

Energy & Heat Transfer

Lecture 5

By: Mohammad Mehrali



Heat Quiz

Practice Path: Conduction

① Fundamentals

② Fins

③ Heat Sources and Sinks

Multi-Layered Walls

Cylindrical Bodys

Fins

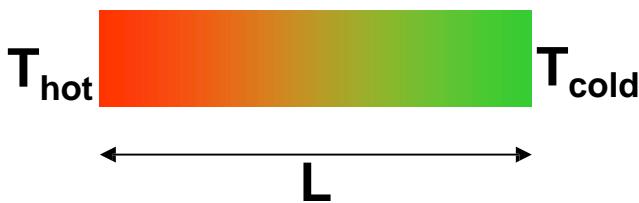
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Recap of last lectures

Heat Transfer Modes

Heat Conduction



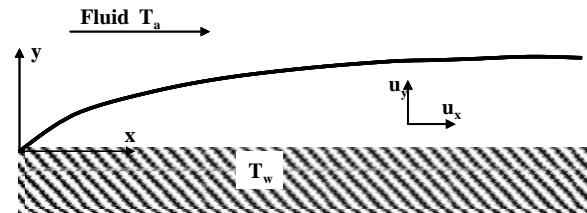
- Fourier Law

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

Thermal Conductivity
[W/m.K]
Material properties

Cross-
Sectional
Area [m^2]

Convection



- Newton's law of cooling

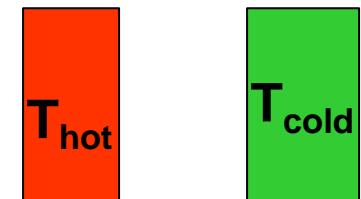
$$\dot{Q} = hA(T_w - T_a) [W]$$



Convective Heat
Transfer Coefficient
[W/m²K]
Flow dependent

- Natural Convection
- Forced Convection

Thermal Radiation



LEARNING OBJECTIVES LECTURE 5

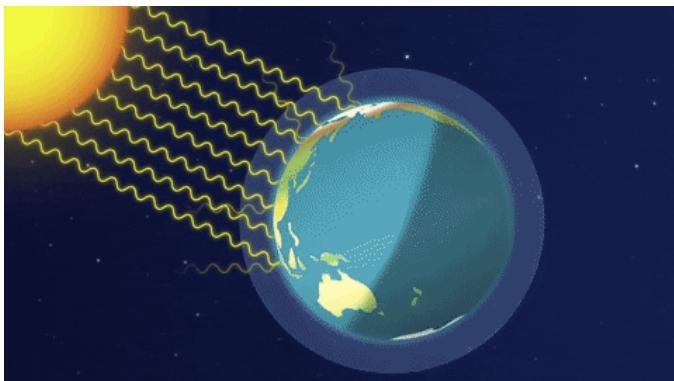


- Concept of Radiation**
- Radiation Laws**
- Non- Ideal Radiation**
- Radiation Heat Transfer**
- Resistance Networks – (Radiation and Convection)**

CONCEPT OF RADIATION

Radiation Examples

Sun



Surface temperature : **5,778 K**

Distance from earth : **149.6 million km**

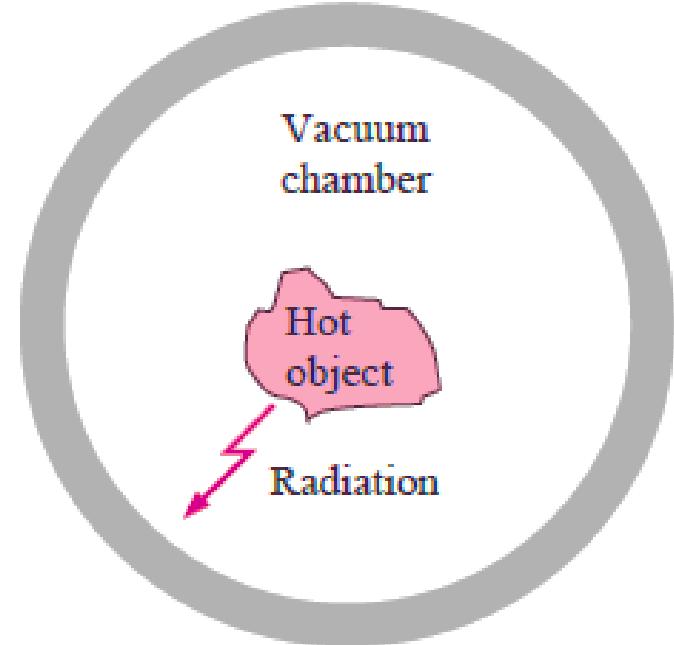
Fire



Flame temperature \sim **750 °C**

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 ? ?

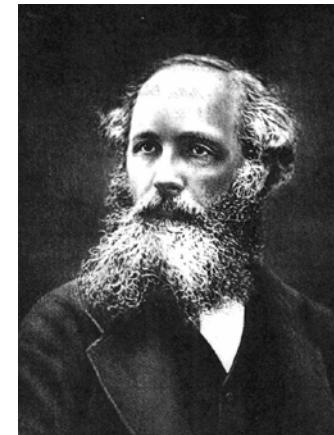
**Electromagnetic Waves or Electromagnetic Radiation
(no medium required!)**

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

Electromagnetic Waves

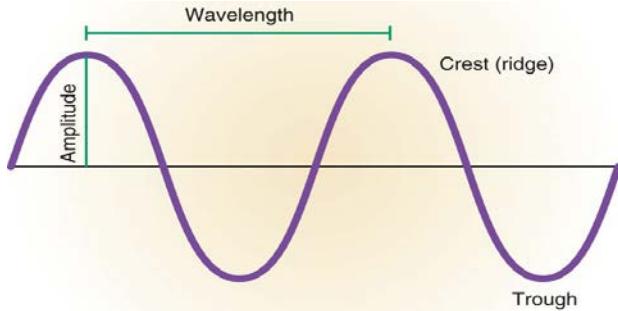
Electromagnetic Waves :

