Chapter 5: Radiation

Repeated Questions:

1. Kirchhoff's Law:

- **Q.** State and Prove Kirchhoff's Law of Radiation. **(SUMMER 2023, 7 Marks; WINTER 2023, 3 Marks; WINTER 2025, 4 Marks OR)**

Answer:

- **Statement:** At thermal equilibrium, the emissivity of a body at a given temperature and wavelength is equal to its absorptivity at the same temperature and wavelength.

$$\boxed{\varepsilon_\lambda = \alpha_\lambda}$$

For a gray body (properties independent of wavelength):

$$\boxed{\varepsilon = \alpha}$$

Proof:

1. Consider a small body of surface area A, emissivity ε, absorptivity α, placed inside an evacuated isothermal black enclosure at temperature T.
2. In thermal equilibrium, the body must emit exactly as much radiation as it absorbs; otherwise its temperature would change.
3. Radiation emitted by the body:

$$Q_{emit} = \varepsilon A \sigma T^4$$

4. Radiation absorbed by the body from the black enclosure (which emits $E_b = \sigma T^4$):

$$Q_{abs} = \alpha A \sigma T^4$$

5. For thermal equilibrium:

$$Q_{emit} = Q_{abs}$$
$$\varepsilon A \sigma T^4 = \alpha A \sigma T^4$$
$$\boxed{\varepsilon = \alpha}$$

This proves Kirchhoff's law.

Significance:

- Good absorbers are good emitters.
- A black body ($\alpha = 1$) is also a perfect emitter ($\varepsilon = 1$).
- At a given temperature, no surface can emit more than a black body.

- **Q.** State and explain Kirchhoff's law of radiation. **(WINTER 2025, 4 Marks OR)**

Answer:

- **Statement:** At thermal equilibrium, the emissivity of a body at a given temperature and wavelength is equal to its absorptivity at the same temperature and wavelength.

$$\boxed{\varepsilon_\lambda = \alpha_\lambda}$$

For a gray body (properties independent of wavelength):

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$$\varepsilon A \sigma T^4 = \alpha A \sigma T^4$$
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This proves Kirchhoff's law.

Significance:

- Good absorbers are good emitters.
- A black body ($\alpha = 1$) is also a perfect emitter ($\varepsilon = 1$).
- At a given temperature, no surface can emit more than a black body.

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2. Radiation Terms & Definitions:

- **Q.** Define and explain terms: Absorptivity, Reflectivity, Transmissivity, Emissivity, Black/Grey Body. **(SUMMER 2023, 3 Marks; SUMMER 2024, 4 Marks; SUMMER 2025, 7 Marks OR; WINTER 2025, 3 Marks; WINTER 2025, 3 Marks OR; SUMMER 2026, 3 Marks)**

Answer:

- **Absorptivity (α):** Fraction of incident radiation absorbed by a surface.

$$\boxed{\alpha = \frac{G_{abs}}{G}}$$

- **Reflectivity (ρ):** Fraction of incident radiation reflected by a surface.

$$\boxed{\rho = \frac{G_{ref}}{G}}$$

- **Transmissivity (τ):** Fraction of incident radiation transmitted through a body.

$$\boxed{\tau = \frac{G_{tr}}{G}}$$

- **Emissivity (ε):** Ratio of emissive power of a real surface to that of a black body at the same temperature.

$$\boxed{\varepsilon = \frac{E}{E_b}}$$

$0 \leq \varepsilon \leq 1$.

- **Black body:** A perfect absorber and perfect emitter; $\alpha = 1$, $\rho = 0$, $\tau = 0$, $\varepsilon = 1$.
- **White body:** A perfect reflector; $\alpha = 0$, $\rho = 1$, $\tau = 0$.
- **Opaque body:** No transmission; $\tau = 0$, so $\alpha + \rho = 1$.
- **Gray body:** A real body whose emissivity and absorptivity are constant and independent of wavelength; $\varepsilon = \alpha < 1$.

