

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

$\lambda_1 < \lambda_2 < \lambda_3$

Cylindrical

Fins

$\lambda_1 = \lambda_2$

Bodys

Fins

$\lambda_1 > \lambda_2 > \lambda_3$

Shuffle

Dr. Dr. Wilko Rohlf's
 Institute of Heat and Mass Transfer
 Augustinerbach 6, 52056 Aachen
 rohlfs@wsa.rwth-aachen.de
 Copyright © 2020 Wilko Rohlf's. All rights reserved

Recap of last lectures

Heat Transfer Modes

Heat Conduction



- **Fourier Law**

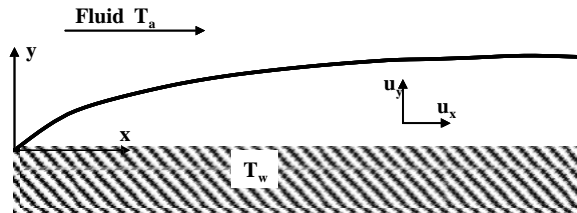
$$\dot{Q} = -kA \frac{\Delta T}{\Delta x} [W]$$

Thermal
Conductivity
[W/m.K]

Material properties

Cross-
Sectional
Area [m^2]

Convection



- **Newton's law of cooling**

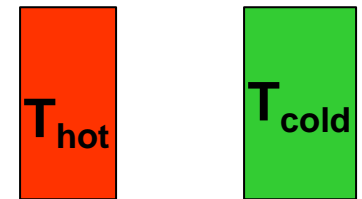
$$\dot{Q} = hA(T_w - T_a) [W]$$

Convective Heat
Transfer Coefficient
[W/m²K]

Flow dependent

- **Natural Convection**
- **Forced Convection**

Thermal Radiation



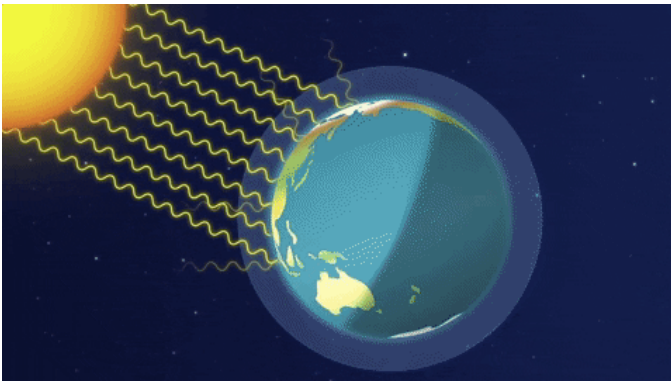
LEARNING OBJECTIVES LECTURE 5

- 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**

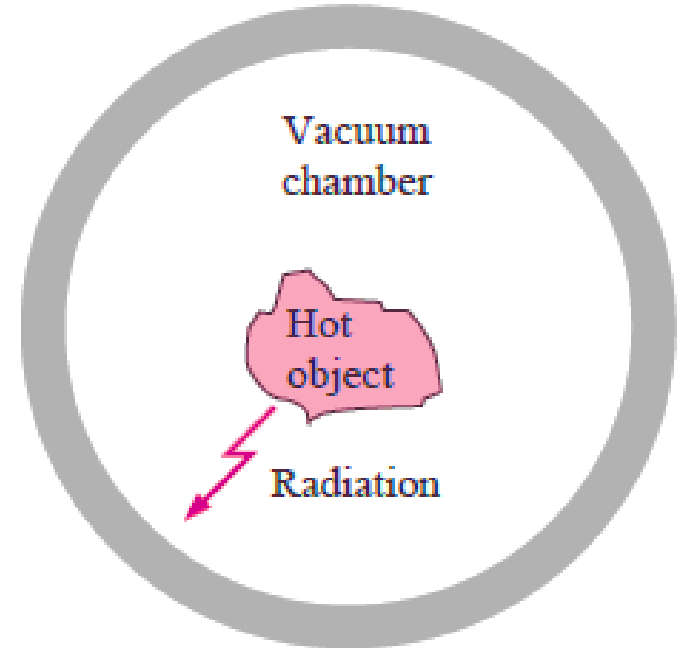
Fire



Flame temperature **$\sim 750^{\circ}\text{C}$**

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 ? ?

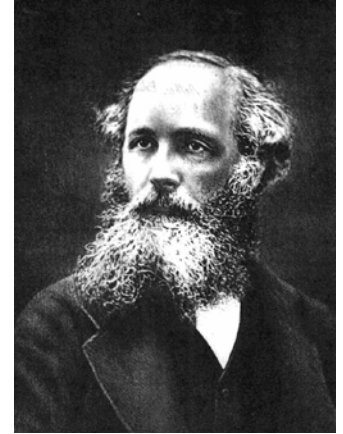
Electromagnetic Waves or Electromagnetic Radiation
(no medium required!)

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

Electromagnetic Waves

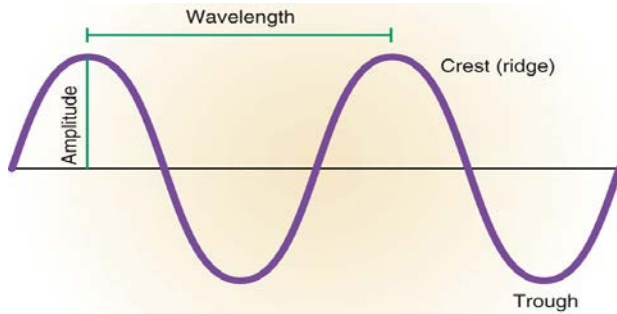
Electromagnetic Waves :

