Fundamentals of Renewable Energy

Semnan University

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CHAPTER 3

Fundamentals of Solar Energy

INTRODUCTION

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The electromagnetic energy emitted by the sun is called solar radiation or solar energy (or solar heat).

Electromagnetic waves are characterized by their frequency ν or wavelength l. These two properties in a medium are related by

$$\lambda = \frac{c}{\nu}$$

Unlike the wavelength and the speed of propagation, the frequency of an electromagnetic wave depends only on the source and is independent of the medium through which the wave travels.

RADIATION FUNDAMENTALS

It has proven useful to view electromagnetic radiation as the propagation of a collection of discrete packets of energy called photons or quanta, as proposed by Max Planck in 1900 in conjunction with his quantum theory. In this view, each photon of frequency ν is considered

$$e = h\nu = \frac{hc}{\lambda}$$

where $h = 6.626069 \times 10^{-34}$ J·s is Planck's constant. Note from the above Eq. that the energy of a photon is inversely proportional to its wavelength. Therefore, shorter wavelength radiation possesses larger photon energies. It is no wonder that we try to avoid very-short-wavelength radiation such as gamma rays and X-rays since they are highly destructive.

RADIATION FUNDAMENTALS

Although all electromagnetic waves have the same general features, waves of different wavelength differ significantly in their behavior. The electromagnetic radiation encountered in practice covers a wide range of wavelengths, varying from less than 10^{-10} μm for cosmic rays to more than 1010 μm for electrical power waves.

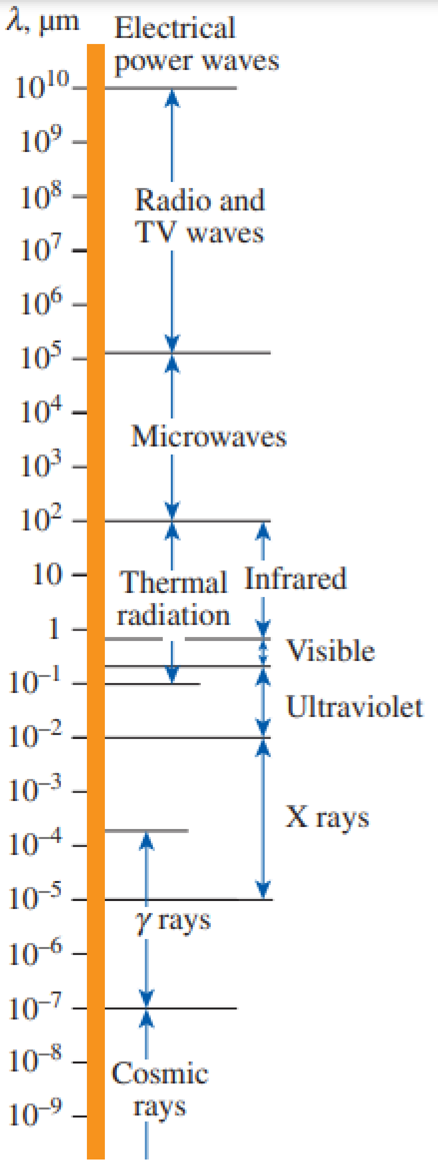

Figure 3-1
The electromagnetic wave spectrum.

RADIATION FUNDAMENTALS

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Thermal radiation is emitted as a result of energy transitions of molecules, atoms, and electrons of a substance. Temperature is a measure of the strength of these activities at the microscopic level, and the rate of thermal radiation emission increases with increasing temperature. That is, everything around us such as walls, furniture, and our friends constantly emits (and absorbs) radiation (Fig. 3-2). Thermal radiation includes the entire visible and IR radiation as well as a portion of the UV radiation.

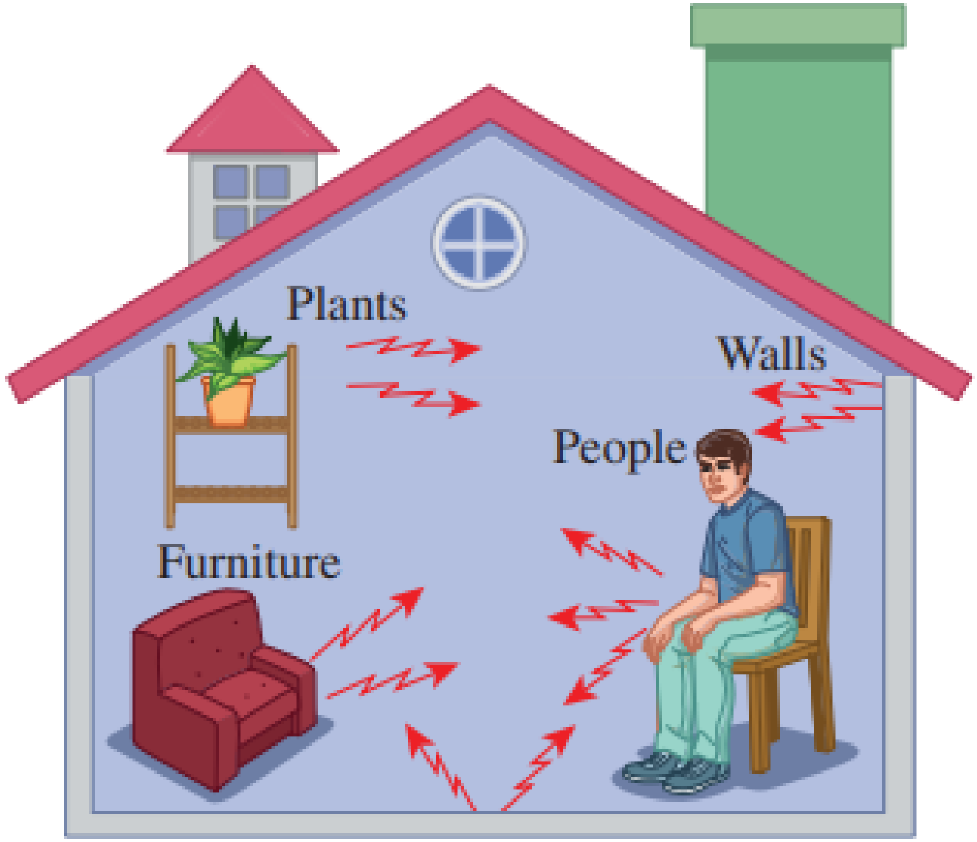

Figure 3-2
Everything around us constantly emits thermal radiation.

RADIATION FUNDAMENTALS

What we call light is simply the visible portion of the electromagnetic spectrum that lies between 0.40 and 0.76 µm. Light is characteristically no different than other electromagnetic radiation, except that it happens to trigger the sensation of seeing in the human eye. Light, or the visible spectrum, consists of narrow bands of color from violet (0.40 to 0.44 µm) to red (0.63 to 0.76 µm)

Blackbody Radiation

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A body at a thermodynamic (or absolute) temperature above zero emits radiation in all directions over a wide range of wavelengths. The amount of radiation energy emitted from a surface at a given wavelength depends on the material of the body and the condition of its surface as well as the surface temperature. The maximum amount of radiation that can be emitted by a surface at a given temperature called a blackbody.

Blackbody Radiation

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A blackbody absorbs all incident radiation, regardless of wavelength and direction. Also, a blackbody emits radiation energy uniformly in all directions per unit area normal to direction of emission (Fig. 3-3). That is, a blackbody is a diffuse emitter. The term diffuse means "independent of direction."

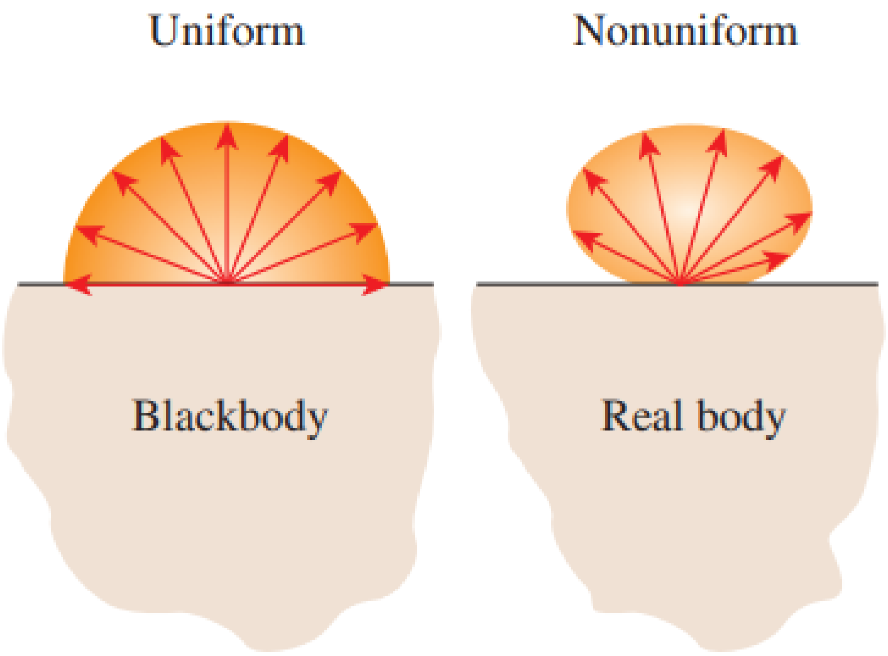

Figure 3-3
A blackbody is said to be a diffuse emitter since it emits radiation energy uniformly in all directions.

