CHAPTER 6 RADIATION HEAT TRANSFER IN BUILDINGS

6.2 Calculation of Thermal Radiation Properties

In this section, we calculate thermal radiation properties over different wavelength ranges. For example, we often need to know how much solar radiation an exterior building surface absorbs; to determine this radiation we need the solar absorptance, which is approximately the fraction of incident solar radiation absorbed for wavelengths shorter than 3µm. Similarly, we may need to calculate the emissivity of a surface at ordinary building temperatures; this is approximately equal to the ratio of emitted radiation (for wavelengths greater than 3µm) to the radiation emitted by a black body at the same temperature. First, we define a few important blackbody parameters.

Spectral blackbody emissive power: $E_{b\lambda}$ is the amount of radiation energy emitted by a blackbody at an absolute temperature T, per unit time, per unit area of surface, per unit wavelength.

$$E_{b\lambda} = \frac{c_1}{\lambda^5 \cdot exp\left(\frac{c_2}{\lambda \cdot T} - 1\right)}$$

Equation (1)

where

$$c_1 := 3.743 \cdot 10^8 \ \frac{W \cdot \mu m^4}{m^2}$$

$$c_2 := 1.4387 \cdot 10^4 \ \mu m \cdot K$$

T = absolute temperature, K

l = wavelength

Stefan-Boltzmann Law: The blackbody emissive power is given by

$$E_b = \int_0^{\infty} E_{b\lambda}\,d\lambda$$

Equation (2)

$$E_b = \sigma \cdot T^4$$

where

$$\sigma := 5.67 \cdot 10^{-8} \frac{W}{m^2 \cdot K^4}$$

Stefan-Boltzmann constant

We often need to determine the fraction f12 of blackbody emissive power between two wavelengths by integration of Equation (1) and division by Equation (2). If the lower wavelength is zero, use instead 0.1 μm to avoid numerical integration errors and similarly replace an upper limit of infinity by 100 μm.

$$f_{12} = \frac{\displaystyle\int_{\lambda_1}^{\lambda_2} \frac{c_1}{\lambda^5 \cdot \left(exp\left(\frac{c_2}{\lambda \cdot T}\right) - 1\right)}\,d\lambda}{\sigma \cdot T^4}$$

Example: A tungsten filament is heated to 2500 K. What fraction of the radiation is in the visible range?

Visible range: $\lambda_1 := 0.4\ \mu m$ $\lambda_2 := 0.7\ \mu m$

$$T := 2500\ K$$

$$f_{12} := \frac{\displaystyle\int_{\lambda_1}^{\lambda_2} \frac{c_1}{\lambda^5 \cdot \left(\exp\left(\frac{c_2}{\lambda \cdot T}\right) - 1\right)}\,d\lambda}{\sigma \cdot T^4}$$

$$f_{12} = 0.0334$$

Therefore, only about 3.3% of the radiation emitted by the lamp is in the visible range.

Radiation properties: The absorptance of a surface is the fraction of total irradiation (incident radiation) absorbed by the body. The reflectance of the surface is equal to the fraction of the irradiation reflected from the surface. The transmittance of surface is the fraction of the irradiation transmitted by the surface (equal to 0 for opaque surfaces). An energy balance at the surfaces shows that

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

where

α = absorptance ρ = reflectance τ = transmittance.

Emissivity, absorptance, transmittance and reflectance generally vary with wavelength. It can be shown that the monochromatic emissivity and absorptance of a surface are equal. The total hemispherical emissivity of a surface is equal to the ratio of the total hemispherical emitted radiation to the total blackbody emissive power:

$$\varepsilon_\lambda = \frac{E_\lambda}{E_{b\lambda}}$$ and

$$\varepsilon = \frac{\int_0^\infty \varepsilon_\lambda \cdot E_{b\lambda} \, d\lambda}{\sigma \cdot T^4}$$ monochromatic emissivity and hemispherical emissivity

Example: The total hemispherical emissivity of an aluminum paint is 0.35 at wavelengths below 3μm and 0.7 at longer wavelengths. Determine the total emissivity at room temperatures of 25 degC and 500 degC:

$\varepsilon_s := 0.35$ shortwave emissivity

$\varepsilon_l := 0.7$ longwave emissivity

$T_1 := (25 + 273)\ K$ $T_2 := (500 + 273)\ K$

$\lambda_1 := 3\ \mu m$

Using these emissivity values in the above integral, we obtain:

$$\varepsilon_1 := \frac{\int_{0.1 \cdot \mu m}^{3 \cdot \mu m} \varepsilon_s \cdot \frac{c_1}{\lambda^5 \cdot \left(\exp\left(\frac{c_2}{\lambda \cdot T_1}\right) - 1\right)} d\lambda + \int_{3 \cdot \mu m}^{100 \cdot \mu m} \varepsilon_l \cdot \frac{c_1}{\lambda^5 \cdot \left(\exp\left(\frac{c_2}{\lambda \cdot T_1}\right) - 1\right)} d\lambda}{\sigma \cdot {T_1}^4}$$

$$\varepsilon_2 := \frac{\displaystyle\int_{0.1 \cdot \mu m}^{3 \cdot \mu m} \varepsilon_s \cdot \frac{c_1}{\lambda^5 \cdot \left(\exp\left(\frac{c_2}{\lambda \cdot T_2}\right) - 1\right)} \, d\lambda + \int_{3 \cdot \mu m}^{100 \cdot \mu m} \varepsilon_l \cdot \frac{c_1}{\lambda^5 \cdot \left(\exp\left(\frac{c_2}{\lambda \cdot T_2}\right) - 1\right)} \, d\lambda}{\sigma \cdot {T_2}^4}$$

$\varepsilon_1 = 0.69704$

$\varepsilon_2 = 0.65685$

emissivities
at T1 and T2

Total emitted radiation:

$$q_1 := \varepsilon_1 \cdot \sigma \cdot {T_1}^4 = 311.67664 \ \frac{W}{m^2}$$

$$q_2 := \varepsilon_2 \cdot \sigma \cdot {T_2}^4 = 13297.33416 \ \frac{W}{m^2}$$

Gray bodies are surfaces with radiation properties whose values can be approximated as independent of wavelength. An acceptable approximation in building thermal analysis is selective gray surfaces; a surface may be assumed to be gray over specific wavelength ranges and associated temperature ranges.

For example, using the integration technique of the previous example, a longwave emissivity of approximately 0.85 - 0.90 is determined for most building materials and paints (not metals) at ordinary temperatures. However, the solar (shortwave) absorptance of a glossy white surface, for example, can be as low as 0.2.