- 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}

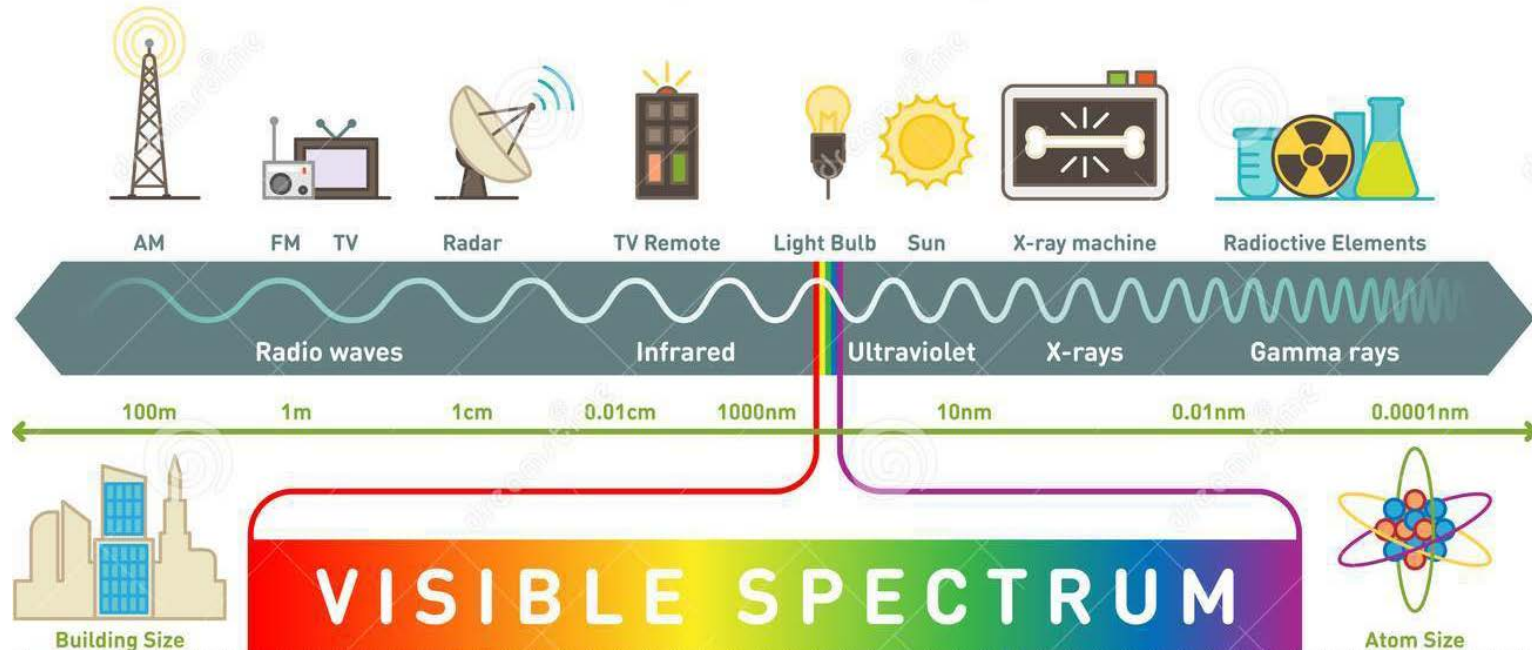


Heinrich Rudolf Hertz

2) Amplitude – the height of the wave

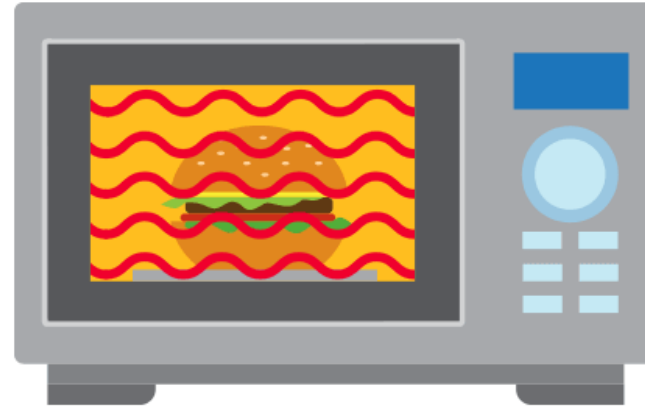
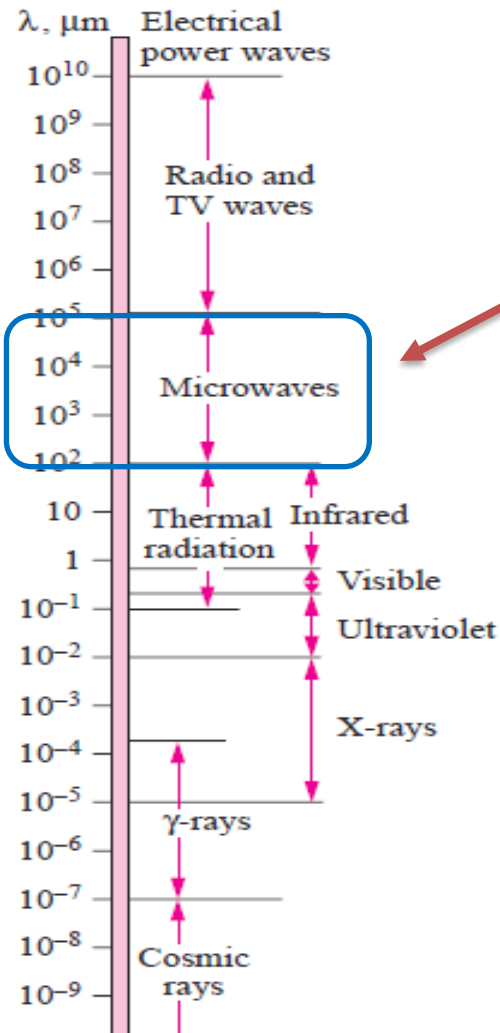
3) Wave speed – constant! - speed of light (vacuum: $2.9979 \times 10^8 \text{ m/s}$)

Electromagnetic spectrum



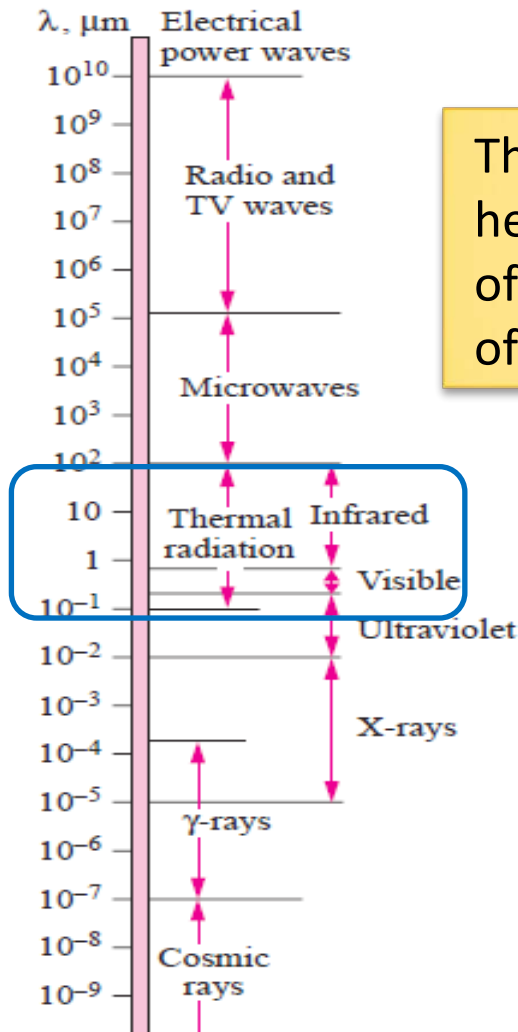
- Gamma rays are produced by nuclear reactions.
- X-rays by the bombardment of metals with high-energy electrons.
- Microwaves by special types of electron tubes such as klystrons and magnetrons.
- Radio waves by the excitation of some crystals or by the flow of alternating current through electric conductors.

Electromagnetic spectrum



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

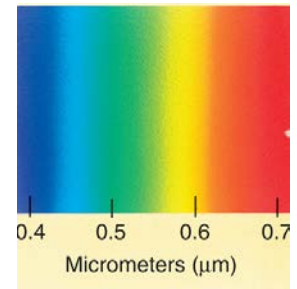
THERMAL RADIATION



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

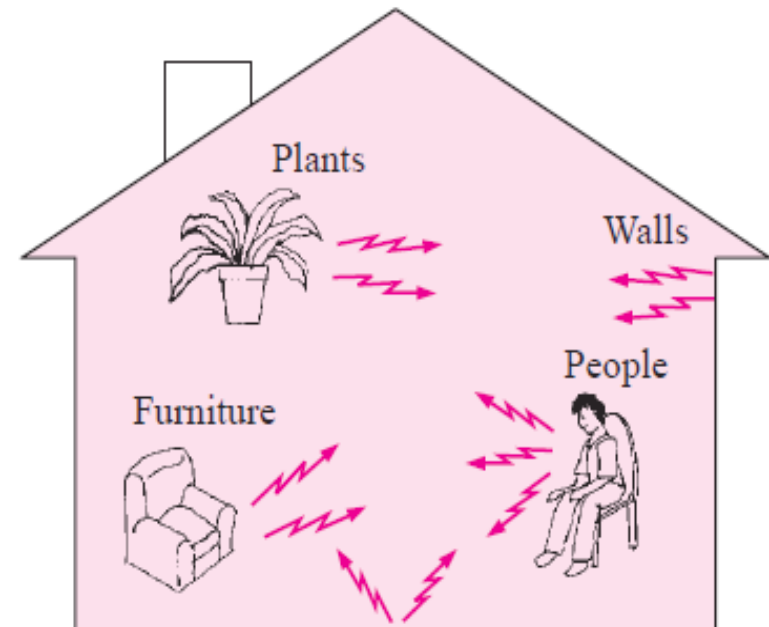
ACTIVITY 2

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

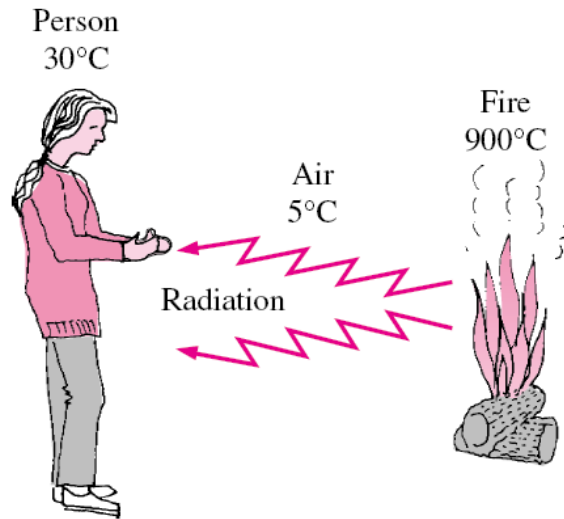
- A. 0 C
- B. 20 C
- C. 1000 C
- D. - 160 C
- E. Others

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)