- 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}

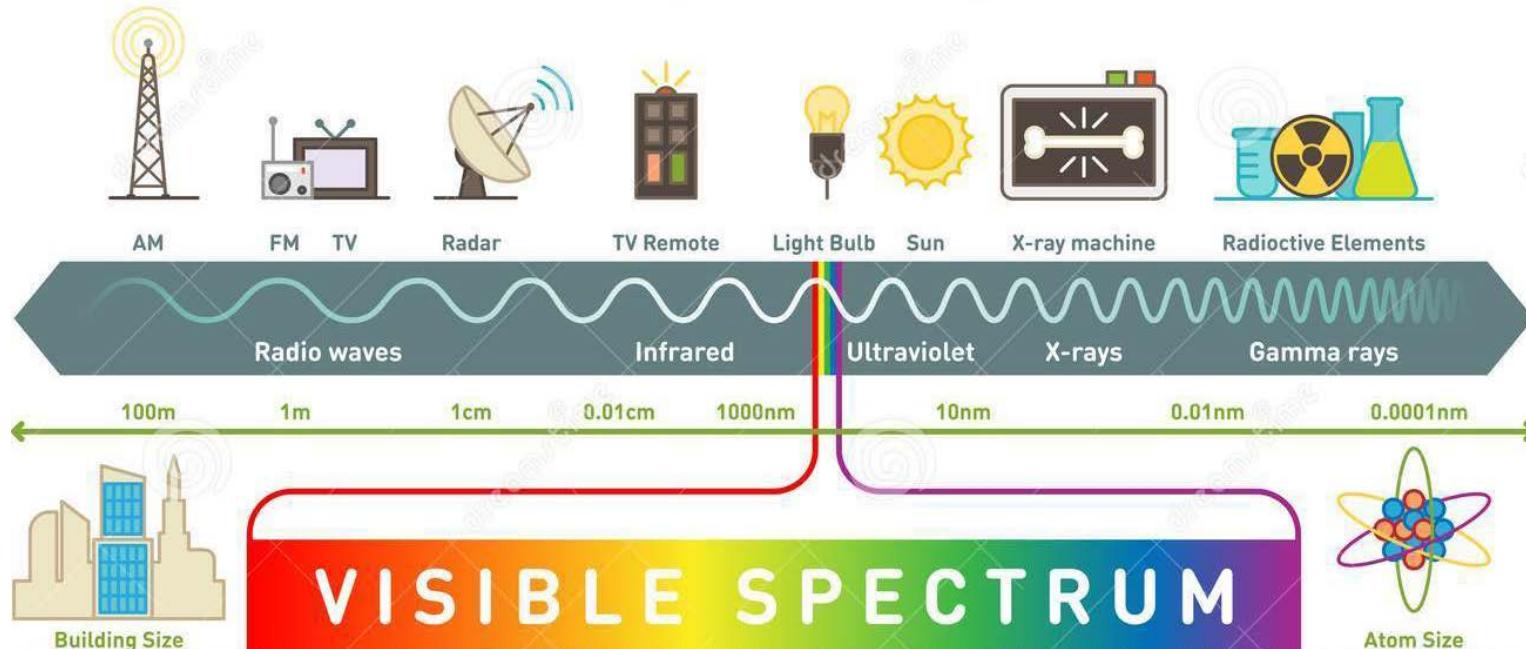


Heinrich Rudolf Hertz

2) Amplitude – the height of the wave

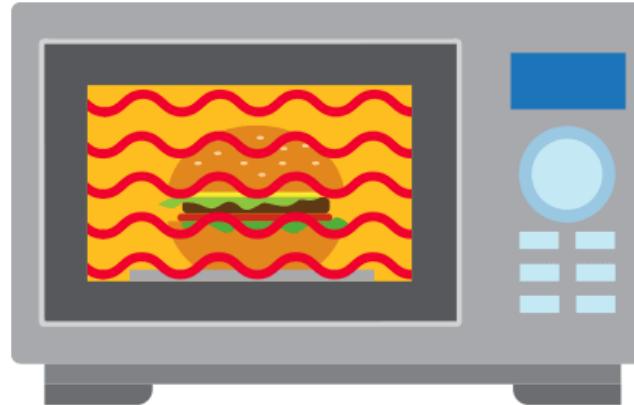
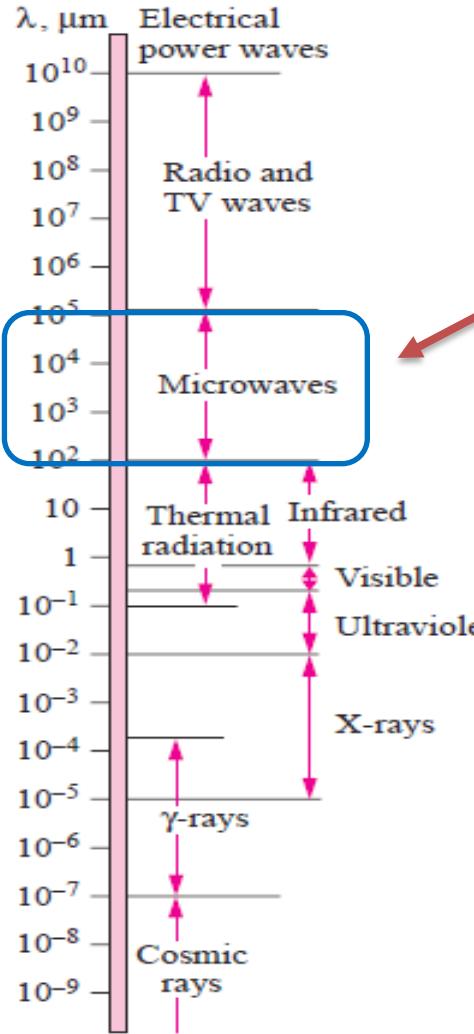
3) Wave speed – constant! - **speed of light (vacuum: 2.9979×10^8 m/s)**

Electromagnetic spectrum



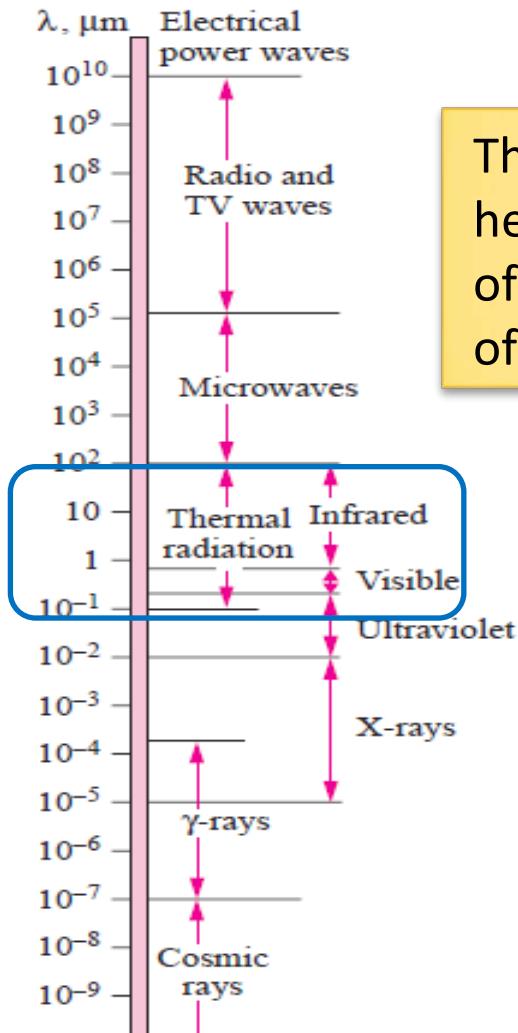
- Gamma rays are produced by nuclear reactions.
- X-rays by the bombardment of metals with high-energy electrons.
- Microwaves by special types of electron tubes such as klystrons and magnetrons.
- Radio waves by the excitation of some crystals or by the flow of alternating current through electric conductors.

Electromagnetic spectrum



- Wavelength $\lambda = 10^2 \dots 10^5 \mu\text{m}$
- Waves are reflected by metal (walls)
- Transmission through glass and plastics (ovendish)
- Absorption in food (mainly water molecules)
- Effective conversion: electric energy \rightarrow radiation energy \rightarrow internal (thermal) energy food

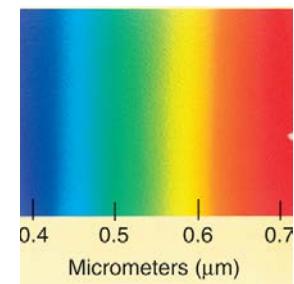
THERMAL RADIATION



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 .



ACTIVITY 1



Only Solids radiate thermal Energy

- A. True**
- B. False**
- C. Not Sure**

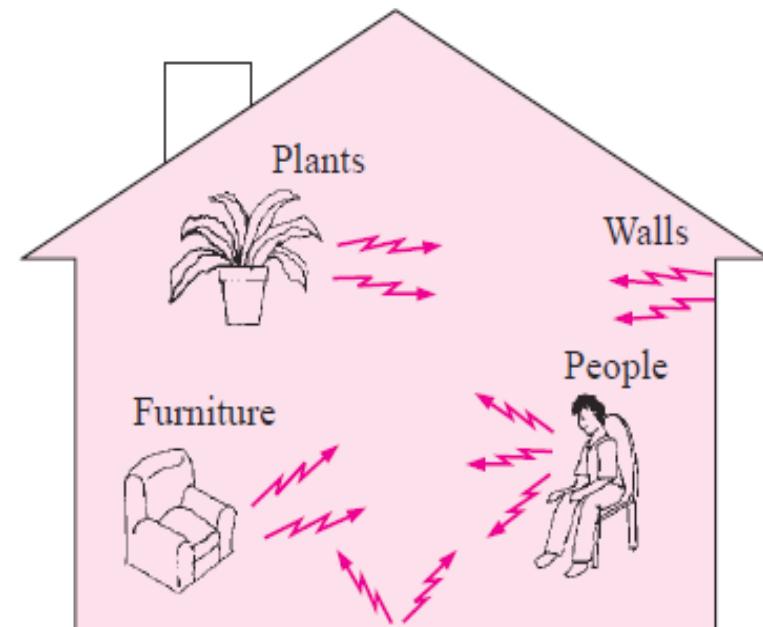
False: Solids, Liquids and gases emit radiation

ACTIVITY 2

What is the minimum temperature required for a body to give out thermal radiation ?

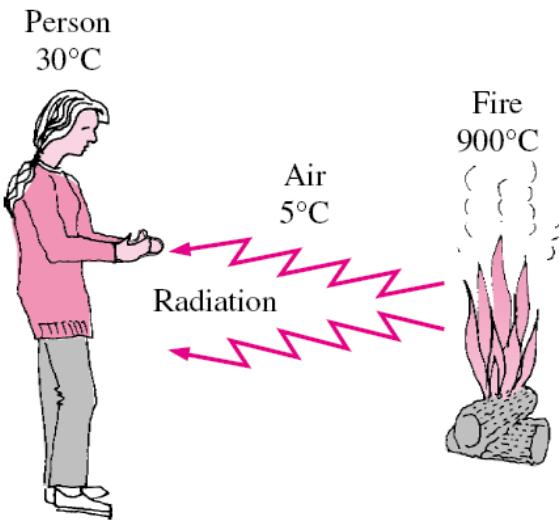
- A. 0 C
- B. 20 C
- C. 1000 C
- D. - 160 C
- E. Others

Thermal radiation is continuously emitted by all matter whose temperature is **above absolute zero (0 K or -273.15 °C)**.



