北京航空航天大學
BEIHANG UNIVERSITY

HT: Radiation

L13: Processes and Properties

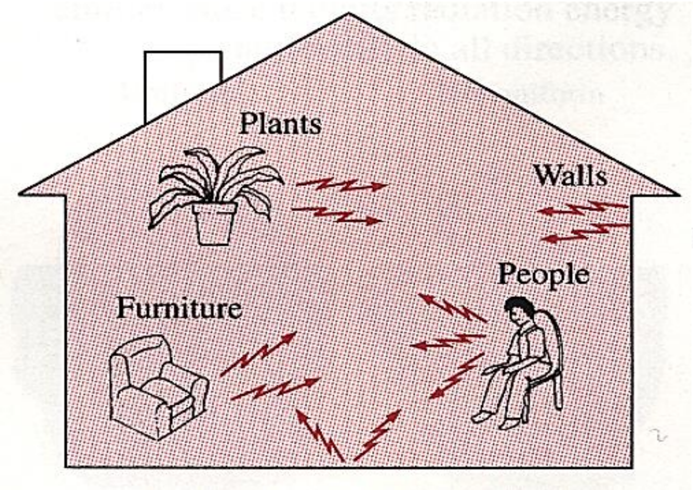
- **Learning Objectives:**
- **Thermal radiation Properties**
- **Fundamental law of blackbody radiation**
- **Angle factors**

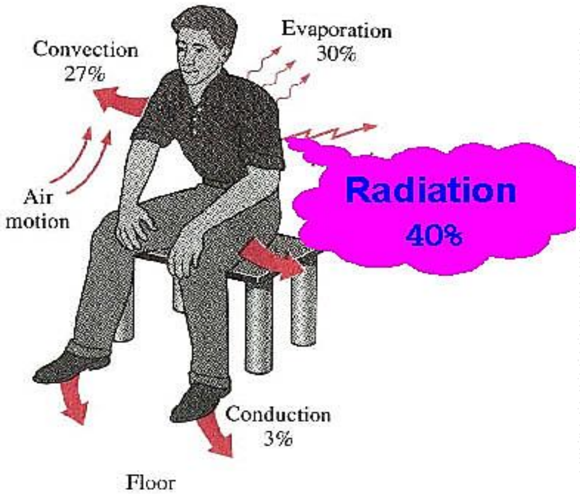
Contents

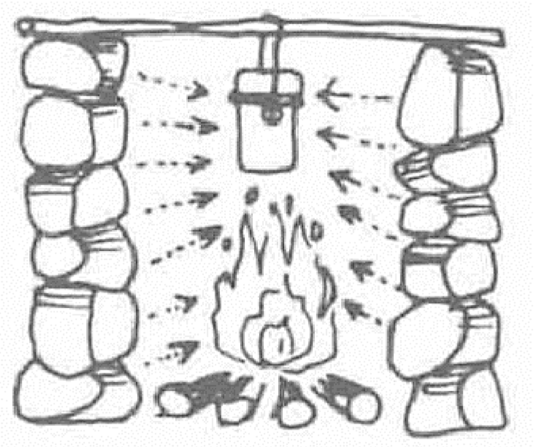
I. Fundamental Concepts

1. Thermal Radiation （热辐射：由于**热的原因**而产生的**电磁波**辐射）

Thermal radiation is electromagnetic radiation emitted by a body due to its temperature.



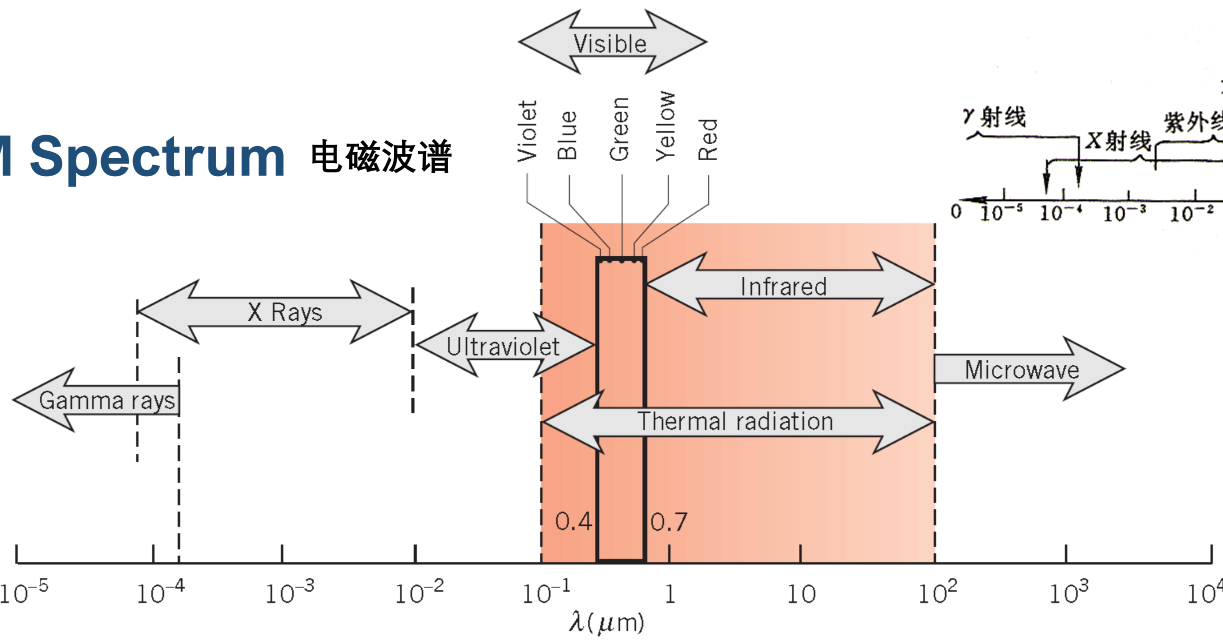




1. Thermal Radiation （热辐射：由于热的原因而产生的电磁波辐射）

Thermal radiation is electromagnetic radiation emitted by a body due to its temperature.

- **EM Spectrum** 电磁波谱



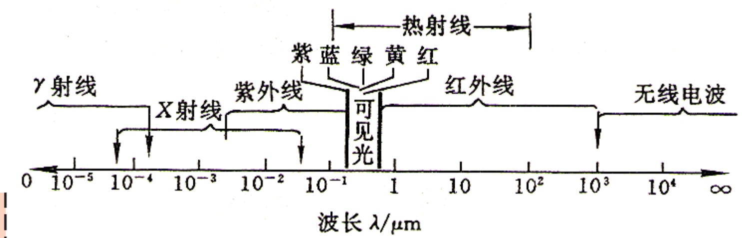


FIGURE 12.3 Spectrum of electromagnetic radiation.