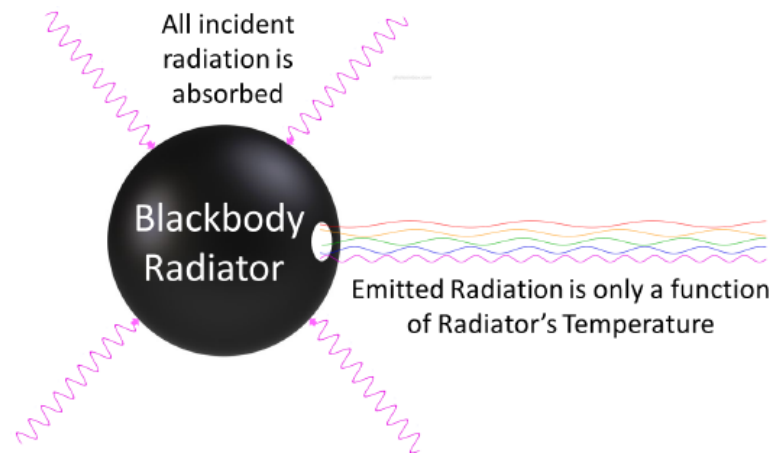
RADIATION LAWS

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

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

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



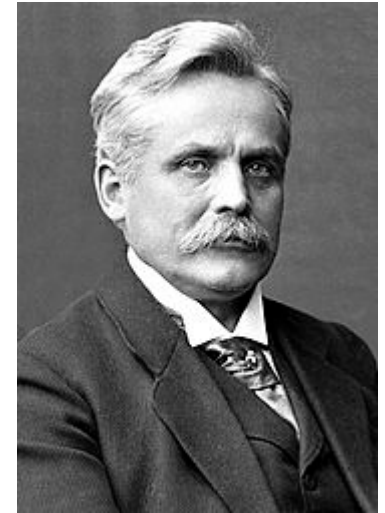
Josef Stefan



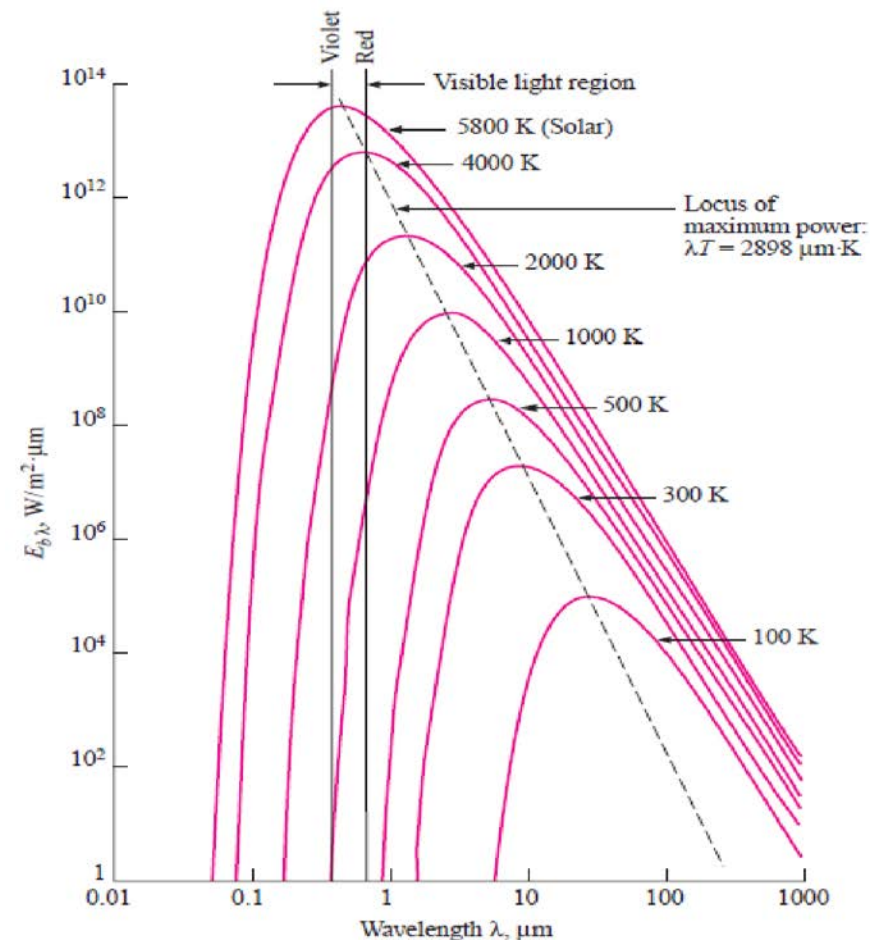
Ludwig Boltzmann

RADIATION LAWS

Wien's displacement law:



Wilhelm Wien



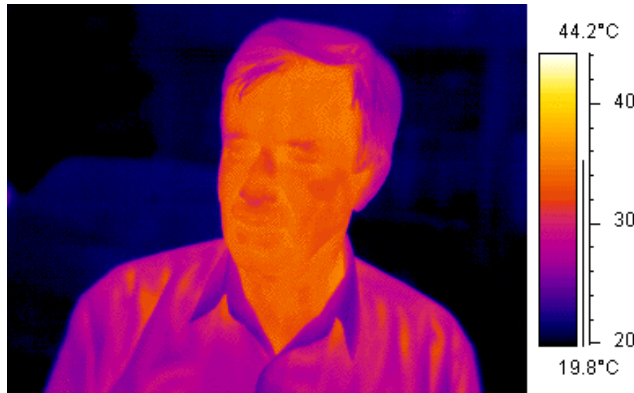
$$(\lambda T)_{\text{max power}} = 2897.8 \mu\text{m} \cdot \text{K}$$

ACTIVITY 3



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

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

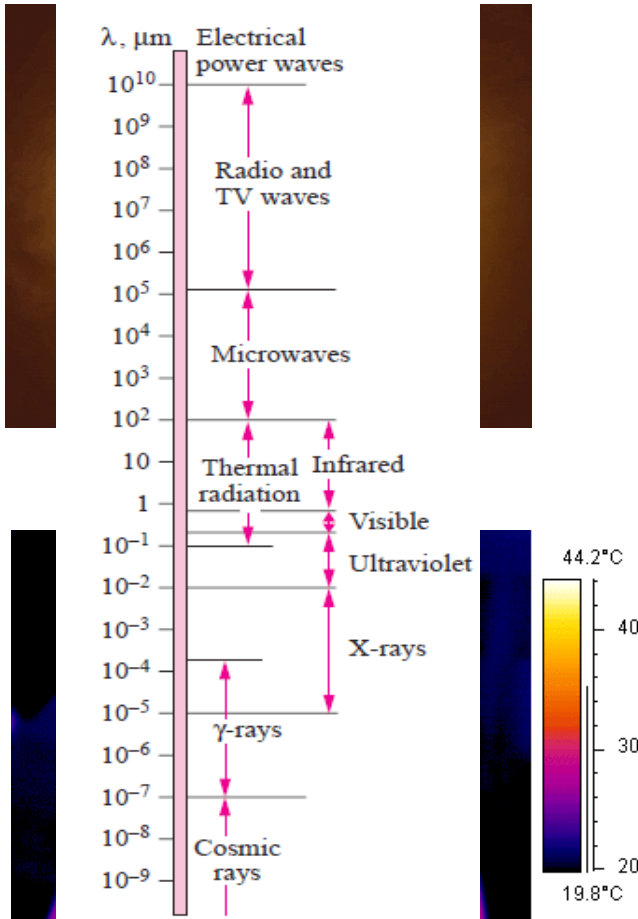


What is the $\lambda_{\text{Max power}}$ of human body ($T=37^\circ\text{C}$) ?

