MCE415
Heat and Mass Transfer

Lecture 06: 30/10/2017

Dr. Ayokunle O. Balogun (A212)
balogun.ayokunle@lmu.edu.ng

Class: Monday (1 – 3 pm)
Venue: B13

Etiquettes and MOP

- Attendance is a requirement.
- There may be class assessments, during or after lecture.
- Computational software will be employed in solving problems
- Conceptual understanding will be tested
- Lively discussions are integral part of the lectures.

Lecture content

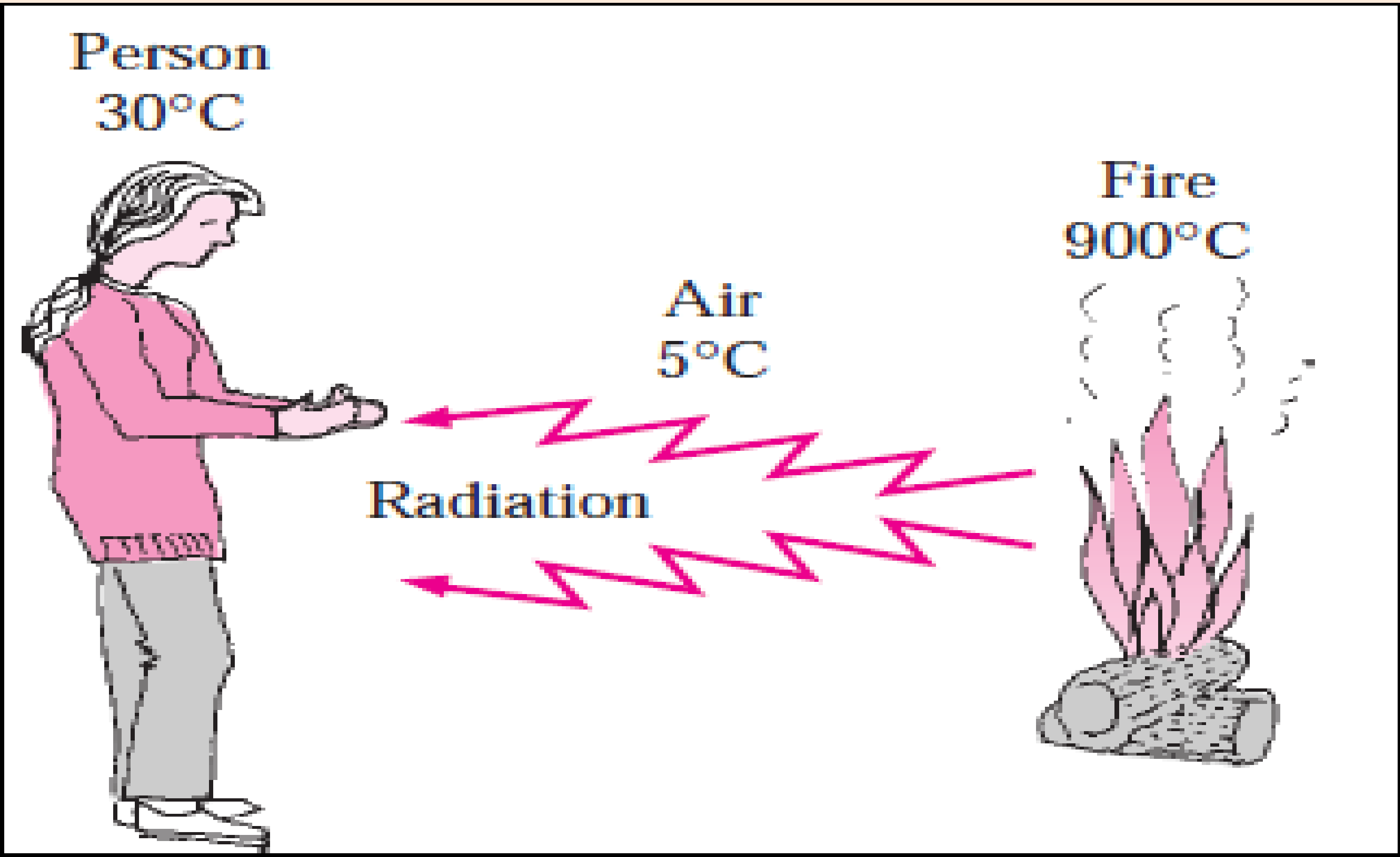
Radiation Heat Transfer

- Thermal Radiation
- Blackbody radiation
- Radiative Properties

Recommended textbook

- Fundamentals of Thermal-Fluid Sciences by Cengel Y.A., Turner R.H., & Cimbala J.M. 3rd edition

Conceptual Understanding



Thermal energy from the burning wood gets across to the human in cold weather! How?