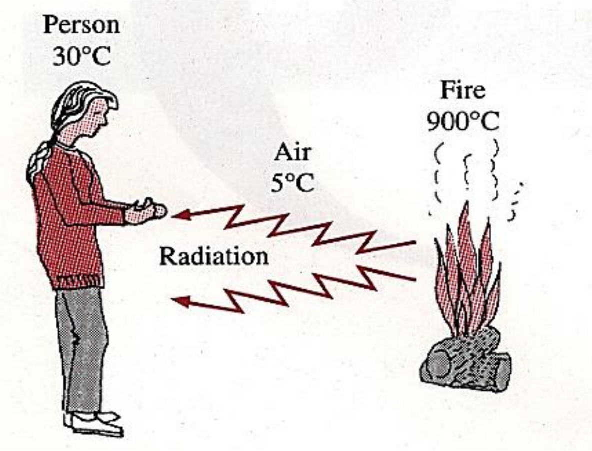
热辐射是电磁辐射（电磁波）的一种

I. Fundamental Concepts

1. Thermal Radiation

Heat transfer by conduction and convection requires the presence of a temperature gradient in some form of matter. In contrast, **heat transfer by thermal radiation requires no matter**.

由于太空的真空环境是天然的热绝缘体，宇航员与太空的热量交换只能通过辐射散热。



与导热和对流不同，热辐射可以发生在两个互相不接触的物体间（即使中间介质的温度低于两物体）。

特点:
不依靠物质接触而进行热量传递，即：不需要介质的存在，在真空中就可以传递能量，且在真空中传递的效率最高

I. Fundamental Concepts

1. Thermal Radiation （热辐射：由于**热的原因**而产生的**电磁波**辐射）

- A material body will emit radiant energy if only its temperature greater than 0 K
- Thermal radiation is changed from its *internal energy* of a body
- A body can certainly absorb the radiant energy emitted by a higher temperature body, it can also absorb the radiant energy from a body at a lower temperature

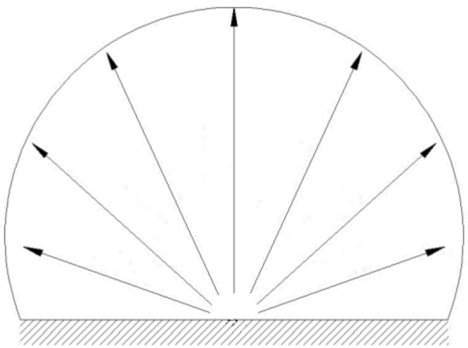
2. Emissive power, *E* (W/m^2) 辐射力

The rate at which radiation is emitted from a surface per unit surface area.

辐射力： 发射体每单位面积在单位时间所发射的全波长能量。

Monochromatic Emissive Power E_λ [W/m3]

The total *emitted* radiant energy at *a particular wavelength* leaving a surface, per unit time, per unit area of emitting surface, to *all possible directions*



$$E = \int_0^\infty E_\lambda d\lambda$$

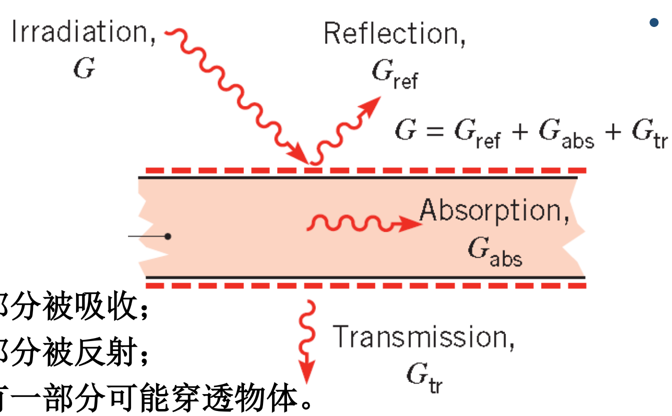
Note that both E and E_λ represent the ability of emitting radiant energy of a material body

3. Irradiation, *G* (W/m^2)

G ≡ incoming radiation (incident)
≡ irradiation

投射辐射G：单位时间内投射到单位面积上的总辐射能。

The rate at which radiation is incident upon the surface per unit surface area.



一部分被吸收；
一部分被反射；
还有一部分可能穿透物体。

- **Irradiation can be reflected, absorbed, or transmitted.**

(a) Reflection: ρ - Reflectivity $0 \le \rho \le 1$
ρG - Reflected

(b) Transmission: τ - Transmissivity $0 \le \tau \le 1$
τG - Transmitted

(c) Absorption: α - Absorptivity $0 \le \alpha \le 1$
αG - Absorbed

α —吸收比；
τ —穿透比；
ρ —反射比；

(surface properties)

