INTERNATIONAL STANDARD

# ISO 9288

First edition
1989-12-01

# Thermal insulation — Heat transfer by radiation — Physical quantities and definitions

*Isolation thermique — Transfert de chaleur par rayonnement — Grandeurs physiques et définitions*



Reference number
ISO 9288 : 1989 (E)

## Contents







International Organization for Standardization
Case postale 56 • CH-1211 Genève 20 • Switzerland
Printed in Switzerland

## Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

Draft International Standards adopted by the technical committees are circulated to the member bodies for approval before their acceptance as International Standards by the ISO Council. They are approved in accordance with ISO procedures requiring at least 75 % approval by the member bodies voting.

International Standard ISO 9288 was prepared by Technical Committee ISO/TC 163, *Thermal insulation*.

Annex A of this International Standard is for information only.

# Introduction

This International Standard forms part of a series of vocabularies related to thermal insulation.

The series will include

ISO 7345 : 1987, *Thermal insulation — Physical quantities and definitions.*

ISO 9229 : —[1], *Thermal insulation — Thermal insulating materials and products — Vocabulary.*

ISO 9251 : 1987, *Thermal insulation — Heat transfer conditions and properties of materials — Vocabulary.*

ISO 9346 : 1987, *Thermal insulation — Mass transfer — Physical quantities and definitions.*



1) To be published.

# Thermal insulation — Heat transfer by radiation — Physical quantities and definitions

## 1 Scope

This International Standard defines physical quantities and other terms in the field of thermal insulation relating to heat transfer by radiation.

## 2 Normative reference

The following standard contains provisions which, through reference in this text, constitute provisions of this International Standard. At the time of publication, the edition indicated was valid. All standards are subject to revision, and parties to agreements based on this International Standard are encouraged to investigate the possibility of applying the most recent edition of the standard indicated below. Members of IEC and ISO maintain registers of currently valid International Standards.

ISO 7345 : 1987, *Thermal insulation — Physical quantities and definitions.*

## 3 General terms

**3.1 thermal radiation**: Electromagnetic radiation emitted at the surface of an opaque body or inside an element of a semi-transparent volume.

The thermal radiation is governed by the temperature of the emitting body and its radiative characteristics. It is interesting from a thermal viewpoint when the wavelength range falls between 0,1 µm and 100 µm (see figure 1).

**3.2 heat transfer by radiation**: Energy exchanges between bodies (apart from one another) by means of electromagnetic waves.

These exchanges can occur when the bodies are separated from one another by vacuum or by a transparent or a semi-transparent medium. To evaluate these radiation heat exchanges it is necessary to know how opaque and semi-transparent bodies emit, absorb and transmit radiation as a function of their nature, relative position and temperature.



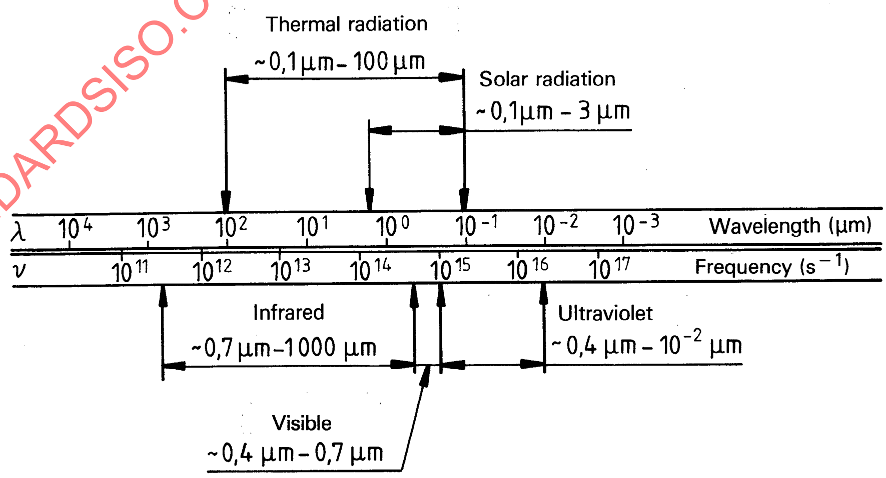



**Figure 1 — Electromagnetic wave spectrum**

### 3.3 Classification of the physical terms associated with thermal radiation

Physical terms associated with thermal radiation are classified according to two criteria:

- spectral distribution
- spatial distribution (directional)

of the radiation.

These physical terms are:

**total,** if they are related to the entire spectrum of thermal radiation (this designation can be considered as implicit);

**spectral or monochromatic,** if they are related to a spectral interval centred on the wavelength $\lambda$;

**hemispherical,** if they are related to all directions along which a surface element can emit or receive radiation;

**directional,** if they are related to the directions of propagation defined by a solid angle around the defined direction.

### 3.4 Classification of materials in relation with radiative transfer

**opaque medium:** Medium which does not transmit any fraction of the incident radiation.

The absorption, emission, reflection of radiation can be handled as surface phenomena.

**semi-transparent medium:** Medium in which the incident radiation is progressively attenuated inside the material by absorption or scattering, or both.

The absorption, scattering and emission of radiation are bulk (volume) phenomena.

The radiative properties of an opaque or semi-transparent medium are generally a function of the spectral and directional distribution of incident radiation and of the temperature of the medium.

NOTE — Thermal insulating materials are generally semi-transparent media.



