

2 Physical background

In this chapter, first the basic radiation heat transfer theory of a black body is analysed from the user point of view (readers interested in a more rigorous analysis may refer to more specialized books, e.g. Siegel and Howell, 1992). Then, some specific information on the behaviour of real bodies is given including a differentiation between dielectric and electrically conducting materials. Finally, a brief description of the atmospheric absorption of radiation is presented.

2.1 Basic radiation heat transfer theory

Heat transfer by *radiation* (or *radiative heat transfer*) is an energy transport mechanism that occurs by means of electromagnetic waves. Atoms and molecules constituting a body contain charged particles (protons and electrons) and their movement results in the emission of electromagnetic radiation, which carries energy away from the body surface.

Contrary to the case of heat conduction (and consequently convection), energy can be transmitted by thermal radiation also in the absence of a medium and, therefore, radiation is the only mechanism that enables the exchange of energy between two unconnected bodies placed in a vacuum.

If a medium is present in between the two exchanging bodies, the transferred energy may be partially or completely absorbed and/or reflected, or may even pass through the medium without downgrading. In the latter case, the medium is called *fully transparent* and this practically enables an IR scanner to *view* the temperature of a body without touching it. A medium can also be *partially transparent*, i.e. if it allows only a fraction of the transmitted energy to pass through.

Thermal radiation can originate from a solid, a liquid or even a gas since all materials at a temperature above absolute zero emit energy by means of electromagnetic waves. At the same time, all materials also absorb electromagnetic waves; both emission and absorption behaviours are possible because materials change their internal energy state at a molecular level.

The amount of thermal radiation which is absorbed or emitted, as well as its propagation, depend not only on the nature of the material and surface finish but also on its thermodynamic state and on the specific wavelength of the considered electromagnetic wave.

The wavelength λ [m] is linked to the frequency of the wave ν [s^{-1}] by the wave speed of propagation (speed of light) c [m/s] in the material (medium):

$$\lambda = \frac{c}{\nu} \quad (2.1)$$

The speed of propagation in a generic medium is related to the propagation speed in vacuum c_o ($2.998 \times 10^8 m/s$, independent of λ) by the relationship:

$$c = \frac{c_o}{n} \quad (2.2)$$

where n is the dimensionless *index of refraction* (or *refractive index*) of the medium, which generally depends also on the wavelength.

While both c and λ depend on the nature of the medium through which the wave travels and its thermodynamic state, ν is a constant dependent only on the source of the electromagnetic wave.

A different approach based on quantum theory, where the radiation is seen as a collection of discrete particles termed *photons* or *quanta*, is quite useful. In this approach, each photon is considered to have an energy e [J] given by:

$$e = h\nu = \frac{hc}{\lambda} \quad (2.3)$$

where $h = 6.626 \times 10^{-34} Js$ is named *Planck's constant*.

From the previous equation, it is clear that, while both c and λ depend on the medium through which the wave travels, ν is constant because the energy of the photon must be conserved.

The entire electromagnetic spectrum is quite roughly divided into a number of wavelength intervals, called *spectral bands* or more simply *bands*, and extends from very small wavelength values ($\lambda \rightarrow 0$) to extremely large ones ($\lambda \rightarrow \infty$).

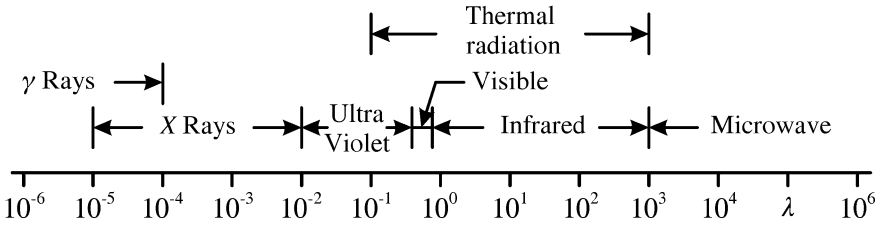


Fig. 2.1 - Electromagnetic spectrum (wavelength λ in micrometres).

On inspection of the relevant portion of the electromagnetic spectrum shown in Fig. 2.1, the *thermal radiation* band is conventionally defined as a relatively small fraction of the complete spectrum, positioned between $0.1\mu m$ and $1000\mu m$, which includes part of the ultraviolet and all of the visible and IR bands.

In particular, when a body is at ambient temperature most of the energy is radiated in the infrared spectral band. This band is generally sub-divided into four

smaller bands with arbitrarily chosen boundaries: *near infrared* ($0.76\div 3\mu\text{m}$), *middle infrared* ($3\div 6\mu\text{m}$), *far or long infrared* ($6\div 15\mu\text{m}$) and *extreme infrared* ($15\div 1000\mu\text{m}$). However, it should be noted that not only the boundaries but also the involved semantics might change according to the particular context.

Most of the currently used IR camera temperature detectors are sensitive in either the middle (MWIR) or the long wavelength (LWIR) spectral bands, though the band between $\sim 5\mu\text{m}$ and $\sim 7.5\mu\text{m}$ is seldom used because of its rather high atmospheric absorption (see [sub-section 2.1.3](#)). Detectors are also available in the near infrared band, sometimes sub-divided into *very near infrared* (VNIR $0.76\div 1.1\mu\text{m}$) and *short wavelength* (SWIR $1.1\div 3\mu\text{m}$) bands, and in the extreme infrared band, but they are used much less for standard thermo-fluid-dynamic applications so these particular bands will not be considered in the following.

As already stated, if the temperature of a solid, liquid or gas is above absolute zero, their electrons, atoms and molecules are in continuous motion, thus radiation is constantly emitted, absorbed and transmitted through them. Therefore, it has to be stressed that radiation is a *volumetric* phenomenon.

