Table 4 .... Emissivities and Absorptivities for a Few Surfaces (See Also Chapter 69 and References 8 and 9)

Class	Surfaces	Total Normal Emissivity[a]		Absorptivity for Solar Radiation
		At 50–100 F	At 1000 F	
1	A small hole in a large box, sphere, furnace, or enclosure	0.97 to 0.99	0.97 to 0.99	0.97 to 0.99
2	Black non-metallic surfaces such as asphalt, carbon, slate, paint, paper	0.90 to 0.98	0.90 to 0.98	0.85 to 0.98
3	Red brick and tile, concrete and stone, rusty steel and iron, dark paints (red, brown, green, etc.)	0.85 to 0.95	0.75 to 0.90	0.65 to 0.80
4	Yellow and buff brick and stone, firebrick, fire clay	0.85 to 0.95	0.70 to 0.85	0.50 to 0.70
5	White or light-cream brick, tile, paint or paper, plaster, whitewash	0.85 to 0.95	0.60 to 0.75	0.30 to 0.50
6	Window glass	0.90	.....	[b]
7	Bright aluminum paint; gilt or bronze paint	0.40 to 0.60	.....	0.30 to 0.50
8	Dull brass, copper, or aluminum; galvanized steel; polished iron	0.20 to 0.30	0.30 to 0.50	0.40 to 0.65
9	Polished brass, copper, monel metal	0.02 to 0.05	0.05 to 0.15	0.30 to 0.50
10	Highly polished aluminum, tin plate, nickel, chromium	0.02 to 0.04	0.05 to 0.10	0.10 to 0.40
11	Selective Surfaces			
	Stainless steel wire mesh	0.23 to 0.28	.....	0.63 to 0.86
	White painted surface	0.92	.....	0.23 to 0.49
	Copper treated with solution of $NaClO_3$ and NaOH	0.13	.....	0.87
	Copper, nickel, and aluminum plate with CuO coating	0.09 to 0.21	.....	0.08 to 0.93

[a] Hemispherical and normal emissivity are not equal in many cases. The hemispherical emissivity may be as much as 30 percent greater for polished reflectors to 7 percent lower for non-conductors.
[b] Absorbs 4 to 40 percent depending upon its transmissivity.

where λ is the wave length, and C_1 and C_2 are universal constants having the values 3.7413×10^{-4} erg cm^2/sec and 1.4388 cm K, respectively.

The symbol $W_{b\lambda}$ denotes the *monochromatic emissive power or intensity*, defined as the energy emitted per unit surface area at wave length λ per unit wave length interval around λ. That is, the rate of energy emission in the interval $d\lambda$ is equal to $W_{b\lambda}d\lambda$.

The Planck law of radiant energy distribution is connected to the Stefan-Boltzmann emissive power W_b by the following relation:

$$W_b = \sigma T^4 = \int_0^\infty W_{b\lambda}\, d\lambda \tag{5}$$

Actual Radiation

Different substances and surfaces show various divergences from the Stefan-Boltzmann and Planck laws. W_b and $W_{b\lambda}$ are the maximum emissive powers for any given surface temperature. Actual surfaces emit and absorb less readily and are called nonblack. The emissive power of a nonblack surface, at temperature T, to the hemispherical region above it is written as:

$$W = \epsilon W_b = \epsilon \sigma T^4 \tag{6}$$

where ϵ is called the *hemispherical emissivity*.* In general, the emissivity is a function of the material, the condition of its surface, and also the temperature of the surface. Selected values are listed in Table 4. Extensive listings of such information may be found in References 8 and 9.

