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2.4 Radiant properties of materials

Radiant properties of a material describe its ability to emit, absorb, reflect and transmit optical radiation.

Terminology of radiant properties of materials is probably one the most confusing areas of technical terminology. Authors of different publications use different and sometimes inconsistent definitions. The situation is so complicated that some parameters used in literature to describe material ability to emit, absorb, reflect and transmit radiation were not included in the well known terminology standard of optical radiation - the International Lighting Vocabulary [1] - as the CIE decided that further work was needed to establish proper names and definitions of some parameters; particularly describing material ability to reflect and transmit radiation. Next, although the ILV can be considered as the most important terminology standard, there are other standards or books [4,5,6] that propose solutions that differ from the ones found in the ILV. Further on, even the authors [7] that generally accepted the terminology proposed in the IVL add their own exceptions. And finally there are publications that use terminology that is inconsistent width both with the ILV or the works [4,5,6].

According to a school of terminology proposed in work [2] the words used to describe the various radiometric properties of materials should have very specific meaning; especially their endings. In this way, any word that ends in *ion* describes a process: emission, absorption, reflection, transmission. Any words that ends in *ance* represents a property of a specific sample. Finally, any words that ends in *ivity* represents a property of the generic material.
The International Lighting Vocabulary of the CIE generally follows this school of thought and proposes following parameters: reflectance and reflectivity, absorptance and absorptivity, transmittance and transmissivity to describe property of a specific sample or a property of the generic material.

Reflectance (for incident radiation of a given spectral composition, polarization and geometrical distribution) (ρ) is defined in the ILV as a ratio of the reflected flux to the incident flux in the given conditions. Reflectivity (of a material) (ρ_∞) is reflectance of a layer of the material of such a thickness that there is no change of reflectance with increase in thickness.

Absorptance (α) is defined as ratio of the flux absorbed by the material to flux incident on it under specified conditions. Spectral absorptivity (of an absorbing material) $\alpha_{i,o}(\lambda)$ is spectral internal absorptance of a layer of the material such that the path of the radiation is of unit length, and under the conditions in which the boundary of the material has no influence.

Transmittance (for incident radiation of a given spectral composition, polarization and geometrical distribution) (τ) is ratio of the transmitted flux to the incident flux in the given conditions. Spectral transmissivity (of an absorbing material) $\tau_{i,o}(\lambda)$ is spectral internal transmittance of a layer of the material such that the path of the radiation is of unit length, and under the conditions in which the boundary of the material has no influence.

As pointed by Siegel and Howell [4] for substances opaque at the wavelengths of emission, the intrinsic and the extrinsic parameters describing material ability to emit radiation would be the same as the emission of radiant flux from a opaque material is a surface phenomenon. Probably because of this reason the ILV uses only one term "the emissivity" and symbol ε to describe emissive properties of non-blackbodies surfaces. However, the *1993 Handbook of Fundamentals of the American Society of Heating , Refrigerating, and Air- Conditioning Engineers* [5] uses term "emittance" and the symbol ε to describe emissive properties of actual pieces of materials and points that the term emissivity refers to the property of materials that are optically smooth and thick enough

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to be opaque. A relatively new American Society for Testing of Materials (ASTM) standard [6] follows this terminology but uses the Roman letter e for emittance and the Greek letter ε for emissivity. Next, there are publications [3] that use the terms "emittance" to mean flux density (an equivalent of earlier defined exitance), not as a mean of radiation efficiency. Further on, there exist publications [8,11] where the terms "absorptivity", "reflectivity" and "transmissivity" have meanings of the terms "absorptance", "reflectance" and "transmittance" defined according to earlier presented scheme. Finally, the term "transmission" is used in the Handbook of Infrared &Electro-Optical Systems of SPIE [9] as a quantity describing material property in situation when according to the mentioned earlier standards [1,5,6] this terms is restricted to describe the process.

We will keep to the recommendation of the ILV through the remainder of this book and use the terms "emissivity", "absorptance", "reflectance" and "transmittance" to describe properties of a specific sample. However, a reader must be aware that this school of terminology is not universally accepted.

