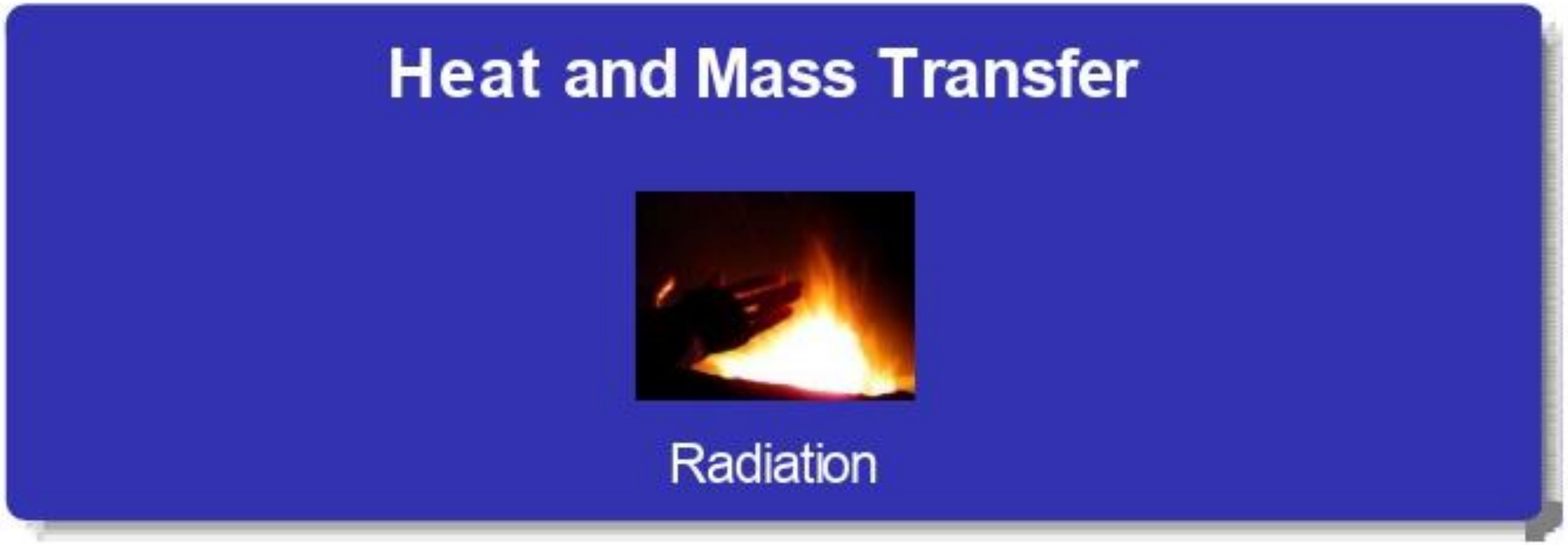
UNIT - V Thermal Radiation



Radiation : Processes and Properties

- Thermal radiation requires nomatter
- Applications: Industrial heating, cooling and drying processes, energy conservation methods - fossil fuel combustion and solar radiation

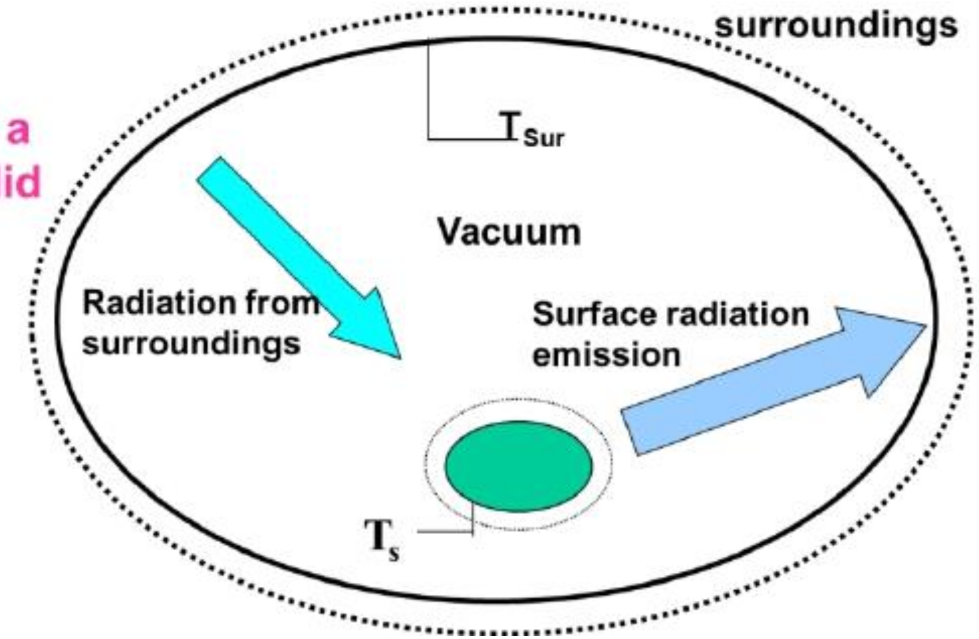
Objectives

- Means by which thermal radiation is generated
- Specific nature of radiation
- Manner in which radiation interacts with matter