However, in many instances, solids and liquids are *opaque* (i.e. completely non-transparent) and, in such cases, the incident non-reflected radiation is absorbed within a few micrometres of their skin. Furthermore, the surrounding molecules absorb the radiation generated within opaque bodies and for these reasons, radiation can be considered as just a *surface* phenomenon.

Therefore, by coating the surface of a body with a very thin layer of opaque material (such as a dull enamel), it is possible to completely change its surface radiation properties and this effect may be very useful when using an IR scanner to measure surface temperatures, particularly of metals (see [sub-section 2.1.2](#)).

Clearly, what we affirmed above is true for the wavelengths of interest in the thermal radiation band but it is of course erroneous if one considers for example the X-ray band for which an enamel layer is practically transparent.

2.1.1 Black body radiation

An opaque body at a specified positive absolute temperature generally emits from its surface thermal radiation in many directions and in a wide range of wavelengths. For a certain body surface temperature, the energy emitted by radiation per unit surface area and unit time (*energy flux*) depends on the material nature of the body and its surface characteristics, including the surface finish. Clearly, the same reasoning is also true for the absorbed energy.

In order to formulate simple general laws for thermal radiation, it is useful to introduce a conceptual body, usually called a *black body*, which has the property of being a perfect emitter and absorber of radiation. A black body is thus able to absorb all the incident radiation, regardless of its wavelength and direction, and is the body that, for a fixed temperature and wavelength, emits the maximum

possible amount of radiation. A black body behaves also as a *diffuse emitter*, in the sense that it emits radiation uniformly in all possible directions.

If one considers only the visible part of the spectrum, a black body (at about ambient temperature) can be approximated by a dull black surface because it absorbs almost the entire incident light without any significant reflection. Since the visible band is a very small part of the complete spectrum, in general a black-coloured surface is seldom a good approximation to an ideal black body.

Instead, a good approximation to a black body is an isothermal cavity with a very small aperture, as shown in Fig. 2.2. In such a cavity, thermal radiation entering the cavity via the aperture undergoes several reflections before leaving the cavity once again through the aperture. Upon each reflection, part of the incident radiation is absorbed by the surface, therefore, the radiation eventually leaving through the aperture is degraded to an extremely small value. Furthermore, also the radiation emitted by the interior surface of the cavity undergoes many reflections before exiting from the aperture (one can simply reverse the direction of the arrows in Fig. 2.2), thus producing a maximum emission in all directions.

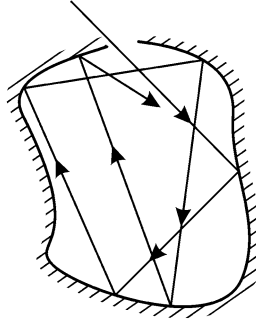


Fig. 2.2 – Isothermal cavity with a small aperture approximating a black body.

The law that enables one to evaluate the energy flux (energy rate per body unit surface area) per wavelength, named *spectral hemispherical emissive power* $E_{b\lambda}$ [W/m^3], which is emitted by a black body in vacuum, is *Planck's law of radiation*:

$$E_{b\lambda}(\lambda, T) = \frac{C_1}{\lambda^5 \left(e^{\frac{C_2}{\lambda T}} - 1 \right)} \quad (2.4)$$

where T [K] is the absolute body temperature and, by indicating with k ($k = 1.381 \times 10^{-23} \text{ J/K}$) the *Boltzmann's constant*, the so-called *first and second radiation constants* C_1 and C_2 are respectively:

$$C_1 = 2\pi \hbar c_o^2 = 3.742 \times 10^{-6} \text{ Wm}^2 = 3.742 \times 10^8 \text{ W } \mu\text{m}^4 / \text{m}^2$$

$$C_2 = \frac{hc_o}{k} = 1.439 \times 10^{-2} Km = 1.439 \times 10^4 K \mu m$$

The second reported value of each radiation constant is useful when measuring the wavelength in micrometres. Planck's law of radiation can be easily extended to a black body that is emitting in a generic medium by substituting in the expression of each radiation constant the speed of light in vacuum with that in the considered medium (see Eq. (2.2)).

The spectral black body emissive power's (in vacuum) dependence on wavelength, as predicted by Eq. (2.4), is plotted in Fig. 2.3 for several absolute temperature values. It is evident that, for each wavelength, the emitted radiation increases significantly with temperature and the different curves never cross each other. Furthermore, the emitted radiation is a continuous function of the wavelength and each isothermal curve tends to zero for both very large and very small values of λ , having a maximum at some intermediate wavelength. Upon an increase in the black body's temperature, the position of this maximum shifts towards smaller wavelengths (dashed straight line).

It is interesting to note that only at very high temperatures does a significant part of the emitted radiation fall in the visible part of the electromagnetic spectrum

