Radiative Heat Transfer

Non-Blackbody Radiation

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Radiative Heat Transfer

General Characteristics

- Radiant characteristics of non-black, real surfaces differ from the ideal blackbodies in the following ways;
  1) E_λ from a real surface differs from a blackbody in both the amount and spectral distribution of emitted radiation at the same T.
  2) Non-black surfaces have values of absorptivity, $\alpha < 1$.
  3) Non-black surfaces may also reflect a portion of the incident radiation.
  4) Non-black surfaces may exhibit non-diffuse and/or spectral behavior.
- More specifically the transfer of radiant energy to/from non-black surfaces in general depends on the emissivity, absorptivity, reflectivity, and directional characteristics of the surfaces.

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Emissivity (ε) Characteristics

The ratio of radiation emitted by real surface to that emitted by blackbody is shown.

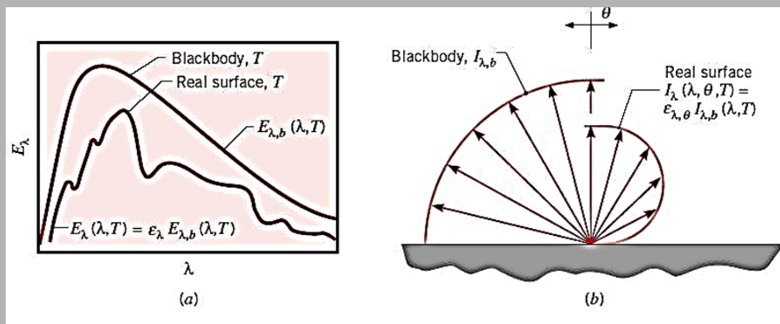

FIGURE 12.15 Comparison of blackbody and real surface emission. (a) Spectral distribution. (b) Directional distribution.

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Emissivity (ε) Characteristics

1) Spectral Hemispherical emissivity (ε_λ) all quantities are evaluated over the entire hemisphere at the same λ and T.

$$\varepsilon_\lambda = \left(\frac{E_\lambda(\lambda, T)}{E_{b\lambda}(\lambda, T)} \right)$$

Therefore, ε_λ = f(λ,T); but the temperature dependence is usually small and hence ignored.

$$E_\lambda = \oint_{\text{hemi}} I_{\lambda,e}(\lambda,\theta,\phi)\cos\theta\sin\theta\, d\theta\, d\phi \Rightarrow \pi I_{\lambda,e}(\lambda)$$

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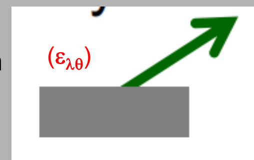
Emissivity (ε) Characteristics

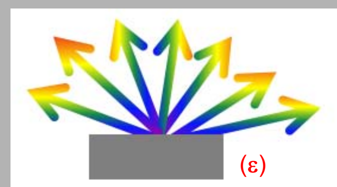
2) Monochromic (Spectral) Directional emissivity ($\varepsilon_{\lambda\theta}$) is of a single wavelength in a specific direction.



3) Total Hemispherical emissivity (ε) is evaluated over the entire hemisphere and all wavelengths.

$$\varepsilon = \frac{E(T)}{E_b(T)}$$

Although, ε = f(T); the T dependence is usually small and typically ignored.



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Emissivity (ε) Characteristics

$$\varepsilon = \frac{\int_0^\infty E_\lambda d\lambda}{\int_0^\infty E_{b\lambda} d\lambda}$$

$$\varepsilon = \frac{\int_0^\infty \varepsilon_\lambda(\lambda,T)E_{b\lambda}(\lambda,T)d\lambda}{\int_0^\infty E_{b\lambda}(\lambda,T)d\lambda}$$

$$\varepsilon = \frac{\int_0^\infty \varepsilon_\lambda(\lambda,T)E_{b\lambda}(\lambda,T)d\lambda}{\sigma T^4}$$

Note:

i) Since $E(T) = \varepsilon\sigma T^4 = \varepsilon E_b(T)$ where ε is a surface property.

ii) Recall, this assumes "n" of the bounding medium is unity.

iii) For the case in which $\varepsilon = \varepsilon_\lambda$ (i.e., wavelength independence), these surfaces are called grey bodies.

