Radiation Heat Transfer

Dr. Sayantan Sengupta
Dept. of Mechanical Engineering
NIT Durgapur

Lecture 2 **Emission, Absorption, Irradiation, Radiosity**

Fundamental Concepts

- Attention is focused on thermal radiation, whose origins are associated with emission from matter at an absolute temperature $T > 0$.

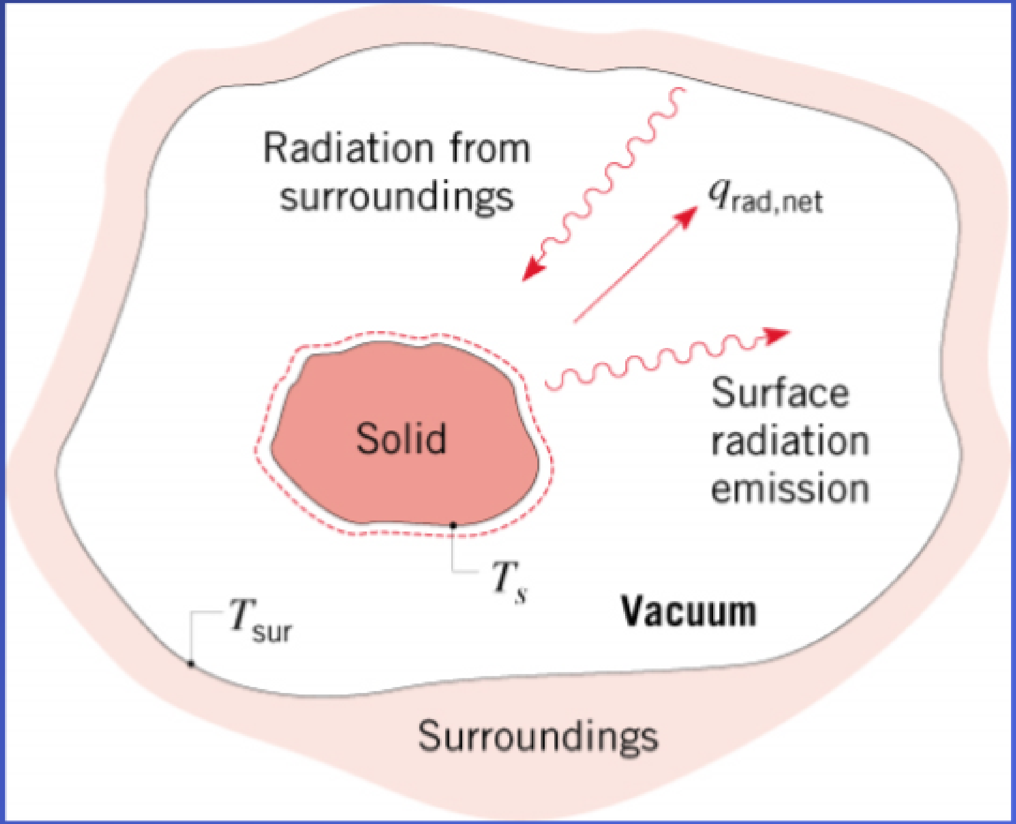
- Emission is due to oscillations and transitions of the many electrons that comprise matter, which are, in turn, sustained by the thermal energy of the matter.

- Emission corresponds to heat transfer from the matter and hence to a reduction in thermal energy stored by the matter.