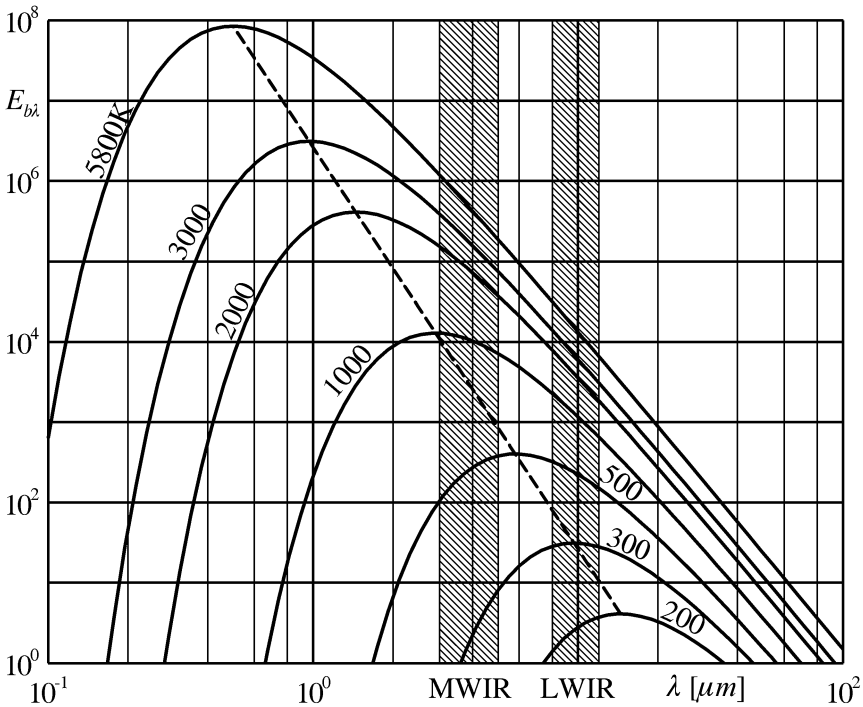


Fig. 2.3 – Spectral hemispherical black body emissive power [$W/m^2 \mu m$] in vacuum for several absolute temperature (K) values as a function of the wavelength λ .

(about $0.4\div 0.76\mu m$). In fact, as early as in 1847, Draper determined that a thin strip of platinum (but also other materials showed a similar behaviour) could be distinguished, in a dark chamber by the human eye, only when its temperature was over about $800K$. At this temperature, the colour of the metal is red because a small part of the emitted energy falls at the very right side of the visible spectrum.

In Fig. 2.3, the bands (MWIR and LWIR) captured by the infrared detectors of the most commonly used IR cameras are also indicated with the dashed areas.

It is feasible to simplify Planck's law of radiation by scaling the emissive power with the fifth power of the temperature $[W/(m^3K^5)]$:

$$\frac{E_{b\lambda}(\lambda, T)}{T^5} = \frac{C_1}{(\lambda T)^5 \left(e^{\frac{C_2}{\lambda T}} - 1 \right)} \quad (2.5)$$

From the previous relationship, it is possible to notice that the scaled emissive power is a function of the sole variable (λT) and, therefore, it can be easily plotted as

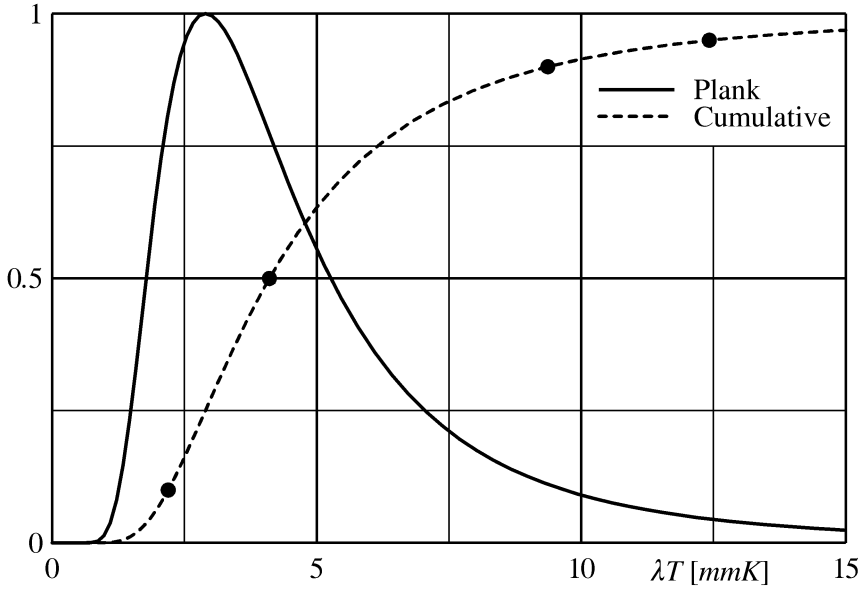


Fig. 2.4 – Normalised spectral hemispherical black body emissive power in vacuum and fractional emissive power function with selected points.

a single curve (see Fig. 2.4, where its normalized value is represented with a solid line). Within this description, it is evident that the curve has a single maximum, for a given λT value. By looking at this curve, or by differentiating Eq. (2.5) with respect to λT and setting to zero the result, the following is obtained:

$$\lambda_{\max} T = 2898 \mu\text{mK} \quad (2.6)$$

This equation represents *Wien's displacement law* which enables one to find the wavelength λ_{\max} at which a black body emits its maximum spectral emissive power as a function of its temperature. Wien's law is also represented by the dashed straight line in Fig. 2.3. For example, at liquid nitrogen temperature (77K) $\lambda_{\max} \approx 38 \mu\text{m}$, at room temperature $\lambda_{\max} \approx 10 \mu\text{m}$, while the sun (at about 5800K) emits radiation peaking around $0.5 \mu\text{m}$ in the visible light band.

Planck's law of radiation can be integrated over the whole spectrum to obtain the *Stefan-Boltzmann law* that enables one to calculate the *total* (energy flux over all wavelengths) *black body hemispherical emissive power* E_b [W/m^2]:

$$E_b = \int_0^{\infty} E_{b\lambda}(\lambda, T) d\lambda = \sigma T^4 \quad (2.7)$$

where $\sigma = \pi^4 C_1 / 15 C_2^4 = 5.670 \times 10^{-8} \text{W}/(\text{m}^2 \text{K}^4)$ is known as the *Stefan-Boltzmann constant*.

