Heat Transfer

Radiation

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Introduction

- A body at any temperature above absolute zero emits thermal radiation.
- Energy transport by radiation does not require an intervening medium between the hot and cold surfaces. If the hot object is separated from the cold one by vacuum, heat transfer between these objects is only through radiation (as heat transfer by conduction or convection is not possible).
- Radiation from a body at temperature T is considered to be emitted at all wavelengths from $\lambda = 0$ to $\lambda = \infty$. At temperatures encountered in most engineering applications, the bulk of the thermal energy emitted lies in the wavalength between 0.1 and 100 μm, and this range of wavelength is generally referred to as the *thermal radiation*.

Black Body

A *black body* is considered to absorb all incident radiation from all directions at all wavelengths without reflecting, transmitting, or scattering it. The radiation emission by a black body at any temperature T is the maximum possible emission at that temperature.

Planck's Distribution Law

Planck's Distribution Law gives the relation for spectral emissive power $E_{b\lambda}(T)$ of a black body as a function of temperature and wavelength.

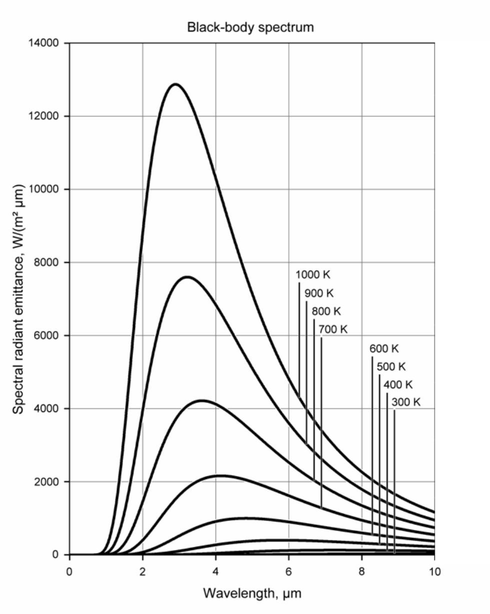
$$E_{b\lambda}(T) = \frac{c_1}{\lambda^5\{\exp[c_2/(\lambda T)] - 1\}} \qquad \text{W}/(\text{m}^2.\mu\text{m})$$

where

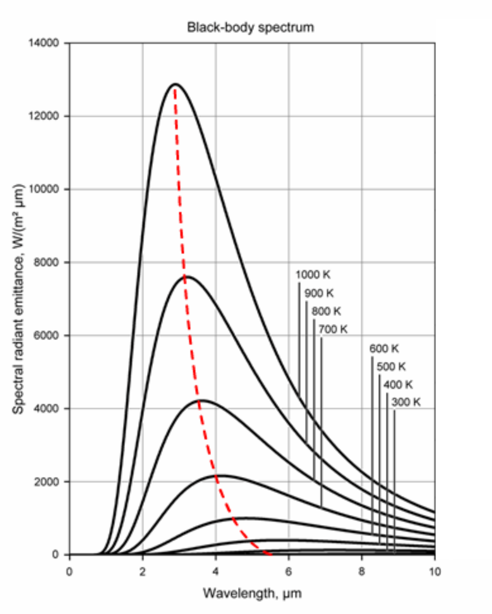
$$\begin{aligned} c_1 &= 3.743 \times 10^8 \ \text{W}.\mu\text{m}^4/\text{m}^2 \\ c_2 &= 1.4387 \times 10^4 \ \mu\text{m.K} \\ T &= \text{absolute temperature, K} \\ \lambda &= \text{wavelength, } \mu\text{m} \end{aligned}$$

According to this law, at any given wavelength, the emissive power increases with increase in temperature; and, at any given temperature, the emitted radiation varies with wavelength and shows a peak. These peaks tend to shift toward smaller wavelengths as the temperature increases. The locus of these peaks is given by Wien's displacement law.

Variation of Spectral Emissive Power



Wien's Displacement Law



Wien's Displacement Law

Wein's Displacement Law states that the wavelength for maximum emission varies inversely with the absolute temperature, or:

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

Stefan-Boltzmann Law

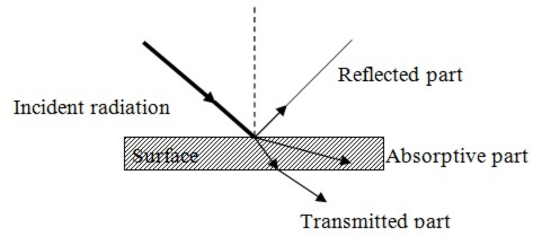
The radiation energy emitted by a blackbody at any absolute temperature T, over all wavelengths per unit unit time per unit area is obtained by integrating the Planck's distribution law from $\lambda = 0$ to $\lambda = \infty$, and given as

$$\boxed{E_b(T) = \sigma T^4 \qquad \mathrm{W/m^2}}$$

where

T	$=$	temperature in Kelvin
σ	$=$	5.67×10^{-8} $\mathrm{W/(m^2.K^4)}$, the Stefan-Boltzmann constant.