This continues till equilibrium is reached with the surrounding

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
- Radiation Heat Transfer
- Resistance Networks – (Radiation and Convection)

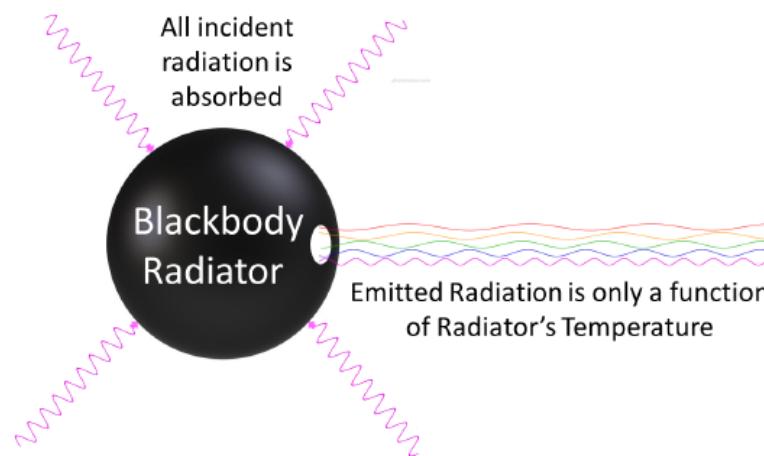
RADIATION LAWS

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.”



RADIATION LAWS

Stefan-Boltzmann law :

- ❖ Estimates the Total power emitted by blackbody

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



Josef Stefan

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

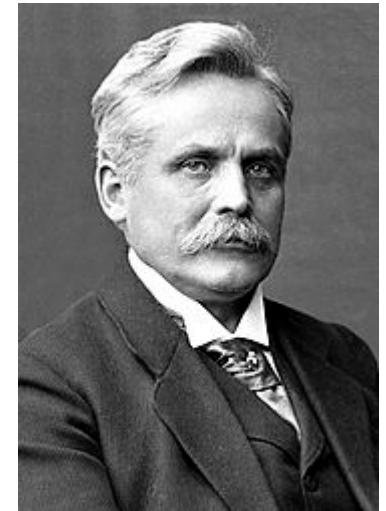
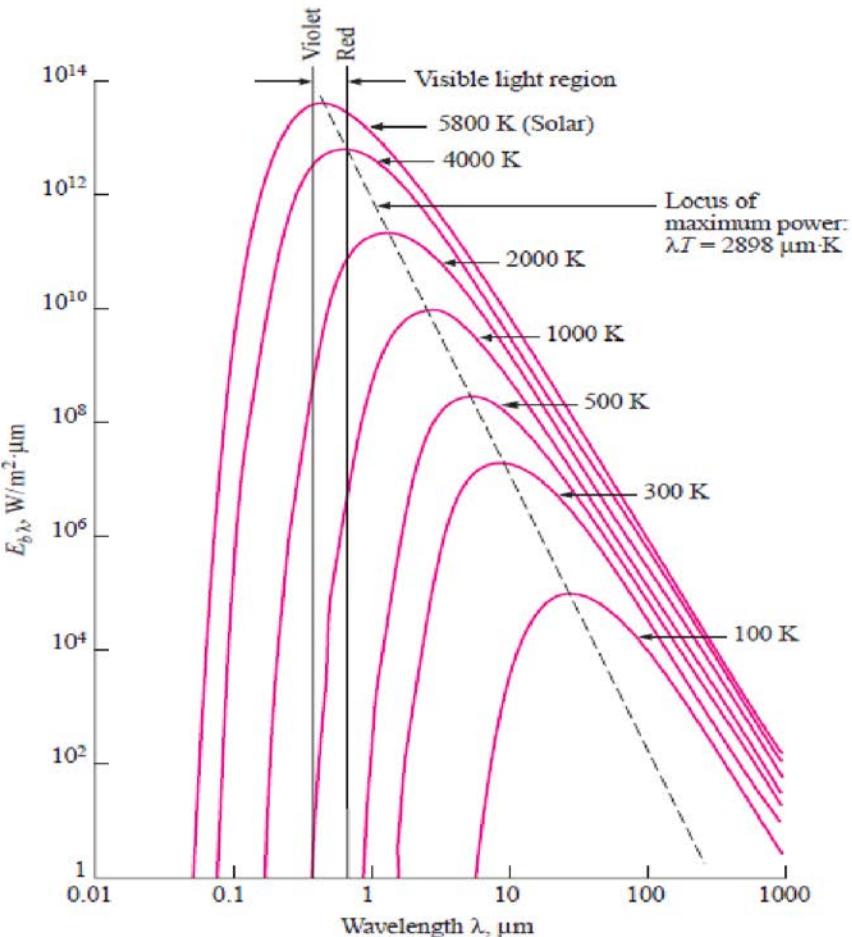
Stefan-Boltzmann
constant



Ludwig Boltzmann

RADIATION LAWS

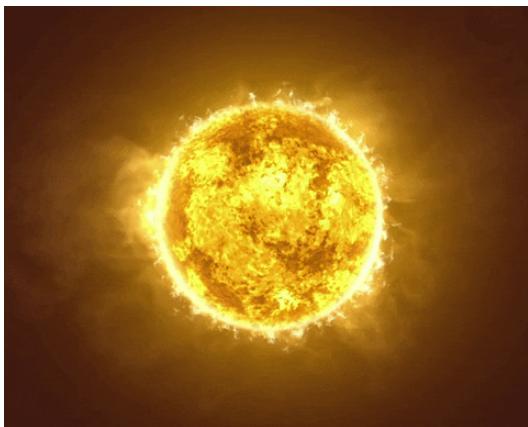
Wien's displacement law:



Wilhelm Wien

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

ACTIVITY 3



What is the $\lambda_{Max\ power}$ of solar radiation($T=5,505\ ^\circ C$) ?

$$\lambda_{Max\ power} = \frac{2897.8\ (\mu m \cdot K)}{(5,505 + 273.15)(K)} = 0.501\ \mu m$$

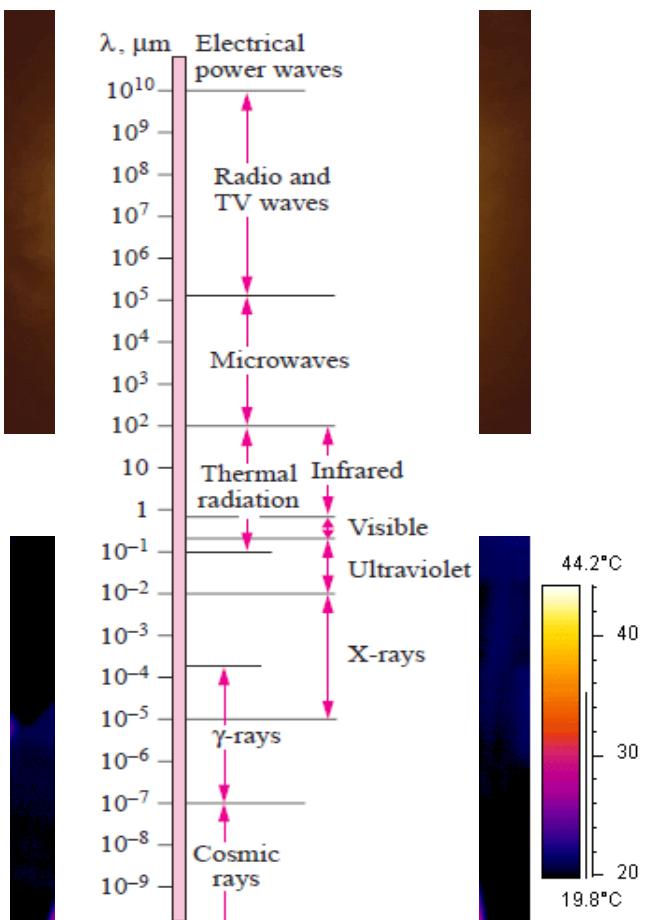


What is the $\lambda_{Max\ power}$ of human body ($T=37\ ^\circ C$) ?

$$\lambda_{Max\ power} = \frac{2897.8\ (\mu m \cdot K)}{(37 + 273.15)(K)} = 9.34\ \mu m$$

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

ACTIVITY 3



What is the $\lambda_{\text{Max power}}$ of solar radiation ($T=5,505^\circ\text{C}$) ?

