26

Radiant Heat Transfer

The Nature of Thermal Radiation

- "Radiant energy of the form called **thermal radiation** is emitted by every body with > 0 K". This does not mean that the amount of thermal radiation emitted is always significant. Its importance in a heat-transfer process depends on the amount of heat being transferred simultaneously by other mechanisms.

- In systems at or below room temperature thermal radiation is likely to be negligible. However, at temperature of "**red heat**" (~550^{o}C) and higher, radiant transmission is often the principal mechanism of heat transfer.

The Nature of Thermal Radiation

- Bodies may emit radiant energy of other forms in addition to thermal radiation. Bombardment of a substance by electrons produces radiation which we call x rays. Exposure to one form of radiation often causes a body to emit another, or secondary, radiation; e.g., certain minerals fluoresce under ultraviolet light.

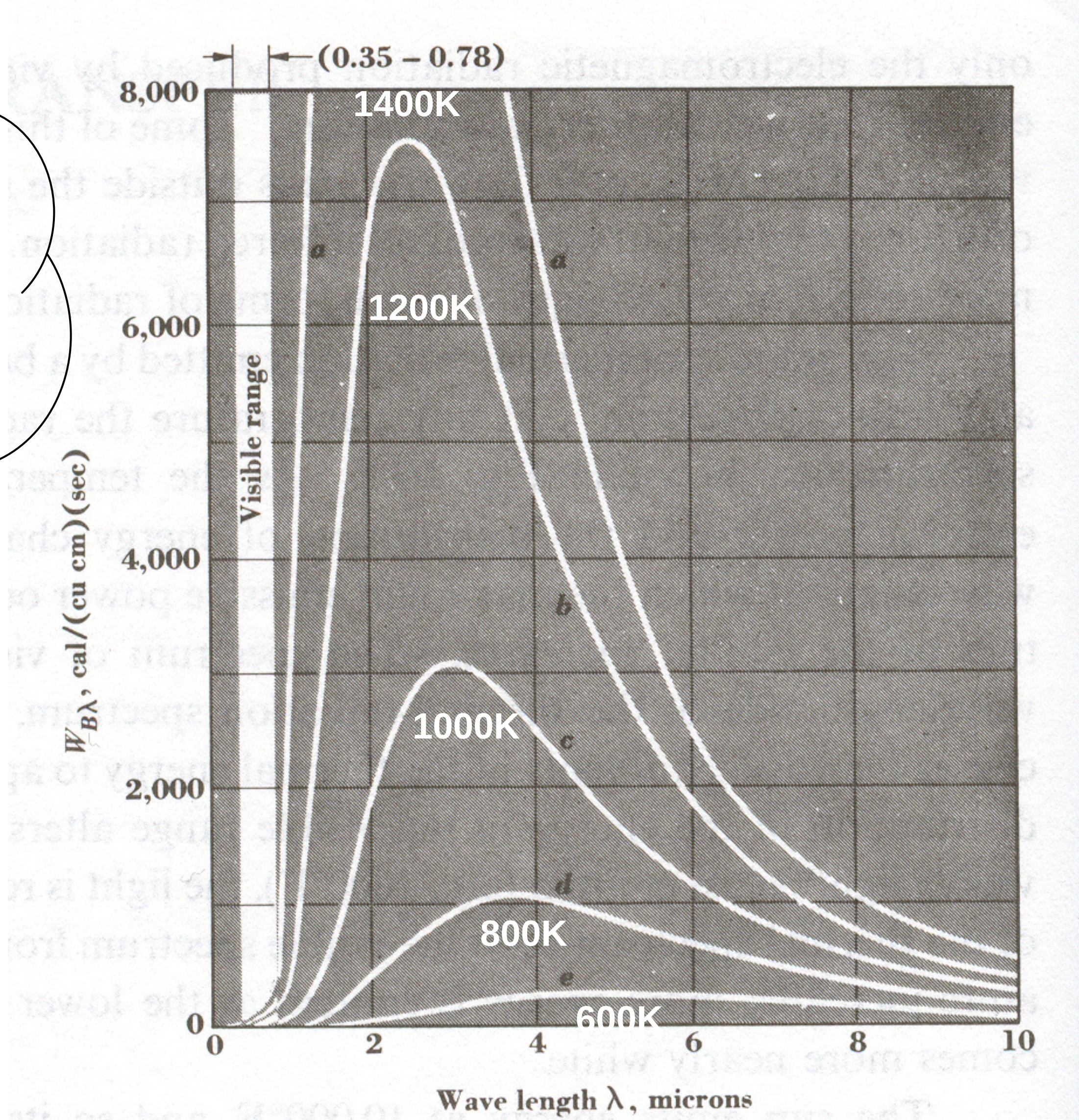
- In fact, there is a continuous spectrum of electromagnetic radiation. All forms have the same velocity of propagation but differ in wavelength and origin. All forms produce heat when absorbed.

- Only the electromagnetic radiation produced by virtue of the temperature of the emitter that we call "thermal radiation".

Fluoresce: 형광을 내다

Special distribution of total energy emitted by a black body

The amount of thermal radiation emitted by a body depends on its temperature and surface condition. At any temperature, the radiation emitted extends over a emissive power and the distribution of energy change.

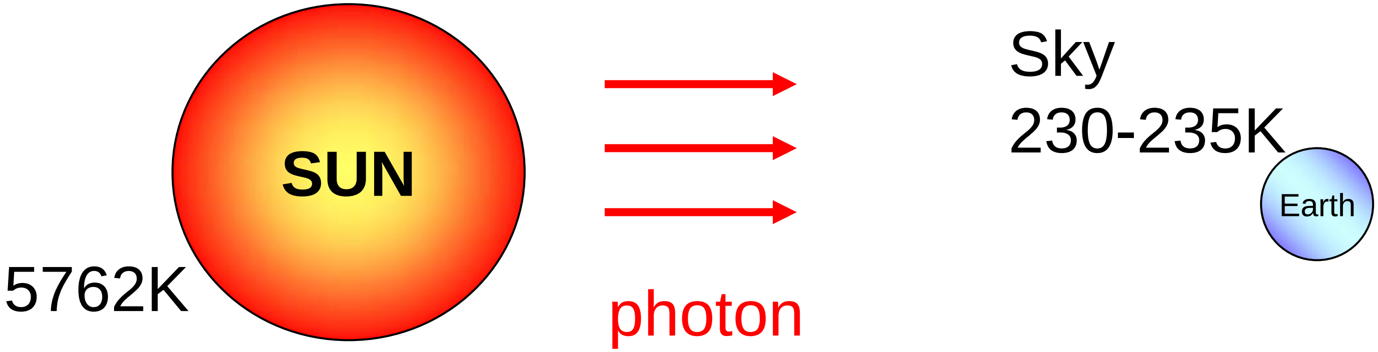


The Nature of Thermal Radiation

- As the temperature changes, both the total emissive power and the distribution of energy change. It can be seen that the wavelength at which the maximum emissive power occurs decreases as the temperature of the emitter increases.

- The spectrum of visible light occurs on the low wavelength side of the thermal-radiation spectrum, so increasing the temperature causes increasing amounts of the thermal energy to appear as light.

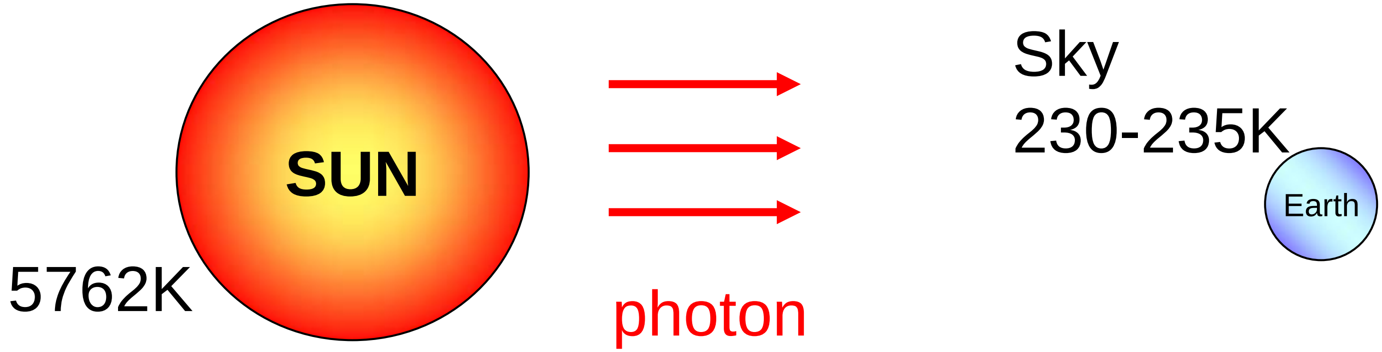
The Nature of Thermal Radiation



The sun emits energy at 10,000^{0}F, and so its spectral distribution curve is shifted substantially to the left of curve a in Fig. 26-1. In fact, the solar spectrum straddles the so-called visible range of 3500 to 7800A. (5%UV, 40% VIS, 55% IR at the earth's surface)

Straddle : 두 다리를 벌리고 서다.

The Nature of Thermal Radiation



Most filament lamp operate with filament temperature below 5,000^{0}F: hence, the light they emit is deficient in ultraviolet and oversupplied with infrared radiation, as compared with solar radiation.

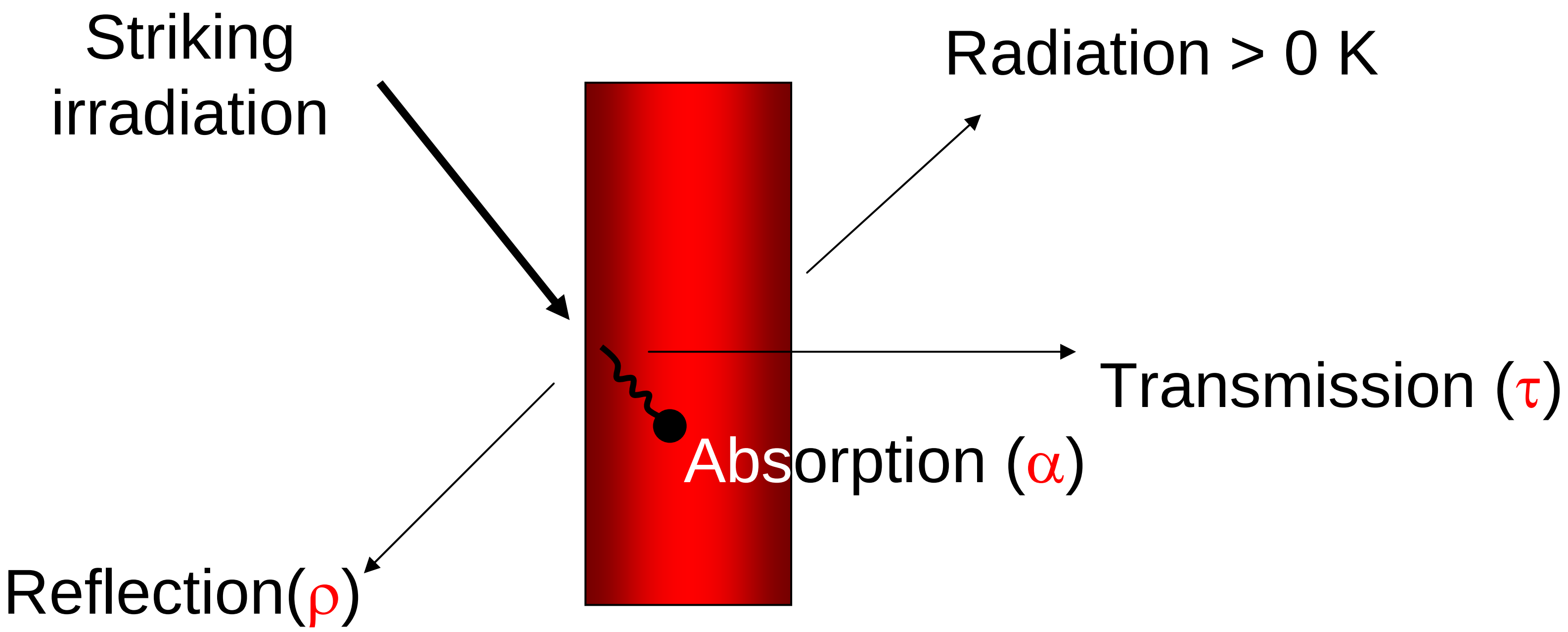
The Nature of Thermal Radiation

All forms have the same velocity of propagation but differ in wavelength and origin. All forms produce heat when absorbed

Characteristic Wavelengths of Radiation	
Cosmic rays	**< 0.001 x 10^{-8} cm**
Gamma rays	**0.01 - 0.15 x 10^{-8} cm**
X-rays	**0.06 - 1000 x 10^{-8} cm**
Ultraviolet	**100 - 3500 x 10^{-8} cm**
Electric lamps	**2000 - 50,000 x 10^{-8} cm**
Visible	**3500 - 7800 x 10^{-8} cm**
Infrared	**7800 x 10^{-8} - 0.04 cm**
Radio	**0.04-10^{7} cm**