For people carrying out not-contact temperature measurements material ability to emit radiation is the most important material property. Therefore, in this subchapter we will concentrate on different kinds of the term "emissivity[1]" used in literature to describe material ability to emit radiation and relationships between emissivity, absorptance, reflectance and transmittance. Because of the mentioned earlier confusion in terminology only these types of emissivity, absorptance, reflectance and transmittance really needed to explain principles of non-contact temperature measurement will be defined next. This limitation is really important as at least eight types of emissivity, four types of absorptance, eight types of reflectance and eight types of transmittance are used in literature to describe material ability to absorb, reflect and transmit radiation.

Emission properties

A blackbody is an ideal radiator which emits as much radiant energy as possible. Such emission can occur only inside an isothermal closed cavity. It is not possible to observe emission of this completely closed cavity. However, it is possible to manufacture a technical blackbody made as a cavity with a small hole in one of the cavity walls. Emission of such a technical blackbody is very close to that of an ideal blackbody.

Emission of real materials is lower that that of an ideal blackbody and we need parameters to characterize the emissive properties of such real materials. The properties are defined by comparison with that of blackbodies at the same temperature and can be described by four parameters: spectral directional emissivity, spectral (hemispherical) emissivity, directional (total) emissivity and total (hemispherical)[2] emissivity [8,11].

The spectral directional emissivity $\varepsilon_{\lambda,\varphi}$ depends on the wavelength λ and the angle φ and is defined as in the formula

$$\varepsilon_{\lambda,\varphi} = \frac{L_{\lambda,\varphi}}{L_{bb,\lambda,\varphi}} \tag{2.16}$$

where $L_{\lambda,\varphi}$ is the spectral radiance of the material for the wavelength λ in the direction φ and $L_{bb,\lambda,\varphi}$ is the spectral radiance of the blackbody for the wavelength λ in the direction φ.

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[1] Only two kinds of emissivity (directional emissivity and hemispherical emissivity) are defined in the ILV.

[2] The adjectives in brackets are usually not mentioned.

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A particular kind of the spectral emissivity in the direction φ occurs for φ=0; in the direction normal to the radiating surface as the value of the spectral emissivity is the greatest in this direction. The spectral emissivity in the normal direction $\varepsilon_{\lambda,n}$ can be expressed by the formula

$$\varepsilon_{\lambda,\varphi} = \frac{L_{\lambda,n}}{L_{bb,\lambda,n}} \qquad (2.17)$$

where $L_{\lambda,n}$ is the spectral radiance of material in the normal direction, and $L_{bb,\lambda,n}$ is the spectral radiance of the blackbody in normal direction.

On account of the needs of visual pyrometry, values of normal spectral emissivity for red light are often presented in many emissivity tables [11]. This quantity is expressed by $\varepsilon_{\lambda=0.65,n}$, where 0.65 is the wavelength in μm.

The spectral (hemispherical) emissivity ε_{λ} is defined as ratio of the material spectral exitance M_{λ} to the blackbody spectral exitance $M_{bb,\lambda}$

$$\varepsilon_{\lambda} = \frac{M_{\lambda,n}}{M_{bb,\lambda,n}}. \qquad (2.18)$$

Directional (total) emissivity in the direction φ is expressed as ratio of the material radiance $L_{T,\varphi}$ in the direction φ to the blackbody radiance $L_{T,\varphi}$ in the direction φ

$$\varepsilon_{T,\varphi} = \frac{L_{T,\varphi}}{L_{bb,T,\varphi}}. \qquad (2.19)$$

Directional total emissivity in the normal direction $\varepsilon_{T,n}$ is a particularly privileged kind of directional total emissivity $\varepsilon_{T,\varphi}$ for the same reasons as the spectral emissivity in normal direction $\varepsilon_{\lambda,n}$. It can be expressed by the formula

$$\varepsilon_{T,n} = \frac{L_{T,n}}{L_{bb,T,n}}. \qquad (2.20)$$

where $L_{T,n}$ is the material radiance in the normal direction, and $L_{bb,T,n}$ is the blackbody radiance in normal direction. This type of emissivity is most frequently measured and quoted in literature. It is often confused with the spectral (hemispherical) emissivity ε_{λ}.

