HEAT TRANSFER

RADIATION

Radiation differs from the other two heat transfer mechanism in that it does not require the presence of a material medium to take place. Energy transfer through radiation is in fact fastest (speed of light) and it suffers no attenuation in a vacuum.

Radiation transfer occurs in solids as well as liquids and gases. In real situations, all three modes of heat transfer occur concurrently at varying degrees.

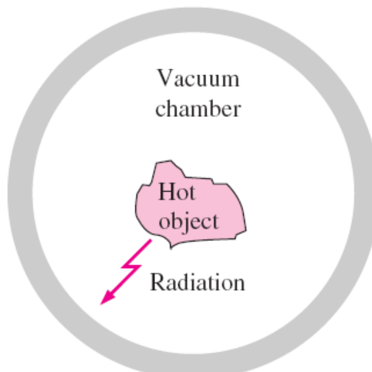


FIGURE 11–1
A hot object in a vacuum chamber loses heat by radiation only.

It is interesting to note that radiation heat transfer can occur between two bodies separated by a medium colder than both bodies.

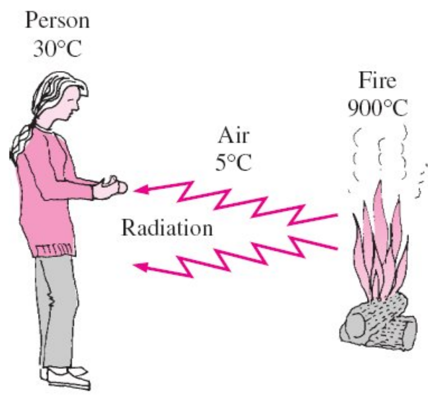


FIGURE 11–2
Unlike conduction and convection, heat transfer by radiation can occur between two bodies, even when they are separated by a medium colder than both of them.

Electromagnetic waves travel at the speed of light in a vacuum, which is $C_0 = 2.9979 \times 10^8$ m/s. They are characterized by their frequency and wavelength. These two properties are related by $\lambda = \dfrac{c}{\upsilon}$ where c is the speed of propagation of a wave in that medium.

Thermal Radiation

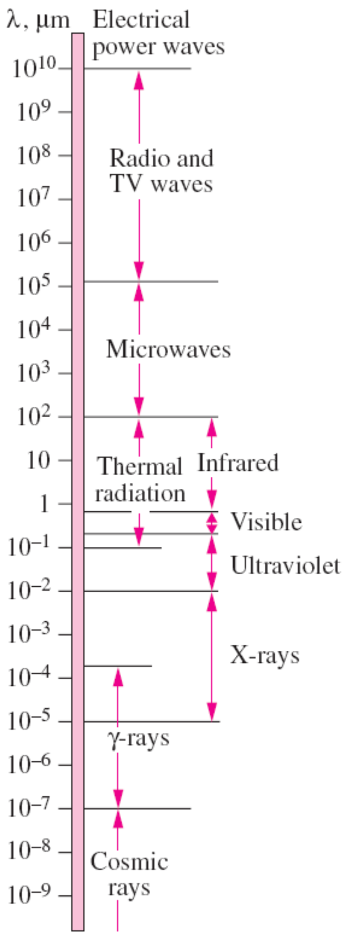


FIGURE 11–3

The electromagnetic spectrum covers a wide range of wavelengths, varying from 10 -10 m for cosmic rays to more that 1010 m for electrival power waves. See figure 11–3.

The type of electromagnetic radiation that is pertinent to heat transfer is the **thermal radiation**. Note how thermal radiation includes the entire visible and infrared radiation (IR) as well as a portion of the ultraviolet radiation (UV).

Blackbody Radiation

A body at a temperature above absolute zero emits radiation in all directions over a wide range of wavelengths. The amount of radiation energy emitted from a surface at a given wavelength depends on the:

1. material of the body
2. condition of its surface and,
3. the surface temperature

A blackbody is defined as a PERFECT EMITTER and PERFECT ABSORBER of radiation. At a specified temperature and wavelength, no surface can emit more energy than a blackbody.

The radiation energy emitted by a blackbody per unit time and per unit surface area is given by
Stefan – Boltzman law: $E_b = \sigma T_4$ (W/m^2)

Where = 5.67×10^{-8} W/m^2·K^4 (Stefan – Boltzman constant)

E_b is called the **blackbody emissive power**.

The Stefan – Boltzman law gives the total blackbody emissive power Eb, which is the sum of the radiation emitted over all wavelengths. Sometimes we need to know the spectral blackbody emissive power, which is the amount of radiation energy emitted by a blackbody at an absolute temperature *T* power unit time, per unit surface area, and per unit wavelength about the wave length λ

$$E_{b\lambda} = \frac{C_1}{\lambda^5\left[\exp\left(C_2/\lambda T\right)-1\right]} \qquad (\mathrm{W/m^2 \cdot \mu m})$$

This relation is called the Plank's law.

THE VIEW FACTOR

Radiation heat transfer depends on the orientation of the surfaces relative to each other as well as their radiation properties and temperatures.

