Radiation Heat Transfer

Dr. Sayantan Sengupta
Dept. of Mechanical Engineering
NIT Durgapur

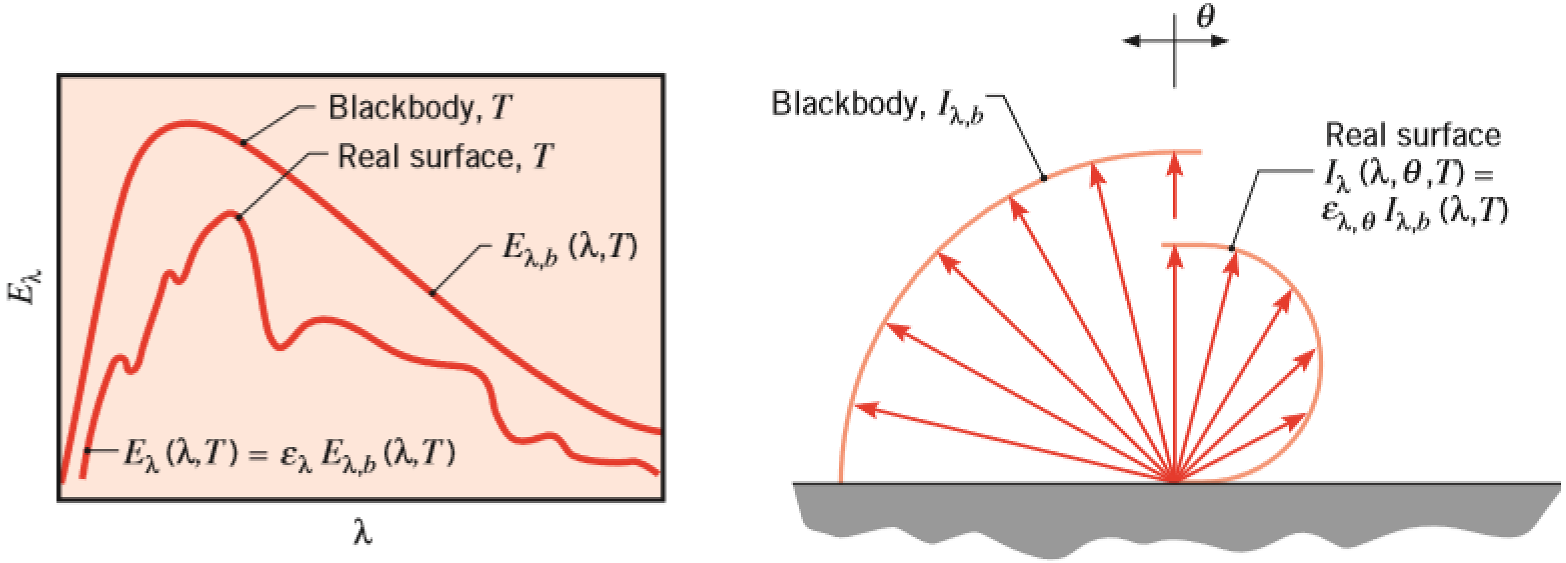
Lecture 4 Real surface vs. Ideal surface, Semitransparent medium, Kirchhoff's Law and Gray body

Real surface vs. Ideal surface

→ No surface can emit more radiation than a blackbody at the same temperature. It is therefore convenient to designate the blackbody as a reference in describing emission from a real surface.

Emissivity

defined as the *ratio* of the radiation emitted by the surface to the radiation emitted by a blackbody at the same temperature.



(*a*) Spectral distribution.

(*b*) Directional distribution.

Comparison of blackbody and real surface emission.