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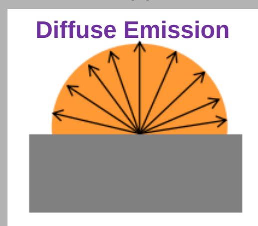
Emissivity (ε) Characteristics

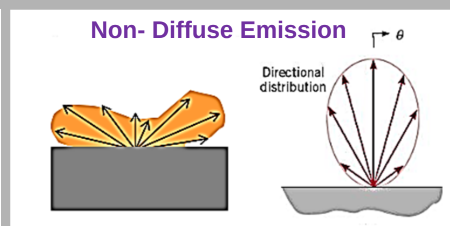
4) Total directional (Specular) emissivity (ε_θ) is over the entire spectrum, but for a single direction.

- Recall, surfaces that emit thermal radiation equally in all directions are diffuse emitters.

$$I_{\lambda,e}(\lambda,\theta,\phi) \Rightarrow I_{\lambda,e}(\lambda)$$

- Fortunately, many real surfaces such as industrially roughened surfaces approach diffuse conditions.





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Emissivity (ε) Characteristics

- The directional emissive power can be determined using the Lambert Cosine Law;

$$E_\theta = E_o \cos\theta$$

where E_o is taken normal to the surfaces.

- Therefore the specular emissivity follows;

$$\varepsilon_\theta = \frac{E_\theta(\theta,T)}{E_{b\theta}(\theta,T)}$$

- This can also be written in terms of flux (Φ);

$$\Phi = E = \oint_{hemi} I_e(\theta,\varphi)\cos\theta \, d\omega$$

$$d\Phi = dE = I_e(\theta,\varphi)\cos\theta \, d\omega$$

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Emissivity (ε) Characteristics

- or

$$I_e(\theta,\phi) = \frac{d\Phi}{d\omega \cos\theta}$$

where dΦ is the differential energy flux, which for emission only, is replaced by

$$I_e(\theta,\phi) = \frac{dE}{d\omega \cos\theta}$$

- This can also be rewritten as;

$$I_e(\theta,\phi)\cos\theta = \frac{dE}{d\omega} = E_\theta$$

and either, $E_\theta = \frac{dE}{d\omega}$ or $E_\theta = I_e(\theta,\phi)\cos\theta$

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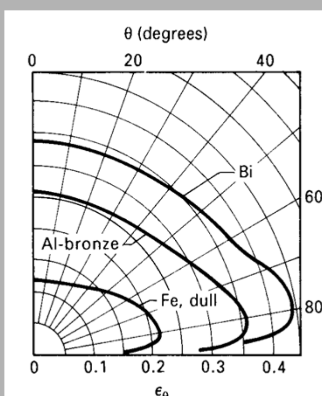
Emissivity (ε) Characteristics

$$\varepsilon_\theta = \frac{E_\theta(\theta,T)}{E_{b\theta}(\theta,T)} = \frac{I_e}{I_{be}}$$

where I is the directional emissive power.

Note:

1) Metallic surfaces follow Lambert's Cosine Law for **θ** < 40°, but for **θ** > 40°, ε_θ increases sharply before falling to zero at 90°.



(a) Metal surfaces.

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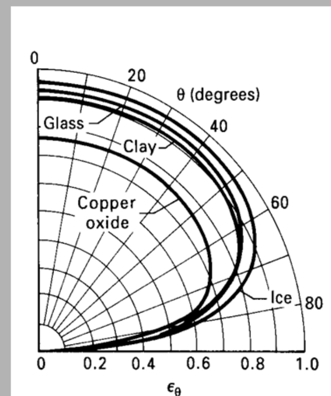
Emissivity (ε) Characteristics

Note:

2) Non-conductors are essentially diffuse for $\theta \leq 50°$, but also violate Lambert's cosine law at larger angles with ε_θ dropping to very small values.

3) Therefore, directional effects must be accounted for in engineering designs. This is usually accomplished by utilizing the hemispherical ε, which accounts for the radiant energy emitted into the entire region above the surface.