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

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

ACTIVITY 3



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

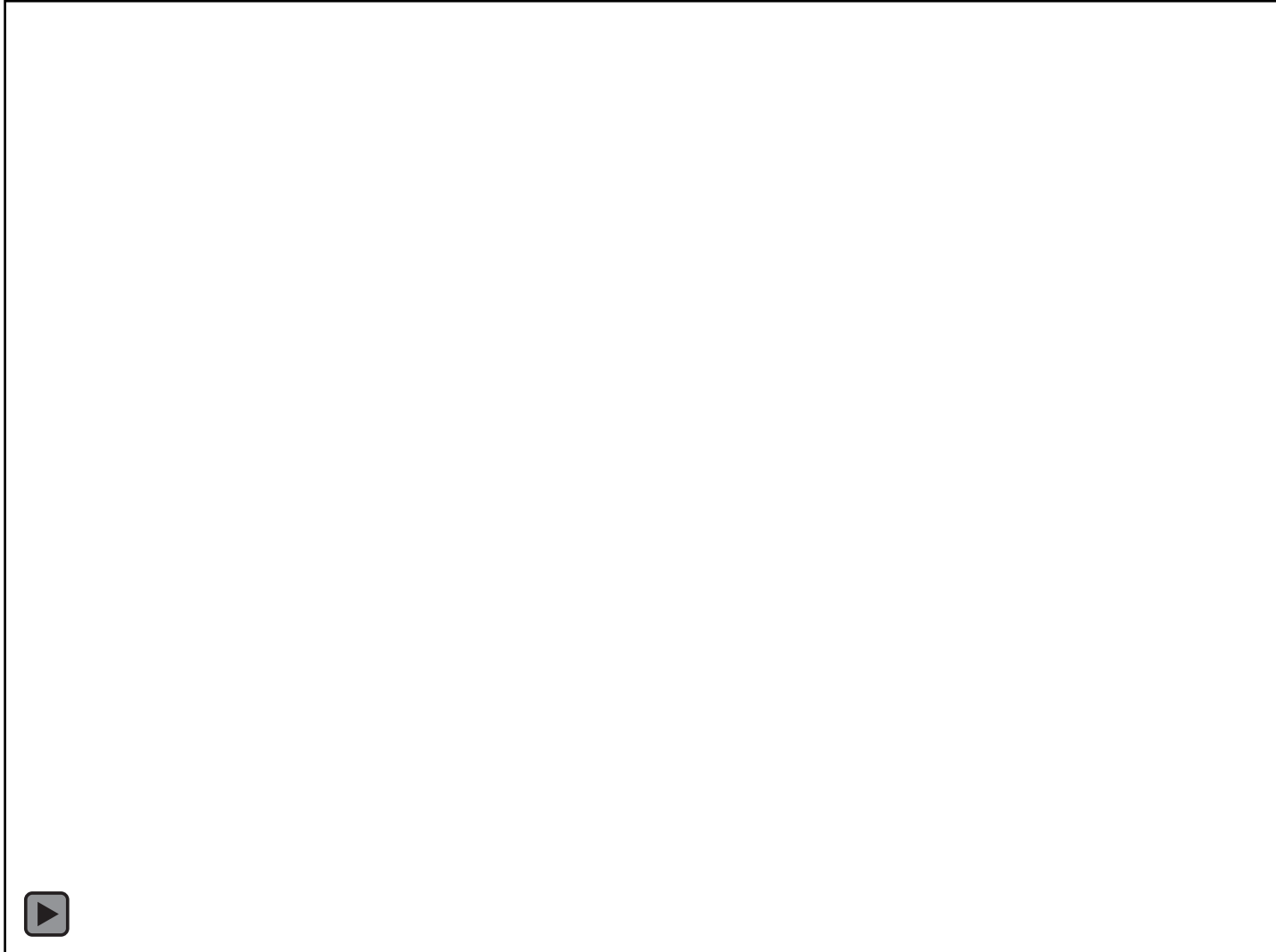
$$\lambda_{\text{Max power}} = \frac{2897.8 (\mu\text{m} \cdot \text{K})}{(5,505 + 273.15)(\text{K})} = 0.501 \mu\text{m}$$

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

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

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

ACTIVITY 3



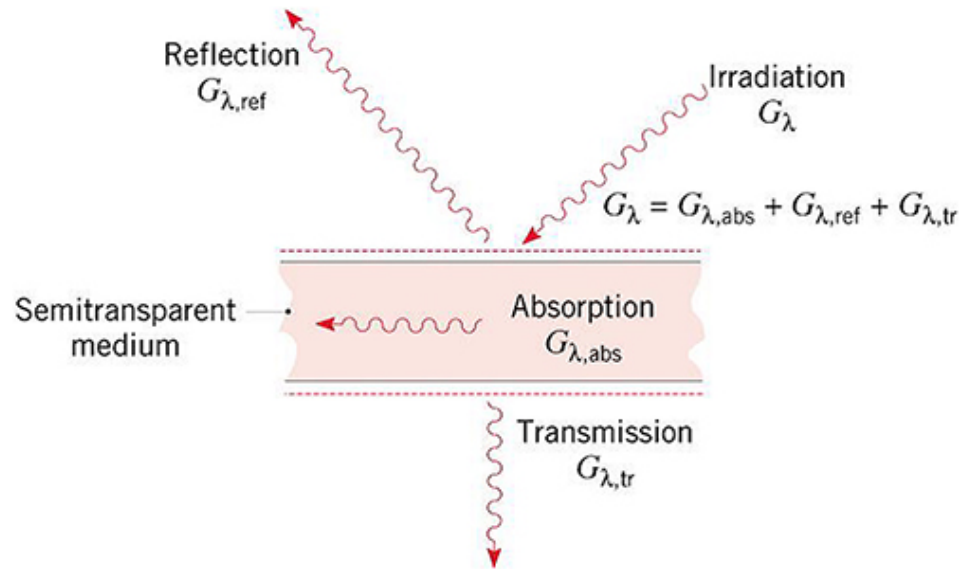
https://www.youtube.com/watch?v=fpx7hsoYEt4&ab_channel=Thunderfoot

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:

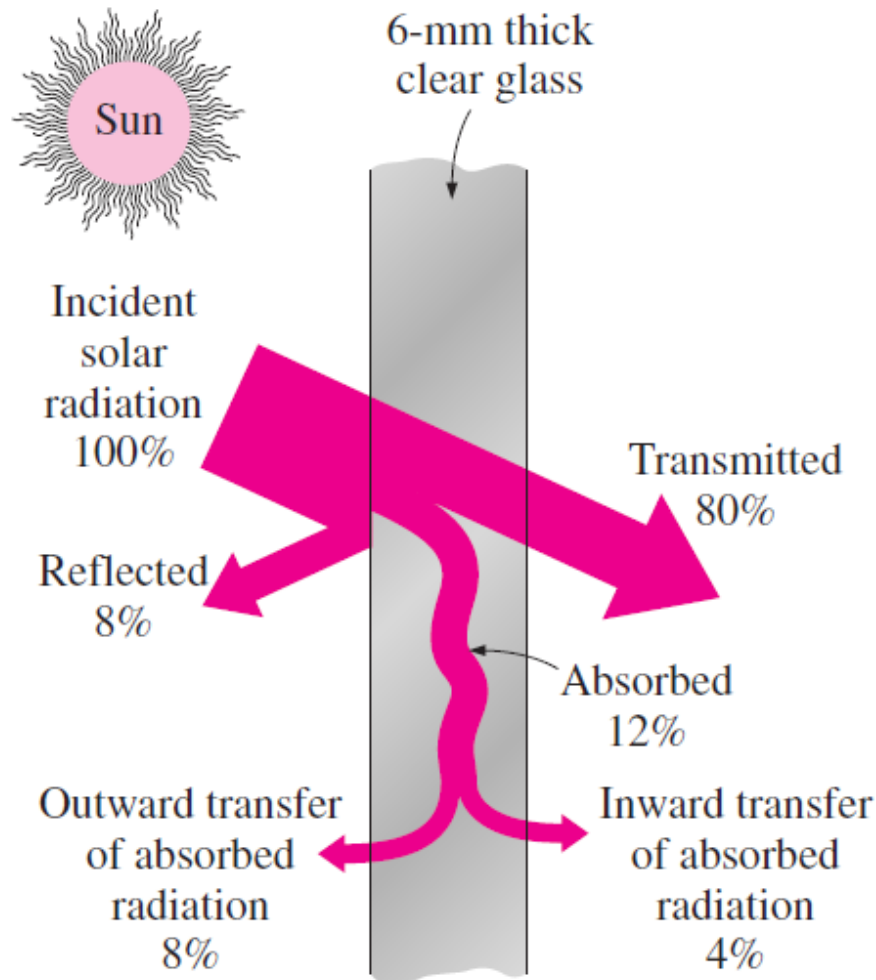
If all of the energy is either reflected or absorbed (no transmitted radiation), we define the body as

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

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

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

NON - IDEAL RADIATION

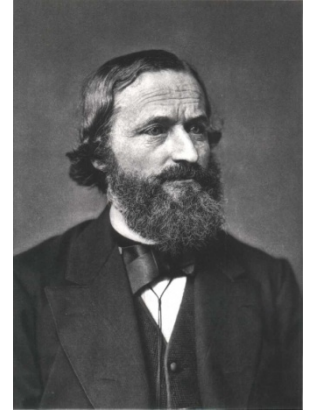


NON - IDEAL RADIATION

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):

