ME265: Thermal Engineering & Heat Transfer

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2. Thermodynamics
3. Mechanical Devices & Systems
4. Heat Transfer

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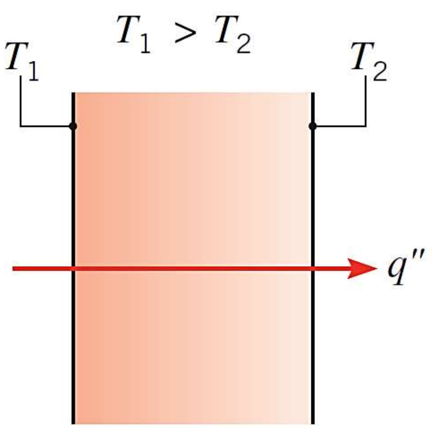
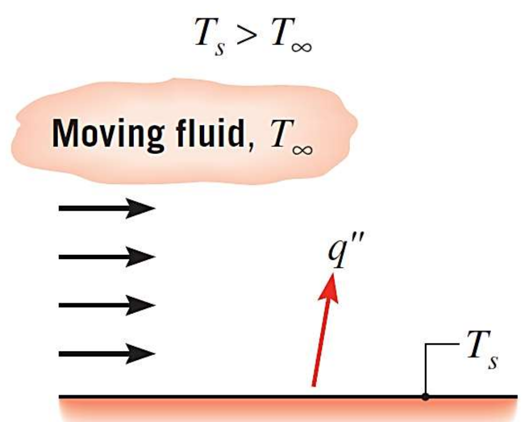
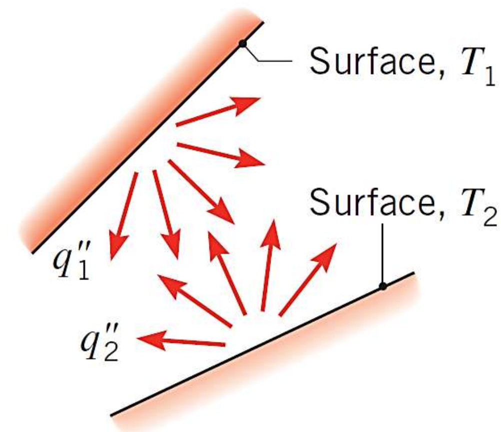
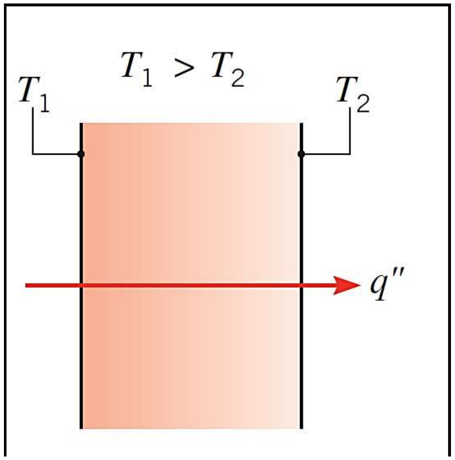
4.1.4 Modes of HT

Conduction through a solid or a stationary fluid	Convection from a surface to a moving fluid	Net radiation heat exchange between two surfaces
		