THERMAL RADIATION

- The electromagnetic wave spectrum consists of diverse forms of radiations as shown in Fig 1.
- The type of electromagnetic radiation that deals with heat transfer phenomenon is called thermal radiation.
- Thermal radiation is the energy emitted on account of the vibrational and rotational motions of molecules, atoms and electrons of a substance.
- Radiation heat transfer is propagated by electromagnetic waves and does not require a material medium like convection and conduction heat transfer.

Radiation heat transfer is efficiently propagated through a vacuum at the speed of light (Fig 2).

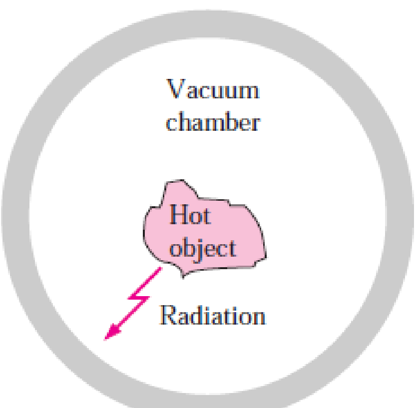


Fig 2: A hot object in a vacuum chamber loses heat by radiation

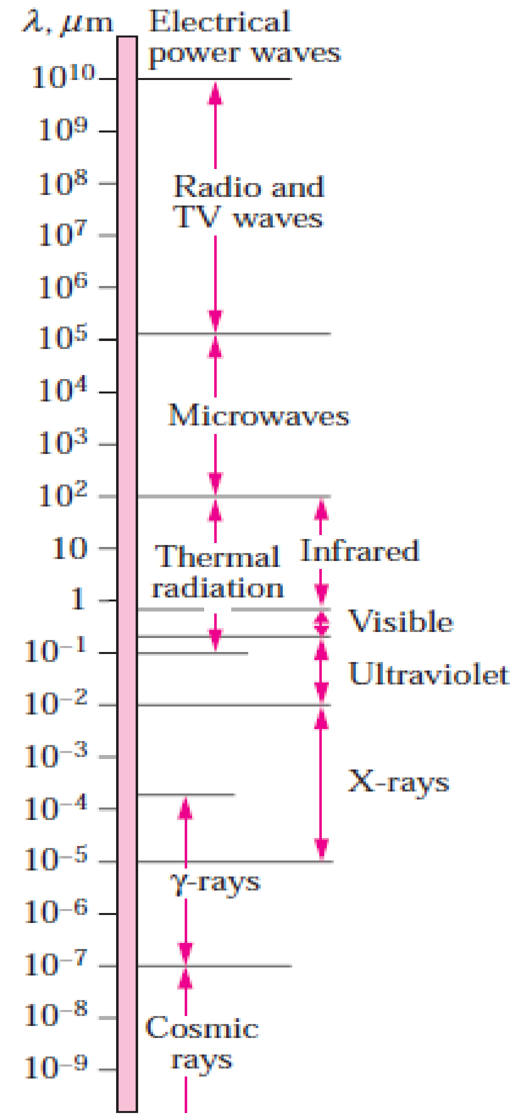


Fig 1: The electromagnetic wave spectrum

THERMAL RADIATION

- All bodies whose temperature is above absolute zero emit thermal radiation (Fig 3).
- Temperature is the measure of the molecular and atomic activities at the microscopic level and thus thermal radiation emission increases with rise in temperature.
- The primary interest in heat transfer studies is the energy emitted by a body on account of its temperature, therefore, our study here is limited to thermal radiation