- **Energy balance**

$$\alpha G + \rho G + \tau G = G$$

$$\boxed{\alpha + \rho + \tau = 1}$$

物体表面的辐射特性，与物体的性质、温度及表面状况有关

4. Opaque surface: $\tau = 0$

不透明体 $\alpha + \rho = 1$

Radiosity, *J*

Rate at which radiation leaves a surface per unit area

辐射度

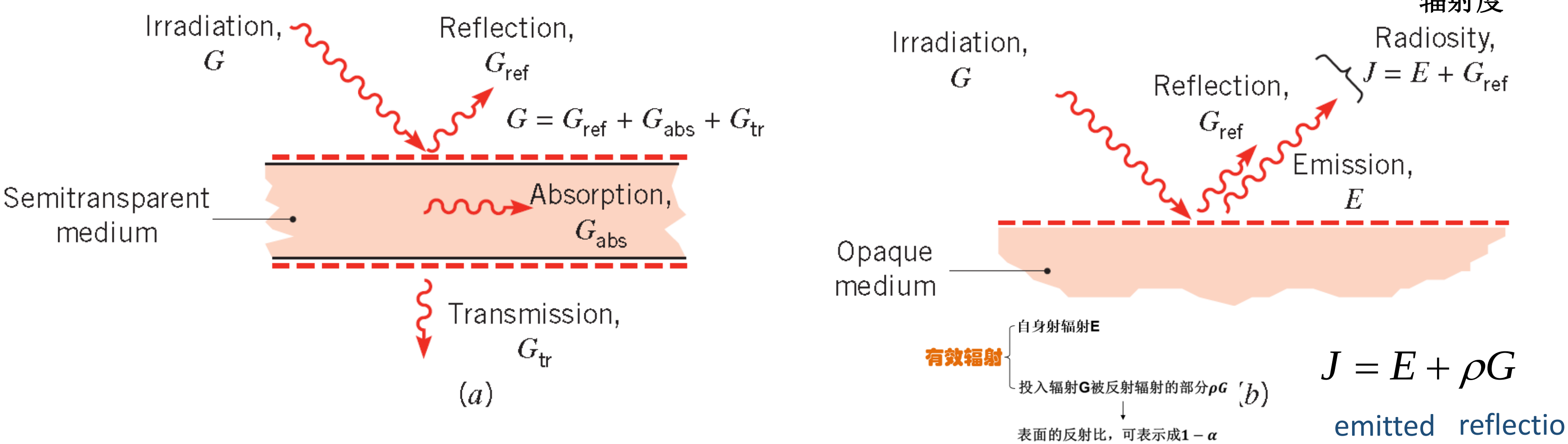


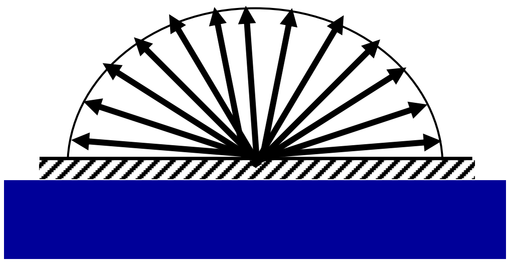
FIGURE 12.5 Radiation at a surface. (*a*) Reflection, absorption, and transmission of irradiation for a semitransparent medium. (*b*) The radiosity for an opaque medium.

Most solid and liquid bodies, the thermal radiation cannot be transmitted, Hence, we say that radiation is only a kind of <u>surface phenomenon</u> for solids and liquids

I. Fundamental Concepts

5. Diffuse emitter:

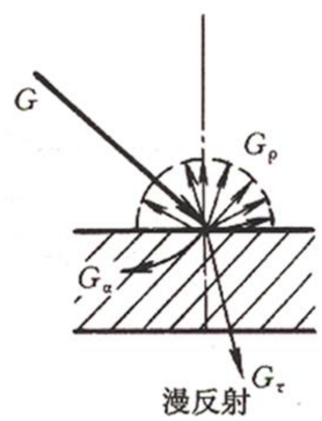
- It emits equally in all directions - No preferred direction of emission

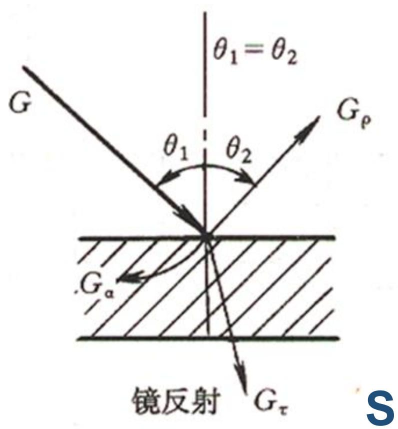


漫辐射表面：辐射强度在空间各个方向上都相等。

黑体表面为漫辐射表面。

6. Diffuse reflector:





7. Diffuse surface:

- Not a function of direction

Specular reflector (mirror-like)

漫射表面：指发射或反射的定向辐射强度与空间方向无关

I. Fundamental Concepts

8. Blackbody

a. Best possible emitter

b. Absorbs all incident radiation

c. Diffuse emitter

$$\alpha = 1; \tau = 0, \quad \rho = 0$$

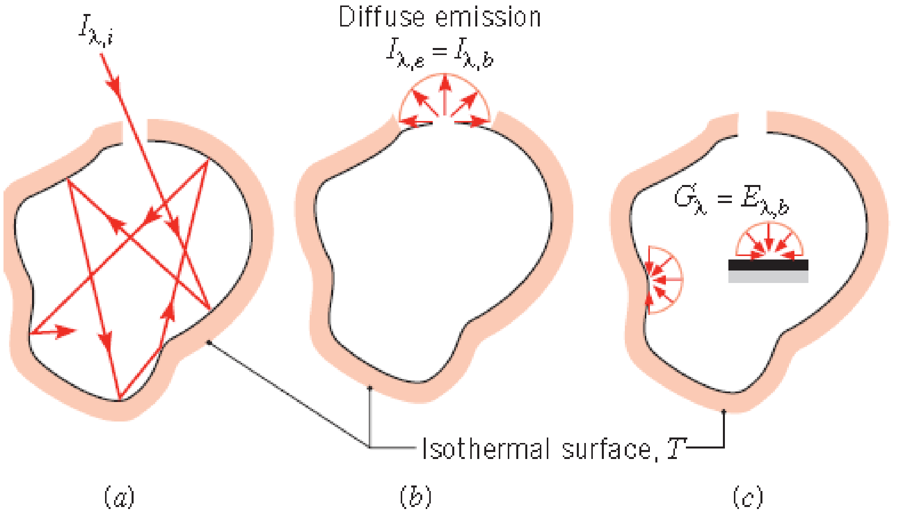


FIGURE 12.11 Characteristics of an isothermal blackbody cavity. (*a*) Complete absorption. (*b*) Diffuse emission from an aperture. (*c*) Diffuse irradiation of interior surfaces.