To account for the effect of orientation on radiation heat transfer between two surfaces, we define a parameter called the **view factor**. It can also be referred to as shape factor, configuration factor, and angle factor.

The view factor from a surface *i* to a surface *j* is demoted by F_{ij} or just F_{ij} is defines as

F_{ij} = the fraction of the radiation leaving surface *i* that strikes surface *j* directly.

For the special case where $j = i$, we have
F_{ii} = the fraction of radiation leaving surface *i* that strikes itself directly.

The value factor ranges from *zero* to *one*. Where for the extreme case $F_{ij} = 0$, the two surfaces do not have a direct view of each other, and thus radiation leaving surface *i* cannot strike surface *j* directly. The other limiting case $F_{ij} = 1$, the surface *j* completely surrounds surface *i* so that the entire radiation leaving surface *i* is intercepted by surface *j*.

View factors for several geometries are given in Tables 12 – 1 and 12 – 2 in analytical form and in Figures 12 – 5 to 12 – 8 in graphical form.

1. The Reciprocity Relation

The **reciprocity relation** for view factors is given by

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

2. The Summation Rule

The sum of the view factors from a surface *i* of an enclosure to all surfaces of the enclosure, including itself, must equal unity. This is known as the summation rule and it is expressed as

$$\sum_{j=1}^{N} F_{ij} = 1$$

For example, applying the summation rule to surface 1 of a three surface enclosure gives

$$\sum_{j=1}^{3} F_{1j} = F_{11} + F_{12} + F_{13} = 1$$

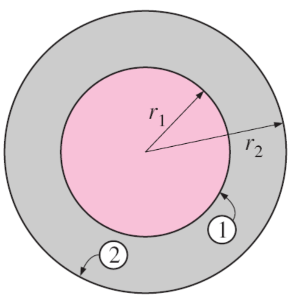
The summation rule can be applied to each surface of an enclosure by varying i from 1 to N. Therefore, the summation rule applied to each of the N surfaces of an enclosure gives N relations for the determination of the view factors. Also, the reciprocity rule gives $\frac{1}{2}N(N-1)$ additional relations. Then the total number of view factors that need to be evaluated directly for an N-surface enclosure becomes

$$N^2 - [N + \tfrac{1}{2}N(N-1)] = \tfrac{1}{2}N(N-1)$$

For example, for a six-surface enclosure, we need to determine only $\frac{1}{2} \times 6(6-1) = 15$ of the $6^2 = 36$ view factors directly. The remaining 21 view factors can be determined from the 21 equations that are obtained by applying the reciprocity and the summation rules.

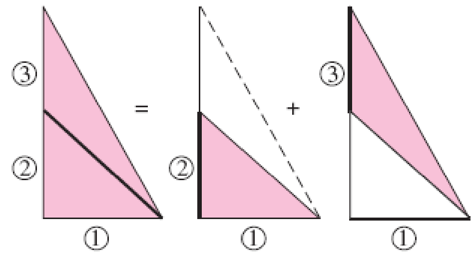
Question 1

Determine the view factors associated with an enclosure formed by two spheres, shown in the figure below.



3. The Superposition Rule

Sometimes the view factor associated with a given geometry is not available in standard tables and charts. For this the **superposition rule** is used where, it is expressed as the view factor from a surface *i* to a surface *j* is equal to the sum of the view factors from surface *i* to the parts of surface *j*. Note the reverse of this is not true.



$F_{1 \to (2,3)} = F_{1 \to 2} + F_{1 \to 3}$

FIGURE 12–11

The radiation that leaves surface 1 and strikes the combined surfaces 2 and 3 is equal to the sum of the radiation that strikes surfaces 2 and 3. Therefore, the view factor from surface 1 to the combined surfaces of 2 and 3 is

$$F_{1(2,3)} = F_{12} + F_{13}$$

4. The Symmetry Rule

The determination of the view factors in a problem can be simplified further if the geometry involved possesses some sort of symmetry.

Therefore, the **symmetry rule** can be expressed as two (or more) surfaces that possess symmetry about a third surface will have identical view factors from that surface (Fig. 12–13).

Question 2

Determine the view factors from the base of the pyramid shown in Figure 12–14 to each of its four side surfaces. The base of the pyramid is a square, and its side surfaces are isosceles triangles.

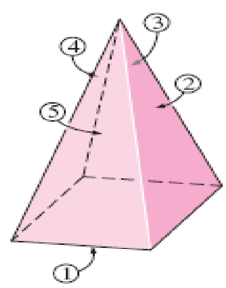


FIGURE 12–14

Question 3

Determine the view factor from any one side to any other side of the infinitely long triangular duct whose cross section is given in Figure 12–15.