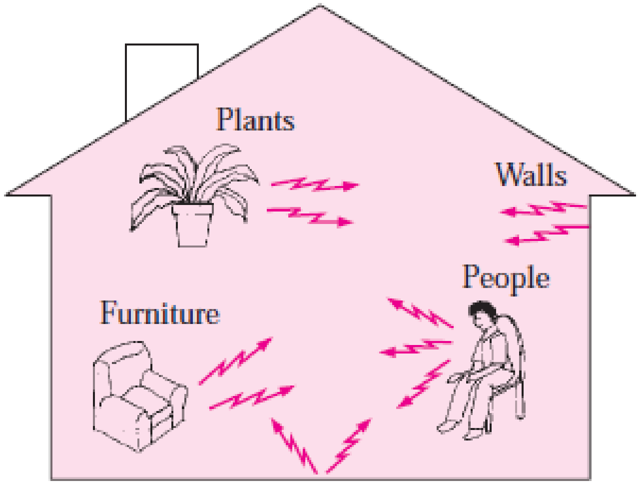
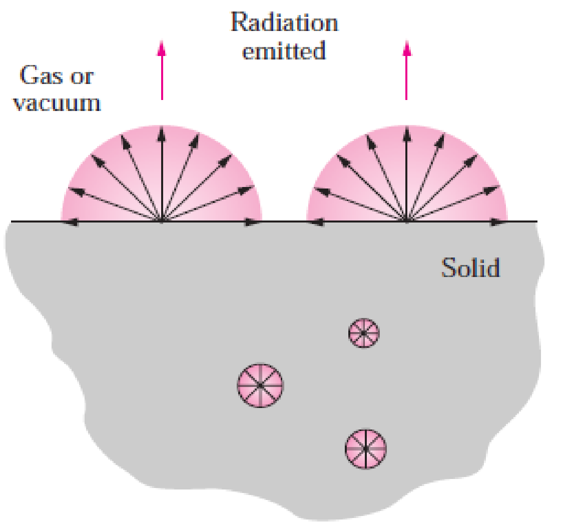


Fig 3: Everything around us constantly emits thermal radiation.



For opaque solids (nontransparent) such as metal, wood and rocks, radiation is treated as a surface phenomenon.

Fig 4: Radiation in opaque solids is considered a surface phenomenon since the radiation emitted only by the molecules at the surface can escape the solid.

- A body at absolute temp above zero emits radiation in all directions over a wide range of wavelengths.
- The amount of radiation energy emitted from a surface depends on the (i) material of the body, (ii) condition of its surface and (iii) surface temp.

> Different bodies may emit different amounts of radiation per unit surface area, even when they are at the same temperature.

- To determine the maximum amount of radiation energy a body emits, an *idealized body*, called a *blackbody* (*BB*) serves as a standard.
- A BB is a *perfect emitter and absorber of radiation*. At specified temp. and wavelength, no surface can emit more energy than a BB.
- A BB absorbs all incident radiation, regardless of wavelength and direction.
- A BB emits radiation energy uniformly in all directions per unit area normal to direction of emission (Fig 5). i.e., it is a *diffuse* emitter.

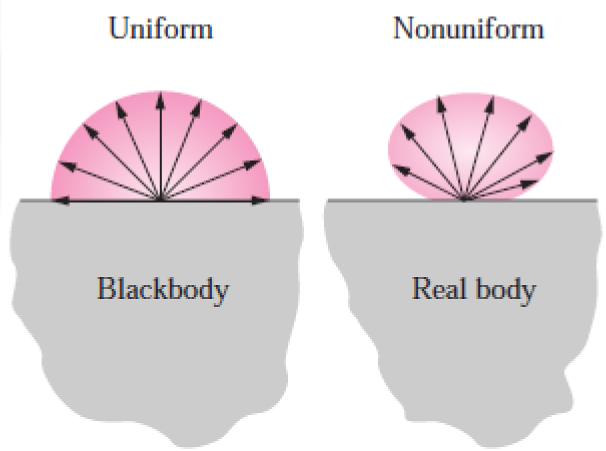


Fig 5: A BB is said to be a diffuse emitter since it emits radiation energy uniformly in all directions.

BLACKBODY RADIATION

- The radiation energy emitted by a BB is given by **Stefan-Boltzmann** law as:

$$E_b(T) = \sigma T^4 \qquad (\text{W/m}^2) \qquad 1$$

Where $\sigma = 5.670 \times 10^{-8}$ is Stefan-Boltzmann constant, T is the absolute temp of the surface in K and E_b is the total blackbody emissive power.

NOTE: There is a distinction between an idealized blackbody and an ordinary black surface.

