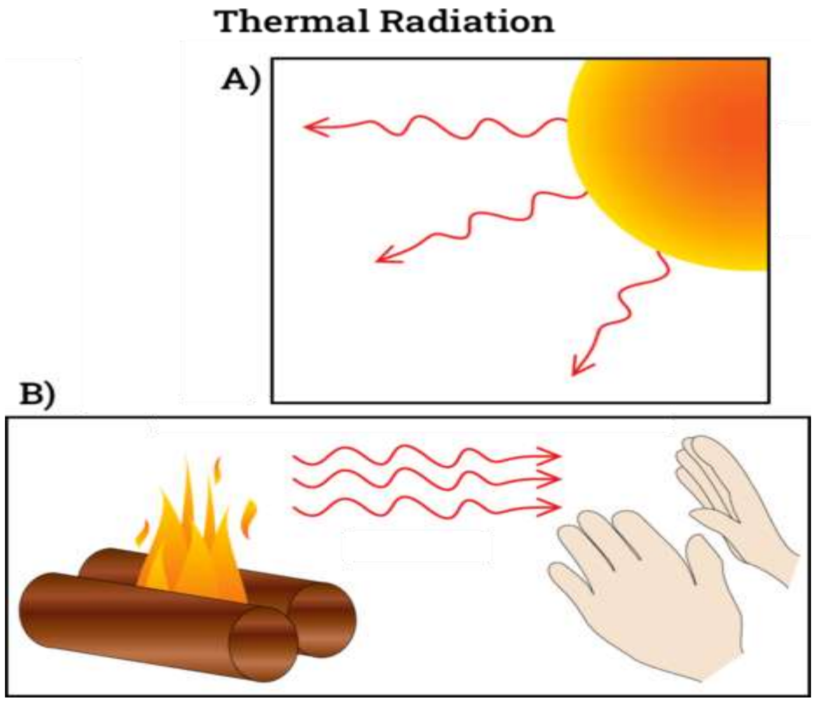
Chapter 5

Heat transfer by Radiation



Heat transfer by Radiation

5.1. Introduction

Thermal radiation is the energy emitted by matter that is at a finite temperature. It has a fundamental difference with respect to conduction and convection: substances that exchange heat do not need to be in contact, but can be separated by a vacuum. Radiation is a term applied generically to all kinds of phenomena related to electromagnetic waves.

We will focus our attention on radiation from solid surfaces, although this radiation can also come from liquids or gases. In thermal radiation, heat is transmitted by electromagnetic waves, like light, but of different wavelengths. Radiant energy depends on the characteristics of the surface and the temperature of the emitting body. By influencing a receptor, part of the energy passes to this other body, depending on its characteristics and its power of absorption. This energy results in an increase in the temperature of the second body. Heat transfer by radiation only involves the transport of energy, it does not need a material support, taking place even in a vacuum.