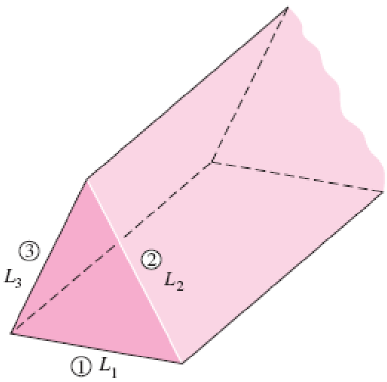


FIGURE 12–15

View Factors between Infinitely Long Surfaces:
The Crossed-Strings Method

To demonstrate this method, consider the geometry shown in Figure 12–16, and let us try to find the view factor F_{12}. The first step is to identify the endpoints of the surfaces (the points A, B, C, and D) and connect them to each other with tightly stretched strings (dashed lines). The view factor F_{12} can be expressed in terms of the lengths of these stretched strings, which are straight lines, as

$$F_{12} = \frac{(L_5 + L_6) - (L_3 + L_4)}{2L_1}$$

Note that $L_5 + L_6$ is the sum of the lengths of the crossed strings, and $L_3 + L_4$ is the sum of the lengths of the uncrossed strings attached to the endpoints. Therefore,

$$Fij = \frac{\sum\left(Crossed \quad Strings\right) - \sum\left(Uncrossed \quad Strings\right)}{2 \times \left(String \quad on \quad surface \quad i\right)}$$

The crossed-strings method is applicable even when the two surfaces considered share a common edge, as in a triangle. In such cases, the common edge can be treated as an imaginary string of zero length. The method can also be applied to surfaces that are partially blocked by other surfaces by allowing the strings to bend around the blocking surfaces.

Question 4

Two infinitely long parallel plates of widths a = 12 cm and b = 5 cm are located a distance c = 6 cm apart as shown in Figure 12–17. Determine the view factor F_{12} from surface 1 to surface 2 by using the crossed-strings method.

RADIATION HEAT TRANSFER
BLACK SURFACES

Consider two black surfaces of arbitrary shape maintained at uniform temperatures T_1 and T_2, as shown in Figure 12–18. Recognizing that radiation leaves a black surface at a rate of $E_b = \sigma T^4$ per unit surface area and that the view factor $F_{1 \to 2}$ represents the fraction of radiation leaving surface 1 that strikes surface 2, the *net* rate of radiation heat transfer from surface 1 to surface 2 can be expressed as

$$\dot{Q}_{1 \to 2} = \begin{pmatrix} \text{Radiation leaving} \\ \text{the entire surface 1} \\ \text{that strikes surface 2} \end{pmatrix} - \begin{pmatrix} \text{Radiation leaving} \\ \text{the entire surface 2} \\ \text{that strikes surface 1} \end{pmatrix}$$
$$= A_1 E_{b1} F_{1 \to 2} - A_2 E_{b2} F_{2 \to 1} \qquad \text{(W)} \qquad \textbf{(12-18)}$$

Applying the reciprocity relation $A_1 F_{1 \to 2} = A_2 F_{2 \to 1}$ yields

$$\dot{Q}_{1 \to 2} = A_1 F_{1 \to 2}\, \sigma(T_1^4 - T_2^4) \qquad \text{(W)} \qquad \textbf{(12-19)}$$

which is the desired relation. A negative value for $\dot{Q}_{1 \to 2}$ indicates that net radiation heat transfer is from surface 2 to surface 1.

Now consider an *enclosure* consisting of *N black* surfaces maintained at specified temperatures. The *net* radiation heat transfer *from* any surface *i* of this enclosure is determined by adding up the net radiation heat transfers from surface *i* to each of the surfaces of the enclosure:

$$\dot{Q}_i = \sum_{j=1}^{N} \dot{Q}_{i \to j} = \sum_{j=1}^{N} A_i F_{i \to j} \sigma(T_i^4 - T_j^4) \qquad \text{(W)} \qquad \textbf{(12-20)}$$

Again a negative value for $\dot{Q}$ indicates that net radiation heat transfer is *to* surface *i* (i.e., surface *i gains* radiation energy instead of losing). Also, the net heat transfer from a surface to itself is zero, regardless of the shape of the surface.

Question 5

Consider the 5-m × 5-m × 5-m cubical furnace shown in Figure 12–19, whose surfaces closely approximate black surfaces. The base, top, and side surfaces of the furnace are maintained at uniform temperatures of 800 K, 1500 K, and 500 K, respectively. Determine (a) the net rate of radiation heat transfer between the base and the side surfaces, (b) the net rate of radiation heat transfer between the base and the top surface, and (c) the net radiation heat transfer from the base surface.

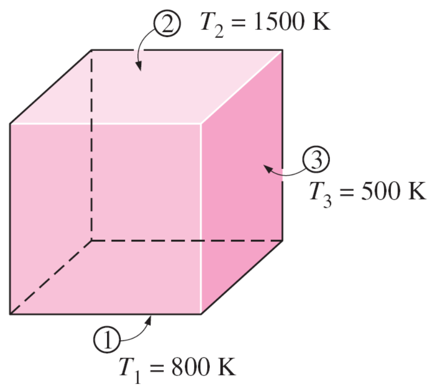


FIGURE 12–19