Concepts

- $T_s > T_{sur}$
- No conduction or convection - still solid will cool
- Solid gets cooled - emission of thermal radiation from the surface of the solid

Radiation cooling of a heated solid



Radiation - Propagation of electromagnetic waves

J.C. Maxwell - accelerated charges or changing electric currents give rise to electric and magnetic fields. These moving fields are called **Electromagnetic Waves or Electromagnetic Radiation**

Electro-magnetic Radiation - energy emitted by matter as a result of the changes in the electronic configurations of the atoms or molecules.

Characteristics of Electro-magnetic Radiation

- Frequency ν (Hz - 1/s)
- Wavelength λ (m)

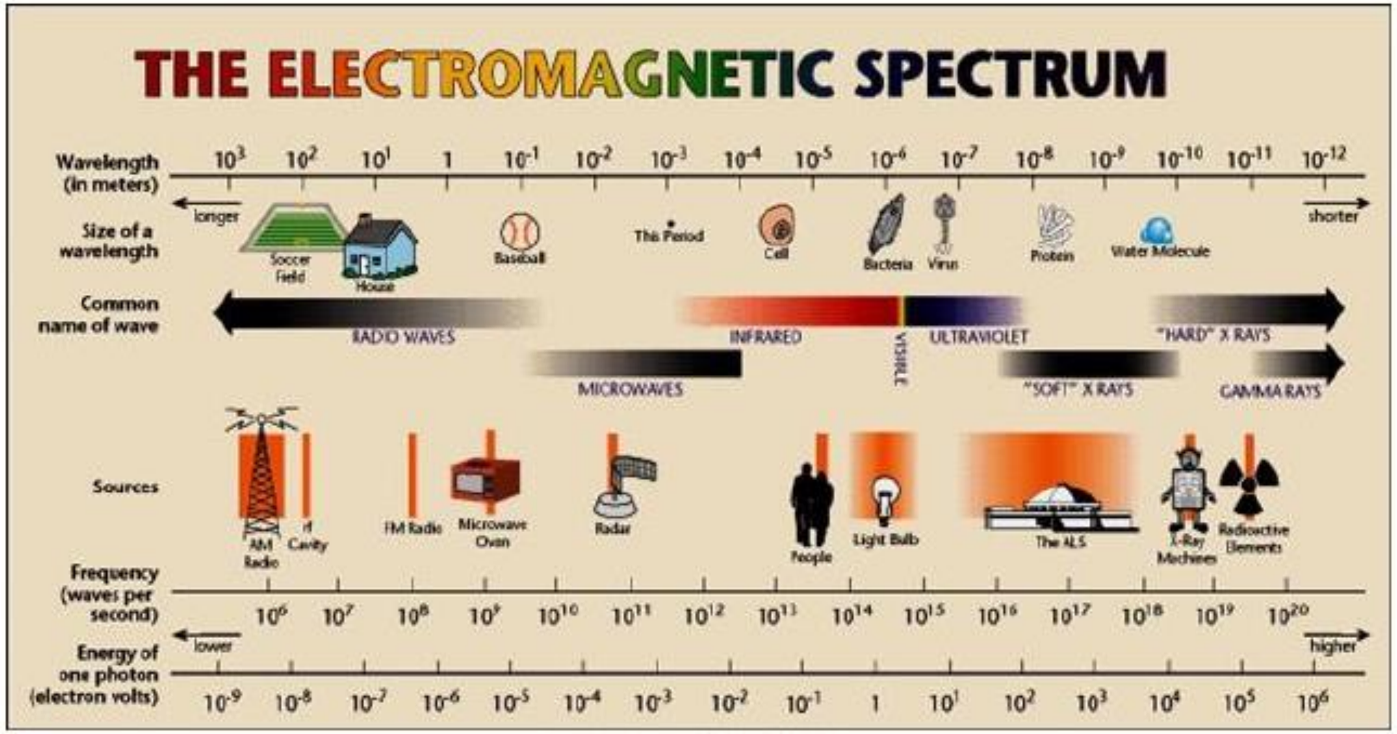
$$\lambda = \frac{c}{\nu} \qquad c = \frac{c_o}{n}$$