## 4 Terms related to surfaces either receiving, transferring or emitting a thermal radiation

| | Symbol for quantity | Symbol for SI unit (including multiple or sub-multiple) |
|---|---|---|
| **4.1 radiant heat flow rate; radiant flux:** Heat flow rate emitted, transferred or received by a system in form of electromagnetic waves.<br>NOTE — This is a total hemispherical quantity. | $\Phi$ | W |
| **4.2 total intensity:** Radiant heat flow rate divided by the solid angle around the direction $\vec{\Delta}$:<br>$I_{\Omega} = \frac{\partial \Phi}{\partial \Omega}$ | $I_{\Omega}$ | W/sr |
| **4.3 total radiance:** Radiant heat flow rate divided by the solid angle around the direction $\vec{\Delta}$ and the projected area normal to this direction:<br>$L_{\Omega} = \frac{\partial^2 \Phi}{\partial \Omega \, \partial (A \cos\theta)}$ | $L_{\Omega}$ | W/(m²·sr) |
| **4.4 spectral radiant heat flow rate:** Radiant heat flow rate divided by the spectral interval centred on the wavelength $\lambda$:<br>$\Phi_{\lambda} = \frac{\partial \Phi}{\partial \lambda}$ | $\Phi_{\lambda}$ | W/m<br>W/µm |
| **4.5 spectral intensity:** Total intensity divided by the spectral interval centred on the wavelength $\lambda$:<br>$I_{\Omega\lambda} = \frac{\partial I_{\Omega}}{\partial \lambda}$ | $I_{\Omega\lambda}$ | W/(sr·m)<br>W/(sr·µm) |

| | Symbol for quantity | Symbol for Si unit (including multiple or sub-multiple) |
|---|---|---|
| **4.6 spectral radiance**: Total radiance divided by the spectral interval centred on the wavelength $\lambda$: | $L_{\Omega\lambda}$ | $W/(m^3 \cdot sr)$<br>$W/(m^2 \cdot sr \cdot \mu m)$ |

$$L_{\Omega\lambda} = \frac{\partial L_\Omega}{\partial \lambda}$$

NOTES

1 Each spectral term $A_\lambda$ is related to the corresponding total term $A$ by a relation of the type

$$A_\lambda = \frac{\partial A}{\partial \lambda} \text{ or } A = \int_0^\infty A_\lambda \, d\lambda$$

Each directional term $A_\Omega$ is related to the corresponding hemispherical term $A$ by a relation of the type

$$A_\Omega = \frac{\partial A}{\partial \Omega} \text{ or } A = \int_{\Omega=4\pi} A_\Omega \, d\Omega$$

and

$$A_{\Omega\lambda} = \frac{\partial^2 A}{\partial \Omega \, \partial \lambda} \text{ or } A = \int_{\Omega=4\pi} \int_0^\infty A_{\Omega\lambda} \, d\lambda \, d\Omega$$

2 Total radiance and spectral radiance are oriented quantities (vectors) defined in each point of space where radiation exists (see figure 3), moreover their values are independent of the particular surface used to define them. Sources which radiate with constant $L_\Omega$ (see 4.3) are called **isotropic** or **diffuse**.

Intensities are again oriented quantities but belong to a surface (see figure 2).

Radiant flows (total or spectral) are not oriented quantities and belong to a surface.

| | | |
|---|---|---|
| **4.7 spectral radiant density of heat flow rate vector**: | $\vec{q}_{r,\lambda}$ | $W/(m^2 \cdot \mu m)$ |

$$\vec{q}_{r,\lambda} = \int_{\Omega=4\pi} L_{\Omega\lambda} \vec{\Delta} \, d\Omega$$

| | | |
|---|---|---|
| **4.8 total radiant density of heat flow rate vector**: | $\vec{q}_r$ | $W/m^3$<br>$W/m^2$ |

$$\vec{q}_r = \int_0^\infty \int_{\Omega=4\pi} L_{\Omega\lambda} \vec{\Delta} \, d\Omega \, d\lambda$$

| | | |
|---|---|---|
| **4.9 spectral radiant density of heat flow rate** (in the direction $\vec{n}$): | $q_{r,\lambda n}$ | $W/m^3$<br>$W/(m^2 \cdot \mu m)$ |

$$q_{r,\lambda n} = \vec{n} \cdot \vec{q}_{r,\lambda} = \int_{\Omega=4\pi} L_{\Omega\lambda} \vec{\Delta} \cdot \vec{n} \, d\Omega$$

| | Symbol for quantity | Symbol for SI unit (including multiple or sub-multiple) |
|---|---|---|
| **4.10 forward component of the spectral radiant density of heat flow rate:** | $q^+_{\mathrm{r},\lambda n}$ | W/m³<br>W/(m²·µm) |

$$q^+_{\mathrm{r},\lambda n} = \vec{n}\cdot\vec{q}_{\mathrm{r},\lambda} = \int_{\Omega=2\pi} L_{\Omega\lambda}\vec{\Delta}\cdot\vec{n}\,\mathrm{d}\Omega$$

when $\vec{\Delta}\cdot\vec{n} > 0$

| | | |
|---|---|---|
| **4.11 backward component of the spectral radiant density of heat flow rate:** | $q^-_{\mathrm{r},\lambda n}$ | W/(m²·µm) |

$$q^-_{\mathrm{r},\lambda n} = \vec{n}\cdot\vec{q}_{\mathrm{r},\lambda} = -\int_{\Omega=2\pi} L_{\Omega\lambda}\vec{\Delta}\cdot\vec{n}\,\mathrm{d}\Omega$$

when $\vec{\Delta}\cdot\vec{n} < 0$

NOTES

1 We can express $q_{\mathrm{r},\lambda n}$ by the following expression:

$$q_{\mathrm{r},\lambda n} = q^+_{\mathrm{r},\lambda n} - q^-_{\mathrm{r},\lambda n}$$

2 In combined unidirectional conduction and radiation heat transfer along a direction $\vec{n}$, we have

$$\vec{q}_n = \vec{q}_{cd,n} + \vec{q}_{\mathrm{r},n}$$

where

$\vec{q}_n$ is the density of heat flow rate as defined in ISO 7345 : 1987, 2.3;

$\vec{q}_{cd,n}$ is the density of heat flow rate by conduction;

$\vec{q}_{\mathrm{r},n}$ is the total radiant density of heat flow rate vector;

$\vec{q}_n$ can be determined experimentally with the guarded hot plate or heat flow meter method.