黑体不反射、也不透射，全部被吸收。

黑体是一个理想的吸收体，它能吸收来自各个方向、各种波长的全部投射能量。通常将黑体作为比较的标准。

黑体表面的辐射属于漫辐射：各方向分布均匀。

黑体： 能全部吸收外来射线的物体，（如带有小孔的空腔接近于黑体）；

- α =1: *black body*
- τ =1: transparent body
- ρ =1: white body

II. Blackbody Radiation

- As the perfect absorber and emitter, the blackbody serves as a *standard* against which the radiative properties of actual surfaces may be compared

- Emissive power, E

  Blackbody emissive power, E_b 黑体的辐射力

  Spectral blackbody emissive power, E_{b_λ}

II. Blackbody Radiation

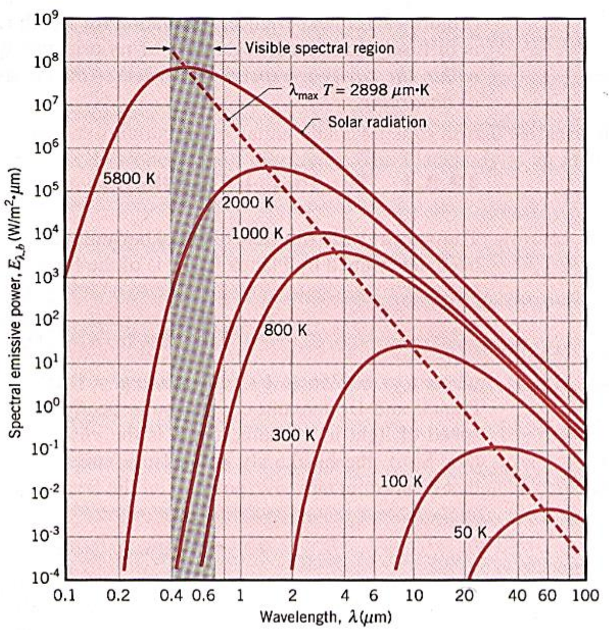
1. The Planck Law

普朗克定律

1900年 Max Planck 在量子理论的基础上，揭示了**真空中黑体的光谱辐射力 $E_{b\lambda}$ 与波长 λ 、热力学温度 T 之间的函数关系**

光谱辐射力

Spectral blackbody emissive power, E_{b_λ}



$$E_{b\lambda} = f(\lambda, T) = \frac{C_1}{\lambda^5[e^{C_2/(\lambda T)} - 1]} \quad [W/(m^2 \cdot \mu m)]$$

Where

λ = wavelength, μm

T = absolute temperature, K

C_1= 3.7430 × 10^8 (W·μm^4)/m^2

C_2=1.4387 × 10^8 μm·K

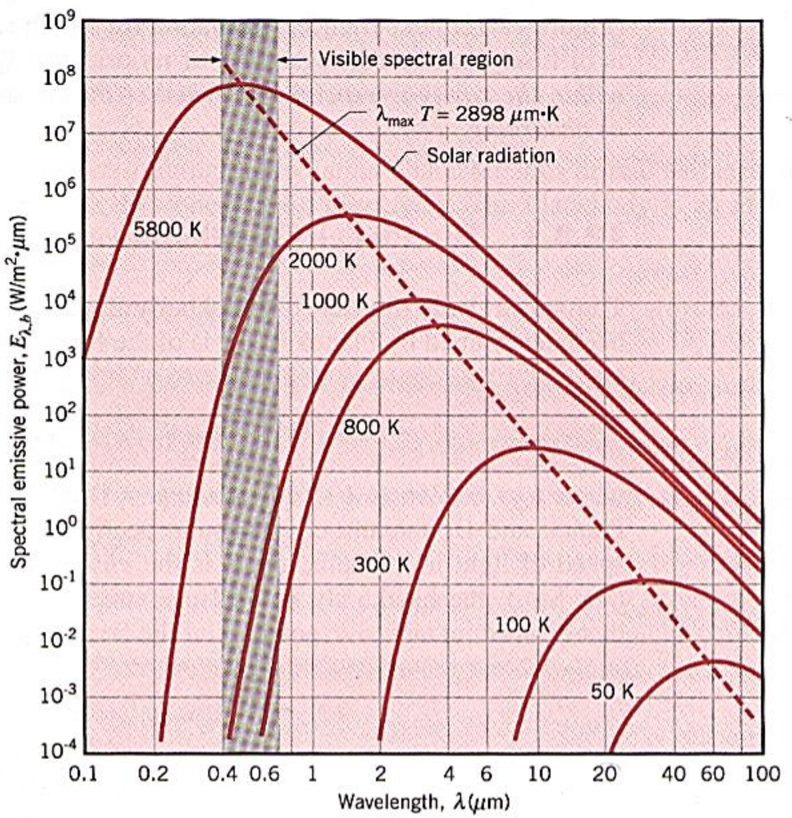
C_1 – 普朗克第一常数， $3.743 \times 10^8\ W \cdot \mu m^4/m^2$

C_2 – 普朗克第二常数， $1.4387 \times 10^4 \mu m \cdot K$

II. Blackbody Radiation

2. Wien's Displacement Law

Conclusions:



a. As temperature goes up, the body is emitted more energy

对任一波长：温度越高，光谱辐射力越强；

b. For any given temperature, the curve goes through a maximum (a peak value)

同一温度下的光谱辐射力存在一最大值，对应 λ_{max}；

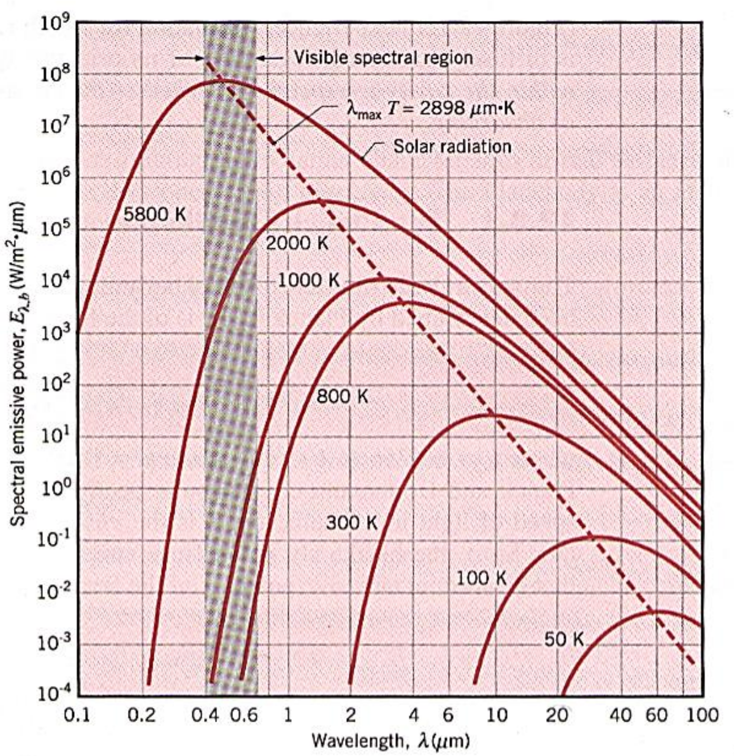
c. As temperature goes down, that peak emissive power value moves to the longer wave length.