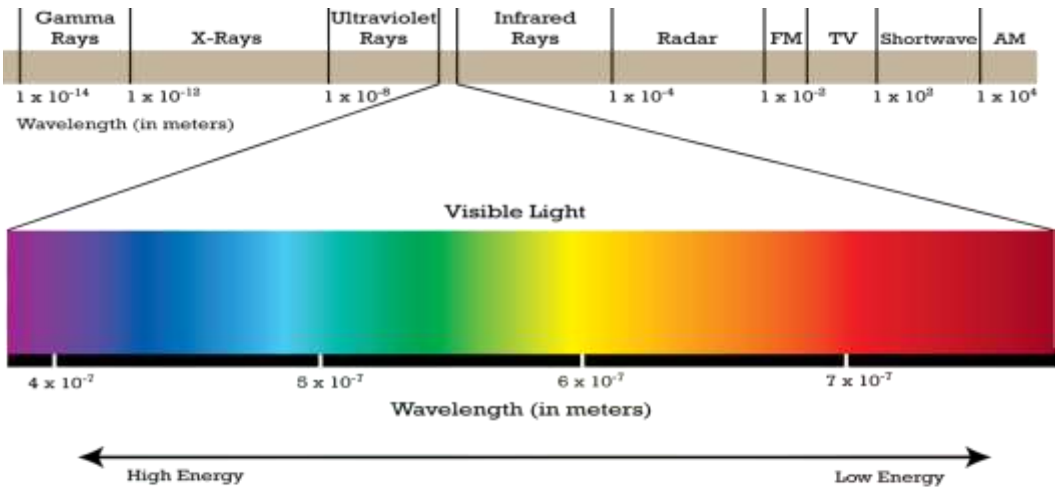


Figure 5. 1. The electromagnetic spectrum

5.2. Principle of heat transfer by radiation

It is a mode of heat (energy) exchange in the form of electromagnetic waves according to Planck's law ($E = h.\upsilon$, such that: υ is the associated wave frequency and $h = 6{,}62.10^{-34}$ J.s is Planck's constant). So it does not require any hardware support, it is analogous to the propagation of light. It propagates in a rectilinear manner at the speed of light ($c=3\times10^8$ m/s). The thermal radiation emitted by bodies is located between wavelengths of 0.1 µm to 100 µm. Practically, the three modes of heat transfer will coexist. But, this mode of transfer becomes predominant at temperatures higher than ordinary temperatures. Generally, all bodies (solid, liquid and gaseous) emit radiation of an electromagnetic nature. We can cite that, vacuum and simple gases like (O_2, H_2 and N_2) represent perfectly transparent media but, compound gases like (CO_2, H_2O, CO and CH_4) and certain liquids and solids like (glasses and polymers) are partially transparent. The majority of solids and liquids are opaque bodies since they stop the propagation of radiation just at their surfaces.

5.3. Preliminary definitions

The physical quantities will be designated according to the spectral composition or spatial distribution of the radiation:

- **Total magnitude**: it is relative to the entire spectrum;
- **Monochromatic quantity**: it only concerns a narrow spectral interval (dl), around a wavelength (l);
- **Hemispherical magnitude**: it is relative to all the directions of space;
- **Directional quantity**: it characterizes a given direction of propagation. When studying the thermal equilibrium of a system, anybody must be considered as:
- **Emitter**: if it sends radiation linked to its temperature (unless it is perfectly transparent);
- **Receiver**: If it receives, radiation emitted or reflected and diffused by the bodies that surround it.

- **Opaque body**: it is a body which does not transmit any radiation through itself, it stops the propagation of all radiation from its surface, it heats up by the absorption of the radiation;
- **Transparent body**: it is a body which transmits all the incident radiation;
- **Black body**: is the one that absorbs all the radiation it receives, it is characterized by an absorbent power ($\alpha\lambda T = 1$). All black bodies radiate in the same way the same temperature, the black body radiates more than a non-black body.
- **Gray body**: is that whose absorbent power ($\alpha\lambda T$) is independent of length wave (λ), it is characterized by ($\alpha\lambda T = \alpha T$). A gray body at high temperature for $\lambda<3\mu m$, sun), a gray body at low temperature for ($\lambda>3\mu m$, atmosphere).
- **Solid angle**: the elementary solid angle ($d\Omega$) under which the contour of a small surface (ds) is seen from a point (O) is given by:

$$\boxed{d\Omega = \frac{dS\cos\alpha}{r^2}} \qquad [sterad\ ]$$

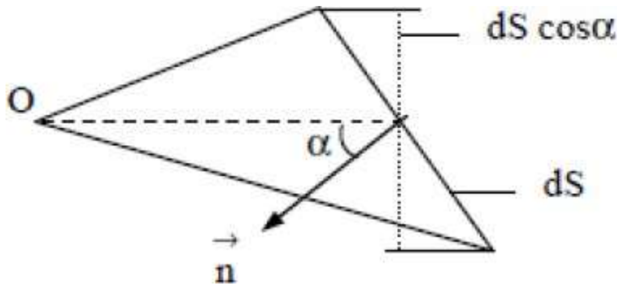


Figure 5. 2. Solid angle

Monochromatic energy emittance: the monochromatic emittance of a source at temperature (T) is given by:

$$\boxed{M_{\lambda T} = d\varphi_{\lambda}^{\lambda+d\lambda} / dS.d\lambda \qquad [W/m^2]} \tag{5.1}$$

Such as; φ: is the energy flow emitted between the two wavelengths (λ) and (λ+dλ). Total energy emittance: defined as the flux density emitted by the elementary surface (dS) over the entire wavelength spectrum:

$$M_T = \int_{\lambda=0}^{\lambda=\infty} M_{\lambda T} d\lambda = d\varphi / dS \qquad [W/m^2] \tag{5.2}$$

Energy intensity in one direction: the flux per unit of solid angle emitted by a surface (ds) under a solid angle (dΩ) surrounding the direction (Ox):

$$I_x = d^2\varphi_x / d\Omega \tag{5.3}$$

Energy luminance in one direction: the energy intensity in the direction (Ox) per unit of apparent emitting surface (the projection of the surface (S) on the plane perpendicular to Ox):

$$L_x = I_x / dS_x = I_x / dS\cos\alpha = d^2\varphi_x / d\Omega dS\cos\alpha \tag{5.4}$$

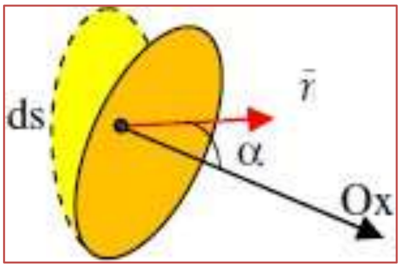


Figure 5. 3. Diagram showing the luminance of surface element ds.