Blackbody Radiation

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The radiation energy emitted by a blackbody per unit time and per unit surface area was determined experimentally by Joseph Stefan in 1879 and expressed as

$$E_b(T) = \sigma T^4 \quad (*)$$

where $\sigma = 5.670 \times 10^{-8}$ W/m2·K4 is the Stefan-Boltzmann constant and T is the absolute temperature of the surface in K. This relation was theoretically verified in 1884 by Ludwig Boltzmann. Equation (*) is known as the Stefan-Boltzmann law and E_b is called the blackbody emissive power.

Blackbody Radiation

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The relation for the spectral blackbody emissive power Ebl was developed by Max Planck in 1901 in conjunction with his famous quantum theory. This relation is known as Planck's law and is expressed as

$$E_{b\lambda}(\lambda, T) = \frac{C_1}{\lambda^5\left[exp\left({}^{C_2}/_{\lambda T}\right)-1\right]} \quad \left({}^{W}/_{m^2.\mu m}\right)$$

where

$$C_1 = 2\pi h c_0^2 = 3.74177 \times 10^8 \quad (W.\mu m^4/m^2)$$

$$C_2 = \frac{hc_0}{k} = 1.43878 \times 10^4 \quad (\mu m.K)$$

Blackbody Radiation

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Also, T is the absolute temperature of the surface, l is the wavelength of the radiation emitted, and k = 1.38065 × 10^{-23} J/K is Boltzmann's constant. This relation is valid for a surface in a vacuum or a gas. For other mediums, it needs to be modified by replacing C_1 by C_1/n^2, where n is the index of refraction of the medium. Note that the term spectral indicates dependence on wavelength.

Blackbody Radiation

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The variation of the spectral blackbody emissive power with wavelength is plotted in Fig. 3-4 for selected temperatures. Several observations can be made from this figure:

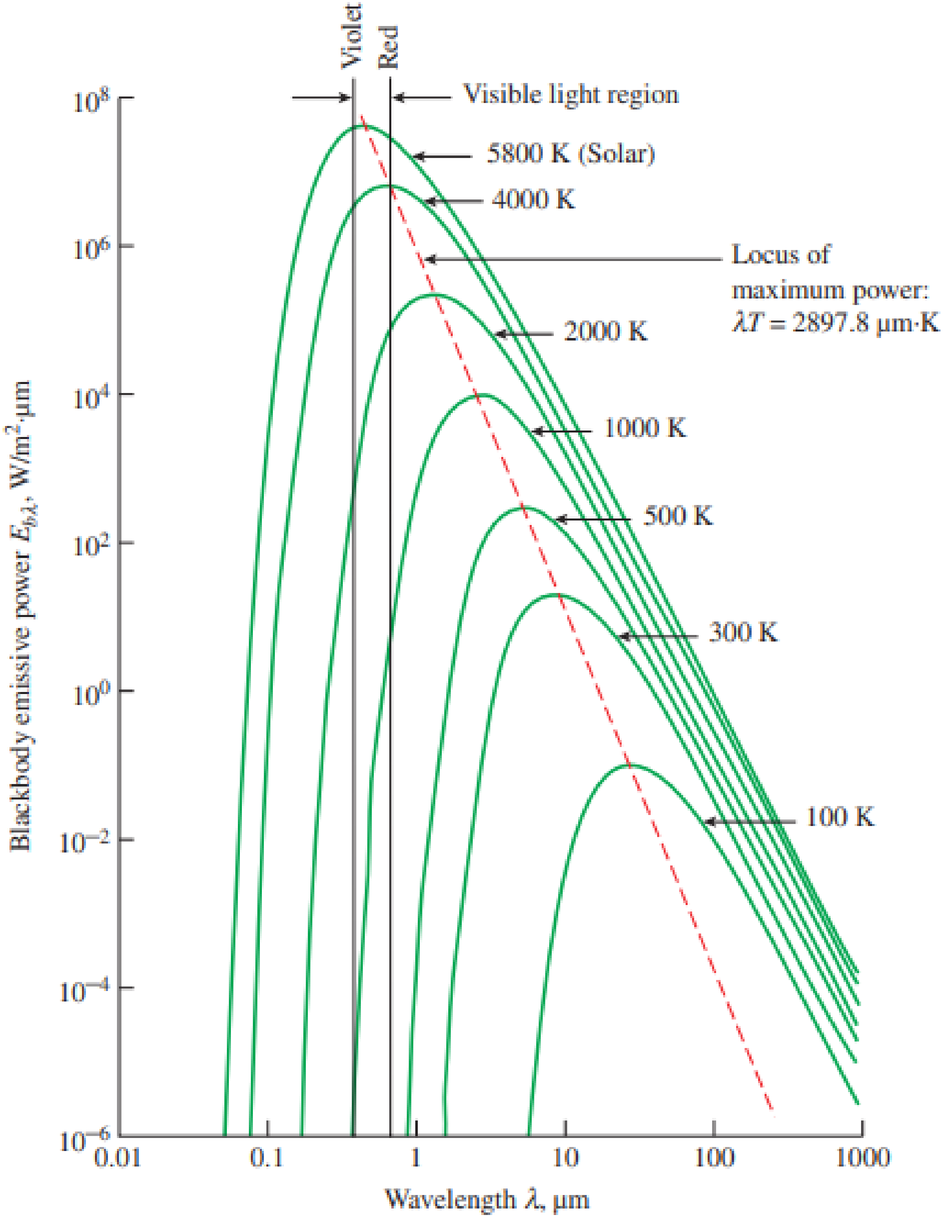

Figure 3-4
The variation of the blackbody emissive power with Wavelength for several temperatures.

Blackbody Radiation

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1. The emitted radiation is a continuous function of wavelength. At any specified temperature, it increases with wavelength, reaches a peak, and then decreases with increasing wavelength.
2. At any wavelength, the amount of emitted radiation increases with increasing temperature.
3. As temperature increases, the curves shift to the left to the shorter wavelength region. Consequently, a larger fraction of the radiation is emitted at shorter wavelengths at higher temperatures.
4. The radiation emitted by the sun, which is considered to be a blackbody at 5780 K (or roughly at 5800 K), reaches its peak in the visible region of the spectrum. Therefore, the sun is in tune with our eyes.

Blackbody Radiation

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As the temperature increases, the peak of the curve in Fig. 3-4 shifts toward shorter wavelengths. The wavelength at which the peak occurs for a specified temperature is given by Wien's displacement law as

