1 Fundamentals of Thermal Radiation

The terms *radiative heat transfer* and *thermal radiation* are commonly used to describe the science of heat transfer caused by electromagnetic (EM) waves. The main goal of this chapter is to introduce the nature of thermal radiation, the fundamental laws of thermal radiation, and the methods for computing radiative heat exchange between two or more surfaces.

1.1 Basic Characteristics of Thermal Radiation

1.1.1 The Nature of Thermal Radiation

Radiation is one of the fundamental modes of heat transfer, and the research on the mechanism and nature of radiation is still ongoing. Our current understanding of radiation is based on classical EM theory and quantum physics. In 1865, Maxwell published the complete equations of EM waves, believing that light is a form of EM radiation [1]. Once the energy is radiated, it propagates as an EM wave, regardless of whether there is a vacuum or matter along its path.

In 1905, Einstein built on the idea of quantization of radiation proposed by Planck, who believed that light is a stream of energy quanta moving at the speed of light [2]. This energy quantum is called a photon whose energy is proportional to its frequency. Radiation is the energy-transfer process by which an object emits photons to the outside. Later, Einstein further pointed out that photons have wave–particle duality [3]. From the relationship between the frequency of photon energy and the EM wavelength, we can simply glimpse the relationship between wave and particle properties.

In general, the energy properties of radiation are explained by Einstein's light-quantum hypothesis, while the propagation properties are explained by Maxwell's EM field theory. This book mainly focuses on the conversion and transfer of radiative energy, so the basic properties of thermal radiation will be explored under the guidance of EM field theory. The core content of EM field theory is the famous Maxwell's equations. These consist of Gauss's laws for the electric field and the magnetic field, Faraday's law of EM effect, and the Ampere–Maxwell law. No doubt, Maxwell's equations are as sacred in the field of electrodynamics as Newton's second law is in classical physics.

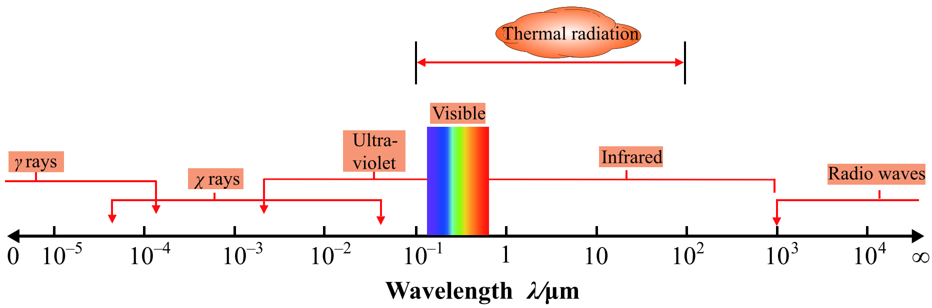

Figure 1.1 The spectrum of EM waves.

According to the EM field theory, the electric field and the magnetic field are interrelated and mutually excited to form a unified EM field. The EM field propagates in vacuum at the speed of light, which is called the EM wave. The wavelength range of EM waves is very wide, covering cosmic rays with wavelengths of less than 10^{-9} m to radio waves with wavelengths of several hundred meters. Figure 1.1 shows the wavelength distribution of various EM waves.

The EM wave generated by thermal motion is called thermal radiation, whose wavelength is in the range of 0.1–100 μm, mainly including the visible region and most of the infrared region. In vacuum, the wavelength of visible light is 0.38–0.76 μm and that of infrared light is 0.76–1000 μm. In the range of temperatures in industry (i.e., below 2000 K), the radiation wavelengths are between 0.8 and 100 μm. The sun is a heat source with a surface temperature of about 5800 K, and the energy of solar radiation is concentrated in the wavelength range of 0.2–2 μm. As long as the temperature of an object is higher than absolute zero (0 K), it always emits continuous thermal radiation outward. At the same time, the object also constantly absorbs the incident thermal radiation on its surface from the surrounding environment and converts the absorbed radiation energy into heat energy. When it is in thermal equilibrium with the surrounding environment, the thermal radiation on its surface is still evolving, but its net radiative heat transfer is equal to zero.

1.1.2 The Effect of Surfaces on Radiation

When the total radiation energy Q from the outside strikes a surface, part of the energy is reflected by the surface (Q_ρ), part is absorbed (Q_α), and part is transmitted (Q_τ) as shown in Fig. 1.2. According to the law of conservation of energy,

$$Q = Q_\rho + Q_\alpha + Q_\tau. \tag{1.1.1}$$

Dividing both sides of this equation by Q, we can obtain

$$1 = \frac{Q_\rho}{Q} + \frac{Q_\alpha}{Q} + \frac{Q_\tau}{Q}. \tag{1.1.2}$$

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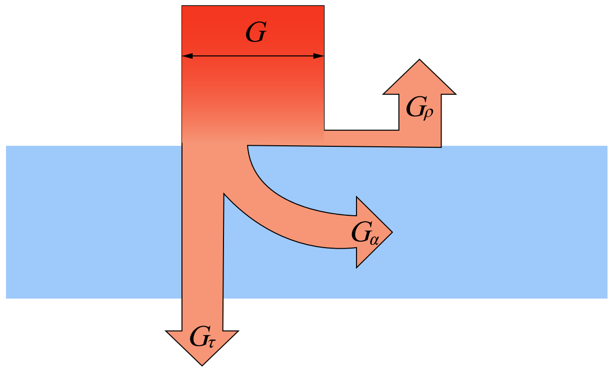

Figure 1.2 Reflection, absorption, and transmission of thermal radiation.

The three parts of energy, Q_ρ/Q, Q_α/Q, and Q_τ/Q, are called reflectivity, absorptivity, and transmissivity of the body, denoted by ρ, α, and τ, respectively. Therefore, Eq. (1.1.2) can be further expressed as

$$\rho + \alpha + \tau = 1. \tag{1.1.3}$$

When the radiation energy is incident on a solid or liquid surface, its absorption occurs only at a very thin layer of the surface owing to tightly arranged molecules. For metal conductors, this thickness is of the order of 1 μm; for most nonconductive materials, this thickness is usually less than 1 mm. Therefore, it can be considered that neither solid nor liquid is allowed to penetrate thermal radiation, that is, $\tau = 0$. Thus, Eq. (1.1.3) can be simplified as

$$\alpha + \rho = 1. \tag{1.1.4}$$

In addition, since thermal radiation cannot penetrate through thick solids and liquids, the absorption of radiation energy takes place only over a very thin surface. In the same way, their radiation should occur at the thin layer of the surface. Therefore, the thermal radiation of solids and liquids is a surface process, which makes the calculation of radiation heat transfer easier. Like visible light, the reflection phenomenon of radiation is also divided into specular reflection and diffuse reflection, which depends on the size of the irregularity of the surface of the object (i.e., the surface roughness) and the magnitude of the wavelength of input radiation. When the wavelength of the input radiation is larger than the irregularity of the object surface, the reflection follows the law of geometric optics and forms specular reflection, as shown in Fig. 1.3. The reflection angle is equal to the incident angle. By contrast, when the wavelength of the input radiation is smaller than the irregularities of the object surface, as shown in Fig. 1.4, diffuse reflection is formed.

Gas has little ability to reflect radiation energy, so the reflectivity can be considered to be 0 ($\rho = 0$). Therefore, Eq. (1.1.3) can be simplified as

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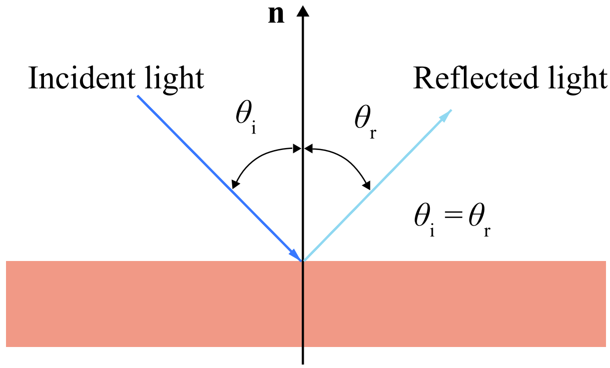

Figure 1.3 Specular reflection.

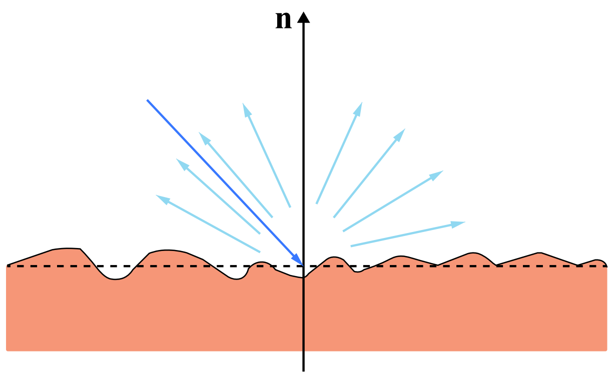

Figure 1.4 Diffuse reflection.

$$\alpha + \tau = 1. \tag{1.1.5}$$

The above discussion shows that the absorption and transmission of thermal radiation by gas characterize a volumetric process.