$$\boxed{\lambda_{max} \cdot T = 2897.6\ \mu m \cdot K}$$

Displacement Law　　维恩(Wien)位移定律

Wien's Displacement Law

3. The Stefan-Boltzmann Law



- If taking one particular temperature curve, then integrate from overall possible wavelength -> the area under the curve, E_b

光谱辐射力曲线下的面积就是该温度下黑体的辐射力

$$E_b = \int_0^\infty E_{b\lambda} d\lambda = \int_0^\infty \frac{C_1}{\lambda^5[e^{C_2/(\lambda T)} - 1]} d\lambda = \sigma T^4 \ \left[\mathrm{W/m^2}\right]$$

- **The Stefan-Boltzmann Law**

$$E_b = \sigma\, T^4 \ \left[\mathrm{W/m^2}\right]$$

Stefan-Boltzmann constant $\sigma = 5.67 \times 10^{-8} \left[\mathrm{W/m^2 \cdot K^4}\right]$

Absolute temperature, *T*

- **Any temperature above zero emits radiation.**

II. Blackbody Radiation

4. Band emission

To account for spectral effects, it is often necessary to know the fraction of the total emission from a blackbody that is in a certain wavelength interval or *band*.

黑体辐射能按波段的分布

黑体在温度T下、在波段（$\lambda_1 - \lambda_2$）范围内所辐射的能量

$$E_{b(\lambda_1-\lambda_2)} = \int_{\lambda_1}^{\lambda_2} E_{b\lambda} d\lambda$$

该波段的辐射能占黑体辐射力的百分数$F_{b(\lambda_1-\lambda_2)}$称为黑体辐射函数。

4. Band emission

How much emission occurs between those two given wavelength?

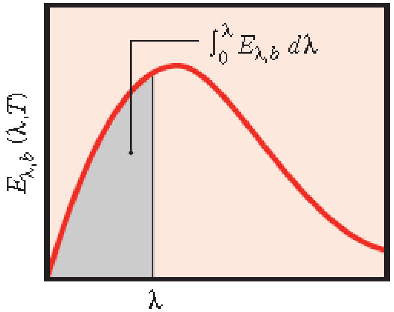


FIGURE 12.13 Radiation emission from a blackbody in

Fraction of thermal radiation

$$F_{(0\to\lambda)} \equiv \frac{\int_0^\lambda E_{\lambda,b}\, d\lambda}{\int_0^\infty E_{\lambda,b}\, d\lambda} = \frac{\int_0^\lambda E_{\lambda,b}\, d\lambda}{\sigma T^4} = \int_0^{\lambda T} \frac{E_{\lambda,b}}{\sigma T^5}\, d(\lambda T) = f(\lambda T)$$

$$F_{(\lambda_1\to\lambda_2)} = \frac{\int_0^{\lambda_2} E_{\lambda,b}\, d\lambda - \int_0^{\lambda_1} E_{\lambda,b}\, d\lambda}{\sigma T^4} = F_{(0\to\lambda_2)} - F_{(0\to\lambda_1)}$$

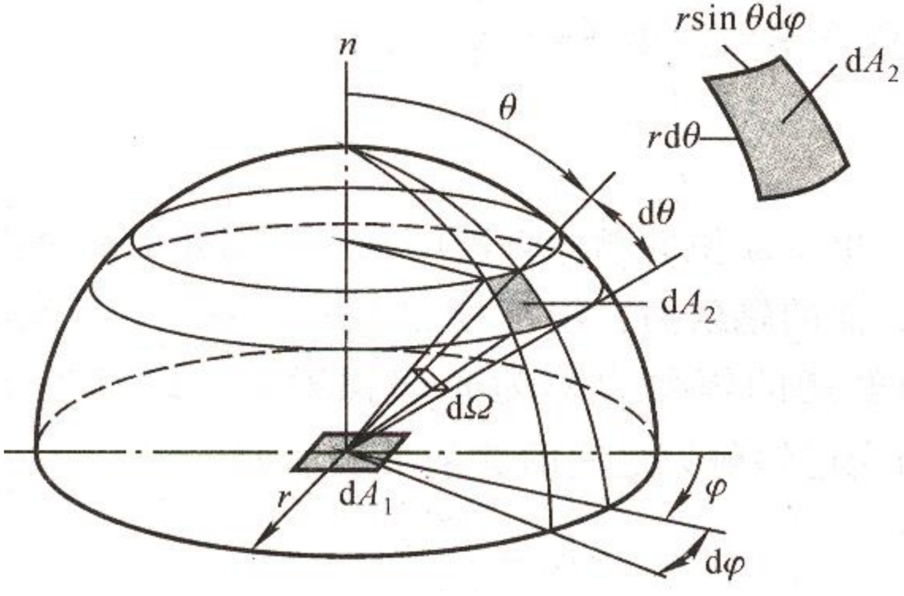
TABLE 12.2 Blackbody Radiation Functions

λT (μm · K)	$F_{(0\to\lambda)}$	$I_{\lambda,b}(\lambda, T)/\sigma T^5$ (μm · K · sr)$^{-1}$	$\dfrac{I_{\lambda,b}(\lambda, T)}{I_{\lambda,b}(\lambda_{max}, T)}$
200	0.000000	0.375034×10^{-27}	0.000000
400	0.000000	0.490335×10^{-13}	0.000000
600	0.000000	0.104046×10^{-8}	0.000014
800	0.000016	0.991126×10^{-7}	0.001372
1,000	0.000321	0.118505×10^{-5}	0.016406
1,200	0.002134	0.523927×10^{-5}	0.072534
1,400	0.007790	0.134411×10^{-4}	0.186082
1,600	0.019718	0.249130	0.344904
1,800	0.039341	0.375568	0.519949
2,000	0.066728	0.493432	0.683123
2,200	0.100888	0.589649×10^{-4}	0.816329
2,400	0.140256	0.658866	0.912155
2,600	0.183120	0.701292	0.970891
2,800	0.227897	0.720239	0.997123
2,898	0.250108	0.722318×10^{-4}	1.000000

5. Lambert Law

Lambert's law gives the distribution law of blackbody radiant energy in the space direction. We must first figure out how to represent the space direction and its magnitude

Solid angle: $$\mathrm{d}\Omega = \frac{dA_c}{r^2}$$



$$\mathrm{d}\Omega = \frac{dA_2}{r^2} = \frac{r\sin\theta \cdot d\varphi \cdot r\,d\theta}{r^2} = \sin\theta \cdot d\theta \cdot d\varphi$$

$$\Omega = \int_0^{2\pi} \int_0^{\pi/2} \sin\theta \cdot d\theta \cdot d\varphi = 2\pi$$