Related terms and their definitions

Spectral, directional emissivity

$$\varepsilon_{\lambda,\theta}(\lambda, \theta, \phi, T) \equiv \frac{I_{\lambda,e}(\lambda, \theta, \phi, T)}{I_{\lambda,b}(\lambda, T)}$$

Total, directional emissivity

$$\varepsilon_{\theta}(\theta, \phi, T) \equiv \frac{I_e(\theta, \phi, T)}{I_b(T)}$$

Spectral, hemispherical emissivity

$$\varepsilon_{\lambda}(\lambda, T) \equiv \frac{E_{\lambda}(\lambda, T)}{E_{\lambda,b}(\lambda, T)}$$

Total, hemispherical emissivity

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

The emissivity that accounts for emission over all wavelengths and in all directions is the *total, hemispherical* emissivity, which is the ratio of the total emissive power of a real surface, $E(T)$, to the total emissive power of a blackbody at the same temperature, $E_b(T)$.

Note

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

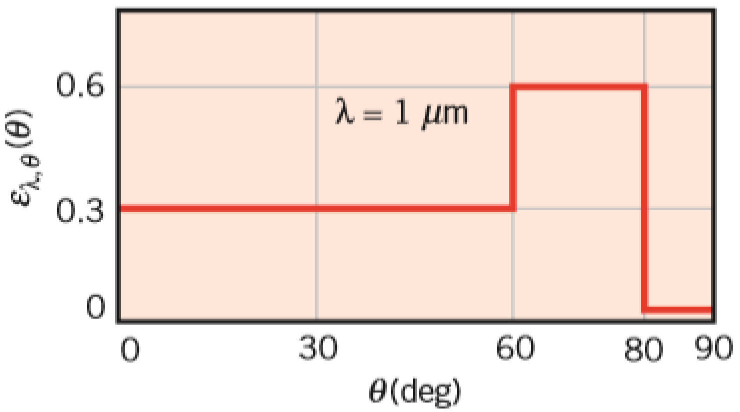
$$\varepsilon_{\lambda}(\lambda, T) E_{\lambda,b}(\lambda, T) = \frac{C_1 \varepsilon_{\lambda}(\lambda, T)}{\lambda^5[\exp(C_2/\lambda T) - 1]}$$

Remember

1. The emissivity of metallic surfaces is generally small, achieving values as low as 0.02 for highly polished gold and silver.
2. The presence of oxide layers may significantly increase the emissivity of metallic surfaces.
3. The emissivity of nonconductors is comparatively large, generally exceeding 0.6.
4. The emissivity of conductors increases with increasing temperature; however, depending on the specific material, the emissivity of nonconductors may either increase or decrease with increasing temperature.

Problem 1

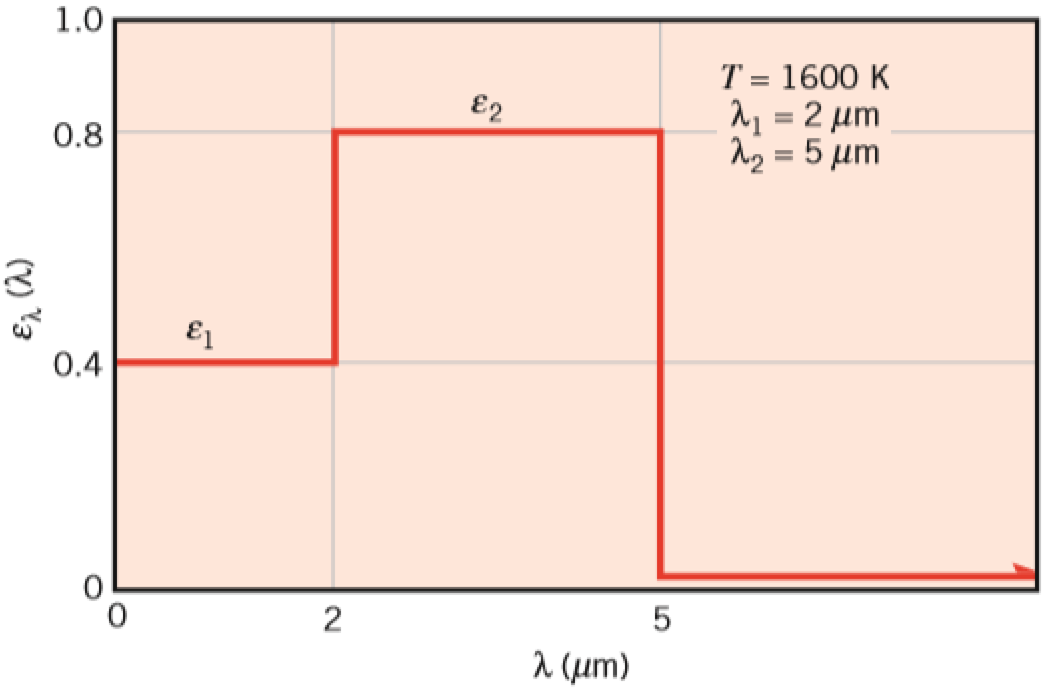
Measurements of the spectral, directional emissivity of a metallic surface at $T = 2000$ K and $\lambda = 1.0\ \mu m$ yield a directional distribution that may be approximated as follows:



Determine corresponding values of the spectral, normal emissivity; the spectral, hemispherical emissivity; the spectral intensity of radiation emitted in the normal direction; and the spectral emissive power.

Problem 2

A diffuse surface at 1600 K has the spectral, hemispherical emissivity shown as follows.

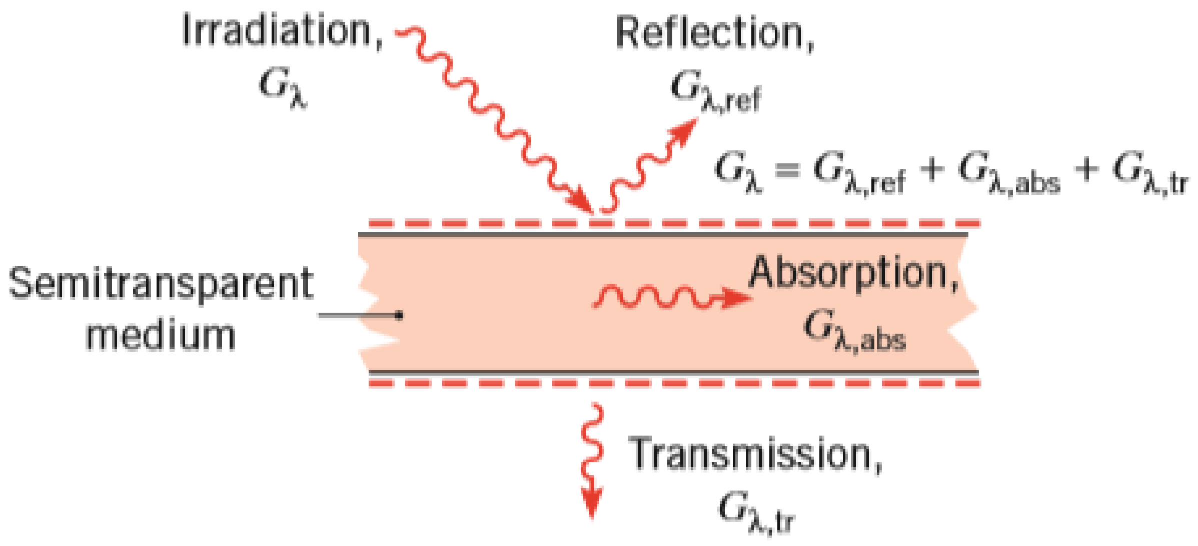


Determine the total, hemispherical emissivity and the total emissive power. At what wavelength will the spectral emissive power be a maximum?

Semitransparent medium

In the most general situation the irradiation interacts with a *semitransparent medium*, such as a layer of water or a glass plate. As shown in the Figure for a spectral component of the irradiation, portions of this radiation may be *reflected*, *absorbed*, and *transmitted*. From a radiation balance on the medium, it follows that

$$G_\lambda = G_{\lambda,\mathrm{ref}} + G_{\lambda,\mathrm{abs}} + G_{\lambda,\mathrm{tr}}$$



A few salient points

In a simpler situation, which pertains to most engineering applications, the medium is *opaque* to the incident radiation. In this case, $G_{\lambda,\mathrm{tr}} = 0$ and the remaining absorption and reflection processes may be treated as *surface phenomena*.

$$G_\lambda = G_{\lambda,\mathrm{ref}} + G_{\lambda,\mathrm{abs}}$$

There is no net effect of the reflection process on the medium, while absorption has the effect of increasing the internal thermal energy of the medium.