1.1.3 Blackbody Model

The radiation properties of real objects are usually very complex. Therefore, some ideal physical models are abstracted in the study of thermal radiation. An object with the absorption rate of $\alpha = 1$ is called an absolute blackbody [4], which means that it can absorb radiation of all wavelengths. As shown in Fig. 1.5, it is a typical blackbody model that is composed of an opening surface of an isothermal cavity. After repeated absorption and reflection, the incident radiation entering the cavity can finally leave the hole with very little radiation energy. Therefore, the opening surface of the isothermal cavity can be regarded as a surface that

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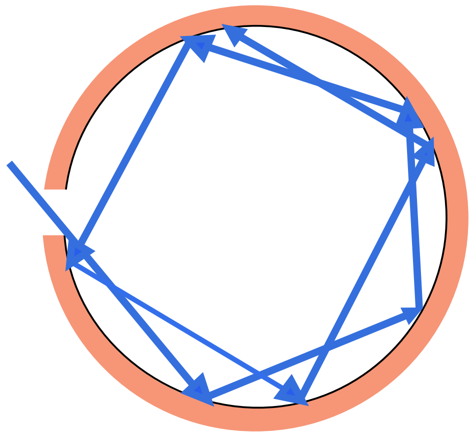

Figure 1.5 Blackbody model.

completely absorbs thermal radiation, namely, an artificial blackbody. And we cannot infer the absorptive capacity of an object to the projection of full-band radiation energy simply by its color. A black object is not necessarily a blackbody.

1.2 Basic Laws of Blackbody Thermal Radiation

Through the introduction of the basic characteristics of thermal radiation, the qualitative understanding of thermal radiation is concluded: thermal radiation is directly related to temperature, and it has spectral characteristics. In addition, the transmission of radiation energy has a certain directivity. Therefore, this section will continue to study the above characteristics of thermal radiation quantitatively, that is, systematically focus on the basic laws of thermal radiation, which respectively reveal the amount of energy radiated from a unit blackbody surface to the outside at a certain temperature from different angles and its distribution law with space direction and wavelength.

1.2.1 Hemispherical Emissive Power and Spectral Emissive Power

In order to quantitatively describe the laws of thermal radiation, the following concepts need to be introduced from the aspects of space geometric properties and energy properties.

Hemispherical Emissive Power

The hemispherical emissive power, $E(\mathrm{W \cdot m^{-2}})$, is defined as the rate at which radiation is emitted per unit area at all possible wavelengths and in all possible directions of the hemispherical space.

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Hemispherical Spectral Emissive Power

The hemispherical spectral emissive power, $E_\lambda(\mathrm{W \cdot m^{-2} \cdot \mu m^{-1}})$, is defined as the rate at which radiation of wavelength λ is emitted per unit surface area with per unit wavelength interval $\mathrm{d}\lambda$ and in all possible directions of the hemispheric space.

Obviously, the relationship between the hemispherical emissive power and the hemispherical spectral emissive power is as follows:

$$E = \int_0^\infty E_\lambda \mathrm{d}\lambda. \tag{1.2.1}$$

Solid Angle

The solid angle, Ω (sr), is defined by a small conical region between the rays of a sphere, and it is measured as the ratio of the area $\mathrm{d}A_c$ on the sphere to the square of the sphere's radius. Accordingly,

$$\Omega = \frac{A_\mathrm{c}}{r^2}, \ \mathrm{d}\Omega = \frac{\mathrm{d}A_\mathrm{c}}{r^2}. \tag{1.2.2}$$

In the spherical coordinate system of Fig. 1.6, φ is called the azimuthal angle, θ is called the zenith angle [5], and from Fig. 1.6, we can conclude that

$$\mathrm{d}A_\mathrm{c} = r\ \mathrm{d}\theta \cdot r \sin\theta \mathrm{d}\varphi. \tag{1.2.3}$$

Rearranging Eq. (1.2.3), it follows that

$$\mathrm{d}\Omega = \sin\theta \mathrm{d}\theta \mathrm{d}\varphi. \tag{1.2.4}$$

Directional Radiation Intensity

Directional radiation intensity, $I(\ \mathrm{W \cdot m^{-2} \cdot sr^{-1}})$, is defined as the rate at which radiation energy is emitted at all wavelengths in a direction per unit area of the emitting surface normal to this direction and per unit solid angle about this direction.

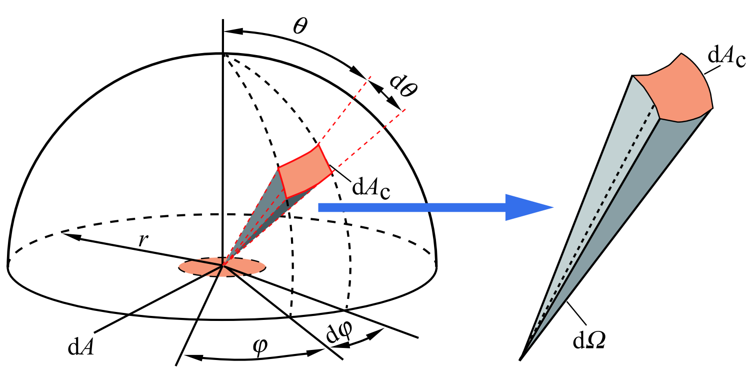

Figure 1.6 The solid angle subtended by $\mathrm{d}A_c$ at a point on $\mathrm{d}A$ in the spherical coordinate system.

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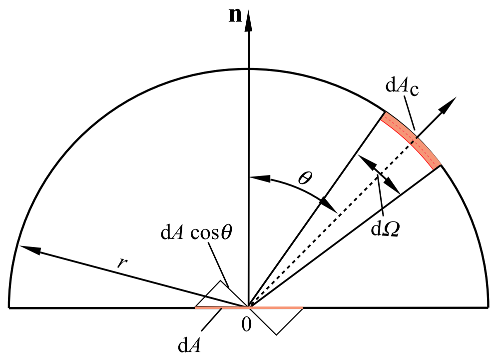

Figure 1.7 The projection of dA normal to the direction of radiation.

And d$\varphi(\theta)$ means the energy emitted from the unit area of the blackbody to the solid angle of the element around the latitude angle of space, and then the experiment shows that

$$\frac{\mathrm{d}\varphi(\theta)}{\mathrm{d}A\ \mathrm{d}\Omega} = I\cos\theta. \tag{1.2.5}$$

That is,

$$I = \frac{\mathrm{d}\varphi(\theta)}{\mathrm{d}A\ \mathrm{d}\Omega\cos\theta}, \tag{1.2.6}$$

where I is a constant, independent of direction, and d$A\cos\theta$ is the normal area in the direction θ (Fig. 1.7).

1.2.2 Planck's Law

Planck's law reveals how the blackbody spectral emissive power varies with wavelength in thermodynamic equilibrium. It is

$$E_{\mathrm{b}\lambda} = \frac{c_1\lambda^{-5}}{\exp\left[c_2/(\lambda T)\right]-1}, \tag{1.2.7}$$

where $E_{\mathrm{b}\lambda}$ is the blackbody spectral emissive power, $\mathrm{W}\cdot\mathrm{m}^{-3}$; λ is the wavelength, m; T is the absolute temperature of the blackbody, K; c_1 is the first radiation constant, 3.7419×10^{-16} $\mathrm{W}\cdot\mathrm{m}^2$; and c_2 is the second radiation constant, 1.4388×10^{-2} $\mathrm{m}\cdot\mathrm{K}$

The blackbody spectral emissive power distribution is plotted in Fig. 1.8, from which we see that the blackbody has a maximum spectral emissive power and that the corresponding wavelength λ_m depends on temperature:

$$\lambda_\mathrm{m}T = 2.8976\times10^{-3}\ \mathrm{m}\cdot\mathrm{K} \approx 2.9\times10^{-3}\ \mathrm{m}\cdot\mathrm{K}. \tag{1.2.8}$$

Equation (1.2.8) is known as Wien's displacement law, and the blackbody temperature can be calculated according to the spectrum of the blackbody. It