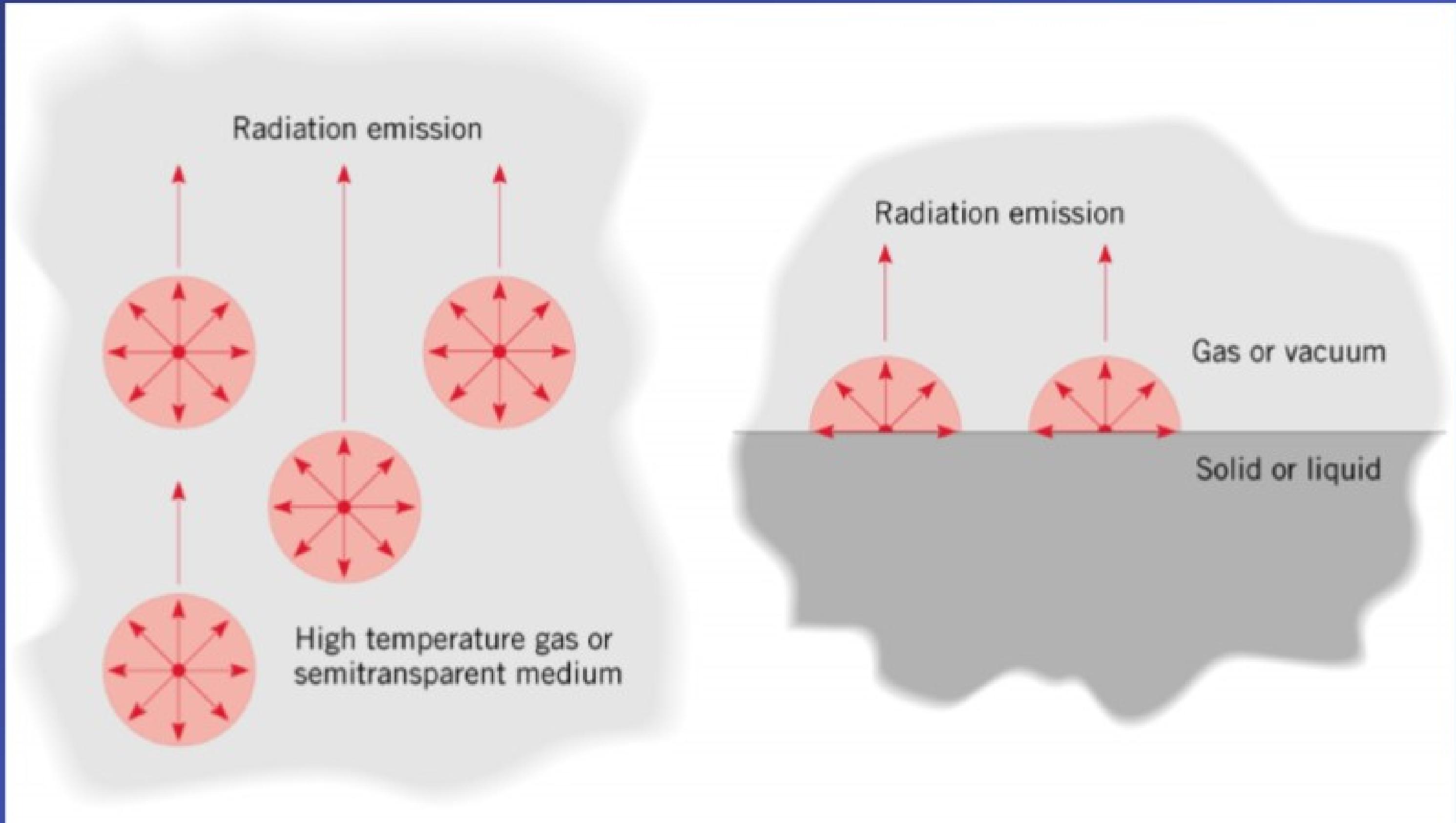
- Absorption results in heat transfer to the matter and hence an increase in thermal energy stored by the matter.

- Consider a solid of temperature T_s in an evacuated enclosure whose walls are at a fixed temperature T_{sur} :

  - What changes occur if $T_s > T_{sur}$? Why?
  - What changes occur if $T_s < T_{sur}$? Why?



- Emission from a gas or a semitransparent solid / liquid is a volumetric phenomenon.
- Emission from an opaque solid / liquid is a surface phenomenon.



(*a*) (*b*)

For an opaque solid or liquid, emission originates from atoms and molecules within $1\,\mu m$ of the surface.

Consideration of Participating Media

In this course, we shall be concerned only with situations involving radiation exchange between surfaces, in which space between the surfaces is considered to be vacuum or occupied by a gas which does not participate in the radiative exchange in any way. Thus the gas neither absorbs any radiation passing from one surface to another, nor does it emit any radiation by virtue of it own temperature level. Radiation exchange problems involving gases which themselves absorb and emit radiation are also of interest in certain high temperature applications. However, their analysis is more involved and will not be discussed in this course.

Emission

spectral, hemispherical emissive power E_λ ($W/m^2 \cdot \mu m$)

the rate at which radiation of wavelength λ is emitted in *all directions* from a surface per unit wavelength interval $d\lambda$ about λ and per unit surface area.

