ME265: Thermal Engineering & Heat Transfer

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3. Mechanical Devices & Systems
4. Heat Transfer

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4.4 Radiation: Fundamentals

Photon Energy: $$e = h\nu = \frac{hc}{\lambda}$$ …. … (4.1)

Stefan-Boltzmann Law: $$E_b(T) = \sigma T^4$$ …. … (4.2)

Planck's Law: $$E_{b\lambda}(T) = \frac{C_1}{\lambda^5[exp(C_2/\lambda T) - 1]}$$ …. … (4.3)

Wien's Displacement Law: $$\lambda T = 2897.8$$ …. … (4.5)

Kirchhoff's Law to be added today

Ref: [1] Cengel et al. Chapter 12

❑ SEP of Blackbody, $E_{b\lambda}$

- We are often interested in the amount of radiation emitted over some wavelength band.
- The radiation energy emitted by a blackbody per unit area over a wavelength band from $\lambda = 0 - \lambda$ is determined from

$$E_{b,0-\lambda}(T) = \int_0^{\lambda} E_{b\lambda}(\lambda, T)\, d\lambda$$

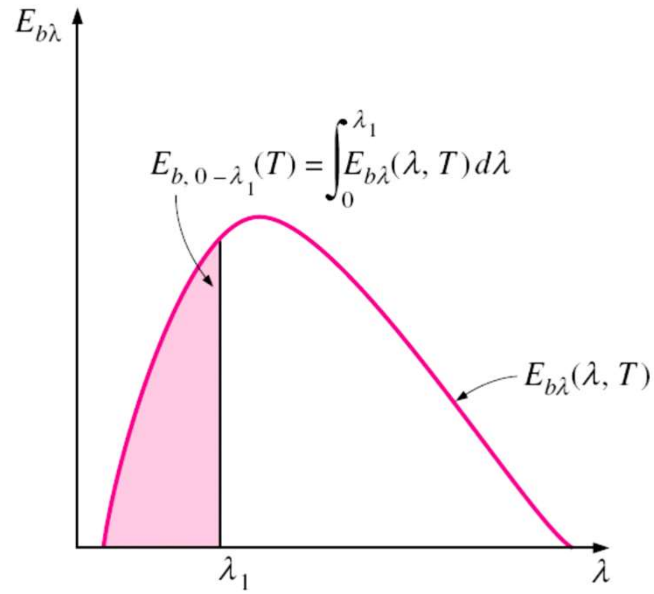


Fig. 4.4.6b $E_{b\lambda} - \lambda$ chart

- Blackbody radiation function f_λ is used for convenience, which is defined by:

$$f_\lambda = \frac{E_{b,0-\lambda}}{E_b} = \frac{\int_0^{\lambda} E_{b\lambda}(\lambda, T)\, d\lambda}{\sigma T^4} \quad \text{…. … (4.6)}$$

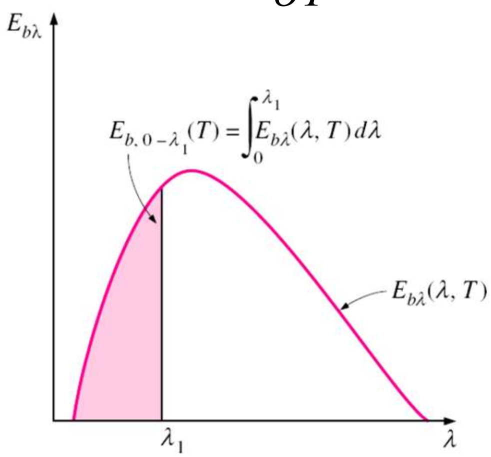
❑ Blackbody radiation function f_λ

TABLE 12–2

Blackbody radiation functions f_λ

λT, µm · K	f_λ	λT, µm · K	f_λ
200	0.000000	6200	0.754140
400	0.000000	6400	0.769234
600	0.000000	6600	0.783199
800	0.000016	6800	0.796129
1000	0.000321	7000	0.808109
1200	0.002134	7200	0.819217
1400	0.007790	7400	0.829527
1600	0.019718	7600	0.839102
1800	0.039341	7800	0.848005
2000	0.066728	8000	0.856288
2200	0.100888	8500	0.874608
2400	0.140256	9000	0.890029
2600	0.183120	9500	0.903085
2800	0.227897	10,000	0.914199
3000	0.273232	10,500	0.923710
3200	0.318102	11,000	0.931890
3400	0.361735	11,500	0.939959
3600	0.403607	12,000	0.945098
3800	0.443382	13,000	0.955139
4000	0.480877	14,000	0.962898
4200	0.516014	15,000	0.969981
4400	0.548796	16,000	0.973814
4600	0.579280	18,000	0.980860
4800	0.607559	20,000	0.985602
5000	0.633747	25,000	0.992215
5200	0.658970	30,000	0.995340
5400	0.680360	40,000	0.997967
5600	0.701046	50,000	0.998953
5800	0.720158	75,000	0.999713
6000	0.737818	100,000	0.999905

