Unit Outline

- Electromagnetic radiation
- Thermal radiation
- Blackbody radiation
- Radiation emitted from a real surface
- Irradiance
- Kirchhoff’s Law
- Diffuse and gray surface
- View factor
- Radiation exchange between black bodies
- Radiation from a diffuse, gray surface
Electromagnetic Radiation

- The electromagnetic energy emitted by matter as a result of the changes in the electronic configurations of the atoms or molecules.
- Electromagnetic radiation energy is transported by waves.
- These waves have a frequency ($\nu$) and wavelength ($\lambda$).
Electromagnetic Radiation

- Frequency $\nu$ and wavelength $\lambda$ are related by:

$$\lambda = \frac{C}{\nu}$$

where,

$C = C_0 / n$

$C$: the speed of propagation of a wave in the medium

$C_0 = 2.9979 \times 10^8$ m/s, the *speed of light* in a vacuum

$n$, the *index of refraction* of that medium

**Examples:**

$n = 1$ (air and most gases)

$n = 1.5$ (glass)

$n = 1.33$ (water)
Radiation differs from conduction and convection.

- It does not require the presence of a material medium.
- Radiation transfer occurs in all types of matter (solid, liquid, or gas).
Electromagnetic Radiation

• Electromagnetic radiation can be viewed as the propagation of a collection of discrete packets of energy called photons or quanta.

• In this view, each photon of frequency (\( \nu \)) is considered to have an energy of:

\[
E = h\nu = \frac{hc}{\lambda}
\]

where \( h \) is called Planck’s constant

\( h = 6.6256 \times 10^{-34} \text{ J.s} \)

• This means that the energy of a photon is inversely proportional to its wavelength
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Thermal radiation is the part of electromagnetic radiation that primarily creates a heating effect.

Thermal radiation is emitted as a result of energy transitions of molecules, atoms, and electrons of a substance.

Temperature is a measure of the strength of these activities at the microscopic level.

Therefore, thermal radiation emission increases with increasing temperature.
Thermal Radiation

- Thermal radiation mainly covers:
  - Infrared radiation
  - Visible light
  - Ultraviolet radiation
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Blackbody Radiation

- A blackbody is a body that absorbs \textit{all} the incident radiation regardless of wavelength and direction \textbf{AND} emits the \textit{maximum} amount radiation at a given temperature.

- It is an idealized body to serve as a standard against which the radiative properties of real surfaces may be compared.
Blackbody Radiation

• The amount of radiation emitted by a blackbody is given by Planck’s Law:

\[
E_{\lambda b} = \frac{2\pi h C_o^2}{\lambda^5 \left[ \exp \left( \frac{h C_o}{\lambda kT} \right) - 1 \right]}
\]

where,

\[ k = 1.381 \times 10^{-23} \text{ J/K (Boltzmann’s Constant)} \]

• Planck’s Law shows that the energy emitted from a blackbody does not depend on direction.

• Blackbody radiation is **diffuse**.
Blackbody Radiation

- From Planck’s Law, we can find the wavelength at which the maximum radiation is emitted by a blackbody.
- This is done by taking the derivative of $E_{\lambda b}$ and setting it to zero.
- The result is called Wien’s displacement law:

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

Locus of maximum power
\[ \lambda T = 2897.8 \, \text{\mu m.K} \]

Visible light region

Wavelength \( \lambda \), \( \text{\mu m} \)

Energy density \( E_{\lambda \lambda} \), \( W/m^2 \text{\mu m} \)
Integrating Planck’s Law yields Stefan-Boltzmann’s Equation:

\[ E_b = \int_0^\infty E_{\lambda b} \, d\lambda = \sigma T^4 \]

where,

\[ \sigma = 5.67 \times 10^{-8} \text{ W/m}^2\text{K}^4 \] (Stefan-Boltzmann Constant)
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Radiation Emitted from a Real Surface

- A real surface does not emit as much energy as a blackbody.
- A real surface does not emit energy uniformly in all directions.
- The amount of energy emitted by a real surface is quantified by **emittance**.
- **Emittance** is the ratio of radiation emitted by a real surface to the radiation emitted by a blackbody at the same temperature.
- When the energy emitted in all directions and at all wavelengths is integrated, the result is the “**total hemispherical emittance**”

\[
\varepsilon(T) = \frac{E(T)}{E_b(T)}
\]

- Emittance ranges from 0 to 1.
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Irradiance

- **Irradiance** is the rate at which radiant energy is incident on a surface per unit area of that surface (\(W/m^2\)).
- Some references refer to irradiance as “incident radiation”
- It is usually denoted with \((G)\).
- Irradiance can be either:
  - Absorbed
  - Reflected
  - Transmitted (if the medium is transparent)
Irradiance

- The ratio of absorbed irradiance to total irradiance is called **absorptance** \( (\alpha) \)
- The ratio of reflected irradiance to total irradiance is called **reflectance** \( (\rho) \)
- The ratio of transmitted irradiance to total irradiance is called **transmittance** \( (\tau) \)
Irradiance

- Absorptance: \( \alpha = \frac{\text{Absorbed radiation}}{\text{Irradiance}} = \frac{G_{\text{abs}}}{G} , \quad 0 \leq \alpha \leq 1 \)