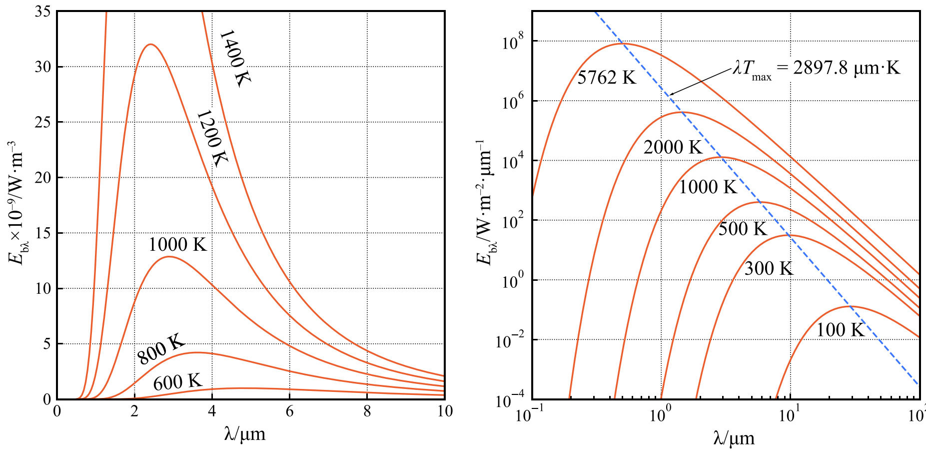

Figure 1.8 Spectral blackbody emissive power.

is concluded completely based on the empirical summary of experimental data, but it can be deduced mathematically from the Planck distribution [6]:

$$\frac{\partial E_{b\lambda}}{\partial \lambda}=\frac{5c_1\lambda^{-6}}{\exp\left[c_2/(\lambda T)\right]-1}\left\{\frac{c_2\exp\left[c_2/(\lambda T)\right]}{5\lambda T\left\{\exp\left[c_2/(\lambda T)\right]-1\right\}}-1\right\}=0. \tag{1.2.9}$$

We set $x=c_2/\left(\lambda_m T\right) x=c_2/\left(\lambda_m T\right)$; rearranging Eq. (1.2.9), it follows that

$$\frac{x\exp x}{5(\exp x-1)}-1=0. \tag{1.2.10}$$

Equation (1.2.10) is the transcendental equation of the variable x, and the solution is as follows:

$$x=c_2/(\lambda_m T)=4.9651. \tag{1.2.11}$$

Hence,

$$\lambda_{\mathrm{m}}T=c_2/4.9651=2.8976\times10^{-3}\ \mathrm{m}\cdot\mathrm{K}. \tag{1.2.12}$$

1.2.3 Stefan–Boltzmann Law

The Stefan–Boltzmann law points out that the blackbody emissive power is proportional to the fourth power of the blackbody's temperature,

$$E_{\mathrm{b}}=\sigma T^4, \tag{1.2.13}$$

where σ is the Stefan–Boltzmann constant, $5.67\times10^{-8}\ \mathrm{W}\cdot\left(\mathrm{m}^2\cdot\mathrm{K}^4\right)^{-1}$. Equation (1.2.13) can be deduced from Eq. (1.2.7) as follows:

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$$E_{\mathrm{b}} = \int_0^\infty E_{\mathrm{b}\lambda} \mathrm{d}\lambda = \int_0^\infty \frac{c_1 \lambda^{-5}}{\exp\left[c_2/(\lambda T)\right] - 1} \, \mathrm{d}\lambda. \tag{1.2.14}$$

We set $x = c_2/(\lambda T)$, it follows that

$$\mathrm{d}\lambda = \frac{-c_2}{T x^2} \, \mathrm{d}x, \tag{1.2.15}$$

$$E_{\mathrm{b}} = \frac{c_1}{{c_2}^4} T^4 \int_0^\infty \frac{x^3}{\exp(x) - 1} \, \mathrm{d}x, \tag{1.2.16}$$

where

$$\begin{aligned} \int_0^\infty \frac{x^3}{\exp x - 1} \, \mathrm{d}x &= \int_0^\infty x^3 \left[\sum_{n=1}^\infty \exp(-nx) \right] \mathrm{d}x \\ &= \sum_{n=1}^\infty \int_0^\infty x^3 \exp(-nx) \mathrm{d}x \\ &= \sum_{n=1}^\infty \frac{3!}{n^4} = \frac{\pi^4}{15}. \end{aligned} \tag{1.2.17}$$

Hence,

$$E_{\mathrm{b}} = \frac{\pi^4 c_1}{15 {c_2}^4} T^4 = \sigma T^4. \tag{1.2.18}$$

For the blackbody emissive power in a prescribed wavelength interval from 0 to λ, it can be obtained by integrating as follows:

$$E_{\mathrm{b}(0-\lambda)} = \int_0^\lambda E_{\mathrm{b}\lambda} \mathrm{d}\lambda. \tag{1.2.19}$$

The fraction of the emission in this wavelength range is determined as follows:

$$F_{\mathrm{b}(0-\lambda)} = \frac{\int_0^\lambda E_{\mathrm{b}\lambda} \mathrm{d}\lambda}{\sigma T^4} = \int_0^\lambda \frac{c_1 (\lambda T)^{-5}}{\exp\left[c_2/(\lambda T)\right] - 1} \frac{1}{\sigma} \mathrm{d}(\lambda T) = f(\lambda T). \tag{1.2.20}$$

This function is called the blackbody radiation function; its value can be easily obtained according to the given value of λT. Meanwhile, the fraction of the radiation between any two wavelengths λ_1 and λ_2 may also be easily obtained

$$E_{\mathrm{b}(\lambda_1-\lambda_2)} = F_{\mathrm{b}(\lambda_1-\lambda_2)} E_{\mathrm{b}} = \left(F_{\mathrm{b}(0-\lambda_2)} - F_{\mathrm{b}(0-\lambda_1)} \right) E_{\mathrm{b}}. \tag{1.2.21}$$

1.2.4 Lambert Law

The Lambert law tells us that the directional radiation intensity of the blackbody is a constant, independent of the direction. This law also shows that the energy emitted from the unit area of the blackbody varies according to the law of cosine of the latitude angle of space: it reaches its maximum in the direction perpendicular to the surface and zero in the direction parallel to the surface.

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The relationship between the Lambert law and the Stefan–Boltzmann law can be derived as follows. Considering Eq. (1.2.6), the blackbody emissive power can be written as

$$E_\mathrm{b} = \int_{\Omega=2\pi} \frac{\mathrm{d}\phi(\theta)}{\mathrm{d}A}\,\mathrm{d}\Omega = I_\mathrm{b}\int_{\Omega=2\pi} \cos\theta \mathrm{d}\Omega = I_\mathrm{b}\int_0^{2\pi}\mathrm{d}\varphi \int_0^{\pi/2} \sin\theta\cos\theta \mathrm{d}\theta = I_\mathrm{b}\pi. \tag{1.2.22}$$

The above equation shows that the blackbody emissive power is π times the directional radiation intensity of the blackbody.

1.2.5 Kirchhoff's Law

Concepts Used to Describe Radiation by the Real Surface

(1) Emissivity

We define the emissivity, ε, as the ratio of the radiation emitted by the surface to the radiation emitted by a blackbody at the same temperature:

$$\varepsilon_T = \frac{E(T)}{E_\mathrm{b}(T)}. \tag{1.2.23}$$

(2) Absorptivity

We define the absorptivity, α, as the fraction of the total radiation absorbed by a surface:

$$\alpha = \frac{G_\mathrm{abs}}{G}, \tag{1.2.24}$$

where G_abs and G represent the absorbed irradiation and incident irradiation, respectively. If the incident radiation originates from an ideal blackbody, then G can be replaced by E_b.

The Relationship between Emissivity and Absorptivity in Thermal Equilibrium

Kirchhoff's law reveals the relationship between the emissivity and absorptivity of a real surface. Consider two parallel plates that are very close to each other (Fig. 1.9); all of the radiation energy emitted from one plate is incident on the other. Assume that plate 1 has a blackbody surface, and its emissive power, absorptivity, and surface temperature are E_b, α, and T_1, respectively. Plate 2 is the surface of any object, and its emissive power, absorptivity, and surface temperature are E, α, and T_2, respectively. The energy emitted per unit area per unit time by plate 2 is absorbed entirely when it is incident on the surface of plate 1. Meanwhile, the energy emitted from plate 1 is absorbed only when $\alpha E_{/rmb}$ is incident on plate 2, and the rest of the energy $(1-\alpha)E_b$ is reflected back to plate 1 and absorbed entirely. The energy difference of plate 2 is the heat flux of the radiative heat transfer between the two plates:

$$q = E - \alpha E_\mathrm{b}. \tag{1.2.25}$$

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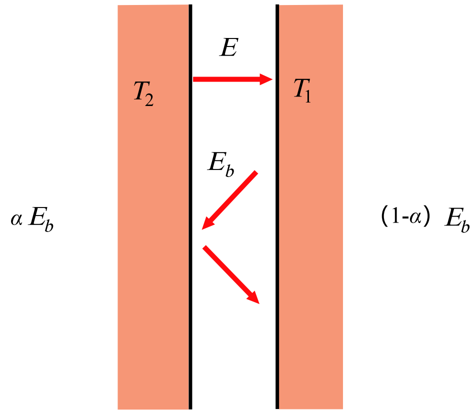

Figure 1.9 Derivation model of Kirchhoff's law.