Relation:

$$\boxed{\alpha + \rho + \tau = 1}$$

For opaque surfaces:

$$\boxed{\alpha + \rho = 1}$$

- **Q.** Define Black body, White body, Opaque body. **(WINTER 2025, 3 Marks)**

Answer:

- **Absorptivity (α):** Fraction of incident radiation absorbed by a surface.

$$\boxed{\alpha = \frac{G_{abs}}{G}}$$

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Relation:

$$\boxed{\alpha + \rho + \tau = 1}$$

For opaque surfaces:

$$\boxed{\alpha + \rho = 1}$$

- **Q.** Define Absorptivity, Reflectivity and Transmissivity of radiation. **(WINTER 2025, 3 Marks OR)**

Answer:

- **Absorptivity (α):** Fraction of incident radiation absorbed by a surface.

$$\boxed{\alpha = \frac{G_{abs}}{G}}$$

- **Reflectivity (ρ):** Fraction of incident radiation reflected by a surface.

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Relation:

$$\boxed{\alpha + \rho + \tau = 1}$$

For opaque surfaces:

$$\boxed{\alpha + \rho = 1}$$

- **Q.** Define Black body, White body, Gray body. **(SUMMER 2026, 3 Marks)**

Answer:

- **Absorptivity (α):** Fraction of incident radiation absorbed by a surface.

$$\boxed{\alpha = \frac{G_{abs}}{G}}$$

- **Reflectivity (ρ):** Fraction of incident radiation reflected by a surface.

$$\boxed{\rho = \frac{G_{ref}}{G}}$$

- **Transmissivity (τ):** Fraction of incident radiation transmitted through a body.

$$\boxed{\tau = \frac{G_{tr}}{G}}$$

- **Emissivity (ε):** Ratio of emissive power of a real surface to that of a black body at the same temperature.

$$\boxed{\varepsilon = \frac{E}{E_b}}$$

$0 \leq \varepsilon \leq 1$.

- **Black body:** A perfect absorber and perfect emitter; $\alpha = 1$, $\rho = 0$, $\tau = 0$, $\varepsilon = 1$.
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- **Gray body:** A real body whose emissivity and absorptivity are constant and independent of wavelength; $\varepsilon = \alpha < 1$.

Relation:

$$\boxed{\alpha + \rho + \tau = 1}$$

For opaque surfaces:

$$\boxed{\alpha + \rho = 1}$$

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3. Emissive Power & Intensity of Radiation:

- **Q.** Prove that Total Emissive Power, Eb = π × Ib (Intensity). **(SUMMER 2022, 7 Marks; WINTER 2022, 7 Marks; SUMMER 2026, 7 Marks)**

Answer:

- **Definition:** Intensity of radiation I is the rate of radiant energy emitted per unit solid angle per unit projected area normal to the direction of radiation.

$$I = \frac{dQ}{dA\cos\theta\, d\omega}$$

Units: $W/m^2\, sr$.

Proof that $E_b = \pi I_b$ (total emissive power of a black body):

Consider a black body emitting radiation in all directions. The intensity I_b is uniform (Lambert's cosine law).

For a differential area dA, the radiation emitted in a direction at angle θ from the normal, within solid angle $d\omega$, is:

$$dQ = I_b \, dA\cos\theta \, d\omega$$

In spherical coordinates:

$$d\omega = \sin\theta \, d\theta \, d\phi$$

Total emissive power (hemispherical):

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

Integrate:

$$E_b = I_b \int_0^{2\pi} d\,\phi \int_0^{\pi/2} \cos\theta \sin\theta \, d\theta$$

$$\int_0^{\pi/2} \cos\theta \sin\theta \, d\theta = \frac{1}{2}$$

$$E_b = I_b (2\pi)\left(\frac{1}{2}\right)$$

$$\boxed{E_b = \pi I_b}$$

Intensity of normal radiation:

$$\boxed{I_{bn} = \frac{E_b}{\pi}}$$

Thus, the intensity of normal radiation is $1/\pi$ times the total emissive power.