$$(\lambda T)_{max\ power} = 2897.8\ \mu m.K$$

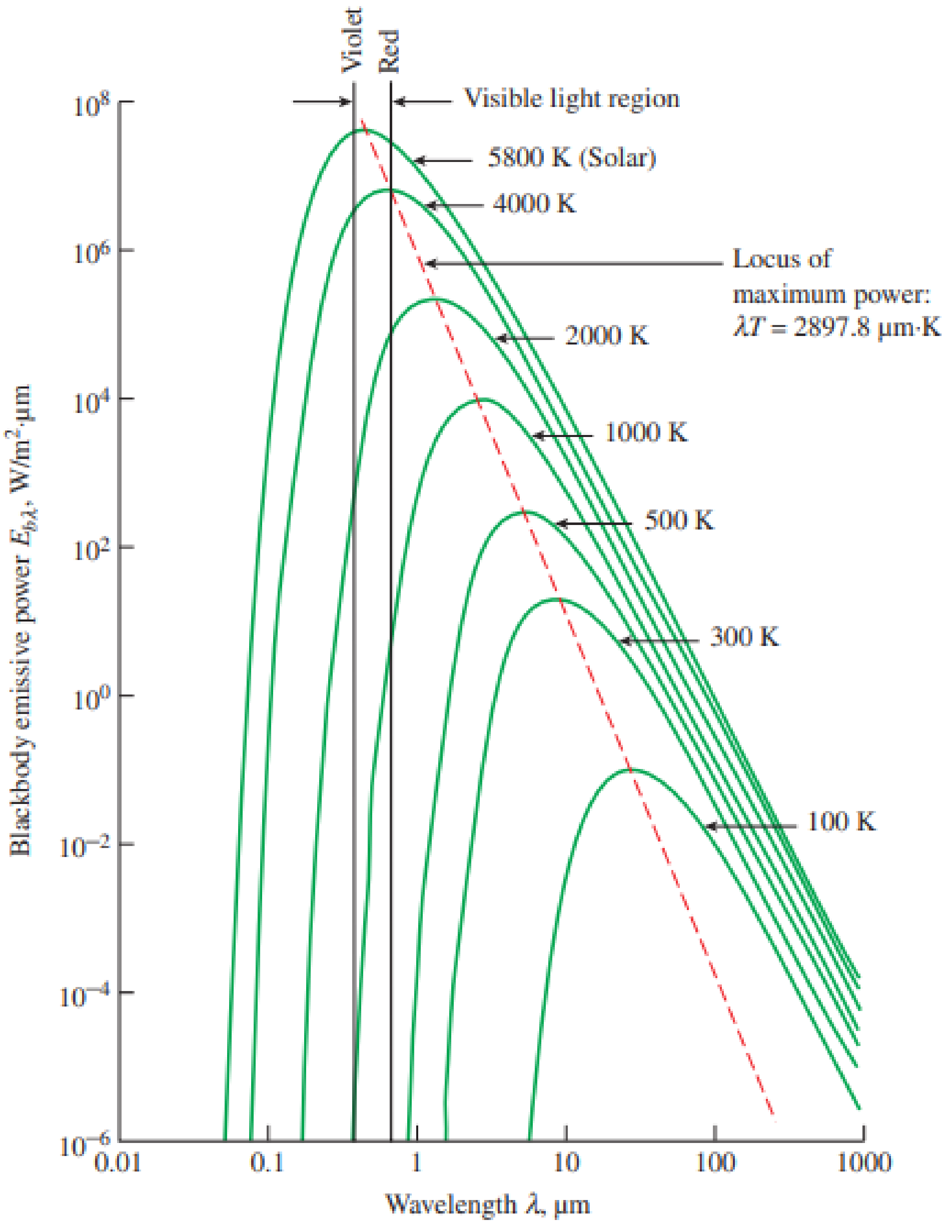

Figure 3-4
The variation of the blackbody emissive power with wavelength for several temperatures.

Blackbody Radiation

The color of a surface depends on the absorption and reflection characteristics of the surface and is due to selective absorption and reflection of the incident visible radiation coming from a light source such as the sun or an incandescent lightbulb. A piece of clothing containing a pigment that reflects red while absorbing the remaining parts of the incident light appears "red" to the eye (Fig. 3-5).

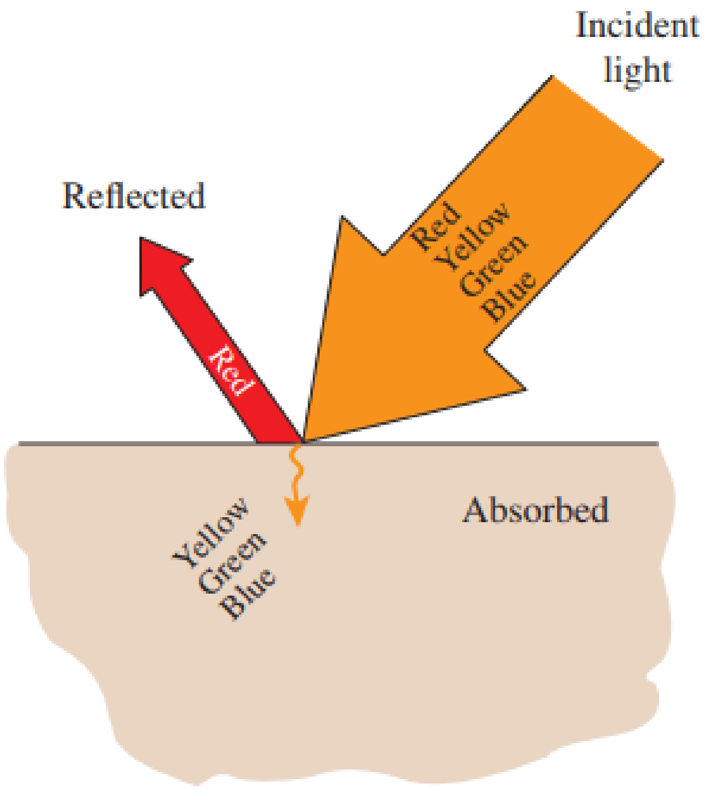

Figure 3-5
A surface that reflects red while absorbing the remaining parts of the incident light appears red to the eye.

Blackbody Radiation

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Integration of the spectral blackbody emissive power $E_{b\lambda}$ over the entire wavelength spectrum gives the total blackbody emissive power E_b:

$$E_b(T) = \int_0^\infty E_{b\lambda}(\lambda, T)\,d\lambda = \sigma T^4 \qquad (W/m^2)$$

Blackbody Radiation

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EXAMPLE 3-1 **Consider a cylindrical body 30 cm in length and 15 cm in diameter at 327°C suspended in the air. Assuming the body closely approximates a blackbody, determine (a) the rate at which the cylinder emits radiation energy and (b) the spectral blackbody emissive power at a wavelength of 2.5 μm. (c) Also, determine the wavelength at which the emission of radiation from the filament peaks.**

Blackbody Radiation

Solution (a) The surface area of the cylindrical body is

$$A_s = \pi DL + 2\frac{\pi d^2}{4} = \pi(0.15m)(0.3m) + 2\frac{\pi(0.15m)^2}{4} = 0.1767m^2$$

The total blackbody emissive power is determined from Stefan-Boltzmann law to be

$$E_b(T) = \sigma T^4 A_s$$
$$= (5.67 \times 10^{-8}\, W/m^2K^4)\,[(327 + 273)K]^4(0.1767m^2) = 1298\, W$$

Blackbody Radiation

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(b) The spectral blackbody emissive power at a wavelength of 2.5 μm is determined from Plank's distribution law,

$$E_{b\lambda} = \frac{C_1}{\lambda^5\left[\exp\left(\frac{C_2}{\lambda T}\right)-1\right]} = \frac{3.74177\times10^8 W.\mu m^4/m^2}{(2.5\mu m)^5\left[\exp\left(\frac{1.43878\times10^4\mu m.K}{(2.5\mu m)(600K)}\right)-1\right]} = 262\ \mathrm{W}/m^2.\mu m$$

(c) The wavelength at which the emission of radiation from the body is maximum is determined from Wien's displacement law to be

$$(\lambda T)_{maxpower} = 2897.8\mu m.\mathbf{K} \rightarrow (\lambda)_{maxpower} = \frac{2897.8\mu m.\mathbf{K}}{600\ K} = 4.83\mu m$$

Note that the radiation emitted from the body peaks in the IR region.

RADIATIVE PROPERTIES

Most materials encountered in practice, such as metals, wood, and bricks, are opaque to thermal radiation.

Some other materials, such as glass and water, allow visible radiation to penetrate to considerable depths before any significant absorption takes place.

RADIATIVE PROPERTIES

We defined a blackbody as a perfect emitter and absorber of radiation and said that nobody can emit more radiation than a blackbody at the same temperature. Therefore, a blackbody can serve as a convenient reference in describing the emission and absorption characteristics of real surfaces.

RADIATIVE PROPERTIES

The emissivity of a surface represents the ratio of the radiation emitted by the surface at a given temperature to the radiation emitted by a blackbody at the same temperature. The emissivity of a surface is denoted by ε, and it varies between zero and one, $0 < \varepsilon < 1$. Emissivity is a measure of how closely areal surface approximates a blackbody, for which $\varepsilon = 1$.

RADIATIVE PROPERTIES

Typical ranges of emissivity of various materials are given in Fig. 3-6. Note that metals generally have low emissivities, as low as 0.02 for polished surfaces, and nonmetals such as ceramics and organic materials have high ones. Also, oxidation causes significant increases in the emissivity of metals.