In vacuum $c_o = 2.998 \times 10^8$ m/s and n is the index of refraction

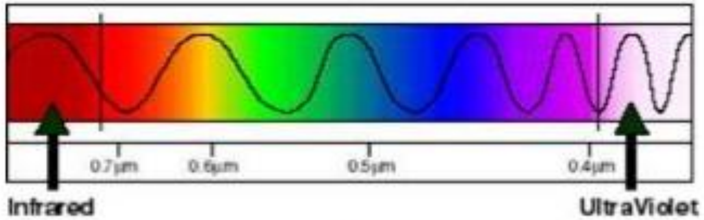
Material	*n*
Air and most gases	1.0
Glass	1.5
Water	1.33

Observations

λ, c: depend on medium through which wave travels.
ν: independent of the medium depends only on the source.



Visible Light Region of the Electromagnetic Spectrum



Semitransparent Medium

Reflectivity, ρ is the fraction of the irradiation that is reflected.

Absorptivity, a is the fraction of the irradiation that is absorbed.

Transmissivity, τ is the fraction of the irradiation that is transmitted.

$$\rho + a + \tau = 1$$

$$J = E + tt_{ref} = E + \rho tt$$

$$q''_{rad} = J - tt = \varepsilon\sigma T_s^4 - att$$

Intensity of Emitted Radiation

Radiation intensity for emitted radiation $I_e(\theta, \varphi)$ is defined as the rate at which the radiation energy dq is emitted in the (θ, φ) direction per unit area normal to this direction and per unit solid angle about this direction.

$$I_e(\theta, \varphi) = \frac{dq}{dA_1 \cos\theta \cdot d\omega} = \frac{dq}{dA_1 \cos\theta \cdot \sin\theta d\theta d\varphi} \quad \text{W/m}^2\ \text{sr}$$

Radiation flux for emitted radiation is the Emissive Power (E): rate at which radiation energy is emitted per unit area of the emitting surface which is expressed in the differential form

$$dE = \frac{dq}{dA_1} = I_e(\theta, \varphi) \cos\theta \sin\theta d\theta d\varphi$$

Emissive Power

Emissive power from the surface into hemisphere surrounding it,

$$E = \int_{hemisphere} dE = \int_{\varphi=0}^{2\pi} \int_{\theta=0}^{\pi/2} I_e(\theta, \varphi) \cos\theta \sin\theta \, d\theta \, d\varphi \ \text{W/m}^2$$

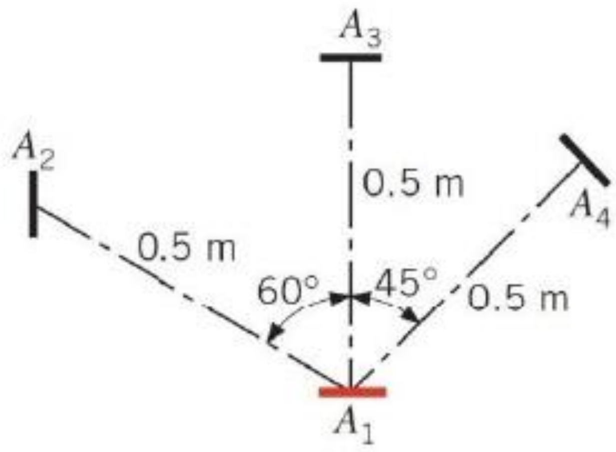
I_e varies with direction (especially with zenith angle θ). Practically approximated as Diffuse, *i.e.*, I_e is constant.

$$\int_{\varphi=0}^{2\pi} \int_{\theta=0}^{\pi/2} \cos\theta \sin\theta \, d\theta \, d\varphi = 2\pi \int_{\theta=0}^{\pi/2} \cos\theta \sin\theta \, d\theta$$

$$= \frac{2\pi}{2} \int_{\theta=0}^{\pi/2} \sin 2\theta \, d\theta = \pi \left[\frac{-\cos 2\theta}{2} \right]_0^{\pi/2} = \pi$$