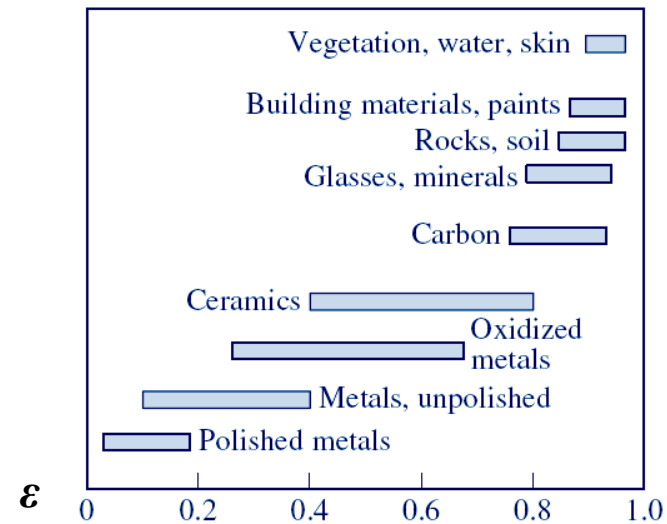
Measure for emitted radiation (\dot{Q}) in comparison to radiation (\dot{Q}_b) emitted by a blackbody ($\varepsilon = 1$) at same temperature.

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

ACTIVITY 4

Which of these materials have the highest Emissivity ?

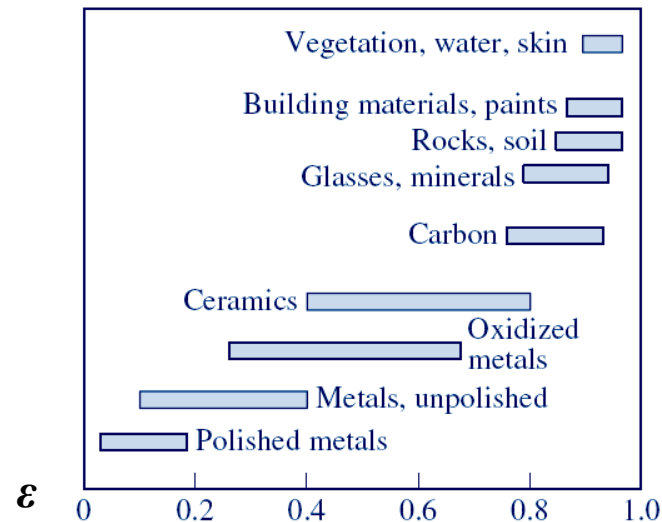
- A. Metal
- B. Polished metal
- C. Skin
- D. Ceramics



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:

$$\varepsilon \sigma A T_s^4$$

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)

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

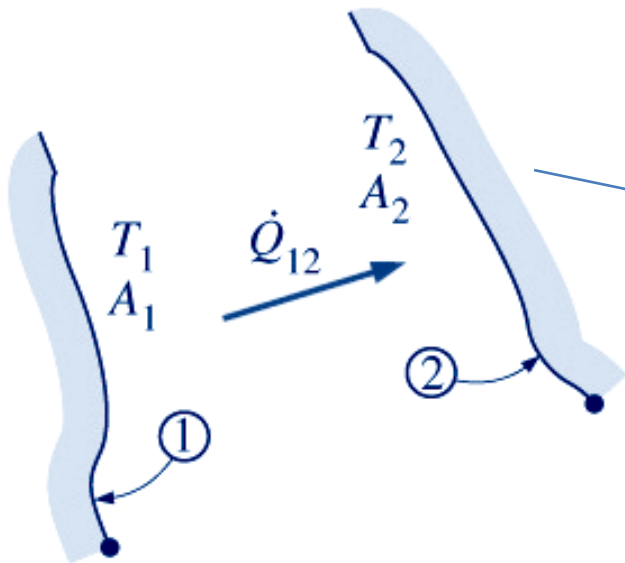
Radiation Heat Transfer

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)

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



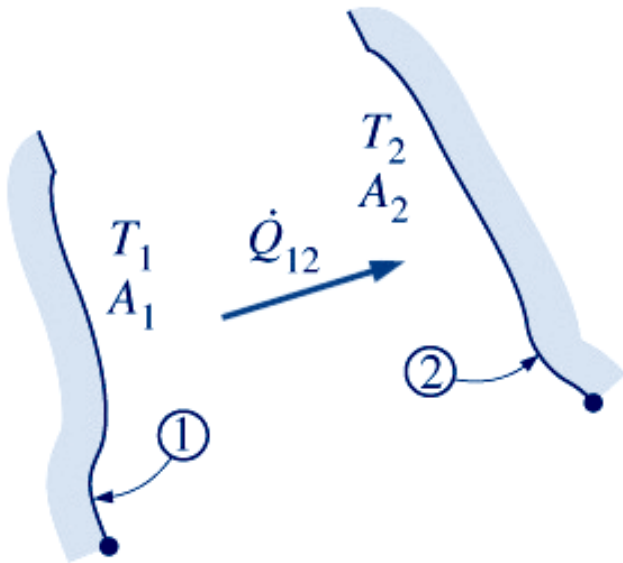
Radiation Heat Exchange (Ideal Case)

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

But what about the orientation and shape of the object ?

Radiation Heat Transfer

VIEW FACTORS



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

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

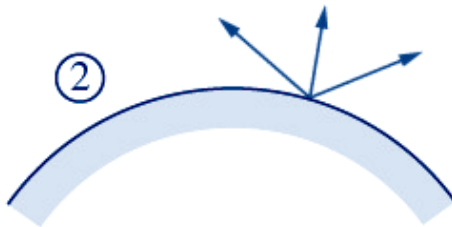
To account for the effects of orientation on radiation heat transfer between two surfaces, we define a new parameter called the view factor, which is a **purely geometric quantity** and is independent of the surface properties and temperature. It is also called the shape factor, configuration factor,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

VIEW FACTORS



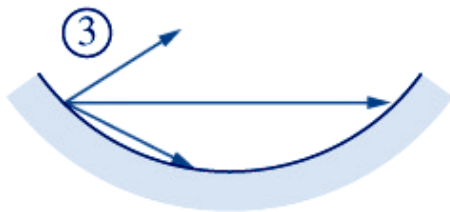
$$F_{1 \rightarrow 1} = 0$$

(a) Plane surface



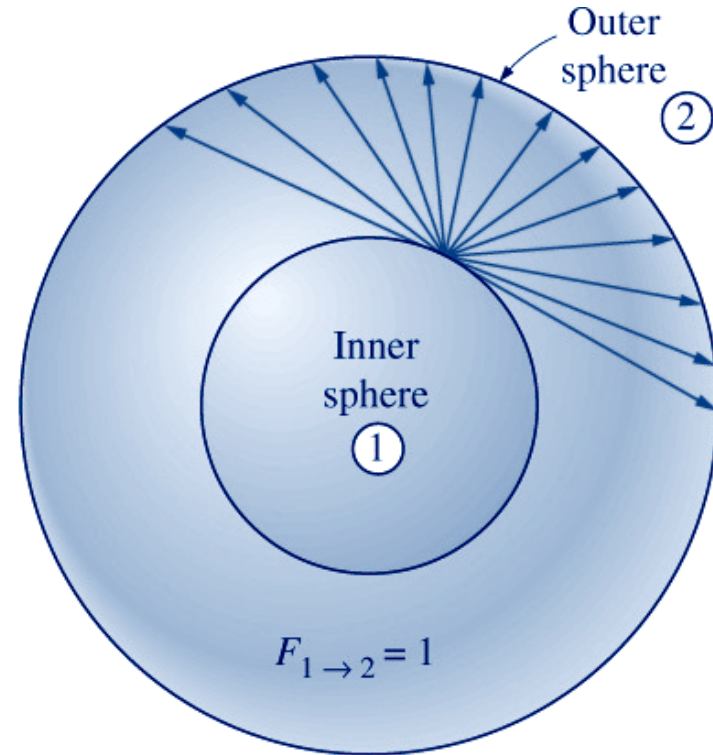
$$F_{2 \rightarrow 2} = 0$$

(b) Convex surface



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

(c) Concave surface



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,

$$F_{j \rightarrow i} = F_{i \rightarrow j} \quad \text{when} \quad A_i = A_j$$

$$F_{j \rightarrow i} \neq F_{i \rightarrow j} \quad \text{when} \quad A_i \neq A_j$$