(b) Electric nonconducting surfaces.

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Emissivity (ε) Characteristics

Note:

i) No surface at the same temperature can emit more radiation than a blackbody on a monochromatic basis.

ii) When one observes metal glowing, radiation is being emitted in the visible wavelength range.

iii) Rules of thumb:

a) Electrical conductors are usually good emitters in the visible wavelength range.

b) Electrical non-conductors (insulators) are usually good emitters in the IR wavelength range.

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Selected Surface Emissivity (ε)

- A few examples of visible and IR emissivity are provided in the table below;

Surface	ε (visible)	ε (IR)
Snow	-------	0.82
Aluminum	0.30	0.05
White Paint	0.18	0.96
Red Paint	0.74	0.96
Black Paint	0.96	0.96

- The following is the greybody approximation for the $E_{g,\lambda}$ (spectral Emissive Power for a grey body);

$$E_{g\lambda} = \varepsilon \, E_{b\lambda}$$

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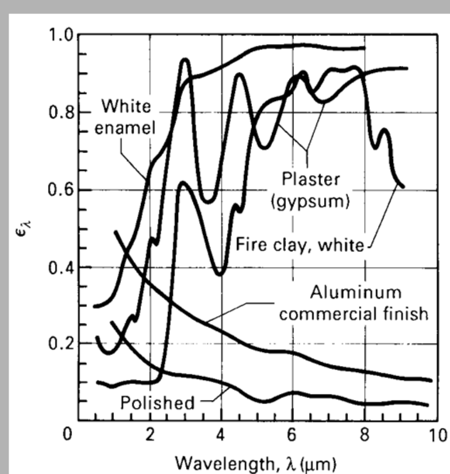
Selected Surface Emissivity (ε)

A table containing the emissivity of various surfaces can be obtained from the following web site at the Lawrence Berkeley National Laboratory at**:**

*www-eng.lbl.gov/~dw/projects/DW4229_LHC.../**emissivity**2.pdf*



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Absorptivity (α) Characteristics

- Real surfaces differ from blackbody surfaces in that they do not absorb all the incident thermal radiation.
- The absorption characteristics of a real surface may be directionally (specula) and/or spectrally selective

$$\alpha = \frac{\text{Absorbed Radiation}}{\text{Incident Radiation}} = \frac{G_\alpha}{G}$$

Recall, α_λ is a function of λ and T, i.e. f(λ,T).

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Absorptivity (α) Characteristics

1) Spectral Hemispherical absorptivity (α_λ) is the absorption of a particular wavelength when incident from the hemisphere. All quantities are evaluated over the entire hemisphere at the same λ.

$$\alpha_\lambda(\lambda) \equiv \frac{G_{\lambda,\text{abs}}(\lambda)}{G_\lambda(\lambda)}$$

where G_λ is the monochromatic irradiation, from all directions, incident on a surface.

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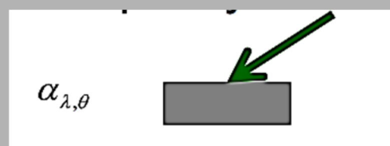
Absorptivity (α) Characteristics

2) Monochromatic (Spectral) Directional absorptivity ($\alpha_{\lambda\theta}$) is the absorption of a particular wavelength when incident from a specific direction.



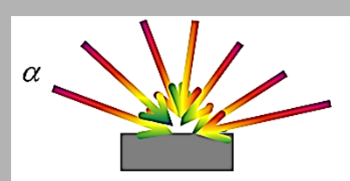
$$\alpha_{\lambda,\theta}(\lambda,\theta,\phi) \equiv \frac{\mathrm{I}_{\lambda,\mathrm{i},\mathrm{absorp}}(\lambda,\theta,\phi)}{\mathrm{I}_{\lambda,\mathrm{i}}(\lambda,\theta,\phi)}$$

Radiative Heat Transfer

Absorptivity (α) Characteristics

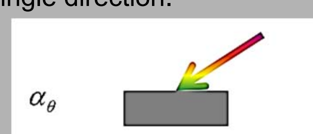
3) Total Hemispherical absorptivity (α) is the absorption of all wavelengths when incident over the entire hemisphere.