- The spectral blackbody emissive power is expressed as **Planck's law** (Eq 2):

$$E_{b\lambda}(\lambda, T) = \frac{C_1}{\lambda^5[\exp(C_2/\lambda T) - 1]} \qquad (\text{W/m}^2 \cdot \mu\text{m}) \qquad 2$$

Where

$$C_1 = 2\pi h c_0^2 = 3.742 \times 10^8 \text{ W} \cdot \mu\text{m}^4/\text{m}^2$$

$$C_2 = hc_0/k = 1.439 \times 10^4 \ \mu\text{m} \cdot \text{K}$$

- T is the absolute temp of the surface, λ is the wavelength of the radiation emitted, and $k = 1.38065 \times 10^{-23}$ J/K is **Boltzmann's constant**. This relations is valid for a surface in a vacuum or a gas.
- For other media, C_1 is replaced by C_1/n^2, where n = refraction index of the medium. The term spectral indicates dependence on wavelength .

BLACKBODY RADIATION

- The variation of the spectral blackbody emissive power with wavelength is shown in Fig 6 for selected temp.
- Among other observations, the peak of the curve shifts toward shorter wavelength as temp increases.
- The wavelength at which the peak occurs for a specified temperature is given by **Wien's displacement law** as:

$$(\lambda T)_{\text{max power}} = 2897.8\ \mu\text{m} \cdot \text{K} \qquad 3$$

- Note the total BB emissive power , E_b, may be obtained by integrating the spectral BB emissive power, $E_{b\lambda}$, over the entire wavelength spectrum to yield

$$E_b(T) = \int_0^\infty E_{b\lambda}(\lambda, T)\, d\lambda = \sigma T^4 \qquad (\text{W/m}^2) \qquad 4$$

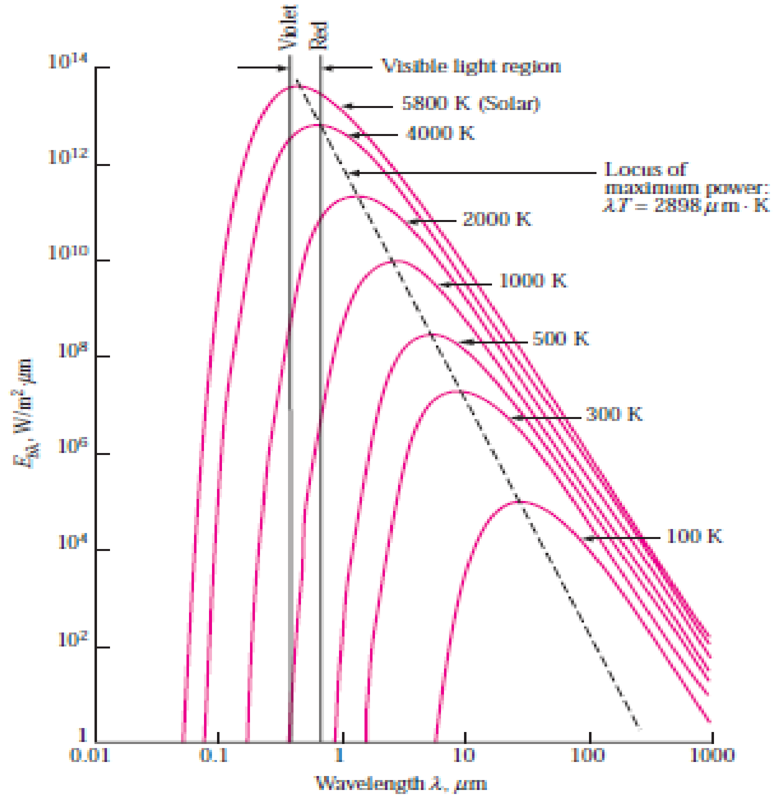


Fig 6: The variation of BB emissive power with wavelengths for several temperature.

- Thus we obtain **Stefan-Boltzmann law** by integrating **Planck's law** over all wavelengths.

BLACKBODY RADIATION

- From the $E_{b\lambda}(\lambda, T)$ function, Fig 7, the spectral emissive power at a given λ can be determined while the area under the curve gives the total emissive power over all wavelengths (Fig 7)

- When interested in the radiation energy emitted in *some wavelength band* , $\lambda=0$ to λ, the relation (Eq. 5) below may be used

$$E_{b,0-\lambda}(T) = \int_0^{\lambda} E_{b\lambda}(\lambda, T)\, d\lambda \qquad (\mathrm{W/m^2}) \qquad 5$$

- It would seem that putting Eq. 2 in to Eq. 5 would yield a solution but Eq.5 does not have a simple closed-form solution and it isn't practical to be do numerical integration each time.