## 5 Terms related to surfaces emitting a thermal radiation

**5.1 emission:** Process in which heat (from molecular agitation in gases or atomic agitation in solids, etc.) is transformed into electromagnetic waves.

| | | |
|---|---|---|
| **5.2 total excitance:** Radiant heat flow rate emitted by a surface divided by the area of the emitting surface: | $M$ | W/m² |

$$M = \frac{\partial\Phi}{\partial A} = q^+_{\mathrm{r}} \text{ or } q^-_{\mathrm{r}}$$

NOTE — $M$ is the areal density of the heat flow rate in each point of an emitting surface. It is a total hemispherical quantity.

| | | |
|---|---|---|
| **5.3 spectral excitance:** Total excitance divided by the spectral interval, centred on the wavelength $\lambda$: | $M_\lambda$ | W/m³<br>W/(m²·µm) |

$$M_\lambda = \frac{\partial M}{\partial\lambda} = q^+_{\mathrm{r},\lambda} \text{ or } q^-_{\mathrm{r},\lambda}$$

| | Symbol for quantity | Symbol for SI unit (including multiple or sub-multiple) |
|---|---|---|

**5.4 black body,** (full radiator or Planck radiator): The black body is one that absorbs all the incident radiation for all wavelengths, directions and polarizations.

At a given temperature, for each wavelength it emits the maximum thermal energy (maximum spectral excitance). For this reason and because rigorous laws define its emission, the emission of real bodies is compared with that of the black body.

NOTE — Terms related to black body bear a superscript notation (°).

| | Symbol for quantity | Symbol for SI unit |
|---|---|---|
| **5.5 black body total excitance**: It is expressed by the Stefan-Boltzmann law: | $M^\circ$ | W/m² |

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

where

$\sigma$ is equal to 5,67 × $10^{-8}$ W/(m²·K⁴);

$T$ is the absolute temperature of the black body.

| | Symbol for quantity | Symbol for SI unit |
|---|---|---|
| **5.6 black body spectral excitance**: It is expressed by Planck's law which relates $M^\circ_\lambda$ to the wavelength $\lambda$ and to the absolute temperature of the black body: | $M^\circ_\lambda$ | W/m³<br>W/(m²·µm) |

$$M^\circ_\lambda = \frac{C_1 \lambda^{-5}}{\exp(C_2/\lambda \cdot T) - 1}$$

where

$C_1 = 2\pi h c_0^2 = 3{,}741 \times 10^{16}$ W/m²;

$C_2 = hc_0/k = 0{,}014\ 388$ m·K.

$h$ and $k$ are, respectively, the Planck constant and the Boltzmann constant, $c_o$ is the speed of electromagnetic waves in vacuum.

A curve $M^\circ_\lambda = f(\lambda)$ with a maximum at $\lambda_m$ can be drawn for each temperature. $\lambda_m$ is a function of temperature, but the product $\lambda_m \cdot T$ is constant (Wien's "displacement law"):

$$\lambda_m \cdot T = 2{,}898 \times 10^{-3}\ \text{m·K}$$

$M^\circ$ and $M^\circ_\lambda$ are hemispherical terms.

The emission of a black body is isotropic or diffuse, i.e. $L^\circ$ and $L^\circ_\lambda$ are independent of the direction (Lambert's law).

The total and the spectral radiance of the black body are expressed by

$$L^\circ = \frac{M^\circ}{\pi}$$

$$L^\circ_\lambda = \frac{M^\circ_\lambda}{\pi}$$

**5.7 emission of real bodies**: The evaluation of the emission properties of real materials is made relative to the black body placed in the same conditions of temperature. In general, these properties depend on the nature and surface aspect of the body and vary with wavelength, direction of emission and surface temperature.

| | Symbol for quantity | Symbol for SI unit (including multiple or sub-multiple) |
|---|---|---|
| **5.8 total directional emissivity:** Total radiance, $L_\Omega$, emitted by the considered surface, divided by total radiance emitted by the black body, $L_\Omega^\circ$, at the same temperature: $$\varepsilon_\Omega = \frac{L_\Omega}{L_\Omega^\circ}$$ | $\varepsilon_\Omega$ | |
| **5.9 spectral directional emissivity:** Spectral radiance, $L_{\Omega\lambda}$, of the considered surface divided by the spectral radiance emitted by the black body, $L_{\Omega\lambda}^\circ$, at the same temperature: $$\varepsilon_{\Omega\lambda} = \frac{L_{\Omega\lambda}}{L_{\Omega\lambda}^\circ}$$ | $\varepsilon_{\Omega\lambda}$ | |
| **5.10 total hemispherical emissivity:** Total hemispherical excitance, $M$, of the considered surface divided by the total hemispherical excitance of the black body, $M^\circ$, at the same temperature: $$\varepsilon = \frac{M}{M^\circ}$$ | $\varepsilon$ | |
| **5.11 spectral hemispherical emissivity:** Spectral excitance, $M_\lambda$, of the considered surface divided by the spectral excitance of the black body, $M_\lambda^\circ$, at the same temperature: $$\varepsilon_\lambda = \frac{M_\lambda}{M_\lambda^\circ}$$ | $\varepsilon_\lambda$ | |
| **5.12 grey body:** Thermal radiator whose hemispherical or directional spectral emissivity is independent of wavelength: $$\varepsilon_\lambda = \varepsilon,\ \varepsilon_{\Omega\lambda} = \varepsilon_\Omega$$ | | |
| **5.13 isotropically emitting body:** Thermal radiator whose total or spectral emissivity is independent of the direction: $$\varepsilon_\Omega = \varepsilon,\ \varepsilon_{\Omega\lambda} = \varepsilon_\lambda$$ | | |
| **5.14 isotropically emitting grey body:** Thermal radiator whose emissivity is independent of both wavelength and direction: $$\varepsilon_\lambda = \varepsilon_{\Omega\lambda} = \varepsilon_\Omega = \varepsilon$$ These emissivities may vary with temperature: $\varepsilon(T)$. | | |
| NOTE — The hypothesis of grey surfaces and isotropic emission, with an emissivity independent of wavelength and direction is generally accepted in computations. In this case the different emissivities of a surface reduce to a single parameter, $\varepsilon$. | | |