Thermal radiation

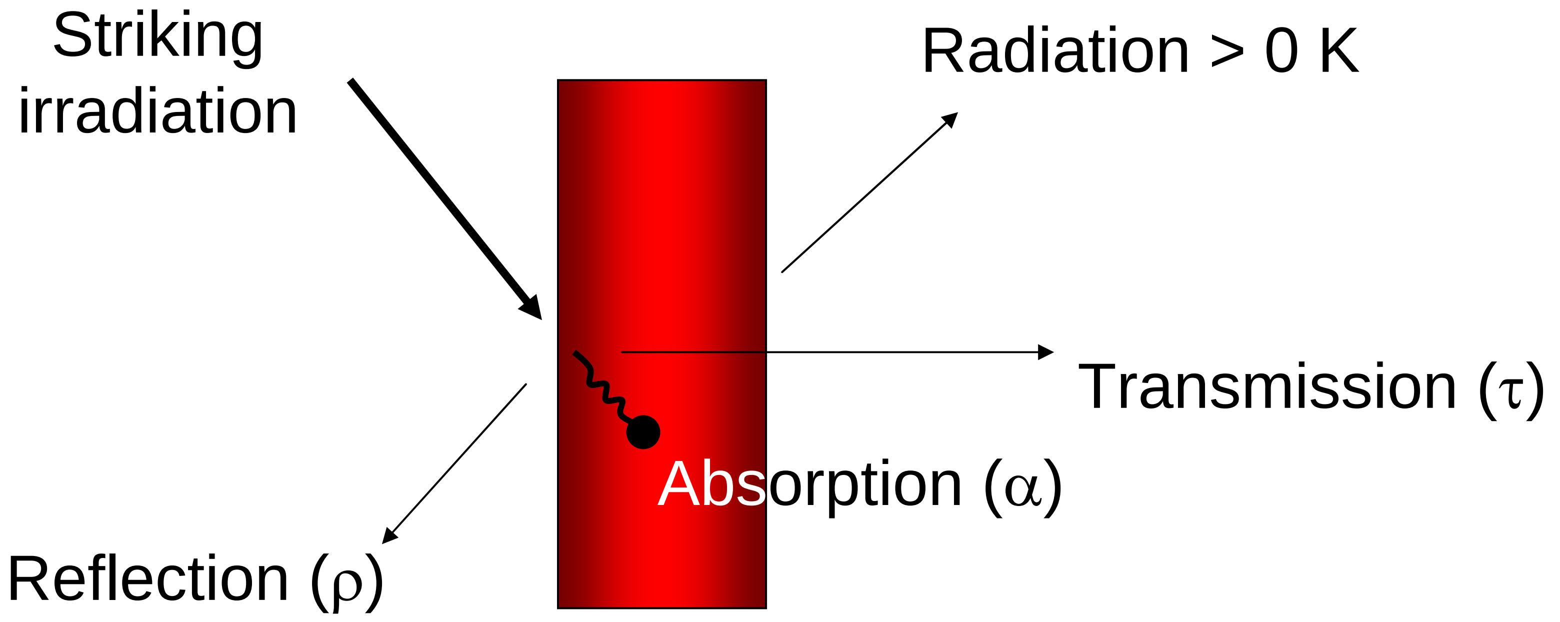
"The electromagnetic radiation produced by virtue of the temperature of the emitter"



$$\alpha + \tau + \rho = 1 \text{ (total energy)} \qquad (26\text{-}1)$$

Absorptivity + transmissivity + reflectivity = 1

Thermal radiation



$\alpha+\tau+\rho=1$ (total energy)

α=1: **black body** (ideal emitter, perfect absorber, $\tau+\rho=0$)

τ=0: **opaque body** ($\alpha+\rho=1$)

Absorption, Reflection and Transmissivity

Absorption does not occur equally for radiation of all wavelengths (Fig. 26-2). Since the spectral distribution of energy is a function of the temperature of the emitter, the absorptivity of a receiver depends on the temperature of the emitter. Selective absorption is especially significant in absorption by gases, which are transparent to radiation of some wavelengths but highly absorbent for others.

The absorptivity of a material also depends on its own temperature. Thus the specification of α for a particular surface requires the designation of two temperature. In solving many problems, it is necessary to assume that the absorptivity of a surface is not a function of the spectral distribution; the surface in these circumstance is spoken of as a **"gray" surface**.

Variation of absorptivity of a solid with wavelength

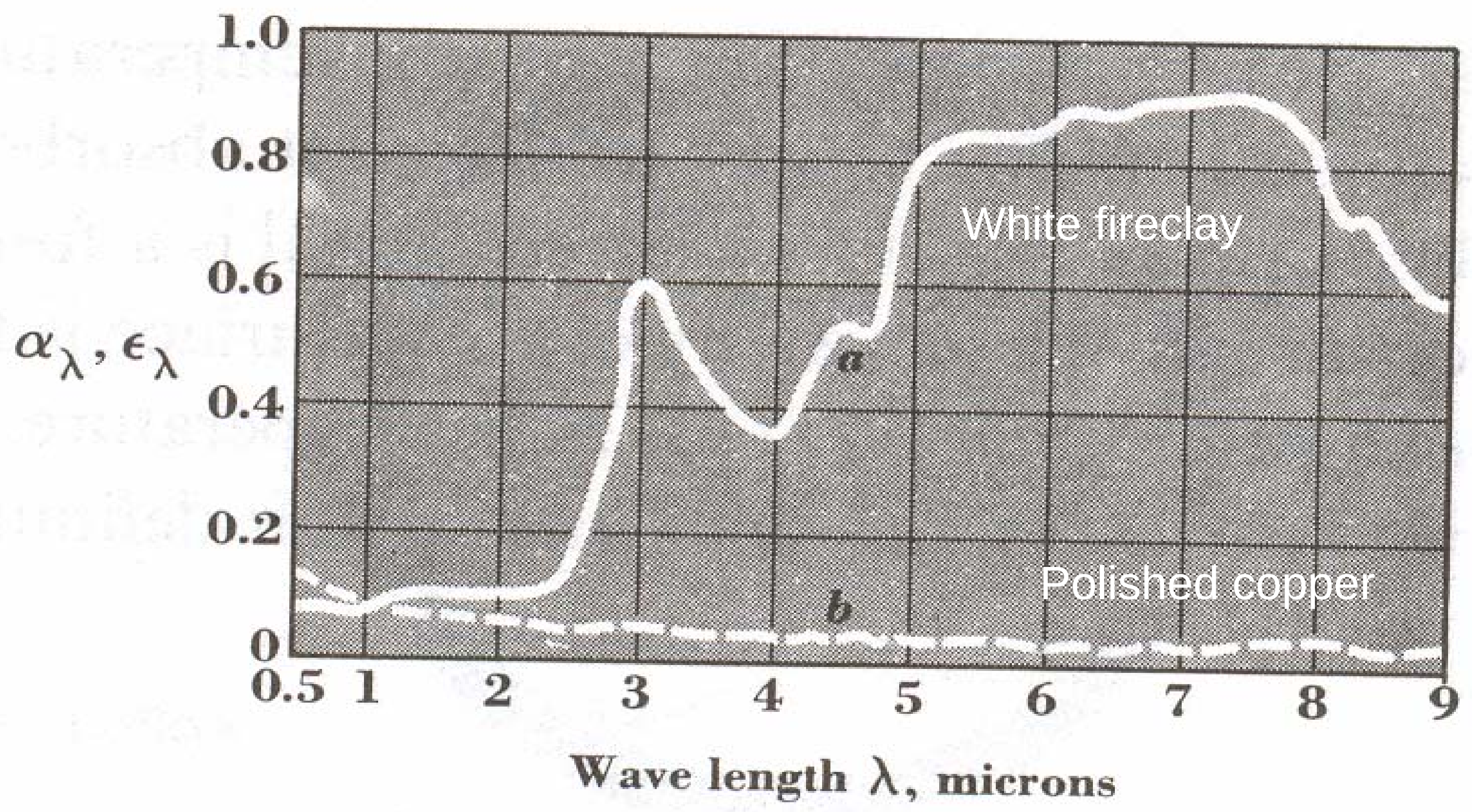


Fig. 26-2

Absorption, Reflection and Transmissivity

Polished metallic surfaces have high reflectivities, and granular surfaces have low reflectivities. Gases and liquids usually transmit most of the radiation incident upon them, although liquid are capable of reflecting substantial amounts of energy.

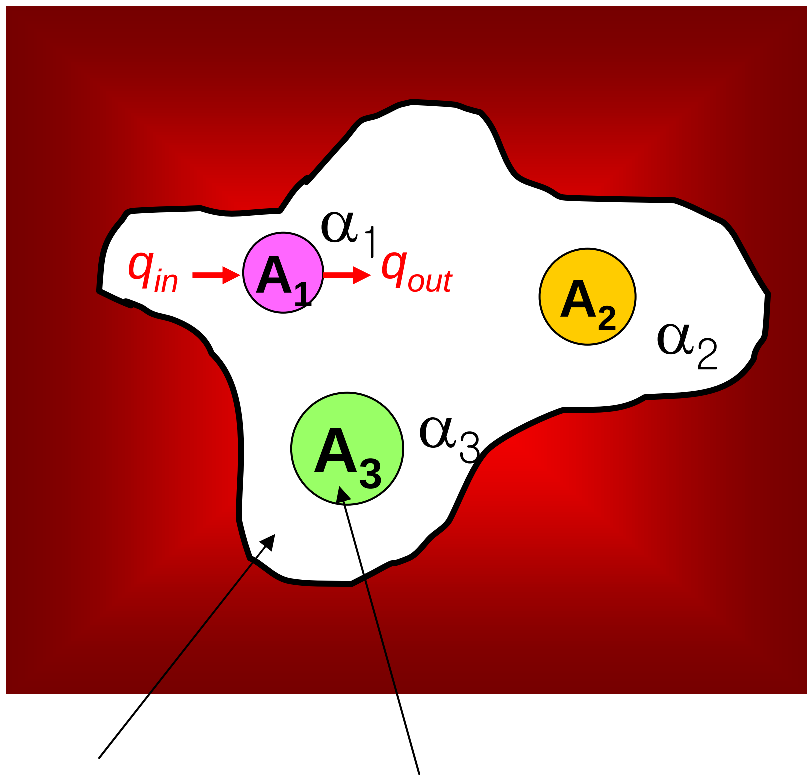
Because of the relation between α, τ, and ρ in Eq. (26-1), the remarks made above concerning variation of absorptivity with temperature obviously apply also to the sum of transmissivity and reflectivity.

Absorption, Reflection and Transmissivity

Reflection from a macroscopic section of surface depends greatly on the character of the surface. If the surface is very smooth, the angles of incidence and reflection are the same.

However, most surfaces encountered in engineering are sufficiently rough so that some reflection occurs in all directions. If the total reflection is independent of the angle of incidence, it is said to be "**diffuse**". This assumption is made in solving most engineering problems.

Emissivity at thermal equilibrium



If one or more small non-heat-generating bodies are contained within a large evacuated enclosure, they will eventually reach a state of thermal equilibrium at which each receives radiant heat at the same rate at which it loses it.

$$q_{in} = q_{out}$$

Kirchhoff's law

$$q_{out} = A_1 W_1 = q_{in} = (\alpha_1 W_o) A_1 \text{ [Btu/hr]}$$

W_1: the total rate of emission of energy per unit area for a body of area A_1 [Btu/hr·ft^2]
W_o: the flux of radiant energy from the enclosure which strikes area A_1[Btu/hr·ft^2]
α_1: absorptivity of surface A_1 [-]

$$W_1 A_1 = W_0 \alpha_1 A_1$$

$$\frac{W_1}{\alpha_1} = W_0$$

$$\boxed{\frac{W_1}{\alpha_1} = \frac{W_2}{\alpha_2} = \cdots = \frac{W_n}{\alpha_n}}$$

Kirchhoff's law:

In a system at thermal equilibrium, all bodies will have the same temperature and all bodies will have the same ratio of total emissive power to absorptivity.

Black body

If one of the surfaces in the enclosure absorbs all the radiation incident upon it, it has an absorptivity of 1 (**α=1; black body**).

Because W/α is fixed, this places an upper limit on the emissive power of that surface, or any other at the same temperature, so that a black body is referred as an **ideal emitter** as well as a **perfect absorber**. Thus the emissive power of a black body [Btu/hr·ft^2] is a function only of its own temperature.

Incident 입사한

Emissivity of real surface, ε_1

Definition:

The emissivity of a real surface (ε_1) is the ratio of its emissive power W_1 to that of a black body W_2 at the same temperature.

$$\varepsilon_1 \equiv \frac{W_1}{W_2}$$

$$\frac{W_1}{\alpha_1} = \frac{W_2}{\alpha_2} = \cdots = \frac{W_n}{\alpha_n}$$

$$\frac{W_1}{W_2} = \frac{\alpha_1}{\alpha_2} = \varepsilon_1$$

Black body

1

$$\boxed{\alpha_1 = \varepsilon_1}$$

In a system at thermal equilibrium, the emissivity of any object in the system is the same as its absorptivity.

Emissivity of real surface, ε_1

$$\alpha_1 = \varepsilon_1$$

In a system where various portions are at different temperatures, this is not true, but is often assumed to be true so that a solution can be obtained to a problem.

As mentioned earlier, the absorptivity of a surface actually varies with the wavelength of the incident radiation; sometimes, however, the surface is assumed to be "gray", and α is assumed to be constant.

Emissivity of real surface, ε_1

In these circumstances, α for a surface is evaluated by determining the emissivity, not at the actual surface temperature, but rather at the temperature of the source of the radiation, because this is the temperature the absorbing surface would have if it were at thermal equilibrium with the emitter.

It is a fact that the temperature of the absorber has some effect on absorptivity as well, but the effect of the temperature of the emitter is usually more important.

Total emissions of some surfaces

Emissivity, like absorptivity, is low for polished metal surfaces, and moderately high for oxidized metal surfaces. It is also high for most nonmetallic substances.

Emissivity, like absorptivity, varies with wavelength and also with the angle between the emitted beam and the emitting surface. The value in Table 26-2 are for the total emissivity, which includes radiation of all wavelengths normal to the emitting surface.