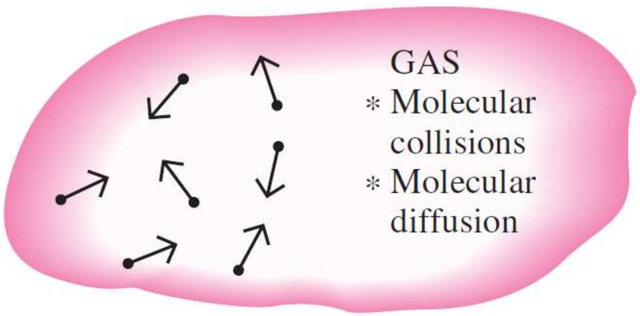
❑ Conduction

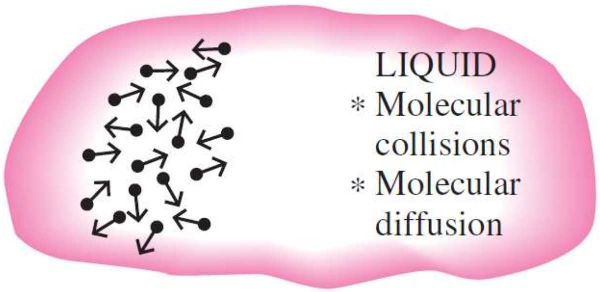


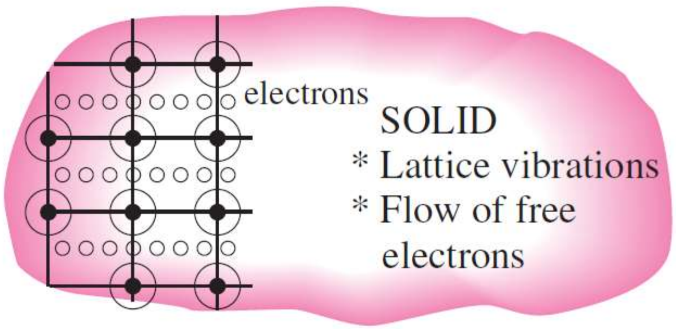
=> diffusion of heat due to molecular/ atomic vibrations of stationary particles

- In **gases and liquids,** conduction is due to the collisions and diffusion of the molecules during their random motion.

- In **solids,** conduction is due to the combination of vibrations of the molecules in a lattice and the energy transport by free electrons.

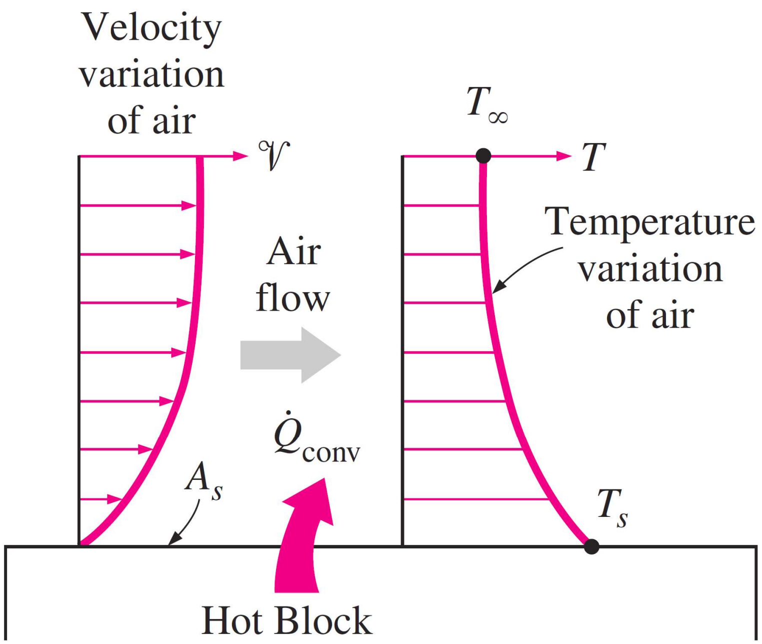






❑ Convection

=>diffusion of heat due to bulk motion of particles of a fluid.

