Energy & Heat Transfer

Lecture 5

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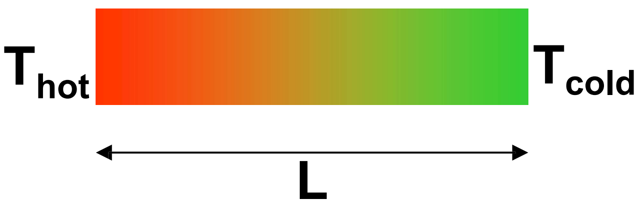
Heat Transfer Modes

Heat Conduction



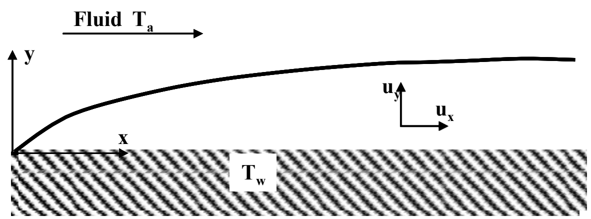
- Fourier Law

$$\dot{Q} = -kA\frac{\Delta T}{\Delta x}\,[W]$$

Thermal Conductivity [W/m.K]
Material properties

Cross-Sectional Area $[m^2]$

Convection



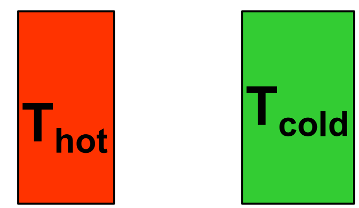
- Newton's law of cooling

$$\dot{Q} = hA(T_w - T_a)\,[W]$$

Convective Heat Transfer Coefficient [W/m^{2}K]
Flow dependent

- Natural Convection
- Forced Convection

Thermal Radiation

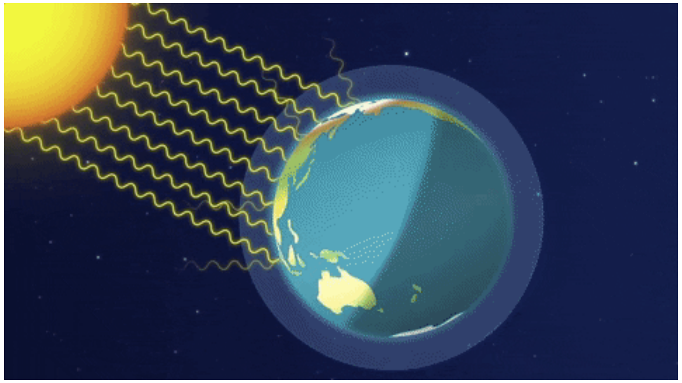


Learning objectives lecture 5

- Concept of Radiation
- Radiation Laws
- Non- Ideal Radiation
- Radiation Heat Transfer
- Resistance Networks – (Radiation and Convection)

Radiation Examples

Sun



Surface temperature : **5,778 K**

Distance from earth : **149.6 million km**

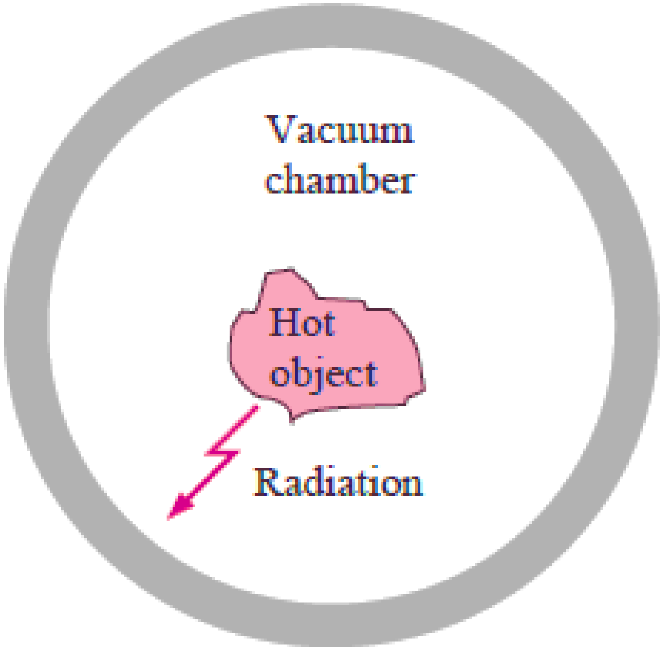
Fire

Flame temperature ~**750 ℃**

Concept of Radiation

- Consider a hot object that is suspended in an evacuated chamber whose walls are at room temperature.

- The Hot object will cool down and reach equilibrium with the chamber walls due to change in **internal energy**.



But How is this heat (internal energy) being transported without any medium ? ?

Electromagnetic Waves or Electromagnetic Radiation

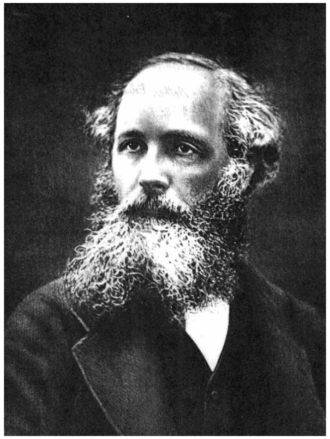
(no medium required!)

Heat transfer in the form of electromagnetic waves due to change in internal energy.

Electromagnetic Waves :

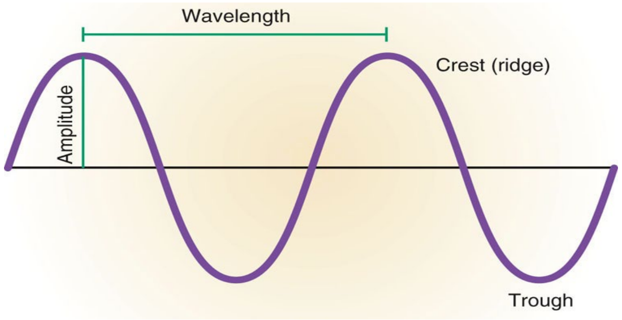
- The theoretical foundation of radiation was established in 1864 by physicist James Clerk Maxwell.

- Accelerated charges or changing electric currents give rise to electric and magnetic fields.



James Clerk Maxwell

1) **Wavelength** – the distance between wave crests



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

c is the speed of light in vacuum

λ is the wavelength in meters

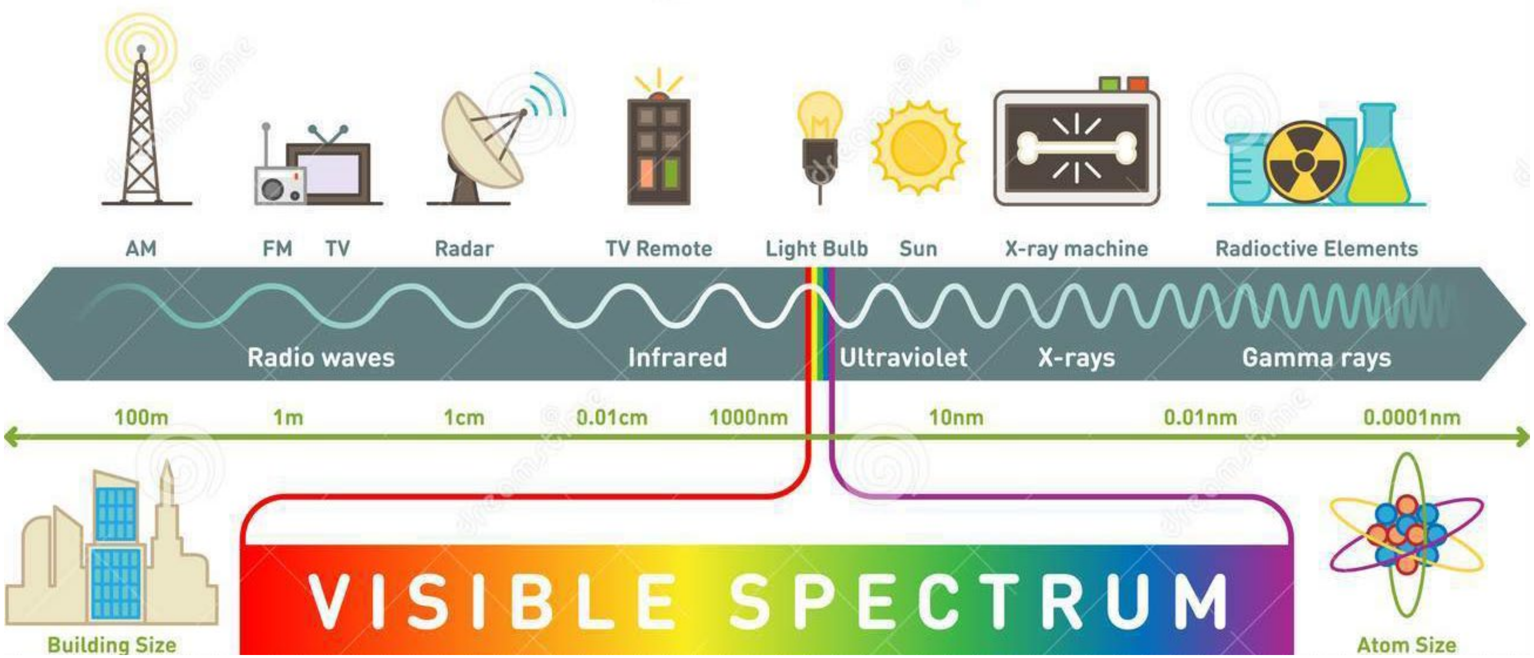
ν is the frequency in Hertz (Hz) or S^{-1}