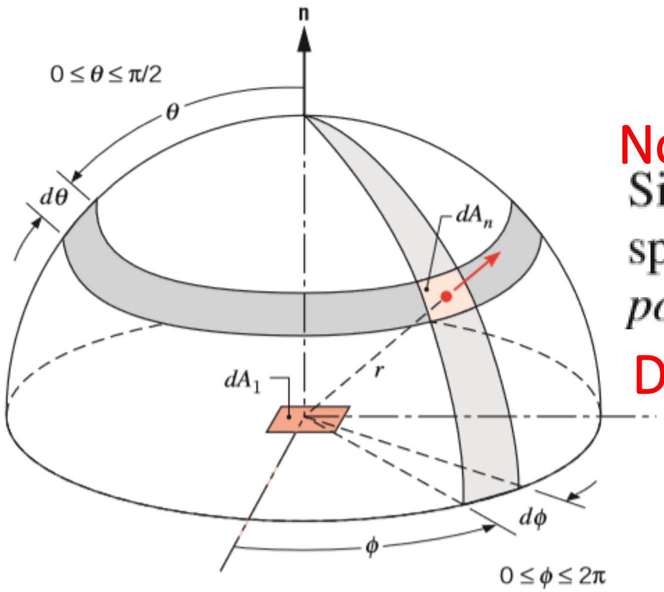
$$E_\lambda(\lambda) = q''_\lambda(\lambda) = \int_0^{2\pi} \int_0^{\pi/2} I_{\lambda,e}(\lambda, \theta, \phi) \cos\theta \sin\theta \, d\theta \, d\phi$$

Note: E_λ is a flux based on the *actual* surface area, whereas $I_{\lambda,e}$ is based on the *projected* area.

total, hemispherical emissive power, E (W/m^2)

the rate at which radiation is emitted per unit area at all possible wavelengths and in all possible directions.

$$E = \int_0^\infty E_\lambda(\lambda) \, d\lambda$$



Note:
Since the term "emissive power" implies emission in all directions, the adjective "hemispherical" is redundant and is often dropped. One then speaks of the *spectral emissive power* E_λ, or the *total emissive power* E

Diffuse: Modifier referring to the directional independence of the intensity associated with emitted, reflected, or incident radiation.

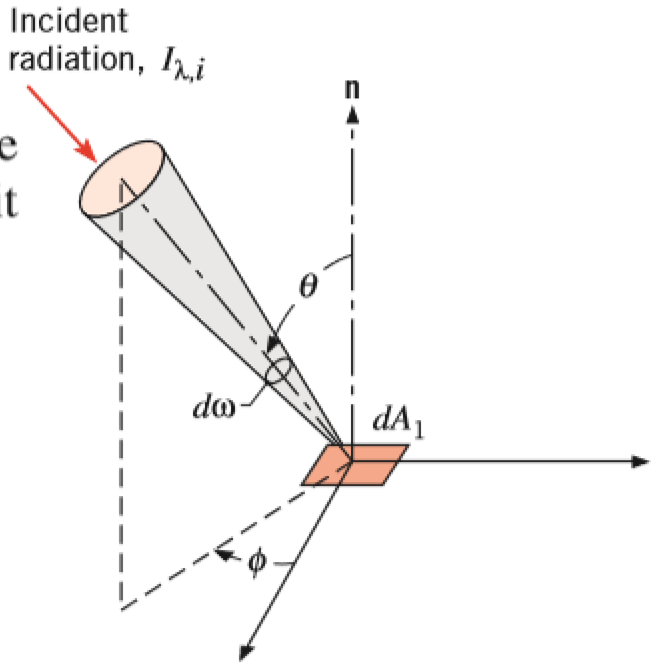
For Diffuse Emitter: $I_{\lambda,e}(\lambda, \theta, \phi) = I_{\lambda,e}(\lambda)$

$$E_\lambda(\lambda) = \pi I_{\lambda,e}(\lambda)$$

$$E = \pi I_e$$

where I_e is the *total intensity* of the emitted radiation.

Irradiation



$I_{\lambda,i}(\lambda, \theta, \phi)$ is defined as the rate at which radiant energy of wavelength λ is incident from the (θ, ϕ) direction, per unit area of the *intercepting surface* normal to this direction, per unit solid angle about this direction, and per unit wavelength interval $d\lambda$ about λ.