It is interesting to note that surface absorption and reflection are responsible for our perception of *color*. Unless the surface is at a high temperature ($T_s \gtrsim 1000$ K), such that it is *incandescent*, color is in no way due to emission, which is concentrated in the IR region, and is hence imperceptible to the eye. Color is instead due to selective reflection and absorption of the visible portion of the irradiation that is incident from the sun or an artificial source of light. A shirt is "red" because it contains a pigment that preferentially absorbs the blue, green, and yellow components of the incident light. Hence the relative contributions of these components to the reflected light, which is seen, is diminished, and the red component is dominant.

A surface appears "black" if it absorbs all incident visible radiation, and it is "white" if it reflects this radiation.

For a prescribed irradiation, the "color" of a surface may not indicate its overall capacity as an absorber or reflector, since much of the irradiation may be in the IR region. A "white" surface such as snow, for example, is highly reflective to visible radiation but strongly absorbs IR radiation, thereby approximating blackbody behavior at long wavelengths.

Absorptivity

The absorptivity is a property that determines the fraction of the irradiation absorbed by a surface.

Spectral, directional absorptivity

$$\alpha_{\lambda,\theta}(\lambda, \theta, \phi) \equiv \frac{I_{\lambda,i,\mathrm{abs}}(\lambda, \theta, \phi)}{I_{\lambda,i}(\lambda, \theta, \phi)}$$

Note In this expression, we have neglected any dependence of the absorptivity on the surface temperature. Such a dependence is small for most spectral radiative properties.

Spectral, hemispherical absorptivity

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

Total, hemispherical absorptivity

$$\alpha \equiv \frac{G_{\mathrm{abs}}}{G}$$

Reflectivity

The reflectivity is a property that determines the fraction of the incident radiation reflected by a surface. However, its specific definition may take several different forms, because the property is inherently *bidirectional*. That is, in addition to depending on the direction of the incident radiation, it also depends on the direction of the reflected radiation. We shall avoid this complication by working exclusively with a reflectivity that represents an integrated average over the hemisphere associated with the reflected radiation and therefore provides no information concerning the directional distribution of this radiation. Accordingly, the *spectral, directional reflectivity*, $\rho_{\lambda,\theta}(\lambda, \theta, \phi)$, of a surface is defined as the fraction of the spectral intensity incident in the direction of θ and ϕ, which is reflected by the surface. Hence