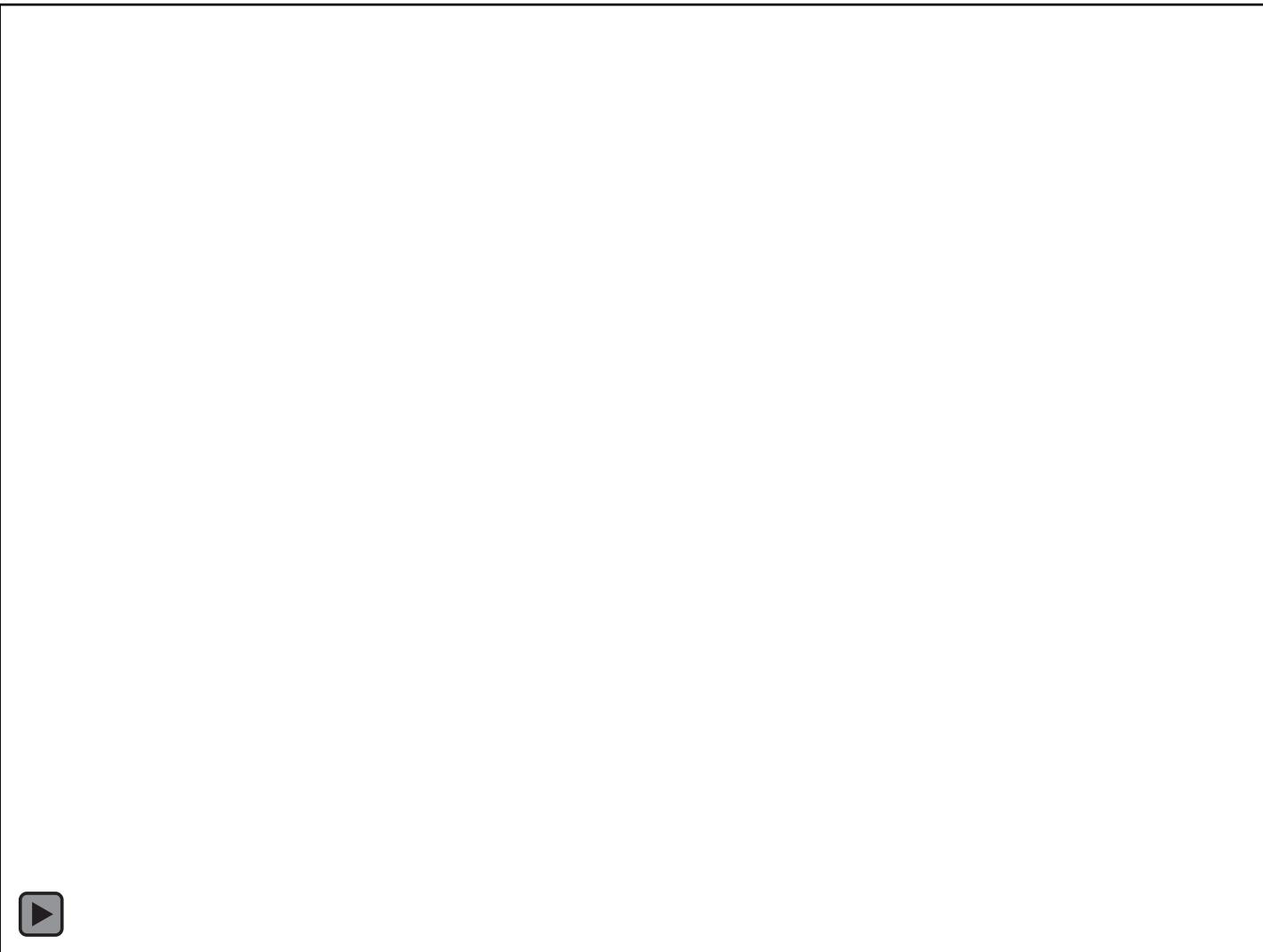
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What is the $\lambda_{\text{Max power}}$ of human body ($T=37^\circ\text{C}$) ?

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

ACTIVITY 3



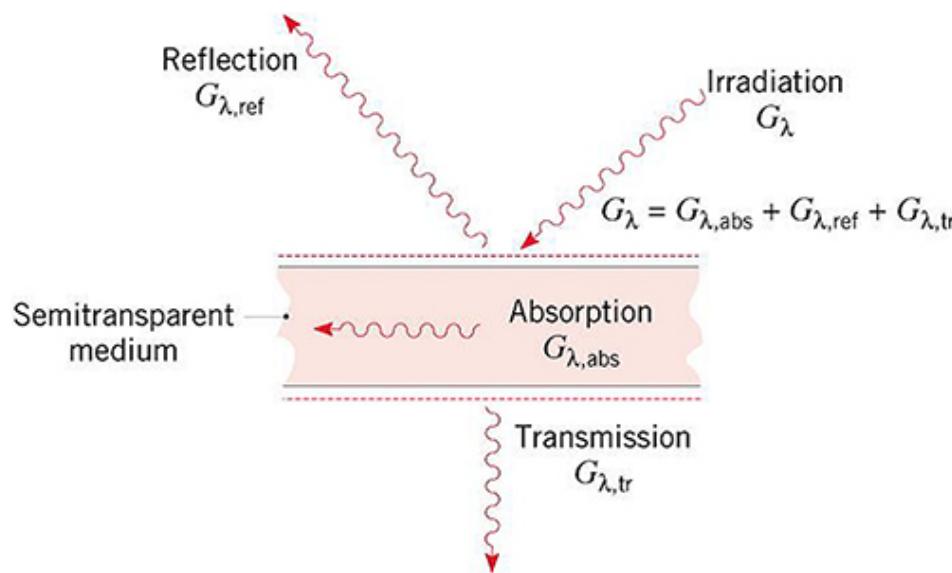
https://www.youtube.com/watch?v=fpx7hsoYEt4&ab_channel=Thunderfoot

LEARNING OBJECTIVES LECTURE 5



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

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



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

Two special cases require definition:

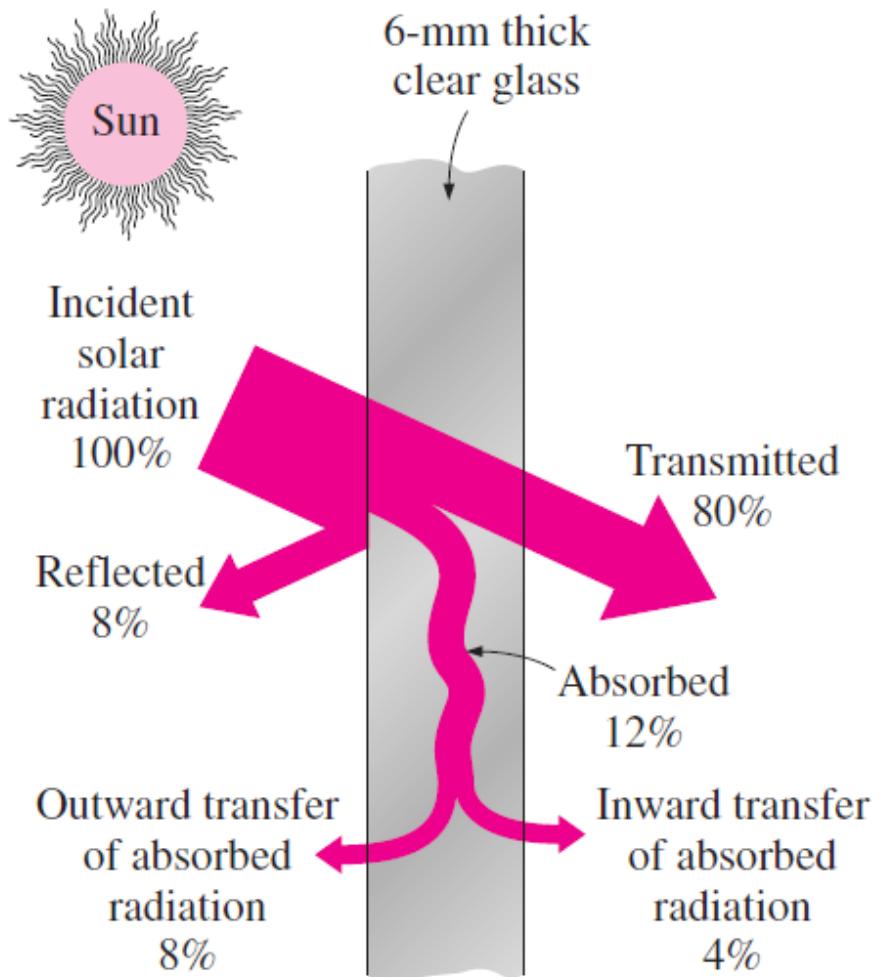
If all of the energy is either reflected or absorbed (no transmitted radiation), we define the body as

Opaque $\alpha + \rho = 1$

If all of the energy striking a surface is absorbed, we define the body as

Black body $\alpha = 1$

NON -IDEAL RADIATION

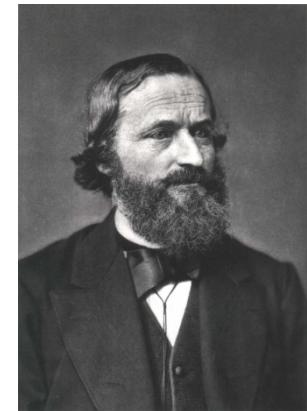


NON -IDEAL RADIATION

KIRCHHOFF`S LAW :

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

$$\varepsilon(T) = \alpha(T)$$



Gustav Robert Kirchhoff

NON -IDEAL RADIATION



EMISSIVITY

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

Adjusted Stefan-Boltzmann Law for emitted radiation from object:

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

Emissivity ε ($0 \leq \varepsilon \leq 1$) of a surface (material property):

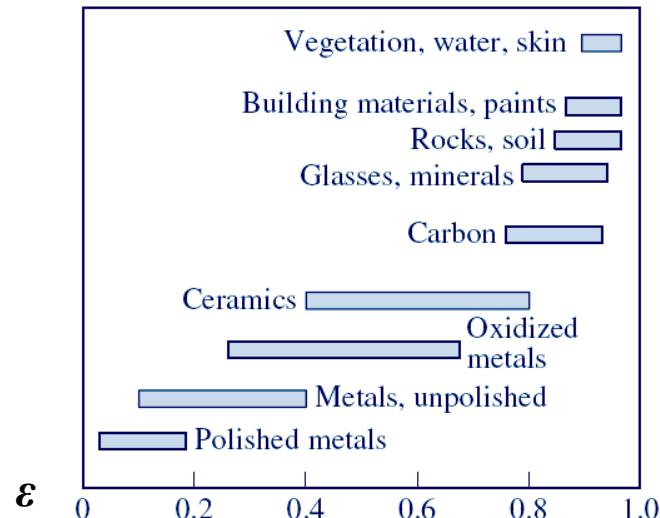
Measure for emitted radiation (\dot{Q}) in comparison to radiation (\dot{Q}_b) emitted by a blackbody ($\varepsilon = 1$) at same temperature.