Absorption, Reflection, and Transmission of Radiation



When thermal radiation is incident on a surface, a part of the radiation may be reflected by the surface, a part may be absorbed by the surface and a part may be transmitted through the surface as shown in figure.

If $\rho, \alpha,$ and τ are the fractions of the incident radiation which are reflected, absorbed and transmitted, respectively, then

$$\rho + \alpha + \tau = 1$$

where ρ is reflectivity, α is absorptivity, and τ is transmissivity.

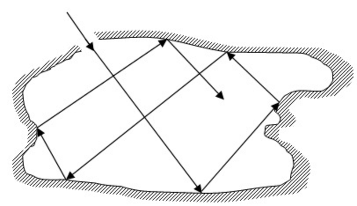
Radiative Properties of Materials

- For most solids, the transmissivity is zero, and thus they may be called *opaque* to thermal radiation. For an opaque body, $\rho + \alpha = 1$.
- A *black body* is one for which $\alpha = 1$. A black body neither reflects nor transmits any thermal radiation.
- Kirchhoff's law: it is a relation between absorptivity and emissivity at a given wavelength (λ) as given below:

$$\varepsilon_\lambda = \alpha_\lambda$$

- A *gray body* is defined as one which has a constant value of emissivity, so that for any temperature range, it radiates the same proportion of energy radiated by a black body. Similarly it will have a constant absorptivity. With the application of Kirchhoff's law, for gray body $\varepsilon = \alpha$.

- A black body absorbs all incoming radiation and emits the maximum possible, $\alpha = \varepsilon = 1$; where ε is emissivity.
- Since we see reflected light (radiation), a so-called black body will appear black, no light being reflected from it. A small hole in a large cavity closely approaches a black body. Radiation incident to the hole has very little opportunity to be reflected back out of the hole.



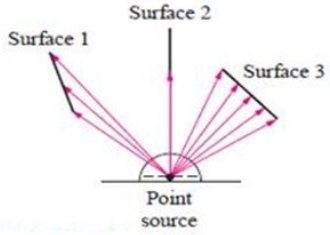
- Highly polished and white surfaces generally have lower emissivities than rough or black surfaces.

Emissivity

Values of emissivity ε have been measured for many materials and it is found that for most industrial non-metallic surfaces and for non-polished metals ε may be taken as 0.9; for highly polished surfaces such as copper or aluminium values of ε as low as 0.03 are obtained.

Materials	Nominal	Polished	Oxidized
Aluminum		0.05	0.15
Brass		0.09	0.60
Cast Iron		0.21	0.70
Copper		0.02	0.60
Galvanized		0.02	0.60
Glass	0.94		
Stainless Steel		0.17	0.85
Steel		0.11	0.75
Rubber	0.86-0.95		
Wood	0.95		

View Factor

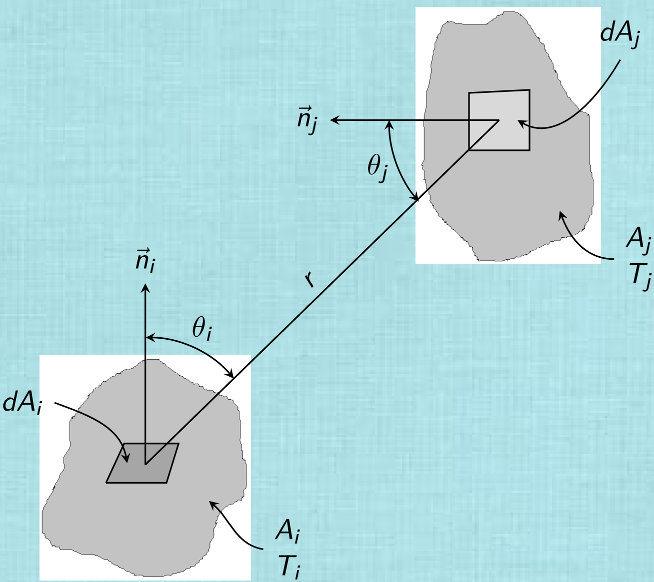


Radiation heat exchange between surfaces depends on the *orientation* of the surfaces relative to each other, and this dependence on orientation is accounted for by the *view factor*.

Definition

View factor (F_{ij}) is defined as the fraction of the radiation leaving surface i that is intercepted by j. View factor is also called as shape factor, angle factor, or configuration factor.

View Factor (contd..)



View Factor (contd..)