- **Q.** Define Intensity of radiation. Prove that the intensity of normal radiation is 1/π times the total emissive power. **(SUMMER 2026, 7 Marks)**

Answer:

- **Definition:** Intensity of radiation I is the rate of radiant energy emitted per unit solid angle per unit projected area normal to the direction of radiation.

$$I = \frac{dQ}{dA\cos\theta \, d\omega}$$

Units: $W/m^2 \, sr$.

Proof that $E_b = \pi I_b$ (total emissive power of a black body):

Consider a black body emitting radiation in all directions. The intensity I_b is uniform (Lambert's cosine law).

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$$dQ = I_b \, dA\cos\theta \, d\omega$$

In spherical coordinates:

$$d\omega = \sin\theta \, d\theta \, d\phi$$

Total emissive power (hemispherical):

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

Integrate:

$$E_b = I_b \int_0^{2\pi} d\,\phi \int_0^{\pi/2} \cos\theta \sin\theta \, d\theta$$

$$\int_0^{\pi/2} \cos\theta \sin\theta \, d\theta = \frac{1}{2}$$

$$E_b = I_b(2\pi)\left(\frac{1}{2}\right)$$

$$\boxed{E_b = \pi I_b}$$

Intensity of normal radiation:

$$\boxed{I_{bn} = \frac{E_b}{\pi}}$$

Thus, the intensity of normal radiation is $1/\pi$ times the total emissive power.

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4. Radiation Shields:

- **Q.** Radiation Shields: Concept and Numerical Problems. **(WINTER 2022, 7 Marks OR; SUMMER 2024, 3 Marks; WINTER 2024, 7 Marks OR; SUMMER 2025, 3 Marks; SUMMER 2026, 4 Marks)**

Answer:

- **Concept:** A radiation shield is a thin, highly reflective surface placed between two surfaces to reduce radiative heat exchange by introducing additional thermal resistance.

Utility:

- Reduces heat transfer by radiation.
- Used in cryogenics, spacecraft, thermos flasks, and furnaces.
- Multiple shields greatly reduce heat transfer (roughly $1/(n+1)$ for n shields between two black surfaces).

For two large parallel black plates with n shields (all black):

$$\boxed{q_{\text{with shields}} = \frac{\sigma(T_1^4 - T_2^4)}{n+1}}$$

Without shields:

$$q_{\text{without}} = \sigma(T_1^4 - T_2^4)$$

Numerical method:

1. Compute radiation resistance between surfaces without shield:

$$R_{12} = \frac{1}{A_1 F_{12}}$$

2. For a shield, add resistances in series:

$$R_{total} = R_{13} + R_{32}$$

3. Heat transfer:

$$Q = \frac{\sigma(T_1^4 - T_2^4)}{R_{total}}$$

- **Q.** Explain the utility of radiation shields. **(SUMMER 2026, 4 Marks)**

Answer:

- **Concept:** A radiation shield is a thin, highly reflective surface placed between two surfaces to reduce radiative heat exchange by introducing additional thermal resistance.

Utility:

- Reduces heat transfer by radiation.
- Used in cryogenics, spacecraft, thermos flasks, and furnaces.
- Multiple shields greatly reduce heat transfer (roughly $1/(n+1)$ for n shields between two black surfaces).