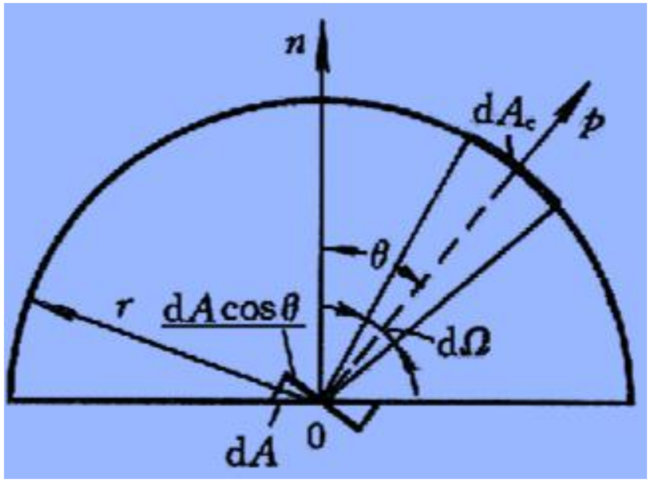
$$\mathrm{d}\Omega = \frac{\mathrm{d}A_n}{r^2}$$

5. Lambert Law

The energy emitted per unit of time from a unit of visible area falling into a unit solid Angle in any direction of space at full wavelength

$$I(\theta,\varphi)=I(\theta)$$
$$I_\lambda(\theta,\varphi)=I_\lambda(\theta)$$

$$I(\theta)=I(\theta,\varphi)=\frac{d\Phi(\theta)}{(dA_1\cos\theta)\,d\Omega}$$



黑体的辐射力：

$$E_b=\int_{\Omega=2\pi}\frac{d\Phi(\theta)}{dA}=I_b\int_{\Omega=2\pi}\cos\theta\,d\Omega$$

II. Blackbody Radiation

- Example:

For the sum, T_{sun}=5800K

Find: fraction of thermal radiation emitted by sum that falls in the UV, vis and IR regions

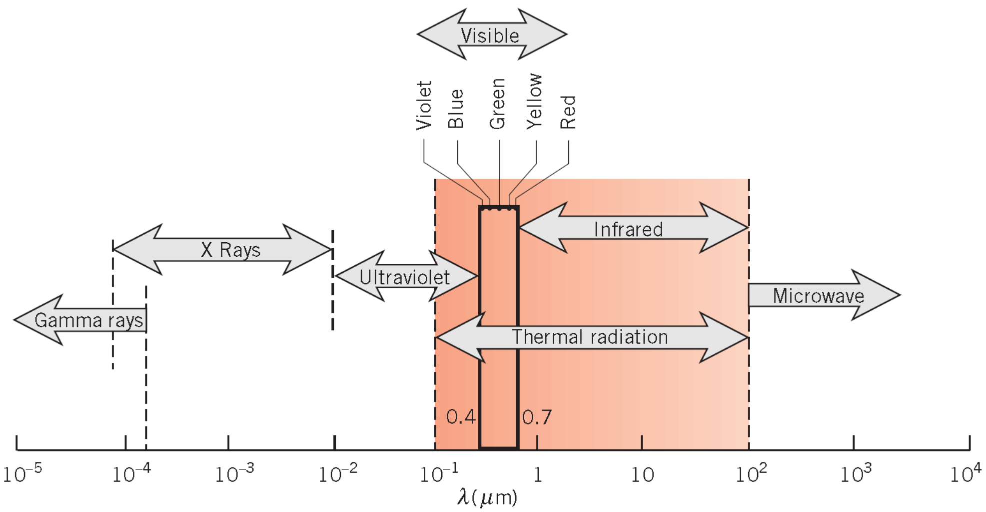


FIGURE 12.3 Spectrum of electromagnetic radiation.

UV: 0.1 to 0.4

Vis: 0.4 to 0.7

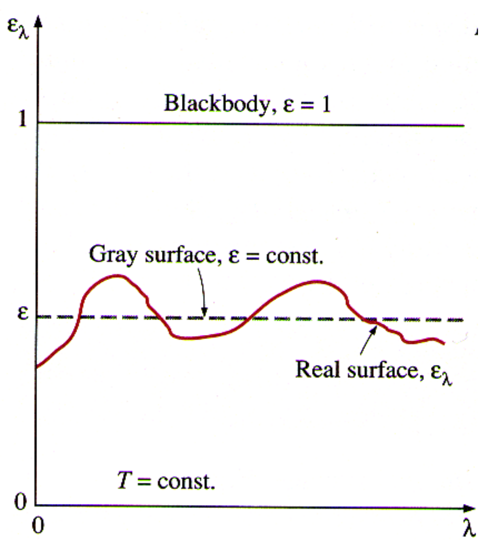
IR: 0.7 to 100

- ***T*=5800K时，峰值在可见光范围，太阳所发射的辐射能约44.6%(43%)在可见光范围；**

III. Emission from Real Surfaces

- Emissivity, ε

The ratio of the radiation emitted by the surface to the radiation emitted by a blackbody at the same temperature



$$\varepsilon = \frac{E(T)}{E_b(T)} = \frac{\int_0^\infty E_\lambda d\lambda}{\sigma_b T^4} = \frac{\int_0^\infty \varepsilon_\lambda E_{b\lambda} d\lambda}{\sigma_b T^4}$$
$$= \frac{\text{实际物体的辐射力}}{\text{同温度条件下黑体的辐射力}}$$

▶ 实际物体的辐射力E总是小于同温度下黑体的辐射力E_b，两者的比值称为实际物体的发射率（或黑度）

黑度ε的大小**表征实际物体的辐射能力与同温度黑体辐射能力的接近程度。**

- Emission from Real Surfaces

实际物体的辐射力

$$E = \varepsilon E_b = \varepsilon \sigma_b T^4 \ \left[W/m^2\right]$$

黑度取决于物体本身的条件：种类、表面状况和温度。

- Blackbody: $\varepsilon = 1$

III. Emission from Real Surfaces

- Emissivity, ε

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

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

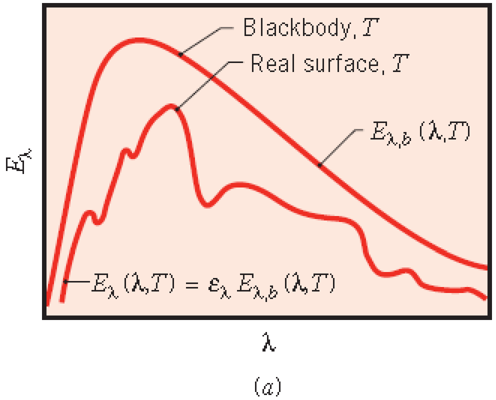


FIGURE 12.15 Comparison of blackbody and real surface emission. (b) Directional distribution.