- Reciprocity relation:

$$A_i F_{ij} = A_j F_{ji}$$

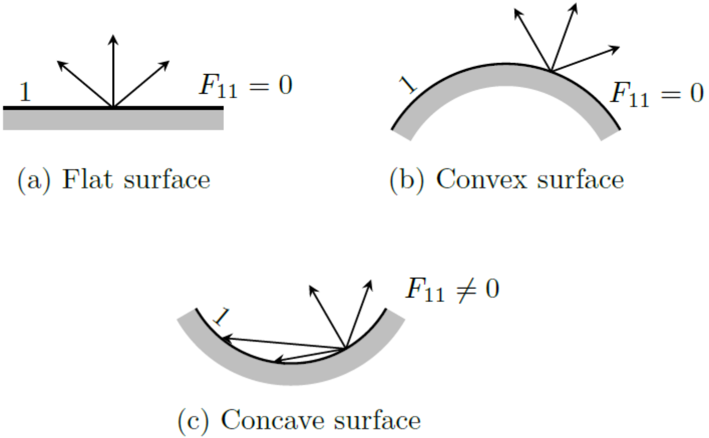
- Summation rule:

$$\sum_j F_{ij} = 1$$

  For exchange between two surfaces, $F_{11} + F_{12} = 1$, and $F_{21} + F_{22} = 1$

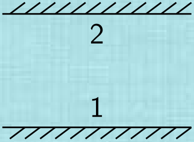
- F_{ii} is the view factor from the surface A_i to itself. $F_{ii} = 0$, for a convex or flat surface. $F_{ii} \neq 0$, if A_i is concave.

View Factor for Simple Geometries

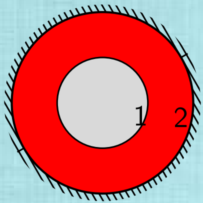


View Factor from a Surface to Itself

View Factor for Simple Geometries (contd..)



Flat surfaces



Cylinrical or spherical surfaces

- **For flat surfaces**

$$F_{11} = 0 \qquad F_{12} = 1$$
$$F_{21} = 1 \qquad F_{22} = 0$$

- **For cylinders & spheres**

$$F_{11} = 0 \qquad F_{12} = 1$$
$$F_{21} = A_1/A_2 \qquad F_{22} = 1 - A_1/A_2$$

Radiation Exchange between Two Surfaces

Radiation exchange (Q) between two surfaces can be stated as

$$Q = Q_{1\text{–}2} = \left(\begin{array}{l} \text{radiation energy} \\ \text{leaving } A_1 \text{ that} \\ \text{strikes } A_2 \end{array} \right) - \left(\begin{array}{l} \text{radiation energy} \\ \text{leaving } A_2 \text{ that} \\ \text{strikes } A_1 \end{array} \right)$$

Radiation exchange (Q) between two surfaces A_1 (at T_1) and A_2 (at T_2) with emissivities ε_1 and ε_2 respectively, is

$$Q = \frac{\sigma T_1^4 - \sigma T_2^4}{\dfrac{1-\varepsilon_1}{A_1\varepsilon_1} + \dfrac{1}{A_1 F_{12}} + \dfrac{1-\varepsilon_2}{A_2\varepsilon_2}} \qquad \text{(where } T_1 > T_2\text{)}$$

For $A_1/A_2 \to 0$, i.e., $A_1 << A_2$, the above equation reduces to

$$Q = A_1\varepsilon_1\sigma(T_1^4 - T_2^4)$$

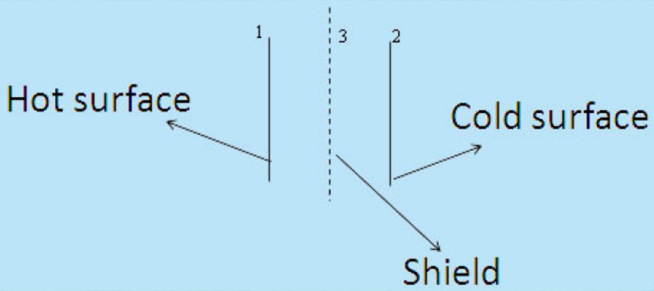
- For transfer between two large parallel plates, with $A_1 = A_2 = A$, the above relation reduces to (as $F_{12} = 1$):

$$Q = \frac{A\sigma(T_1^4 - T_2^4)}{1/\varepsilon_1 + 1/\varepsilon_2 - 1}$$

- For long concentric cylinders or concentric spheres, the heat transfer rate is given by (inner=1; outer=2):

$$Q = \frac{A_1\sigma(T_1^4 - T_2^4)}{1/\varepsilon_1 + (A_1/A_2)(1/\varepsilon_2 - 1)}$$

The radiation heat transfer between two surfaces can be reduced significantly if a radiation shield made of low-emissivity materials is placed between them.



Radiation Shields (contd..)

- Radiation shield (plate 3) between flat plates (plates 1 and 2): Heat transfer rate for this case is given by

$$Q = \frac{A\sigma(T_1^4 - T_2^4)}{(1/\varepsilon_1 + 1/\varepsilon_2 - 1) + (1/\varepsilon_{3,1} + 1/\varepsilon_{3,2} - 1)}$$

  where $\varepsilon_{3,1}$ is the emissivity of the surface of plate 3 (the radiation shield) facing the plate 1; and $\varepsilon_{3,2}$ is the emissivity of the surface of plate 3 (the radiation shield) facing the plate 2.

- Radiation shield between concentric cylinders or spheres (inner=1; outer=2; shield=3, which is placed between 1 and 2):

$$Q = \frac{A_1\sigma(T_1^4 - T_2^4)}{1/\varepsilon_1 + (A_1/A_2)(1/\varepsilon_2 - 1) + (A_1/A_3)(1/\varepsilon_{3,1} + 1/\varepsilon_{3,2} - 1)}$$