For two large parallel black plates with n shields (all black):

$$\boxed{q_{\text{with shields}} = \frac{\sigma(T_1^4 - T_2^4)}{n+1}}$$

Without shields:

$$q_{\text{without}} = \sigma(T_1^4 - T_2^4)$$

Numerical method:

1. Compute radiation resistance between surfaces without shield:

$$R_{12} = \frac{1}{A_1 F_{12}}$$

2. For a shield, add resistances in series:

$$R_{total} = R_{13} + R_{32}$$

3. Heat transfer:

$$Q = \frac{\sigma(T_1^4 - T_2^4)}{R_{total}}$$

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5. Laws of Radiation (Planck, Wien, Stefan-Boltzmann):

- **Q.** State and explain the laws (Planck's, Wien's, Stefan-Boltzmann). **(SUMMER 2022, 3 Marks; SUMMER 2025, 7 Marks OR; WINTER 2025, 4 Marks)**

Answer:

- **Planck's law:** Spectral emissive power of a black body at wavelength λ and temperature T:

$$\boxed{E_{b\lambda} = \frac{C_1 \lambda^{-5}}{e^{C_2/(\lambda T)} - 1}}$$

where $C_1 = 3.742 \times 10^{-16}\ W \cdot m^2$, $C_2 = 1.4388 \times 10^{-2}\ m \cdot K$.

- **Wien's displacement law:** Wavelength of maximum emission is inversely proportional to absolute temperature:

$$\boxed{\lambda_{max} T = 2898\ \mu m \cdot K}$$

As T increases, λ_{max} shifts to shorter wavelengths.

- **Stefan–Boltzmann law:** Total emissive power of a black body:

$$\boxed{E_b = \sigma T^4}$$

For a real surface:

$$\boxed{E = \varepsilon \sigma T^4}$$

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

- **Q.** State and explain Wien's displacement law. **(WINTER 2025, 4 Marks)**

Answer:

- **Planck's law:** Spectral emissive power of a black body at wavelength λ and temperature T:

$$\boxed{E_{b\lambda} = \frac{C_1 \lambda^{-5}}{e^{C_2/(\lambda T)} - 1}}$$

where $C_1 = 3.742 \times 10^{-16}\ W \cdot m^2$, $C_2 = 1.4388 \times 10^{-2}\ m \cdot K$.

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$$\boxed{E_b = \sigma T^4}$$

For a real surface:

$$\boxed{E = \varepsilon \sigma T^4}$$

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

Other Important Questions:

1. Numericals on Radiation Laws:

- **Q.** Numericals on monochromatic energy and total energy using Planck's law. **(SUMMER 2022, 7 Marks)**

Answer:

Method (when data given):

1. Use Planck's law to find spectral emissive power at given λ and T:

$$E_{b\lambda} = \frac{C_1 \lambda^{-5}}{e^{C_2/(\lambda T)} - 1}$$

2. Monochromatic emissive power of a real surface:

$$E_\lambda = \varepsilon_\lambda E_{b\lambda}$$

3. Total emissive power:

$$E = \int_0^\infty E_\lambda \, d\lambda = \varepsilon \sigma T^4$$

4. For a given wavelength band λ_1 to λ_2, use black body radiation functions $F_{0-\lambda T}$:

$$E_{\lambda_1 - \lambda_2} = \sigma T^4 \left(F_{0-\lambda_2 T} - F_{0-\lambda_1 T}\right)$$

- **Final Answer:** Substitute numerical values into the above equations to obtain $E_{b\lambda}$, E_λ, and E.

- **Q.** A hot body at 800 K having an area of 0.12 m². Calculate: (i) Total rate of energy emitted, (ii) intensity of normal radiation. **(WINTER 2025, 7 Marks)**

Answer:

Given:

- Temperature $T = 800\ K$
- Area $A = 0.12\ m^2$
- Assume black body ($\varepsilon = 1$)
- $\sigma = 5.67 \times 10^{-8}\ W/m^2K^4$

To find: (i) Total rate of energy emitted Q, (ii) Intensity of normal radiation I_n.