Illumination (relative to a receiver): It is the flow received per unit of receiving surface, coming from all directions (Emittance).

5.4. Process of reception of radiation by a body

A heated equipment point emits electromagnetic radiation in all directions that are on the same side of the plane as the equipment point. When this radiation hits a body, some of the energy is reflected, some is transmitted through the body, and the rest is absorbed quantitatively as heat.When incident radiation of energy (φλ) strikes a body (C) at temperature (T) (see figure opposite), we

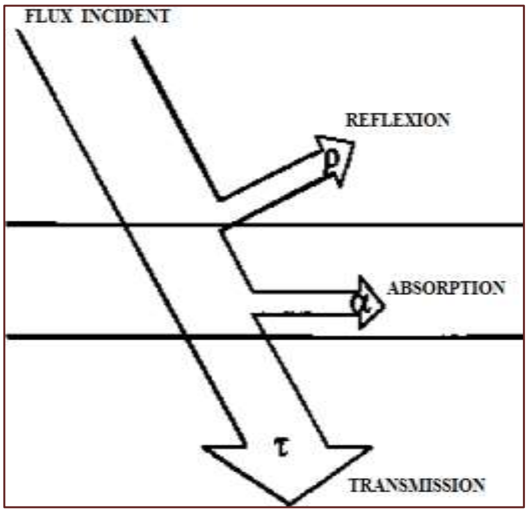


Figure 5. 4 .Process of reception of radiation by a body.

Notice that:

- Part of the energy ($\varphi\lambda\ .\rho\lambda T$) is reflected by the surface (S) of the body;
- Part of the energy ($\varphi\lambda\ .\alpha\lambda T$) is absorbed by the body by heating it;
- The rest of the energy ($\varphi\lambda\ .\tau\lambda T$) is transmitted by continuing the path. Such as;
- From where;

$$\boxed{\varphi_\lambda = \varphi_\lambda . \rho_{\lambda T} + \varphi_\lambda . \alpha_{\lambda T} + \varphi_\lambda . \tau_{\lambda T}} \quad (5.5)$$

$$\boxed{\rho_{\lambda T} + \alpha_{\lambda T} + \tau_{\lambda T} = 1} \quad (5.6)$$

which respectively represent; the monochromatic reflective power (ρλT), the monochromatic absorbing power (αλT) and the monochromatic transmittance power (τλT). These powers depend on the nature of the body, its thickness, its temperature (T), the wavelength (λ), the incident radiation and the angle of incidence.

5.5. Laws of radiation:

5.5.1. Planck's law

For a black body, the monochromatic Emittance only depends on the wave length (λ) and the temperature (T):

$$E_\lambda = \frac{d\varphi_\lambda}{dS} = \frac{C_1}{\lambda^5\left(e^{\frac{C_2}{\lambda T}} - 1\right)} \quad ; \quad \left[W/m^2.\mu m^{-1}\right] \tag{5.7}$$

Such as ;

T: temperature in °K

λ: The wavelength in μm

$C \;=2\pi\; hc^2=3,74\times10^8 W\cdot\mu^4\cdot m^{-2}$: Planck constant

$C_2 = hc/k = 14400\mu K$ k: Stefan-Boltzmann constant and c the speed of light ($c = 3\times10^8\ m/s$).

Remarks

1. In the visible region (small wavelengths)

$$e^{\frac{C_2}{\lambda T}} \gg 1 \text{ ; d'où } E_\lambda = M^0_{\lambda,T} = C_1\lambda^{-5}e^{\frac{-C_2}{\lambda T}}$$

2. In the far infrared domain (long wavelengths), the development of $(e^{\frac{C_2}{\lambda T}})$ allows us to express $(M^0_{\lambda,T})$ by:

$$E_\lambda = M^0_{\lambda,T} = C_1T/C_2\,\lambda^4$$

Planck's law makes it possible to draw isothermal curves representing the variations of E_λ as a function of wavelength for various temperatures:

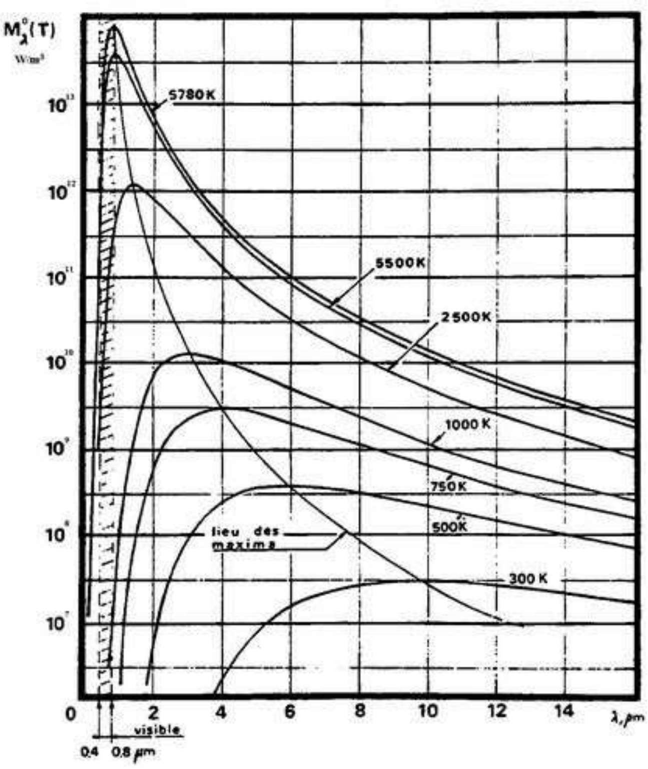


Figure 5. 5. Monochromatic emittance of the black body

5.5.2. Laws of Wien

5.5.2.1. Wien's first law

Wien's first law makes it possible to express or evaluate the wavelengths corresponding to the maximum monochromatic emittance (for which the radiation is maximum) as a function of temperature. For its derivation, it is enough to cancel the derivative of the emittance:

$$\boxed{\frac{dM^0_{\lambda,T}}{d\lambda} = 0 \Leftrightarrow \quad \lambda_m = \frac{2898}{T}; \quad [\mu m]} \tag{5.8}$$

Noticed

- At room temperature (T = 300 K, λm = 9.6 µm), a body emits long-wavelength infrared radiation which surrounds us but is not visible to our eye [(0.36 ÷ 0.75)] µm

- At the temperature of the sun (T = 5790 K, λm = 0.5 µm, maximum radiation), it is the visible yellow for which our eye has maximum luminous efficiency.

5.5.2.2. Wien's second law:

This law expresses the value of the maximum monochromatic emittance, it is enough to replace (λm) by its value in Planck's law to obtain:

With; (5.9)

$$\boxed{M^0_{\lambda m,T} = B.T^5}$$

$$B = 1.287\times10^{-5} W\cdot m^{-3}\cdot K^{-5} \text{ et T en °K}$$

5.5.3 Stefan-Boltzmann law

It gives the total black body emittance, with the summation of all monochromatic emittances for all wavelengths or the integration of:

$$\boxed{E = \frac{d\varphi}{dS} = \int_0^\infty E_\lambda d\lambda = M^0 = \int_0^\infty M^0_{\lambda,T} d\lambda = \sigma.T^4 \quad ; \quad [W/m^2]} \qquad (5.10)$$

Such as ;

$\sigma = 5.67\times10^{-8}\, W\, m^2\cdot K^4$ Stefan-Boltzmann constant

5.6. Radiation of real bodies

The emissive properties of real bodies are defined relative to the emissive properties of black bodies in the same temperature and wavelength range, and they are distinguished using coefficients called emissivity factors. These monochromatic or total coefficients are defined as follows;

$$\boxed{\varepsilon_{\lambda T} = \frac{M_{\lambda T}}{M_{0\lambda T}} \text{ et } \varepsilon_T = \frac{M_T}{M_{0T}}}$$

According to Kirchhoff's law, we show that:

$$\boxed{\alpha_{\lambda T} = \varepsilon_{\lambda T}} \qquad (5.11)$$

5.7. Gray body radiation

Gray bodies are characterized by $\alpha_{\lambda T} = \alpha_T$ so $\varepsilon_{\lambda T} = \varepsilon_T$ or

$M_T = \varepsilon_T \times M_{0T}$ we let us deduce the gray body emittance at temperature T:

$$\boxed{M_T = \varepsilon_T \times \sigma \times T^4} \qquad (5.12)$$