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

ACTIVITY 4

Which of these materials have the highest Emissivity ?

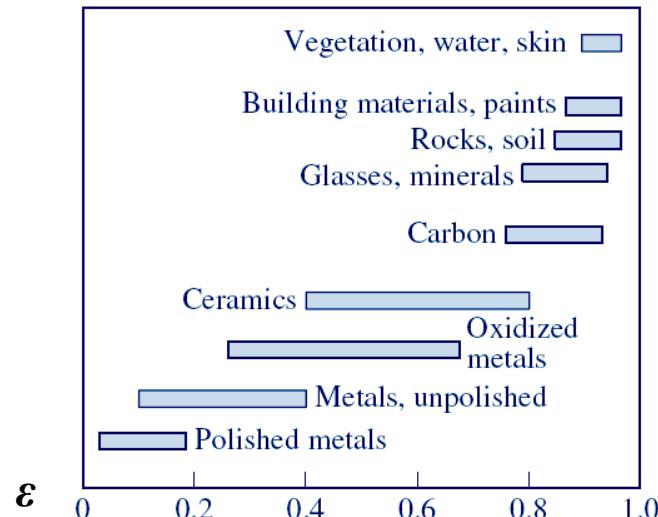
- A. Metal
- B. Polished metal
- C. Skin
- D. Ceramics



ACTIVITY 4

Which of these materials have the highest Emissivity ?

- A. Metal
- B. Polished metal
- C. Skin
- D. Ceramics



Can Emissivity be changed/Altered ?

- A. Yes
- B. No
- C. Not sure

Can be Changed via
-Thermal Treatment
- Polishing,...

DEMONSTRATION



https://www.youtube.com/watch?v=ClRrU6JuBOc&ab_channel=QuantumBoffin

LEARNING OBJECTIVES LECTURE 5



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

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:

$$\varepsilon\sigma AT_s^4$$

power
input:

$$\sigma\alpha AT_\infty^4$$

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)

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

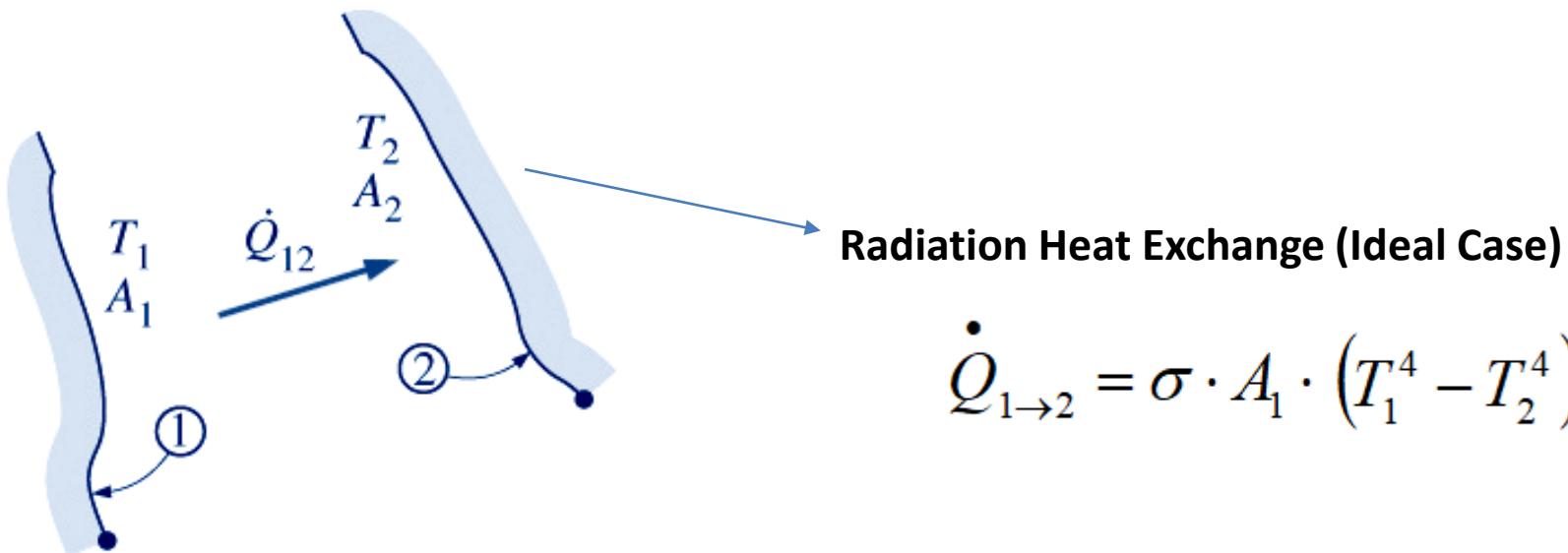
Radiation Heat Transfer

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

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

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

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

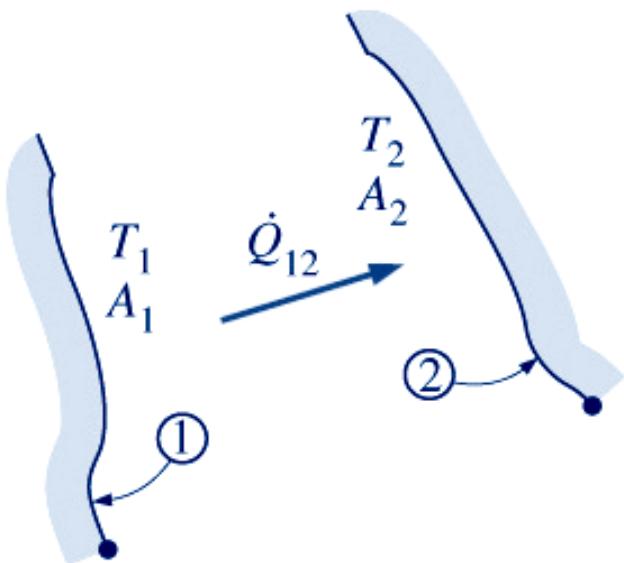


$$\dot{Q}_{1 \rightarrow 2} = \sigma \cdot A_1 \cdot (T_1^4 - T_2^4)$$

But what about the orientation and shape of the object ?

Radiation Heat Transfer

VIEW FACTORS

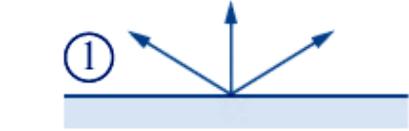


$F_{i \rightarrow j}$ is the 'view factor':

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

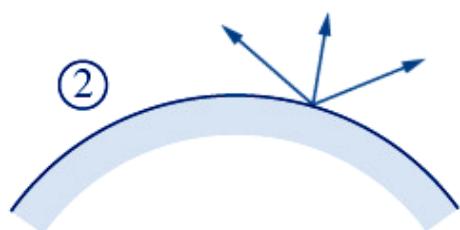
To account for the effects of orientation on radiation heat transfer between two surfaces, we define a new parameter called the view factor, which is a **purely geometric quantity** and is independent of the surface properties and temperature. It is also called the shape factor, configuration factor,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