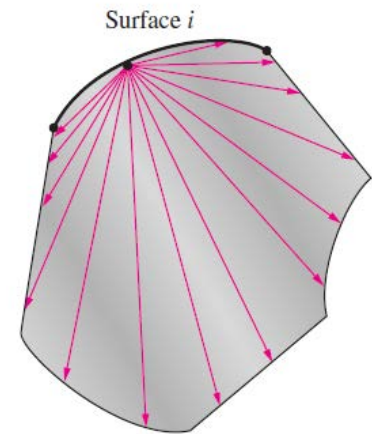
$$A_1 F_{12} = A_2 F_{21}$$

2 The Summation Rule

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

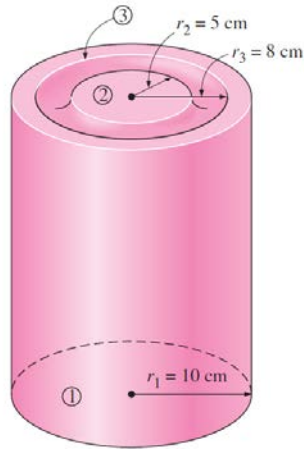
where N is the number of surfaces of the enclosure. For example, applying the summation rule to surface 1 of a three-surface enclosure yields

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



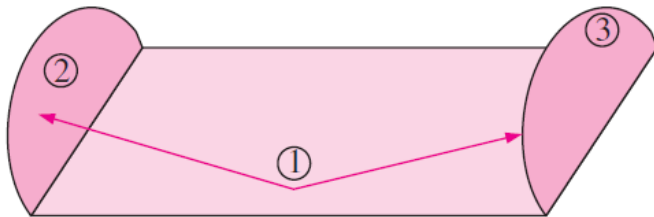
VIEW FACTORS

3 The Superposition Rule



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

4 The Symmetry Rule

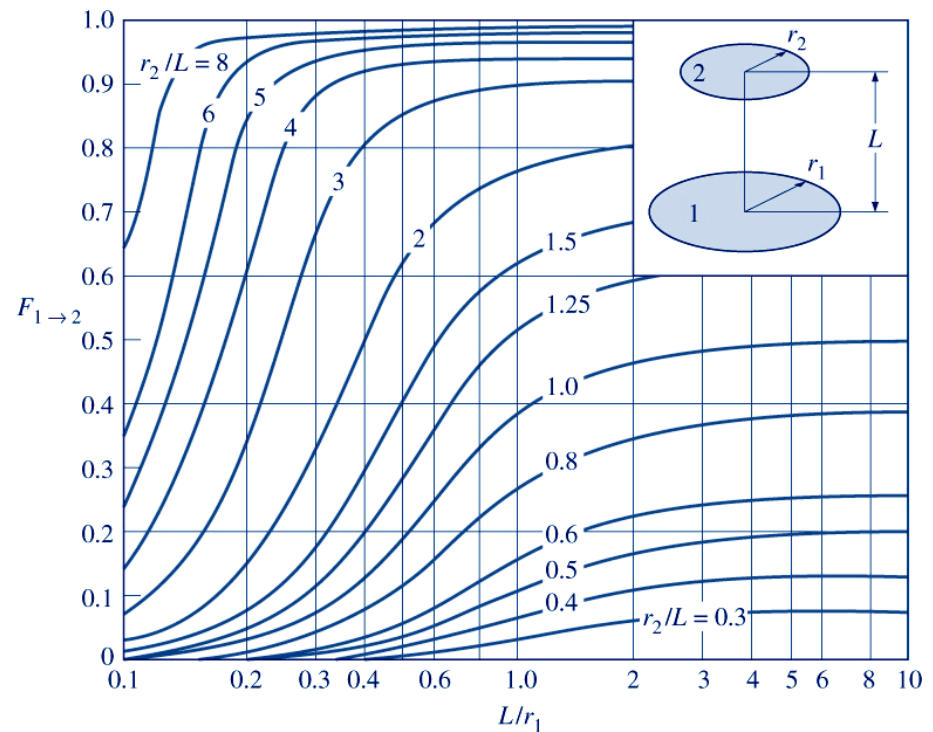
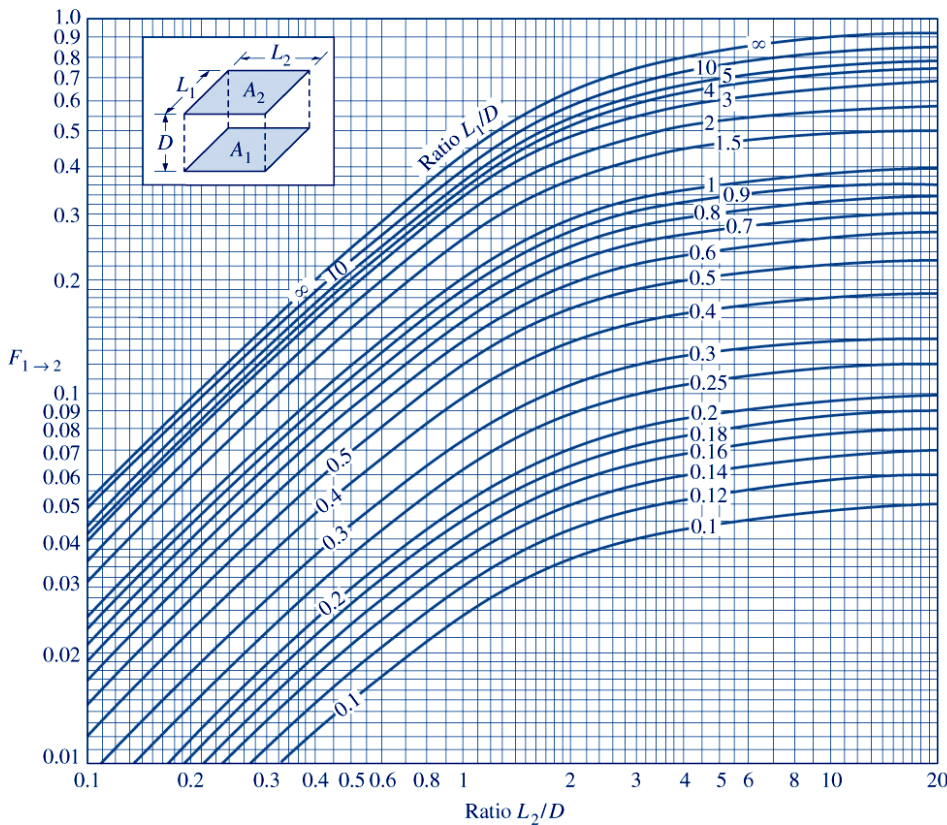