## 6 Terms related to opaque or semi-transparent surfaces receiving a thermal radiation

When radiant energy of a wavelength $\lambda$ strikes a material surface along a direction $\vec{\Delta}$ inside the solid angle $\Omega$

— a part $\varrho_{\Omega\lambda}$ of the total incident radiation is reflected;

| | Symbol for quantity | Symbol for SI unit (including multiple or sub-multiple) |
|---|---|---|

— a part $\alpha_{\Omega\lambda}$ is absorbed inside the material; and

— a part $\tau_{\Omega\lambda}$ may be transmitted.

The three terms $\alpha_{\Omega\lambda}$, $\varrho_{\Omega\lambda}$, $\tau_{\Omega\lambda}$ follow the relationship

$$\alpha_{\Omega\lambda} + \varrho_{\Omega\lambda} + \tau_{\Omega\lambda} = 1$$

Similar relations can be written for spectral, directional and total hemispherical terms. Spectral and total terms imply isotropic and incident radiation.

$\alpha = 1$ for the black body

$\tau = 0$ for opaque bodies

$\alpha = \alpha_\lambda$; $\varrho = \varrho_\lambda$; $\tau = \tau_\lambda$ for grey bodies

$\alpha = \alpha_{\Omega\lambda}$; $\varrho = \varrho_{\Omega\lambda}$; $\tau = \tau_{\Omega\lambda}$ for isotropic or diffuse grey bodies.

For a radiation of given direction and wavelength, we have in all cases

$$\alpha_{\Omega\lambda}(T) = \varepsilon_{\Omega\lambda}(T)$$

expression of the Kirchhoff law: for each wavelength and each direction of propagation of the radiation emitted or received by a surface, at a given temperature, the spectral directional emissivity and absorbtivity are equal.

The Kirchhoff law holds also for monochromatic hemispherical terms:

$$\varepsilon_\lambda(T) = \alpha_\lambda(T)$$

but generally this relation cannot be extended to the total radiation emitted and absorbed by a body. Thus, it is not possible to write $\varepsilon = \alpha$, except for grey and black bodies and/or in the case where the spectral distribution of the incident radiation is identical to the one of the black body at the same temperature as the considered surface.

| | Symbol for quantity | Symbol for SI unit |
|---|---|---|
| **6.1 total irradiance:** Radiant heat flow rate received by a surface divided by the area of this surface: $$E = \frac{\partial \Phi}{\partial A} = q_r^+ \text{ or } q_r^-$$ NOTE — $E$ is the areal density of the radiant heat flow rate in each point of a receiving surface. It is a total hemispherical quantity. | $E$ | W/m² |
| **6.2 spectral irradiance:** Irradiance divided by spectral interval centred on the wavelength $\lambda$: $$E_\lambda = \frac{\partial E}{\partial \lambda} = q_{r,\lambda}^+ \text{ or } q_{r,\lambda}^-$$ | $E_\lambda$ | W/m³<br>W/(m²·µm) |
| **6.3 total radiosity:** Radiant heat flow rate emitted and reflected by an opaque surface divided by the area of the surface: $$J = \frac{\partial \Phi}{\partial A} = q_r^+ \text{ or } q_r^-$$ NOTE — $J$ is the areal density of radiant heat flow rate in each point of an opaque surface as a result of the emission and the reflection of the surface. | $J$ | W/m² |

| | Symbol for quantity | Symbol for SI unit (including multiple or sub-multiple) |
|---|---|---|
| **6.4 spectral radiosity:** Total radiosity divided by the spectral interval centred on the wavelength $\lambda$:<br>$J_\lambda = \frac{\partial J}{\partial \lambda}$ | $J_\lambda$ | W/m³<br>W/(m²·µm) |
| **6.5 total absorptance:** Radiant heat flow rate absorbed by a surface, $\Phi_a$, divided by the incident radiant heat flow rate, $\Phi_i$:<br>$\alpha = \frac{\Phi_a}{\Phi_i}$ | $\alpha$ | |
| **6.6 total reflectance:** Radiant heat flow rate reflected by a surface, $\Phi_r$, divided by the incident radiant heat flow rate, $\Phi_i$:<br>$\varrho = \frac{\Phi_r}{\Phi_i}$ | $\varrho$ | |
| **6.7 total transmittance:** Radiant heat flow rate transmitted by a surface, $\Phi_t$, divided by the incident radiant heat flow rate, $\Phi_i$:<br>$\tau = \frac{\Phi_t}{\Phi_i}$ | $\tau$ | |
| **6.8 spectral absorptance:** Spectral radiant heat flow rate absorbed by a surface, $\Phi_{\lambda a}$, divided by the incident spectral radiant heat flow rate, assuming that the incident radiation is isotropic:<br>$\alpha_\lambda = \frac{\Phi_{\lambda a}}{\Phi_{\lambda i}}$ | $\alpha_\lambda$ | |
| **6.9 spectral reflectance:** Spectral radiant heat flow rate reflected by a surface, $\Phi_{\lambda r}$, divided by the incident spectral radiant heat flow rate, assuming that the incident radiation is isotropic:<br>$\varrho_\lambda = \frac{\Phi_{\lambda r}}{\Phi_{\lambda i}}$ | $\varrho_\lambda$ | |
| **6.10 spectral transmittance:** Spectral radiant heat flow rate transmitted by a surface, $\Phi_{\lambda t}$, divided by the incident spectral radiant heat flow rate, assuming that the incident radiation is isotropic:<br>$\tau_\lambda = \frac{\Phi_{\lambda t}}{\Phi_{\lambda i}}$ | $\tau_\lambda$ | |
| **6.11 spectral directional absorptance:** Spectral radiance absorbed by a surface, $L_{\Omega\lambda a}$, divided by the spectral directional incident radiance, $L_{\Omega\lambda i}$:<br>$\alpha_{\Omega\lambda} = \frac{L_{\Omega\lambda a}}{L_{\Omega\lambda i}}$ | $\alpha_{\Omega\lambda}$ | |