Formula:

$$Q = A\sigma T^4$$

$$I_n = \frac{E_b}{\pi} = \frac{\sigma T^4}{\pi}$$

Solution:

$$T^4 = (800)^4 = 4.096 \times 10^{11}$$

$$E_b = \sigma T^4 = 5.67 \times 10^{-8} \times 4.096 \times 10^{11} = 23224\ W/m^2$$

Total rate:

$$Q = 0.12 \times 23224 = 2786.9\ W$$

Intensity of normal radiation:

$$I_n = \frac{23224}{\pi} = 7392.6\ W/m^2\ sr$$

Final Answer:

$$\boxed{Q \approx 2787\ W, \quad I_n \approx 7393\ W/m^2\ sr}$$

- **Q.** State Stefan-Boltzmann law. Determine the surface temperature of sun and emissive power at that temperature when the sun emits radiation at λ = 0.52 µm. Assuming sun as black body. **(WINTER 2025, 7 Marks OR)**

Answer:

- **Stefan–Boltzmann law:** Total emissive power of a black body:

$$\boxed{E_b = \sigma T^4}$$

For a real surface:

$$\boxed{E = \varepsilon \sigma T^4}$$

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

Given:

- $\lambda_{max} = 0.52\ \mu m = 0.52 \times 10^{-6}\ m$
- Sun assumed black body.
- Wien's constant $b = 2898\ \mu m \cdot K$

To find: Surface temperature T and emissive power E_b.

Formula:

$$\lambda_{max} T = 2898\ \mu m \cdot K$$
$$E_b = \sigma T^4$$

Solution:

Temperature:

$$T = \frac{2898}{0.52} = 5573\ K$$

Emissive power:

$$E_b = 5.67 \times 10^{-8} \times (5573)^4$$
$$(5573)^4 = 9.646 \times 10^{14}$$
$$E_b = 5.67 \times 10^{-8} \times 9.646 \times 10^{14} = 5.47 \times 10^7\ W/m^2$$

Final Answer:

$$\boxed{T \approx 5573\ K, \quad E_b \approx 5.47 \times 10^7\ W/m^2}$$

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2. Radiation Heat Exchange & Shape Factor:

- **Q.** Numerical on radiation heat exchange between two surfaces. **(WINTER 2023, 7 Marks)**

Answer:

General formula:

$$\boxed{Q_{1-2} = \frac{\sigma(T_1^4 - T_2^4)}{\frac{1-\varepsilon_1}{\varepsilon_1 A_1} + \frac{1}{A_1 F_{12}} + \frac{1-\varepsilon_2}{\varepsilon_2 A_2}}}$$

For two large parallel plates ($A_1 = A_2 = A$, $F_{12} = 1$):

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

For two concentric cylinders/spheres ($F_{12} = 1$):

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

- **Method:** Identify geometry, compute shape factor, substitute in appropriate resistance network, and solve for Q.

- **Q.** Define shape factor and list any two salient features of it. **(SUMMER 2026, 3 Marks OR)**

Answer:

- **Definition:** The shape factor (view factor) F_{12} is the fraction of radiation leaving surface 1 that is directly intercepted by surface 2.

$$\boxed{F_{12} = \frac{Q_{1\to2}}{Q_1}}$$

Salient features:

- Reciprocity relation:

$$\boxed{A_1F_{12} = A_2F_{21}}$$

- Summation rule for an enclosure:

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

- $F_{ii} = 0$ for flat or convex surfaces; $F_{ii} > 0$ for concave surfaces.
- Shape factor depends only on geometry and orientation, not on temperature or surface properties.

- **Q.** Consider a thin hollow cylinder of 8 cm diameter and 10 cm length. If the radiant shape factor of the circular surface of this cylinder is 0.172, find the shape factor of curved surface of cylinder with respect to itself. [Diagram required – refer to the original question paper of SUMMER 2026] **(SUMMER 2026, 7 Marks)**

Answer:

Given:

- Cylinder diameter $D = 8\ cm = 0.08\ m$
- Length $L = 10\ cm = 0.10\ m$
- Radiant shape factor of the circular surface 0.172; taken as $F_{12} = 0.172$, where 1 and 2 are the two circular ends.

To find: F_{cc} (curved surface with respect to itself).

Solution:

Let surface 1 = top circular end, surface 2 = bottom circular end, surface 3 = curved surface.