Finally, the total hemispherical emissivity ε_T is defined as ratio of the material exitance M_T to the blackbody exitance $M_{bb,T}$

$$\varepsilon_{T} = \frac{M_{T}}{M_{bb,T}}. \qquad (2.21)$$

The spectral directional emissivity $\varepsilon_{\lambda,\varphi}$ gives information about material emissive properties for any the wavelength λ and the angle φ. On the basis of the known spectral directional emissivity $\varepsilon_{\lambda,\varphi}$ it is possible to calculate other types of emissivity: the spectral (hemispherical) emissivity ε_{λ}, the directional total emissivity $\varepsilon_{T,n}$ and the total hemispherical emissivity ε_T. However, as the spectral directional emissivity $\varepsilon_{\lambda,\varphi}$ is often a complex function of the wavelength λ and the angle φ it is difficult to determine it experimentally. Therefore, functions of the spectral directional emissivity $\varepsilon_{\lambda,\varphi}$ are very rarely published in literature.

There are four types of emissivity that are usually presented in emissivity tables found in literature: the total hemispherical emissivity ε_T, the directional total emissivity in normal direction $\varepsilon_{T,n}$, the spectral directional emissivity in normal direction $\varepsilon_{\lambda,n}$ and spectral directional emissivity in the normal direction $\varepsilon_{\lambda=0.65,n}$ for wavelength λ=0.65μm. However, their usefulness for user of modern non-contact radiation thermometers is usually limited because of a few reasons.

First, the total emissivity ε_T gives information about material emission into whole hemisphere and in whole optical range. Therefore, values of the ε_T are useful only in case of diffusive gray-body types objects, emissive properties of which do not depend on the angle φ and the wavelength λ.

Second, directional total emissivity in the normal direction $\varepsilon_{T,n}$ presents information about material ability to emit radiation only into one direction (φ = 0) and in whole range of optical radiation. The angle φ often differs from 0 during real measurements. As emissive properties of most material depend on the angle of observation φ the value of the $\varepsilon_{T,n}$ can be misleading. There is also other reason for limited usefulness of the directional total emissivity in the normal direction $\varepsilon_{T,n}$. Most real materials are selective materials, emissive properties of which depend on wavelength in situation when sensitivity of most non-contact thermometers depend on wavelength, too.

Third, the spectral directional emissivity in the normal direction $\varepsilon_{\lambda,n}$ presents information about material ability to emit radiation into only one direction (φ = 0). Therefore, the values of $\varepsilon_{\lambda,n}$ can be misleading when measurements are done for other angles. In spite of this, the published functions $\varepsilon_{\lambda,n}(\lambda)$ are usually quite useful as they enable estimation of object emissivity in the thermometer spectral band. However, there is often a problem to find suitable data of $\varepsilon_{\lambda,n}$ in the required spectral band.

Fourth, values of spectral directional emissivity in the normal direction $\varepsilon_{\lambda=0.65,n}$ for the wavelength λ=0.65μm are often useless in case of typical infrared systems as the spectral emissivity $\varepsilon_{\lambda,n}$ in infrared range can differ quite significantly from $\varepsilon_{\lambda=0.65,n}$.

Relationships between radiative properties of materials

There are two most important relationships between radiative properties of materials. The first is the radiative energy balance that connects absorptance, reflectance and transmittance. The second is Kirchhoff's law that relates absorptance and emissivity.

Applying energy balance on the surface element, we get that that the sum of hemispherical total absorptance α_T, the hemispherical total reflectance ρ_T and the hemispherical total transmittance τ_T equals 1

$$\alpha_T + \rho_T + \tau_T = 1 \tag{2.22}$$

Next, assuming elementary spectral interval and that some phenomena (luminescence, Raman scattering) are negligible we can write

$$\alpha_\lambda + \rho_\lambda + \tau_\lambda = 1 \tag{2.23}$$

where α_λ is the hemispherical spectral absorptance of radiation from the hemisphere, ρ_λ is the hemispherical spectral reflectance of radiation from hemisphere into hemisphere, and τ_λ is hemispherical spectral transmittance of radiation from hemisphere into hemisphere.

Radiation that reaches material surface comes often not from the whole hemisphere but only from a certain direction. For such a situation the relationships between directional quantities that can be treated as directional spectral energy balance can be written as

$$\alpha_{\lambda,\varphi} + \rho_{\lambda,\varphi} + \tau_{\lambda,\varphi} = 1 \tag{2.24}$$

where $\alpha_{\lambda,\varphi}$ is the directional spectral absorptance of radiation from the direction φ, $\rho_{\lambda,\varphi}$ is directional-hemispherical spectral reflectance of radiation from the direction φ into hemisphere, and $\tau_{\lambda,\varphi}$ is the directional-hemispherical spectral transmittance.