| | Symbol for quantity | Symbol for SI unit (including multiple or sub-multiple) |
|---|---|---|
| **6.12 spectral directional reflectance**: Spectral radiance reflected by a surface in the direction $\Omega'$, $L_{\Omega'\lambda r}$, divided by the spectral directional incident radiance, $L_{\Omega\lambda i}$:<br>$\varrho_{\Omega\lambda} = \frac{L_{\Omega'\lambda r}}{L_{\Omega\lambda i}}$<br>NOTE — The reflection can be either diffuse or specular. | $\varrho_{\Omega\lambda}$ | |
| **6.13 spectral directional transmittance**: Spectral radiance transmitted by a surface in the direction $\Omega'$, $L_{\Omega'\lambda t}$, divided by the spectral incident radiance, $L_{\Omega\lambda i}$:<br>$\tau_{\Omega\lambda} = \frac{L_{\Omega'\lambda t}}{L_{\Omega\lambda i}}$<br>NOTE — The transmission can be either unidirectional or diffuse. | $\tau_{\Omega\lambda}$ | |

## 7 Terms related to a semi-transparent medium receiving a thermal radiation — Combined conduction and radiation heat transfer

| | | |
|---|---|---|
| **7.1 spectral directional extinction coefficient**: Spectral radiance linear attenuation due to absorption along the direction $\vec{\Delta}$ and scattering along any other direction, divided by the incident spectral radiance:<br>$\beta_{\Omega\lambda} = \frac{dL^{E}_{\Omega\lambda}}{ds} \times \frac{1}{L_{\Omega\lambda}}$ | $\beta_{\Omega\lambda}$ | $m^{-1}$ |
| **7.2 spectral directional absorption coefficient**: Spectral radiance linear attenuation due to absorption along the direction $\vec{\Delta}$, divided by the incident spectral radiance:<br>$\varkappa_{\Omega\lambda} = \frac{dL^{A}_{\Omega\lambda}}{ds} \times \frac{1}{L_{\Omega\lambda}}$ | $\varkappa_{\Omega\lambda}$ | $m^{-1}$ |
| **7.3 spectral directional scattering coefficient**: Spectral radiance linear attenuation along the direction $\vec{\Delta}$, due to scattering along any other direction, divided by the incident spectral radiance:<br>$\sigma_{\Omega\lambda} = \frac{dL^{S}_{\Omega\lambda}}{ds} \times \frac{1}{L_{\Omega\lambda}}$<br>NOTE — The terms $\beta_{\Omega\lambda}$, $\varkappa_{\Omega\lambda}$ and $\sigma_{\Omega\lambda}$ follow the relationship<br>$\beta_{\Omega\lambda} = \varkappa_{\Omega\lambda} + \sigma_{\Omega\lambda}$ | $\sigma_{\Omega\lambda}$ | $m^{-1}$ |
| **7.4 mass spectral directional extinction coefficient**: Spectral directional extinction coefficient divided by the density of the semi-transparent medium:<br>$\beta'_{\Omega\lambda} = \frac{\beta_{\Omega\lambda}}{\varrho}$ | $\beta'_{\Omega\lambda}$ | $m^2/kg$ |

| Symbol for quantity | Symbol for SI unit (including multiple or sub-multiple) |
|---|---|

**7.5 mass spectral directional absorption coefficient:** Spectral directional absorption coefficient divided by the density of the semi-transparent medium:

Symbol: $\varkappa'_{\Omega\lambda}$ ; SI unit: m²/kg

$$\varkappa'_{\Omega\lambda} = \frac{\varkappa_{\Omega\lambda}}{\varrho}$$

**7.6 mass spectral directional scattering coefficient:** Spectral directional scattering coefficient divided by the density of the semi-transparent medium:

Symbol: $\sigma'_{\Omega\lambda}$ ; SI unit: m²/kg

$$\sigma'_{\Omega\lambda} = \frac{\sigma_{\Omega\lambda}}{\varrho}$$

NOTE — If the semi-transparent medium is an isotropic material we have

$$\beta_{\Omega\lambda} = \beta_\lambda, \varkappa_{\Omega\lambda} = \varkappa_\lambda, \sigma_{\Omega\lambda} = \sigma_\lambda$$

If it is an isotropic and grey material we have

$$\beta_{\Omega\lambda} = \beta, \varkappa_{\Omega\lambda} = \varkappa, \sigma_{\Omega\lambda} = \sigma$$

**7.7 spectral directional optical thickness:** Value defined by

Symbol: $\tau_{\Omega\lambda}$

$$\tau_{\Omega\lambda}(d) = \int_0^d \beta_{\Omega\lambda}(s)\, \mathrm{d}s$$

for a layer of thickness $d$, is a measure of the ability of a given path length of semi-transparent material to attenuate thermal radiation of wavelength $\lambda$. For homogeneous isotropic and isothermal layers $\beta_{\Omega\lambda}(d)$ = constant, and $\tau_\lambda = \beta_\lambda \cdot d$.