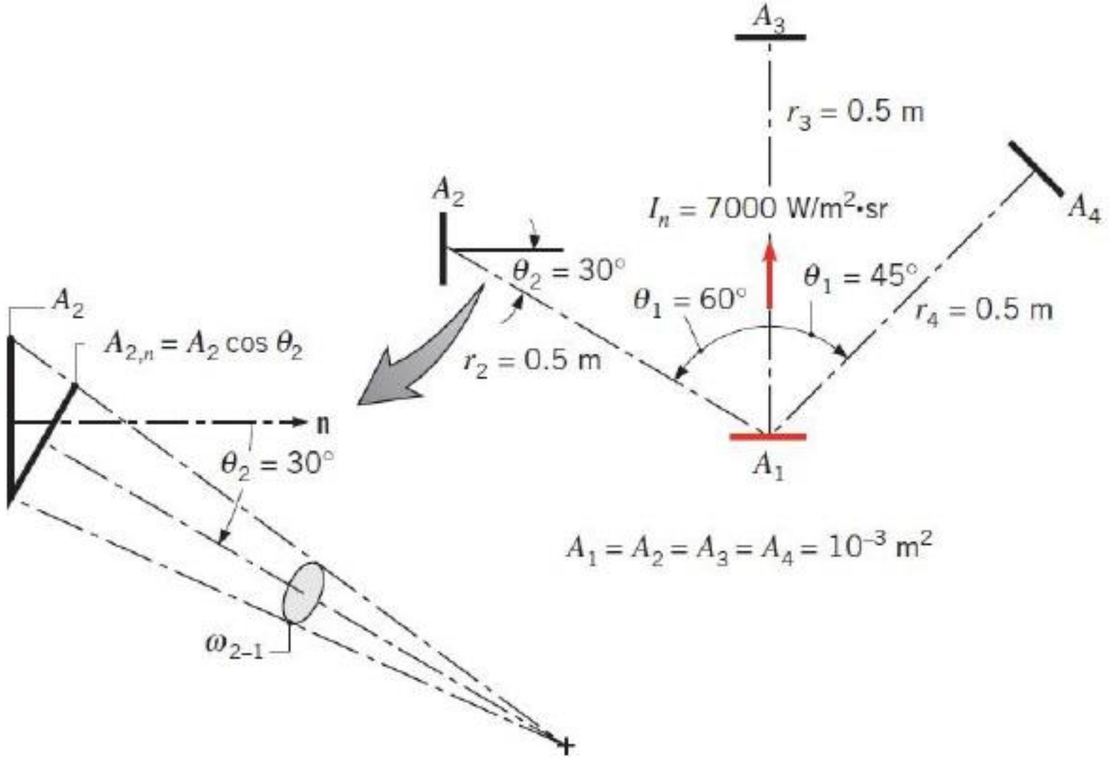
$$\boxed{E = \pi I_e}$$

A small surface of area $A_1 = 10^{-3}$ m^2 is known to emit diffusely and from measurements the total intensity associated with emission in the normal direction is $I_n = 7000$ W/m^2 sr. Radiation emitted from the surface is intercepted by other surfaces of area $A_2 = A_3 = A_4 = 10^{-3}$ m^2, which are 0.5 m from A_1. What is the intensity associated with emission in each of the three directions? What are the solid angles subtended by the three surfaces when viewed from A_1? What is the rate at which radiation emitted by A_1 is intercepted by the three surfaces?



Assumptions

- Surface A_1 emits diffusely
- A_1, A_2, A_3, A_4 may be approximated as differential surfaces, $A_j/r_j^2 1$



Intensity is independent of direction, $I = 7000$ W/m^2 sr

$$\omega_{3-1} = \omega_{4-1} = \frac{dA_n}{r^2} = \frac{A_3}{r^2} = 4 \times 10^{-3} \text{ sr}$$

$$\omega_{2-1} = \frac{A_2 \cos \theta_2}{r^2} = 3.46 \times 10^{-3} \text{ sr}$$

$$q_{1-j} = I \times A_1 \cos \theta_1 \times \omega_{j-1}$$

$$q_{1-2} = 12.1 \times 10^{-3} \text{ W}$$

$$q_{1-3} = 28.0 \times 10^{-3} \text{ W}$$

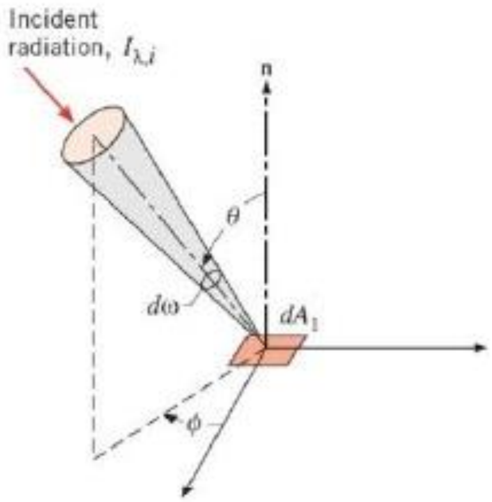
$$q_{1-4} = 19.8 \times 10^{-3} \text{ W}$$