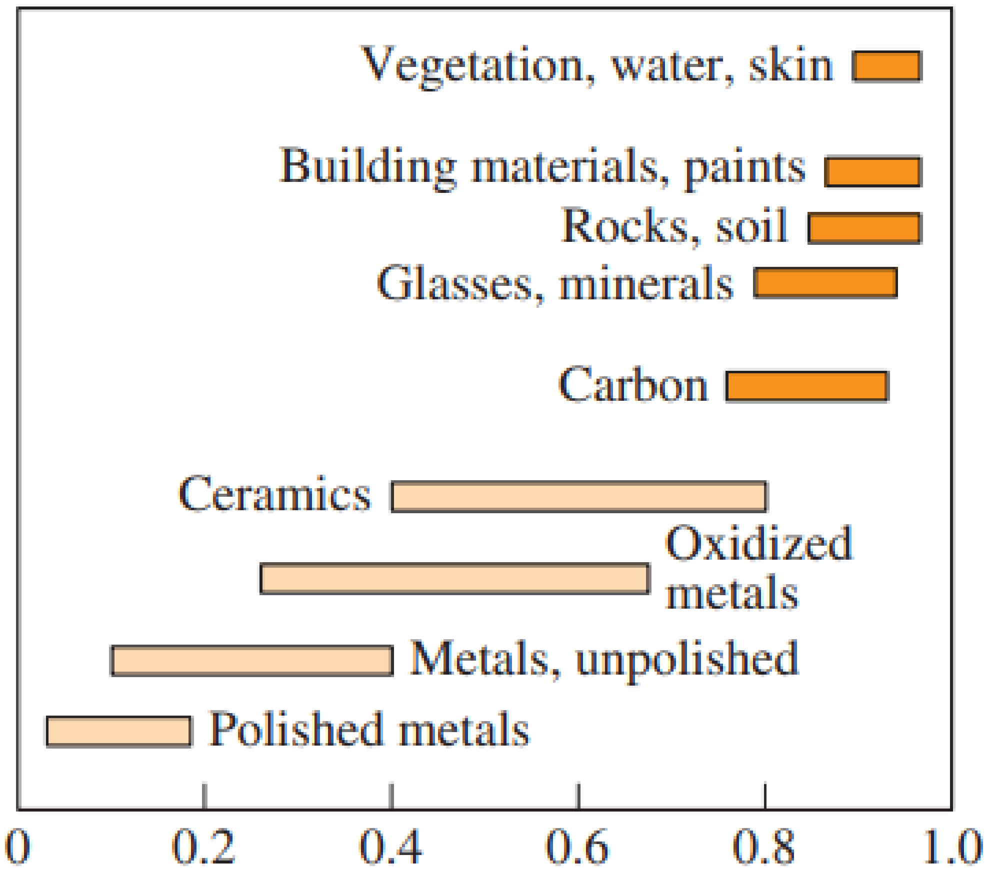

Figure 3-7
Typical ranges of emissivity for various materials.

Absorptivity, Reflectivity, and Transmissivity

The radiation flux incident on a surface from all directions is called irradiation or incident radiation and is denoted by G. It represents the rate at which radiation energy is incident on a surface per unit area of the surface. When radiation strikes a surface, part of it is absorbed, part of it is reflected, and the remaining part, if any, is transmitted, as illustrated in Fig. 3-7.

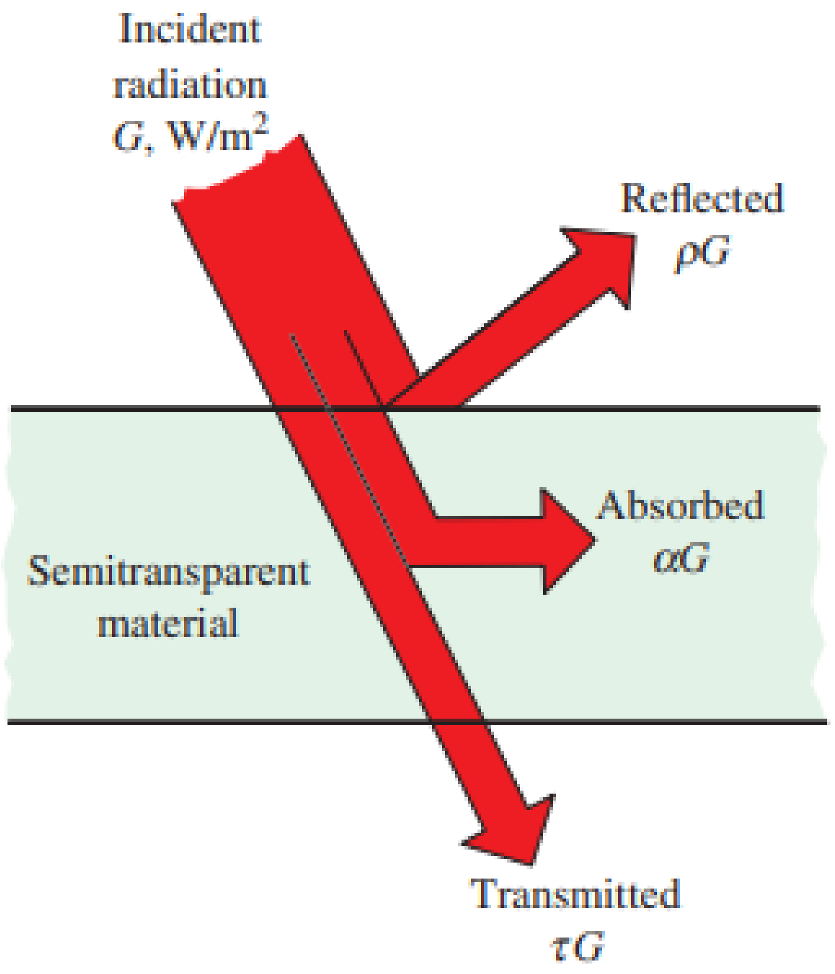

Figure 3-7
The absorption, reflection, and transmission of incident radiation by a semitransparent material.

Absorptivity, Reflectivity, and Transmissivity

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The fraction of irradiation absorbed by the surface is called the absorptivity α, the fraction reflected by the surface is called the reflectivity ρ, and the fraction transmitted is called the transmissivity τ. That is,

Absorptivity: $\alpha = \frac{G_{abs}}{G}$ $\quad 0 < \alpha < 1$

Reflectivity: $\rho = \frac{G_{ref}}{G}$ $\quad 0 < \rho < 1$

Transmissivity: $\tau = \frac{G_{tr}}{G}$ $\quad 0 < \tau < 1$

Absorptivity, Reflectivity, and Transmissivity

where G is the radiation flux incident on the surface, and G_{abs}, G_{ref}, and G_{tr} are the absorbed, reflected, and transmitted portions of it, respectively. The first law of thermodynamics requires that the sum of the absorbed, reflected, and transmitted radiation be equal to the incident radiation. That is,

$$G_{abs} + G_{ref} + G_{tr} = G$$

Dividing each term of this relation by G yields

$$\alpha + \rho + \tau = 1$$

Absorptivity, Reflectivity, and Transmissivity

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For idealized blackbodies which are perfect absorbers, $\rho = 0$ and $\tau = 0$, and Eq. (*) reduces to $\alpha = 1$. For opaque surfaces such as most solids and liquids, $\tau = 0$, and thus

$$\alpha + \rho + \tau = 1 \quad (*)$$

$$\alpha + \rho = 1$$

Absorptivity, Reflectivity, and Transmissivity

Unlike emissivity, the absorptivity of a material is practically independent of surface temperature. However, the absorptivity depends strongly on the temperature of the source at which the incident radiation is originating.