Heinrich Rudolf Hertz

2) **Amplitude** – the height of the wave

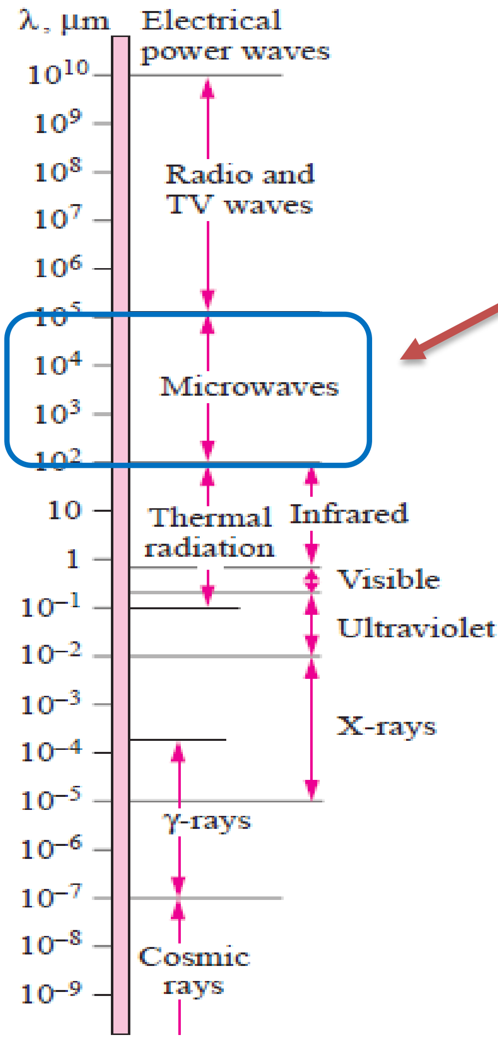
3) Wave speed – constant! - **speed of light (vacuum: $2.9979*10^8$ m/s)**

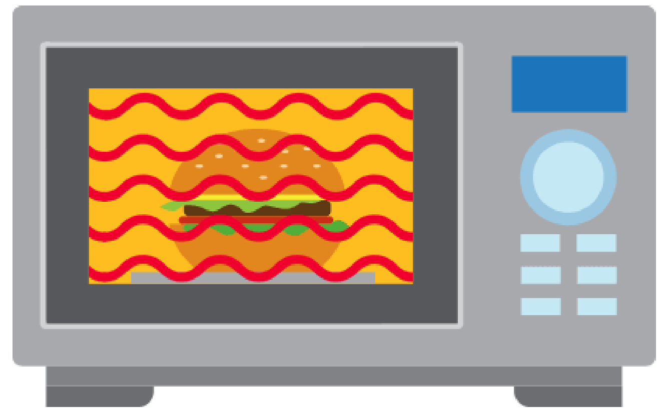
Electromagnetic spectrum



- Gamma rays are produced by nuclear reactions.
- X-rays by the bombardment of metals with high-energy electrons.
- Microwaves by special types of electron tubes such as klystrons and magnetrons.
- Radio waves by the excitation of some crystals or by the flow of alternating current through electric conductors.

Electromagnetic spectrum

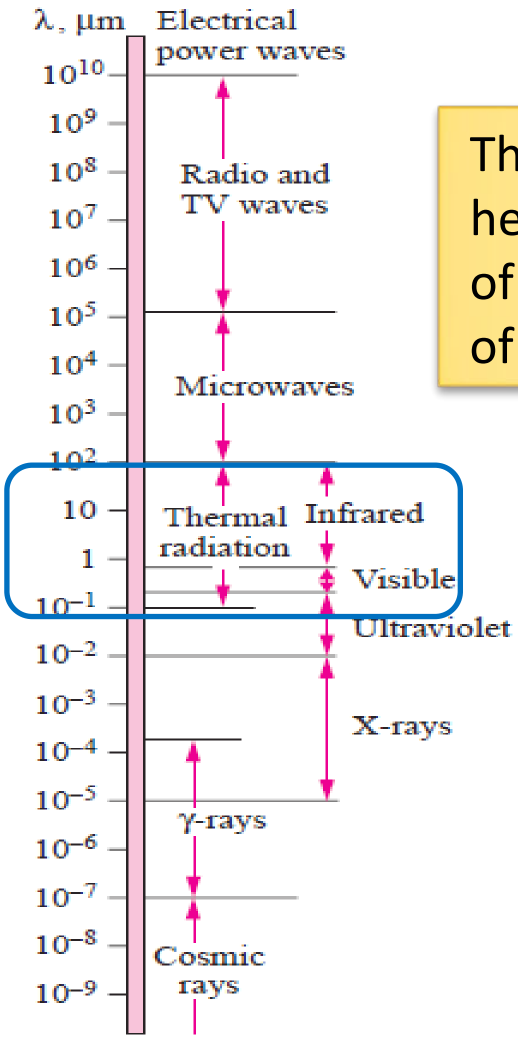




- Wavelength λ = 10^2 … 10^5 μm
- Waves are reflected by metal (walls)
- Transmission through glass and plastics (ovendish)
- Absorption in food (mainly water molecules)
- Effective conversion: electric energy →

  radiation energy → internal (thermal) energy food

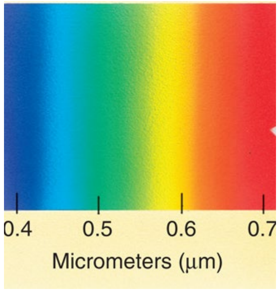
THERMAL RADIATION



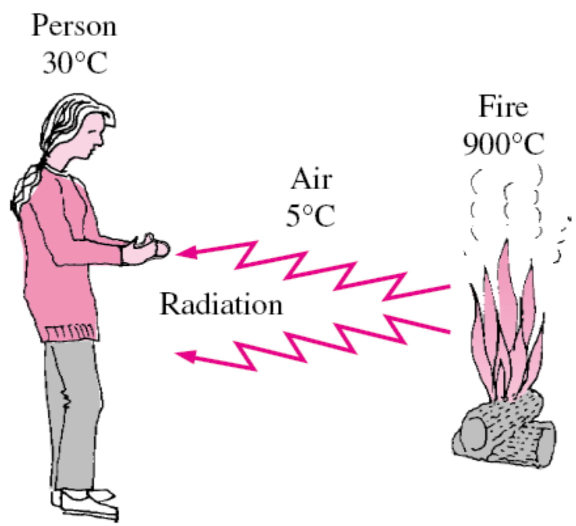
But what is a Thermal Radiation ?

The type of electromagnetic radiation that is pertinent to heat transfer is the thermal radiation emitted as a result of energy transitions of molecules, atoms, and electrons of a substance.

What we call light is simply the visible portion of the electromagnetic spectrum that lies between 0.40 and 0.76 μm.