$$F_{1 \rightarrow 2} = F_{1 \rightarrow 3}$$

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

VIEW FACTORS

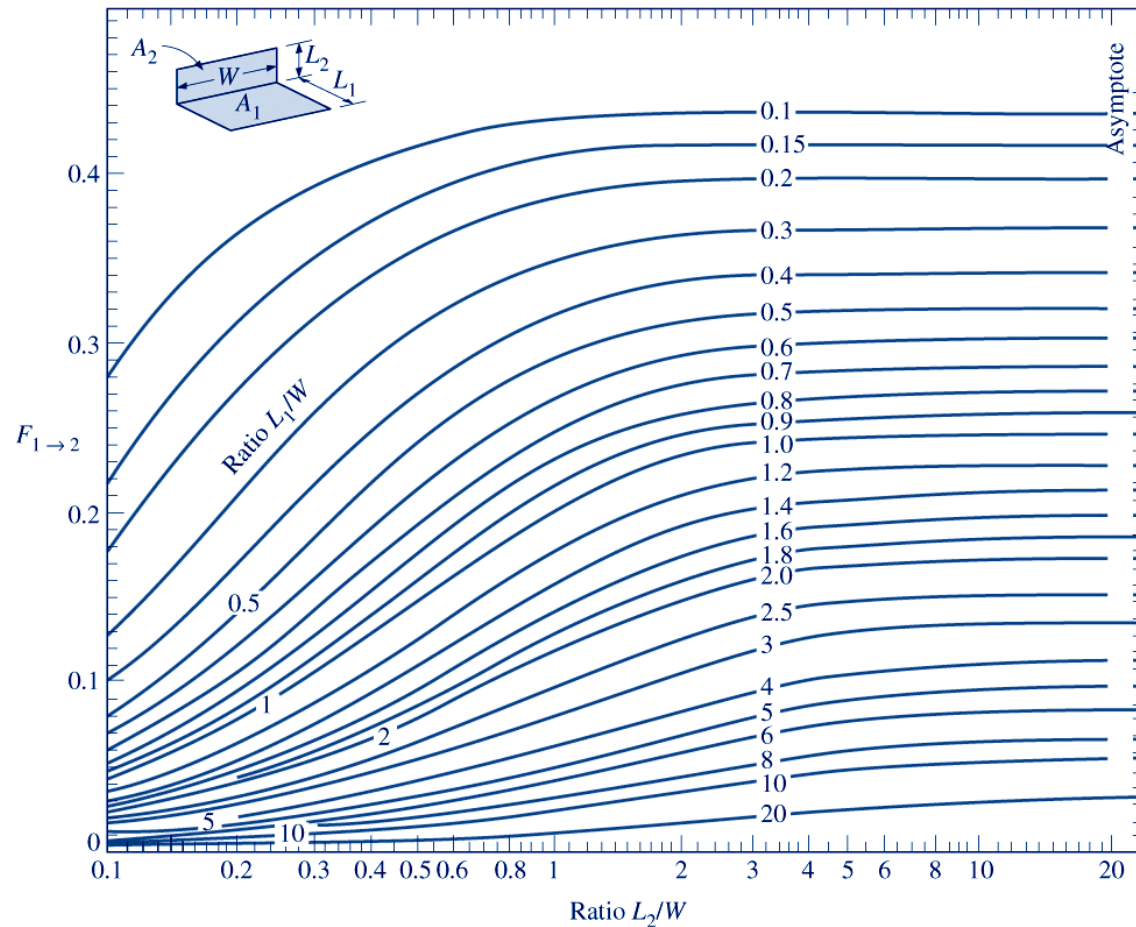
PARALEL PLANES



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

VIEW FACTORS

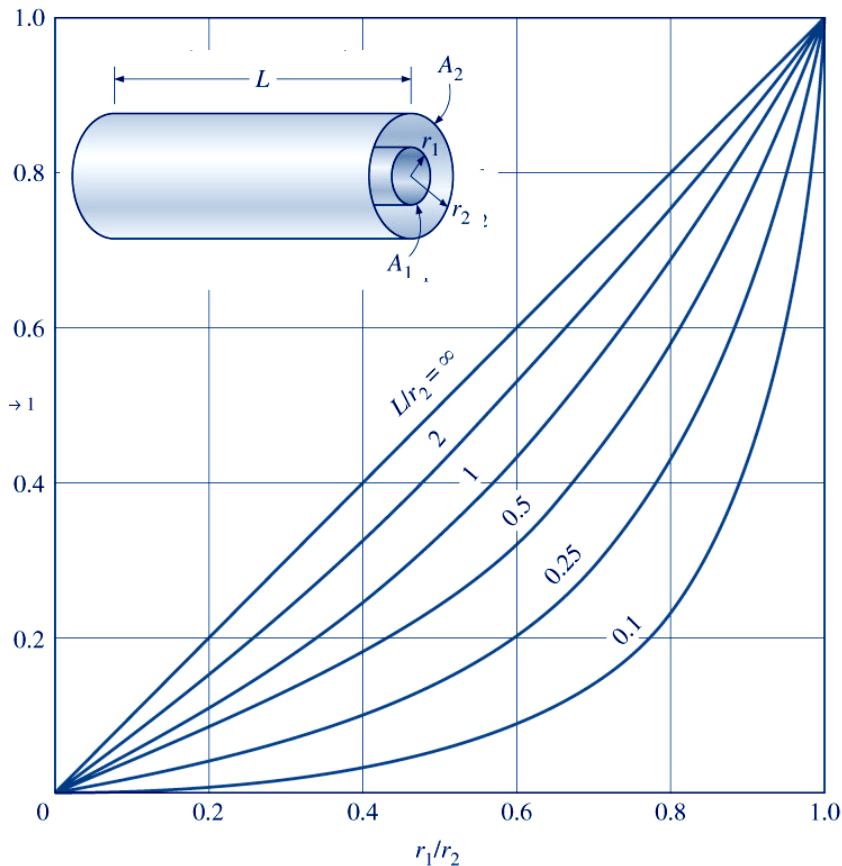
PERPENDICULAR, ATTACHED RECTANGLES



VIEW FACTORS

CONCENTRIC CYLINDERS

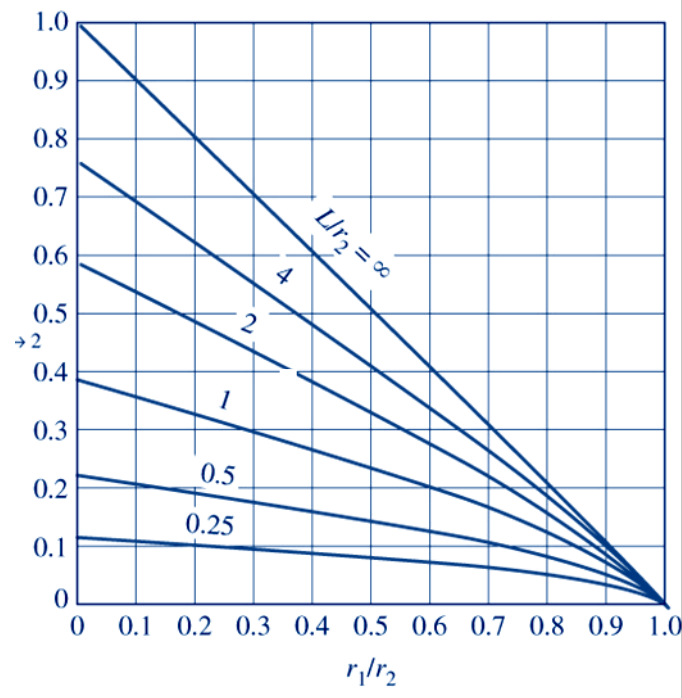
$F_{2 \rightarrow 1}$



Established earlier:

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

$F_{2 \rightarrow 2}$



Heat Quiz



Practise path: View Factors

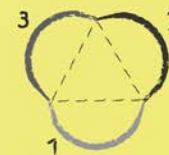
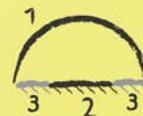
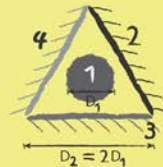
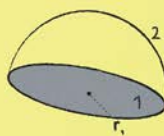
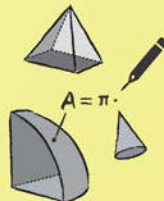
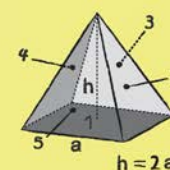
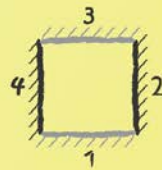
Hints

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



Dr. Dr. Wilko Rohlf's
Institute of Heat and Mass Transfer
Augustinerbach 6, 52056 Aachen
rohlfs@wsa.rwth-aachen.de
Copyright © 2020 Wilko Rohlf's. All rights reserved

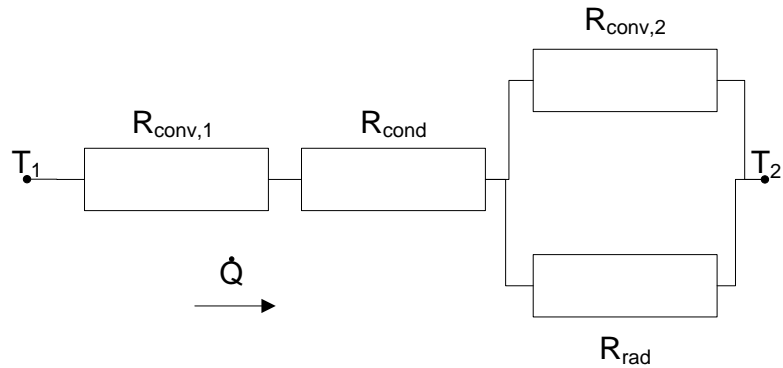


LEARNING OBJECTIVES LECTURE 5

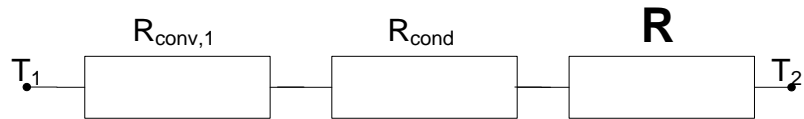


- **Concept of Radiation**
- **Radiation Laws**
- **Non- Ideal Radiation**
- **Radiation Heat Exchange**
- **Resistance Networks – (Radiation and Convection)**