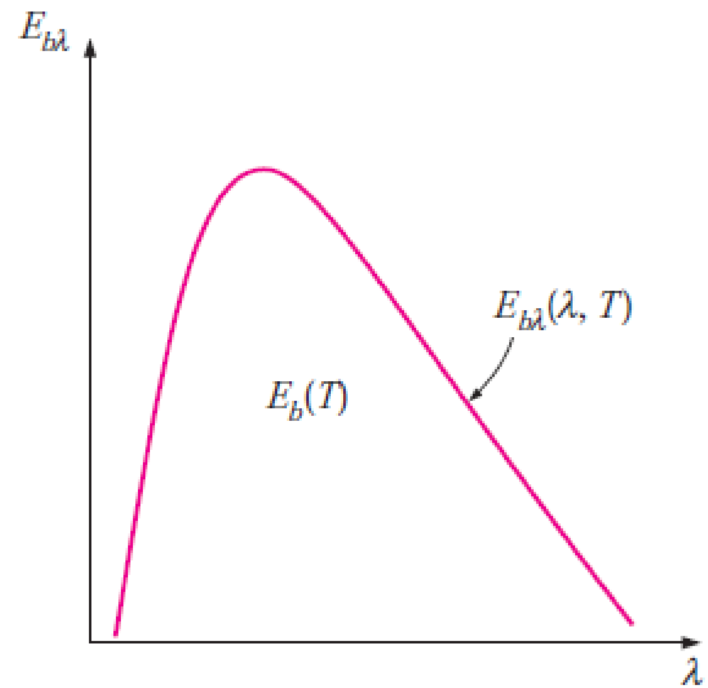


Fig 7: On a $E_{b\lambda} - \lambda$ chart, the area under the curve for given temp, represents the total radiation energy emitted by a BB at that temp.

- Therefore a dimensionless quantity f_λ called the BB radiation function is defined as

$$f_\lambda(T) = \frac{\int_0^\lambda E_{b\lambda}(\lambda, T)\, d\lambda}{\sigma T^4} \qquad 6$$

- The function f_λ represents the fraction of radiation emitted from a BB at temp T in the wavelength band from $\lambda = 0$ to λ

- The values of f_λ are listed in Table as function of λ*T, where λ is in μm and T is in K

- The fraction of radiation energy emitted by a BB at temp T over a finite wavelength band from λ_1 to λ_2 is determined as

$$f_{\lambda_1-\lambda_2}(T) = f_{\lambda_2}(T) - f_{\lambda_1}(T) \qquad 7$$

where $f_{\lambda_2}(T)$ and $f_{\lambda_1}(T)$ are BB radiation functions corresponding to $\lambda_2 * T$ and $\lambda_1 * T$, respectively.

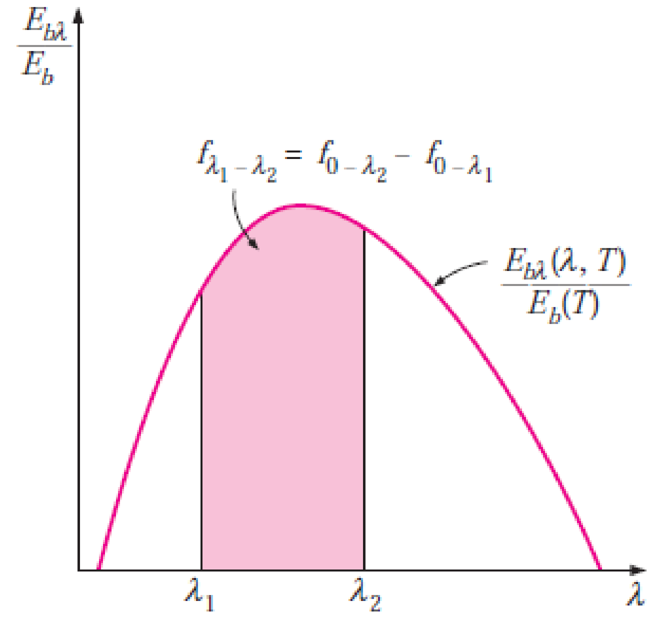
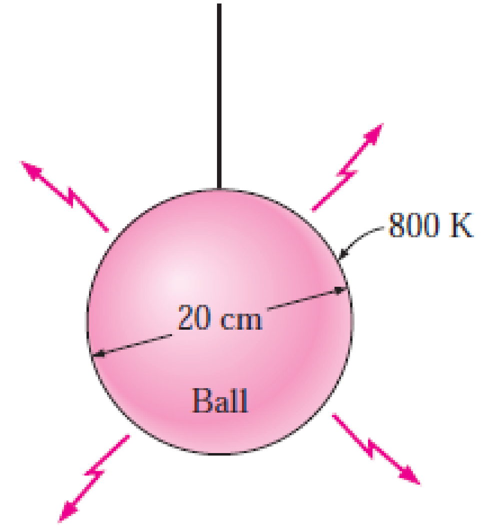