CONCEPT OF RADIATION



- Radiation is independent of medium through which it travels, as opposed to conduction/convection

- Energy transport through radiation continues till equilibrium is reached, just as for conduction/convection:

- Solids, Liquids and gases emit radiation

- For non transparent materials radiation can be considered as a surface phenomenon

Learning objectives lecture 5

- Concept of Radiation
- Radiation Laws
- Non- Ideal Radiation
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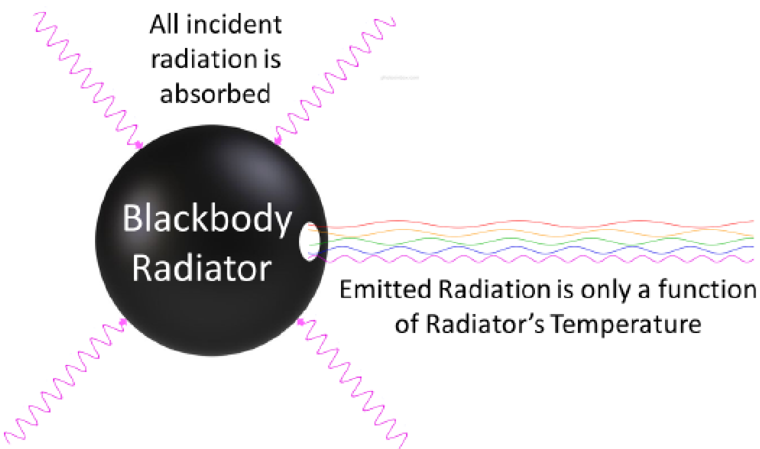
What is Blackbody ?

A perfect emitter and absorber of radiation.

A blackbody absorbs all incident radiation, regardless of wavelength and direction.

A blackbody is a diffuse emitter. Diffuse means "independent of direction."



Stefan-Boltzmann law :

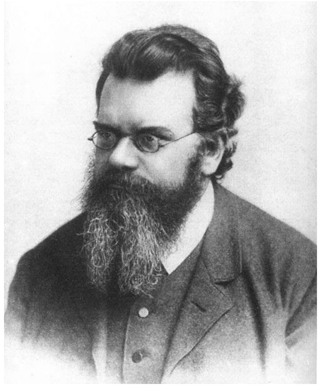
- Estimates the **Total power** emitted by blackbody

$$\dot{Q}_b = \sigma \cdot A \cdot T^4 \ [W]$$

$$\sigma = 5.670 \times 10^{-8} \ \frac{\mathrm{W}}{\mathrm{m^2K^4}}$$

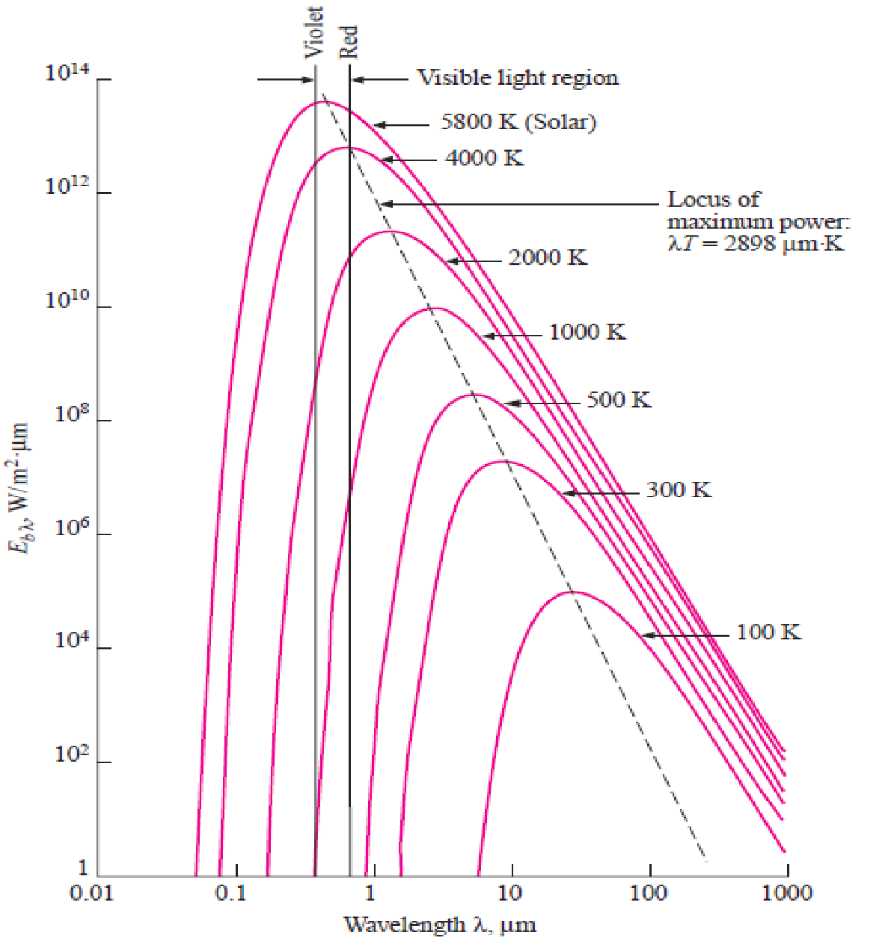
Stefan-Boltzmann constant

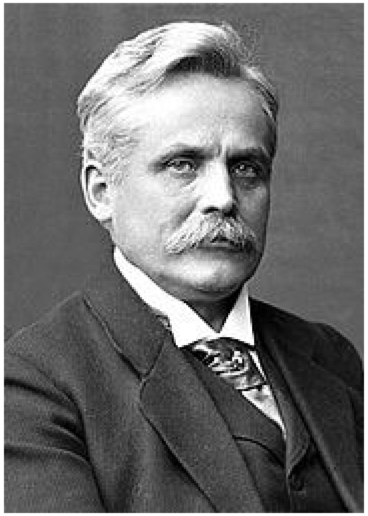
Josef Stefan



Ludwig Boltzmann

Wien's displacement law:





Wilhelm Wien

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

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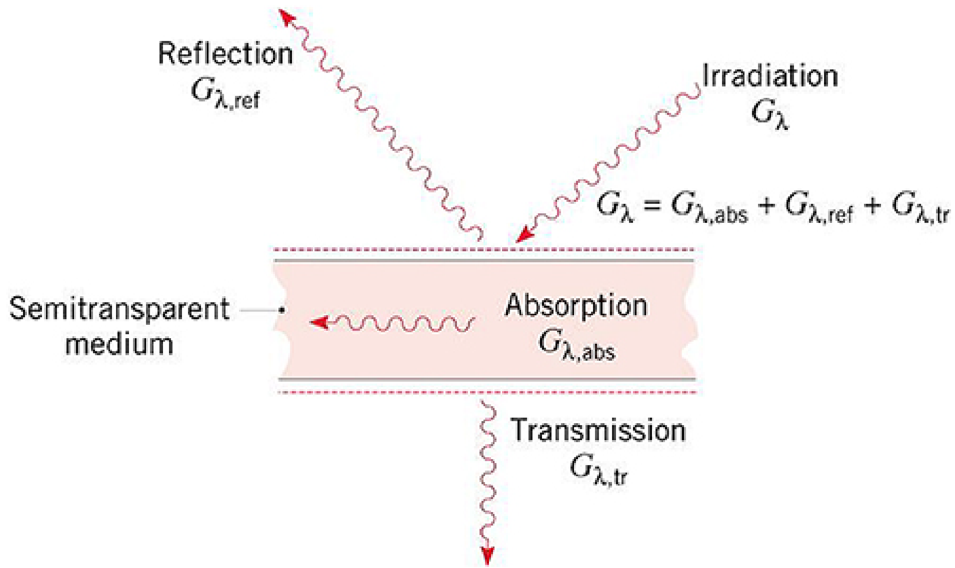
NON –IDEAL RADIATION



Radiation striking a solid surface has one of three fates:

1. Absorption absorptivity (α)

2. Transmission transmissivity (τ)

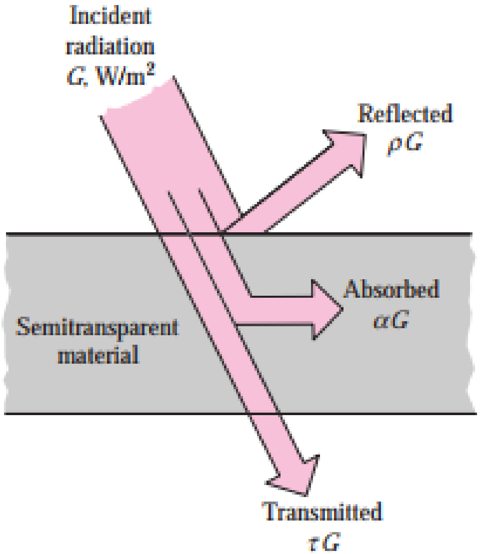
3. Reflection reflectivity (ρ)

NON –IDEAL RADIATION

Absorptivity: $\alpha = \dfrac{\text{Absorbed radiation}}{\text{Incident radiation}}$

Reflectivity: $\rho = \dfrac{\text{Reflected radiation}}{\text{Incident radiation}}$

Transmissivity: $\tau = \dfrac{\text{Transmitted radiation}}{\text{Incident radiation}}$



How are these properties related ?