However, while making measurements with IR thermography, since (as already seen in Fig. 2.3) infrared camera detectors capture only a limited band of the whole electromagnetic spectrum, a definite integral of Planck's law is more appropriate to find the energy flux sensed by the detector in a certain band λ_1 - λ_2 :

$$E_{b, \lambda_1 - \lambda_2}(T) = \int_{\lambda_1}^{\lambda_2} E_{b\lambda}(\lambda, T) d\lambda \quad (2.8)$$

Then, to simplify the evaluation of this integral it is convenient to introduce the dimensionless *fractional emissive power function*:

$$f(\lambda T) = \frac{\int_0^{\lambda} E_{b\lambda}(\lambda, T) d\lambda}{\int_0^{\infty} E_{b\lambda}(\lambda, T) d\lambda} = \int_0^{\lambda T} \frac{E_{b\lambda}(\lambda, T)}{\sigma T^5} d\lambda T \quad (2.9)$$

where the integrand of the last term of the previous equation is a function of the only variable λT . The function defined by Eq. (2.9) is plotted in Fig. 2.4 with a dashed line. Particular percentages (10, 50, 90 and 95%) of emitted flux are also indicated on this line with the easily recognizable dots.

A closed form of the fractional emissive power function was presented by Chang and Rhee (1984):

$$f(\lambda T) = \frac{15}{\pi^4} \sum_{n=1}^{\infty} \left(\frac{e^{-n\zeta}}{n} \left(\zeta^3 + \frac{3\zeta^2}{n} + \frac{6\zeta}{n^2} + \frac{6}{n^3} \right) \right) \quad (2.10)$$

where $\zeta = C_2 / \lambda T$.

By using the previous equation in combination with Wien's law and/or by looking at the curves of Fig. 2.4, one can determine that, irrespective of the temperature of the black body, the percentage of emissive power radiated at wavelengths smaller than λ_{max} is about 25% of the total.

The definite integral defined by Eq. (2.8) can now be easily evaluated with the relationship:

$$E_{b,\lambda_1-\lambda_2}(T) = \sigma T^4 (f(\lambda_2 T) - f(\lambda_1 T)) \quad (2.11)$$

As already affirmed, infrared scanners can operate in different spectral bands and the previous equation can be used to compute the fraction of the total energy radiated by the black body in the band of interest.

It is quite interesting to evaluate this fraction for the two bands most typically used by IR scanners for thermo-fluid-dynamic applications: the 3-5 μm band of the MWIR scanners and the 8-12 μm band of the LWIR ones.

For a black body temperature of 300K, it is found that the energy radiated in the LWIR band is about 26% of the total, while for the MWIR band this percentage is reduced to 1.3%. In this case, the LWIR band appears to have a clear advantage but, by increasing the temperature to 600K, the MWIR band behaves a little better (23% for MWIR against 21% for LWIR).

Besides, it has to be noted that, by doubling the absolute temperature, the total energy emitted is amplified by a factor of 16 and this reduces the importance of having a larger percentage of energy radiated in the working band.

However, it must be clear that receiving a larger quantity of energy is not the only relevant parameter and other considerations are given in [sub-section 3.4.5](#).

2.1.2 Radiation of real bodies

The radiation characteristics of real bodies are normally different from those of a black body. Both emitted and absorbed radiations of a black body are upper limits for real bodies that may possibly be approached only in certain spectral bands and under certain conditions.

The incident radiation (often called *irradiation*) is completely absorbed by a black body but, as shown in Fig. 2.5 for a real slab of finite thickness, only a fraction of it is absorbed. The remaining fraction of the irradiation may be partially reflected and/or partially transmitted across the slab medium.

By denoting with α_r the fraction of irradiation absorbed by the slab, with ρ_r the fraction of irradiation reflected and with τ_r the fraction of irradiation transmitted through the slab, energy conservation requires:

$$\alpha_r + \rho_r + \tau_r = 1 \quad (2.12)$$

where α_r , ρ_r and τ_r are respectively called *absorptivity* (or *absorptance*), *reflectivity* (or *reflectance*) and *transmissivity* (or *transmittance*) *coefficients* (all dimensionless) of the body under consideration.

Clearly, the above-mentioned coefficients are positive and smaller than, or at most equal to 1. For example, for a black body, $\alpha_r = 1$ and, consequently, both reflectance and transmittance are equal to zero; for an opaque body, $\alpha_r = 1 - \rho_r$.

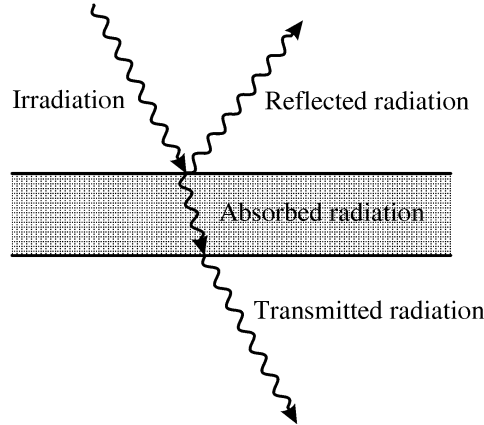


Fig. 2.5 - Reflection, absorption and transmission of the irradiation in a slab.

In general, the coefficients α_r , ρ_r and τ_r depend on the nature of the slab material, its surface finish, its thermodynamic state as well as on the wavelength (spectral subscript λ , not indicated above) and direction (directional subscript ϑ , not indicated above) of the impinging radiation.