Fig 8: Graphical representation of the fraction radiation emitted in the wavelength band λ_1 to λ_2.

EXAMPLE

1. Consider a 20-cm-diameter spherical ball at 800 K suspended in air as shown in the Fig Assuming the ball closely approximates a blackbody, determine the (*a*) total blackbody emissive power, (*b*) total amount of radiation emitted by the ball in 5 min, and (*c*) spectral blackbody emissive power at a wavelength of 3 μm.



2. The temperature of the filament of an incandescent light bulb is 2500 K. Assuming the filament to be a blackbody, determine the fraction of the radiant energy emitted by the filament that falls in the visible range. Also, determine the wavelength at which the emission of radiation from the filament peaks.

RADIATIVE PROPERTIES

- Materials such as metals, wood and bricks are *opaque* to thermal radiation and thus radiation are considered *surface phenomenon* for such materials.
- Materials can exhibit different behaviour at different wavelengths, and the dependence on wavelength is crucial for the study of radiative properties.
- The radiative properties include emissivity, absorptivity, reflectivity and transmissivity of materials.

> Recall that a BB is perfect *emitter* and *absorber* of radiation and no body can emit more radiation than a BB at the same temperature.

EMISSIVITY

- The **emissivity** of a surface is the ratio of the radiation emitted by the surface at a given temp to the radiation emitted by a blackbody at the same temp.
- The emissivity of a surface varies between one and zero, $0 \leq \varepsilon \leq 1$.
- The emissivity of a real surface is not a constant rather it depends on the temp of the surface, wavelength and direction of the emitted radiation.
- Therefore different emissivities can be defined for a surface, depending on the effects being considered.

EMISSIVITY

- For instance the emissivity of a surface at a specified wavelength is called *spectral emissivity* and is denoted ε_λ. Likewise, emissivity in a specified direction called *directional emissivity*, denoted ε_θ, where θ is the angle between the direction of radiation and the normal of the surface.
- Note that BB radiation is independent of direction.
- In practice, radiation properties are usually averaged over all directions and are referred to as *hemispherical properties*.

- So different emissivities may be defined as shown below:
- **Spectral hemispherical emissivity**

$$\varepsilon_\lambda(\lambda, T) = \frac{E_\lambda(\lambda, T)}{E_{b\lambda}(\lambda, T)} \qquad 8$$

- **Total hemispherical emissivity**

$$\varepsilon(T) = \frac{E(T)}{E_b(T)} = \frac{\int_0^\infty \varepsilon_\lambda(\lambda, T) E_{b\lambda}(\lambda, T)\, d\lambda}{\sigma T^4} \qquad 9$$

EMISSIVITY

- Radiation is a complex phenomenon as it is, and the consideration of the wavelength and direction dependence of properties, assuming sufficient data exist, makes it even more complicated
- Therefore, the *gray* and *diffuse* approximations are often utilized in radiation calculations.
- A surface is said to be *diffuse* if its properties are *independent of direction*, and *gray* if its properties are *independent of wavelength*.
- Therefore, the emissivity of a gray, diffuse surface is simply the total hemispherical emissivity of that surface because of independence of direction and wavelength.

ABSORPTIVITY, REFLECTIVITY AND TRANSMISSIVITY

- Recall that radiation flux incident on a surface is called **irradiation** and is denoted by G.
- When radiation strikes a surface, part of it is absorbed, part of it is reflected and the remaining, if any, is transmitted as shown in the Fig 9.
- The fraction of irradiation absorbed by the surface is called the *absorptivity* α, the fraction reflected by the surface is called *reflectivity* ρ, and the fraction transmitted is called the *trasnmissivity* τ. That is,

Absorptivity:
$$\alpha = \frac{\text{Absorbed radiation}}{\text{Incident radiation}} = \frac{G_{abs}}{G}, \qquad 0 \le \alpha \le 1$$

Reflectivity:
$$\rho = \frac{\text{Reflected radiation}}{\text{Incident radiation}} = \frac{G_{ref}}{G}, \qquad 0 \le \rho \le 1$$

Transmissivity:
$$\tau = \frac{\text{Transmitted radiation}}{\text{Incident radiation}} = \frac{G_{tr}}{G}, \qquad 0 \le \tau \le 1$$

- Where G is the radiation flux incident on the surface, and G_{abs}, G_{ref}, and G_{tr} are the absorbed, reflected and transmitted portions of it respectively.