VIEW FACTORS



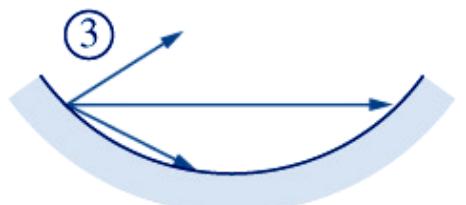
$$F_{1 \rightarrow 1} = 0$$

(a) Plane surface



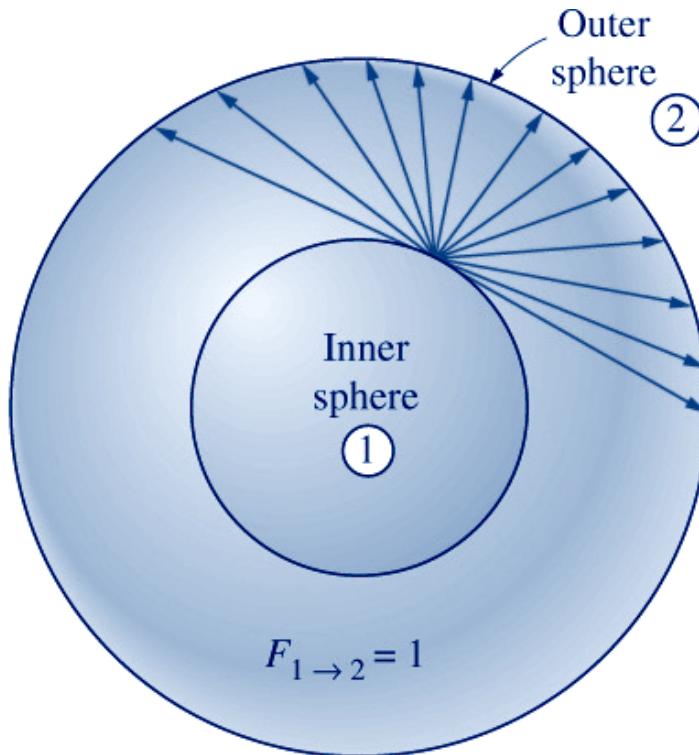
$$F_{2 \rightarrow 2} = 0$$

(b) Convex surface



$$F_{3 \rightarrow 3} \neq 0$$

(c) Concave surface



$$F_{1 \rightarrow 2} = 1$$

Cylinder/sphere:

- $F_{1 \rightarrow 1} = 0$
- $F_{1 \rightarrow 2} = 1$

VIEW FACTORS

Rules/Theorem's

1 The Reciprocity Relation

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

$$\begin{aligned} F_{j \rightarrow i} &= F_{i \rightarrow j} && \text{when } A_i = A_j \\ F_{i \rightarrow i} &\neq F_{i \rightarrow i} && \text{when } A_i \neq A_j \end{aligned}$$

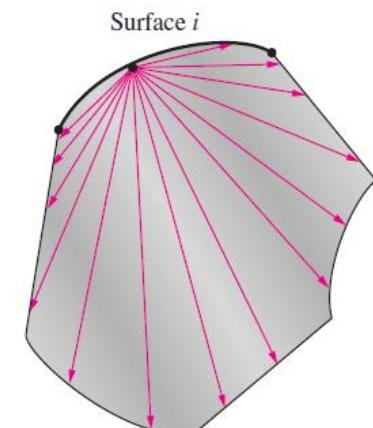
$$A_1 F_{12} = A_2 F_{21}$$

2 The Summation Rule

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

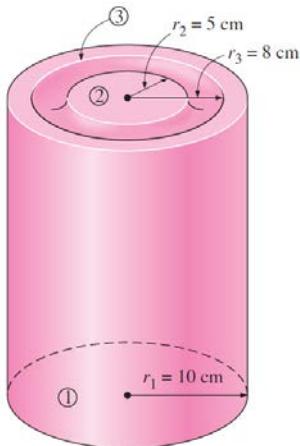
where N is the number of surfaces of the enclosure. For example, applying the summation rule to surface 1 of a three-surface enclosure yields

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



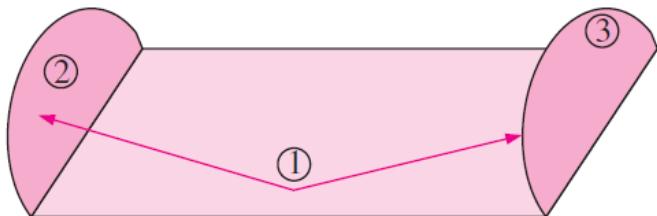
VIEW FACTORS

3 The Superposition Rule



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

4 The Symmetry Rule

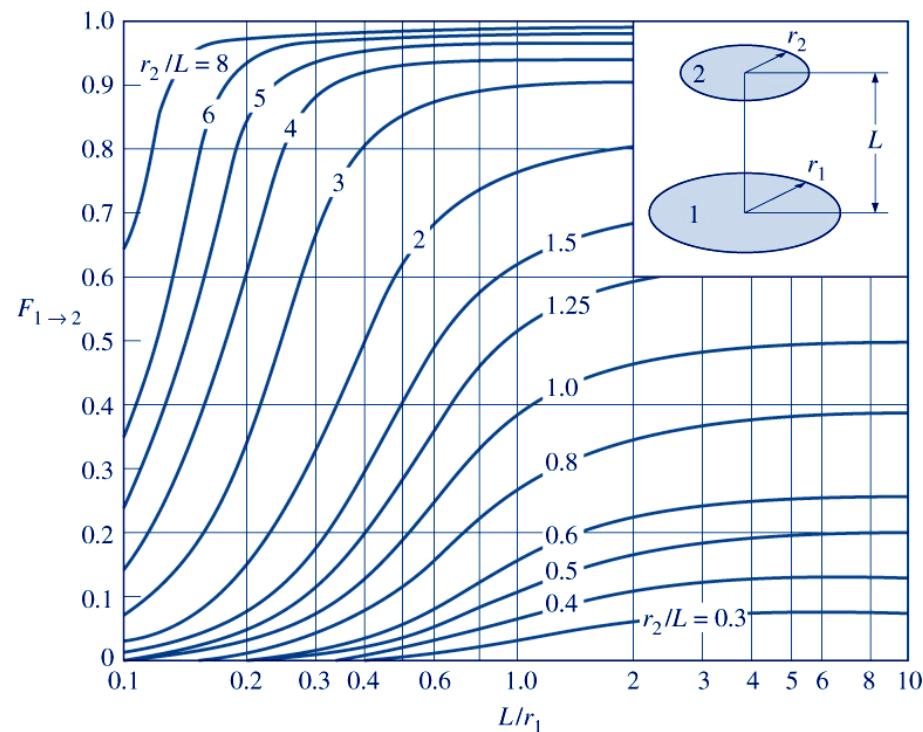
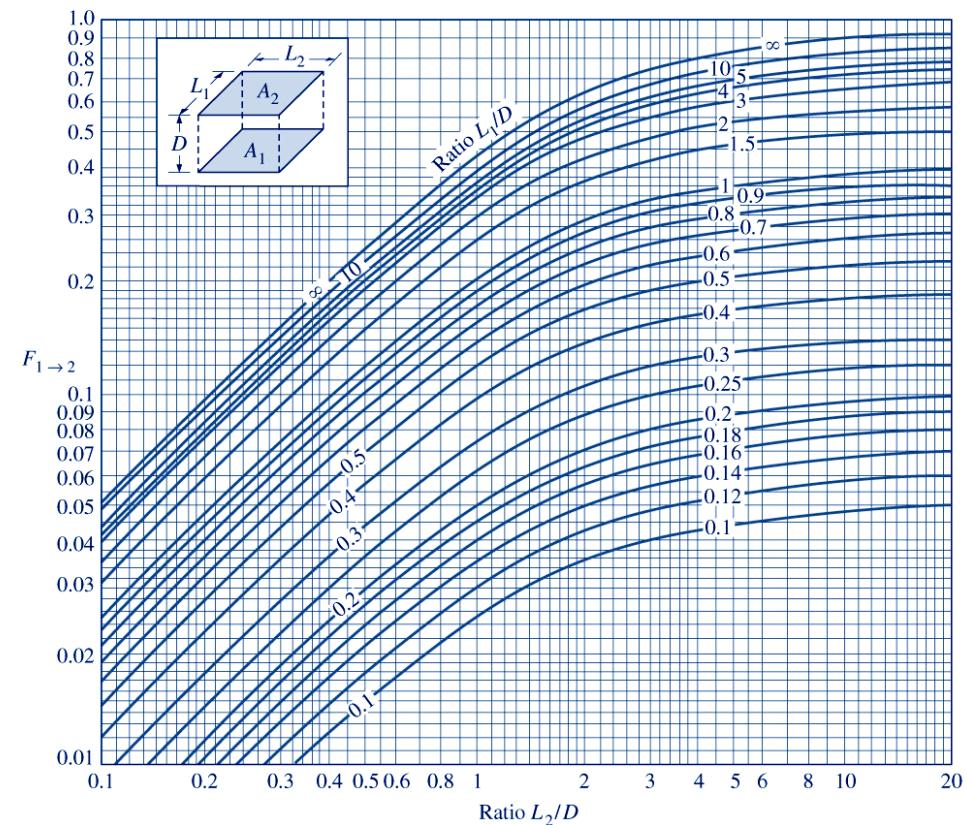