$$f_{\lambda_1}(T) = \frac{\int_0^{\lambda_1} E_{b\lambda}(\lambda, T)\, d\lambda}{\sigma T^4}$$



$$f_{\lambda_1-\lambda_2}(T) = f_{\lambda_2}(T) - f_{\lambda_1}(T)$$

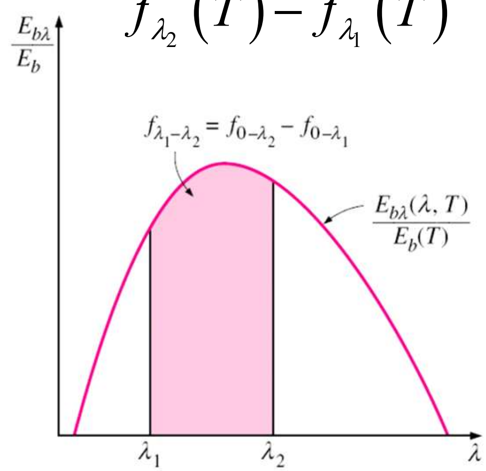


Fig. 4.6c $E_{b\lambda} - \lambda$ charts

4.4 Radiation: Fundamentals

EP#4.1 **(Cengel et. al. Example 12-7)**

Charged-coupled device (CCD) image sensors, that are common in modern digital cameras, respond differently to light sources with different spectral distributions. Daylight and incandescent light are emitted, respectively, from the sun and lightbulb having effective surface temperatures of 5800 K and 2800 K. If these light sources are approximated as blackbodies, determine the fraction of radiation emitted within visible spectrum. Also find calculate the **wavelength of maximum radiation** emitted from the bulb.

❑ Radiation Components

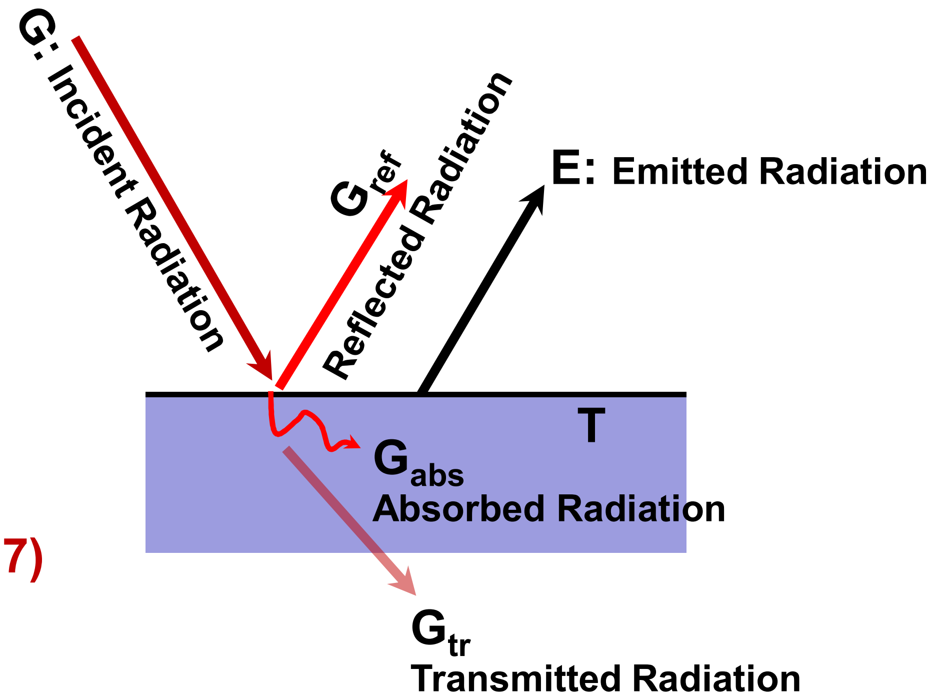


Fig. 4.4.7 Components of Radiation

$$G = G_{abs} + G_{ref} + G_{tr} \quad \ldots\ldots \text{(6.7)}$$

Irradiation → **Incident radiation, G**

Radiosity → **Radiation leaving any surface, $J = E + G_{ref}$**

Ref: [1] Cengel et al. Chapter 12

4.4 Radiation: Fundamentals

❑ Radiation Properties

$$\text{Emissivity} = \frac{\text{Radiation emitted by a surface at given temperature}}{\text{Radiation emitted by a blackbody at the same temperature}}$$