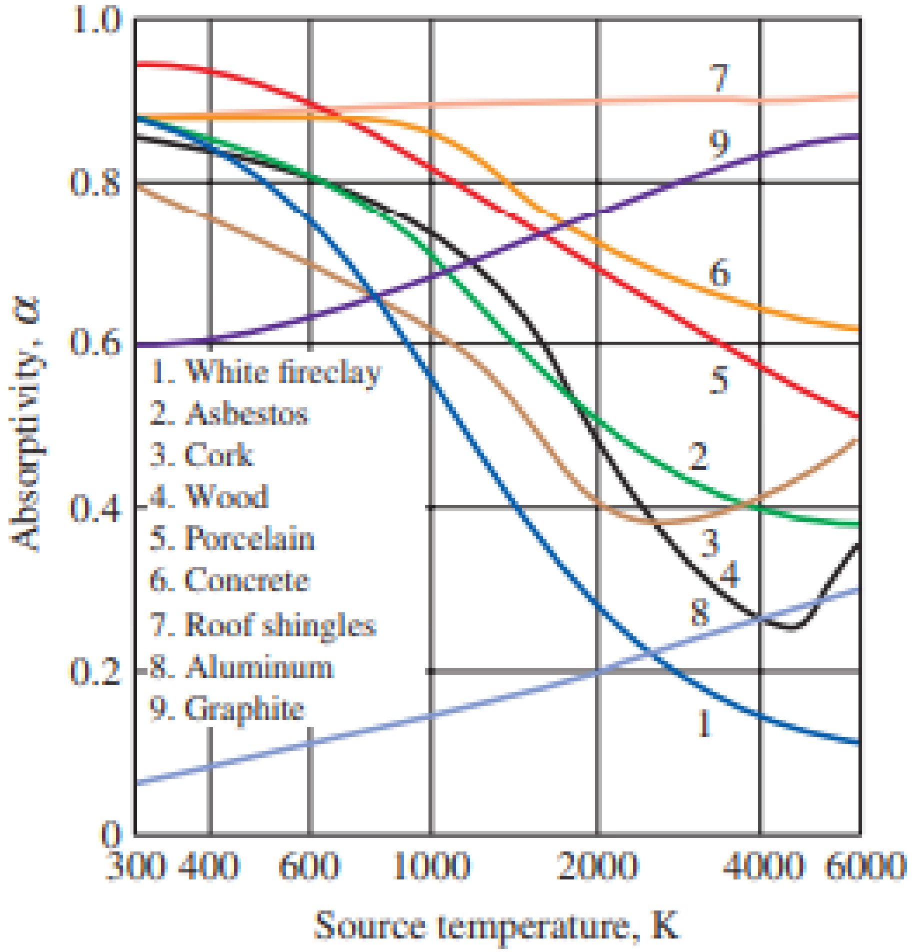

Figure 3-8
Variation of absorptivity with the temperature of the source of irradiation for various common materials at room temperature.

Absorptivity, Reflectivity, and Transmissivity

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For example, the absorptivity of the concrete roof of a house is about 0.6 for solar radiation (source temperature: 5780 K) and 0.9 for radiation originating from the surrounding trees and buildings (source temperature: 300 K), as illustrated in Fig. 3-9.

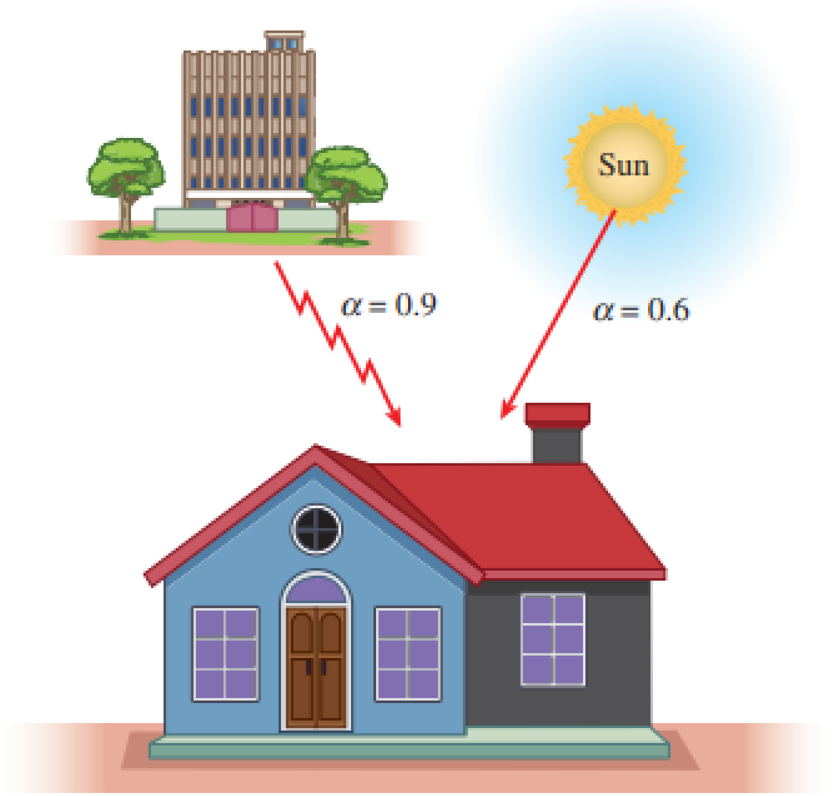

Figure 3-9
The absorptivity of a material may be quite different for radiation originating from sources at different temperatures.

Absorptivity, Reflectivity, and Transmissivity

A relationship between the emissivity and absorptivity a surface can be obtained

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

Absorptivity, Reflectivity, and Transmissivity

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EXAMPLE 3-2 **An opaque horizontal plate is well insulated on the edges and the lower surface (Fig. 3-10). The irradiation on the plate is 2500 W/m2 , of which 800 W/m2 is reflected. The plate has a uniform temperature of 700 K and has an emissive power of 9000 W/m2. Determine the total emissivity and absorptivity of the plate.**

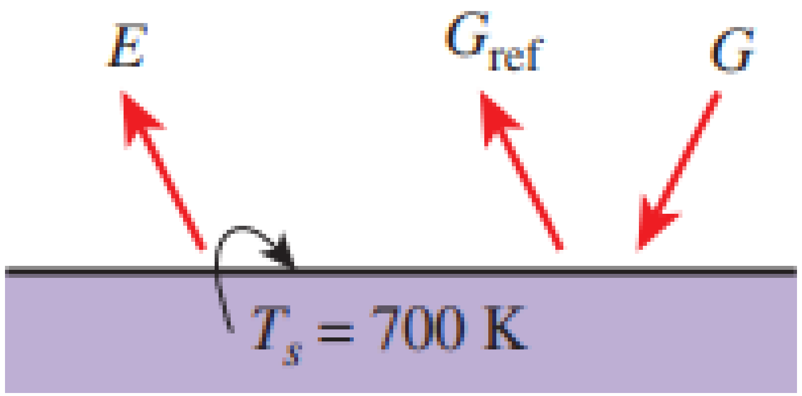

Figure 3-10
Schematic for Example 3-2.

Absorptivity, Reflectivity, and Transmissivity

SOLUTION The total emissivity of the plate can be determined using

$$\varepsilon = \frac{E}{E_b} = \frac{E}{\sigma T_s^4} = \frac{9000\ W/m^2}{(5.67 \times 10^{-8}\ W/m^2 K^4)(700K)^4} = 0.661$$

The total absorptivity of the plate is determined using

$$\alpha + \rho + \tau = 1 \rightarrow \alpha = 1 - \rho \qquad \text{(for opaque surface, } \tau = 0)$$

The reflectivity of the plate is

$$\rho = \frac{G_{ref}}{G} = \frac{800\ W/m^2}{2500\ W/m^2} = 0.32$$

Absorptivity, Reflectivity, and Transmissivity

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Hence, the total absorptivity of the plate is

$$\alpha = 1 - 0.32 = 0.68$$

The Greenhouse Effect

We observe from this figure that glass at thicknesses encountered in practice transmits over 90 percent of radiation in the visible range and is practically opaque (nontransparent) to radiation in the longer-wavelength IR regions of the electromagnetic spectrum (roughly λ > 3 μm).

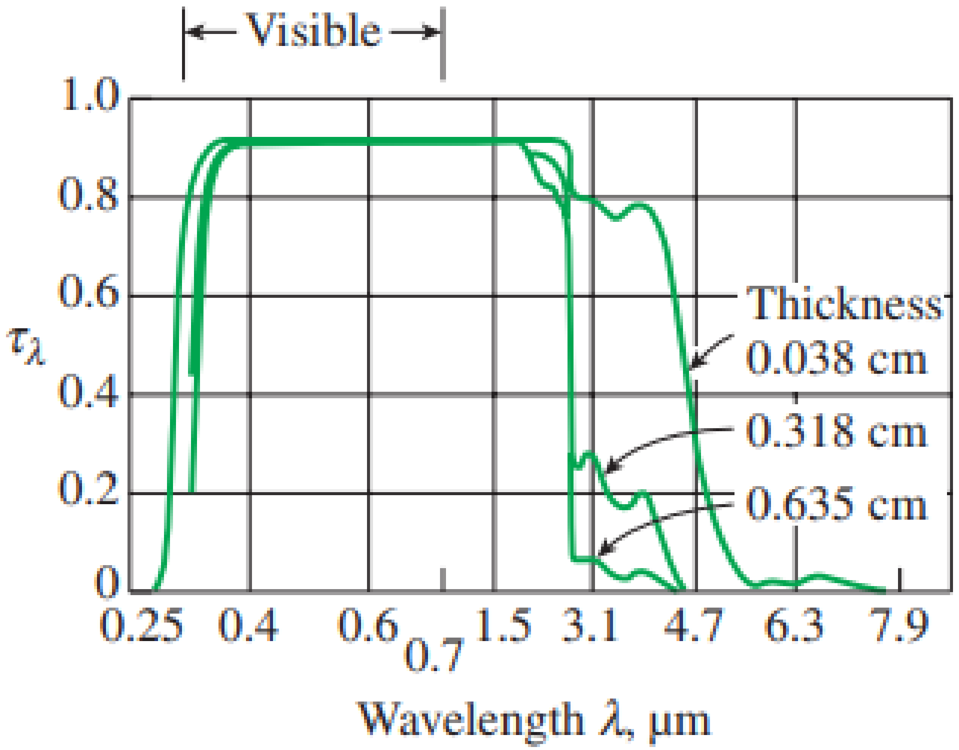

Figure 3-11
Schematic for Example 3-2.