In a semi-infinite absorbing medium, the spectral transmissivity coefficient is exponentially linked to the wave travelled depth x :

$$\tau_{r\lambda} = \exp(-\varsigma x) \quad (2.13)$$

where ς is the *spectral absorption coefficient* [1/m] that, for most materials, does not depend on the layer thickness but on the wavelength of the incident radiation and on the nature of the material. For what happens in a slab, see Eq. (3.2).

In addition, the emission from real opaque bodies is different from that of a black body and does not definitely follow Planck's and consequent laws. As already mentioned, the radiation emitted by a black body is an upper limit for real bodies, that may possibly be approached only in certain spectral bands and under certain conditions.

On a total basis, a real body generally emits only a fraction E of the heat flux E_b emitted by a black body at the same temperature. Of course, this happens to be true also on a spectral basis, i.e. $E_\lambda \leq E_{b\lambda}$. In the following, for sake of ease, E is always referred to as the *total hemispherical emissive power* and E_λ is the *spectral hemispherical emissive power*.

The *spectral hemispherical emissivity coefficient* ε_λ (dimensionless) is defined:

$$\varepsilon_\lambda(\lambda, T) = \frac{E_\lambda(\lambda, T)}{E_{b\lambda}(\lambda, T)} \quad (2.14)$$

which, once known, enables one to easily compute the hemispherical emissive power of a real body by simply substituting Planck's law in Eq. (2.14).

Similarly, the *total hemispherical emissivity coefficient* ε_t is defined as:

$$\varepsilon_t(T) = \frac{E(T)}{E_b(T)} \quad (2.15)$$

which can be used with Eq. (2.7).

As will be seen later in more detail, generally the emissivity coefficient is also a function of the angle ϑ between the direction normal to the emitting surface and the direction of the emitted radiation. When the last dependency does not occur, the body is called a *diffuse emitter*.

Apart from the surface temperature, the spectral emissivity of a real body may depend strongly on the wavelength of the emitted radiation, the emitting body material and composition as well as on the conditions of its surface.

Bodies having their emissivity independent of λ are called *grey bodies*.

Even if no real surface is truly grey over the whole electromagnetic spectrum, often a real surface can have an almost constant spectral emissivity in the used IR detector band so that, at least from a practical detection point of view, the grey hypothesis can be assumed to be satisfied.

For a diffuse emission (or a diffuse irradiation), Kirchhoff's law states that the spectral emissivity is equal to the spectral absorptivity coefficient; accordingly, for an opaque body ($\tau_r = 0$) such as those generally used for measurements with IR thermography, Eq. (2.12) becomes:

$$\varepsilon_\lambda + \rho_{r\lambda} = 1 \quad (2.16)$$

As a consequence, materials with low emissivity (such as shiny metallic surfaces) not only emit less energy but also reflect a large amount of the radiation coming from the ambient environment and impinging on them. Whenever possible, they should not be employed in infrared applications or, if they must be used for some reason and transient heat transfer is not involved (see [chapter 4](#)), the viewed surface should be covered with a thin layer of thermally black paint such as dull enamel. Strangely enough, the authors find that, at least for the LWIR band, the white enamel they use has a slightly higher emissivity than a black one.

The electromagnetic theory can be used to find the dependence of the spectral directional emissivity on the refractive index n and the dimensionless *extinction coefficient* κ (an imaginary part of the complex refractive index, linked to ς) of the material. Both n and κ are a function of the thermodynamic state and electrical

properties of the material, in particular of the electrical resistivity r_e as well as of the radiation wavelength.

Clearly, the theory has been developed with some limiting assumptions so that the emissivity of real bodies may differ significantly from what is predicted and it is normally advisable to measure it with *ad hoc* tests (e.g. see [section 6.3](#)). Nevertheless, the theory provides important information on the functional dependence of the directional emissivity coefficient on the above-mentioned parameters.

The radiation behaviour of dielectric materials and that of metals are different from each other and are treated separately below. In particular, the electrical resistivity is supposed to be extremely large in the former case (ideal dielectric) while relatively small in the latter. In the following, it is also assumed that the radiation is emitted in air, it being a good approximation to vacuum since normally, for air, $n \cong 1$ with less than a per thousand accuracy (e.g. Gladstone-Dale's law, see Merzkirch, 1987).

2.1.2.1 Dielectric materials

Dielectrics are materials that conduct electricity poorly and include most of the liquids, plastics, paints, glasses, woods and also metal oxides. Normally, for dielectric materials, the extinction coefficient κ is very small and the refractive index n is less than 3. According to the theory, the spectral (being n a function of λ) directional emissivity coefficient $\varepsilon_{\lambda,\vartheta}$, for a smooth opaque medium, can be calculated with the relationship (Baehr and Stephan, 2006):

$$\varepsilon_{\lambda,\vartheta} = \frac{2 \cos(\vartheta) \sqrt{n^2 - \sin^2(\vartheta)}}{\left(\cos(\vartheta) + \sqrt{n^2 - \sin^2(\vartheta)} \right)^2} \left(1 + \frac{n^2}{\left(\cos(\vartheta) \sqrt{n^2 - \sin^2(\vartheta)} + \sin^2(\vartheta) \right)^2} \right) \quad (2.17)$$

which, for $n = 1$, gives $\varepsilon_{\lambda,\vartheta} = 1$, independent of ϑ .

A plot of the dependence on ϑ of the emissivity coefficient, as predicted by the previous equation is shown in [Fig. 2.6](#) for some values of the refractive index $n > 1$. For the considered n values, the emissivity coefficient is almost constant for relatively small ϑ values (practically up to about 45°) but decreases rapidly when the emitted radiation tends towards being parallel to the surface ($\vartheta = 90^\circ$). With increasing refractive index, the maximum value of $\varepsilon_{\lambda,\vartheta}$ decreases, its later drop being more abrupt and, consequently, confined to a smaller high ϑ values range.