Relation to Irradiation

The intensity of incident radiation, $I_i(\theta, \varphi)$ is the rate at which radiation energy dtt is incident from the (θ, φ) direction per unit area of the receiving surface normal to this direction and per unit solid angle about this direction.

$$tt_\lambda(\lambda) = \int_{\varphi=0}^{2\pi}\int_{\theta=0}^{\pi/2} I_{\lambda,i}(\lambda, \theta, \varphi) \cos\theta \sin\theta d\theta d\varphi$$

$$tt = \int_0^\infty tt_\lambda(\lambda)\, d\lambda$$

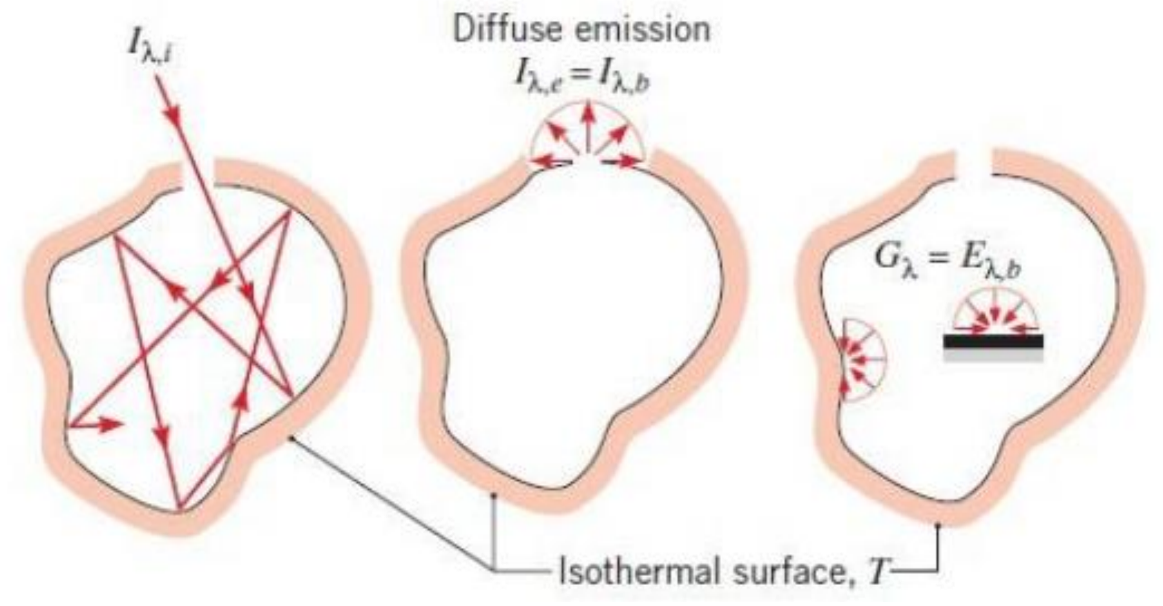


If the incident radiation is diffuse,

$$tt_\lambda = \pi I_{\lambda,i}(\lambda); \qquad tt = \pi I_i$$

Black Body

1. Absorbs all incident radiation, regardless of wavelength and direction.
2. For a given T, λ, no surface can emit more energy than a blackbody.
3. $I_e \equiv f\ (\lambda, T)$, independent of direction, Diffuse emitter.



Plank: Plank Distribution

The spectral distribution of blackbody emission,

$$I_{\lambda,T} = \frac{2hc_o^2}{\lambda^5 \left[\exp\left(\frac{hc_o}{\lambda kT}\right) - 1\right]}$$

Planck constant: $h = 6.625 \times 10^{-34}$ J s

Boltzmann constant: $k = 1.3805 \times 10^{-23}$ J/K

The spectral emissive power of a blackbody (diffuse emission)

$$E_{\lambda,T} = \pi I_{\lambda,T} = \frac{C_1}{\lambda^5 \left[\exp\left(\frac{C_2}{\lambda kT}\right) - 1\right]}$$

The first and second radiation constants are:

$C_1 = 2\pi hc_o^2 = 3.742 \times 10^8$ W μm^4/m^2

$C_2 = (hc_o/k) = 1.439 \times 10^4$ μm K

Wien’s Displacement Law

$$\lambda_{max} T = C_3 = 2897.8\ \mu\text{m K}$$

1. Maximum spectral power is displaced to shorter λ with increasing T
2. Solar radiation - middle of the spectrum ($\lambda = 0.5\ \mu$m), since 5800 K
3. Blackbody at 1000 K, peak emission - 2.9 μm
4. With increasing T, shorter λ become more prominent, until eventually significant emission occurs over the entire visible spectrum
5. Tungsten filament lamp - 2900 K ($\lambda_{max} = 1.0\ \mu$m) emits white light, although most of the emission remains in infrared region

Stefan Bolzmann Law

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

$$\sigma = 5.67 \times 10^{-8} \text{ W/m}^2 \text{ K}^4$$

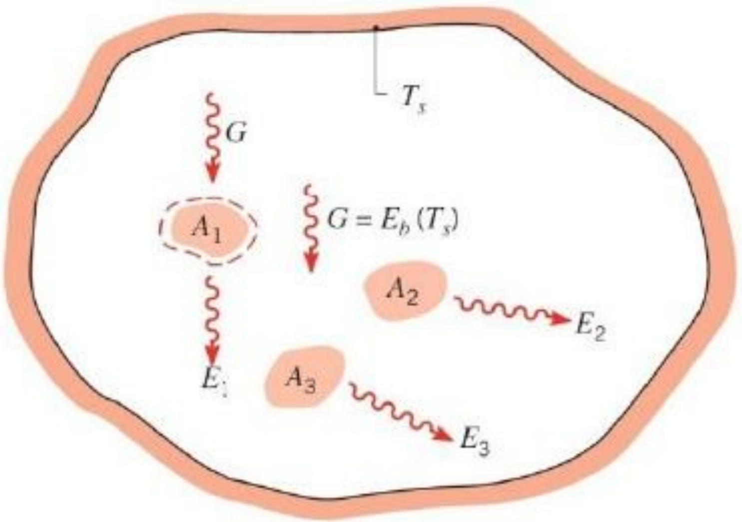
This enables calculation of the amount of radiation emitted in all directions and over all wavelengths simply from the knowledge of the temperature of the blackbody.

The total intensity associated with blackbody emission is:

$$I_b = \frac{E_b}{\pi} \text{ W/m}^2 \text{ sr}$$

Kirchoff's Law

Consider a large, isothermal enclosure of T_S within which several small bodies are confined.



Regarless of its orientation, the irradiation experienced by any body in the cavity is diffuse and equal to emission from a blackbody at T_S.

Under steady state conditions, thermal equilibrium must exist, $T_1 = T_2 = T_3 = \ldots = T_s$ and the net rate of energy transfer to each surface must be zero.

Applying energy balance to a control surface about body 1,

$$a_1 tt A_1 - E_1(T_s) A_1 = 0$$

$$a_1 E_b(T_s) - E_1(T_s) = 0 \qquad \because tt = E_b(T_s)$$

$$\frac{E_1(T_s)}{a_1} = \frac{E_2(T_s)}{a_2} = \frac{E_3(T_s)}{a_3} = \ldots = E_b(T_s)$$

This relation is known as Kirchoff's law . No real surface can have an emissive power exceeding that of a black surface at the same temperature, and the notion of the black body as an ideal emitter is confirmed.

$$\frac{\varepsilon_1}{a_1} = \frac{\varepsilon_2}{a_2} = \frac{\varepsilon_3}{a_3} = \ldots = 1$$

Hence, for any surface in the enclosure, $\varepsilon = a$.

Total hemispherical emissivity = total hemispherical absorptivity.

The restrictive conditions inherent in this derivation is:

- the surface irradiation has been assumed to correspond to emission from a blackbody at the same temperature as the surface.

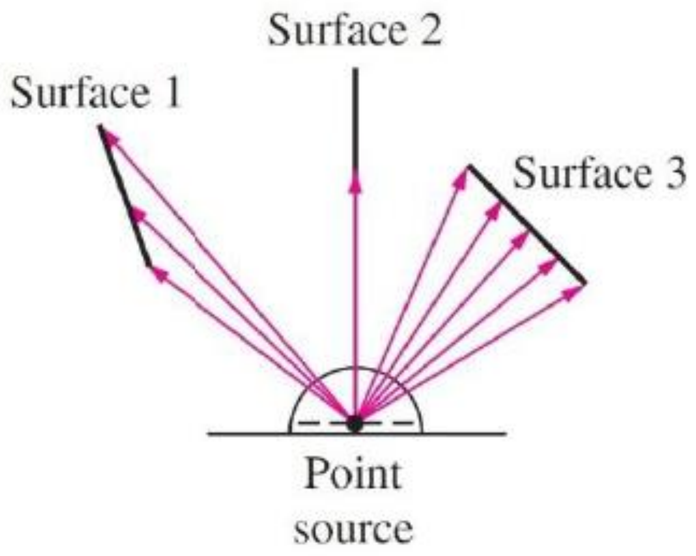
$\varepsilon_\lambda(T) = a_\lambda(T)$, valid when tt is independent of direction.