Spectral, directional reflectivity

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

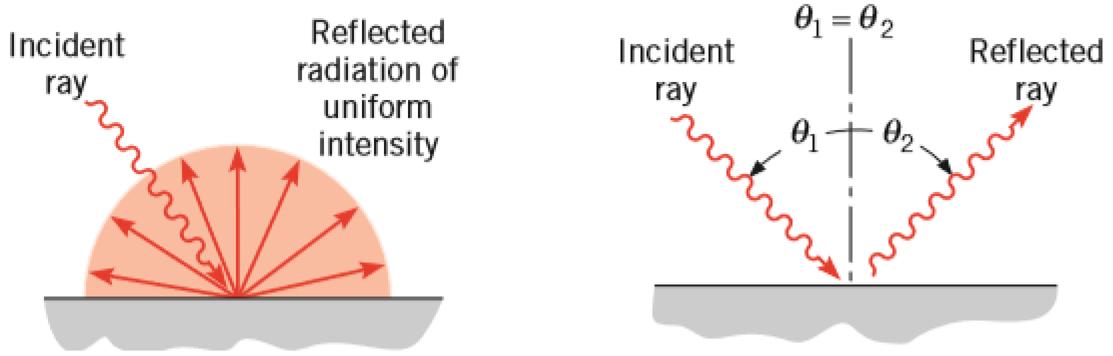
Spectral, hemispherical reflectivity

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

Total, hemispherical reflectivity

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

Surfaces may be idealized as *diffuse* or *specular*, according to the manner in which they reflect radiation (Figure 12.21). Diffuse reflection occurs if, regardless of the direction of the incident radiation, the intensity of the reflected radiation is independent of the reflection angle. In contrast, if all the reflection is in the direction of θ_2, which equals the incident angle θ_1, specular reflection is said to occur. Although no surface is perfectly diffuse or specular, the latter condition is more closely approximated by polished, mirror-like surfaces and the former condition by rough surfaces. The assumption of diffuse reflection is reasonable for most engineering applications.



Diffuse and specular reflection.

Remember

From the radiation balance for a *semitransparent* medium.

$$\rho_\lambda + \alpha_\lambda + \tau_\lambda = 1$$

if the medium is *opaque*

$$\alpha_\lambda + \rho_\lambda = 1$$

Hence knowledge of one property implies knowledge of the other.

Transmissivity

Spectral, hemispherical transmissivity

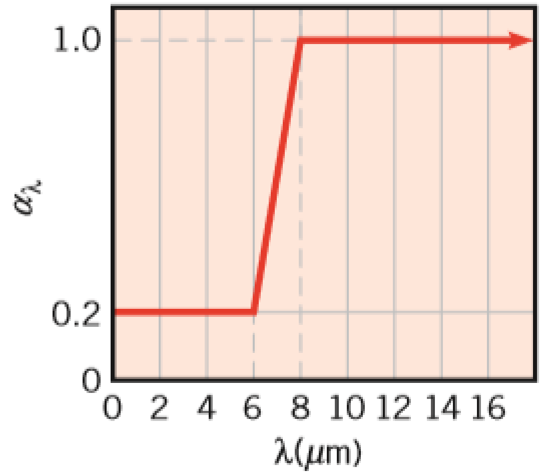
$$\tau_\lambda = \frac{G_{\lambda,\mathrm{tr}}(\lambda)}{G_\lambda(\lambda)}$$

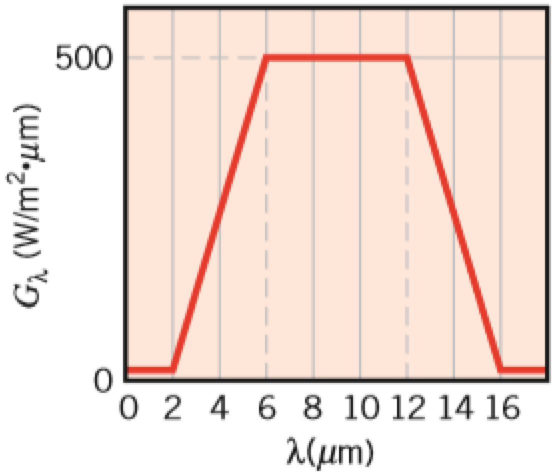
Total, hemispherical transmissivity

$$\tau = \frac{G_{\mathrm{tr}}}{G}$$

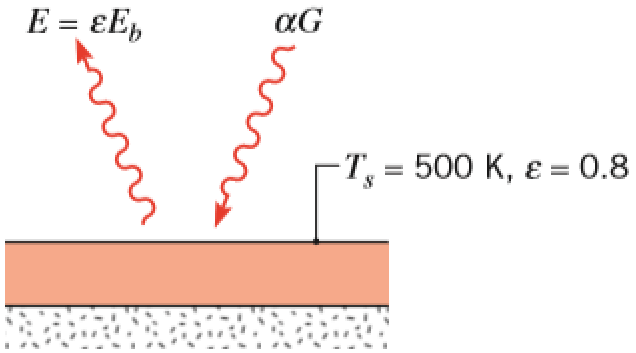
Problem 3

The spectral, hemispherical absorptivity of an opaque surface and the spectral irradiation at the surface are as shown.