The intensity of the incident radiation may be related to the irradiation, which encompasses radiation incident *from all directions*. The *spectral irradiation* G_λ $(\mathrm{W/m^2 \cdot \mu m})$ is defined as the rate at which radiation of wavelength λ is incident on a surface, per unit area of the surface and per unit wavelength interval $d\lambda$ about λ. Accordingly,

$$G_\lambda(\lambda) = \int_0^{2\pi}\int_0^{\pi/2} I_{\lambda,i}(\lambda, \theta, \phi) \cos\theta \sin\theta \, d\theta \, d\phi$$

Note: G_λ is a flux based on the actual surface area, whereas $I_{\lambda,i}$ is defined in terms of the projected area.

total irradiation G $(\mathrm{W/m^2})$ represents the rate at which radiation is incident per unit area from all directions and at all wavelengths, it follows that

$$G = \int_0^\infty G_\lambda(\lambda) \, d\lambda$$

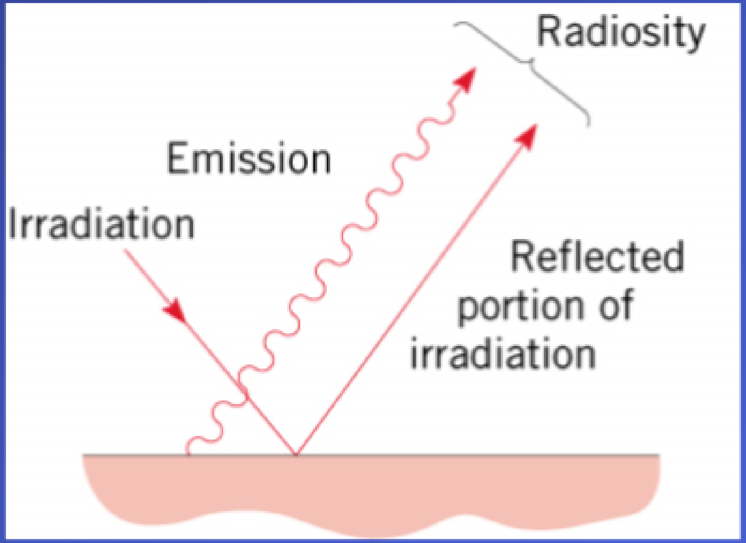
If the incident radiation is diffuse

$$G_\lambda(\lambda) = \pi I_{\lambda,i}(\lambda)$$

$$G = \pi I_i$$

Radiosity

- The radiosity of an opaque surface accounts for all of the radiation leaving the surface in all directions and may include contributions from both reflection and emission.



- With $I_{\lambda,e+r}$ designating the spectral intensity associated with radiation emitted by the surface and the reflection of incident radiation, the spectral radiosity $\left(\mathrm{W/m^2 \cdot \mu m}\right)$ is:

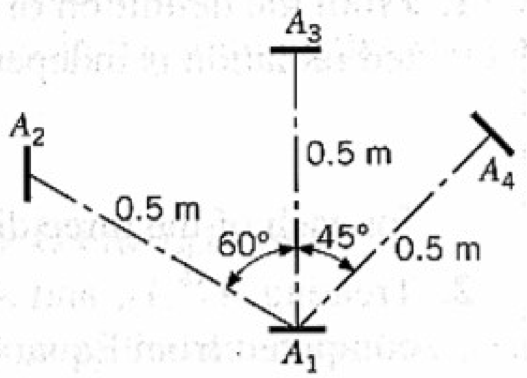
$$\boxed{J_\lambda(\lambda) = \int_0^{2\pi}\int_0^{\pi/2} I_{\lambda,e+r}(\lambda,\theta,\phi)\cos\theta\ \sin\theta\ d\theta\ d\phi}$$

and the total radiosity $\left(\mathrm{W/m^2}\right)$ is: $\boxed{J = \int_0^\infty J_\lambda(\lambda)\, d\lambda}$