Spectral hemispherical emissivity

$$\boldsymbol{\varepsilon_\lambda(\lambda, T) = \frac{E_\lambda(\lambda, T)}{E_{b\lambda}(\lambda, T)}} \qquad \text{.... ... (4.8a)}$$

Total hemispherical emissivity

$$\boldsymbol{\varepsilon(T) = \frac{E\,(T)}{E_{b\lambda}(T)}} \qquad \text{.... ... (4.8b)}$$

$$\boldsymbol{\varepsilon(T) = \frac{\int_0^\infty E_\lambda d\lambda}{\sigma T^4} = \frac{\int_0^\infty \varepsilon_\lambda E_{b\lambda}\, d\lambda}{\sigma T^4}} \qquad \text{.... ... (4.8c)}$$

❑ Grey Surface and Real Surface

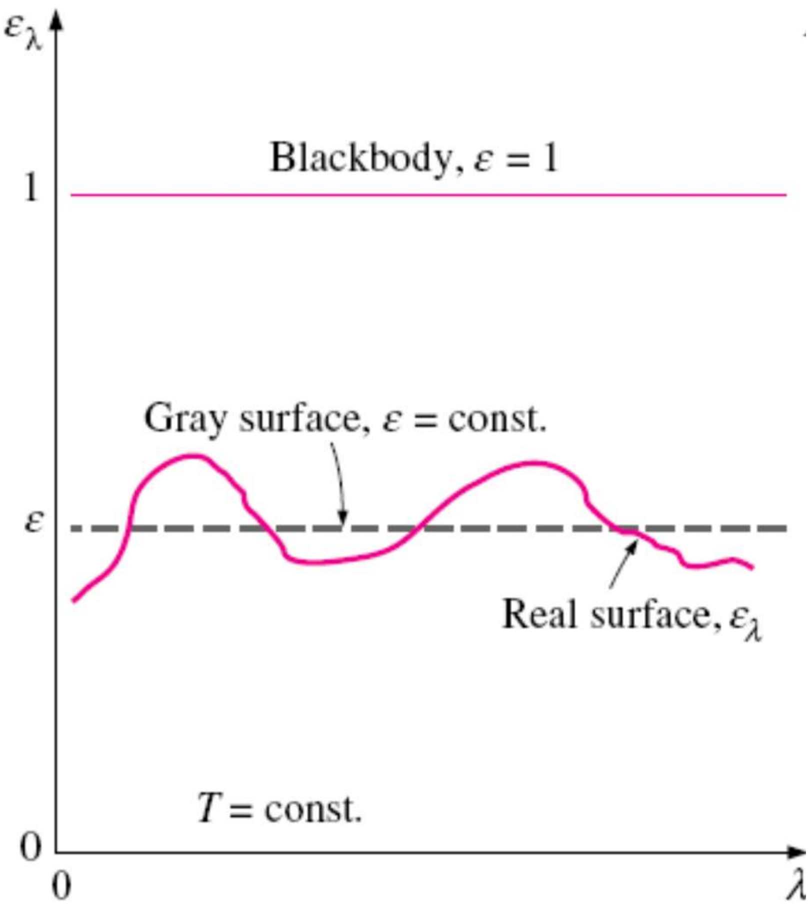


Fig. 4.4.8a Spectral Emissivity

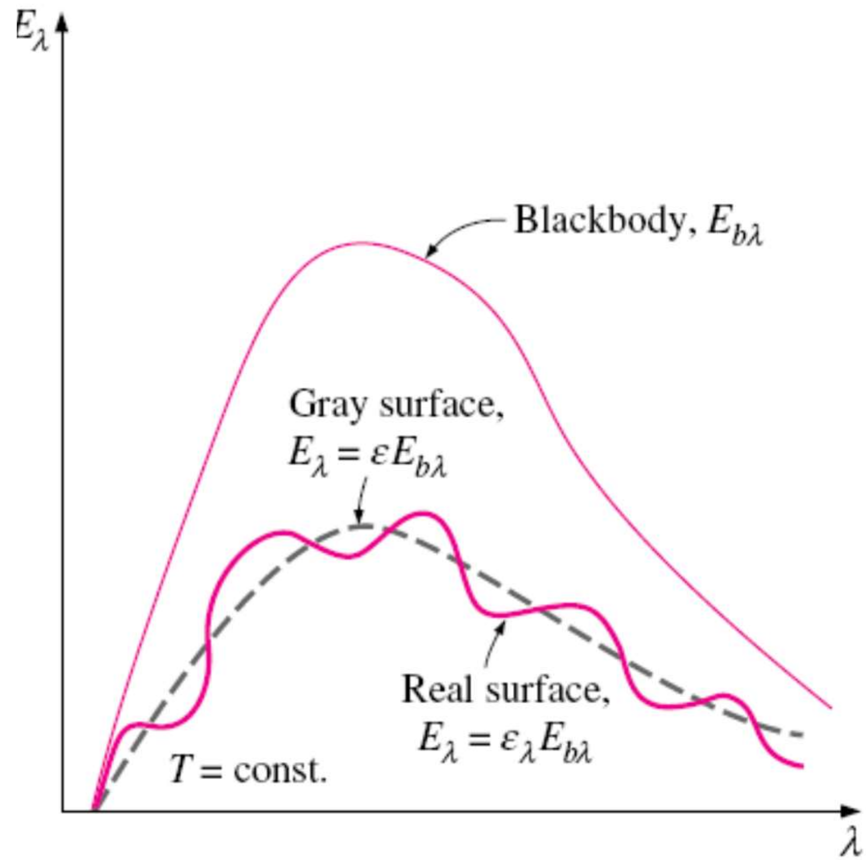


Fig. 4.4.8b Spectral emissive power

Radiative Properties