The Greenhouse Effect

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glass allows the solar radiation to enter but does not allow the IR radiation from the interior surfaces to escape. This causes a rise in the interior temperature as a result of the energy buildup in the car. This heating effect, which is due to the non-gray characteristic of glass (or clear plastics), is known as the greenhouse effect, since it is utilized extensively in greenhouses (Fig. 3-12).

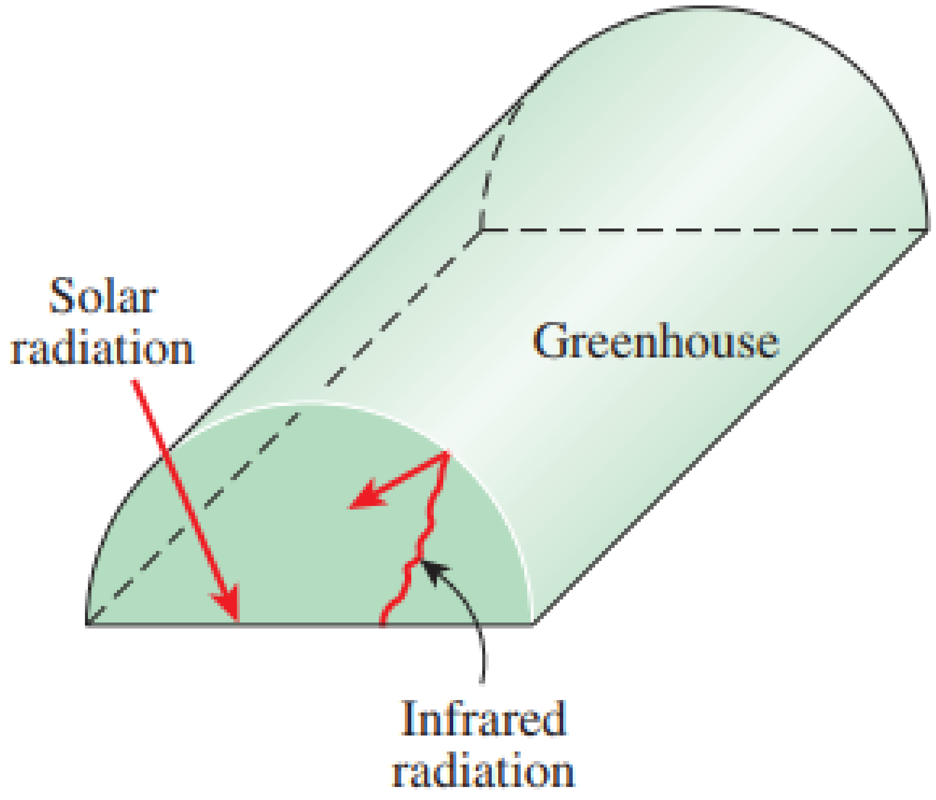

Figure 3-12
A greenhouse traps energy by allowing solar radiation to come in but not allowing IR radiation to go out.

The Greenhouse Effect

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The greenhouse effect is also experienced on a larger scale on earth. The surface of the earth, which warms up during the day as a result of the absorption of solar energy, cools down at night by radiating its energy into deep space as IR radiation. Greenhouse gases such as CO2 and water vapor in the atmosphere transmit the bulk of the solar radiation but absorb the IR radiation emitted by the surface of the earth. Thus, there is concern that the energy trapped on earth will eventually cause global warming and thus drastic changes in weather patterns.

SOLAR RADIATION

The sun is our primary source of energy. The energy coming off the sun, called solar energy, reaches us in the form of electromagnetic waves after experiencing considerable interactions with the atmosphere. The radiation energy emitted or reflected by the constituents of the atmosphere form the atmospheric radiation.

The sun is a nearly spherical body that has a diameter of $D = 1.393 \times 10^9$ m and a mass of $m \approx 2 \times 10^{30}$ kg and is located at a mean distance of $L = 1.496 \times 10^{11}$ m from the earth. It emits radiation energy continuously at a rate of Esun $\approx 3.8 \times 10^{26}$W. Less than a billionth of this energy (about 1.7×10^{17} W) strikes the earth, which is sufficient to keep the earth warm and to maintain life through the photosynthesis process.

SOLAR RADIATION

The energy of the sun is due to the continuous fusion reaction during which two hydrogen atoms fuse to form one atom of helium. Therefore, the sun is essentially a nuclear reactor, with temperatures as high as 40,000,000 K in its core region. The temperature drops to about 5800 K in the outer region of the sun, called the convective zone, as a result of the dissipation of this energy by radiation. The solar energy reaching the earth's atmosphere is called the total solar irradiance Gs , whose value is

$$G_s = 1373\ W/m^2$$

SOLAR RADIATION

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The total solar irradiance (also called the solar constant) represents the rate at which solar energy is incident on a surface normal to the sun's rays at the outer edge of the atmosphere when the earth is at its mean distance from the sun (Fig. 3-13).

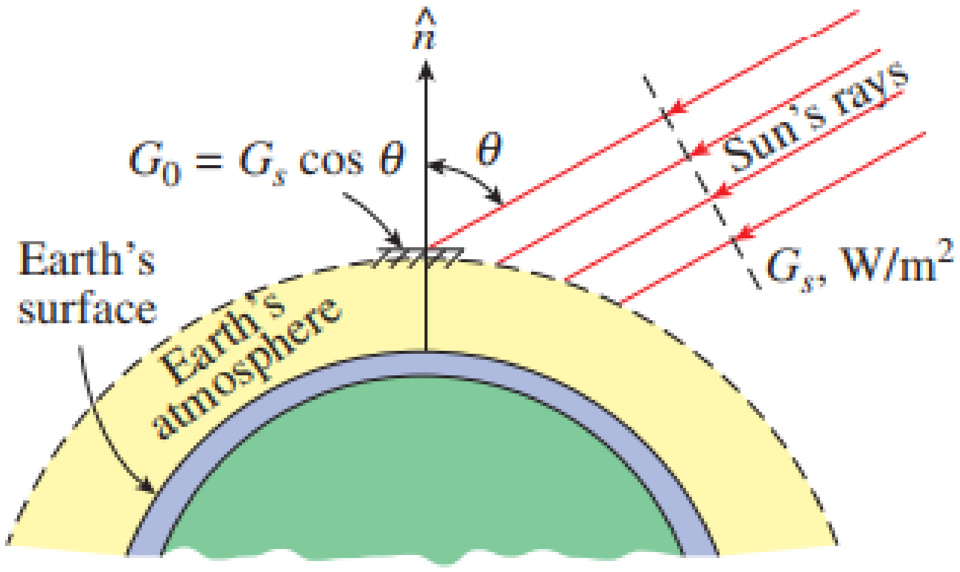

Figure 3-13
Solar radiation reaching the earth's atmosphere and the total solar irradiance.

SOLAR RADIATION

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The value of the total solar irradiance can be used to estimate the effective surface temperature of the sun from the requirement that

$$(4\pi L^2)G_s = (4\pi r^2)\sigma T_{sun}^4$$

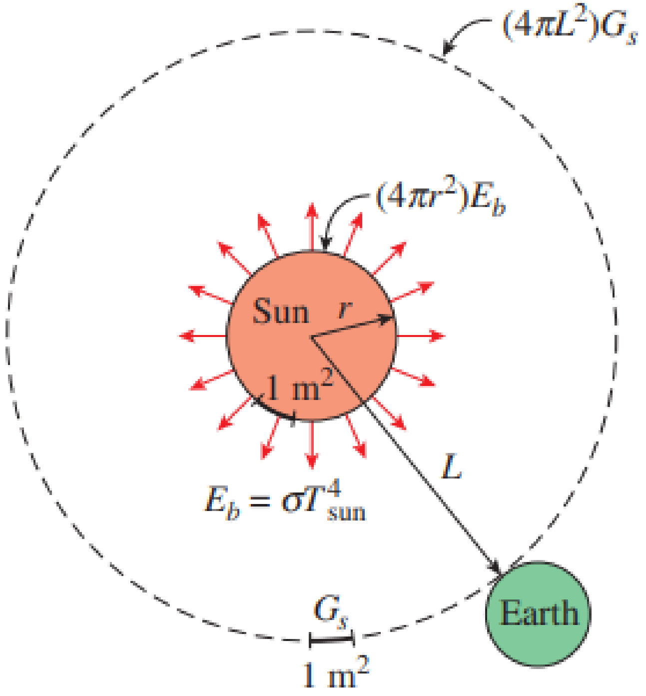

Figure 3-14
The total solar energy passing through concentric spheres remains constant, but the energy falling per unit area decreases with increasing radius.