$$F_{1 \rightarrow 2} = F_{1 \rightarrow 3}$$

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

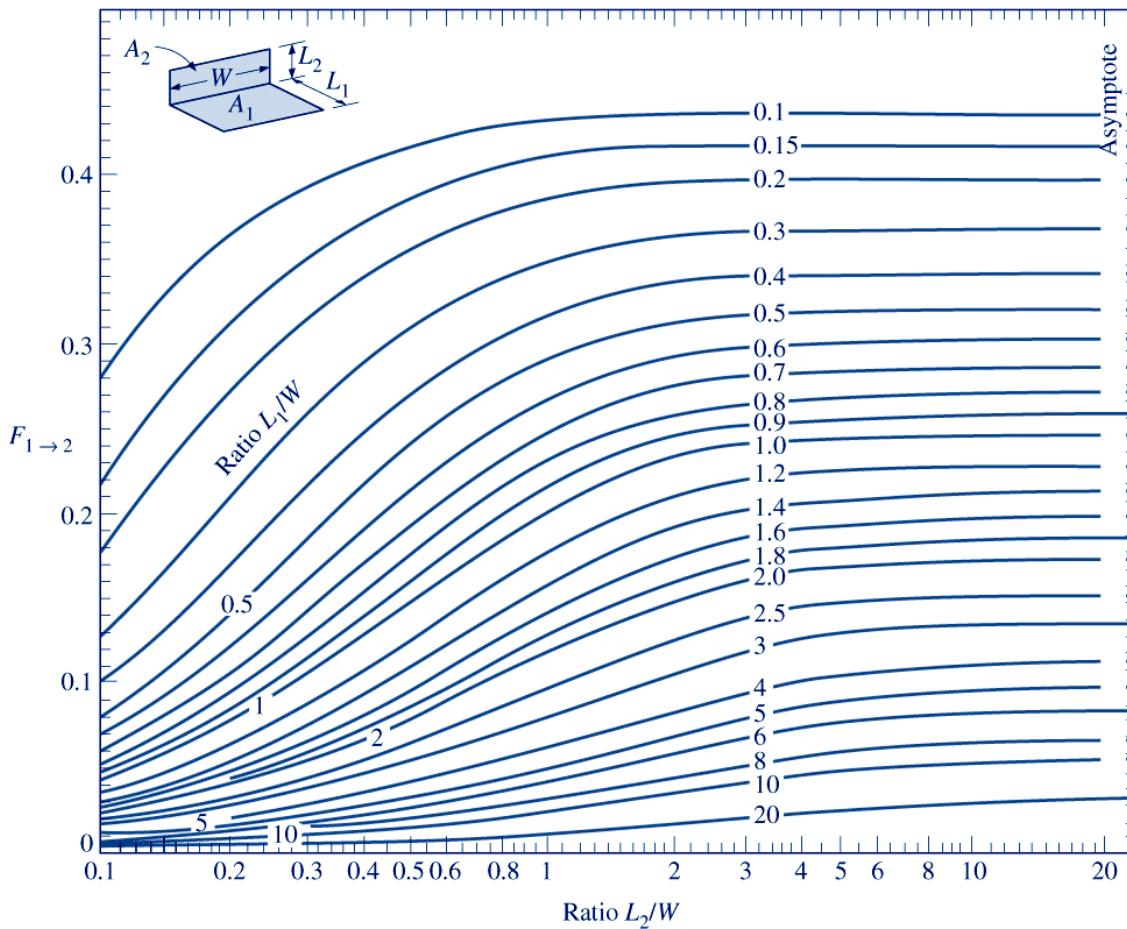
VIEW FACTORS

PARALEL PLANES



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

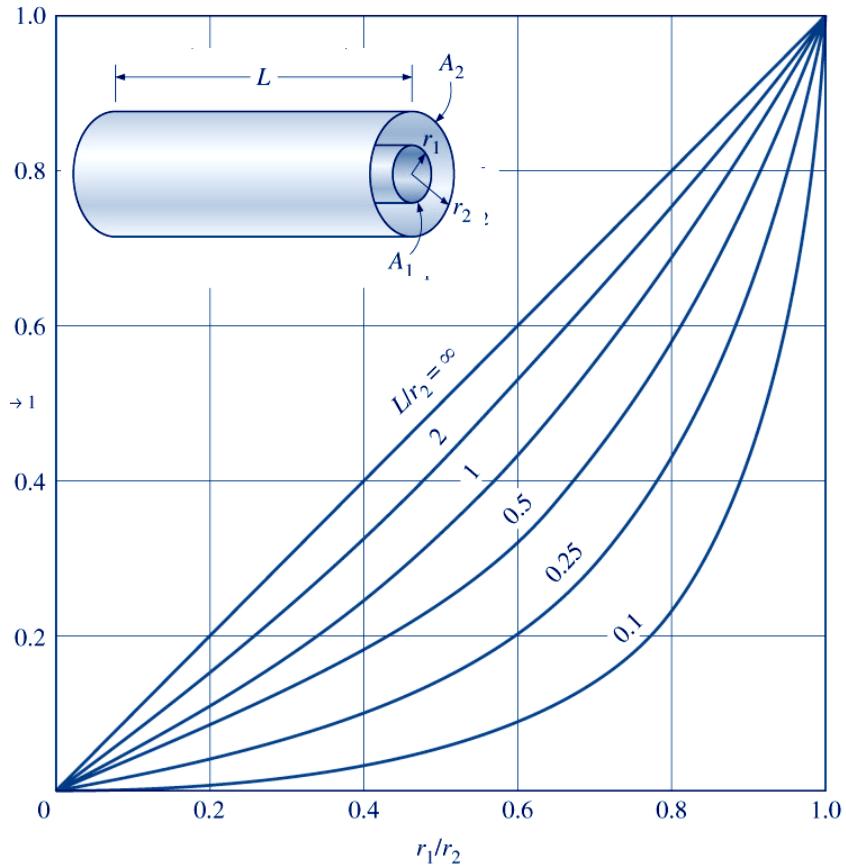
VIEW FACTORS



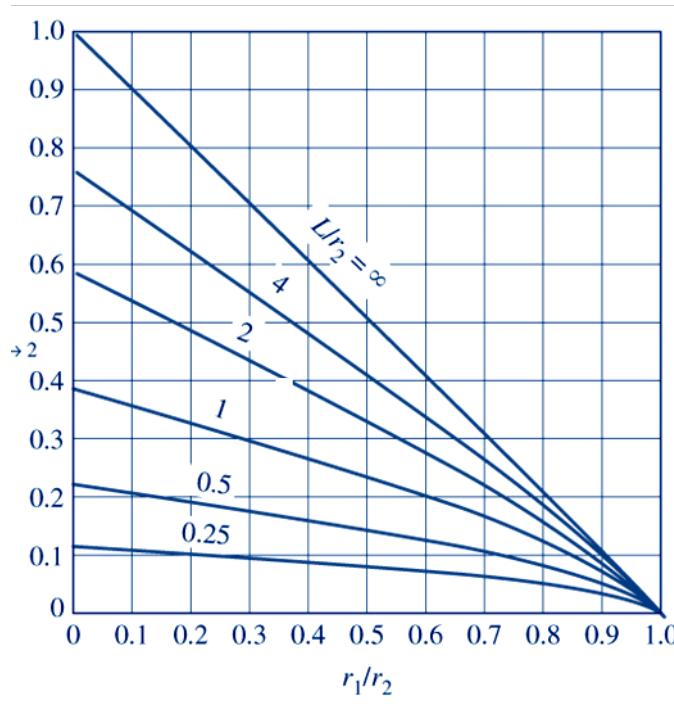
VIEW FACTORS

CONCENTRIC CYLINDERS

$F_{2 \rightarrow 1}$



$F_{2 \rightarrow 2}$



Established earlier:

- $F_{1 \rightarrow 1} = 0$
- $F_{1 \rightarrow 2} = 1$

Heat Quiz



Hints

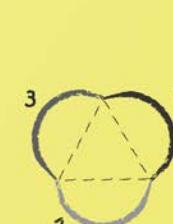
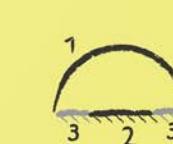
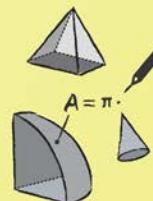
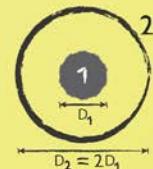
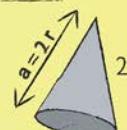
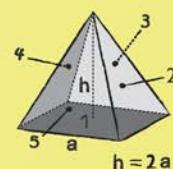
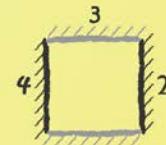
Summation rule: $\sum_j \phi_{ij} = 1$

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

Make use of symmetries

Think of auxiliary planes

Practise path: View Factors



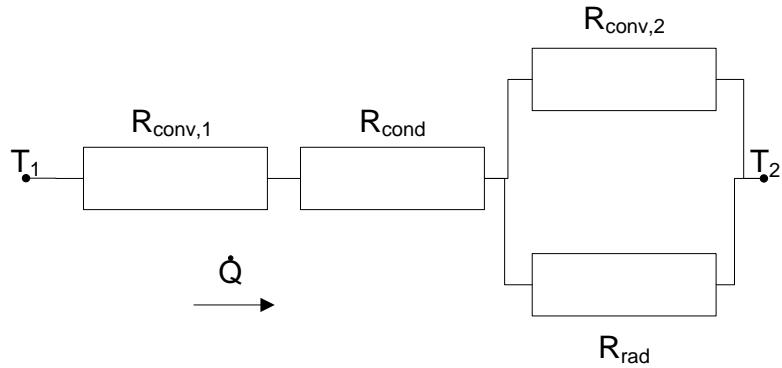
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LEARNING OBJECTIVES LECTURE 5