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

Non –Ideal radiation

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

Two special cases require definition:

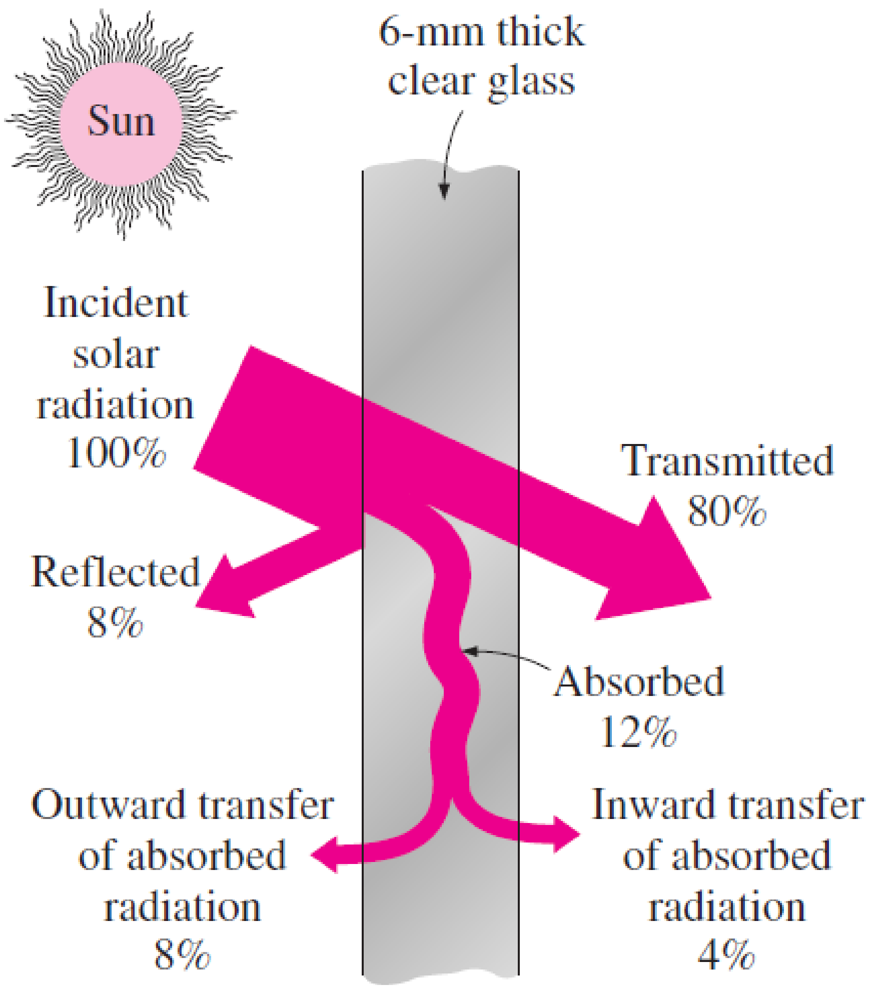
If <u>all</u> of the energy is either <u>reflected or absorbed</u> (no transmitted radiation), we define the body as

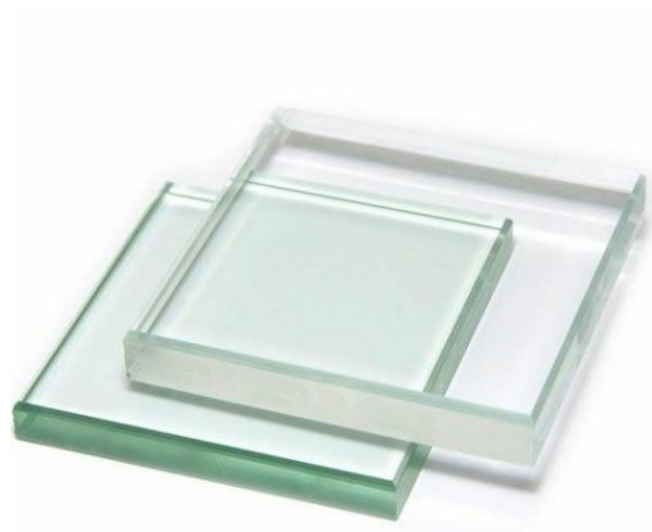
$$\boxed{\text{Opaque} \quad \alpha + \rho = 1}$$

If <u>all</u> of the energy striking a surface is <u>absorbed</u>, we define the body as

$$\boxed{\text{Black body} \quad \alpha = 1}$$

NON –IDEAL RADIATION

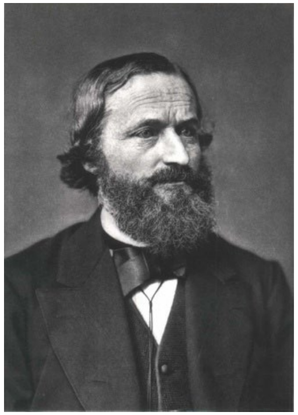




KIRCHHOFF`S LAW :

The emissivity of an object is equal to the absorptivity of this object at the same temperature.

$$\boxed{\varepsilon(T)=\alpha(T)}$$



Gustav Robert Kirchhoff

EMISSIVITY

- In reality all materials: non ideal emitter
- Less power emitted than blackbody

Adjusted Stefan-Boltzmann Law for emitted radiation from object:

$$\dot{Q}_{\boldsymbol{b}} = \sigma \cdot A \cdot T^4 \ (W) \ \ \textbf{so} \ \ \dot{Q} = \varepsilon \cdot \sigma \cdot A \cdot T^4 (\mathrm{W})$$

Emissivity *ε* (0 ≤ *ε* ≤ 1) of a surface (material property):
Measure for emitted radiation ($\dot{Q}$ ***) in comparison to radiation*** $(\dot{Q}_b)$ ***emitted by a blackbody (ε = 1) at same temperature.***

$$\varepsilon = \frac{\dot{Q}}{\dot{Q}_b}$$

Learning objectives lecture 5

- Concept of Radiation
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Radiation Heat Transfer

To calculate the heat transfer rate by radiation, we must include terms for power output and energy received from the surroundings.

power output: $\varepsilon \sigma A T_s^4$

power input: $\sigma \alpha A T_\infty^4$

Making the usual assumption that $\varepsilon = \alpha$, and multiplying by area yields:

$$\dot{Q} = \varepsilon \sigma A (T_s^4 - T_\infty^4)$$

This is the expression for an object totally enclosed by surroundings at T_∞.

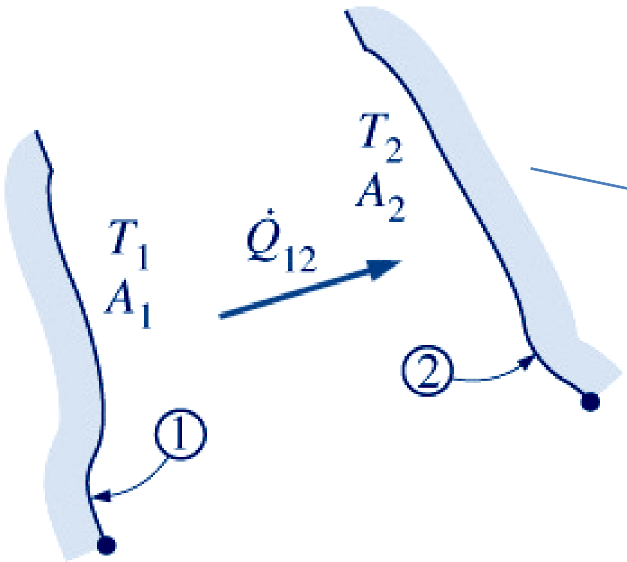
Radiation Heat Transfer

Radiation from a single body at certain temperature T (Black Body)

$$\dot{Q} = \sigma \cdot A \cdot T^4 \quad (W)$$

Radiation from a single body at certain temperature T (non ideal)

$$\dot{Q} = \varepsilon \cdot \sigma \cdot A \cdot T^4 \quad (\mathrm{W})$$

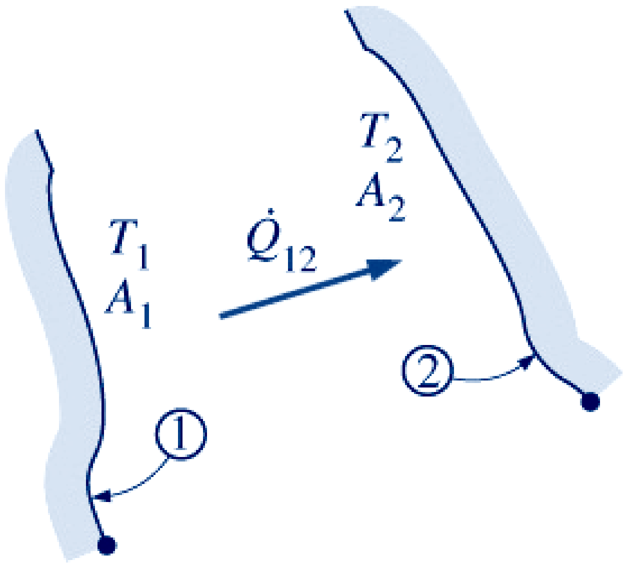


Radiation Heat Exchange (Ideal Case)

$$\dot{Q}_{1\to 2} = \sigma \cdot A_1 \cdot \left(T_1^4 - T_2^4\right)$$

But what about the orientation and shape of the object ?