When the system is at the thermal equilibrium condition, that is, when $q=0$, we obtain

$$\frac{E}{\alpha}=E_{\mathrm{b}}. \tag{1.2.26}$$

Extending this relation to any object, the following equations can be written

$$\frac{E_1}{\alpha_1}=\frac{E_2}{\alpha_2}=\cdots=E_{\mathrm{b}}, \tag{1.2.27}$$

$$\alpha=\frac{E}{E_{\mathrm{b}}}=\varepsilon. \tag{1.2.28}$$

The meaning of Eq. (1.2.27) can be expressed as follows. At the thermal equilibrium condition, the ratio of an object's radiation to its absorption of radiation from a blackbody is the same as the emissive power of the blackbody at the same temperature. Similarly, the meaning of Eq. (1.2.28) can be briefly expressed as: at thermal equilibrium condition, the absorptivity of any object to the blackbody's incident radiation is equal to the emissivity of the object at the same temperature.

The Relationship between the Absorptivity and Emissivity of the Diffuse Gray Surface

In reality, most of the radiation is not emitted from the blackbody; to broaden the application scope of Kirchhoff's law, an assumption called the diffuse gray body, of which the emissivity does not change with direction and absorptivity does not change with wavelength, is introduced.

First of all, assume that a diffuse gray body and a blackbody are at a thermal equilibrium condition, and then the blackbody is removed to allow another non-blackbody to radiate different temperatures that are incident on its surface, whereas the diffuse gray body still keeps its temperature unchanged. Since the

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Table 1.1 Three expressions of Kirchhoff's law.

Level	Expression	Constraint condition
Spectral, direction	$\varepsilon(\lambda,\varphi,\theta,T)=\alpha(\lambda,\varphi,\theta,T)$	Unconditional, θ is the latitudinal angle
Spectral, hemispherical	$\varepsilon(\lambda,T)=\alpha(\lambda,T)$	Diffuse surface
Total, hemispherical	$\varepsilon(T)=\alpha(T)$	Should be at a thermal equilibrium condition with blackbody radiation or a diffuse gray surface

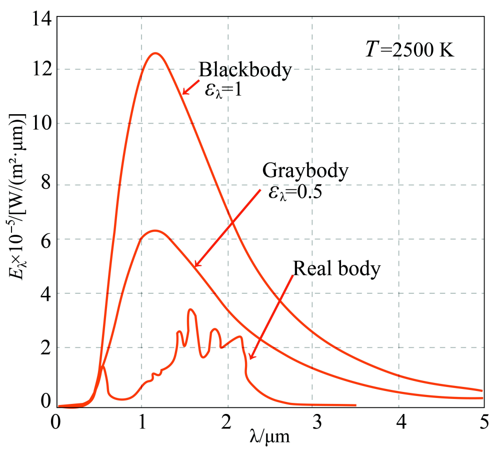

Figure 1.10 Schematic diagram of the spectral emissive power of the gray body and the real surface.

emissivity and absorptivity of the diffuse gray body do not change, the energy emitted by the diffuse gray body at the same temperature should be equal to the energy absorbed, that is, the absorptivity at the same temperature is equal to the emissivity. In conclusion, the total hemispherical absorptivity for a diffuse gray body is equal to its total hemispherical emissivity, regardless of whether the diffuse gray body is at a thermal equilibrium condition with other substances or the environment and regardless of whether other substances are blackbodies. This the conclusion simplifies the calculation of radiative heat transfer and establishes the relationship between the absorptivity and emissivity of the real surface.

According to Kirchhoff's law, the larger the emissive power of an object is, the greater its absorption capacity will be, so a blackbody has the largest emissive power at the same temperature. In addition, Kirchhoff's law can be divided into three levels [7] according to the application conditions, as shown in Table 1.1, and each level corresponds to different constraint conditions. Figure 1.10 qualitatively shows the variation of spectral emissive power with the wavelength of a gray

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body and the real surface. (For a diffuse gray body at a specific temperature, its spectral emissivity $\varepsilon(\lambda)$ is a constant.)

1.3 Gas Radiation Characteristics and Solar Radiation

1.3.1 Gas Radiation Characteristics

Being different from solid and liquid radiation, gas radiation has the following two characteristics. First, gas radiation is strongly wavelength selective, and gas is not a gray body. The radiating gas can be composed of molecules, atoms, ions, and free electrons with various energy levels. The energy associated with the motion of vibration and the rotation of a molecule has specific quantized values, and hence gas emits and absorbs radiation in discrete energy intervals dictated by the allowed states within the molecule. Gas molecules tend to have radiative and absorptive abilities only within a specific wavelength range. For example, ozone absorbs almost all UV wavelengths of less than 0.3 μm [8], so the ozone layer in the atmosphere protects life on the Earth from UV damage. As a greenhouse gas, carbon dioxide has three main absorption bands: 2.65–2.8, 4.15–4.45, and 13.0–17.0 μm [9]. This makes it difficult for radiation from the ground to penetrate the atmosphere into the universe. In addition, water vapor also has three main bands: 2.55–2.84, 5.6–7.6, and 12–30 μm [10]. Figure 1.11 schematically shows the main bands of carbon dioxide and water vapor.

Another property of gas radiation is that the radiation and absorption of gas occur throughout the volume. In a container filled with gas, radiation and absorption occur along its path, regardless of the direction along which the radiation propagates. To study the absorption of a certain part of gas in a container, it is necessary to consider the influence of the whole container, including the size, shape, and wall characteristics of the container. Besides, emission, absorption, and scattering occur all the time in the radiation path, which involves the surrounding gas in the study of radiation. To comprehensively study the gas radiation in a container, a more complicated model is needed to describe it, which will be introduced in Chapter 2.

1.3.2 Emissivity and Absorptivity of Water Vapor and Carbon Dioxide

Many factors affect gas emissivity and absorptivity. This section will introduce some of the key influencing factors and a theoretical system describing gas emissivity and absorptivity. In most engineering applications, we only care about the total radiation ability. Therefore, we can temporarily ignore the spectral properties and only concentrate on the total gas emissivity at a certain temperature. In Section 1.3.1, we also pointed out the volumetric properties of gas radiation, that is, the shape and size of the volume also have a certain influence on gas radiation.

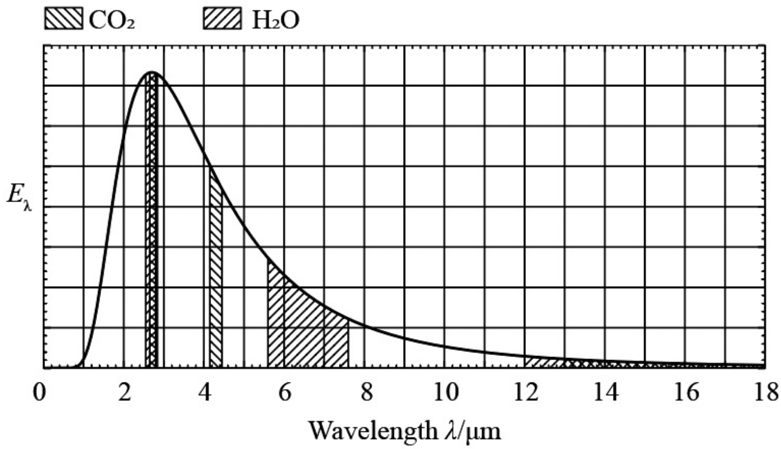

Figure 1.11 Schematic diagram of main optical bands of CO_2 and H_2O.

Mean Beam Length

The radiation ability of gas is related to the shape of the gas volume and the location of the research object. Parameters describing the radiation path need to be developed based on the shape of the volume and the location of the search object. Assume the radiation from a hemispherical gas volume to a differential area element located in the center. In this case, all the paths between the hemisphere and the area have the same length as the radius of the hemisphere, R, as shown in Fig. 1.12. And the mean beam length is R itself [11]. For gas volumes with other shapes, the equivalent hemisphere method can be applied to obtain the mean beam length. The so-called equivalent hemisphere is a hemisphere filled with the same gas in the same state as in the volume, and the radiation power on the center of the hemisphere from the equivalent hemisphere is equivalent to that on the studied area from the gas volume. The radius of such an equivalent hemisphere is the mean beam length of the gas. The equivalent hemisphere method is only a simple approximation, and there are more accurate formulas for other typical volume gases [12, 13]. In simple processing, the mean beam length of gas with any geometry can be calculated as follows, where V is the volume of gas (m^3) and A is the area of cladding (m^2):

$$s = 3.6\frac{V}{A}. \tag{1.3.1}$$

Emissivity

The mean beam length takes the volumetric properties of gas radiation into account, while the emissive power of the gas on the wall or on a specified point on the wall is also affected by the temperature, composition of the gas, and the number of absorbent gas molecules along the path. The number of gas molecules

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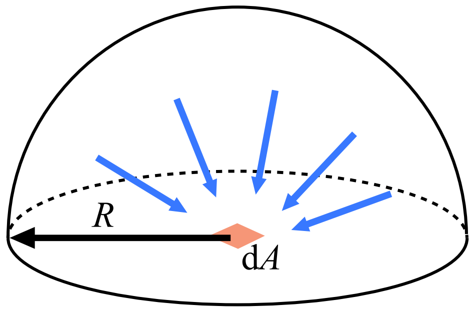