- Reflectance: \( \rho = \frac{\text{Reflected radiation}}{\text{Irradiance}} = \frac{G_{\text{ref}}}{G} , \quad 0 \leq \rho \leq 1 \)

- Transmittance: \( \tau = \frac{\text{Transmitted radiation}}{\text{Irradiance}} = \frac{G_{\text{tr}}}{G} , \quad 0 \leq \tau \leq 1 \)

- \( G_{\text{abs}} + G_{\text{ref}} + G_{\text{tr}} = G \)

- \( \alpha + \rho + \tau = 1 \)

- \( \alpha + \rho = 1 \) (for opaque surfaces)
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Kirchhoff’s Law

The total hemispherical emittance of a surface at temperature $T$ is equal to its total hemispherical absorptance for radiation coming from a blackbody at the same temperature.

- $\varepsilon(T) = \alpha(T)$
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• A **gray** surface is a surface whose $\varepsilon$ and $\alpha$ are independent of wavelength.

• If the surface is diffuse and gray:

\[ \varepsilon = \alpha \]

• In this case, the source of irradiation does not have to be a blackbody and the source’s temperature does not have to be equal to the surface temperature.
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View Factor

- The **view factor** \((F_{ij})\) is the fraction of the radiation leaving surface \(i\) that strikes surface \(j\) directly.
- The view factor ranges between 0 and 1.
EXAMPLE

- The view factor $F_{12} = 1$ since all the radiation leaving Surface 1 hits Surface 2.
- $F_{21} < 1$, since not all the radiation leaving Surface 2 will hit Surface 1.
- Some of the radiation leaving one part of Surface 2 will hit another part on Surface 2 itself.
View factor between two aligned parallel rectangles of equal size
View factor between two coaxial parallel disks
View factors for two concentric cylinders of finite length
The Reciprocity Relation

\[ F_{j \rightarrow i} = F_{i \rightarrow j} \quad \text{when} \quad A_i = A_j \]
\[ F_{j \rightarrow i} \neq F_{i \rightarrow j} \quad \text{when} \quad A_i \neq A_j \]

\[ A_i F_{i \rightarrow j} = A_j F_{j \rightarrow i} \]
View Factor Relations

The Summation Rule

\[ \sum_{j=1}^{N} F_{i \rightarrow j} = 1 \]
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• If Surface 1 and Surface 2 are blackbodies, the net radiation heat transfer from Surface 1 to Surface 2 is:

\[
\dot{Q}_{1 \rightarrow 2} = \left(\text{Radiation leaving the entire surface 1 that strikes surface 2}\right) - \left(\text{Radiation leaving the entire surface 2 that strikes surface 1}\right)
\]

\[
= A_1 E_b F_{1 \rightarrow 2} - A_2 E_b F_{2 \rightarrow 1}
\]

• The reciprocity relation asserts that: \(A_1 F_{1 \rightarrow 2} = A_2 F_{2 \rightarrow 1}\)
• Also: \(E_b = \sigma T^4\)
• Therefore,

\[
\dot{Q}_{1 \rightarrow 2} = A_1 F_{1 \rightarrow 2} \sigma (T_1^4 - T_2^4)
\]
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Radiosity

• Radiation from a diffuse gray surface differs from radiation from a black body in two ways:
  • The radiation emitted is $\varepsilon E_b$ (instead of $E_b$)
  • The reflected radiation is $\rho G$ (instead of 0)
• The total radiation energy leaving a surface per unit time and per unit area is called radiosity ($J$).
$$J_i = (\text{Radiation emitted by surface } i) + (\text{Radiation reflected by surface } i)$$

$$J_i = \varepsilon_i E_b + \rho_i G_i$$

- But $\rho_i + \alpha_i = 1$
- For a diffuse gray surface, $\alpha_i = \varepsilon_i$
- Therefore: $\rho_i + \varepsilon_i = 1$

$$\rightarrow \rho_i = 1 - \varepsilon_i$$

$$J_i = \varepsilon_i E_b + (1 - \varepsilon_i) G_i$$

$$G_i = \frac{J_i - \varepsilon_i E_b}{1 - \varepsilon_i}$$
Net Rate of Radiation Heat Transfer from a Diffuse Gray Surface

\[ \dot{Q}_i = \left( \text{Radiation leaving entire surface } i \right) - \left( \text{Radiation incident on entire surface } i \right) \]

\[ = A_i (J_i - G_i) \]

\[ = A_i \left( J_i - \frac{J_i - \varepsilon_i E_b}{1 - \varepsilon_i} \right) \]

\[ = \frac{A_i \varepsilon_i}{1 - \varepsilon_i} (E_{bi} - J_i) \]
Radiation Heat Transfer in Two-Surface Enclosures

\[ \dot{Q}_{12} = \frac{\sigma(T_1^4 - T_2^4)}{1 - \varepsilon_1} + \frac{1}{A_1 F_{12}} + \frac{1}{A_2 \varepsilon_2} \]

This is true for any two diffuse gray surfaces.

Example: Radiation from a horizontal solar collector to the sky at night

- The sky can be considered a blackbody at a temperature below ambient