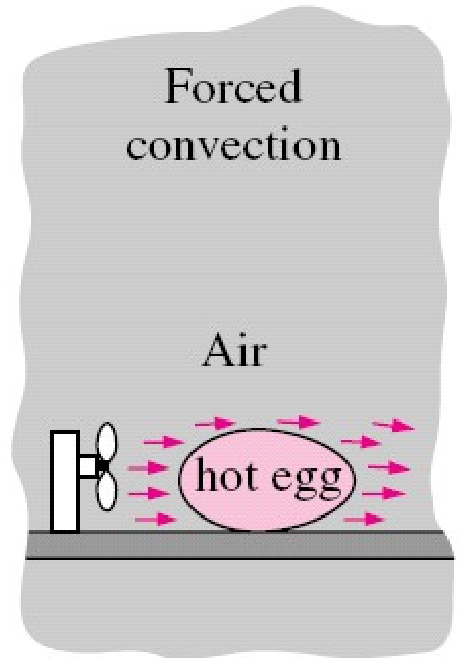


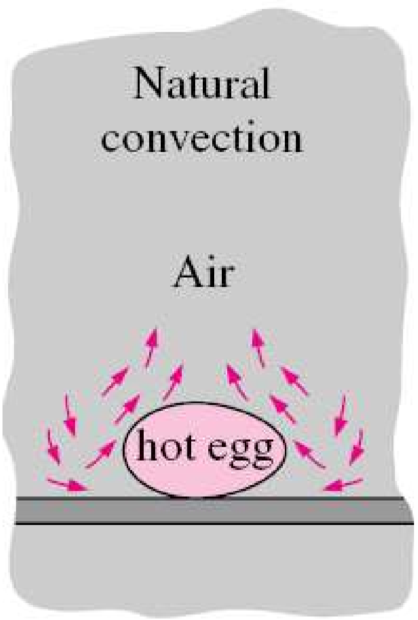
- It involves the combined effects of *conduction* and *advection (fluid motion).*
- The faster the fluid motion, the greater the convection heat transfer.
- In the absence of bulk fluid motion, heat transfer between a solid surface and the adjacent fluid is by pure conduction.

❑ Convection

Forced convection:

- When the fluid is forced to flow over the surface by external means such as a fan, pump, or the wind.
- There can be external and internal FC

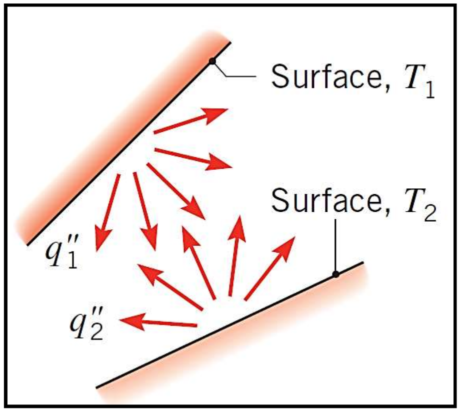




Natural (or **free**) **convection:**

- When the fluid motion is caused by buoyancy forces that are induced by density differences due to the variation of temperature in the fluid.

❑ Radiation



=> diffusion of heat due to net exchange of electromagnetic waves.

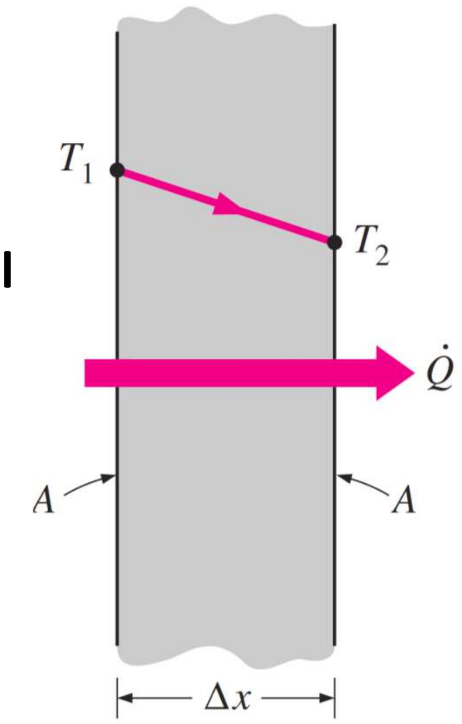
- Generally, Radiation is the energy emitted by matter in the form of *electromagnetic waves* (or *photons*) as a result of the changes in the electronic configurations of the atoms or molecules.
- It requires no intervening medium.
- In heat transfer studies, we are interested in *thermal radiation* (radiation emitted by bodies because of their temperature).
- Energy transfer by radiation is fastest (at the speed of light) and it suffers no attenuation in a vacuum.

❑ Fourier Law of Heat Conduction

$$\text{Rate of heat conduction} \propto \frac{(\text{Area})(\text{Temperature difference})}{\text{Thickness}}$$

$$\dot{Q}_{cond} = kA\frac{T_1 - T_2}{\Delta x} = -kA\frac{\Delta T}{\Delta x}$$

where the proportionality constant, ***k*** is the **thermal conductivity** of the material.