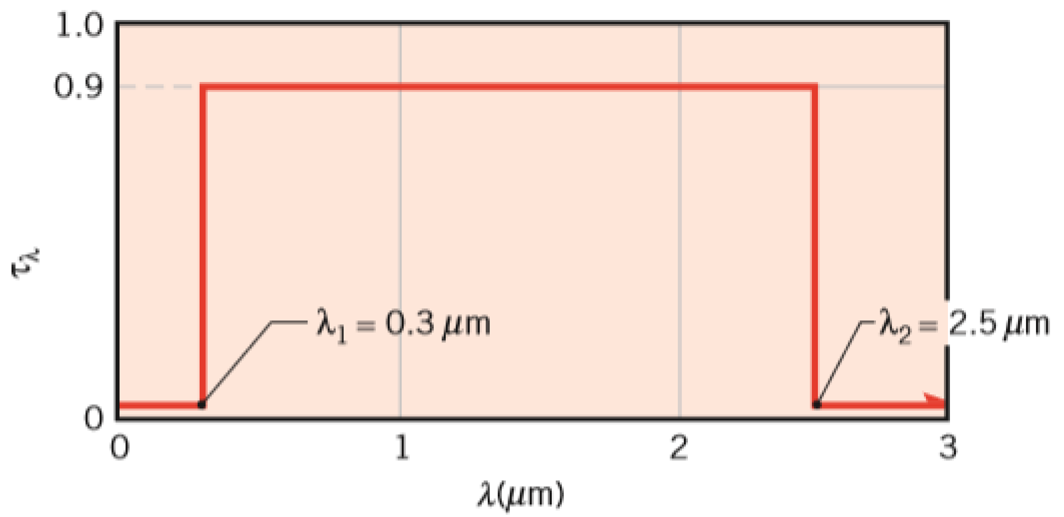




How does the spectral, hemispherical reflectivity vary with wavelength? What is the total, hemispherical absorptivity of the surface? If the surface is initially at 500 K and has a total, hemispherical emissivity of 0.8, how will its temperature change upon exposure to the irradiation?



Problem 4 The cover glass on a flat-plate solar collector has a low iron content, and its spectral transmissivity may be approximated by the following distribution.



What is the total transmissivity of the cover glass to solar radiation?

Kirchhoff's Law

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

Proof:

We consider an insulated enclosure with an isothermal surface at temperature T. A small blackbody at the same temperature is placed inside the enclosure. If the enclosure is evacuated then the heat exchange between the surface and the blackbody is by radiation only. Since the blackbody is at equilibrium, an energy balance requires that spectral energy emitted be equal to the spectral energy received. That is

$$E_{b\lambda}(\lambda, T) = G_\lambda(\lambda, T) \qquad (1)$$

where, $G_\lambda(\lambda, T)$ is the spectral irradiation from the surface of the enclosure. If a small real body at temperature T is placed in the enclosure it too will be at equilibrium with the surface. Assuming that it does not disturb the irradiation field $G_\lambda(\lambda, T)$, an energy balance for the real body gives

$$E_\lambda(\lambda, T) = \alpha_\lambda(\lambda, T)\, G_\lambda(\lambda, T) \qquad (2)$$

Using Eq. (1) to eliminate in Eq. (2) gives

$$\frac{E_\lambda(\lambda, T)}{E_{b\lambda}(\lambda, T)} = \alpha_\lambda(\lambda, T) \qquad (3)$$

However, according to the definition of spectral, hemispherical emissivity

$$\varepsilon_\lambda(\lambda, T) \equiv \frac{E_\lambda(\lambda, T)}{E_{\lambda,b}(\lambda, T)} \qquad (4)$$

Hence, it can be shown that $\varepsilon_\lambda(\lambda, T) = \alpha_\lambda(\lambda, T)$.

Gray body

A gray body is defined as a substance whose emissivity and absorptivity are independent of wavelength. Thus a gray body is also an ideal body, but its emissivity and absorptivity values are both less than 1 (unlike blackbody). Therefore, for a gray body Kirchhoff's law would be reduced as follows:

$$\varepsilon\,(T) = \alpha\,(T)$$

Thank you