The form of the Kirchoff's law that involves no restrictions is the spectral directional form,

$$\varepsilon_{\lambda,\theta}(T) = a_{\lambda,\theta}(T)$$

- It is very tempting to use Kirchoff's law in radiation analysis ∵ the relation $\varepsilon = a$ together with $\rho = 1 - a$ enables us to determine all three properties of a opaque surface from a knowledge of only one property.
- Although, $\varepsilon = a$ gives acceptable results in most cases, in practice, care should be exercised when there is considerable difference between T_{surface} and T_{source}.

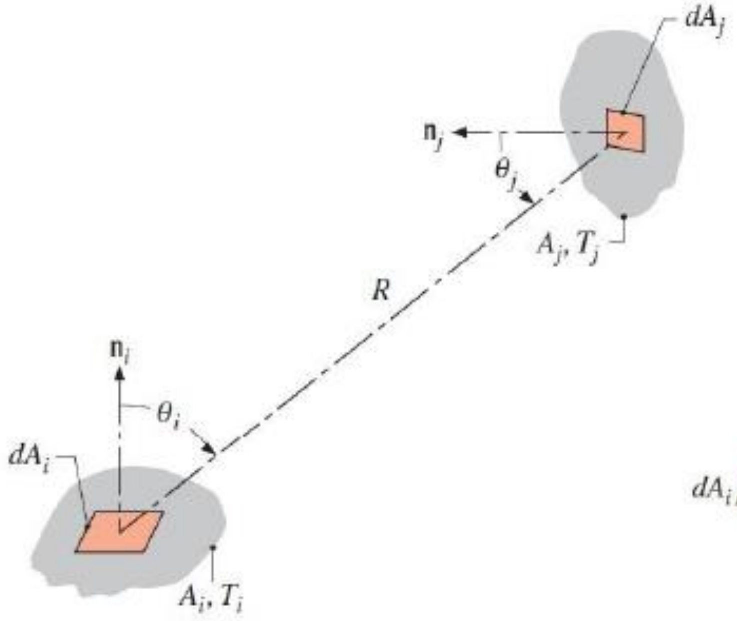
Radiation Exchange Between surfaces

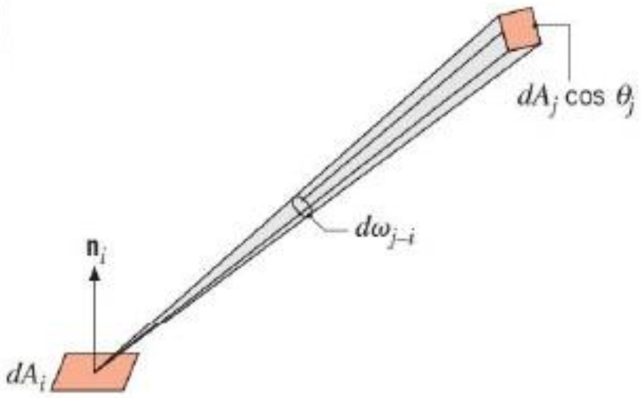


- Radiation heat transfer between surfaces depends on the orientation of the surfaces relative to each other as well as their radiation properties and temperatures.
- This dependence is accounted for by the view factor.
- By facing the fire from front or back - maximum radiation
- By facing the fire from the side - minimum radiation

View/Shape/Angle Factor

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





The rate at which radiation leaves dA_i and is intercepted by dA_j is,

$$dq_{i\rightarrow j} = I_{e+r,i} \cos\theta_i dA_i d\omega_{j-i}$$

$I_{e+r,i}$ - intensity of radiation leaving surface i, and $d\omega_{j-i}$ - solid angle subtended by dA_j when viewed from dA_i: $d\omega_{j-i} = \frac{\cos\theta_j dA_j}{R^2}$

$$dq_{i\rightarrow j} = I_{e+r,i} \frac{\cos\theta_i \cos\theta_j}{R^2} dA_i dA_j$$

Assuming that surface i emits and reflects diffusely,

$$dq_{i\rightarrow j} = J_i \frac{\cos\theta_i \cos\theta_j}{\pi R^2} dA_i dA_j$$