SOLAR RADIATION

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The value of the total solar irradiance can be used to estimate the effective surface temperature of the sun from the requirement that

$$(4\pi L^2)G_s = (4\pi r^2)\sigma T_{sun}^4$$

SOLAR RADIATION

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The effective surface temperature of the sun is determined from Eq. in the previous slide to be Tsun= 5780 K. That is, the sun can be treated as a blackbody at a temperature of 5780 K. This is also confirmed by the measurements of the spectral distribution of the solar radiation just outside the atmosphere plotted in Fig. 3-15, which shows only small deviations from the idealized blackbody behavior.

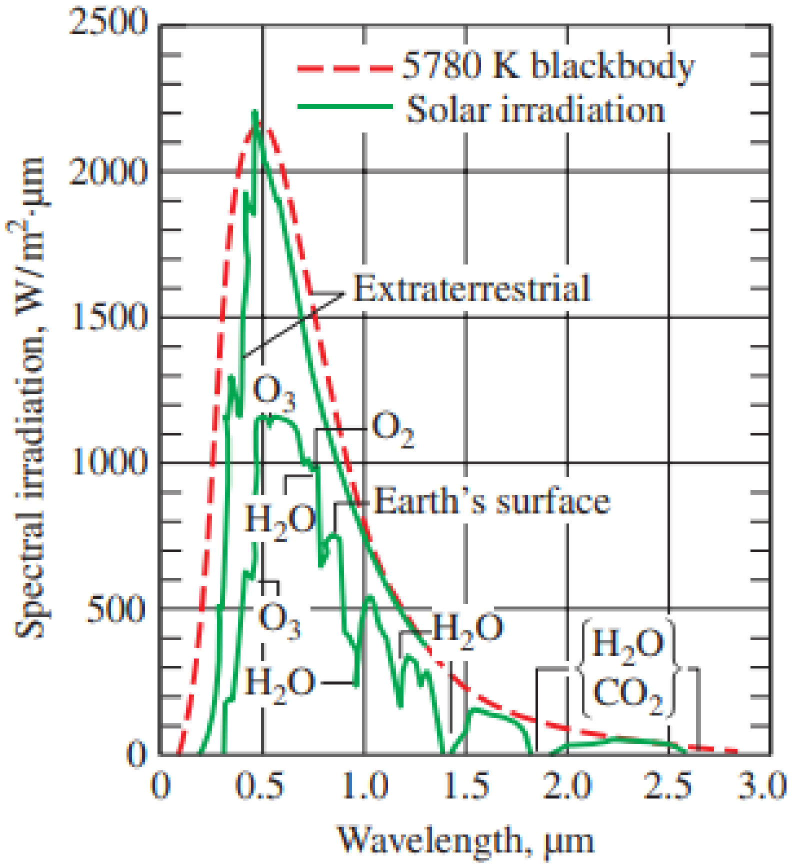

Figure 3-15
Spectral distribution of solar radiation just outside the atmosphere, at the surface of the earth on a typical day, and comparison with blackbody Radiation at 5780 K.

SOLAR RADIATION

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The spectral distribution of solar radiation on the ground plotted in Fig. 3-15 shows that the solar radiation undergoes considerable attenuation as it passes through the atmosphere as a result of absorption and scattering. About 99 percent of the atmosphere is contained within a distance of 30 km from the earth's surface. The several dips on the spectral distribution of radiation on the earth's surface are due to absorption by the gases O2, O3(ozone), H2O, and CO2. Absorption by oxygen occurs in a narrow band about λ = 0.76 µm. The ozone absorbs UV radiation at wavelengths below 0.3 µm almost completely, and radiation in the range 0.3 to 0.4 µm considerably.

SOLAR RADIATION

Another mechanism that attenuates solar radiation as it passes through the atmosphere is scattering or reflection by air molecules and the many other kinds of particles such as dust, smog, and water droplets suspended in the atmosphere.

SOLAR RADIATION

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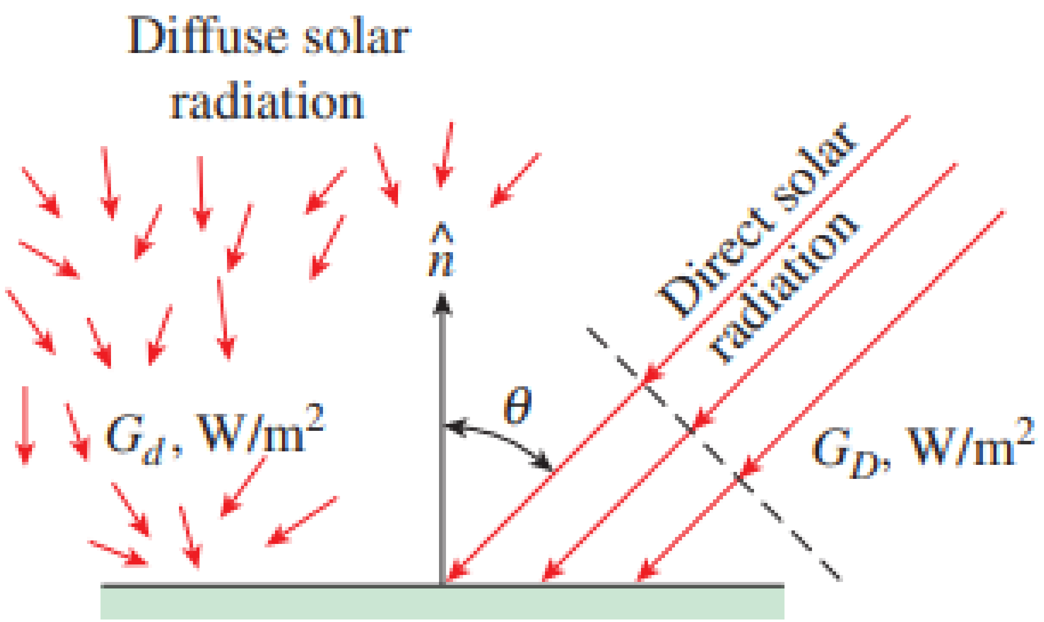
The solar energy incident on a surface on earth is considered to consist of direct and diffuse parts. The part of solar radiation that reaches the earth's surface without being scattered or absorbed by the atmosphere is called direct solar radiation GD. The scattered radiation is assumed to reach the earth's surface uniformly from all directions and is called diffuse solar radiation Gd.



$$G_{solar} = G_D \cos\theta + G_d$$

Figure 3-16
The direct and diffuse radiation incident on a horizontal surface on earth's surface.

SOLAR RADIATION

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The radiation emission from the atmosphere to the earth's surface is expressed as

$$G_{sky} = \sigma T_{sky}^4$$

The sky radiation absorbed by a surface can be expressed as

$$E_{sky,absorbed} = \alpha G_{sky} = \alpha \sigma T_{sky}^4 = \varepsilon \sigma T_{sky}^4$$

SOLAR RADIATION

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The net rate of radiation heat transfer to a surface exposed to solar and atmospheric radiation is determined from an energy balance (Fig. 3-17):

$$\dot{q}_{net} = E_{solar,absorbed} + E_{sky,absorbed} - E_{emitted} = \alpha_s G_{solar} + \varepsilon\sigma T_{sky}^4 - \varepsilon\sigma T_s^4$$