The Kirchhoff's law states that at local thermodynamic equilibrium of an element of material surface, that the directional spectral emissivity $\varepsilon_{\lambda,\varphi}$ is equal to the directional spectral absorptance $\alpha_{\lambda,\varphi}$

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$$\varepsilon_{\lambda,\varphi} = \alpha_{\lambda,\varphi} \qquad (2.25)$$

It means that material ability to emit radiation into the direction φ is directly connected to its ability to absorb radiation from the direction φ.

Formulas (2.24, 2.25) enable indirect determination of the directional spectral emissivity $\varepsilon_{\lambda,\varphi}$ when the directional-hemispherical spectral reflectance $\rho_{\lambda,\varphi}$ and the directional-hemispherical spectral transmittance $\tau_{\lambda,\varphi}$ are known

$$\varepsilon_{\lambda,\varphi} = 1 - \rho_{\lambda,\varphi} - \tau_{\lambda,\varphi} \,. \qquad (2.26)$$

For opaque materials the above presented relationship can be transformed to a new form

$$\varepsilon_{\lambda,\varphi} = 1 - \rho_{\lambda,\varphi} \,. \qquad (2.27)$$

Principle of temperature measurement with active systems is based on equations (2.26, 2.27) as they enable indirect way of emissivity determination by measuring relations between the incident flux, the reflected flux and the transmitted flux. However, it must be emphasized that to determine $\varepsilon_{\lambda,\varphi}$ accurately it is necessary to measure not the radiation reflected into the direction φ but into the hemisphere. This misconception brought significant errors in great number of measurements.

Emissivity of common materials

Tables or graphs with data about the four types of emissivity (the total hemispherical emissivity ε_T, directional total emissivity in the normal direction $\varepsilon_{T,n}$, the spectral directional emissivity in normal direction $\varepsilon_{\lambda,n}$ and spectral directional emissivity in the normal direction $\varepsilon_{\lambda=0.65,n}$ for wavelength λ=0.65µm) can be found in great number of books, papers, reports etc. However, in addition to the discussed in Section 2.4.1 limitations of these parameters there are additional problem with interpretation of typical emissivity data found in literature. First, different sources present sometimes completely inconsistent values. Second, emissivity values are often unclearly defined or they are not defined at all. Parameters in many tables are termed only “emissivity” without any additional explanation whether it is the total hemispherical emissivity ε_T, directional total emissivity in the normal direction $\varepsilon_{T,n}$ or spectral directional emissivity in the normal direction $\varepsilon_{\lambda=0.65,n}$ for the wavelength λ=0.65µm. As an example can be treated Tab. 2.5 and Tab. 2.6 with emissivities of common materials published by one of leading manufacturers of thermal cameras [12]. The manufacturer, however, honestly emphasizes that the presented values are meant to be used only as a guide and can vary depending on many different factors. To summarize, we can say that in spite of numerous sources with emissivity data it is often difficult to find in literature information about value of object emissivity in real measurement conditions.

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Tab. 2.5. Typical emissivities of common metals

Material		**Temperature [°C]**	**Emissivity**
Aluminum:	foil (bright)	20	0.04
	weathered	20	0.83 - 0.94
Iron	cast, oxidized	100	0.64
	sheet, heavily rusted	20	0.69 - 0.96
Copper:	polished	100	0.05
	heavily oxidized	0.78	0.78
Nickel:	electroplated, polished	20	0.05
Stainless Steel (type 18-8)	polished	20	0.16
	oxidized	60	0.85
Steel	polished	100	0.07
	oxidized	200	0.79

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Tab. 2.6. Typical emissivities of other materials

Other materials:			
Brick	common red	20	0.93
Carbon candle soot		20	0.95
Concrete	dry	35	0.95
Glass	chemical ware	35	0.95
Oil	lubricating	17	0.87
	film thickness 0.03 mm	20	0.27
	film thickness 0.13 mm	20	0.72
	thick coating	20	0.82
Paint, oil	average of 16 colors	20	0.94
Paper	white	20	0.7 - 0.90
Plaster		20	0.86 - 0.90
Rubber	black 5	20	0.95
Skin	human	32	0.98
Soil	dry	20	0.92
	saturated with water	20	0.95
Water	distilled	20	0.96
	frost crystals	-10	0.98
	snow	-10	0.85
Wood	planed oak	20	0.90