For surface 1 (flat), $F_{11} = 0$. By summation:

$$F_{12} + F_{13} = 1$$

Given $F_{12} = 0.172$, so:

$$F_{13} = 1 - 0.172 = 0.828$$

By reciprocity:

$$A_1F_{13} = A_3F_{31}$$

Areas:

$$A_1 = \frac{\pi D^2}{4} = \frac{\pi(0.08)^2}{4} = 0.005027\ m^2$$
$$A_3 = \pi DL = \pi(0.08)(0.10) = 0.02513\ m^2$$
$$F_{31} = \frac{A_1}{A_3}F_{13} = \frac{0.005027}{0.02513} \times 0.828 = 0.1656$$

For surface 3 (curved), by symmetry $F_{31} = F_{32}$. Summation:

$$F_{31} + F_{32} + F_{33} = 1$$
$$2(0.1656) + F_{33} = 1$$
$$F_{33} = 1 - 0.3312 = 0.6688$$

Final Answer:

$$\boxed{F_{cc} \approx 0.669}$$

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3. Combined Convection & Radiation:

- **Q.** A polished metal pipe 50 cm outside diameter and 370 K temperature at the outer surface is exposed to ambient conditions at 295 K temperature. The emissivity of the surface is 0.2 and the convection coefficient of heat transfer is 11.35 W/m²-deg. Calculate the heat transfer by radiation and natural convection per meter length of the pipe. Take thermal radiation constant σb = 5.67 × 10^{-8} W/m²-deg K⁴. Find the overall heat transfer coefficient of heat by combined mode of convection and radiation. **(SUMMER 2026 OR)**

Answer:

Given:

- Pipe outside diameter $D = 50\ cm = 0.5\ m$
- Surface temperature $T_s = 370\ K$
- Ambient temperature $T_\infty = 295\ K$
- Emissivity $\varepsilon = 0.2$
- Convection coefficient $h = 11.35\ W/m^2K$
- $\sigma = 5.67 \times 10^{-8}\ W/m^2K^4$

To find: Radiation heat transfer per meter Q_{rad}, natural convection heat transfer per meter Q_{conv}, and overall heat transfer coefficient U for combined mode.

Formula:

$$Q_{rad} = \varepsilon\sigma(\pi DL)(T_s^4 - T_\infty^4)$$
$$Q_{conv} = h(\pi DL)(T_s - T_\infty)$$
$$Q_{total} = Q_{rad} + Q_{conv}$$
$$U = \frac{Q_{total}}{A(T_s - T_\infty)}$$

with $A = \pi DL$ and $L = 1\ m$.

Solution:

Surface area per meter:

$$A = \pi(0.5)(1) = 1.5708\ m^2$$

Radiation:

$$T_s^4 - T_\infty^4 = 370^4 - 295^4 = 1.874 \times 10^{10} - 7.57 \times 10^9 = 1.117 \times 10^{10}$$
$$Q_{rad} = 0.2 \times 5.67 \times 10^{-8} \times 1.5708 \times 1.117 \times 10^{10}$$

$$Q_{rad} = 0.2 \times 5.67 \times 1.5708 \times 111.7 = 198.8 \text{ W/m}$$

Convection:

$$Q_{conv} = 11.35 \times 1.5708 \times (370 - 295) = 11.35 \times 1.5708 \times 75 = 1337.4 \text{ W/m}$$

Total:

$$Q_{total} = 198.8 + 1337.4 = 1536.2 \text{ W/m}$$

Overall heat transfer coefficient:

$$U = \frac{1536.2}{1.5708 \times 75} = \frac{1536.2}{117.81} = 13.04\ W/m^2K$$

Final Answer:

$$\boxed{Q_{rad} \approx 199 \text{ W/m},\ Q_{conv} \approx 1337 \text{ W/m},\ Q_{total} \approx 1536 \text{ W/m},\ U \approx 13.0\ W/m^2K}$$