Overall resistance Network



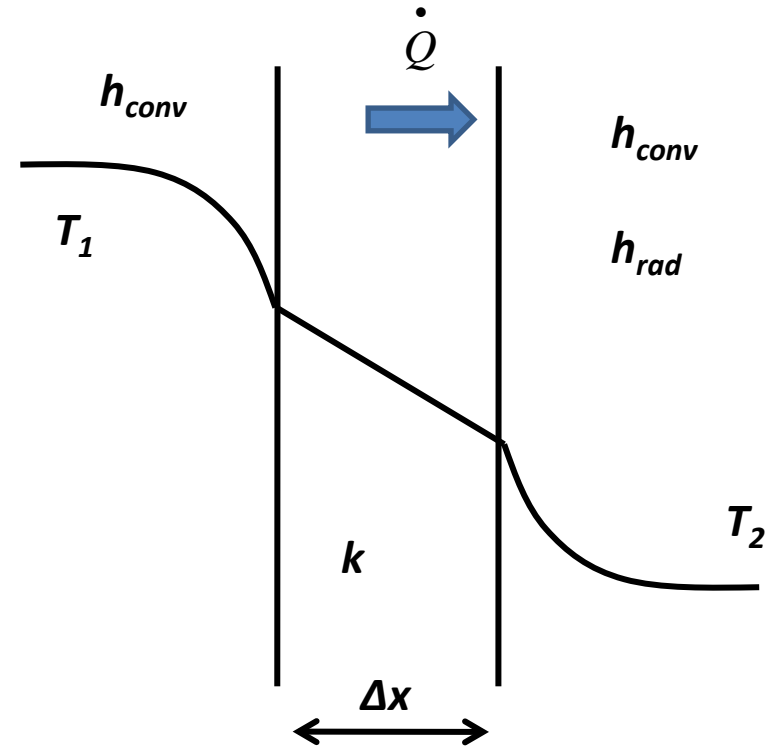
$$\downarrow \quad \frac{1}{R} = \frac{1}{R_{conv,2}} + \frac{1}{R_{rad}}$$



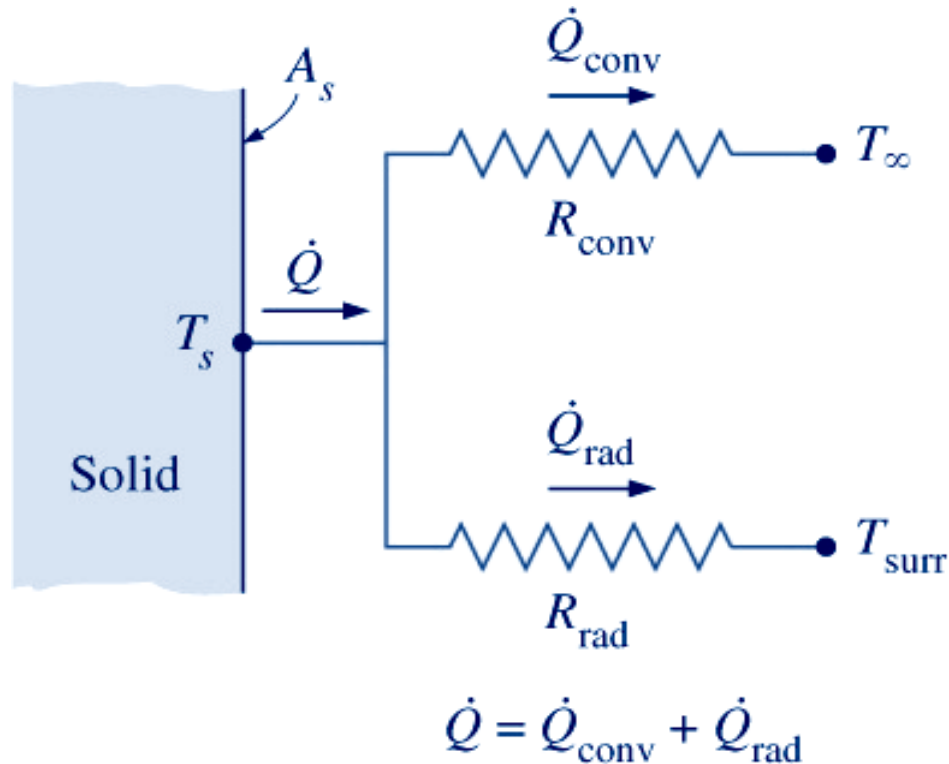
$$\downarrow \quad R_{tot} = R_{conv,1} + R_{cond} + R$$

Diagram illustrating the final simplified thermal resistance network. The entire network is represented by a single resistance R_{tot} connected between T_1 and T_2 .

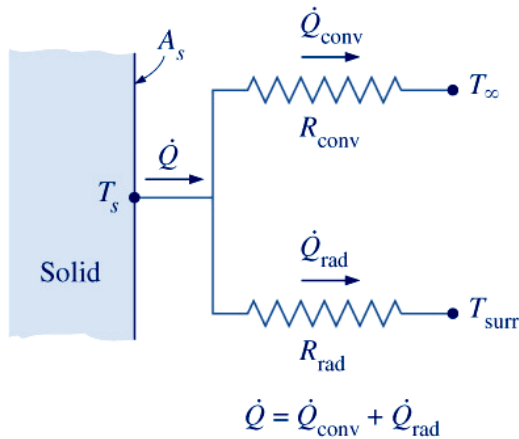
$$\dot{Q} = \frac{T_1 - T_2}{R_{tot}}$$



Radiation and convection



Radiation and convection



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

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

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

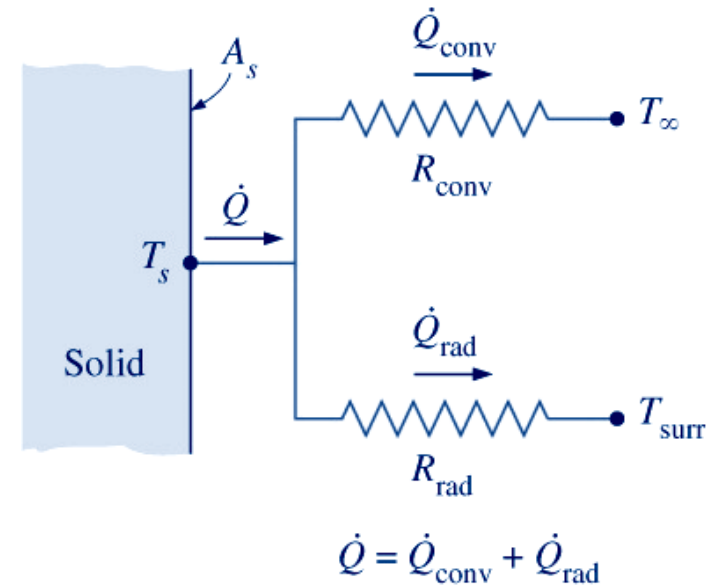
$$\dot{Q}_{rad} = \frac{T_s - T_\infty}{R_{rad}} \quad \text{with } R_{rad} = \frac{1}{h_{rad} A}$$

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

Radiation and convection

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

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



SUMMARY LECTURE 5 (1/2)

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

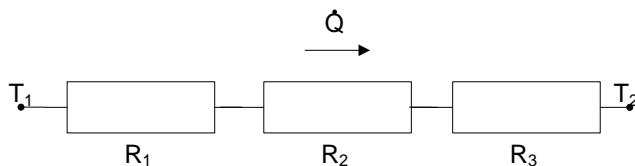
$$\dot{Q} = \varepsilon \cdot \sigma \cdot A \cdot T^4 \quad (\text{W})$$

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

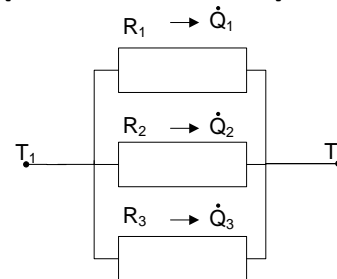
$$\dot{Q} = \varepsilon \cdot \sigma \cdot A \cdot (T^4 - T_{\infty}^4)$$

- 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!...*