**7.8 phase function:** Mathematical function describing the space distribution of the scattered radiation:

Symbol: $p_\lambda$

$$\frac{p_\lambda(\vec{\Delta}' \rightarrow \vec{\Delta})\mathrm{d}\Omega}{4\pi}$$

represents the probability for an incident radiation inside the solid angle $\mathrm{d}\Omega'$ around the direction $\vec{\Delta}'$ to be scattered in the unit solid angle around direction $\vec{\Delta}$.

NOTE — It characterizes an anisotropic scattering material. If the scattered radiation is isotropic $p_\lambda(\vec{\Delta}' \rightarrow \vec{\Delta}) = 1$.

**7.9 spectral directional albedo:** Spectral directional scattering coefficient divided by the spectral directional extinction coefficient:

Symbol: $\omega_{\Omega\lambda}$

$$\omega_{\Omega\lambda} = \frac{\sigma_{\Omega\lambda}}{\beta_{\Omega\lambda}}$$

NOTE — For isotropic media, $\omega_{\Omega\lambda}$ is independent of the direction and the spectral term $\omega_\lambda$ may replace it. For absorbing, non-scattering media ($\sigma_\lambda = 0$), $\omega_\lambda = 0$, and for scattering non-absorbing ($\varkappa_\lambda = 0$), $\omega_\lambda = 1$.

**7.10 semi-transparent plane layer:** Semi-transparent layer of thickness $d$, limited by two infinite, plane and parallel boundaries of given thermal and optical characteristics.

| | Symbol for quantity | Symbol for SI unit (including multiple or sub-multiple) |
|---|---|---|
| 7.11 – 7.13 | | |
| 7.14 | $\lambda_r$ | W/(m·K) |
| 7.15 | $\mathcal{T}$ | W/(m·K) |
| 7.16 | $\lambda_r$ | W/(m·K) |

**7.11 equation of radiative transfer:** Mathematical relation describing the variation along a path of the spectral radiance in an absorbing, emitting and scattering medium.

NOTE — The solution of this equation will depend on the radiative properties of the medium: spectral extinction coefficient, spectral albedo and spectral phase function, and on the thermal and optical boundary conditions.

**7.12 Rosseland, diffusion approximation:** Approximation of the equation of radiative transfer considering the medium optically thick and without taking into consideration the boundary conditions.

**7.13 Schuster-Schwartzschild, two-flux approximation:** Approximation of the equation of radiative transfer for one dimensional planar geometry (semi-transparent plane layer) based on the assumption that the spectral radiances with positive components of direction can be integrated in a single term, $q_{r\lambda}^{+}$, while spectral radiances with negative components can be integrated in a single term, $q_{r\lambda}^{-}$.

**7.14 radiative thermal conductivity or radiativity:** Quantity defined by the following relation:

$$\vec{q}_r = -\lambda_r \operatorname{grad} T$$

For a plane layer the relationship may be rewritten in the following way:

$$q_r = -\lambda_r \frac{\partial T}{\partial n}$$

where $n$ is the normal to the layer.

NOTE — These relations are the consequence of Rosseland approximation (7.12) and their advantage is that they provide simple relations to express the total radiative density of heat flow rate, similar to Fourier's law for pure conductive heat transfer.

In case of insulating materials there can be situations where the thickness is high enough to allow for the characterization of the layer through the sum of two independent terms, one corresponding to conduction through the solid matrix and enclosed gas, and another to radiation. The last term is then called "radiativity", $\lambda_r$, as opposed to "conductivity". While considering only radiation heat transfer within an insulating material, radiativity is formally defined as radiative thermal conductivity, but to adhere to test procedures, is best understood, thinking of material layers of increasing thickness, as an increment in layer thickness divided by the corresponding increment in layer resistance when the conditions outlined in 7.15 to 7.18 apply (see also figure 4). In this case, 7.14 is identical to 7.16.

**7.15 transfer factor:** Characterizes an insulating **product** in relation with the combined conduction and radiation heat transfer; it depends on experimental conditions and is expressed by

$$\mathcal{T} = \frac{qd}{\Delta T} = \frac{d}{R}$$

NOTE — It may be derived from the measurement of $q$, $d$ and $\Delta T$ in a guarded hot plate; it is a material property only when $d \gg d_\infty$ (see figure 4).

**7.16 radiativity:** Characterizes an insulating material in relation with the radiation heat transfer only; it is expressed by

$$\lambda_r = \left(\frac{\Delta d}{\Delta R_r}\right)_{d > d_\infty}$$

| Symbol for quantity | Symbol for SI unit (including multiple or sub-multiple) |
|---|---|

where $R_r$ can be seen as a thermal resistance due to heat transfer by radiation alone and where $d_\infty$ is as shown in figure 4.

NOTE — It may be derived from the measurement of $q$, $d$ and $\Delta T$ under vacuum when the conduction heat transfer in the solid matrix is negligible.