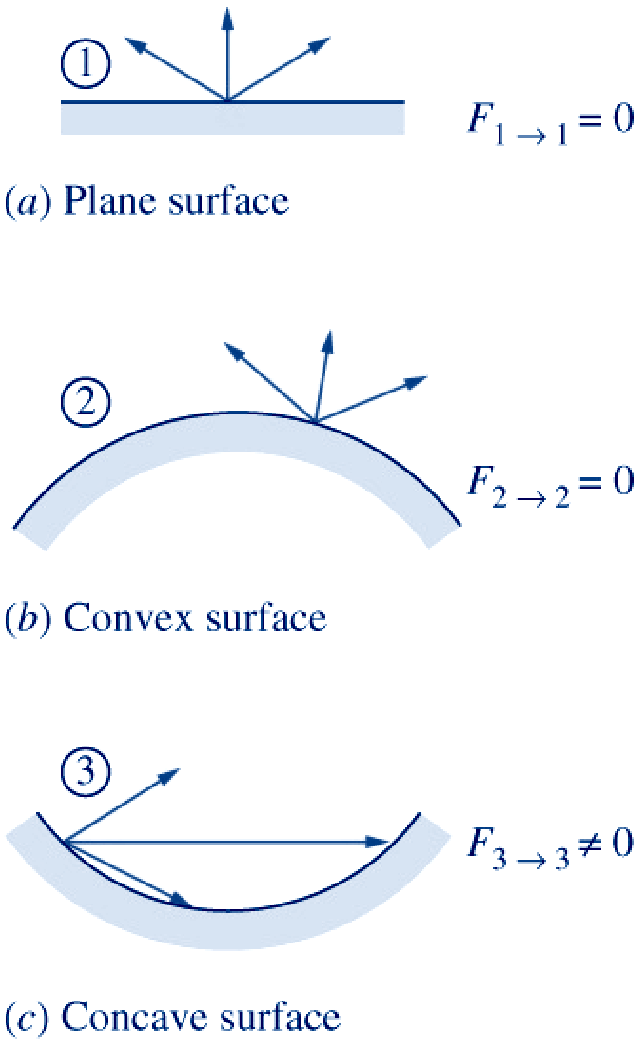
VIEW FACTORS

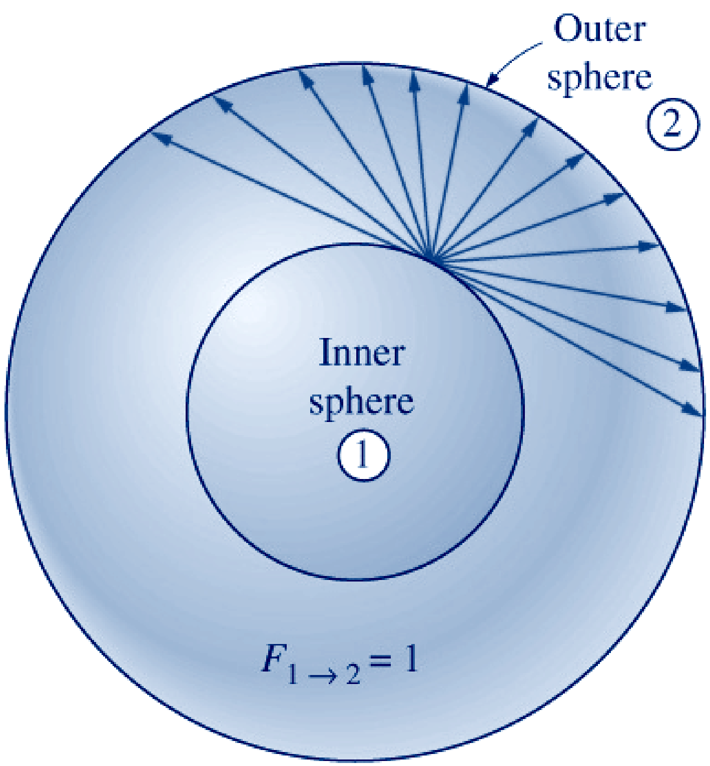


$F_{i\to j}$ is the 'view factor':

$$\boxed{F_{i\to j} = \frac{\dot{Q}_{i\to j}}{\dot{Q}_i}}$$

To account for the effects of orientation on radiation heat transfer between two surfaces, we define a new parameter called the view factor, which is a purely geometric quantity and is independent of the surface properties and temperature. It is also called the shape factor, configuration factor, and angle factor.





Cylinder/sphere:

- $F_{1\to1} = 0$
- $F_{1\to2} = 1$

Rules/Theorem's

1 The Reciprocity Relation

The view factors $F_{i\to j}$ and $F_{j\to i}$ are *not* equal to each other unless the areas of the two surfaces are. That is,

$$F_{j\to i} = F_{i\to j} \qquad \text{when} \qquad A_i = A_j$$

$$F_{j\to i} \neq F_{i\to j} \qquad \text{when} \qquad A_i \neq A_j$$

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

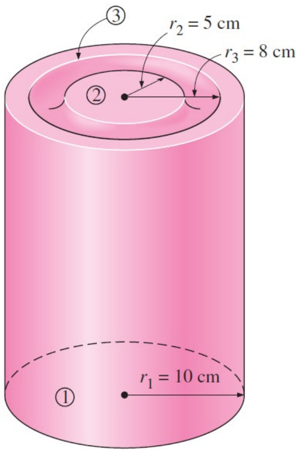
2 The Summation Rule

$$\sum_{j=1}^{N} F_{i\to j} = 1$$

where N is the number of surfaces of the enclosure. For example, applying the summation rule to surface 1 of a three-surface enclosure yields

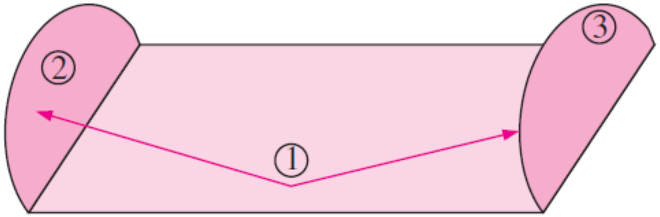
$$\sum_{j=1}^{3} F_{1\to j} = F_{1\to 1} + F_{1\to 2} + F_{1\to 3} = 1$$