Experimental results, obtained by dello Ioio (2008) for machined Macor[®] (which is a material often used for thin film sensors), are also reported in the figure and the data fit well with the theoretical curve for $n = 1.7$.

The limit of Eq. (2.17) for $\vartheta \rightarrow 0^\circ$ gives the spectral emissivity coefficient, for a radiation flux *normal* to the emitting surface ($\varepsilon_{\lambda,\vartheta} = 0 = \varepsilon_{\lambda n}$), a condition that can be relatively easily encountered in experiments:

$$\varepsilon_{\lambda, \vartheta=0} = \varepsilon_{\lambda n} = \frac{4n}{(n+1)^2} = 1 - \left(\frac{n-1}{n+1} \right)^2 = 1 - \rho_{\lambda n} \quad (2.18)$$

Obviously, the term in brackets of the third equality member of Eq. (2.18) is the normal spectral reflectivity coefficient $\rho_{\lambda n}$ (for $\vartheta \rightarrow 0$).

From Eq. (2.18) (but also from Fig. 2.7) and since, as already said, generally $n < 3$, high normal spectral emissivity values, larger than 0.75, are expected for dielectric materials. This is effectively observed in experimental measurements for $\lambda > 2\mu\text{m}$, i.e. in the bands of the electromagnetic spectrum normally used in most infrared thermography applications. Furthermore, it may be affirmed that, often within each of these bands, dielectrics frequently approximate the behaviour of a grey body.

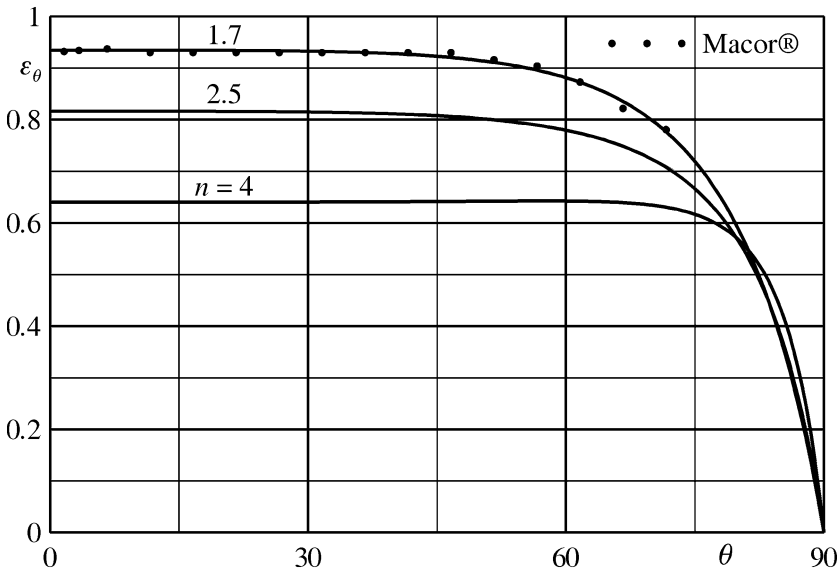


Fig. 2.6 – Spectral directional emissivity coefficient of dielectric materials for some n values.

The spectral hemispherical emissivity coefficient can be found by integrating Eq. (2.17) over all directions and, as shown in Fig. 2.7, the result is particularly interesting. In fact, the hemispherical and normal spectral emissivities are not much different from each other for most practical n values, within less than 10%. This can be very useful when evaluating sensor radiation losses to the ambient environment (see chapter 4).

Clearly, when using an IR scanner, care should be taken while performing measurements if the scanned object surface is not locally normal to the viewed rays. To evidence viewing angle effects, the thermogram of the wall of a vertical PVC (dielectric) pipe, full of stirred warm water and under natural convection

conditions, is shown in Fig. 2.8. Measured wall temperature should be constant cross-wise (along the dashed horizontal straight line); instead, it appears to decrease towards the cylinder edges due to the high viewing angle that causes, according to both Fig. 2.6 and Eq. (2.17), the fast decay of the directional emissivity coefficient, there.

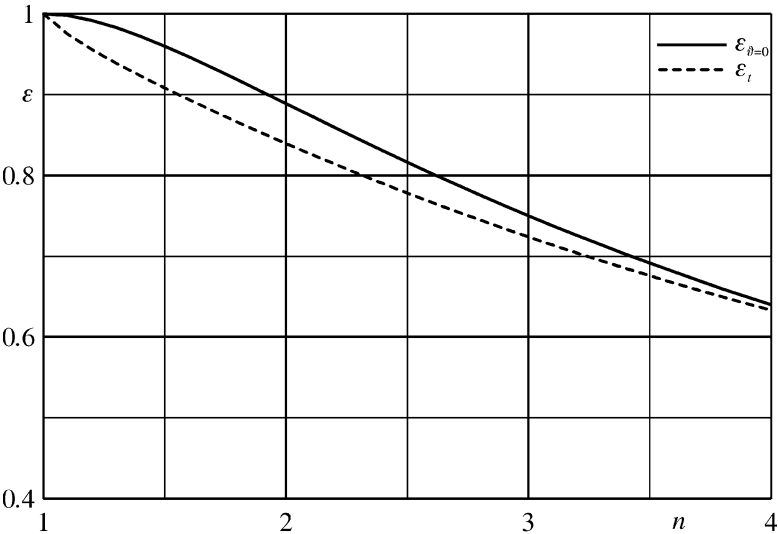


Fig. 2.7 - Normal and total emissivity coefficients as a function of n .