The *monochromatic emissivity* is defined as the ratio of the monochromatic emissive power of the body to the monochromatic emissive power of a blackbody at the *same* wavelength and temperature.

III. Emission from Real Surfaces

The Absorptivity :

Definition:

- α_λ is a function of the wavelength, hence the absorption of the radiant energy by a real surface is wavelength-selective
- It is a function not only of the surface itself but also of the surroundings
- Dependent on the direction and wavelength of the incident radiation.

Monochromatic absorptivity α_λ

$$\alpha_\lambda = \frac{G_{\lambda,\alpha}}{G_\lambda} = f(\lambda, T) = f(T, T_i)$$

The Total Absorptivity α

$$\alpha = \frac{G_\alpha}{G} = \frac{\int_0^\infty \alpha_\lambda(T,\lambda) G_\lambda \, d\lambda}{\int_0^\infty G_\lambda \, d\lambda} = f(T, T_i)$$

Gray Body

- **The fact that the absorptivity of a real surface depends on irradiation is due to the fact that α_λ is a function of the wavelength**
- **Suppose that α_λ is independent λ, that is $\alpha_\lambda = f\,(T\,)$, then**

$$\alpha = \frac{\int_0^\infty \alpha_\lambda(T,\lambda) G_\lambda \, d\lambda}{\int_0^\infty G_\lambda \, d\lambda} = \frac{\int_0^\infty \alpha_\lambda(T) G_\lambda \, d\lambda}{\int_0^\infty G_\lambda \, d\lambda} = \alpha_\lambda(T)$$

III. Emission from Real Surfaces

- Emissivity ε
- Absorptivity α

发射辐射与**吸收辐射**之间具有什么样的联系呢?

★ 1859年，Kirchhoff 用热力学方法回答了这个问题，从而提出了**Kirchhoff 定律**。

$$q = E - \alpha E_b = 0$$

$$\frac{E}{\alpha} = E_b \quad \Rightarrow \quad \alpha = \frac{E}{E_b} = \varepsilon$$

$$\frac{E_1}{\alpha_1} = \frac{E_2}{\alpha_2} = \cdots = \frac{E}{\alpha} = E_b$$

$$\frac{E}{\alpha} = E_b \quad \Rightarrow \quad \alpha = \frac{E}{E_b} = \varepsilon$$

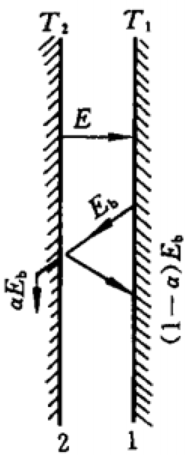


Plate 2 real body
α, T_2

Plate I black
α=1,T_1

$\varepsilon(\lambda,T) = \alpha(\lambda,T)$　　漫射表面

$\varepsilon(T) = \alpha(T)$　　与黑体处于热平衡或对漫灰表面

This is Kirchhoff' s Law, it tells us that under *thermodynamic equilibrium* conditions, the ratio of the emissive power of any body to its absorptivity of the *blackbody irradiation* is equal to the emissive power of a *blackbody at the same temperature*.

III. Emission from Real Surfaces

- **A good emitter must be a good absorber**
- **A perfect blackbody defines a perfect absorber**

$$\varepsilon = \frac{E(T)}{E_b(T)} \leq 1$$

$$\alpha = \frac{E(T)}{E_b(T)} = \varepsilon, \quad \alpha = \varepsilon$$

This tells us that the *absorptivity* of a body to the blackbody irradiation of the same temperature *equals to its emissivity*.

Since the absorptivity of a graybody is independent of its surroundings, therefore the Kirchhoff Law is *always true for gray bodies*.

III. Emission from Real Surfaces

- Emissivity ε

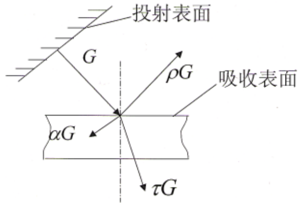
$$\varepsilon_\lambda(\lambda, T) \equiv \frac{E_\lambda(\lambda, T)}{E_{\lambda,b}(\lambda, T)}$$

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

- Absorptivity

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

$$\alpha = \frac{\int_0^\infty \alpha_\lambda(\lambda) G_\lambda(\lambda)\, d\lambda}{\int_0^\infty G_\lambda(\lambda)\, d\lambda}$$



- Reflectivity

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

$$\rho = \frac{\int_0^\infty \rho_\lambda(\lambda) G_\lambda(\lambda)\, d\lambda}{\int_0^\infty G_\lambda(\lambda)\, d\lambda}$$

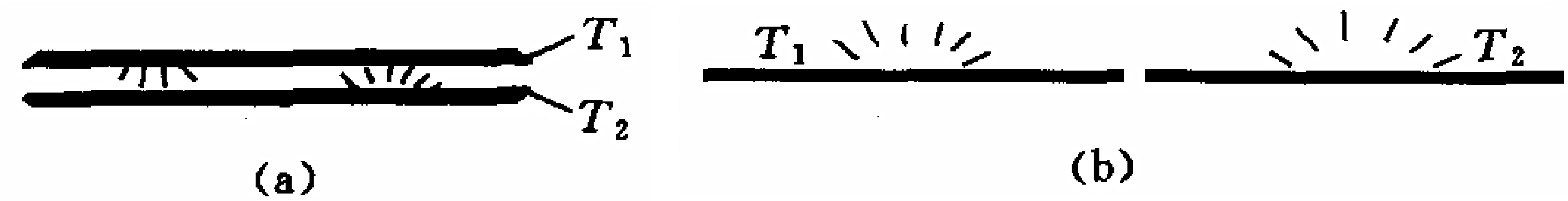
- Transmissivity

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

$$\tau = \frac{\int_0^\infty G_{\lambda,\text{tr}}(\lambda)\, d\lambda}{\int_0^\infty G_\lambda(\lambda)\, d\lambda} = \frac{\int_0^\infty \tau_\lambda(\lambda) G_\lambda(\lambda)\, d\lambda}{\int_0^\infty G_\lambda(\lambda)\, d\lambda}$$

IV. Angle factor or shape factor

The radiative heat transfer between two surfaces is highly dependent on the relative position of the two surfaces:



When the relative position between the two surfaces is different, the percentage of radiant energy emitted from one surface that falls on the other surface varies, thus affecting the heat transfer.