3 The Superposition Rule



$$F_{1 \to (2,3)} = F_{1 \to 2} + F_{1 \to 3}$$

4 The Symmetry Rule

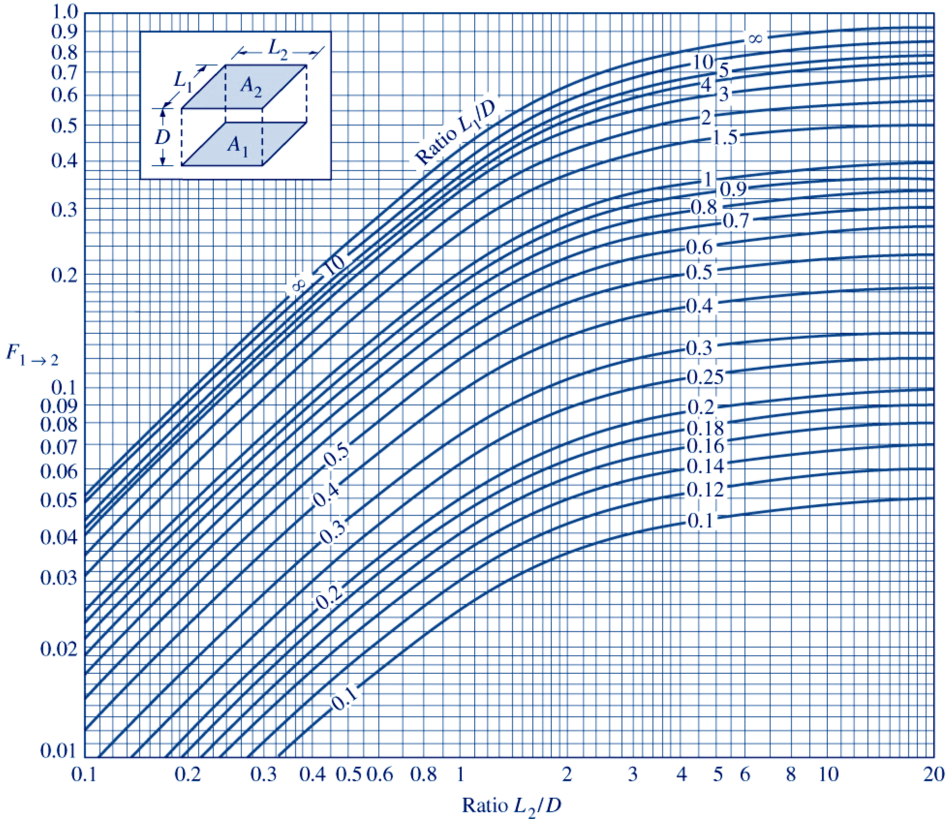


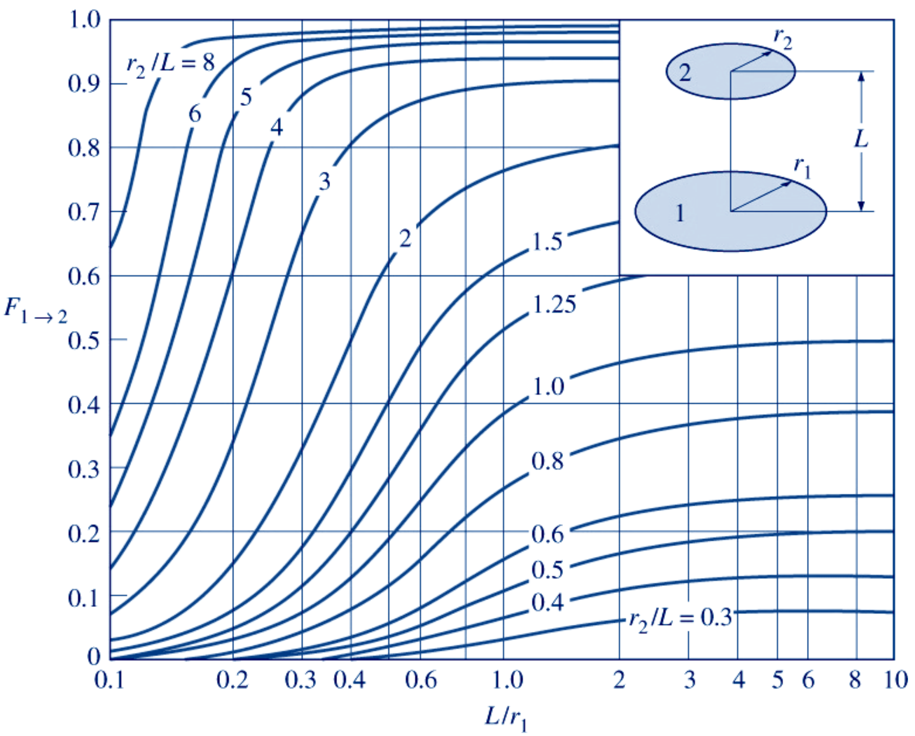
$F_{1 \to 2} = F_{1 \to 3}$

(Also, $F_{2 \to 1} = F_{3 \to 1}$)

VIEW FACTORS

PARALEL PLANES

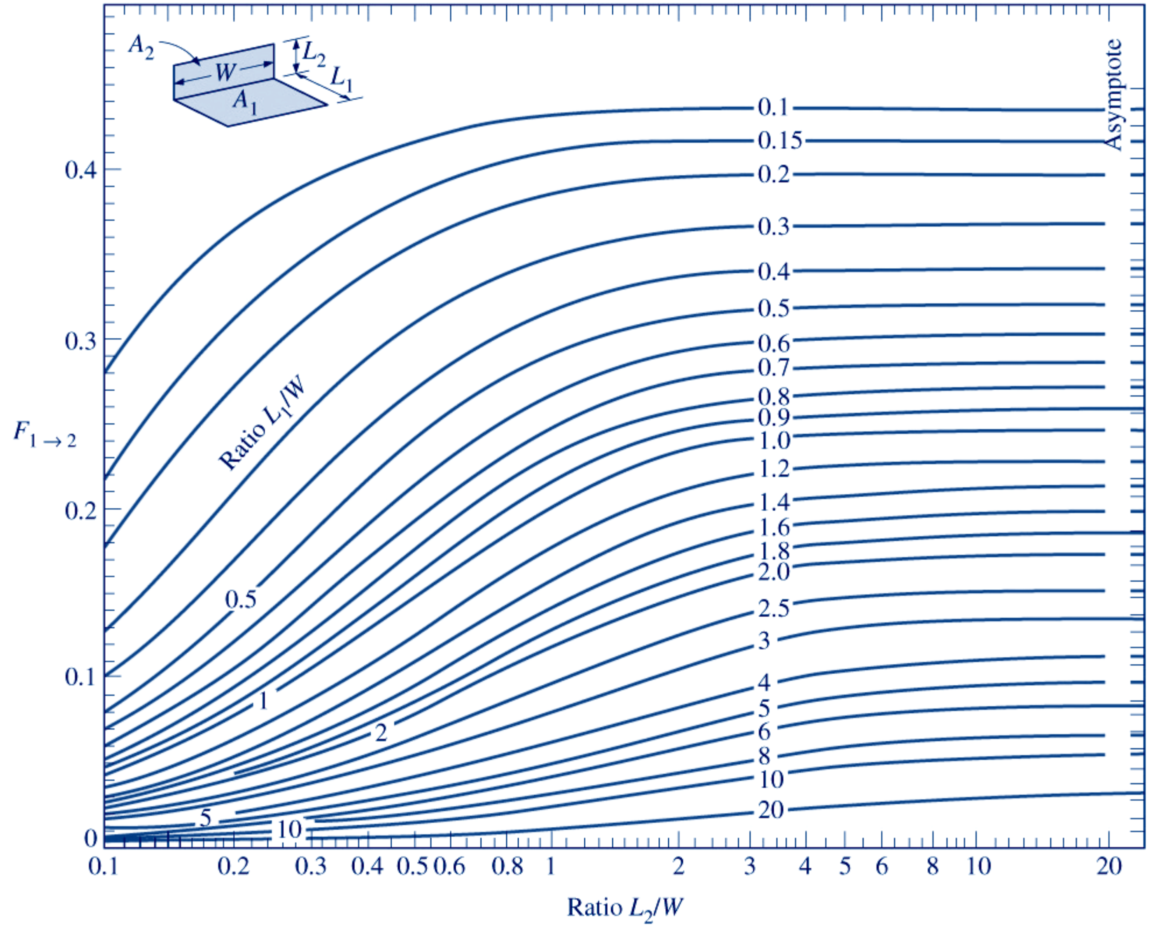




Beware: not valid if the surfaces are shifted in their plane (surfaces have to be alligned or coaxial)