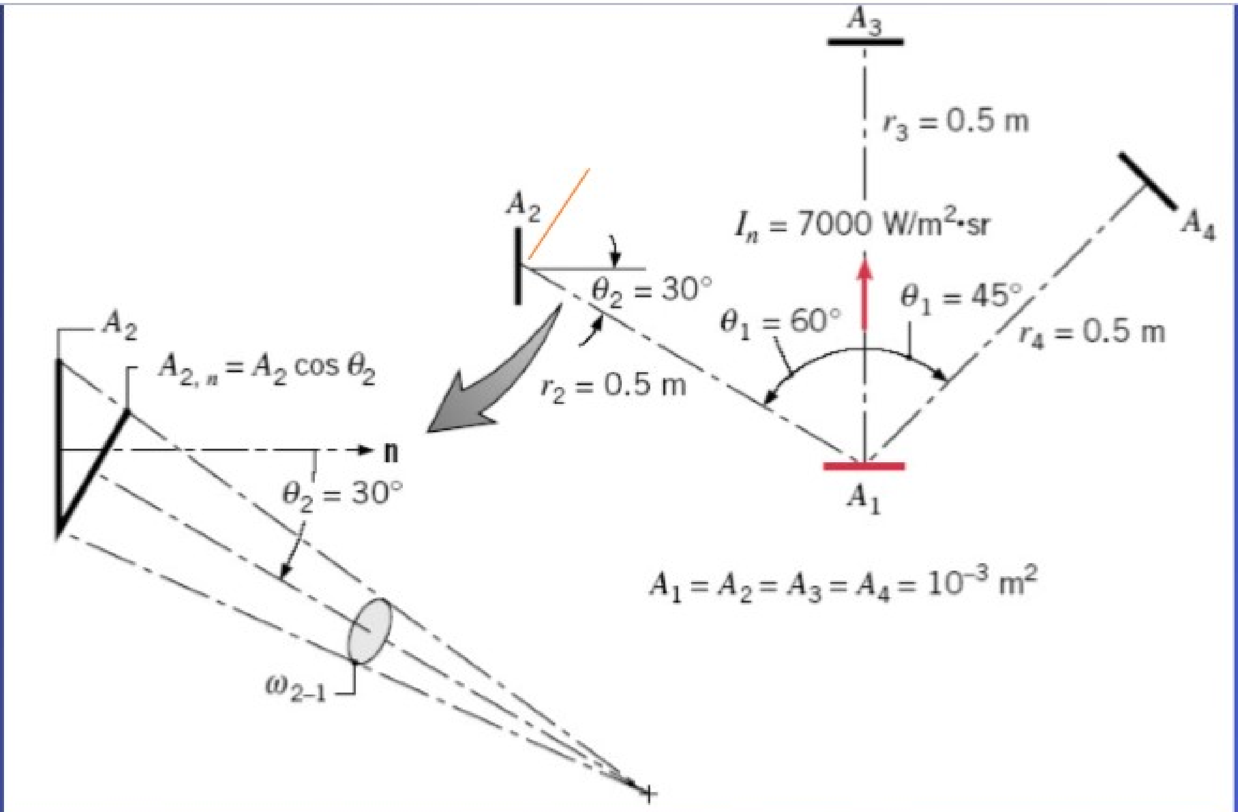
➢ How may J_λ and J be expressed if the surface emits and reflects diffusely?

Numerical Exp 1

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 $I_n = 7000\ W/m^2 \cdot sr$.



Radiation emitted from the surface is intercepted by three other surfaces of area $A_2 = A_3 = A_4 = 10^{-3}\ m^2$, which are 0.5 m from A_1 and are oriented as shown. 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?



Analysis:

1. From the definition of a diffuse emitter, we know that the intensity of the emitted radiation is independent of direction. Hence

$$\boxed{I = 7000 \text{ W/m}^2 \cdot \text{sr}} \quad \triangleleft$$

for each of the three directions.

2. Treating A_2, A_3, and A_4 as differential surface areas, the solid angles may be computed from Equation 12.2

$$d\omega \equiv \frac{dA_n}{r^2}$$

where dA_n is the projection of the surface normal to the direction of the radiation. Since surfaces A_3 and A_4 are normal to the direction of radiation, the solid angles subtended by these surfaces can be directly found from this equation as

$$\omega_{3-1} = \omega_{4-1} = \frac{A_3}{r^2} = \frac{10^{-3}\ \mathrm{m}^2}{(0.5\ \mathrm{m})^2} = 4.00 \times 10^{-3}\ \mathrm{sr} \qquad \triangleleft$$