Figure 1.12 Schematic diagram of gas radiation to the center in hemispheres.

along the path can be expressed by the product of the partial pressure (p) of gas and the mean beam length (s):

$$\varepsilon_g = f(T_g, ps). \tag{1.3.2}$$

For water vapor, in addition to the synthetic parameter ($p_{H_2O}s$) that affects the gas emissivity, there is also a separate effect of p_{H_2O}. After extrapolating the single effect of p_{H_2O} to the limit case, where p_{H_2O} is zero under certain conditions, as the basis for drawing the graph line $\varepsilon^*_{H_2O} = f(T_g, p_{H_2O}s), p = 10^5$ Pa, the separate effects of the total pressure $p \neq 10^5$ Pa, and p_{H_2O} is then corrected by introducing a coefficient C_{H_2O}. Thus, the emissivity of water vapor is

$$\varepsilon_{H_2O} = C_{H_2O}\varepsilon^*_{H_2O}. \tag{1.3.3}$$

Similarly, the emissivity of carbon dioxide is confirmed by Eq. (1.3.4):

$$\varepsilon_{CO_2} = C_{CO_2}\varepsilon^*_{CO_2}. \tag{1.3.4}$$

When both water vapor and carbon dioxide exit in the mixture, a correction quantity needs to be introduced for the overlapping part of the wavebands of two gases. The gas emissivity is calculated by the following formula [13]:

$$\varepsilon_g = C_{H_2O}\varepsilon^*_{H_2O} + C_{CO_2}\varepsilon^*_{CO_2} - \Delta\varepsilon. \tag{1.3.5}$$

Absorptivity

When the gas emits radiation energy, it also absorbs radiation from the wall and/or other gas. Kirchhoff's law is no longer applicable to obtain gas absorptivity mainly for two reasons. Gas radiation is strong wavelength selective, so gas cannot be regarded as a gray body. Besides, gas diffuses in the whole container, and there is heat transfer between the gas and the wall. Hence, the internal temperature is not necessarily balanced, that is, the thermal equilibrium state is not necessarily satisfied. Similar to the emittance calculation, we can write the absorptivity of a mixture of water vapor and carbon dioxide to the radiation from the blackbody shell:

$$\alpha_g = C_{H_2O}\alpha^*_{H_2O} + C_{CO_2}\alpha^*_{CO_2} - \Delta\alpha, \tag{1.3.6}$$

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where $C_{\mathrm{H_2O}}$ and $C_{\mathrm{CO_2}}$ are the same as that in Eqs. (1.3.3) and (1.3.4), respectively, and $\alpha^*_{\mathrm{H_2O}}$, $\alpha^*_{\mathrm{CO_2}}$, $\Delta\alpha$ can be calculated by the following empirical formulas in which T_{w} is the wall temperature [13]:

$$\alpha^*_{\mathrm{H_2O}} = \left[\varepsilon^*_{\mathrm{H_2O}}\right]_{T_{\mathrm{W}}, p_{\mathrm{H_2O}} s\left(\frac{T_{\mathrm{W}}}{T_{\mathrm{g}}}\right)} \left(\frac{T_{\mathrm{g}}}{T_{\mathrm{W}}}\right)^{0.45}, \tag{1.3.7}$$

$$\alpha^*_{\mathrm{CO_2}} = \left[\varepsilon^*_{\mathrm{CO_2}}\right]_{T_{\mathrm{W}}, p_{\mathrm{CO_2}} s\left(\frac{T_{\mathrm{W}}}{T_{\mathrm{g}}}\right)} \left(\frac{T_{\mathrm{g}}}{T_{\mathrm{W}}}\right)^{0.65}, \tag{1.3.8}$$

$$\Delta\alpha = [\delta\varepsilon]_{T_{\mathrm{W}}}. \tag{1.3.9}$$

1.3.3 Solar Radiation

The Sun is a nearly spherical body that has a diameter of 1.39×10^9 m and is located at a distance of 1.50×10^{11} m from the Earth. The Sun, where a thermonuclear reaction occurs continually, radiates to the Earth at a rate of 1.7×10^{17} W, of which 30% is reflected and 23% is absorbed by the atmosphere, and the rest reaches the Earth's surface. Figure 1.13 shows the blackbody radiation spectrum of 5 770 K and the solar spectrum at the outer edge of the atmosphere and that on the ground. The radiation reaching the outer surface of the Earth's atmosphere has spectral properties (shown in Fig. 1.13) close to that of a blackbody at 5 770 K. But through the atmosphere, the energy spectrum reaching the ground would appear to fluctuate because of the strong selective absorption of the gases. At the average distance between the Sun and the Earth, the solar radiation energy received by the unit surface area perpendicular to the solar rays at the outer edge of the atmosphere is $(1\,370 \pm 6)\,\mathrm{Wm^{-2}}$. This value is called the solar constant [14], and it is independent of geographical location or time of day (see Fig. 1.14). In fact, the amount of solar input per unit area received at the horizontal surface of the outer edge of the atmosphere is

$$G_{\mathrm{s,o}} = S_{\mathrm{c}} f \cos\theta. \tag{1.3.10}$$

1.4 View Factor of Radiative Heat Transfer

Radiative heat transfer between surfaces is closely related to geometrical factors, such as surface geometry and orientations, which are usually considered as the view factor. The concept of view factor was put forward in the 1920s with the appearance and development of the radiation heat transfer calculation method on solid surfaces.

1.4.1 Definition and Calculation of View Factor

To separate geometric relations between surfaces from radiation intensity and make the view factor only contains the geometric relations, the enclosures are summed to be opaque, diffuse, and gray [15]. For surfaces that do not meet the

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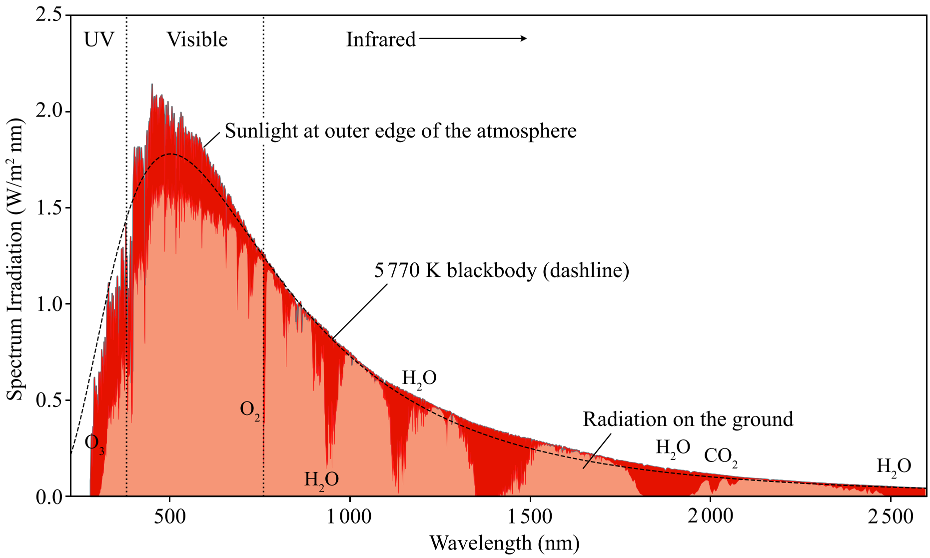

Figure 1.13 Spectral distribution of solar radiation.

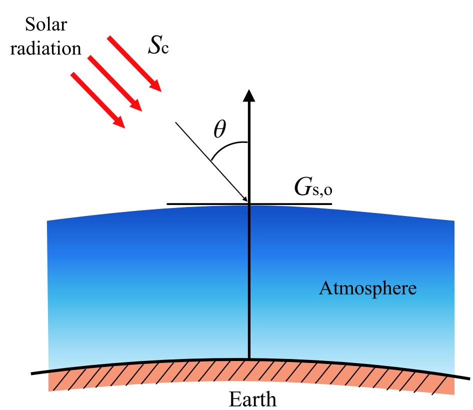

Figure 1.14 Solar radiation at the outer edge of the atmosphere.

first condition, that is, nondiffuse surfaces, the influence of geometric factors on radiative heat transfer is related to the direction, so the concept of view factor cannot be generally used, but its calculation method and principle are basically similar to that of the view factor. For the convenience of discussion, the object is treated as a blackbody in the study of the view factor, but the conclusions obtained are suitable for a diffuse gray surface.