$$\alpha \equiv \frac{\mathrm{G}_{\mathrm{absorb}}}{\mathrm{G}}$$



4) Total directional (Specular) absorptivity (α_θ) s the absorption over the entire spectrum but for single direction.

$$\alpha_\theta(\theta,\phi) \equiv \frac{\mathrm{I}_{\mathrm{i},\mathrm{absorb}}(\theta,\phi)}{\mathrm{I}_{\mathrm{i}}(\theta,\phi)}$$



where $\mathrm{I}_{\lambda,\mathrm{i}} \rightarrow$ incident monochromatic intensity

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Absorptivity (α) Characteristics

- The notation α (T, source) is utilized to place emphasis on the fact that the total absorptivity α, depends on the spectral, directional and spatial characteristics of the incident radiation.

Note:

1) ε = f(T, surface characteristics)
2) α = f(T, surface characteristics, G characteristics)
3) As a result, the absorptivity (α) cannot be easily tabulated due to variations related to the radiation source.
4) For the case of opaque surfaces, the transmissivity, $\tau = 0$, so $\rho_\lambda + \alpha_\lambda = 1$ and also $\rho + \alpha = 1$ apply.

Radiative Heat Transfer

Reflectivity (ρ) Characteristics

1) Spectral Hemispherical reflectivity (ρ_λ) is the reflection of a particular wavelength incident on a surface and evaluated over the entire hemisphere at the same λ.

$$\rho_\lambda(\lambda) \equiv \frac{G_{\lambda,\mathrm{ref}}(\lambda)}{G_\lambda(\lambda)}$$

where G_λ is the monochromatic irradiation, from all directions, incident on a surface.

2) Monochromic (Spectral) Directional reflectivity ($\rho_{\lambda,\theta}$) is the reflection of a particular wavelength when incident from a specific direction.

$$\rho_{\lambda,\theta}(\lambda,\theta,\phi) \equiv \frac{I_{\lambda,\mathrm{i},\mathrm{ref}}(\lambda,\theta,\phi)}{I_{\lambda,\mathrm{i}}(\lambda,\theta,\phi)}$$

Radiative Heat Transfer

Reflectivity (ρ) Characteristics

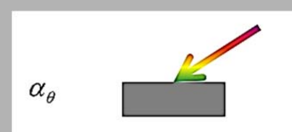
3) Total Hemispherical reflectivity (ρ) is the reflection of all wavelengths incident on a surface and evaluated over the entire hemisphere.

$$\rho = \frac{\text{Reflected Radiation}}{\text{Incident Radiation}} = \frac{G_\rho}{G}$$

$$\rho \equiv \frac{G_{ref}}{G}$$

4) Total directional (Specular) reflectivity (ρ_θ) is the reflection of all wavelengths incident on a surface, but evaluated for single direction.

$$\rho_\theta(\theta,\phi) \equiv \frac{I_{i,ref}(\theta,\phi)}{I_i(\theta,\phi)}$$



where $I_i \rightarrow$ total incident intensity

Radiative Heat Transfer

Reflectivity (ρ) Characteristics

- The reflection is diffuse if the intensity of the reflected thermal radiation is constant for all angles of irradiation and reflection.
- If the angle of reflection is equal to the angle of incidence, the reflection is specular (i.e. directional).
- Real surfaces have neither diffuse or specular irradiation properties.
- However, for design purposes, one can consider industrially rough surfaces to have diffuse properties, while polished and smooth surfaces exhibit near-specular characteristics.

Radiative Heat Transfer

Transmissivity (τ) Characteristics

- Ratio of transmitted irradiation to incident irradiation

$$\tau = \frac{\text{Transmitted Radiation}}{\text{Incident Radiation}} = \frac{G_\tau}{G}$$

Note:

a) Kirchhoff's law is always true, (e.g., spectral energy balance):

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

b) Diffuse emissivity and absorptivity do not vary with angle. So if a surface is diffuse or if a surface has diffuse irradiation then:

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

c) A hypothetical surface that would radiate as a blackbody, but with an $\varepsilon \leq 1$ and a constant λ is referred to as a Grey body.