Absorptivity: $$\alpha = \frac{\text{Absorbed radiation}}{\text{Incident radiation}} = \frac{G_{abs}}{G}$$

Reflectivity: $$\rho = \frac{\text{Reflected radiation}}{\text{Incident radiation}} = \frac{G_{ref}}{G}$$

Transmissivity: $$\tau = \frac{\text{Transmitted radiation}}{\text{Incident radiation}} = \frac{G_{tr}}{G}$$

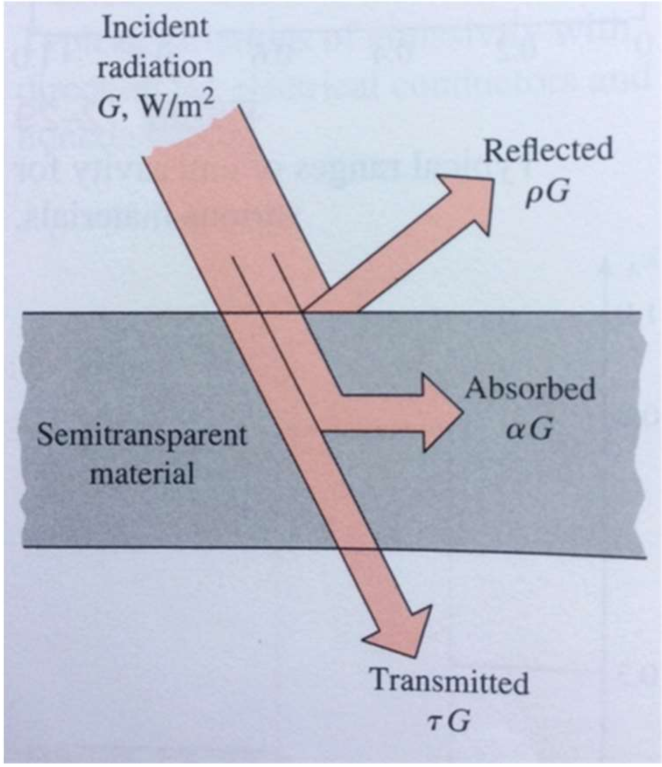


Fig. 6.9 Radiation properties

Surface Energy Balance: $$\alpha + \rho + \tau = 1 \quad \text{.... ... (6.9)}$$

For blackbody: $$\alpha = 1$$

For opaque solids and liquids: $$\alpha + \rho = 1$$

4.4 Radiation: Fundamentals

❑ Radiative Properties: Kirchhoff's Law

Radiation incident on any part of the small body at temperature T **=** Radiation emitted by the large surface of the isothermal enclosure