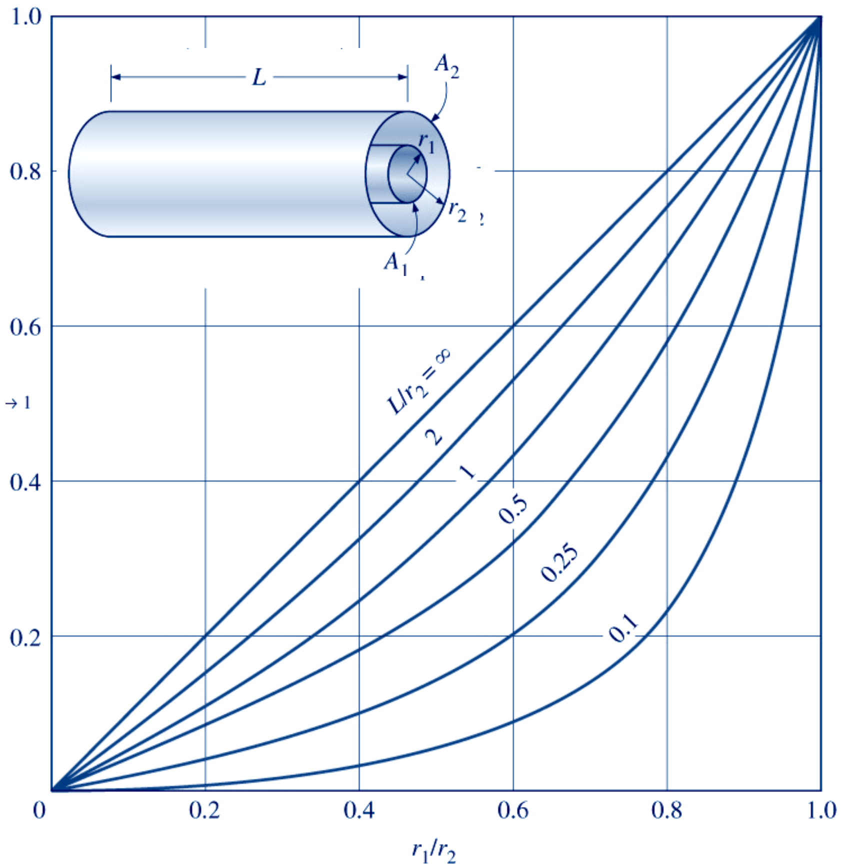
VIEW FACTORS

PERPENDICULAR, ATTACHED RECTANGLES

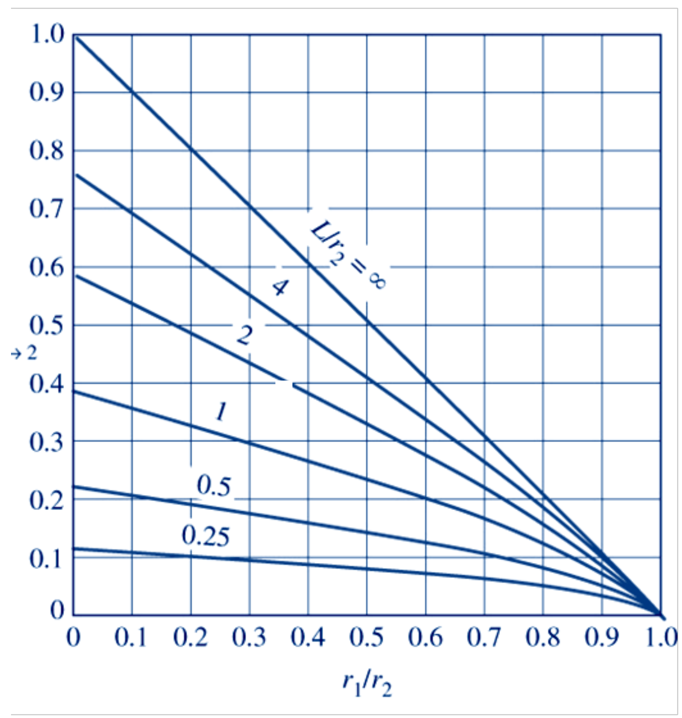


CONCENTRIC CYLINDERS

$F_{2\to1}$



$F_{2\to2}$



Established earlier:

- $F_{1\to1} = 0$
- $F_{1\to2} = 1$

Heat Quiz

Practise path: View Factors

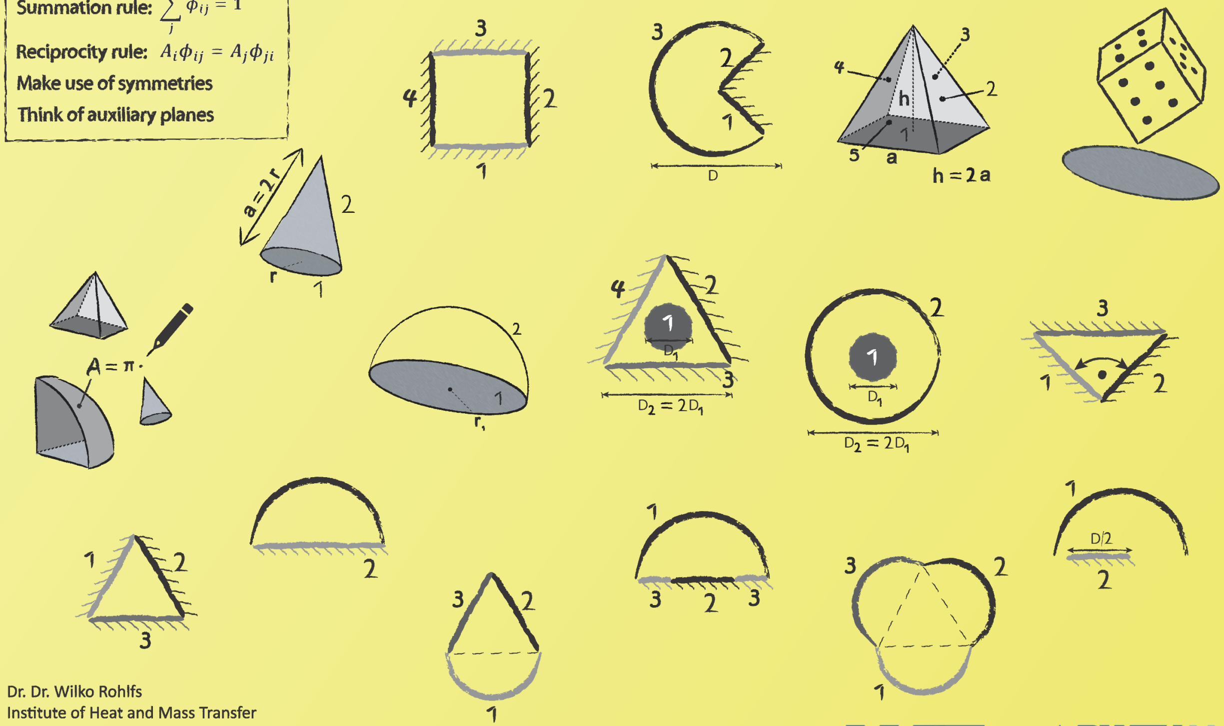
Hints

Summation rule: $\sum_j \phi_{ij} = 1$

Reciprocity rule: $A_i \phi_{ij} = A_j \phi_{ji}$

Make use of symmetries

Think of auxiliary planes



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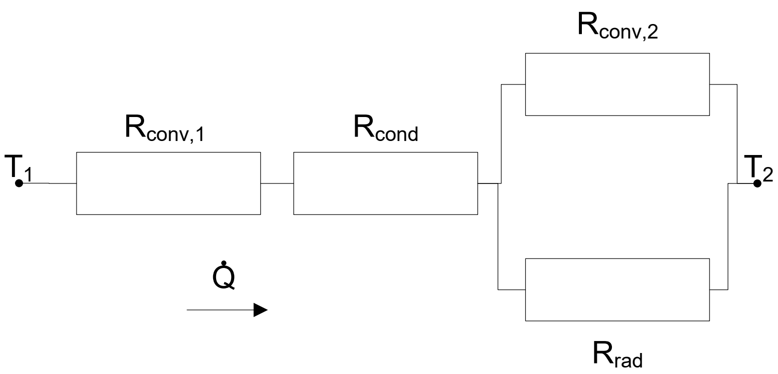
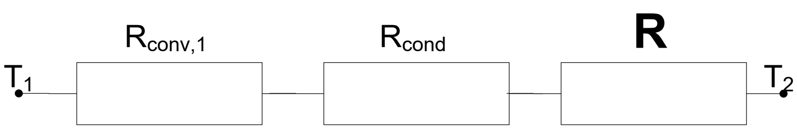
LEARNING OBJECTIVES LECTURE 5

- Concept of Radiation
- Radiation Laws
- Non- Ideal Radiation
- Radiation Heat Exchange
- Resistance Networks – (Radiation and Convection)