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Let there be two surfaces 1 and 2, both of which meet the above conditions, such as there exist two diffuse surfaces between transparent media. Then, the view factor of surface 1 to surface 2, $X_{1,2}$, is the fraction of uniform diffusive radiation leaving surface 1 that is intercepted by surface 2. The definition of the view factor can thus be written as

$$X_{1,2} = \frac{\text{The incident radiation from surface 1 to surface 2}}{\text{The effective radiation from surface 1}}. \tag{1.4.1}$$

The relative spatial position of two surfaces directly affects the radiative heat transfer between them and hence affects the view factor. For example, when two opposite-placed surfaces are infinitely close to each other, the incident radiation from one to the other is equivalent to the effective radiation, and the view factor is 1. However, for two surfaces in the same plane, since neither surface can receive the incident radiation from the other, the radiative heat transfer and view factor are zero. Besides, the shape of the surface will also affect the value of the view factor. This section will specifically study the influence of the shape and relative position of the surfaces on the view factor and how to compute view factors between surfaces.

1.4.2 Properties of the View Factor

According to the definition of the view factor and the spatial geometric relationship, when the assumptions are satisfied, four basic algebraic properties of view factors can be obtained. For two surfaces with other special relative positions and geometric relations, there may be other properties of the view factor. Here we will only introduce the basic three properties and their derivations.

Reciprocity Rule

For the view factor from a differential area element, $\mathrm{d}A_1$, to another element, $\mathrm{d}A_2$, denoted as $X_{\mathrm{d1,\ d2}}$, as shown in Fig. 1.15, where the subscripts d1 and d2 represent $\mathrm{d}A_1$ and $\mathrm{d}A_2$ respectively. According to the definition,

$$X_{\mathrm{d1,\ d2}} = \frac{\text{Irradiation from d1 to d2}}{\text{Effective radiation of d1}} = \frac{I_{\mathrm{b1}} \cos\theta_1 \ \mathrm{d}A_1 \ \mathrm{d}\Omega_1}{E_{\mathrm{b1}} \ \mathrm{d}A_1} = \frac{\mathrm{d}A_2 \cos\theta_1 \cos\theta_2}{\pi r^2}. \tag{1.4.2}$$

Similarly,

$$X_{\mathrm{d2,\ d1}} = \frac{\mathrm{d}A_1 \cos\theta_1 \cos\theta_2}{\pi r^2}. \tag{1.4.3}$$

So

$$\mathrm{d}A_1 X_{\mathrm{d1,\ d2}} = \mathrm{d}A_2 X_{\mathrm{d2,\ d1}}. \tag{1.4.4}$$

The relativity of the view factor between two finite surfaces can be obtained by analyzing the radiative heat transfer between two isothermal blackbody surfaces. Thus, the relativity expression of the view factor between two finite surfaces is

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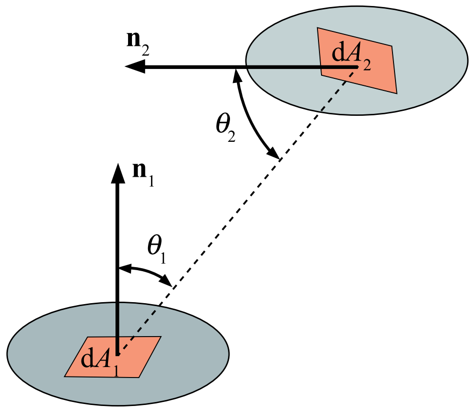

Figure 1.15 Reciprocity rule proof of the infinitesimal surface.

$$A_1 X_{1,2} = A_2 X_{2,1}. \tag{1.4.5}$$

This property is called the reciprocity rule.

Summation Rule

Assuming that the surface A_k forms an enclosure with other surrounding surfaces, all the radiation leaving the surface A_k is intercepted by the enclosure surfaces. Therefore, the effective radiation of A_k is equal to the radiation intercepted by all surfaces of the enclosure, that is,

$$Q_k = \sum_{i=1}^{n} Q_{k,i}. \tag{1.4.6}$$

Wherein, n is the number of closed body surfaces, as shown in Fig. 1.16. Using the definition of the view factor and Eq. (1.4.6), we can obtain

$$Q_k = \sum_{i=1}^{n} Q_k X_{k,i}. \tag{1.4.7}$$

Therefore,

$$\sum_{i=1}^{n} X_{k,i} = 1. \tag{1.4.8}$$

This property is called the summation rule.

Consider a set of surfaces $s = \{2, 2', 2'', \ldots\}$ shown in Fig. 1.17; any surface in the set is covered by surface 1. According to the summation rule, we have $X_{1,j} + X_{1,1} = 1$, for $j \in s$; thus, it can be obtained that

$$1 - X_{1,1} = X_{1,2} = X_{1,2'} = X_{1,2''}. \tag{1.4.9}$$

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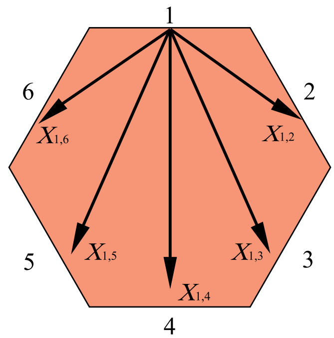

Figure 1.16 Proof of summation rule.

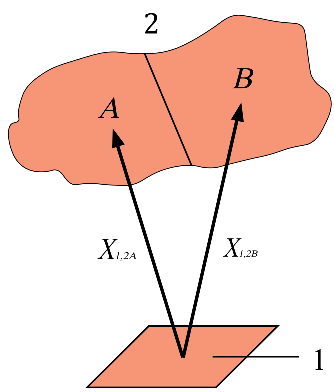

Figure 1.17 Proof of equivalence rule.

Superposition Rule

Consider the view factor of surface 1 against surface 2 as shown in Fig. 1.18. Since the total energy falling on surface 2 from surface 1 is equal to the sum of the radiation energy falling on the parts of surface 2,

$$A_1 E_{\mathrm{b}1} X_{1,2} = A_1 E_{\mathrm{b}1} X_{1,2A} + A_1 E_{\mathrm{b}1} X_{1,2B}. \tag{1.4.10}$$

So

$$X_{1,2} = X_{1,2A} + X_{1,2B}. \tag{1.4.11}$$

If surface 2 is further divided into several small pieces, then

$$X_{1,2} = \sum_{i=1}^{n} X_{1,2i}. \tag{1.4.12}$$

When the superposition rule of view factor is used, only the second term in the subscript symbol is additive, while the first one does not have a relation similar to eq. (1.4.12), that is, $X_{1,2} \neq X_{2A,1} + X_{2B,1}$. This property is called the superposition rule.

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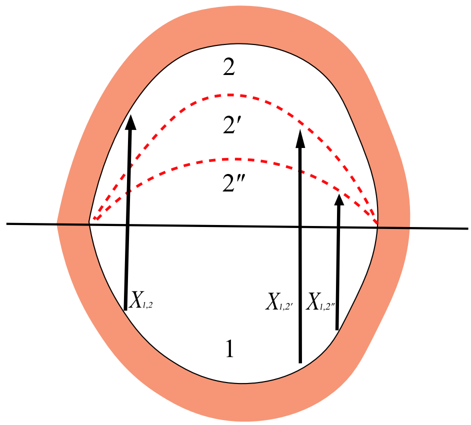

Figure 1.18 Proof of superposition rule.

1.4.3 Calculation Methods of the View Factor

There are many methods [16] for calculating the view factor. The most basic method is the integral method, whereas the most used one in engineering is the algebraic analysis. The concept of view factor was proposed very early, and many research findings were achieved in the 1950s and 1960s. For most of the systems with typical geometries, view factors have been calculated and compiled into manuals [17, 18].

Method of Direct Integration

The integral expression of the view factor between any two diffusive gray surfaces can be derived from the view factor of the differential area elements 1 and 2 in Eq. (1.4.2):

$$X_{1,2} = \frac{1}{A_1} \int \left(\int \frac{\cos\theta_1 \cos\theta_2 \ \mathrm{d}A_2}{\pi r^2} \right) \mathrm{d}A_1. \tag{1.4.13}$$

This integral formula is a quadruple integral and is rather complicated to obtain an analytical result. For complex cases, the numerical method may be applied to calculate the view factor. Literature [18] gives some formulas of the view factor between two-dimensional geometric structures, three typical three-dimensional geometric structures, and plots for engineering use. To expand the scope of calculation, these lines are often plotted in logarithmic coordinates, and attention should be paid to the logarithmic coordinates and the surface indicated by the subscripts 1 and 2.

Method of Algebraic Analysis

For the surface satisfying the condition of the view factor: (1) The surface should be a diffuse surface and (2) there should be uniform effective radiation on all

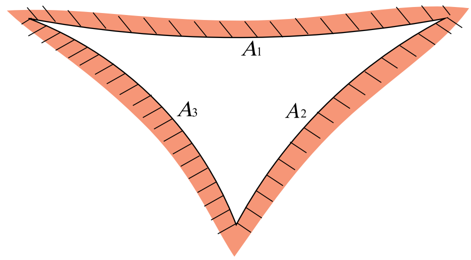

Figure 1.19 Enclosure with three surfaces.

surfaces. Applying the properties of the view factor, the method of obtaining the view factor by solving algebraic equations is called the method of algebraic analysis.