d) If a surface is "diffuse and grey" then,

$$\varepsilon = \alpha$$

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Reflectivity (ρ) Determination

- Spectral basis: $\tau_\lambda + \alpha_\lambda + \rho_\lambda = 1$
  - For opaque case: $\rho_\lambda = 1 - \alpha_\lambda \quad since \ \tau_\lambda = 0$
    - If diffuse: $\alpha_\lambda = \varepsilon_\lambda$ So $\rho_\lambda = 1 - \varepsilon_\lambda$
- Total basis: $\tau + \alpha + \rho = 1$
  - For opaque case: $\rho = 1 - \alpha \quad \text{since} \ \tau = 0$
    - If diffuse: $\alpha = \varepsilon$ So $\rho = 1 - \varepsilon$

Radiative Heat Transfer

Non-Blackbody Radiation

Example 3.1: A diffusely emitting surface at 500 K has a spectral, directional emittance ($\varepsilon_{\lambda,\theta}$) that can be approximated as 0.5 in the range $0 < \lambda < 5$ μm and 0.3 for $\lambda > 5$ μm.

What is the total, hemispherical emissivity of this surface when surrounded by (a) air, and (b) a dielectric medium with an refractive index , n = 2 ?

Solution:

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Non-Blackbody Radiation

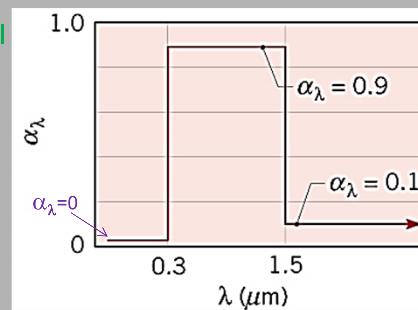
--- The End ---

Radiative Heat Transfer

Non-Blackbody Radiation

Example 12.49: Determination of the solar absorptivity and total emissivity of a opaque diffuse surface from knowledge of the spectral distribution of $\alpha_\lambda(\lambda)$ and the surface temperature.

Given: The Spectral, hemispherical absorptivity of an opaque surface.



FIND:
(a) Solar absorptivity, and
(b) Total, hemispherical emissivity for T_s = 340K.

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Example 12.49: Continued

--- The End ---

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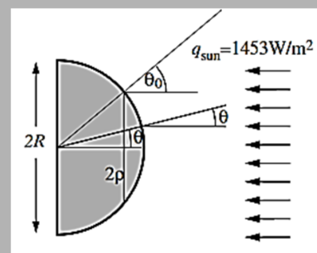
Non-Blackbody Radiation

Example 3.27: An antenna of a satellite may be approximated by a long half cylinder of length (L), which is exposed to sunshine as shown.

The antenna has a high thermal conductivity (i.e., is isothermal), and is coated with the material that may be assumed to act as a grey surface with the following directional characteristics $\varepsilon_{\theta\lambda}$:

$$\varepsilon_{\theta\lambda} = \begin{cases} 0.9, & 0 \le \theta < 40^\circ, \\ 0, & \theta > 40^\circ. \end{cases}$$

Determine the equilibrium temperature of the antenna, assuming it exchanges thermal energy with the sun and the cold outer space only.



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Non-Blackbody Radiation

Example 3.27: Solution Continued:

Radiative Heat Transfer

Non-Blackbody Radiation

Example 3.27: Solution Continued:

Radiative Heat Transfer

Non-Blackbody Radiation

Example 3.27: Solution Continued:

Radiative Heat Transfer

Non-Blackbody Radiation

Example 3.27: Solution Continued:

--- The End ---

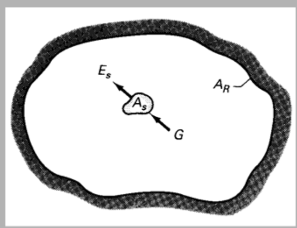
Radiative Heat Transfer

Derivation of Kirchhoff's Law

- Consider a small non-blackbody (A_s) placed within a large isothermal enclosure (A_R).
- Develop a relation between α and ε of the small body A_s.