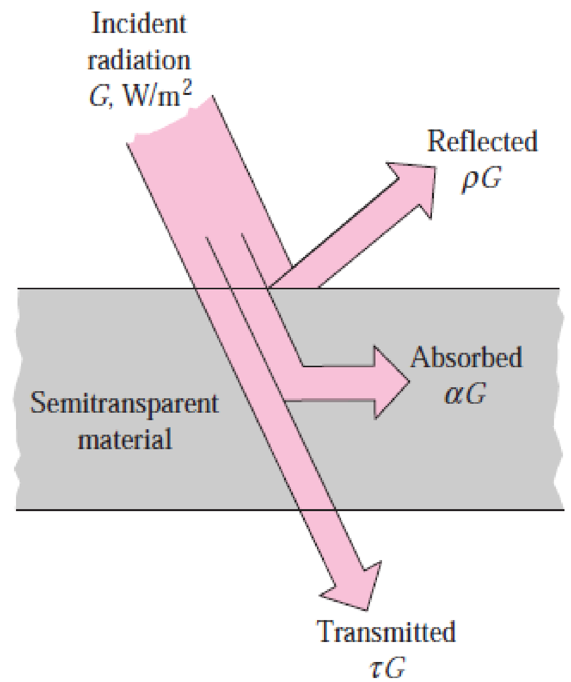


Fig 9: The absorption, reflection, and transmission of incident radiation by a semi-transparent material.

ABSORPTIVITY, REFLECTIVITY AND TRANSMISSIVITY

- The first law of thermodynamics require that the sum of the absorbed, reflected, and transmitted radiation be equal to the incident radiation.