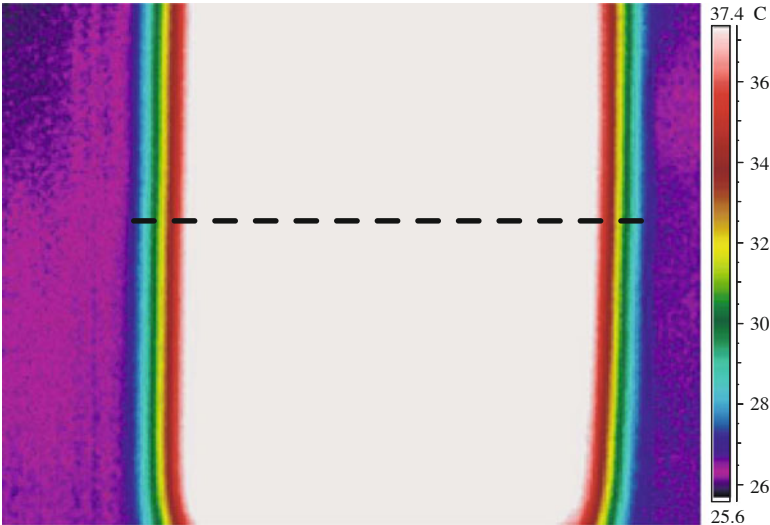


Fig. 2.8 - Temperature map of a vertical PVC cylinder under natural convection. From Carlomagno and Cardone (2010).

From Fig. 2.6 it is also evident that, when the viewing angle is relatively small, the directional emissivity of the surface can be correctly assumed to be constant and equal to the normal one. With it being necessary to work at high viewing angles, a careful calibration of $\varepsilon_{\lambda,\vartheta}$ as a function of ϑ must be performed. Therefore, in order to also take into account the viewing angle variations within the field of view, an optical calibration of the IR scanner should likewise be accomplished (see section 6.4) in order to correctly estimate the local viewing angles on the tested model.

However, while performing experiments with complex model shapes, very high viewing angles should be avoided, because of the steep decrease of $\varepsilon_{\lambda,\vartheta}$ in that range. In such a case and whenever possible, it is much better to take two or more images of the model to be tested from different viewing angles and to reconstruct the thermal image of the model surface.

2.1.2.2 Electrically conducting materials

Metals are the most common electrically conducting materials and, in contrast to dielectrics, the extinction coefficient κ is no longer neglectable with respect to the refractive index n , which is much higher. Also in this case, the electromagnetic theory provides a relationship for the evaluation of the spectral directional emissivity coefficient but, since it is significantly more complex than Eq. (2.18), it will not be reported herein (see Siegel and Howell (1992) for more details).

It is interesting to plot, for some $n = \kappa$ values, the spectral directional emissivity coefficient because, as clearly shown in Fig. 2.9, its behaviour is different from that of dielectric materials. Usually, the emissivity coefficient of electric conductors has smaller values, with respect to dielectrics, and a relative minimum in the normal direction. The maximum is obtained for large values of the angle ϑ and these effects are more pronounced for larger extinction coefficients.

The spectral normal directional emissivity can be evaluated with the following straightforward formula:

$$\varepsilon_{\lambda,\vartheta=0} = \frac{4n}{(n+1)^2 + \kappa^2} = 1 - \frac{(n-1)^2 + \kappa^2}{(n+1)^2 + \kappa^2} = 1 - \rho_{\lambda,\vartheta=0} \quad (2.19)$$

As compared to dielectrics, the significant decrease of the normal emissivity of metals is associated with the higher n values and with the addition of the term κ^2 to the denominator of the first fraction of Eq. (2.18).

Experimental data show that most metals, unless oxidized or with a rough surface, have a normal emissivity that seldom exceeds 0.2 and very often, if they have a well-polished surface, values can fall below 0.1. Consequently, the perpendicularly emitted radiation is low and the reflected one is high.

This is the reason why, while using IR thermography, metal models are not to be used as such but must be covered with a thin layer of thermally black paint

(such as dull enamel) or superficially treated. The former practice cannot be carried out if transient heat transfer is involved, such as when using thin film or thin skin sensors (see [sections 4.2](#) and [4.3](#)).

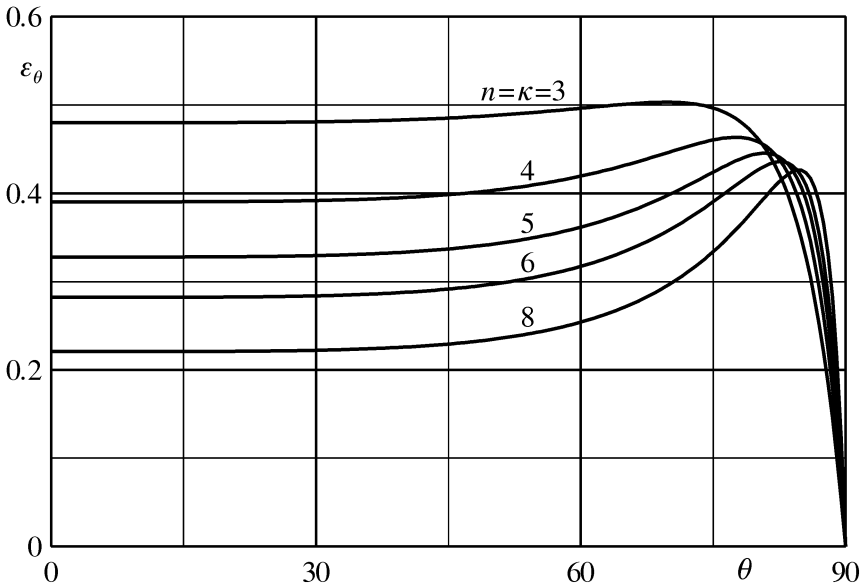


Fig. 2.9 - Spectral directional emissivity coefficient of conductor materials.