Assume :

1) Steady State
2) Thermal equilibrium
3) The surface of the enclosure A_R is opaque ($\tau = 0$)
4) No reflected radiation ($\rho = 0$)
5) The enclosure forms a blackbody



- Perform a radiation energy balance:

Absorbed Thermal Radiation = Emitted Thermal Radiation

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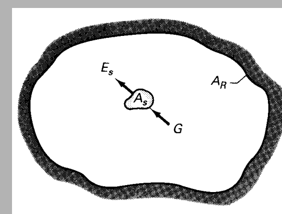
Derivation of Kirchhoff's Law

Absorbed Thermal Radiation = Emitted Thermal Radiation

$$\alpha_s G A_s = E_s A_s$$



where G is a result of the emitted radiation from the surface A_R, which is considered a blackbody, i.e.

$$G = E_b(T_R)$$

$$\alpha_s E_b(T_R) A_s = E_s A_s$$

- If the system is in thermal equilibrium: $T_R = T_s$ than the energy balance becomes;

$$\alpha_s E_b(T_s) A_s = \varepsilon_s E_b(T_s) A_s$$

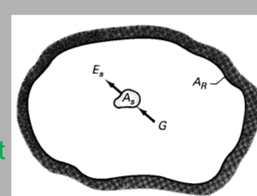
Radiative Heat Transfer

Derivation of Kirchhoff's Law

Absorbed Thermal Radiation = Emitted Thermal Radiation

$$\alpha_s E_b(T_s) = \varepsilon_s E_b(T_s)$$

$$\alpha_s = \varepsilon_s$$



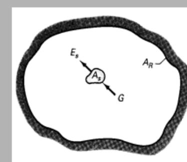
- Therefore a blackbody, which is a perfect absorber is also a perfect emitter.
- Note that the restrictions of thermal equilibrium and an isothermal blackbody enclosure were applied.
- A more general form of Kirchhoff's Law states that for a system in thermodynamic equilibrium

$$\alpha_\lambda = \varepsilon_\lambda$$

Radiative Heat Transfer

Derivation of Kirchhoff's Law

- Although this equation was derived under the equilibrium condition, this relation also applies to non-equilibrium system conditions or local thermodynamic equilibrium (LTE).



Note:

i) In general LTE asserts that the properties of the medium are functions of the local state of the medium.

ii) For radiation, LTE postulates that emission and absorption are determined by processes confined to a small volume element, i.e. small compared to the overall size of the system under study.

iii) Another way of stating LTE is when a material's population of energy states, which take part in the absorption and emission processes, can be approximated by their equilibrium distribution.

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Derivation of Kirchhoff's Law

- This is a consequence of α_λ and ε_λ being surface properties, that is they depend solely on the nature of the surface and it's temperature. Therefore, these magnitudes are independent of whether or not equilibrium or non-equilibrium conditions prevail.

- Although no distinction is usually made with regard to directional effects, in general the previous eqn is strictly valid for each direction and for each component of polarization, so:

$$\varepsilon_\lambda'(\lambda,\beta,\theta,\mathrm{T}) = \alpha_\lambda'(\lambda,\beta,\theta,\mathrm{T})$$

- In the case where both the irradiation is diffuse and the surface is diffuse, the following is valid.

$$\alpha_\lambda = \varepsilon_\lambda$$

Radiative Heat Transfer

Optical Characteristics

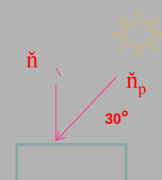
Example 1.11: A window (consisting of a vertical sheet of glass) is exposed to direct sunshine at a strength of 1,000 W/m^2. Assume the sun's T = 5,777 K. The window is pointing due south, while the sun is in the southwest, 30 degrees above the horizon.

Estimate the amount of solar energy that (i) penetrates into the building, (ii) is absorbed by the window, and (iii) is reflected by the window. The window is either (a) plain glass, (b) tinted glass, whose radiative properties may be approximated by;

$$\rho_\lambda = 0.08 \quad \text{for all wavelengths (both glasses),}$$

$$\tau_\lambda = \begin{cases} 0.90 & \text{for } 0.35\,\mu\text{m} < \lambda < 2.7\,\mu\text{m} \\ 0 & \text{for all other wavelengths} \end{cases} \quad \text{(plain glass)}$$

$$\tau_\lambda = \begin{cases} 0.90 & \text{for } 0.5\,\mu\text{m} < \lambda < 1.4\,\mu\text{m} \\ 0 & \text{for all other wavelengths} \end{cases} \quad \text{(tinted glass).}$$



(c) By what fraction is the amount of visible light (0.4 μm < λ < 0.7 μm) reduced, if tinted rather that plain glass is used?