Figure 1.19 shows a composed of three convex surfaces extending infinitely along the direction perpendicular to the paper surface. The radiative energy spilling from both ends of the system can be ignored, and the system can be considered a closed system. Assume that the areas of the three surfaces are A_1, A_2, and A_3 respectively. According to the reciprocity rule and summation rule of the view factor, we have

$$\begin{aligned} X_{1,2}+X_{1,3}&=1, \quad A_1X_{1,2}=A_2X_{2,1},\\ X_{2,1}+X_{2,3}&=1, \quad A_1X_{1,3}=A_3X_{3,1},\\ X_{3,1}+X_{3,2}&=1, \quad A_2X_{1,3}=A_3X_{3,2}. \end{aligned}$$

By solving the above equation group, the view factors can thus be obtained as follows:

$$X_{i,j}=\frac{A_i+A_j-A_k}{2A_i}, \qquad \text{for } i\neq j\neq j\in\{1,2,3\}. \tag{1.4.14}$$

The other five view factors are also found. Since the three surfaces are of equal length in the direction perpendicular to the paper surface, it is simplified as

$$X_{i,j}=\frac{l_i+l_j-l_k}{2l_i}, \qquad \text{for } i\neq j\neq j\in\{1,2,3\}. \tag{1.4.15}$$

For a system containing nonadjacent surfaces, as shown in Fig. 1.20, the crossline method can be used to determine the view factor between A_1 and A_2. The auxiliary lines ad and bc were added between A_1 and A_2 to form an enclosure $abcd$. It is easy to obtain the view factor from the conclusion in formula (1.4.14) of the summation rule of the view factor

$$X_{ab,cd}=\frac{(bc+ad)-(ac+bd)}{2ab}. \tag{1.4.16}$$

Thus, for a system consisting of multiple surfaces extending infinitely in length in one direction, the view factor between any two surfaces can be summarized as

$$X_{1,2}=\frac{\text{Sum of crossed lines} - \text{Sum of uncrossed lines}}{\text{Twice the cross-sectional length of the surface 1}}. \tag{1.4.17}$$

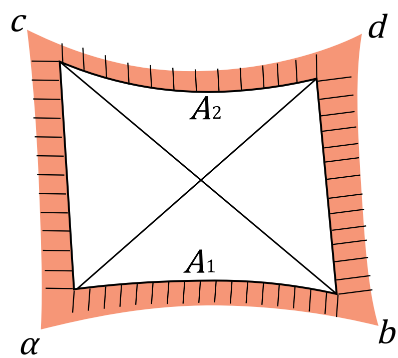

Figure 1.20 Diagram of the crossline method.

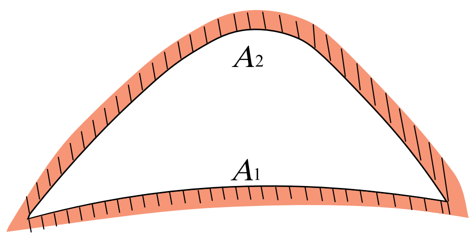

Figure 1.21 Enclosure composed of two black surfaces.

1.5 Calculation of Radiation Exchange in Multisurface Enclosures

1.5.1 Radiation Exchange in Enclosures Composed of Two Surfaces

Radiation Exchange in Enclosures Composed of Black Surfaces

When calculating the radiative heat transfer in an enclosure where all surfaces are black, no reflections need to be considered. Figure 1.21 shows an enclosure model [19] formed by two black surfaces. Thus, the net radiation exchange between the two surfaces is

$$\Phi_{1,2} = A_1 E_{\mathrm{b}1} X_{1,2} - A_2 E_{\mathrm{b}_2} X_{2,1} = A_1 X_{1,2}\left(E_{\mathrm{b}1} - E_{\mathrm{b}2}\right) = A_2 X_{2,1}\left(E_{\mathrm{b}1} - E_{\mathrm{b}2}\right). \tag{1.5.1}$$

Radiation Exchange in Enclosures Composed of Diffuse Gray Surfaces

Different from the enclosures composed of two black surfaces, the surface absorption of a gray body is less than 1, and it can only be absorbed after multiple reflections. Moreover, the energy emitted by the gray body includes both its own radiation energy and the reflected radiation energy. Therefore, the radiative heat transfer in enclosures composed of diffuse gray surfaces is more complicated. The term q, which is the net radiation leaving the surface, represents the net effect

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of radiative interactions occurring at the surface. It is equal to the difference between the surface radiosity and irradiation and can be expressed as Eq. (1.5.2). The outflow energy consists of the sum of the surface's own radiation εE_b and the energy reflected by the solid surface ρG. It is called radiosity, denoted as J:

$$q = J - G. \tag{1.5.2}$$

The net radiation exchange can also be expressed as

$$q = \varepsilon E_b - \rho G. \tag{1.5.3}$$

The relationship between the radiosity J and the net radiation exchange q is obtained by establishing the Eqs. (1.5.1) and (1.5.2):

$$J = E_\mathrm{b} - \left(\frac{1}{\varepsilon} - 1\right) q. \tag{1.5.4}$$

Radiation exchange in enclosures consisting of two gray surfaces is analyzed using the concept of radiosity.

In a two-dimensional enclosure composed of two isothermal opaque gray surfaces (areas A_1 and A_2), the radiative heat transfer between the two surfaces is

$$q_{1,2} = A_1 J_1 X_{1,2} - A_2 J_2 X_{2,1}, \tag{1.5.5}$$

and $q_{1,2} = -q_{2,1}$ is obtained in conjunction with Eqs. (1.5.4) and Eq. (1.5.5).

$$q_{1,2} = \frac{E_{\mathrm{b}1} - E_{\mathrm{b}2}}{\frac{1-\varepsilon_1}{\varepsilon_1 A_1} + \frac{1}{A_1 X_{1,2}} + \frac{1-\varepsilon_2}{\varepsilon_2 A_2}}. \tag{1.5.6}$$

(1) When surface 1 is a nonconcave surface, $X_{1,2} = 1$, then

$$q_{1,2} = \frac{A_1 \left(E_{\mathrm{b}1} - E_{\mathrm{b}2}\right)}{\frac{1}{\varepsilon_1} + \frac{A_1}{A_2}\left(\frac{1}{\varepsilon_2} - 1\right)}. \tag{1.5.7}$$

(2) When $A_1/A_2 \to 1$ and surface 1 is a nonconcave surface, such as two parallel infinite plates, then

$$q_{1,2} = \frac{A_1 \left(E_{\mathrm{b}1} - E_{\mathrm{b}2}\right)}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1}. \tag{1.5.8}$$

(3) When $A_1/A_2 \to 0$ and surface 1 is a nonconcave surface, then

$$q_{1,2} = \varepsilon_1 A_1 \left(E_{\mathrm{b}1} - E_{\mathrm{b}2}\right). \tag{1.5.9}$$

The Two-Surface Enclosure Network

The parameters in Eq. (1.5.6) are similar to the EM parameters in Ohm's law. Heat transfer (q) is analogous to the current intensity; $E_{\mathrm{b}1} - E_{\mathbf{b}2}$ is analogous to the electric potential difference; the surface radiation thermal resistance $\left(\frac{1-\varepsilon}{\varepsilon A}\right)$ and the space radiation thermal resistance $\left(\frac{1}{A_1 X_{1,2}}\right)$ are analogous to the electrical resistance. E_b is analogous to the source electromotive force. J is analogous to

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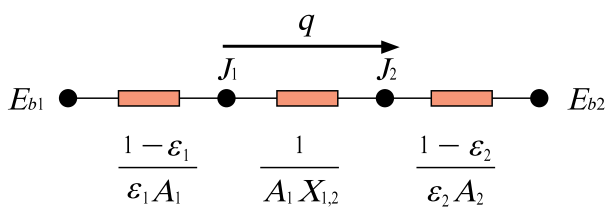

Figure 1.22 Radiation heat transfer equivalent network diagram of the two-surface enclosure.

the node voltage. The two-surface gray enclosure network is shown in Fig. 1.22. This method is called the network method of radiation exchange [20, 21].