$$\dot{Q}_{cond} = -kA\frac{dT}{dx}$$

$$q = \frac{\dot{Q}_{Cond}}{A} = -k\frac{dT}{dx}$$

where q is called **heat flux**

4.1.5 Empirical Laws of Heat Transfer

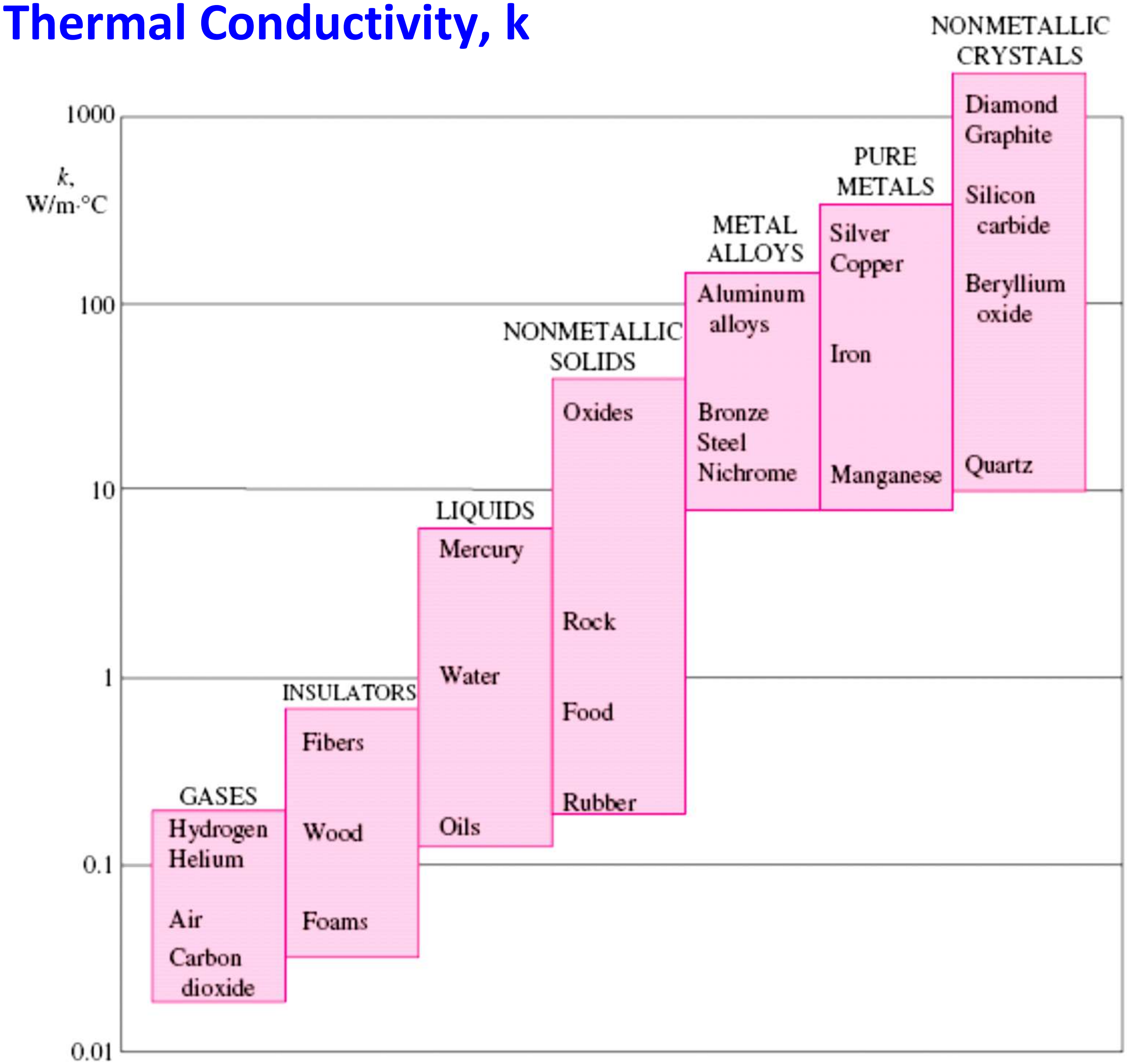
❑ Thermal Conductivity, k

- **Thermal conductivity, k** of a material is a measure of its ability to conduct heat.
- High value of k → good conductor
- Low value of → bad conductor or *insulator*
- Generally, metallic solids are good conductors.
- Some non-metallic crystals are good conductors as well. Carbon nano-tubes (CNTs) have higher conductivity values.