The variation of emissivity with angle often is not large; in such circumstances the variation is neglected and the value of Table 26-2 are taken as being total hemispherical emissivities. Some of the values are so close to unity that the surfaces may be considered to be black bodies.

Total emissions of some surfaces

Surface	Temp(^{o}F)	Emissivity
Polished Al	73	0.040
Polished Cu	242	0.023
Polished Fe	800-1800	0.144-0.377
Cast iron, newly turned	72	0.435
Oxidized iron	212	0.736
Asbestos board	74	0.96
Red brick	70	0.93
Sixteen different oil paints	212	0.92-0.96
Water	32-212	0.95-0.963

* For black body, $\varepsilon = 1$

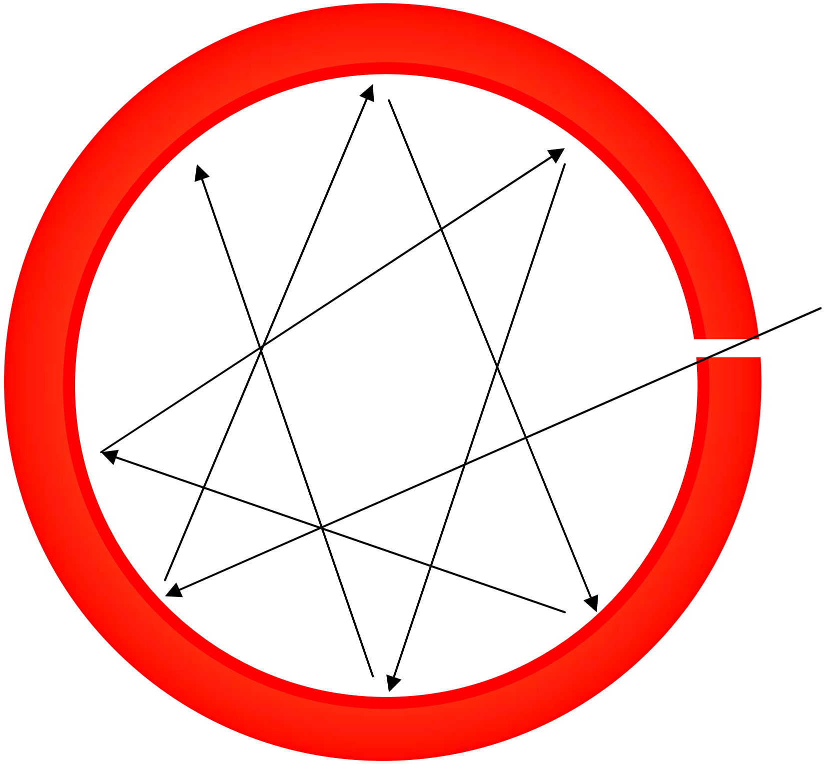
Achieving nearly perfect black body condition

Absorption or emission of radiation
through a small hole in a hollow container

Each time it impinges on the surface, a fraction α is absorbed, so that after a few reflections, nearly all the radiation which entered is absorbed.

In effect, the hole in the container is equivalent to a surface of the same area with an absorptivity of 1.

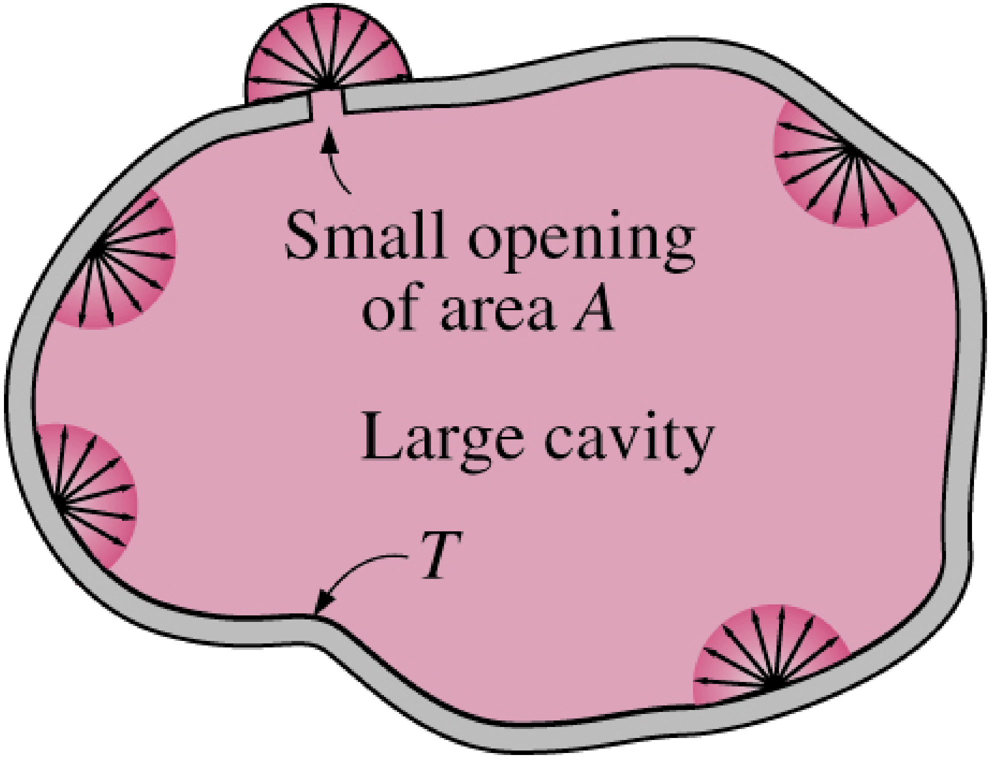
Similarly, in its emissive characteristics, the effect of the hole is that of a black body of the same area at a temperature equal to the temperature of the enclosure.



Principle of pyrometer

Achieving nearly perfect black body condition

Absorption or emission of radiation
through a small hole in a hollow container



Stefan-Boltzmann Law

The total emissive power (W, Btu/(h)(ft^2)) of a black body is proportional to the fourth power of the absolute temperature. The Stefan-Boltzmann law applies to the total radiant energy of all wavelengths emitted in all directions.

Black body

$$\boxed{W_B = \sigma T^4} \qquad (26\text{-}6)$$

real body

$$\boxed{W = \varepsilon \sigma T^4} \qquad (26\text{-}7)$$

σ : *Stefan-Boltzmann constant*

5.676 x 10^{-8} W/m^2K^4 or 0.1714 x 10^{-8} Btu/(h)(ft^2)(R^4)

Planck's Law

An expression for the monochromatic emissive power of black body $W_{B\lambda}$ as a function of wavelength was derived from quantum theory by Planck in 1900.

$$W_{B\lambda} = \frac{C_1 \lambda^{-5}}{e^{C_2/\lambda T} - 1} \qquad (26\text{-}8)$$

$W_{B\lambda}$: energy / (area)(time)(unit increment of wavelength)

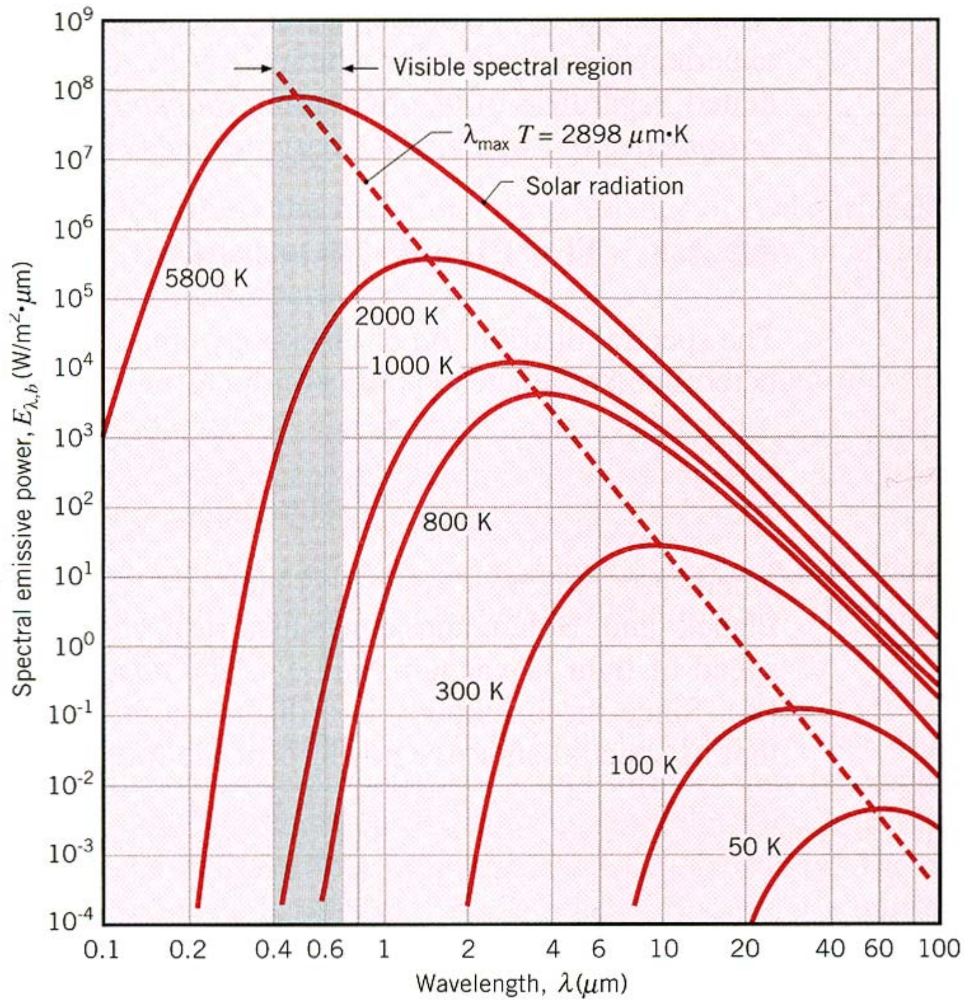
$W_{B\lambda}$: erg/(s)(cm^3) when C_1=3.74 x 10^{-5} erg cm^2/s, and C_2=2.59 cmR

C_1= 3.74 x 10^8 W·μm^4, and C_2= 1.44 x 10^4 μm·K

Monochromatic : 단일 파장의

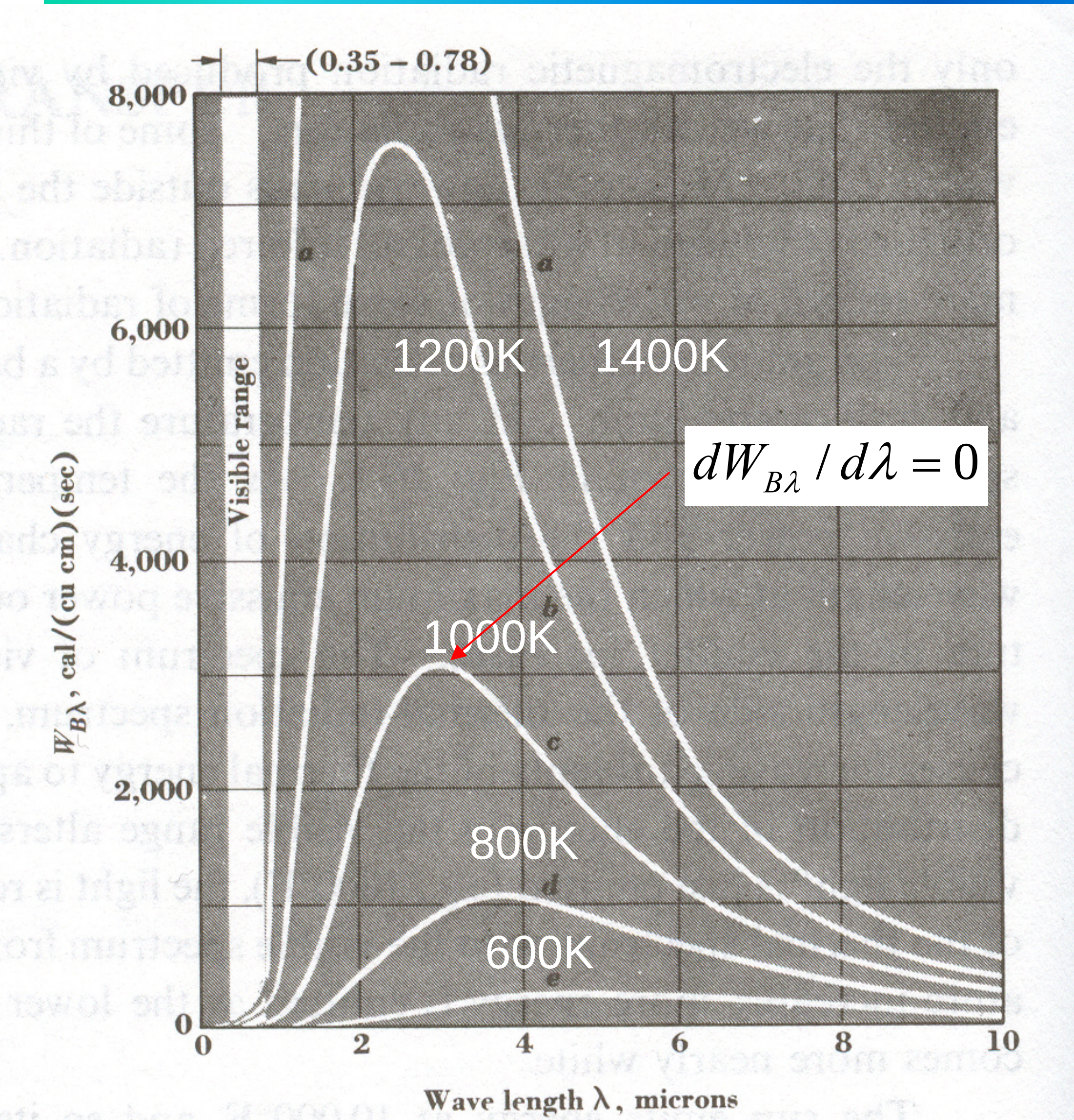
Special distribution of total energy emitted by black body

The amount of thermal radiation emitted by a body depends on its temperature and surface condition. At any temperature, the radiation emitted extends over a emissive power and the distribution of energy change.