When transient heat transfer is present, one way to increase surface emissivity is through fine sandblasting of the metal model. The generated superficial roughness acts as a series of microscopic black bodies, so providing a higher emissivity coefficient. However, while studying boundary layers, this practice should be used cautiously since it may change the layer's behaviour.

Slightly oxidizing the model surface or the use of chemicals may also be appropriate since they exhibit almost the same effect as sandblasting.

2.1.3 Atmospheric transmittance

When performing an actual measurement, the infrared scanner normally views the tested object through a medium (frequently air), which may not be completely transparent, so that part of the emitted radiation is absorbed and not captured by the scanner. Also the presence in the rays' path of viewing windows (such as those used in some wind tunnels or in controlled atmosphere chambers) attenuates the radiation emitted by the object and impinging on the camera lens.

By focusing the attention on an air layer, the different molecules that are present in it partially absorb the thermal radiation and, as already said, they also emit, perhaps at different wavelengths.

Furthermore, particles (such as those in a gaseous suspension) may also scatter part of the incident radiation but, unless dealing with very dirty streams and/or high viewing distances, normally this effect is negligible when performing IR measurements. Otherwise, a radiometric calibration is required.

For thermographic measurements, one has to use the two so-called *atmospheric windows*, which are respectively located between the visible band and about $5\mu\text{m}$ and between $7.5\mu\text{m}$ and $13.5\mu\text{m}$ spectral bands. They justify the adopted MWIR and LWIR bands, the former being downwards limited by the low emissive power at usual temperatures.

To emphasize the atmospheric absorption effect, in Fig. 2.10 the spectral transmissivity coefficient of a 1km thick standard air layer is plotted as a function of the radiation wavelength.

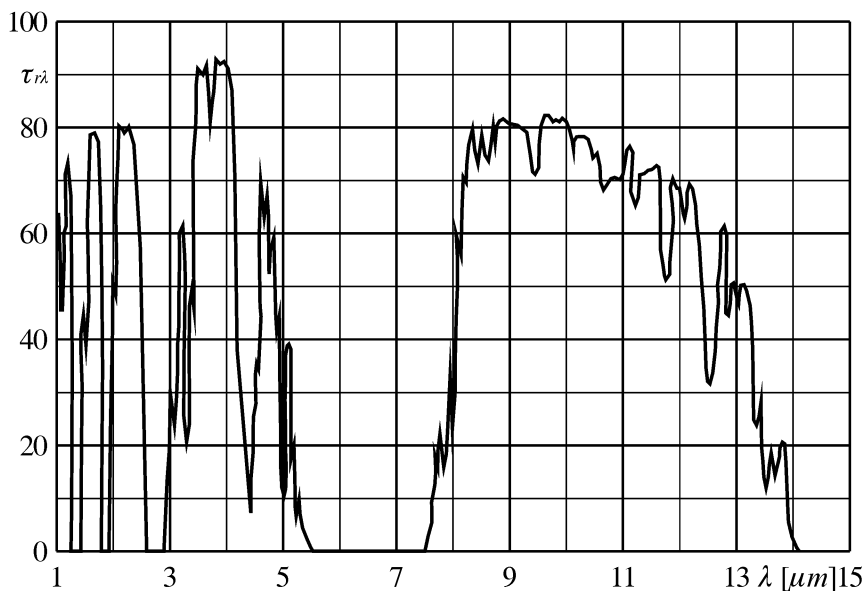


Fig. 2.10 – Spectral transmittance of a 1 km thick atmospheric layer in the near, middle and long infrared bands as a function of λ . Data from Gebbie et al. (1951).

The significant absorptions (especially in the $5\text{--}7.5\mu\text{m}$ band) are essentially linked to the presence of water vapour and carbon dioxide¹. In particular, while in the $8\text{--}12\mu\text{m}$ band $\tau_{r\lambda}$ is practically constant, in the $3\text{--}5\mu\text{m}$ band there are a few strongly absorbed wavelengths, which if not taken into account, may produce some errors in the measurement of the object temperature.

¹ Also other gases, such as O_3 , absorb but they are only slightly present in a conventional atmosphere.

Should it be required, the high-resolution transmission molecular absorption database HITRAN (<http://www.cfa.harvard.edu/HITRAN>), which is a compilation of spectroscopic parameters, can be used to predict and simulate the transmission and emission of radiation - also in the infrared bands - within a gas.

The HITRAN database represents the recognized international standard for providing the necessary fundamental spectroscopic parameters that enable one to perform diverse atmospheric, as well as laboratory, transmission and radiance calculations for a variety of gases.

The HITRAN compilation is used for a vast number of applications including terrestrial and planetary atmospheric remote sensing, transmission simulations, fundamental studies in laboratory spectroscopy, monitoring of industrial processes and pollution analyses. An international HITRAN advisory committee, composed of several experts in the field of spectroscopy, has been established under the auspices of NASA. This committee examines and evaluates the latest spectroscopic data and makes recommendations for updates and replacements in the database.

By considering that when performing laboratory convective heat transfer measurements the typical thickness of the air layer is of the order of a meter, one may conclude that, both in the middle (MWIR) and in the long (LWIR) spectral bands, the spectral transmissivity coefficient is normally quite high, i.e. it can be considered very close to unity.

Of course, the same conclusion is not legitimate for viewing windows, which are addressed in [sub-section 3.1.1](#).

Infrared Thermography for Thermo-Fluid-Dynamics

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2013, XXII, 226 p., Hardcover

ISBN: 978-3-642-29507-2