphi_a}{\varphi_i}}$$

φ_i : Incident flux ; φ_a : Absorbed flux

It is a dimensionless quantity between 0 and 1, where:

- 0 indicates perfect transparency (no absorption),,
- 1 indicates perfect absorption (a black body)..

b. Total Hemispherical Reflectivity

This coefficient describes the fraction of incident radiation that is reflected by a surface over the entire hemisphere.

$$\rho = \frac{\text{Total hemispherical reflected power}}{\text{Total hemispherical incident power}}$$

$$\boldsymbol{\rho = \frac{\varphi_r}{\varphi_i}}$$

φ_i : Incident flux ; φ_r : reflected flux

Like emissivity, it is a dimensionless quantity between 0 and 1.

c. Total Hemispherical Transmissivity

$$\tau = \frac{\text{Total hemispherical transmitted power}}{\text{Total hemispherical incident power}}$$

$$\boldsymbol{\tau} == \frac{\boldsymbol{\varphi_t}}{\boldsymbol{\varphi_i}}$$

φ_t : Transmitted flux ; φ_i : Incident flux

The relationship between the total hemispherical absorption coefficient (α), total hemispherical reflectivity (ρ), and total hemispherical transmissivity (τ) can be expressed as:

$$\boldsymbol{\alpha+\rho+\tau=1}$$

This relationship emphasizes the conservation of energy, stating that the sum of the absorbed, reflected, and transmitted fractions of incident radiation is equal to

Understanding these coefficients is essential in the analysis of radiative heat transfer, where the exchange of thermal radiation between surfaces plays a significant role. These coefficients are fundamental in characterizing how materials interact with incident radiation.

5. Transparent, black, gray and opaque bodies (Corps transparents, noirs, gris et corps opaque)

a. Transparent Bodies:

A perfectly transparent medium is one in which the propagation of electromagnetic radiation is not accompanied by any reduction in its energy. This is the case of the absolute vacuum.

Real transparent media such as liquids (e.g. water) or solids (e.g. glass in the visible range) are also known as partially transparent media.

Behavior: Transparent materials transmit **most** of the incident light or radiation.

Example: Glass, Simple gases and clear plastic are common examples of transparent materials.

b. Black Bodies:

A blackbody is a body that absorbs all incoming radiation, whatever its thickness, temperature, angle of incidence or wavelength. It is characterized by its absorption coefficient:

$$\boldsymbol{\alpha = \frac{\varphi_a}{\varphi_i} = 1}$$

Behavior: Black bodies are perfect absorbers and emitters; they appear black because they absorb all colors of light.

Example: No real material is a perfect black body, but a cavity with a small hole (known as a cavity radiator) can approximate a black body.

This relationship can be seen as a definition of the black body. Moreover, the body is an "ideal" emitter. It radiates a maximum of energy at a given temperature for each wavelength.

Note:

- Following the definition of the body, all black bodies radiate in the same way.

c. Gray Bodies:

It is a body defined by its absorbing power, independent of the wavelength λ of the incident radiation received. It is then defined by its absorption coefficient:

$$\alpha_{\lambda T} = \alpha_T$$

Behavior: Gray bodies absorb and emit a fraction of incident radiation, and their emissivity is constant over a broad range of wavelengths.

Example: Many common materials, such as concrete or certain metals, can be considered gray bodies under certain conditions.

d. Opaque Bodies:

It's a body that doesn't let radiation pass through. It stops it at its surface.

Behavior: Opaque materials may absorb and re-emit radiation or reflect it entirely, preventing transmission.

Example: Most everyday objects, such as walls, metals, and wood, are opaque to visible light.

V-4. Formalism - Radiation laws (Formalisme - Lois du rayonnemen

a.Lambert's Law :

- **Definition of an orthotropic source:**

A light source is said to be orthotropic if its luminance is angularly uniform. It is therefore identical in all directions. This type of source is also known as a Lambertian source, because it obeys Lambert's law, which follows.