Blackbody spectral emissive power

Special distribution of total energy emitted by black body



1. 모든 파장에서 온도가 증가하면 방사도는 증가한다.
2. 각 곡선은 하나의 최대 점을 보인다.
3. 온도가 증가함에 따라 최대 점은 단파장 쪽으로 이동한다.

Comparison of blackbody and real surface emission

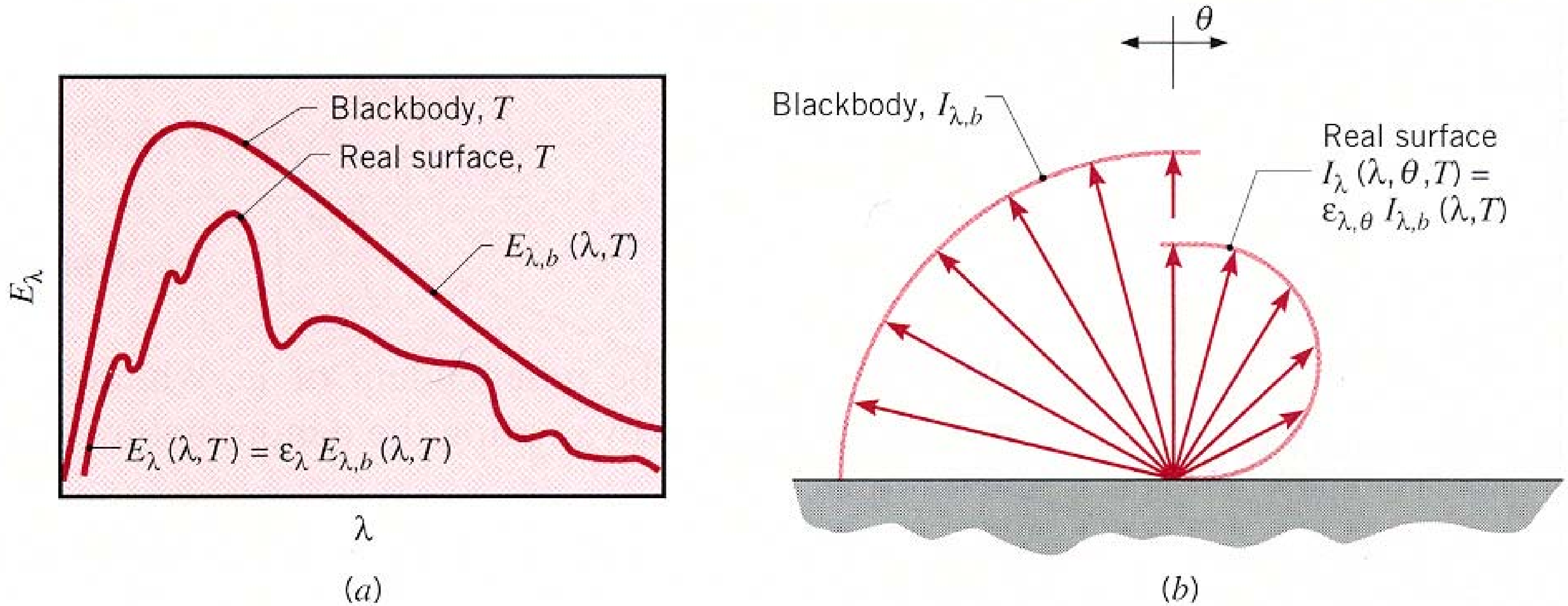
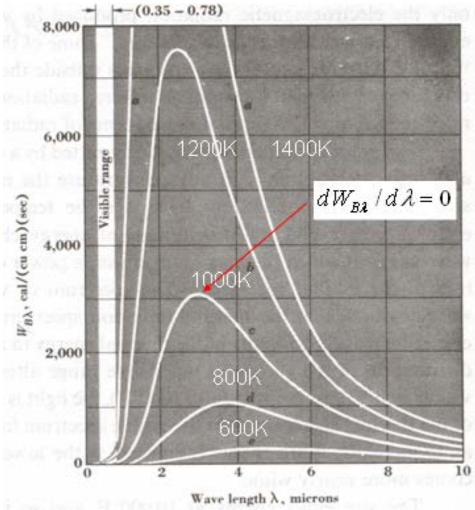


FIGURE 12.16 Comparison of blackbody and real surface emission. (*a*) Spectral distribution. (*b*) Directional distribution.

Wien's Displacement Law

Planck's Law

$$W_{B\lambda} = \frac{C_1 \lambda^{-5}}{e^{C_2/\lambda T} - 1} \qquad (26\text{-}8)$$



$$dW_{B\lambda}/d\lambda = 0$$

$$5\lambda T(1 - e^{-C_2/\lambda T}) = C_2$$

unit: cm·R

$$\lambda_{\max} = \frac{0.5216}{T} \qquad (26\text{-}8)$$

A decreasing wavelength at peak emissive power for increasing temperature.

The surface temperature of sun

$$\lambda_{max} = \frac{0.5216}{T}$$ (T=R, λ=cm)

높은 온도를 측정하는데 사용

$$\lambda_{max} = \frac{2898}{T}$$ (T=K, λ=μm)

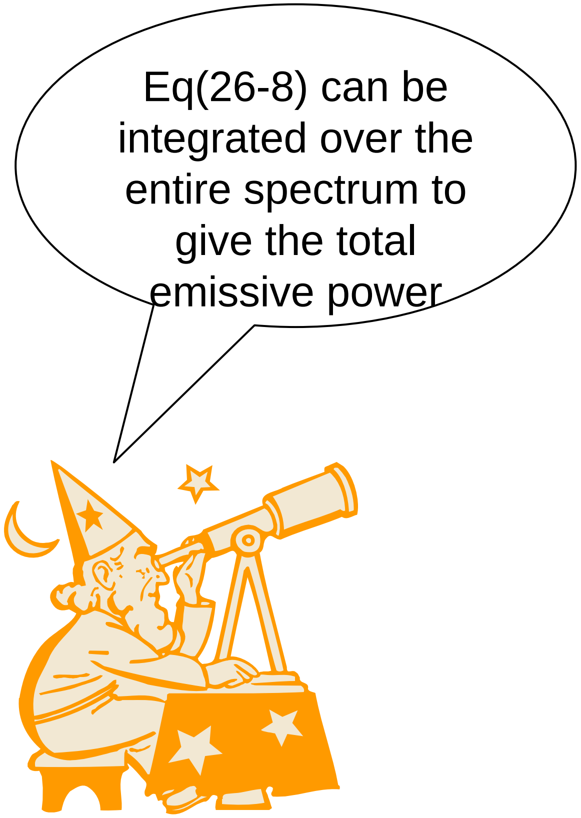
The radiation from the sun has a maximum intensity at a wavelength of approximately 5 x 10 $^{-5}$ cm

$$T = \frac{0.5216}{\lambda_{max}} = \frac{0.5216}{5 \times 10^{-5}} = 10{,}400 \text{ R}$$

$$= 5800\text{K}$$

Stefan-Boltzmann Constant

Monochromatic emissive power $$W_{B\lambda} = \frac{C_1 \lambda^{-5}}{e^{C_2/\lambda T} - 1} \qquad W_B = \sigma T^4$$ (26-8) (26-6)



$$\sigma = \frac{1}{T^4}\int_0^\infty W_{B\lambda}\, d\lambda \qquad (26\text{-}11)$$

$$= \frac{C_1}{T^4}\int_0^\infty \frac{\lambda^{-5}}{e^{C_2/\lambda T} - 1}\, d\lambda$$

$$= \frac{C_1}{C_2^4}\int_0^\infty \frac{(C_2/\lambda T)^5}{e^{C_2/\lambda T} - 1}\, d\,\frac{\lambda T}{C_2}$$

$$= \frac{C_1}{C_2^4}\int_0^\infty \frac{(C_2/\lambda T)^3}{e^{C_2/\lambda T} - 1}\, d\,\frac{C_2}{\lambda T} \qquad (26\text{-}12)$$

$$= \frac{C_1}{15}\left(\frac{\pi}{C_2}\right)^4$$

This value is about 1.5% smaller than the best experimental measurements.

$$= 0.1714 \times 10^{-8}\ \mathrm{Btu/(h)(ft^2)(R^4)}$$

$$\sigma = 5.670 \times 10^{-8}\ W/(\mathrm{m}^2)(K^4)$$

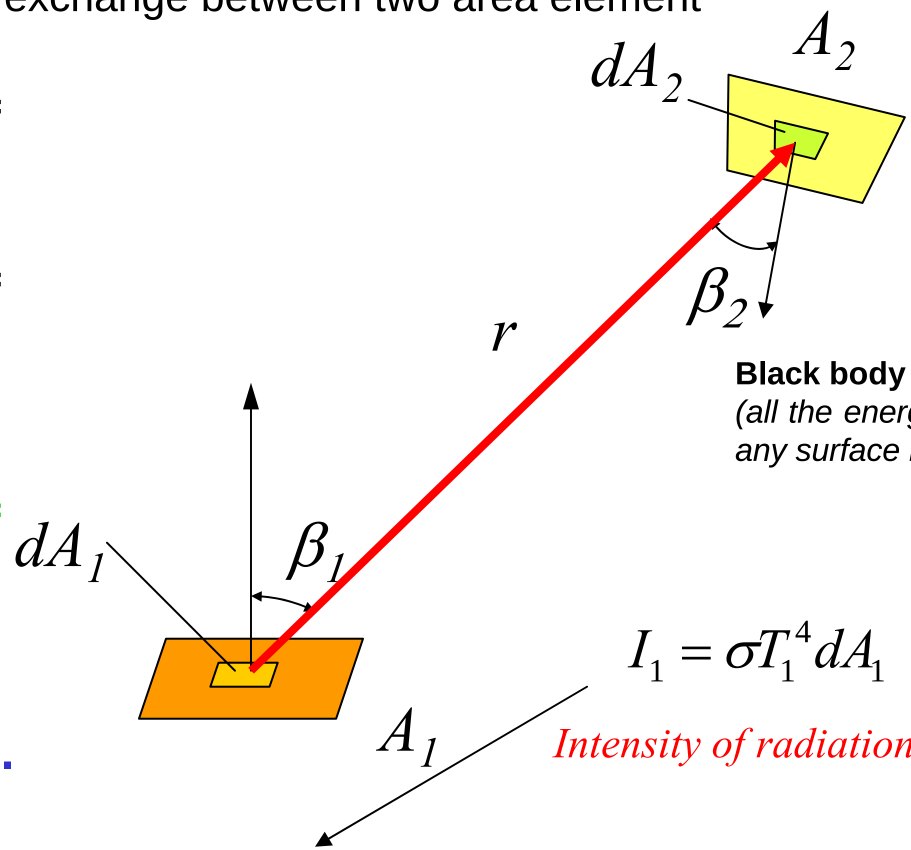
Radiant Heat Exchange between Black Surfaces

Radiant heat exchange between two area element

The rate of transfer of radiant heat from 1 to 2, depends on the spatial arrangement of the two surfaces, is proportional to the product of

(1) the apparent areas of the elements and

(2) inversely proportional to the square of the distance between them.