**7.17 combined gaseous and solid conductivity**: Characterizes an insulating material in relation with the pure conduction heat transfer; similarly to $\lambda_r$, it is expressed by

| Symbol for quantity | Symbol for SI unit |
|---|---|
| $\lambda_{cd}$ | W/(m·K) |

$$\lambda_{cd} = \left(\frac{\Delta d}{\Delta R_{cd}}\right)_{d > d_\infty}$$

where $R_{cd}$ can be seen as a thermal resistance due to heat transfer by pure conduction and $d_\infty$ is as shown in figure 4.

NOTE — Generally, $\lambda_{cd}$ is computed from a theoretical model.

**7.18 thermal transmissivity**: Characterizes an insulating **material** in relation with the combined conduction and radiation heat transfer; it is independent of the experimental conditions and it is expressed by

| Symbol for quantity | Symbol for SI unit |
|---|---|
| $\lambda_t$ | w/(m·K) |

$$\lambda_t = \left(\frac{\Delta d}{\Delta R}\right)_{d > d_\infty}$$

where $R$ is the thermal resistance due to combined conduction and radiation heat transfer (see ISO 7345 : 1987, 2.7); $d_\infty$ is as shown in figure 4.

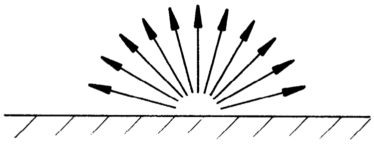
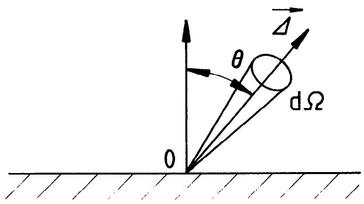
NOTE — According to the preceding definitions, the thermal transmissivity can also be written as

$$\lambda_t = \lambda_{cd} + \lambda_r$$

Thermal transmissivity can be seen as the limit reached by the transfer factor in thick layers where combined conduction and radiation heat transferred are considered.

This quantity is sometimes called "apparent", "equivalent", or "effective" thermal conductivity (see ISO 7345 : 1987, annex). See figure 4.

**Table 1 — Summary of the concepts**

| Hemispherical | Directional |
|---|---|
|  |  |
| **Spectral hemispherical** | **Spectral directional** |
| $\Phi_\lambda, M_\lambda, \varepsilon_\lambda, E_\lambda, J_\lambda$<br>$\alpha_\lambda, \varrho_\lambda, \tau_\lambda$<br>$\beta_\lambda, \varkappa_\lambda, \sigma_\lambda$<br>$\beta'_\lambda, \varkappa'_\lambda, \sigma'_\lambda$ | $I_{\Omega\lambda}, L_{\Omega\lambda}, \varepsilon_{\Omega\lambda}$<br>$\alpha_{\Omega\lambda}, \varrho_{\Omega\lambda}, \tau_{\Omega\lambda}$<br>$\beta_{\Omega\lambda}, \varkappa_{\Omega\lambda}, \sigma_{\Omega\lambda}$<br>$\beta'_{\Omega\lambda}, \varkappa'_{\Omega\lambda}, \sigma'_{\Omega\lambda}$ |
| **Total hemispherical** | **Total directional** |
| $\Phi, M, \varepsilon, E, J$<br>$\alpha, \varrho, \tau$<br>$\beta, \varkappa, \sigma$ | $I_\Omega, L_\Omega, \varepsilon_\Omega$<br>$\alpha_\Omega, \varrho_\Omega, \tau_\Omega$<br>$\beta_\Omega, \varkappa_\Omega, \sigma_\Omega$<br>$\beta'_\Omega, \varkappa'_\Omega, \sigma'_\Omega$ |