On dit qu’une source lumineuse est orthotrope si la luminance est uniforme angulairement. Elle est donc identique dans toutes les directions. Ce type de source est dit aussi source lambertienne, parcequ’elle obeit à la loi de Lambert, qui suit.

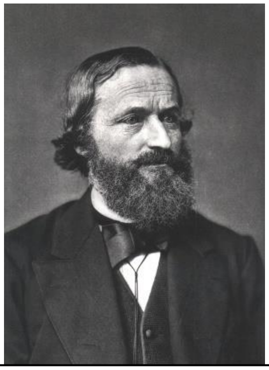
- **Lambert's Law :**

Consider an orthotropic light source. Emittance is proportional to luminance and the proportionality coefficient π is . Then :

$$M = \pi . L$$

M: emittance; L : Luminance.

b.Kirchhoff's law (relationship :Absorption-emission/1859)



Gustav Robert Kirchhoff
1824-1887

For a given wavelength, a given T and a given direction, we'll assume, without demonstration, that (Emissivity ε is the ratio of the luminance of the real body to the luminance of the black body brought to the same temperature.) and the directional monochromatic absorptivity are equal:

$$\varepsilon_{ox,\lambda} = \alpha_{ox,\lambda}$$

- For a gray body, we get: $\varepsilon_{ox,\lambda} = \varepsilon = \alpha_{ox,\lambda} = \alpha$
- For a black body, we get : $\varepsilon_{ox,\lambda} = \alpha_{ox,\lambda} = 1$

c. **Planck's law**

Max Planck

Max Planck en 1901.

This is a relationship between the monochromatic emittance of the black body at wavelength and temperature: $M^0_{\lambda m,T} = \frac{C_1.\lambda^{-5}}{\exp\left(\frac{C_2}{\lambda.T}\right)-1}$

$$C_1 = 3,741\,.\,10^{-16};\ C_2 = 1,4388\,.\,10^{-2}$$

$$M_{0_{\lambda T}} = \frac{C_1\lambda^{-5}}{exp\left(\frac{C_2}{\lambda T}\right)-1}$$

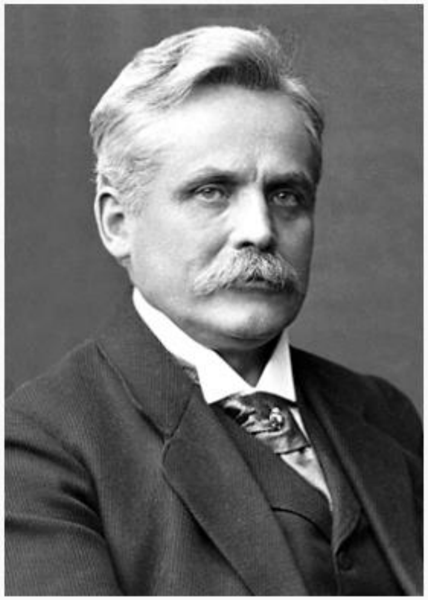
$$C_1=3,741.10^{-16} \quad C_2=1,4388.10^{-2}$$

By fixing the temperature, Planck's law can be used to draw the isotherms: $M_{0_{\lambda,T}} = f(\lambda, T = cte)$

d.Wien’s law

- **Wein's 1st law :**

Wilhelm Wien



Wilhelm Wien

Wien's law gives the relationship between the wavelength of the black body and its temperature (source temperature). This wavelength, then, corresponds to the wavelength at which emission is at its maximum.

$$\lambda_{max} = \frac{2,898 \, . \, 10^{-3}}{T}$$

- **2nd Wein's law :**

Wien's second law relates the maximum emittance of a blackbody to its temperature:

$$\boldsymbol{M_{0_{\lambda max}} = 1287\ 10^{-8}.T^{5}}$$

e. Stefan-Boltzmann's law

Stefan-Boltzmann's law gives the relationship between emissivity, temperature and emittance of a black body

$$M = \sigma \epsilon T^4$$

σ : Stefan-Boltzmann constant : 5.670×10^{-8} (W / (m^2 x K^4))