Black body
(all the energy incident upon any surface is absorbed)

$$I_1 = \sigma T_1^4 dA_1$$

Intensity of radiation from surface 1

The rate of transfer of radiant heat from 1 to 2

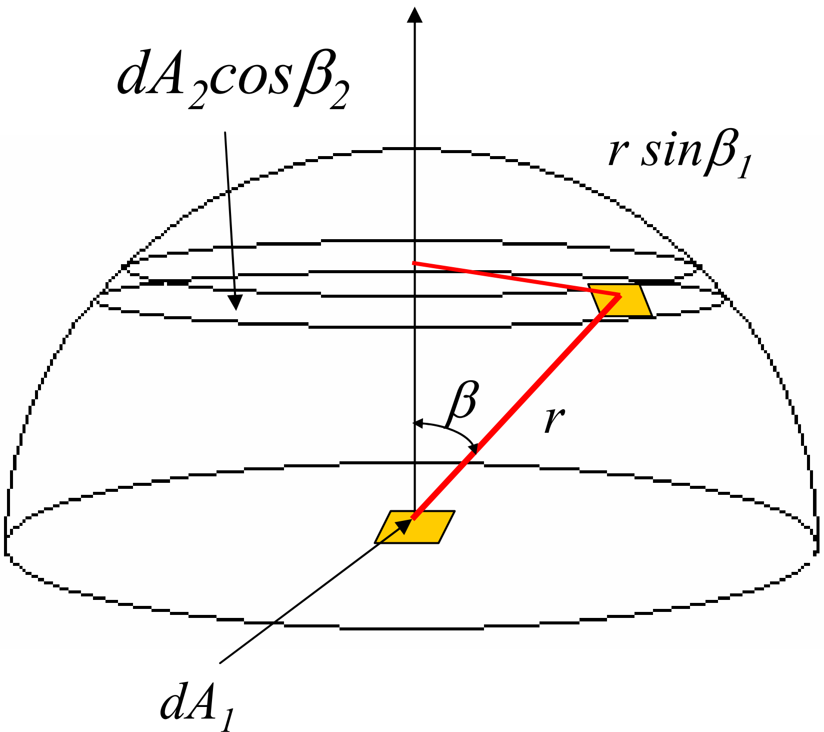
$$dq_{1\to 2} = \frac{I_1 dA_1 \cos\beta_1 dA_2 \cos\beta_2}{r^2} \qquad (26\text{-}13)$$

$$\frac{dA_2 \cos\beta_2}{r^2} = d\omega = differential\ solid\ angle$$

Radiant Heat Exchange between Black Surfaces

$$dq_{1\to 2} = I_1 dA_1 \cos\beta_1 \frac{dA_2 \cos\beta_2}{r^2}$$

$$= I_1 dA_1 \cos\beta_1 \underline{d\omega}$$



$$solid\ angle,\ \omega \equiv \frac{A}{r^2}$$

$$d\omega = \frac{dA}{r^2} = \frac{\cos\beta_2 dA_2}{r^2}$$

$$dq_{1\to 2} = I_1 dA_1 \int_0^{2\pi} \cos\beta_1 d\omega = \pi I_1 dA_1$$

Hemispherical model for determining intensity of radiation

$$dA_2 \cdot \cos\beta_2 = \int_0^{2\pi} (r d\beta_1)(r\sin\beta_1) d\phi = 2\pi r^2 \sin\beta_1 d\beta_1$$

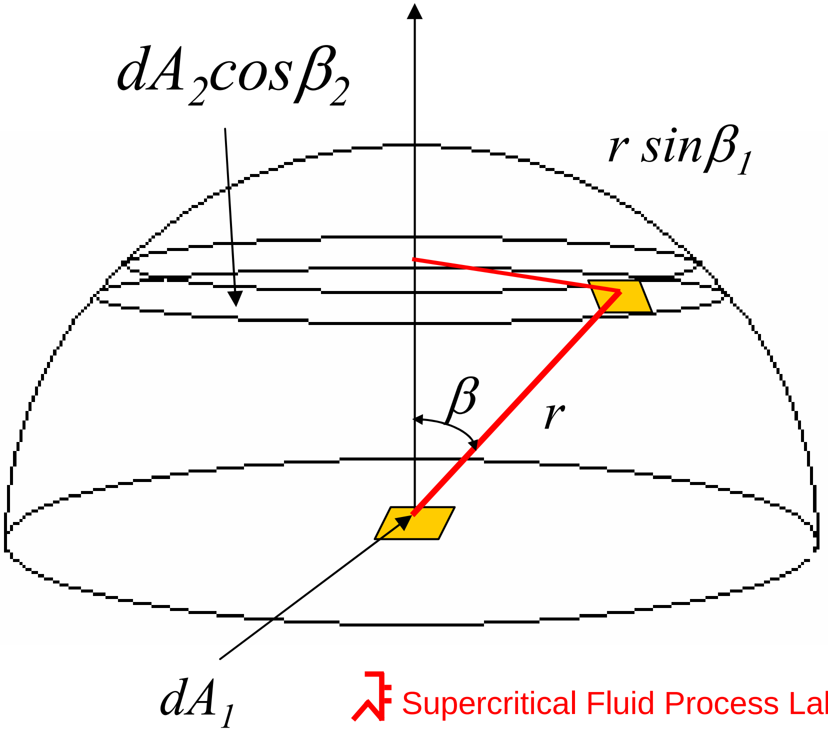
$$dq_{1\to 2} = I_1 dA_1 \int_0^{\pi/2} \cos\beta_1 \frac{2\pi r^2 \sin\beta_1}{r^2} d\beta_1$$

$$= 2\pi I_1 dA_1 \int_0^{\pi/2} \frac{1}{2}(\sin 2\beta_1 - \sin\theta) d\beta_1$$

$$= \pi I_1 dA_1 \left(-\frac{1}{2}\cos 2\beta_1 \right)\Bigg|_0^{\pi/2}$$

$$= \pi I_1 dA_1$$

$$\frac{dq_{1\to 2}}{dA_1} = \pi I_1 = \sigma T_1^4 \qquad \therefore \boxed{I_1 = \frac{\sigma T_1^4}{\pi}}$$



Radiant Heat Exchange between Black Surfaces

$$dq_{1\to 2} = I_1 dA_1 \cos\beta_1 \frac{dA_2 \cos\beta_2}{r^2} \tag{26-13}$$

$$\boxed{I_1 = \frac{\sigma T_1^4}{\pi}}$$

$$= \frac{\sigma T_1^4 dA_1 \cos\beta_1 dA_2 \cos\beta_2}{\pi r^2} \tag{26-14}$$

$$dq_{2\to 1} = \frac{\sigma T_2^4 dA_1 \cos\beta_1 dA_2 \cos\beta_2}{\pi r^2} \tag{26-15}$$

Net flow of heat

$$dq_{12} = dq_{1\to 2} - dq_{2\to 1} = \frac{\sigma dA_1 \cos\beta_1 dA_2 \cos\beta_2}{\pi r^2}\left(T_1^4 - T_2^4\right)$$

(26-16)

Radiant Heat Exchange between Black Surfaces

$$q_{12} = \sigma\left(T_1^4 - T_2^4\right)\int_{A_2}\int_{A_1}\frac{dA_1\cos\beta_1 dA_2\cos\beta_2}{\pi r^2}$$

$$= \sigma A_1 F_{12}\left(T_1^4 - T_2^4\right) \qquad (26\text{-}20)$$

where $$\boxed{F_{12} = \frac{1}{A_1}\int_{A_2}\int_{A_1}\frac{dA_1\cos\beta_1 dA_2\cos\beta_2}{\pi r^2}} \qquad (26\text{-}21)$$

$$q_{21} = \sigma\left(T_2^4 - T_1^4\right)\int_{A_2}\int_{A_1}\frac{dA_1\cos\beta_1 dA_2\cos\beta_2}{\pi r^2}$$

$$= \sigma A_2 F_{21}\left(T_2^4 - T_1^4\right) \qquad (26\text{-}19)$$

where $$\boxed{F_{21} = \frac{1}{A_2}\int_{A_2}\int_{A_1}\frac{dA_1\cos\beta_1 dA_2\cos\beta_2}{\pi r^2}}$$

View Factors

$$q_{1\to 2} = \sigma A_1 F_{12} T_1^4 \qquad (26\text{-}17)$$

$$q_{2\to 1} = \sigma A_2 F_{21} T_2^4 \qquad (26\text{-}18)$$

$\boldsymbol{F_{12} = F_{21}}$ = **view factor**

$\boldsymbol{F_{12}}$ = the fraction of the total radiation leaving surface 1 which strikes 2

$\boldsymbol{F_{21}}$ = the fractional impingement of radiation from 2 on 1

If $T_1=T_2$, then $q_{1\to 2}=q_{2\to 1}$

$$\boldsymbol{A_1F_{12}=A_2F_{21}}$$

Back body에서 유도 되었지만
non-black body에서도 적용 가능함.

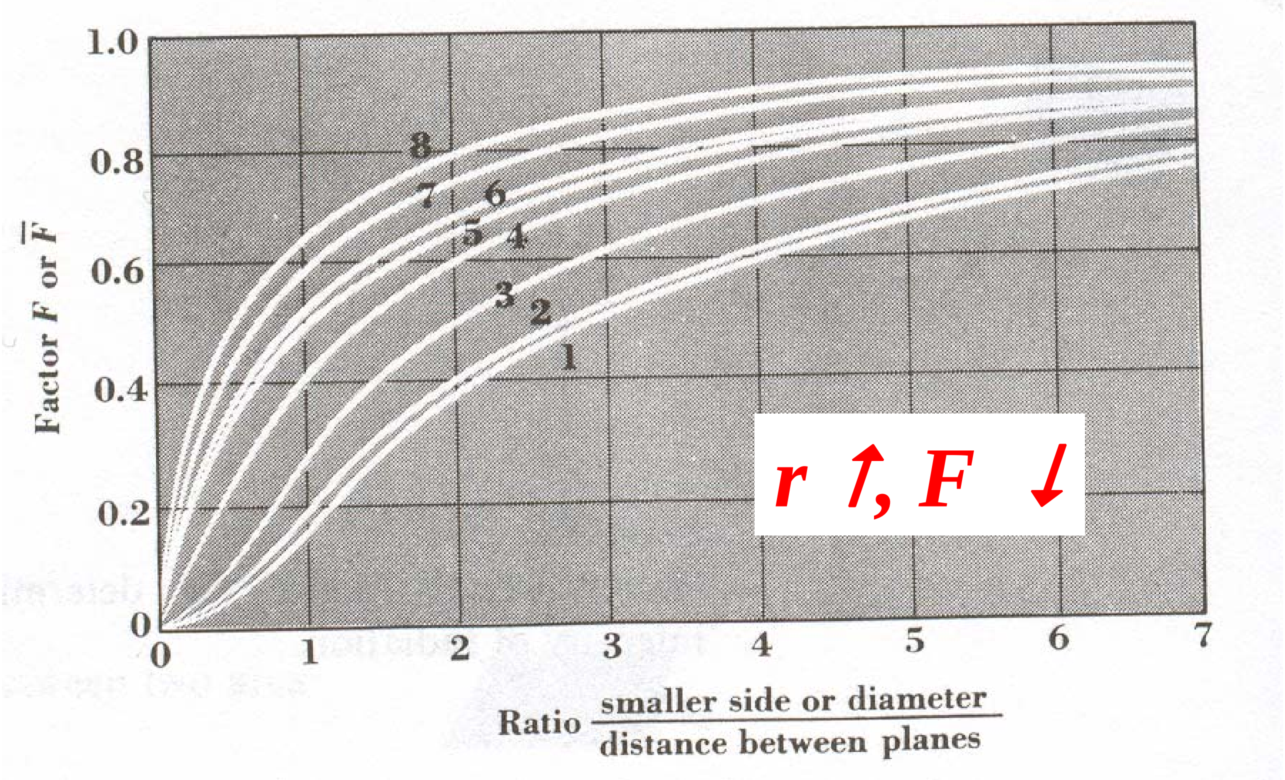
Evaluation of the view factor

$$F_{12} = \frac{1}{A_1} \int_{A_2} \int_{A_1} \frac{dA_1 \cos\beta_1 dA_2 \cos\beta_2}{\pi r^2} \qquad (26\text{-}21)$$

Value of the view factor have been calculated for a number of spatial arrangements shown in Fig. 26-6. Other values are given in Perry, sec 10. The method of determining these factors is illustrated in Example 26-2.

View factor F and interchange factor $\bar{F}$ for opposed parallel disks, squares, and rectangles

Fig. 26-6



1,2,3,4 Direct radiation between the planes, ***F***

5,6,7,8 Planes connected by nonconducting but reradiating walls $\bar{F}$

1 and 5 Disks

3 and 7 2:1 rectangle

2 and 6 Squares

4 and 8 Long, narrow rectangles

View Factors

1. Reciprocal relation, $A_1F_{12}=A_2F_{21}$, is always valid.

2. The view factor is independent of temperature.

(It is purely geometric.)

3. For an enclosure, $F_{11}+F_{12}+F_{13}+\ldots\ F_{1i}=1$

4. If surface 1 cannot "see" itself, $F_{11}=0$

Example 26-2 : view factor between disks, F_{12}=? ($A_2>>A_1$)

Determine the view factor for radiant-heat transfer between a small disk of area A_1 and a parallel large disk of area A_2. The disks are assumed to be directly opposed; i.e., a line joining their centers is normal to both disks. The large disk has a radius a, and the distance between centers is r_0. The system is shown in Fig. 26-7.