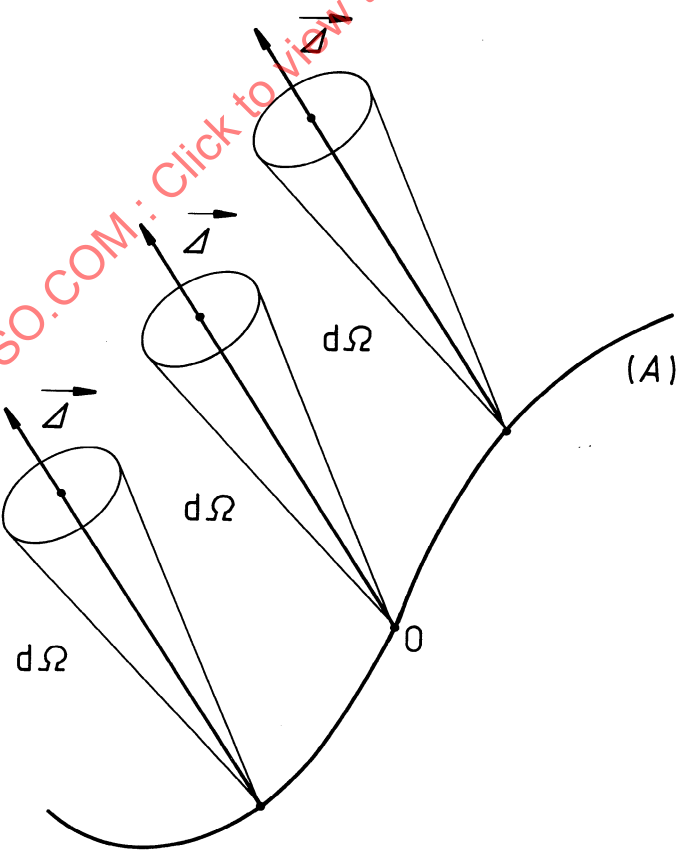



**Figure 2 — Definition of the intensity**

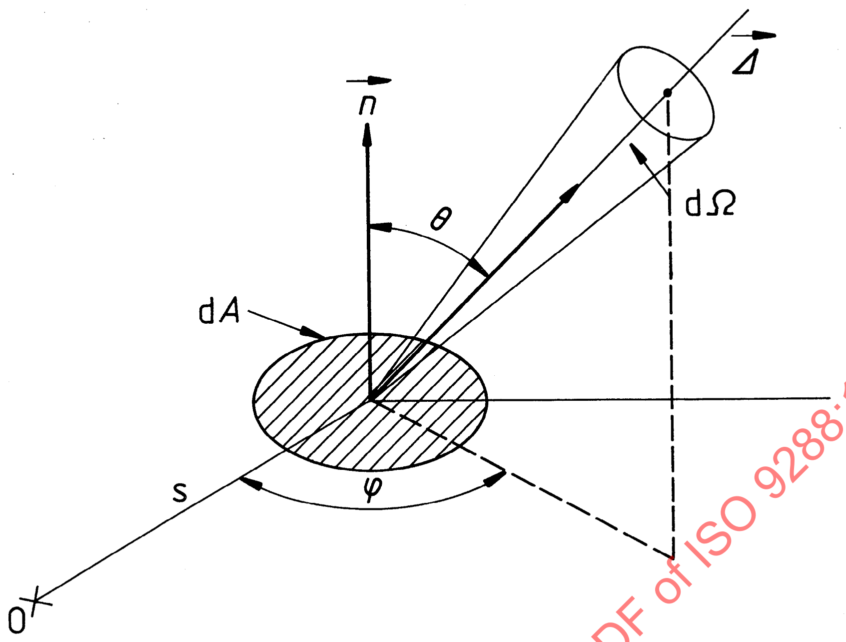
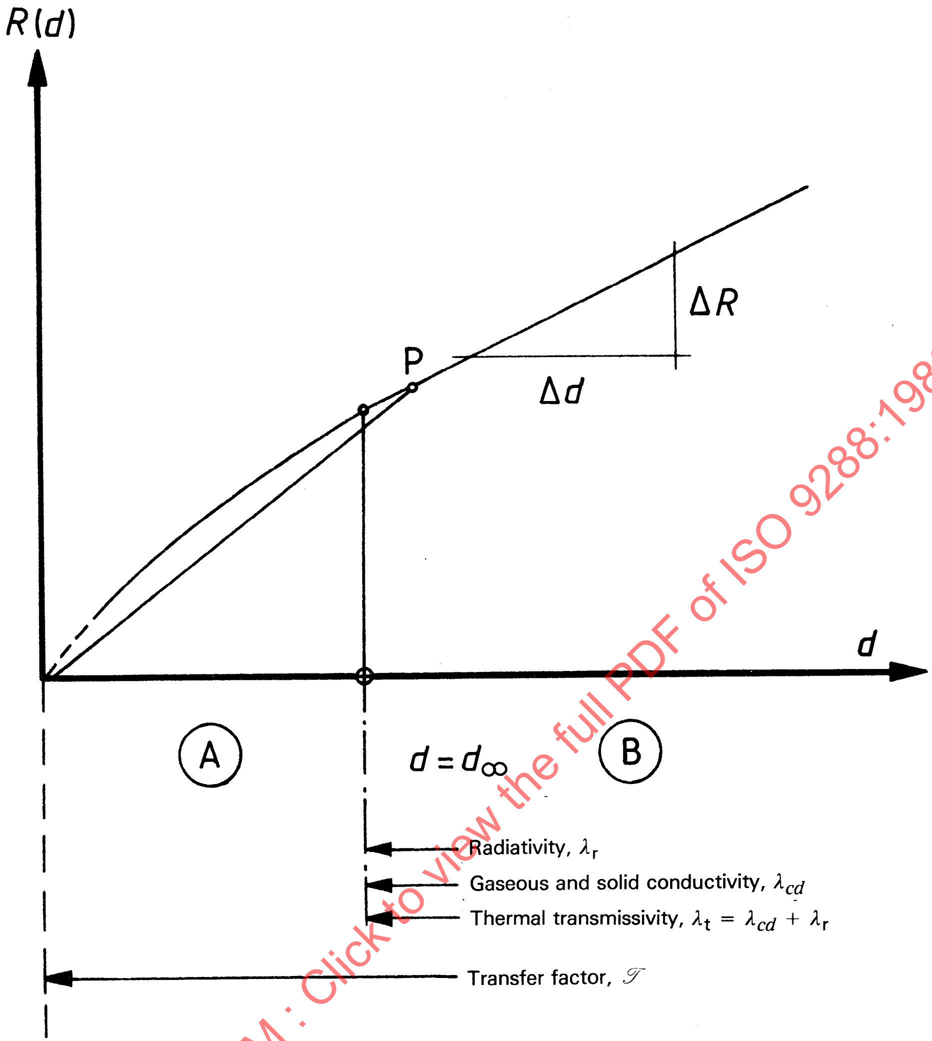



Figure 3 — Definition of the radiance






Zone A ($d < d_\infty$): The ratio $\Delta d/\Delta R$ is not constant, $\lambda_t$ cannot be measured; the transfer factor, $\mathscr{T}$, is not an intrinsic material property as it depends on experimental conditions.

Zone B ($d \geqslant d_\infty$): The ratio $\Delta d/\Delta R$ is constant; the thermal transmissivity, $\lambda_t$, that is an intrinsic material property independent of the experimental conditions, can now be measured. In this case we can also define $\lambda_r$ and $\lambda_{cd}$ as material properties and put $\lambda_t = \lambda_{cd} + \lambda_r$. Nevertheless , $\mathscr{T} = d/R$ is not yet independent of the thickness $d$; see point P. $\mathscr{T} = \lambda_t$ will take place only for $d \gg d_\infty$.

**Figure 4 — Thermal resistance versus thickness**