$$G_{abs} + G_{ref} + G_{tr} = G$$

- Dividing each term by G yields

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

- For opaque surfaces, $\tau = 0$, and thus

$$\alpha + \rho = 1$$

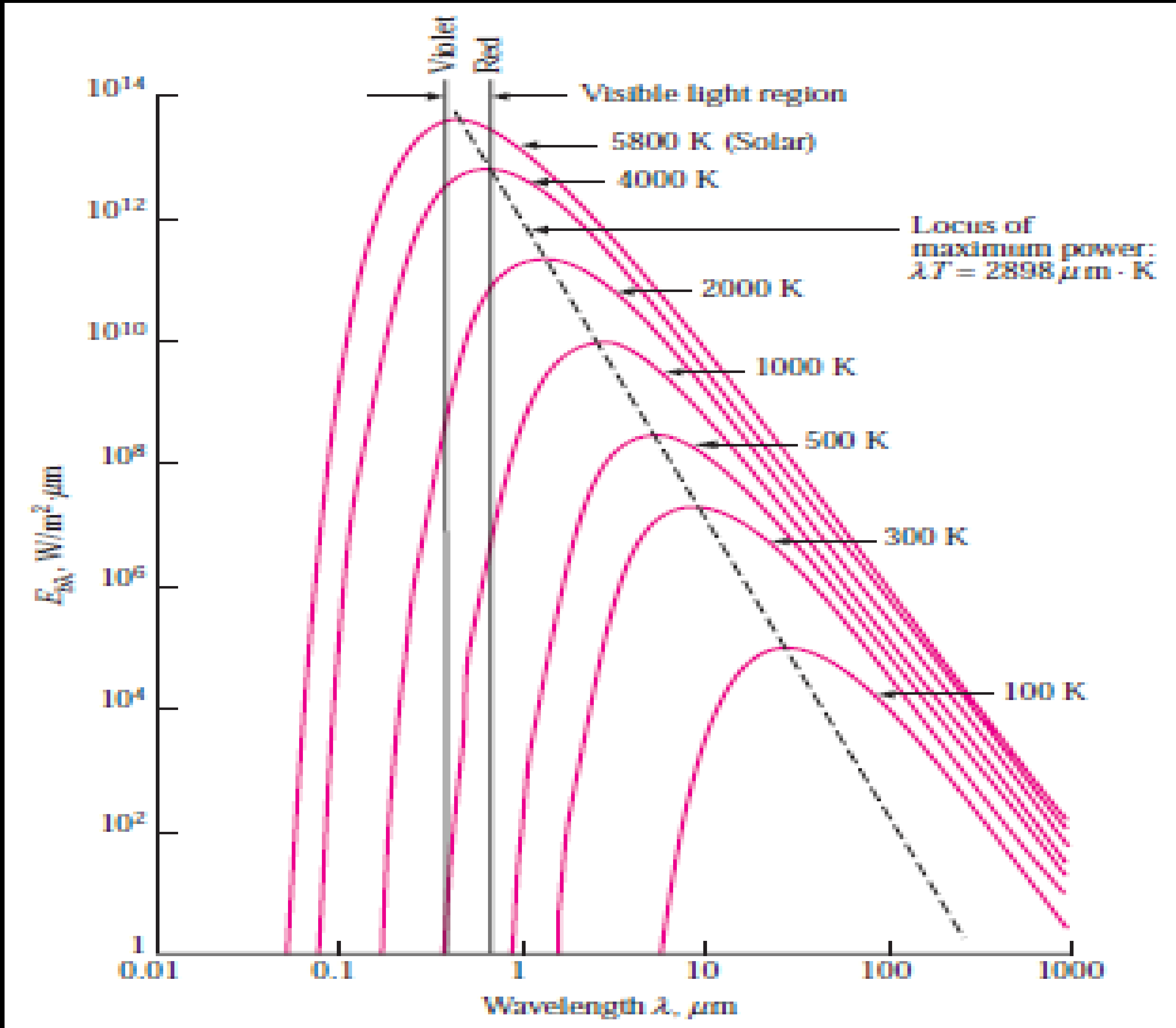
- This is an important property relation since it enables us to determine both the absorptivity and reflectivity of an opaque surface by measuring either of these properties.
- These definitions are for *total hemispherical* properties, since G represents the radiation flux incident on the surface from all directions over the hemispherical space and over all wavelengths.
- Thus, a, r, and t are the *average* properties of a medium for all directions and all wavelengths. However, like emissivity, these properties can also be defined for a specific wavelength and/or direction.

ABSORPTIVITY, REFLECTIVITY AND TRANSMISSIVITY

- **Kirchhoff's Law**: The total hemispherical emissivity of a surface at temperature T is equal to its total hemispherical absorptivity for radiation coming from a blackbody at the same temperature.

Table 1: Blackbody Radiation functions, f_λ

λT, $\mu m \cdot K$	f_λ	λT, $\mu m \cdot K$	f_λ
200	0.000000	6200	0.754140
400	0.000000	6400	0.769234
600	0.000000	6600	0.783199
800	0.000016	6800	0.796129
1000	0.000321	7000	0.808109
1200	0.002134	7200	0.819217
1400	0.007790	7400	0.829527
1600	0.019718	7600	0.839102
1800	0.039341	7800	0.848005
2000	0.066728	8000	0.856288
2200	0.100888	8500	0.874608
2400	0.140256	9000	0.890029
2600	0.183120	9500	0.903085
2800	0.227897	10,000	0.914199
3000	0.273232	10,500	0.923710
3200	0.318102	11,000	0.931890
3400	0.361735	11,500	0.939959
3600	0.403607	12,000	0.945098
3800	0.443382	13,000	0.955139
4000	0.480877	14,000	0.962898
4200	0.516014	15,000	0.969981
4400	0.548796	16,000	0.973814
4600	0.579280	18,000	0.980860
4800	0.607559	20,000	0.985602
5000	0.633747	25,000	0.992215
5200	0.658970	30,000	0.995340
5400	0.680360	40,000	0.997967
5600	0.701046	50,000	0.998953
5800	0.720158	75,000	0.999713
6000	0.737818	100,000	0.999905


Violet
Red
Visible light region
5800 K (Solar)
4000 K
Locus of maximum power: λT = 2898 μm · K
2000 K
1000 K
500 K
300 K
100 K
10^{14}
10^{12}
10^{10}
10^{8}
10^{6}
10^{4}
10^{2}
1
$E_{b\lambda}$, W/m²·μm
0.01
0.1
1
10
100
1000
Wavelength λ, μm