The monochromatic emissive power of a nonblack surface is similarly written as:

$$W_\lambda = e_\lambda W_{b\lambda} = e_\lambda \frac{C_1 \lambda^{-5}}{e^{C_2/\lambda T} - 1} \tag{7}$$

* The term ϵ is often called emittance, particularly when referring to a piece of material as it actually exists. In this case, the term emissivity is reserved for describing the property of the bulk material, independent of geometry or surface condition.

where e_λ is called the monochromatic hemispherical emissivity. The relationship between ϵ and e_λ is given by:

$$W = \epsilon \sigma T^4 = \int_0^\infty W_\lambda d\lambda = \int_0^\infty e_\lambda W_{b\lambda} d\lambda$$

or

$$\epsilon = \frac{1}{\sigma T^4} \int_0^\infty e_\lambda W_{b\lambda} d\lambda \tag{8}$$

One type of monochromatic emissivity characteristic is of special importance because of the simplicity of the resulting relation between ϵ and e_λ. If e_λ does not depend upon λ, then from Equation 8, $\epsilon = e_\lambda$. Surfaces having this characteristic are called *gray*. In heat transfer calculations, gray-surface characteristics are often assumed because several important classes of surfaces approximate this condition, at least in some regions of the spectrum. The resulting simplicity is desirable, but care must be exercised, especially if the temperatures involved are high. The assumption of grayness is sometimes unavoidable, because of the absence of information relating e_λ and λ.

When radiant energy falls on a surface it can be absorbed, reflected or transmitted through the material. Therefore, from the first law of thermodynamics:

$$\alpha + \tau + \rho = 1 \tag{9}$$

where

α = fraction of incident radiation absorbed or *absorptivity*.
τ = fraction of incident radiation transmitted or *transmissivity*.
ρ = fraction of incident radiation reflected or *reflectivity*.

For an opaque surface, $\tau = 0$ and $\alpha + \rho = 1$; for a black surface, $\alpha = 1$, by definition. However, no really black surfaces exist. Platinum black and gold black, which are about as black as any found in nature, exhibit absorptivities of about 0.98.

A useful relation between emissivity and absorptivity of any opaque surface, called *Kirchhoff's law*, may be developed directly from thermodynamic considerations. This relation

states that for any surface $e_\lambda = \alpha_\lambda$. If the surface is gray, or the incident radiation is from a black surface at the same temperature, then also $\epsilon = \alpha$. However, many surfaces are not gray as may be seen from the data in Table 4. For most surfaces listed, absorptivity for solar radiation is different than emissivity for low temperature level radiation. This is because the wave length distributions are different in the two cases, and e_λ varies with wave length.

The foregoing discussion relates to total hemispherical radiation from surfaces. No regard is given to the way in which the energy is distributed over such a hemispherical region above the surface. However, the nature of the distribution of energy in the region above an emitting surface has an important effect upon the rates of heat transfer in various geometric arrangements.

Very early in the study of radiation phenomena the question of the spatial distribution of the emitted energy was investigated. One result of these investigations was the formulation of a law of radiant energy distribution subsequently called *Lambert's law*. Lambert's law states that the intensity of radiant energy over a hemispherical surface above the emitting surface varies as the cosine of the angle between the normal to the radiating surface and the line joining the radiating surface to the point of the hemispherical surface. Such radiation is called *diffuse* radiation. It can be seen that the Lambert intensity variation is equivalent to the assumption that the radiation from a surface in a direction other than normal occurs as if it came from an equivalent area having the same emissive power (per unit area) as the original surface. This equivalent area is obtained by projecting the original area upon a plane normal to the direction of radiation.

Black surfaces obey the Lambert law exactly. The law holds approximately for many actual radiation and reflection processes, especially those involving rough surfaces and nonmetallic materials. However, it has many exceptions.

The subsequent discussion deals with techniques used for the estimation of heat transfer rates between surfaces of different geometries, radiation characteristics, and orientations. The following assumptions are made: (1) all surfaces are either gray or black; (2) radiation and reflection processes are diffuse; (3) properties are uniform over the extent of the surfaces; (4) absorptivity is equal to emissivity and independent of the temperature of the source of incident radiation; (5) the material occupying the space between the radiating surfaces neither emits nor absorbs radiation.