$$G = E_b(T) = \sigma T^4$$

From surface energy balance of small body,

$$G_{abs} = E_{emit}$$

$$\alpha G = \varepsilon \sigma T^4$$

$$\Rightarrow \alpha = \varepsilon \quad \text{.... ... (4.10)}$$

This is called Kirchhoff's Law

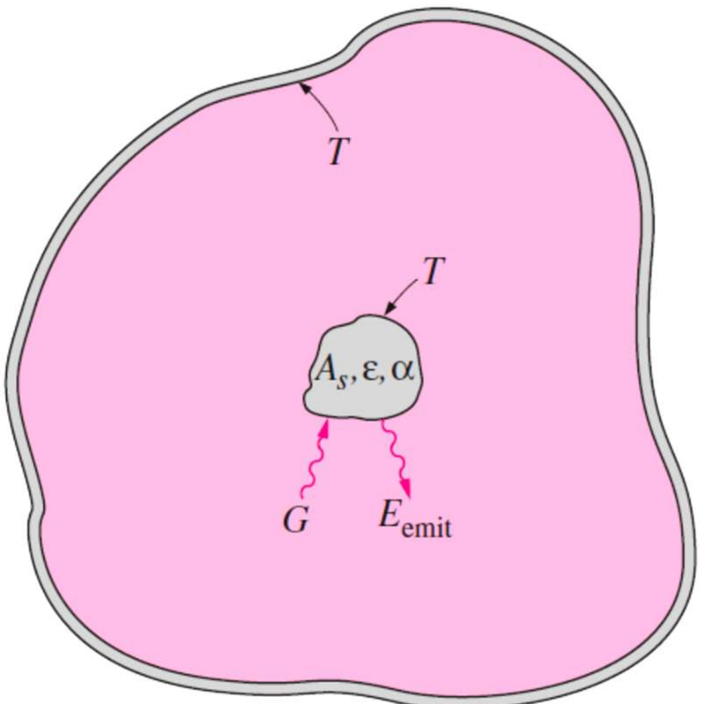


Fig. 4.4.10 Small body contained in a large isothermal enclosure

It is very tempting to use Kirchhoff's law in radiation analysis since the relation $\alpha = \varepsilon$ together with $\alpha + \rho = 1$ enables us to determine all three properties of an opaque surface from a knowledge of only one property.

4.4 Radiation: Fundamentals

Energy Balance of a surface exposed to solar and atmospheric radiation:

$$q_{net,rad} = \sum E_{absorbed} - \sum E_{emitted}$$

$$\begin{aligned} q_{net,rad} &= E_{solar,abs} + E_{sky,abs} - E_{emitted} \\ &= \alpha_s G_{solar} + \varepsilon G_{sky} - \varepsilon \sigma T_s^4 \\ &= \alpha_s G_{solar} + \varepsilon \sigma \left(T_{sky}^4 - T_s^4\right) \end{aligned}$$