1.5.2 Radiation Heat Transfer of Multisurface in an Enclosure

In a multisurface enclosure, the net radiation heat transfer of a surface is the sum of the heat transfer of the other surfaces. The network method can be used to obtain simultaneous equations for calculating the effective radiation of each surface. As for a three-surface enclosure: (1) draw the equivalent network diagram as shown in Fig. 1.23; (2) list the current equation of the nodes according to each node J in the network graph; (3) get J_1, J_2, and J_3 by solving Eq. (1.5.10) and then obtain the net radiation heat transfer:

$$\begin{aligned}
J_1 &: \frac{E_{\mathrm{b}1}-J_1}{\frac{1-\varepsilon_1}{\varepsilon_1 A_1}}+\frac{J_2-J_1}{\frac{1}{A_1X_{1,2}}}+\frac{J_3-J_1}{\frac{1}{A_1X_{1,3}}}=0,\\
J_2 &: \frac{E_{\mathrm{b}2}-J_2}{\frac{1-\varepsilon_2}{\varepsilon_2 A_2}}+\frac{J_1-J_2}{\frac{1}{A_1X_{1,2}}}+\frac{J_3-J_2}{\frac{1}{A_1X_{1,3}}}=0,\\
J_3 &: \frac{E_{\mathrm{b}3}-J_3}{\frac{1-\varepsilon_3}{\varepsilon_3 A_3}}+\frac{J_1-J_3}{\frac{1}{A_1X_{1,3}}}+\frac{J_2-J_3}{\frac{1}{A_2X_{2,3}}}=0.
\end{aligned} \tag{1.5.10}$$

1.6 Strengthening and Weakening of Thermal Radiation

The strengthening and weakening of thermal radiation is an important part of heat transfer. The physical mechanisms of radiation heat transfer, heat conduction, and convection heat transfer are different, so the control methods are also different.

1.6.1 Principles of Strengthening and Weakening Thermal Radiation

According to the network method of radiative heat transfer, the method of strengthening or weakening the radiative heat transfer between two surfaces changes the surface resistance and the space resistance.

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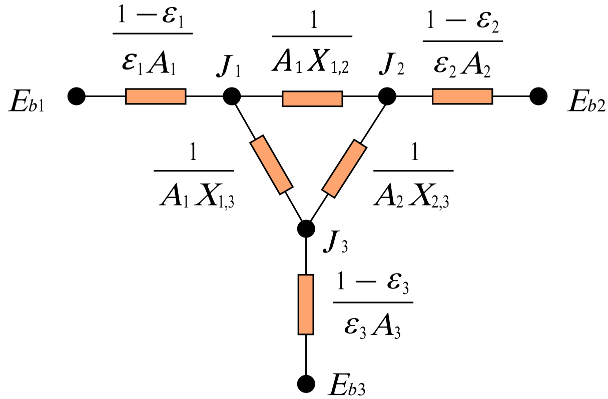

Figure 1.23 The heat transfer equivalent network diagram of a three-surface enclosure.

1. *Changing the surface resistance.* According to the definition of surface resistance ($\frac{1-\varepsilon}{\varepsilon A}$), changing the surface resistance can be achieved by changing the surface area or surface emissivity [22–24]. It is worth noting that when using the method of changing surface reflectivity to control radiation heat transfer, the surface emissivity that has the greatest impact on radiant heat transfer should be changed first.
2. *Changing the space resistance.* According to the definition of space resistance ($\frac{1}{A_i X_{i,j}}$), the area A_i generally depends on the specific heat dissipation or insulation surface [25–27]. Therefore, the view factor between the surfaces is generally adjusted to change the space resistance.

1.6.2 Application of Radiation Heat Transfer

In engineering applications, one of the most effective methods to weaken radiation heat transfer is using radiation shields, 1. The principle of radiation shields When inserting a thin metal plate between two plates, the radiation heat transfer between the two plates will be reduced. The thin metal plate is called a radiation shield [28–31]. When the radiation shield is not added, the radiation thermal resistances between two plates compose of two surface resistances and one space resistance. After adding the radiation shield, two surface resistances, and one space resistance will be added. Therefore, the total radiation resistance increases and the radiation heat transfer between two plates decreases. This is the principle of radiation shields. Take the insertion of a radiation shield between two parallel large plates as an example to illustrate the influence of the radiation shield on radiation exchange. Radiation network diagrams with or without the radiation shield between the parallel large plates are shown in Fig. 1.24.

Since the plate is infinite, the view factor is

$$X_{1,3} = X_{3,1} = X_{1,2} = 1 \tag{1.6.1}$$

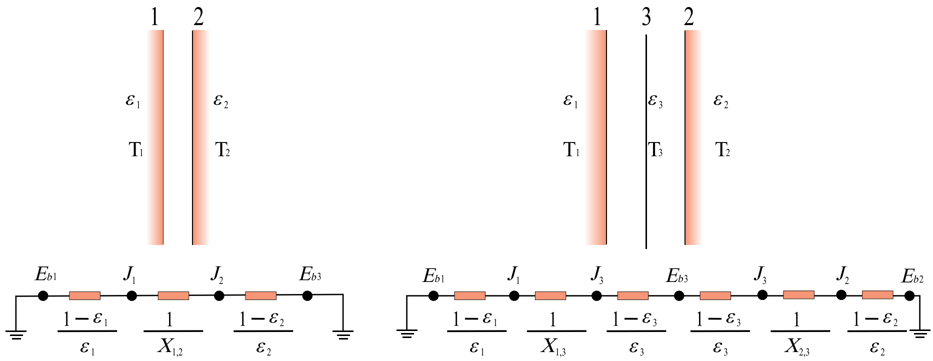

Figure 1.24 Radiation heat transfer with or without a radiation shield between two large plates.

because of

$$A_1 = A_2 = A_3 = A. \tag{1.6.2}$$

Then the heat transfer without and with the radiation shield would be as follows. Without the radiation shield,

$$q_{1,2} = \frac{\sigma\left(T_1^4 - T_2^4\right)}{\frac{1-\varepsilon_1}{\varepsilon_1 A_1} + \frac{1}{A_1 X_{1,2}} + \frac{1-\varepsilon_2}{\varepsilon_2 A_2}} = \frac{\sigma\left(T_1^4 - T_2^4\right)}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1}. \tag{1.6.3}$$

With a radiation shield,

$$\begin{aligned} q_{1,3,2} = q_{1,3} = q_{3,2} &= \frac{E_{\text{b}1} - E_{\text{b}2}}{\frac{1-\varepsilon_1}{\varepsilon_1 A_1} + \frac{1}{A_1 X_{1,3}} + \frac{1-\varepsilon_{3,1}}{\varepsilon_{3,1} A_3} + \frac{1-\varepsilon_{3,2}}{\varepsilon_{3,2} A_3} + \frac{1}{A_3 X_{3,2}} + \frac{1-\varepsilon_2}{\varepsilon_2 A_2}} \\ &= \frac{\sigma\left(T_1^4 - T_2^4\right) A}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_{3,1}} - 1 + \frac{1}{\varepsilon_{3,2}} + \frac{1}{\varepsilon_2} - 1}. \end{aligned} \tag{1.6.4}$$

Obviously, $q_{1,3,2} < q_{1,2}$. If $\varepsilon_1 = \varepsilon_2 = \varepsilon_{3,1} = \varepsilon_{3,2} = \varepsilon$, we will have $q_{1,3,2} = q_{1,2}/2$. It can be proved that the radiation heat transfer when inserting a radiation shield (thin metal plate) with the same frequency on the surface of the two parallel large flat walls is $1/(n+1)$ of the radiation heat transfer without radiation shields.

Finally, it is very convenient to use the network method to analyze the radiation shields. When the emissivity of each surface is different, the network method can be used to calculate the radiation heat transfer and the temperature of the radiation shields.

1.7 Summary

This chapter introduces the basic concepts of thermal radiation, and then mainly discusses the calculation method of the radiative heat transfer between objects, focusing on the radiation heat transfer between the surfaces of an enclosure.

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Some basic concepts are listed below:

Irradiation: Rate at which radiation is incident on a surface from all directions per unit area of the surface.

Radiosity: Rate at which radiation leaves a surface due to emission and reflection in all directions per unit area of the surface.

Blackbody: The ideal emitter and absorber. Modifier refers to ideal behavior.

Diffuse: Modifier referring to the directional independence of the intensity associated with an emitter, reflected, or incident radiation.

Gray surface: A surface for which the spectral absorptivity and emissivity are independent of wavelength over the spectral regions of surface irradiation and emission.

Planck's law: Spectral distribution of emission from a blackbody.

Stefan–Boltzmann law: Emissive power of a blackbody.

Wien's displacement law: Locus of the wavelength corresponding to peak emission by a blackbody.

Kirchhoff's law: Relation between emission and absorption properties for surfaces.

View factor: The percentage of radiation energy emitted by one surface that falls on another surface

Basic properties of the view factor: Under the assumption of the uniform surface radiant heat flow and the diffuser, the view factor is a pure geometric factor and has nothing to do with surface emissivity and temperature. From the perspective of energy balance, the relativity, completeness, and additivity of the view factor can be derived.

Effective radiation: The total radiation energy emitted from the unit surface includes self-radiation and emitted radiation. The introduction of effective radiation simplifies the calculation of radiation heat transfer among gray-body surfaces and avoids the complexity of analyzing multiple absorption and reflection.

Surface resistance of radiation heat transfer: Determined by the surface area and emissivity, $\frac{1-\varepsilon}{A\varepsilon}$.

Space resistance of radiation heat transfer: Determined by the area and shape of the surface and the relative position of the other surface, $1/(AX_{1,2})$.