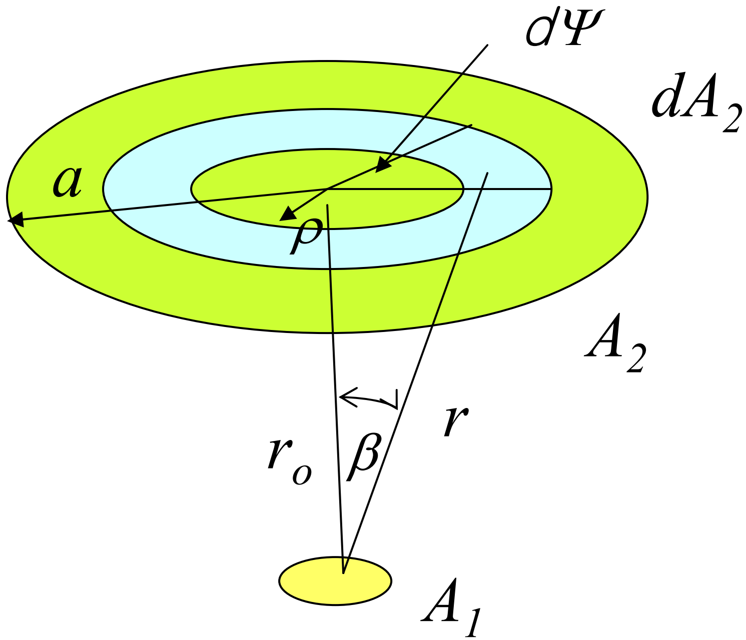


Figure 26-7
Parallel disks

Example 26-2 : view factor between disks, F_{12}=? $(A_2>>A_1)$

$$F_{12} = \frac{1}{A_1}\int_{A_2}\int_{A_1}\frac{dA_1\cos\beta_1 dA_2\cos\beta_2}{dr} \qquad \textbf{(26-21)}$$

$$\beta_1 = \beta_2 = \beta, \quad \int_{A_1} dA_1 = A_1$$

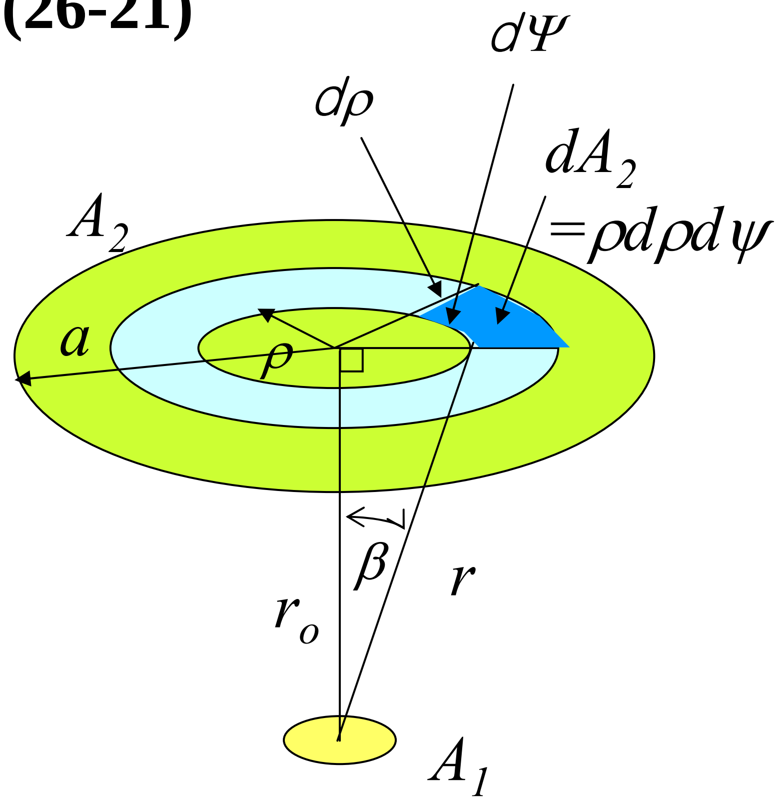
$$F_{12} = \int_{A_2}\frac{\cos^2\beta dA_2}{\pi r^2}$$

$$dA_2 = \rho d\psi d\rho, \quad \cos\beta = r_o / r$$

$$F_{12} = \int_0^a\int_0^{2\pi}\frac{r_0^2}{\pi r^4}\rho d\psi d\rho = \int_0^a \frac{2r_0^2}{r^4}\rho d\rho$$

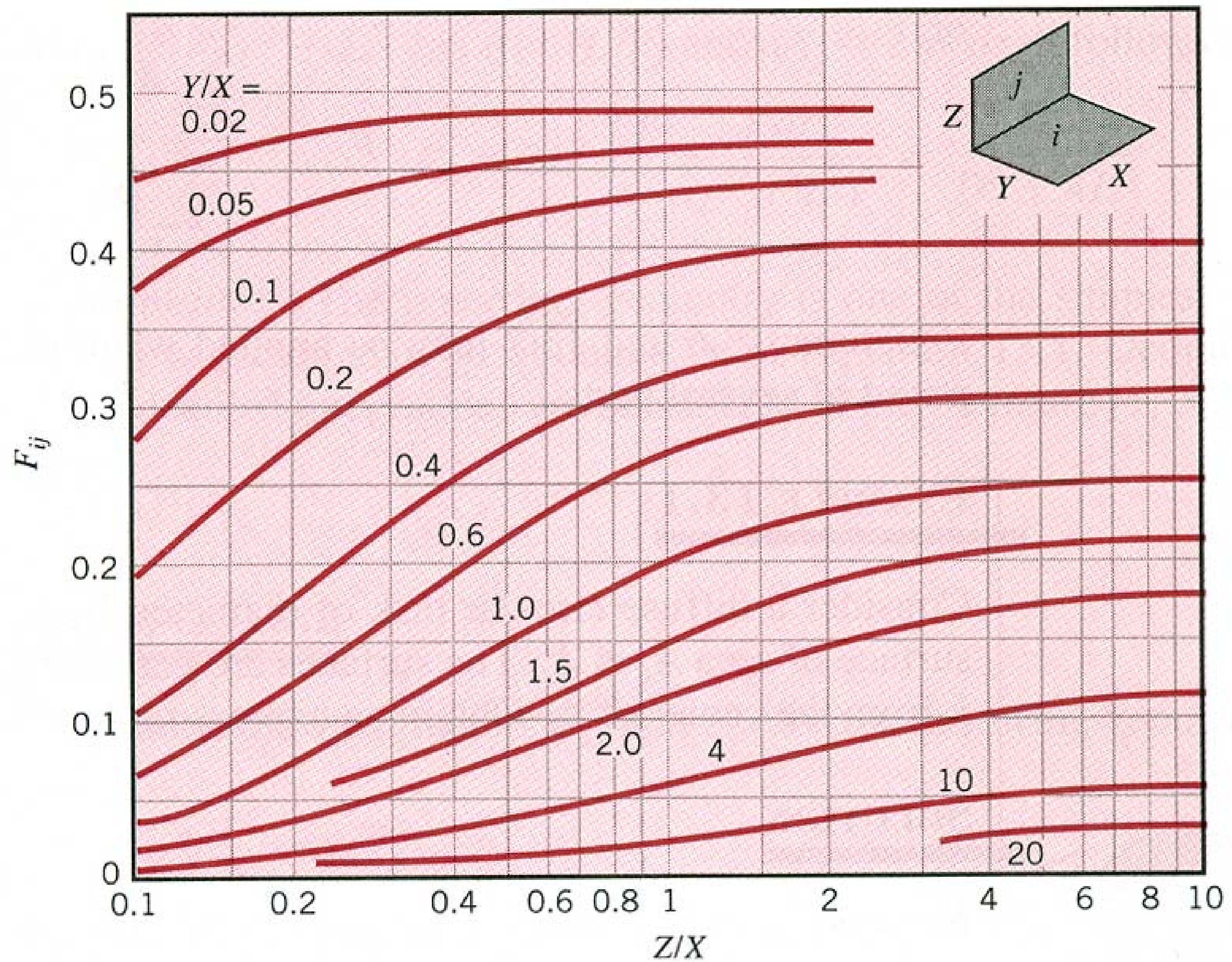
$$r^2 = \rho^2 + r_0^2$$

$$F_{12} = \int_0^a \frac{2r_0^2}{(\rho^2+r_0^2)^2}\rho d\rho = \int_0^a \frac{r_0^2 d\rho^2}{(\rho^2+r_0^2)^2} = \frac{a^2}{a^2+r_0^2}$$

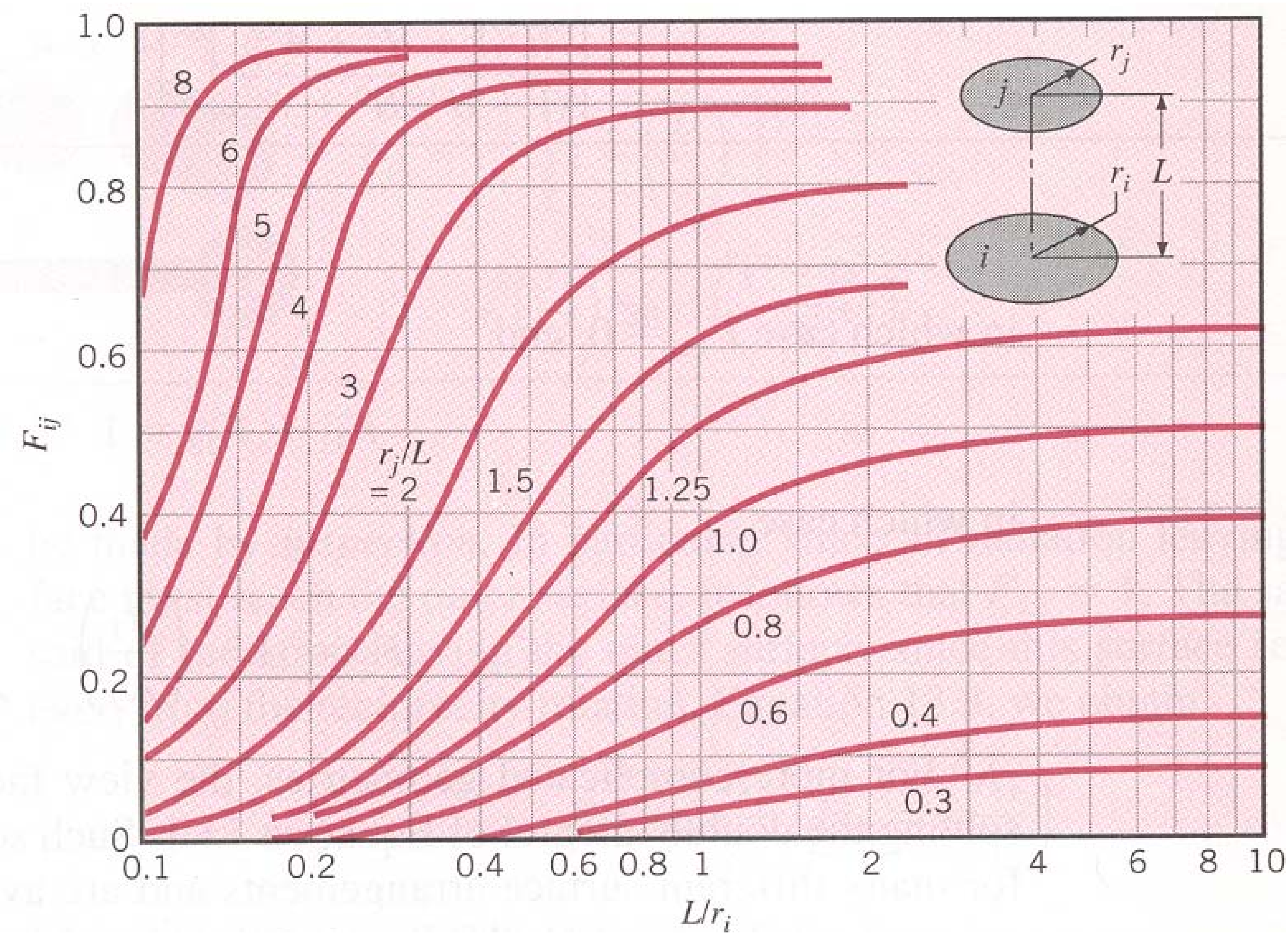


$$\boxed{F_{12} = \frac{a^2}{a^2+r_0^2}}$$

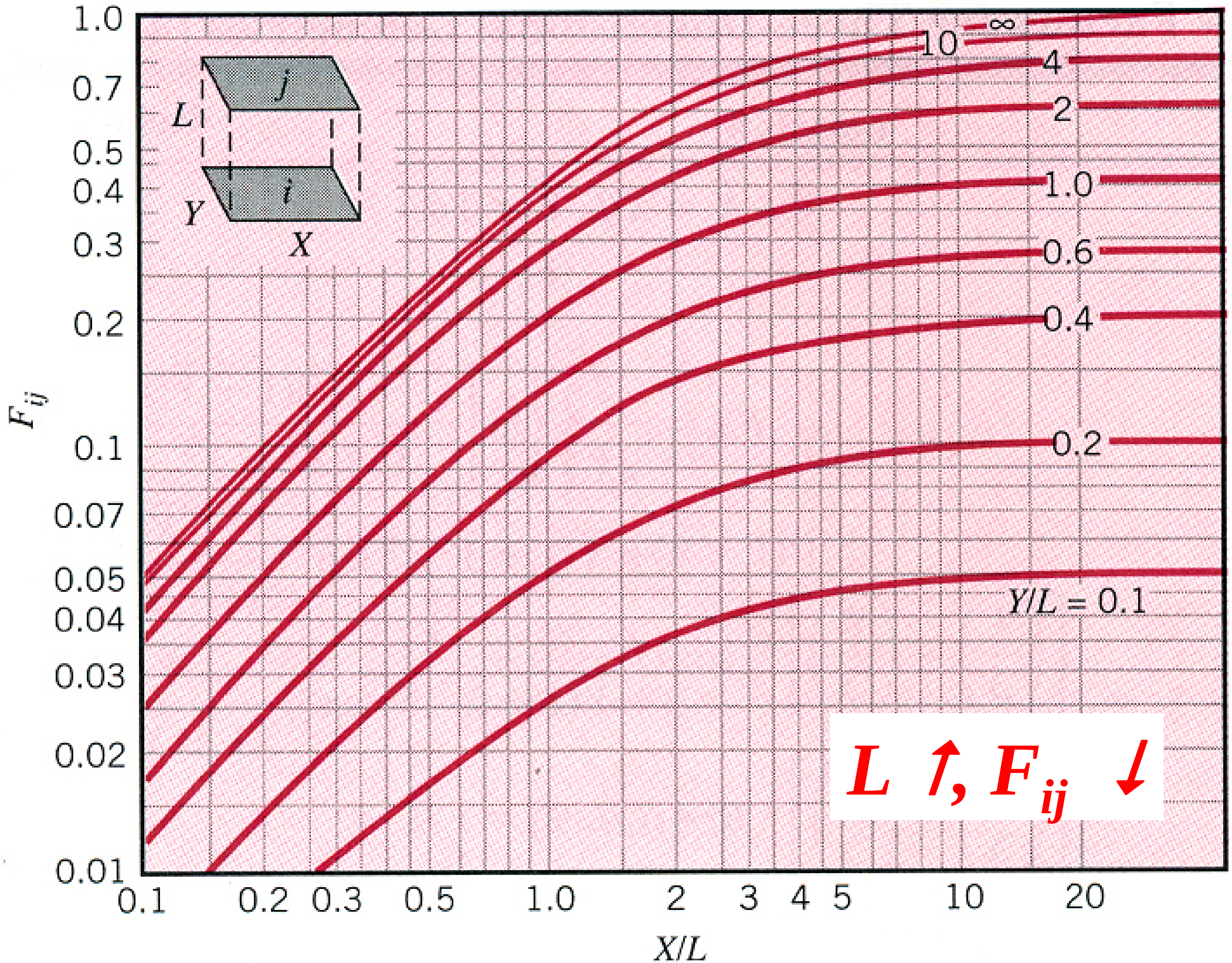
View Factor for perpendicular rectangles with common edge