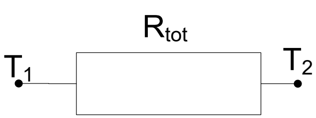
Overall resistance Network



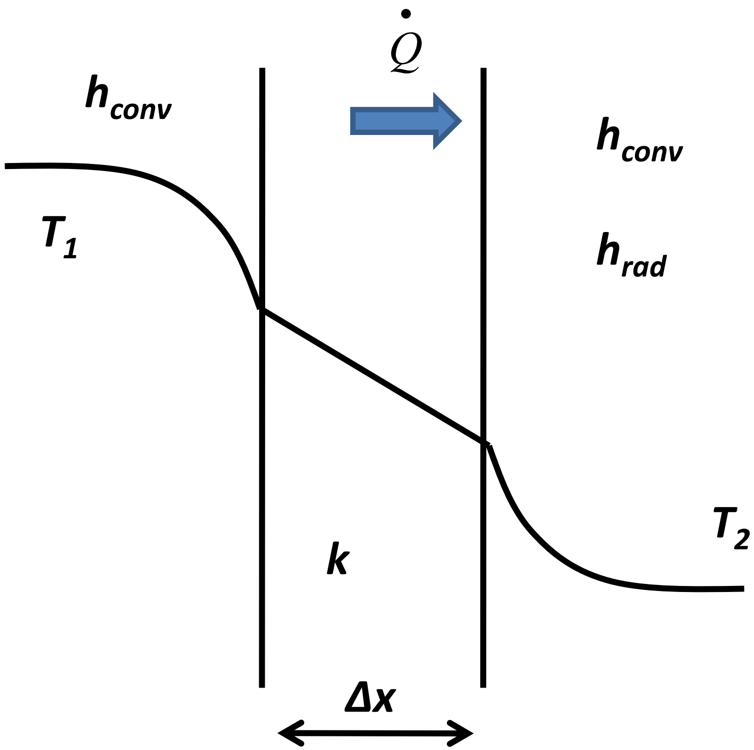
$$\frac{1}{R}=\frac{1}{R_{conv,2}}+\frac{1}{R_{rad}}$$



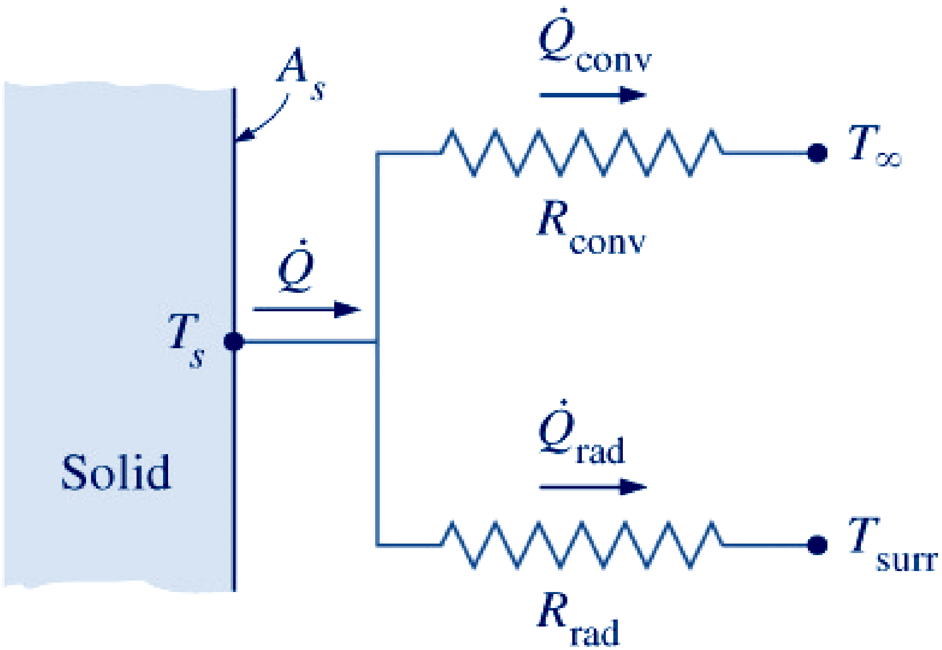
$$R_{tot}=R_{conv,1}+R_{cond}+R$$



$$\dot{Q}=\frac{T_1-T_2}{R_{tot}}$$

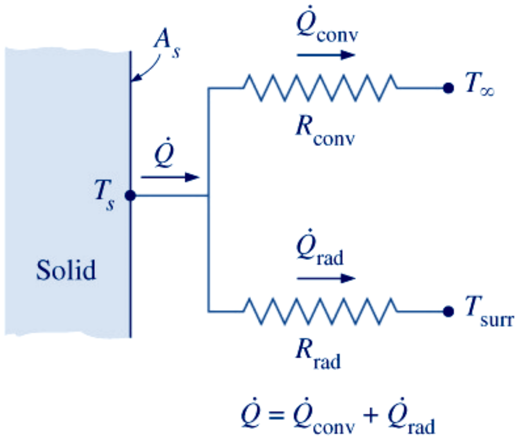


Radiation and convection



$$\dot{Q} = \dot{Q}_{conv} + \dot{Q}_{rad}$$

Radiation and convection



$$\dot{\boldsymbol{Q}}_{\boldsymbol{rad}} = \varepsilon \cdot \sigma \cdot A \cdot (T_s^4 - T_\infty^4)$$

$$Let, h_{rad} = \varepsilon \cdot \sigma \cdot \left(T_s^2 + T_\infty^2\right) \cdot \left(T_s + T_\infty\right)$$

$$Therefore, \dot{\boldsymbol{Q}}_{\boldsymbol{rad}} = h_{rad} \cdot A \cdot (T_s - T_\infty)$$

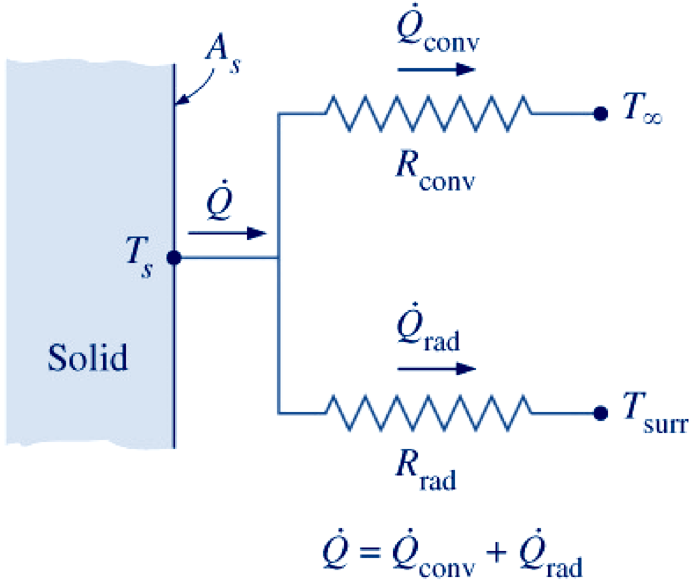
$$\dot{\boldsymbol{Q}}_{\boldsymbol{rad}} = \frac{T_s - T_\infty}{R_{rad}} \quad \text{with } R_{rad} = \frac{1}{h_{rad} A}$$

$$\frac{1}{R_{tot}} = \frac{1}{R_{conv}} + \frac{1}{R_{rad}}$$

Radiation and convection

$$\dot{Q} = \dot{Q}_{conv} + \dot{Q}_{rad}$$
$$= h_{conv} A \Delta T + h_{rad} A \Delta T$$
$$= (h_{conv} + h_{rad}) A \Delta T$$

$$\Rightarrow \dot{Q} = h_{tot} A \Delta T \quad \text{with} \quad h_{tot} = h_{conv} + h_{rad}$$



Summary lecture 5 (1/2)

- Radiation
  - Does not need a transport medium
  - Thermal: 0,1 µm < λ < 100 µm
- Blackbody:
- Non ideal emitters
  - Emissivity ε
  - Absorptivity α
  - Reflectivity ρ
  - Transmissivity τ

SUMMARY LECTURE 5 (2/2)

- Stefan-Boltzmann's Law for radiation coming **from** all emittors (blackbody: ε = 1)

$$\dot{Q} = \varepsilon \cdot \sigma \cdot A \cdot T^4 \ \ (\mathrm{W})$$

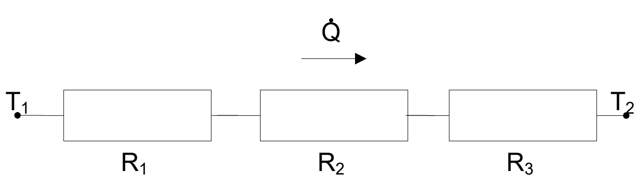
- **Net** radiation from non ideal emitter towards environment (with ε <1)

$$\boxed{\dot{Q} = \varepsilon \cdot \sigma \cdot A \cdot \left(T^4 - T_\infty^4\right)}$$

- View factor: fraction of radiation from surface i that directly hits surface j ($F_{i \rightarrow j}$)

- Radiation and convection: $h_{tot} = h_{conv} + h_{rad}$

- Series resistors: $R_{tot} = \sum_i R_i$
  (add resistors)



Parallel resistors: $\frac{1}{R_{tot}} = \sum_i \frac{1}{R_i}$
(add heat flows)