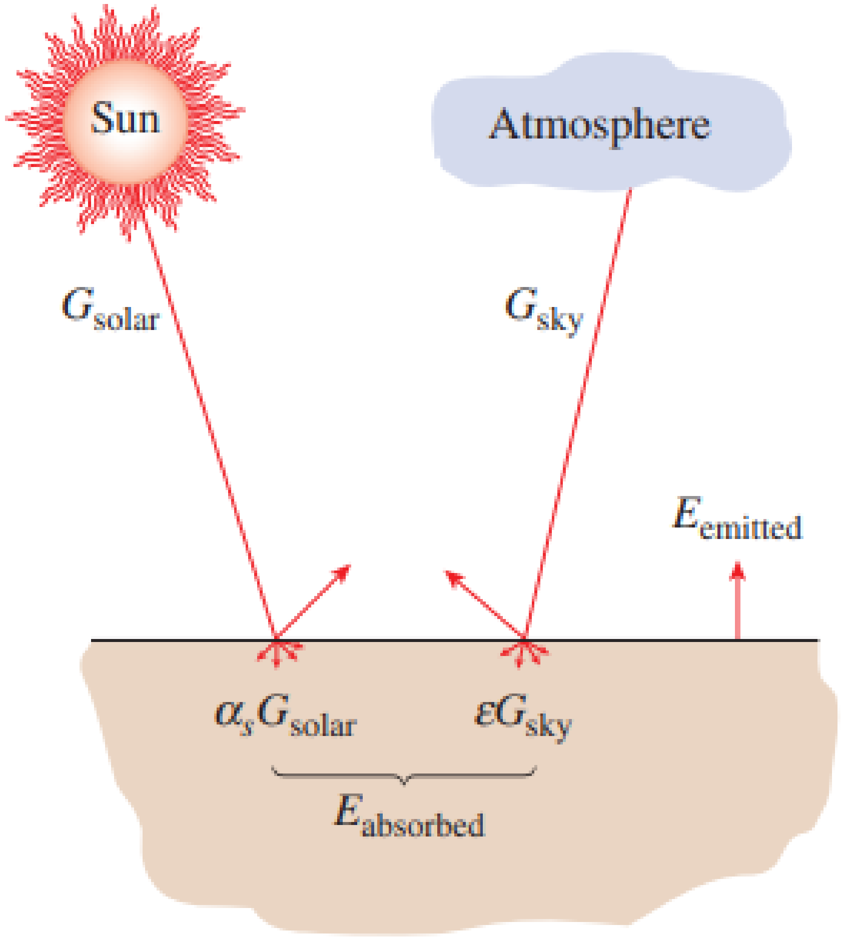

Figure 3-17
Radiation interactions of a surface exposed to solar and atmospheric radiation.

SOLAR RADIATION

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The net rate of radiation heat transfer to a surface exposed to solar and atmospheric radiation is determined from an energy balance (Fig. 3-17):

$$\dot{q}_{net,rad} = E_{solar,absorbed} + E_{sky,absorbed} - E_{emitted}$$
$$= \alpha_s G_{solar} + \varepsilon\sigma T_{sky}^4 - \varepsilon\sigma T_s^4$$

EXAMPLE 3-3 The absorber surface of a solar collector is made of aluminum coated with black chrome (α_s= 0.87 and ε= 0.09). Solar radiation is incident on the surface at a rate of 720 W/m2 (Fig. 3-18). The air and the effective sky temperatures are 25 and 15°C, respectively, and the convection heat transfer coefficient is 10 W/m2 ·K. For an absorber surface temperature of 70°C, determine the net rate of solar energy delivered by the absorber plate to the water circulating behind it.

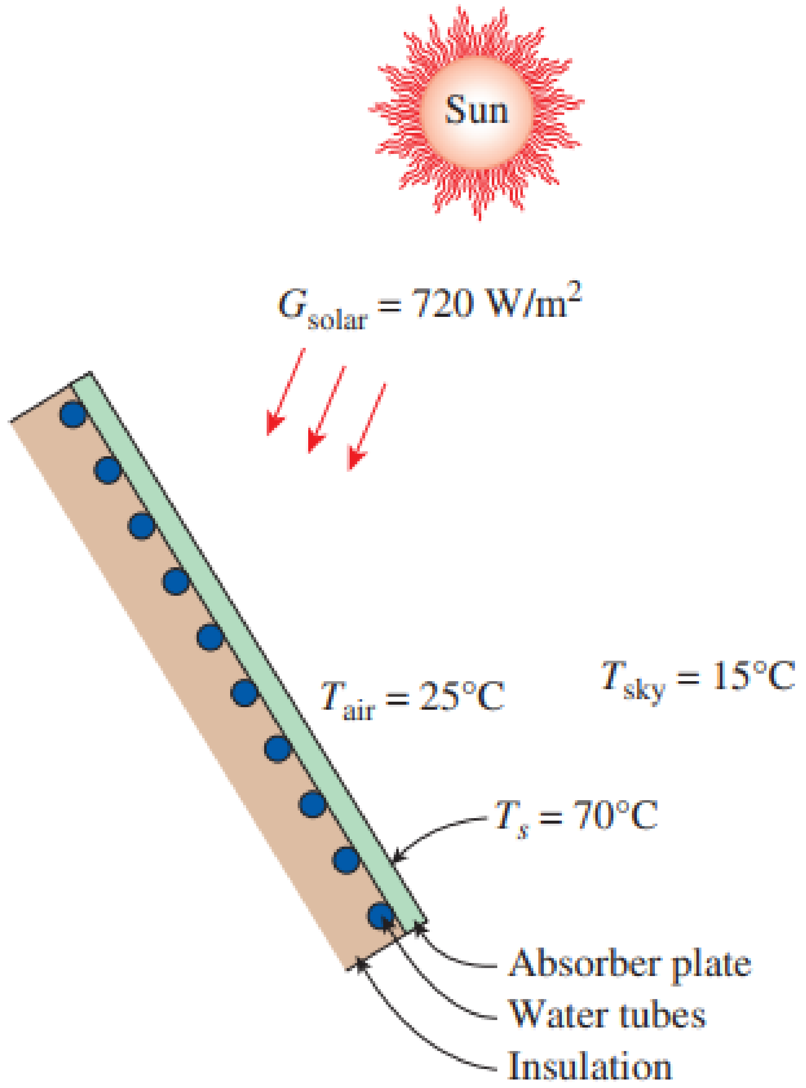

Figure 3-18
Schematic for Example 3-3.

SOLUTION The net rate of solar energy delivered by the absorber plate to the water circulating behind it can be determined from an energy balance to be

$$\dot{q}_{net} = \dot{q}_{gain} - \dot{q}_{loss}$$

$$\dot{q}_{net} = \alpha_s G_{solar} - [\varepsilon\sigma(T_s^4 - T_{sky}^4) + h(T_s - T_{air})$$

Then,

$$\dot{q}_{net} = 0.87 \times (720\, W/m^2) - 0.09(5.67 \times 10^{-8}\, W/m^2.K^4)[(70 + 273K)^4 - (15 + 273K)^4] - 10\, W/m^2.K)(70℃ - 25℃) = 141\, W/m^2$$

Therefore, heat is gained by the plate and transferred to water at a rate of 141 W per m^2 surface area.

EXAMPLE 3-4 **Determine the solar constant using below Eq. Take the effective surface temperature of the sun as Tsun= 5778 K.**

$$(4\pi L^2)G_s = (4\pi r^2)\sigma T_{sun}^4$$

Blackbody Radiation

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Solution The sun is a nearly spherical body that has a diameter of D = 1.393 × 10⁹ m and is located at a mean distance of L = 1.496 × 10¹¹ m from the earth. Also, the effective surface temperature of the sun is Tsun= 5778 K.

$$(4\pi L^2)G_s = (4\pi r^2)\sigma T_{sun}^4$$

$$(4\pi(1.496 \times 10^{11} m)^2)G_s = 4\pi(0.5 \times 1.393 \times 10^9 m)^2 (5.67 \times 10^{-8}\, W/m^2.K^4)\,(5778\, K)^4$$

$$G_s = 1370\, W/m^2$$

Blackbody Radiation

EXAMPLE 3-5 **Estimate the amount of solar energy input to a horizontal collector per year whose surface area is 5.5 m2 for Las Vegas, NV and Cleveland, OH. Determine the equivalent amount of coal that would provide the same amount of energy. Take the higher heating value of coal to be 30,000 kJ/kg.**

Blackbody Radiation

Semnan University

Solution (sing the average daily solar radiation values on a horizontal surface from Table 3-5, the amount of solar energy input to the collector surface is determined for each city as

$$G_{Las\,Vegas} = G_{ave} \times A \times time$$

$$= \left(20,330\,\frac{kJ}{m^2}.day\right)(5.5\,m^2)(365\,days) = 4.081 \times 10^7\,kJ$$

$$G_{Cleveland} = G_{ave} \times A \times time$$

$$= \left(13,510\,\frac{kJ}{m^2}.day\right)(5.5\,m^2)(365\,days) = 2.712 \times 10^7\,kJ$$

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The equivalent amount of coal that would provide the same amount of energy for each city is

$$m_{coal,Las\,Vegas} = \frac{G_{Las\,Vegas}}{HHV_{coal}} = \frac{4.081 \times 10^7\ kJ}{30,000\ kJ/kg} = 1360\ kg$$

$$m_{coal,Cleveland} = \frac{G_{Cleveland}}{HHV_{coal}} = \frac{2.712 \times 10^7\ kJ}{30,000\ kJ/kg} = 904\ kg$$