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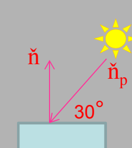
Radiative Heat Transfer

Optical Characteristics

Example 1.11 Continued: Solution



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Optical Characteristics

Example 1.11: Continued:

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Example 1.11: Continued:

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Optical Characteristics

Example 1.11: Continued:

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Radiative Heat Transfer

Optical Characteristics

Example 1.15: Consider a pyrometer, which also has a detector area of 1mm × 1mm, which is black in the wavelength range between 1.0 μm ≤ λ ≤ 1.2 μm, and perfectly reflecting elsewhere.

In front of the detector is a focusing lens (f = 10 cm) D = 2 cm in diameter, and a transmissivity, τ = 0.9 (around 1μm). In order to measure the temperature inside a furnace, the pyrometer is focused onto a hot black surface inside the furnace, a distance of 1 m away from the lens.

(a) How large a spot on the furnace wall does the detector see? *Remember that geometric optics* dictates;

$$\frac{1}{f} = \frac{1}{d_o} + \frac{1}{d_i} \quad \textit{and} \quad M = \frac{h(\text{detector size})}{H(\text{spot size})} = \frac{d_i}{d_o}$$

where d_o = 1m is the distance from lens to furnace wall, and d_i is the distance from lens to detector.

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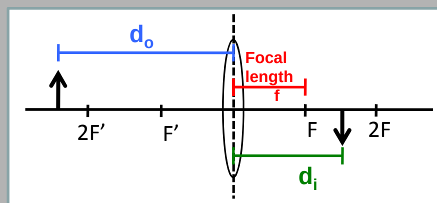
Optical Characteristics

Example 1.15: Continued:



(b) If the temperature of the furnace wall is 1200 K, how much energy is absorbed by the detector per unit time?

(c) It turns out the furnace wall is not really black, but has an emissivity (ε) = 0.7 (at approximately 1μm). Assuming there is no radiation reflected from the furnace surface reaching the detector, what is the true surface temperature for the pyrometer reading of case b?

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Optical Characteristics

Example 1.15: Continued:

Radiative Heat Transfer

Optical Characteristics

Example 1.15: Continued:

Radiative Heat Transfer

Optical Characteristics

Example 1.15: Continued:

Radiative Heat Transfer

Optical Characteristics

Example 1.15: Continued:

--- The End ---

Radiative Heat Transfer

Polarization

- Electromagnetic radiation travels as transverse waves, i.e., waves that vibrate in a direction perpendicular to their direction of propagation.
- Polarization is a phenomenon that is peculiar to transverse waves.
- Polarization is the distribution of the electric field in a plane normal to the propagation direction.
- Unpolarized radiation (or randomly polarized) is an electromagnetic wave in which the orientation of the electrical vector changes randomly.

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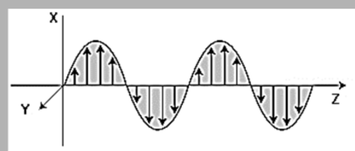
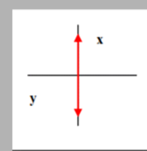
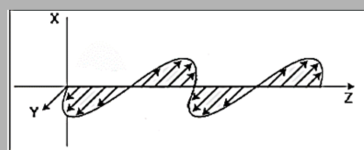
Polarization

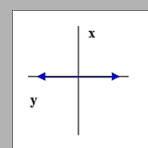
- A vertically polarized wave is one for which the electric field resides in the x-z plane only.





- For horizontally polarized wave the electric field resides only in the y-z plane.





- Horizontal and vertical polarization is an example of linear polarization.

Radiative Heat Transfer

Polarization

- There is also circular and elliptical states of polarization.