View Factor for coaxial parallel disks



View Factor for aligned parallel rectangles



Multiple surface

$$\cancelto{0}{F_{11}} + F_{12} + F_{13} + \cdots\cdots + F_{1n} = \sum_{i=1}^{n} F_{1i} = 1 \qquad (26\text{-}22)$$

If the surface are all black, the net heat flow between surface 1 and all other surfaces is

$$q_{1,net} = \sigma A_1 F_{12} T_1^4 - \sigma A_2 F_{21} T_2^4 + \sigma A_1 F_{13} T_1^4 - \sigma A_3 F_{31} T_3^4 + \cdots \quad (26\text{-}23)$$

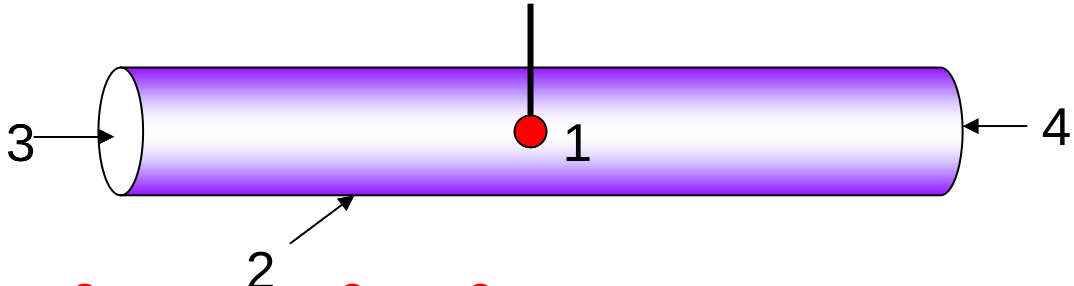
The terms containing sA1T14 can be collected and expressed as a single term using the summation expressed in Eq. (26-22)

$$q_{1,net} = \sigma A_1 T_1^4 - \sigma\left(A_2 F_{21} T_2^4 + A_3 F_{31} T_3^4 + \cdots + A_i F_{i1} T_i^4\right) \qquad (26\text{-}24)$$

Multiple surface: long cylinder

$$\cancelto{0}{F_{11}} + F_{12} + F_{13} + \cdots\cdots + F_{1n} = \sum_{i=1}^{n} F_{1i} = 1 \qquad (26\text{-}22)$$

If surface 1 cannot "see" itself, $F_{11}=0$.



$$\cancelto{0}{F_{11}} + F_{12} + \cancelto{0}{F_{13}} + \cancelto{0}{F_{14}} = 1 \qquad \therefore \quad F_{12} = 1$$

Long cylinder

$$F_{21} + F_{22} + F_{23} + F_{24} = 1$$

1에서 떠난 것은 100%로 2로 가고, 2에서 떠난 것은 A1/A2의 비율로 1에 도달한다.

1는 1를 볼 수 없다.

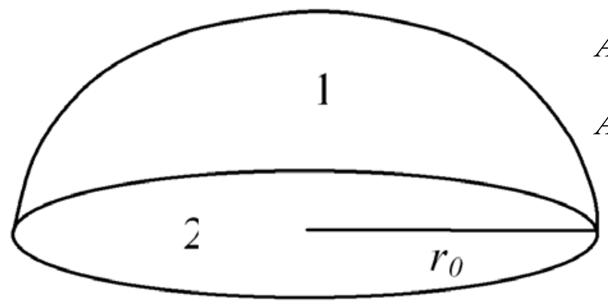
$$A_1F_{12} = A_2F_{21} \qquad \therefore F_{21} = A_1 / A_2$$

$$q_{21} = \sigma(T_2^4 - T_1^4)A_1\cancelto{1}{F_{12}}$$

Multiple surface: hemisphere

$$F_{11} + F_{12} = 1$$

$$F_{21} + \cancelto{0}{F_{22}} = 1 \quad \rightarrow \quad F_{21} = 1$$



$$A_1 = \frac{4\pi r_0^2}{2} = 2\pi r_0^2$$

$$A_2 = \pi r_0^2$$

$$A_1 F_{12} = A_2 F_{21}$$

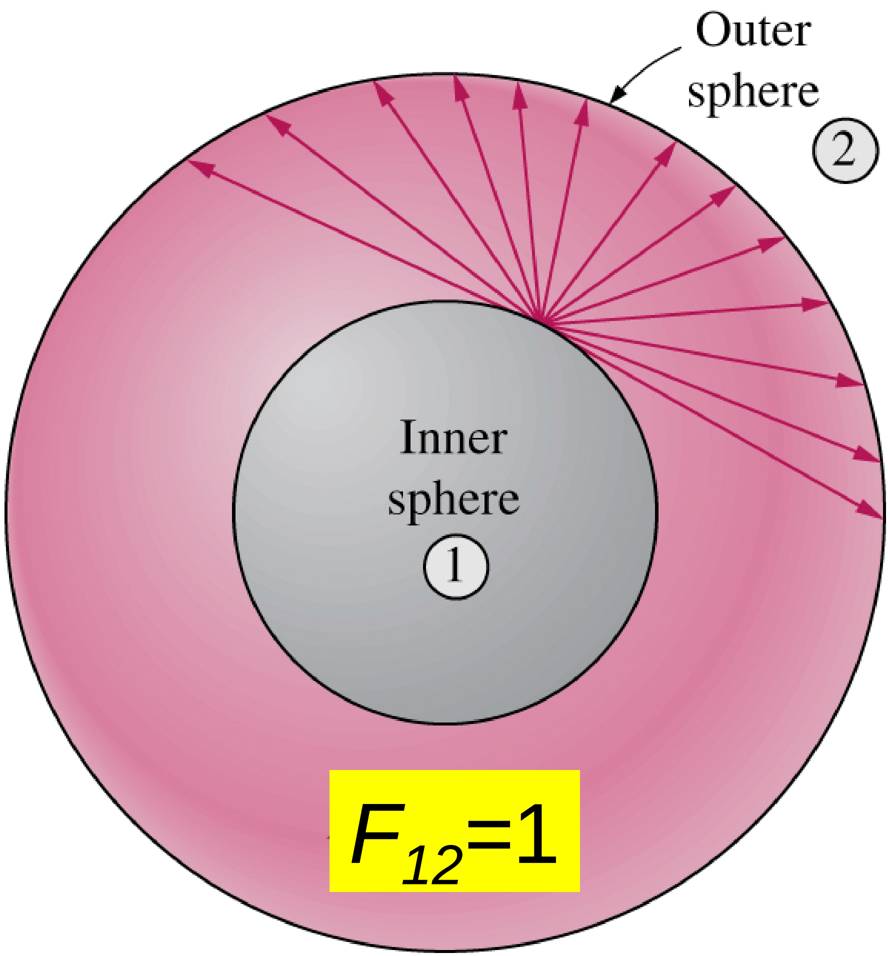
If surface 2 cannot "see" itself, F_{22}=0.

$$2\pi r_0^2 F_{12} = \pi r_0^2 \cancelto{1}{F_{21}} = \pi r_0^2 \qquad \therefore \quad F_{12} = \frac{1}{2}, \quad F_{11} = \frac{1}{2}$$

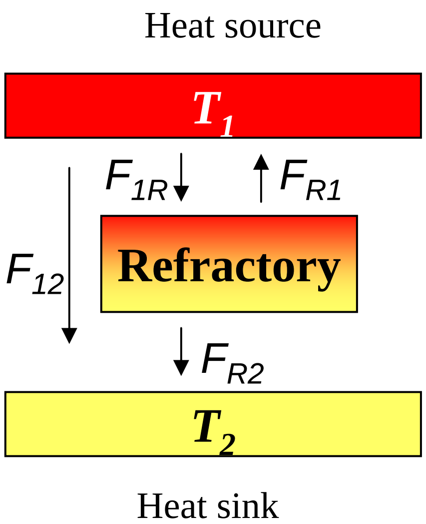
$$F_{11} = \frac{1}{2}, \quad F_{12} = \frac{1}{2}, \quad F_{21} = 1, \quad F_{22} = 0$$

- 2를 떠난 것은 100%로 1로 가고, 1을 떠난 것은 50%는 1로 50%는 2로 도달한다.
- 2는 2를 볼 수 없다.

Multiple surface: hemisphere



Refractory surfaces



$\overline{F}_{12}$: the interchange factor Can be found in Fig. 26-6

(radiation heat flux F_{12} + absorption + reradiation)

$$\overline{F}_{12} = F_{12} + F_{1R} \times \frac{F_{R2}}{F_{R1} + F_{R2}} \qquad (26\text{-}25)$$

If both sides of Eq. (26-25) are multiplied by A_1

$$A_1 F_{1R} = A_R F_{R1}$$

$$A_R F_{R2} = A_2 F_{2R}$$

$$A_1 \overline{F}_{12} = A_1 F_{12} + \frac{1}{1/A_2 F_{2R} + 1/A_1 F_{1R}} \qquad (26\text{-}26)$$

Net radiant exchange: (26-27, 26-28)

$$A_1 \overline{F}_{12} = A_2 \overline{F}_{21}$$

$$q_{12} = \sigma A_1 \overline{F}_{12} T_1^4 - \sigma A_2 \overline{F}_{21} T_2^4 = \sigma A_1 \overline{F}_{12} (T_1^4 - T_2^4)$$

Gray Surfaces (~real surface)

- If the surfaces from which there is a net heat flux are not black bodies, the emissive power of each of the surfaces is determined by using the Stefan-Boltzmann equation multiplied by the emissivity (ε).

- The absorption of energy on each surface is not complete, but equals the amount of energy incident on the surface multiplied by the absorptivity.

- These two factors make an accurate analysis of radiant transfer between real surfaces much more complicated than between black body.

- Absorptivity is independent of the wavelength of incident radiation, and thus of the temperature and other characteristics of the emitter.

- In effect, the emissivity and absorptivity of a surface are assumed to be the same. ($\alpha_1=\varepsilon_1$)

Gray Surfaces (~real surface)

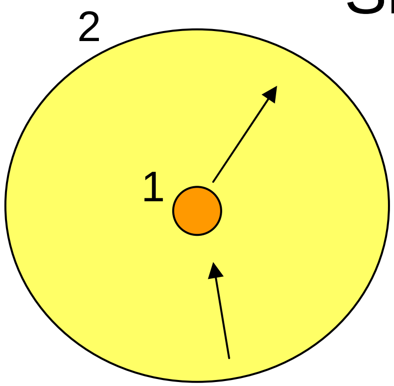
H.C. Hottel and A.F. Sarofim, “Radiation Transfer”, McGraw-Hill, New York, 1967

For the case of two surfaces 1 and 2, between which there is net heat flux, connected by any number of refractory reradiating zones, the net flux can be represented by

$$q_{12} = \sigma A_1 \mathbf{F_{12}} \left(T_1^{\ 4} - T_2^{\ 4} \right) \qquad (26\text{-}29)$$

$$\boxed{\mathbf{F_{12}} = \frac{1}{\left(1/\bar{F}_{12}\right) + \left[(1/\varepsilon_1) - 1\right] + \left(A_1/A_2\right)\left[(1/\varepsilon_2) - 1\right]}} \qquad (26\text{-}30)$$

Gray Surfaces (~real surface)



Small body 1 in a large enclosure 2
(a pipe in a room)

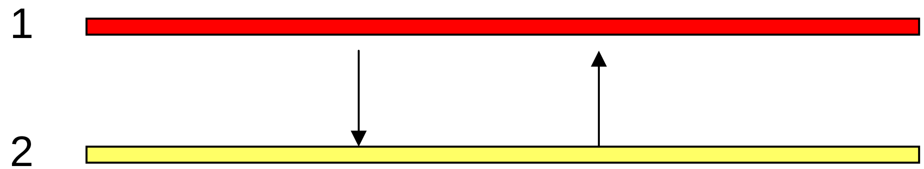
$$q_{12} = \sigma A_1 \mathbf{F}_{12} \left(T_1^{\,4} - T_2^{\,4}\right)$$

$$\mathbf{F}_{12} = \frac{1}{\left(1/\underbrace{\bar{F}_{12}}_{1}\right) + \left[(1/\varepsilon_1) - 1\right] + \left(\underbrace{A_1/A_2}_{0}\right)\left[(1/\varepsilon_2) - 1\right]} \qquad \text{(26-30)}$$

$$\boxed{\mathbf{F}_{12} = \varepsilon_1} \quad \Rightarrow \quad q_{12} = \sigma A_1 \varepsilon_1 \left(T_1^{\,4} - T_2^{\,4}\right)$$

Gray Surfaces (~real surface)