Since surface A_2 is not normal to the direction of radiation, we use $dA_{n,2} = dA_2 \cos\theta_2$, where θ_2 is the angle between the surface normal and the direction of the radiation. Thus

$$\omega_{2-1} = \frac{A_2 \cos\theta_2}{r^2} = \frac{10^{-3}\ \mathrm{m}^2 \times \cos 30^\circ}{(0.5\ \mathrm{m})^2} = 3.46 \times 10^{-3}\ \mathrm{sr} \qquad \triangleleft$$

3. Approximating A_1 as a differential surface, the rate at which radiation is intercepted by each of the three surfaces may be found from Equation 12.6, which, for the total radiation, may be expressed as

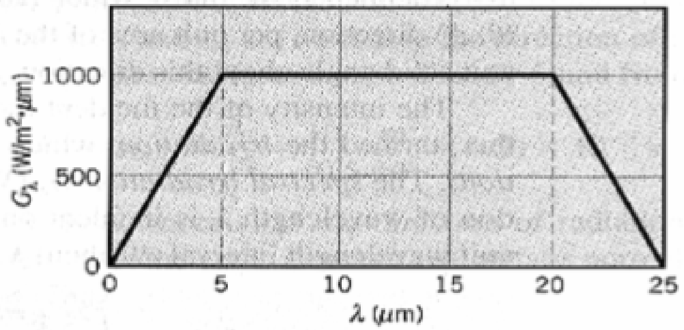
$$q_{1-j} = I \times A_1 \cos\theta_1 \times \omega_{j-1}$$

where θ_1 is the angle between the normal to surface 1 and the direction of the radiation. Hence

$$q_{1-2} = 7000\ \mathrm{W/m^2 \cdot sr}\,(10^{-3}\ \mathrm{m}^2 \times \cos 60^\circ)3.46 \times 10^{-3}\ \mathrm{sr}$$
$$= 12.1 \times 10^{-3}\ \mathrm{W} \qquad \triangleleft$$
$$q_{1-3} = 7000\ \mathrm{W/m^2 \cdot sr}\,(10^{-3}\ \mathrm{m}^2 \times \cos 0^\circ)4.00 \times 10^{-3}\ \mathrm{sr}$$
$$= 28.0 \times 10^{-3}\ \mathrm{W} \qquad \triangleleft$$
$$q_{1-4} = 7000\ \mathrm{W/m^2 \cdot sr}\,(10^{-3}\ \mathrm{m}^2 \times \cos 45^\circ)4.00 \times 10^{-3}\ \mathrm{sr}$$
$$= 19.8 \times 10^{-3}\ \mathrm{W} \qquad \triangleleft$$

Numerical Exp 2

The spectral distribution of surface irradiation is as follows:



What is the total irradiation?

SOLUTION

Known: Spectral distribution of surface irradiation.

Find: Total irradiation.

Analysis: The total irradiation may be obtained from Equation 12.14

$$G = \int_0^\infty G_\lambda \, d\lambda$$

The integral is readily evaluated by breaking it into parts. That is,

$$\boxed{G = \int_0^{5\mu m} G_\lambda \, d\lambda + \int_{5\mu m}^{20\mu m} G_\lambda \, d\lambda + \int_{20\mu m}^{25\mu m} G_\lambda \, d\lambda + \int_{25\mu m}^{\infty} G_\lambda \, d\lambda}$$

Hence

$$G = \tfrac{1}{2}(1000 \text{ W/m}^2 \cdot \mu\text{m})(5 - 0)\ \mu\text{m} + (1000 \text{ W/m}^2 \cdot \mu\text{m})(20 - 5)\ \mu\text{m} + \tfrac{1}{2}(1000 \text{ W/m}^2 \cdot \mu\text{m})(25 - 20)\ \mu\text{m} + 0$$

$$= (2500 + 15{,}000 + 2500) \text{ W/m}^2$$

$$G = 20{,}000 \text{ W/m}^2 \quad \triangleleft$$

Net Radiative Flux for an Opaque Surface

$$q''_{\text{rad}} = \int_0^{\infty}\int_0^{2\pi}\int_0^{\pi/2} I_{\lambda,e+r}(\lambda, \theta, \phi) \cos\theta \sin\theta \, d\theta \, d\phi \, d\lambda - \int_0^{\infty}\int_0^{2\pi}\int_0^{\pi/2} I_{\lambda,i}(\lambda, \theta, \phi) \cos\theta \sin\theta \, d\theta \, d\phi \, d\lambda$$

Thank you