These assumptions are not strictly valid in many problems of practical importance. They are usually used because of the considerable simplification they provide, although the results in such circumstances must be considered approximate. In many cases the development of new techniques not requiring these assumptions would involve computations so lengthy and complex as to be impractical.

The Angle Factor

The distribution of radiation leaving a surface, among the surfaces it irradiates, is indicated by a quantity variously called an interception, view, configuration, or angle factor. In terms of two surfaces, i and j, the *angle factor* from surface i to surface j, F_{ij}, is defined as the fraction of radiant energy emitted by surface i which falls directly upon j (i.e., is intercepted by j). The angle factor from j to i is similarly defined merely by interchanging the roles of i and j. This second angle factor will not, in general, be numerically equal to the first. However, under the assumptions noted previously, $F_{ij}A_i = F_{ji}A_j$, where A indicates surface area. Note that a concave surface may *see* itself, $F_{ii} \neq 0$, and that if n surfaces form an enclosure:

$$\sum_{j=1}^{n} F_{ij} = 1 \tag{10}$$

Equations and graphs for angle factors for many surface arrangements are available in References 10 and 11. One such chart is reproduced in Fig. 1. A useful technique for visualizing the angle factor is given by Eckert and Drake.[12] In addition, several mathematical methods have been introduced for the calculation of values not given in charts.[11,13]

Calculation of Radiant Exchange

The information of principal interest to the engineer in a radiant energy exchange calculation is the net rate of radiant energy loss from a surface. This quantity will be denoted by q, or by q_j for A_j. It is the rate of emission of the surface minus the total rate of radiant energy absorption at the surface due to all radiant effects in its surroundings, including perhaps the return of some of its own emission. That is, q is the rate at which energy must be supplied to the surface material by other exchange processes if its temperature is to remain constant. Therefore, in order that q be defined, the total radiant surroundings must be specified. These total surroundings constitute in effect an *enclosure* and, from this point of view, all problems are enclosure problems.

Consider a simple enclosure, made up of three black surfaces, A_1, A_2, and A_3. There being no reflections, the rate of radiant energy loss from A_1 is:

$$q_1 = W_1A_1 - F_{11}W_1A_1 - F_{12}W_2A_2 - F_{13}W_3A_3 \tag{11}$$

Many more complicated enclosure problems have been solved.[14,15] For an enclosure made up of two gray surfaces one of which, A_1, does not *see* itself, the result is:

$$q_1 = \frac{\sigma A_1 (T_1^4 - T_2^4)}{\frac{1}{e_1} + \frac{A_1}{A_2}\left(\frac{1}{e_2} - 1\right)} = -q_2 \tag{12}$$

Equation 12 is strictly valid only if A_1 and A_2 uniformly irradiate each other. Special applications of this equation are for infinite parallel plates, $A_1/A_2 = 1$, and for a small object placed in a large enclosure, $A_1/A_2 \approx 0$.

Most engineering problems require the calculation of radiant energy loss rates from surfaces whose effective radiant surroundings are made up of many surfaces, some of which may be reflecting. Since simple solutions do not exist for these more complicated cases, a number of methods have been developed for treating them.[8,14,15] A technique [15,17] for calculating q_i directly for an n-surface effective enclosure is presented here. This method is simple and direct, and is convenient for machine calculation.

Consider the jth surface, which emits at a rate W_jA_j, in an n-surface enclosure. The other enclosure surfaces, A_i, emit at a rate W_iA_i. Some of this emission may be absorbed at A_j due to direct irradiation or after reflections and re-reflections from the n surfaces. An absorption factor B_{ij} is defined as the fraction of the emission of A_i absorbed at A_j. Thus, B_{ij} is similar to F_{ij}, but takes reflections into account. By the definition of B_{ij}, the net rate of energy loss may be written:

$$q_j = W_jA_j - \sum_{i=1}^{n} B_{ij}W_iA_i \tag{13}$$

The n values of B_{ij} necessary to compute q_i may be found by summing absorption rates at j due to the emission rates of