IV. Angle factor or shape factor

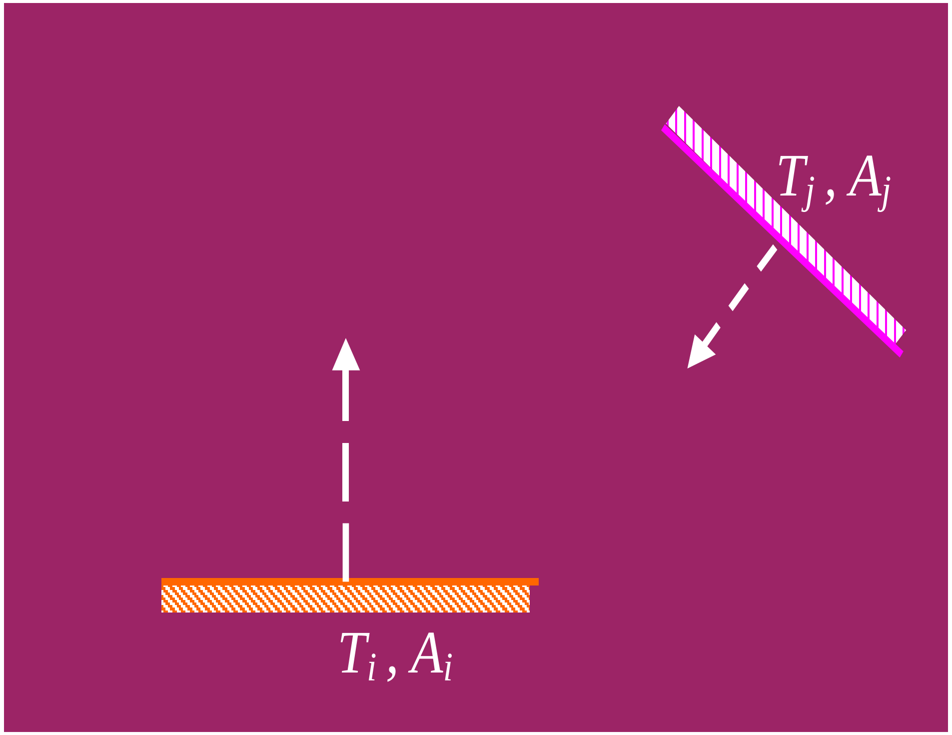
Definition:

The *radiation shape factor* $X_{i\text{-}j}$ of A_i with respect to A_j

A geometrical parameter!

Fraction of energy leaving surface A_i which reaches surface A_j directly.

“发出” — 包含表面1自身的辐射和反射的辐射；
“落到” — 不管表面2是否能够吸收；



$$X_{i-j} = \frac{\text{energy that leaves } A_i \text{ and directly strikes } A_j}{\text{total energy that leaves } A_i}$$

The *radiation shape factor* $X_{j\text{-}i}$ of A_j with respect to A_i

$$X_{j-i} = \frac{\text{energy that leaves } A_j \text{ and directly strikes } A_i}{\text{total energy that leaves } A_j}$$

IV. Angle factor or shape factor

两黑体表面间的辐射传热量 ➡ $\Phi_{1,2} = A_1 E_{b1} X_{1,2} - A_2 E_{b2} X_{2,1}$

当$\boldsymbol{T_1} = \boldsymbol{T_2}$时，净辐射传热量为零，即$\boldsymbol{E_{b1}} = \boldsymbol{E_{b2}}$

$$\boxed{A_1 X_{1,2} = A_2 X_{2,1}}$$

故$X_{d1,d2}$和$X_{d2,d1}$不是独立的。

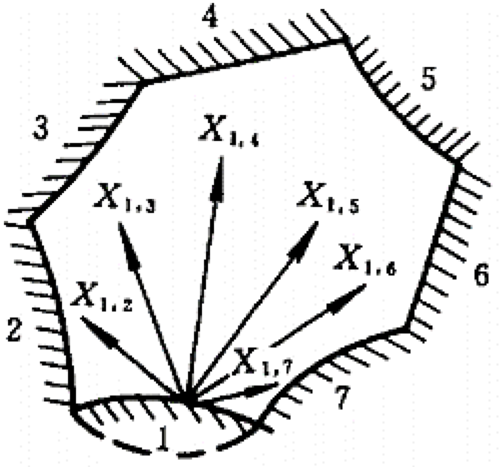
The reciprocity rule of the angle factors。

IV. Angle factor or shape factor

For a closed system composed of n surfaces, energy conservation can be obtained:

The radiant energy emitted from any surface must all fall on the surfaces of the closed system

$$X_{1,1} + X_{1,2} + X_{1,3} + \cdots + X_{1,n} = \sum_{i=1}^{n} X_{1,i} = 1$$

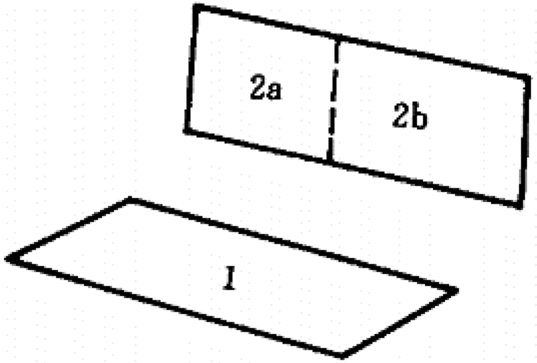


The summation rule of the angle factor。

Concave or convex，$X_{1,1}$ = ?。

IV. Angle factor or shape factor

The total energy from surface 1 falling on surface 2 is equal to the sum of the radiant energy from the parts falling on surface 2, so we have:



$$A_1 E_{b1} X_{1,2} = A_1 E_{b1} X_{1,2a} + A_1 E_{b1} X_{1,2b}$$

$$\Rightarrow \quad X_{1,2} = X_{1,2a} + X_{1,2b}$$

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

The superposition rule of the angle factor。