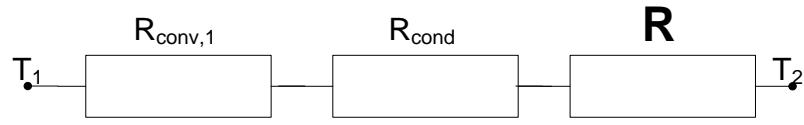


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- Radiation Heat Exchange
- Resistance Networks – (Radiation and Convection)

Overall resistance Network

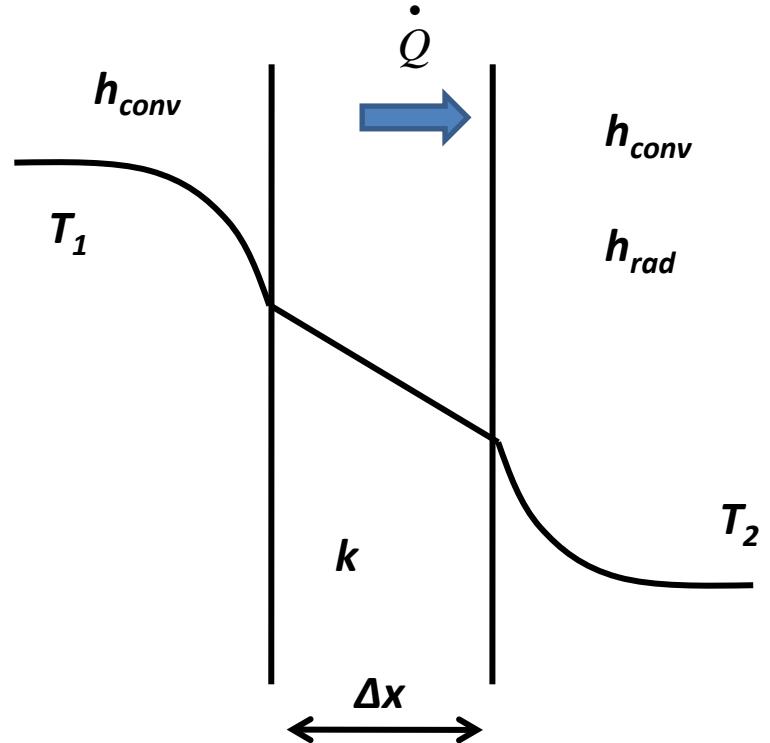


$$\frac{1}{R} = \frac{1}{R_{conv,2}} + \frac{1}{R_{rad}}$$

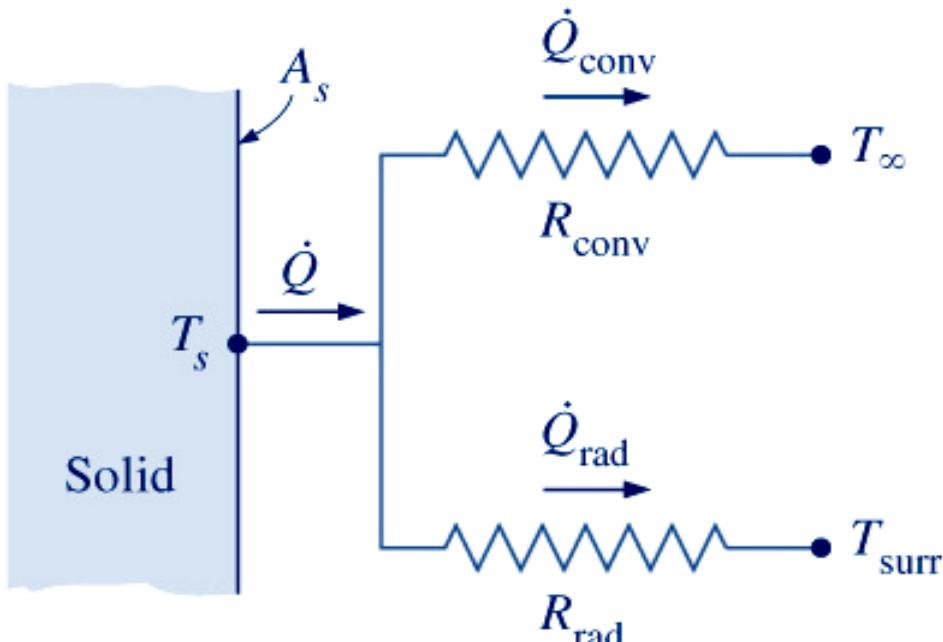


$$R_{tot} = R_{conv,1} + R_{cond} + R$$

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

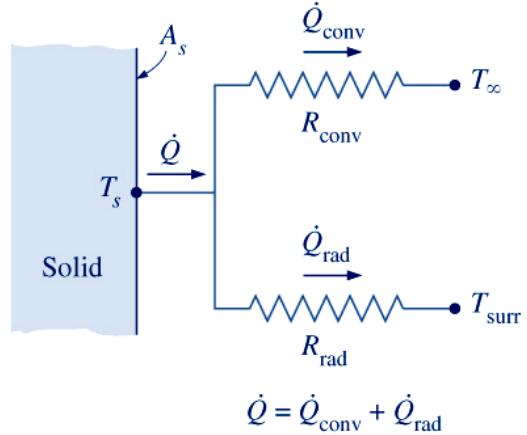


Radiation and convection



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

Radiation and convection



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

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

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

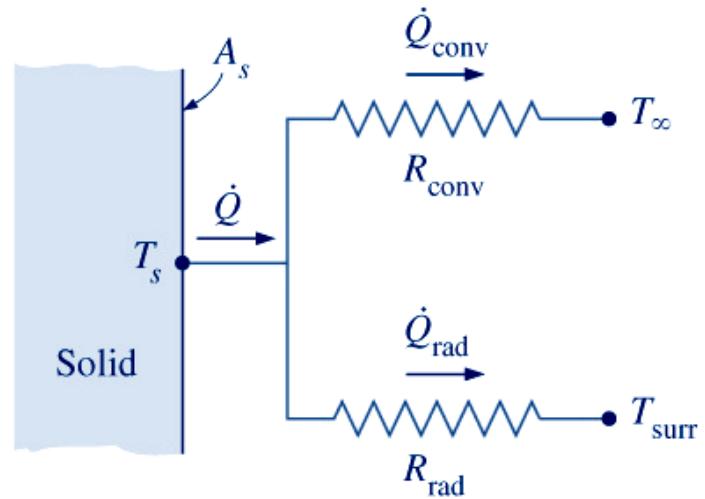
$$\dot{Q}_{\text{rad}} = \frac{T_s - T_\infty}{R_{\text{rad}}} \quad \text{with } R_{\text{rad}} = \frac{1}{h_{\text{rad}} A}$$

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

Radiation and convection

$$\begin{aligned}\dot{Q} &= \dot{Q}_{\text{conv}} + \dot{Q}_{\text{rad}} \\ &= h_{\text{conv}} A \Delta T + h_{\text{rad}} A \Delta T \\ &= (h_{\text{conv}} + h_{\text{rad}}) A \Delta T\end{aligned}$$

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



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

SUMMARY LECTURE 5 (1/2)



- Radiation
 - Does not need a transport medium
 - Thermal: $0,1 \mu\text{m} < \lambda < 100 \mu\text{m}$
- 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 emitters (blackbody: $\varepsilon = 1$)

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

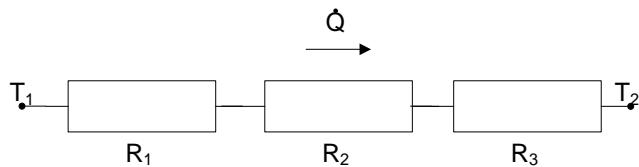
- Net radiation from non ideal emitter towards environment (with $\varepsilon < 1$)

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

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

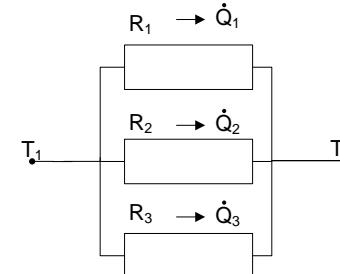
- Radiation and convection: $h_{tot} = h_{conv} + h_{rad}$

- Series resistors:
(add resistors)



- Parallel resistors:
(add heat flows)

$$\frac{1}{R_{tot}} = \sum_i \frac{1}{R_i}$$



LECTORIAL 2

- ⇒ Lecture 6- Preparation (Activities & Slides)
- ⇒ On campus Lectorial : 30 Sept: 08:45 – 10:30
- ⇒ Assignments: bundle on Canvas
- ⇒ Deadlines: schedule on Canvas

*Ready, set,
GO!...*