Radiation energy is exchanged between two parallel planes



$$\mathbf{F}_{12} = \frac{1}{\left(1/\underbrace{\bar{F}_{12}}_{1}\right)+\left[\left(1/\varepsilon_1\right)-1\right]+\left(\underbrace{A_1/A_2}_{1}\right)\left[\left(1/\varepsilon_2\right)-1\right]} \qquad (26\text{-}30)$$

$$\boxed{\mathbf{F}_{12} = \frac{1}{1/\varepsilon_1 + 1/\varepsilon_2 - 1}}$$

$$q_{12} = \sigma A_1 \mathbf{F}_{12} \left(T_1^{\,4} - T_2^{\,4}\right)$$

The Radiation Heat-Transfer Coefficient

w/o vacuum, radiation is accompanied by convection. In dealing with both mechanisms simultaneously, it is convenient to define a heat-transfer coefficient for radiation in the manner of a convective coefficient.

$$q = h_r A(t_{s1} - t_{s2}) = h_r A(T_1 - T_2)$$ ← Absolute temp

$$\text{if black surfaces, view factor} = 1,$$

$$q = \sigma A(T_1^4 - T_2^4)$$

h_r is strong function of temperature.

$$h_r = \sigma \frac{T_1^4 - T_2^4}{T_1 - T_2} \quad (26\text{-}34)$$

$$h_r = \sigma(T_1^3 + T_1^2 T_2 + T_1 T_2^2 + T_2^3) \quad (26\text{-}35)$$

Radiation-heat-transfer coefficient

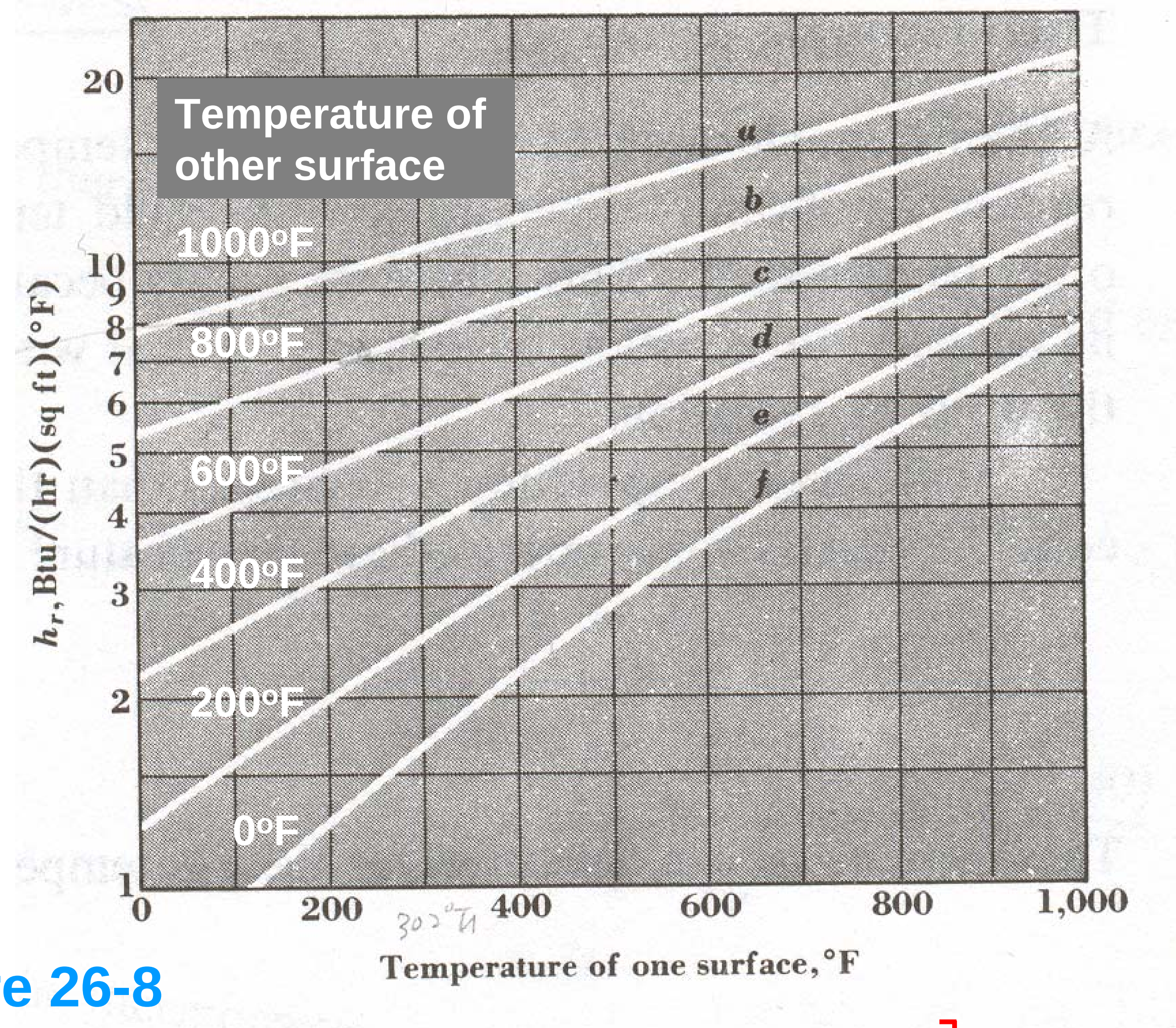
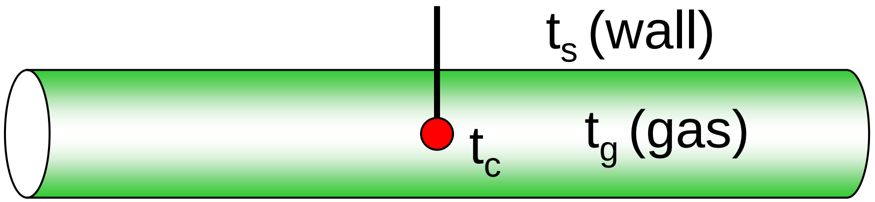


Figure 26-8

Thermocouple Error

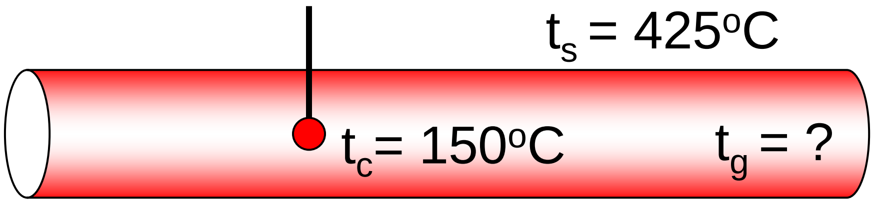


A thermocouple used to measure a fluid temperature in a container may give a reading significantly different from the fluid temperature if the walls are at some other temperature.

$$q = \underbrace{h_r A_c \mathcal{F}_{cs} (t_s - t_c)}_{\text{radiation}} = \underbrace{h A_c (t_c - t_g)}_{\text{convection}}$$

$$\boxed{t_g = t_c - \frac{h_r \mathcal{F}_{cs}}{h}(t_s - t_c)} \qquad (26\text{-}36)$$

Example 26-3:Thermocouple Error



h_r=43 W/m²K

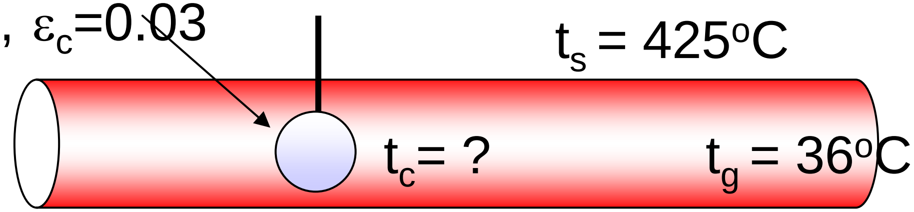
ε_c=0.96, h=100 W/m²K (Fig 26-8)

(a) Air temperature?

$$\mathcal{F}_{cs} = \frac{1}{\left(1/\underbrace{\bar{F}_{cs}}_{1}\right) + \left[(1/\varepsilon_c) - 1\right] + \left(\underbrace{A_c / A_s}_{0}\right)\left[(1/\varepsilon_s) - 1\right]} = \varepsilon_c = 0.96$$

$$t_g = t_c - \frac{h_r\, \mathcal{F}_{cs}}{h}(t_s - t_c) = 150 - \frac{(43)(0.96)}{100}(425 - 150) = 36^\circ C$$

Example 26-3:Thermocouple Error



ε_c=0.96, h=100 W/m²K

(b) If silver foil is wrapped, what will be the new thermometer reading?

Assume t_c=40°C; using Fig. 26-8, h_r=34 W/m²K

$$t_g = t_c - \frac{h_r\ F_{cs}}{h}(t_s - t_c) = t_c - \frac{(34)(0.03)}{100}(425 - t_c) = 36^\circ C$$

By trial and error

New thermometer reading= 40°C

Radiation from Gases

1. Gases which do not emit radiation do not absorb it.
2. Monatomic and diatomic gases emit scarcely any radiation.
3. Only with a dipole moment triatomic and higher polyatomic emit radiation (water vapor & carbon dioxide).

Radiation from Gases

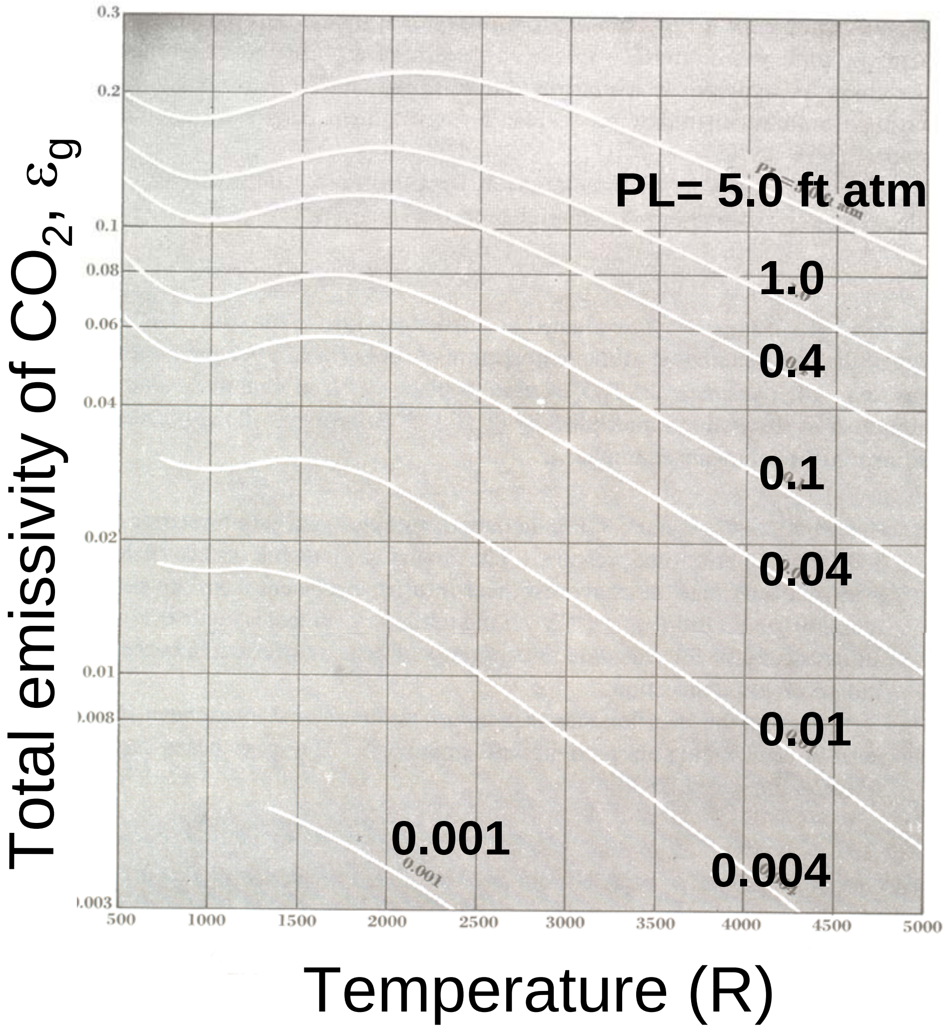
4. The gases which radiate energy also absorb it,
   but only within the same bands in which it is emitted.

   The vibrational or rotational motion of a molecule may have only certain values.

$$\nu = \Delta E / h$$

CO_2	:	$2.4 \sim 3.0 \mu m$	
		$4.0 \sim 4.8$	
		$12.5 \sim 16.5$	$IR\ region$
H_2O	:	$2.2 \sim 3.3$	
		$4.8 \sim 8.5$	
		$12 \sim 25$	

Total emissivity of carbon dioxide



P=the partial pressure of CO_2 in atmospheres

L=the beam length in feet

Table 26-3 EQUIVALENT BEAM LENGTHS FOR GAS RADIATION

Shape	*Equivalent beam length, L*
Sphere	0.60 × diameter
Cylinder of infinite length	0.90 × diameter
Space between infinite parallel planes	2.0 × distance between planes
Space outside an infinite bank of tubes	
with centers on equilateral triangles:	
tube diameter equals clearance	2.8 × clearance

* From H. C. Hottel, chap. 4 in W. H. McAdams, “Heat Transmission,” 3d ed., McGraw-Hill Book Company, New York, 1954. See also H. C. Hottel and A. F. Sarofim,”Radia-Tive Transfer,” chap. 7, McGraw-Hill Book Company, New York, 1967.

Net rate of radiant heat transfer

Radiant heat transfer between a gas and a black surface

$$q = \sigma A(\varepsilon_g T_g^4 - \alpha_g T_1^4)$$

Evaluated at the temperature of the gas

Evaluated at the temperature of the surface

Homework

26-3

26-5

26-12