The total rate of radiation leaving surface i towards j,

$$q_{i\rightarrow j} = J_i \int_{A_i}\int_{A_j} \frac{\cos\theta_i \cos\theta_j}{\pi R^2} dA_i dA_j$$

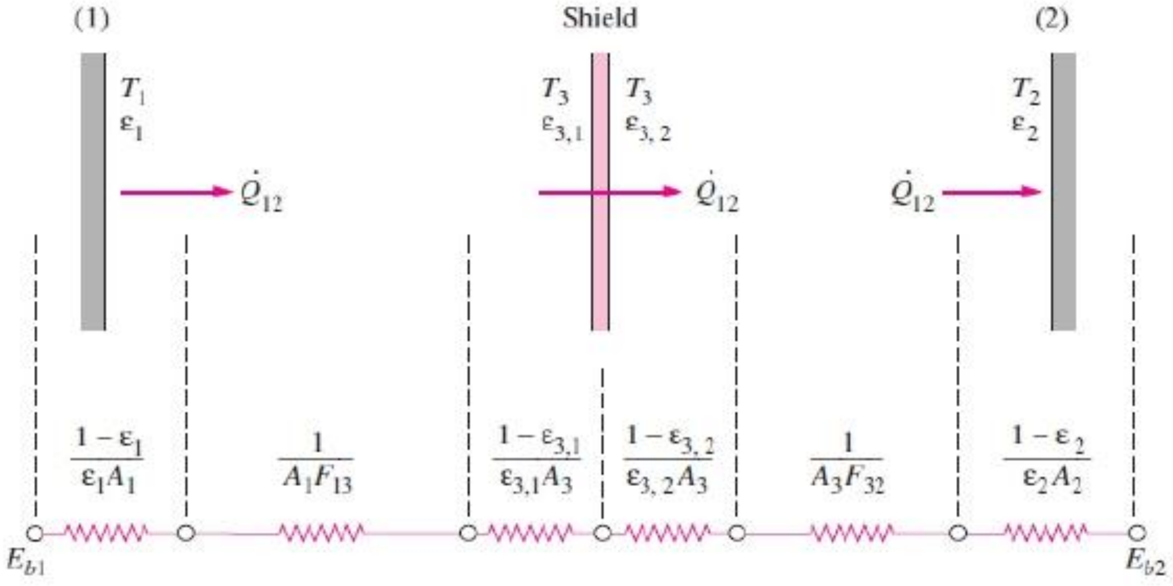
$$F_{ij} = \frac{q_{i\rightarrow j}}{A_i J_i}$$

$$F_{ij} = \frac{1}{A_i} \int_{A_i} \int_{A_j} \frac{\cos\theta_i \cos\theta_j dA_j}{\pi R^2} dA_i dA_j$$

$$F_{ji} = \frac{1}{A_j} \int_{A_i} \int_{A_j} \frac{\cos\theta_i \cos\theta_j dA_j}{\pi R^2} dA_i dA_j$$

These equations may be used to determine the view factor associated with any two surfaces that are diffuse emitters and reflectors and have uniform radiosity.

Radiation Shields



$$q_{12,\text{no shield}} = \frac{A_1\sigma(T_1^4 - T_2^4)}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1}$$

$$q_{12} = \frac{E_{b,1} - E_{b,2}}{\frac{1-\varepsilon_1}{\varepsilon_1} + \frac{1}{A_1 F_{1,2}} + \frac{1-\varepsilon_{3,1}}{\varepsilon_{3,1}} + \frac{1-\varepsilon_{3,2}}{\varepsilon_{3,2}} + \frac{1}{A_3 F_{3,2}} + \frac{1-\varepsilon_2}{\varepsilon_2}}$$

$$F_{13} = F_{32} = 1$$

$$q_{12} = \frac{A_1\sigma(T_1^4 - T_2^4)}{\left(\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1\right) + \left(\frac{1}{\varepsilon_{3,1}} + \frac{1}{\varepsilon_{3,2}} - 1\right)}$$

$$(q_{12})_N = \frac{A_1\sigma(T_1^4 - T_2^4)}{\left(\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1\right) + \left(\frac{1}{\varepsilon_{3,1}} + \frac{1}{\varepsilon_{3,2}} - 1\right) + \ldots + \left(\frac{1}{\varepsilon_{N,1}} + \frac{1}{\varepsilon_{N,2}} - 1\right)}$$

If all emissivities are equal,

$$(q_{12})_N = \frac{1}{N + 1}(q_{12})_0$$

$(q_{12})_0$ is the radiation transfer rate with no shields ($N = 0$).