.... **(4.11)**

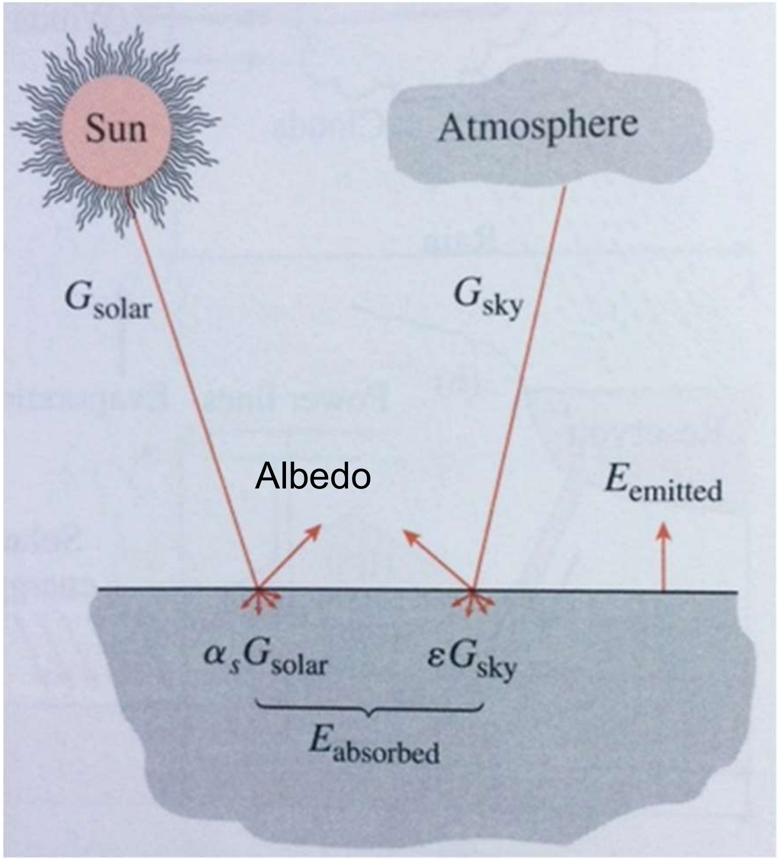


Fig. 4.4.11 Radiation interaction of a surface exposed to solar and atmospheric radiation

4.4 Radiation: Fundamentals

$$q_{net,rad} = \alpha_s G_{solar} + \varepsilon\sigma\,(T_{sky}^4 - T_s^4)$$

…. … **(4.11)**

Comparison of the solar absorptivity α_s of some surfaces with their emissivity ε at room temperature

Surface	α_s	ε
Aluminum		
Polished	0.09	0.03
Anodized	0.14	0.84
Foil	0.15	0.05
Copper		
Polished	0.18	0.03
Tarnished	0.65	0.75
Stainless steel		
Polished	0.37	0.60
Dull	0.50	0.21
Plated metals		
Black nickel oxide	0.92	0.08
Black chrome	0.87	0.09
Concrete	0.60	0.88
White marble	0.46	0.95
Red brick	0.63	0.93
Asphalt	0.90	0.90
Black paint	0.97	0.97
White paint	0.14	0.93
Snow	0.28	0.97

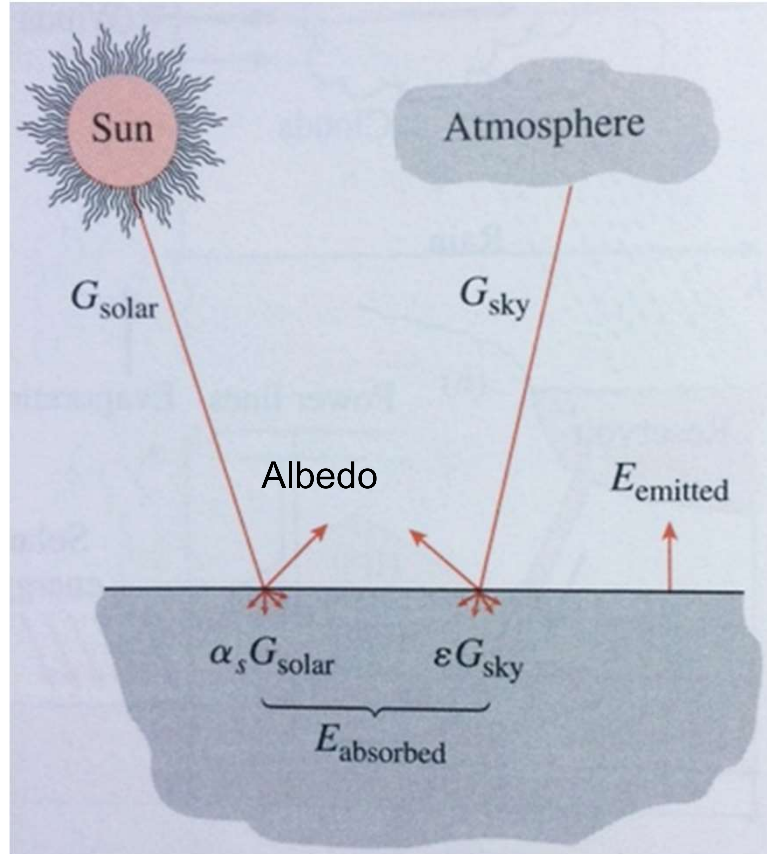


Fig. 4.4.11 Radiation interaction of a surface exposed to solar and atmospheric radiation

4.4 Radiation: Fundamentals

Radiation heat transfer between surfaces depends on the following:

- **Temperature of the surfaces**
- **Surface radiative property, ε (emissivity)**
- **How well the surfaces can see each other**

↓

View Factor / Configuration Factor / Shape Factor