Material	k, W/m · °C*
Diamond	2300
Silver	429
Copper	401
Gold	317
Aluminum	237
Iron	80.2
Mercury (l)	8.54
Glass	0.78
Brick	0.72
Water (l)	0.613
Human skin	0.37
Wood (oak)	0.17
Helium (g)	0.152
Soft rubber	0.13
Glass fiber	0.043
Air (g)	0.026
Urethane, rigid foam	0.026

4.1.5 Empirical Laws of Heat Transfer

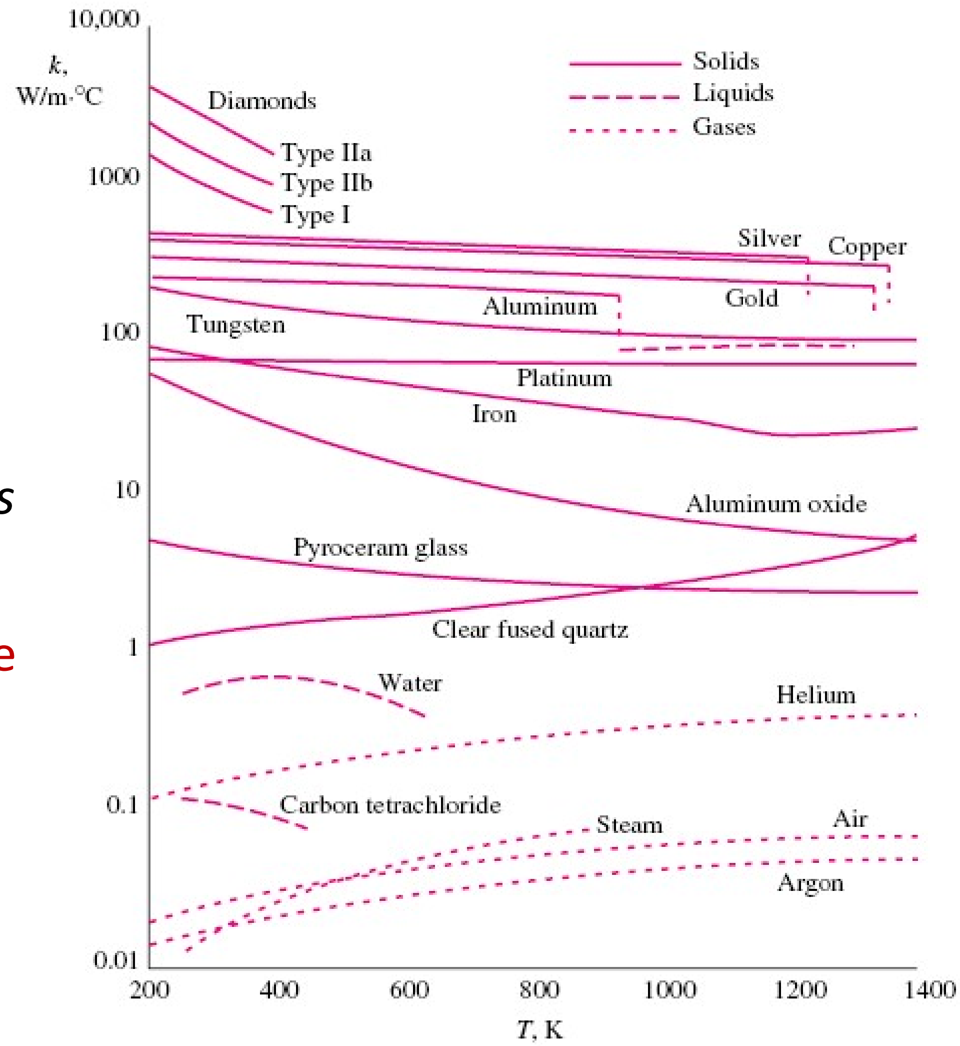
Thermal Conductivity, k



4.1.5 Empirical Laws of Heat Transfer

Thermal conductivity, k variations with Temperature

- Variation of *k* with temperature is negligible for some materials, but significant for others.
- *k* of gases is proportional to the *square root of T,* and inversely proportional to the *square root of the molar mass M.*
- The temperature dependence of *k* causes complexity in conduction analysis.



4.1.5 Empirical Laws of Heat Transfer

❑ Thermal Diffusivity, α:

A material property that appears in heat conduction analysis.

$$\alpha = \frac{\text{Heat conducted}}{\text{Heat stored}} = \frac{k}{\rho c_p} \qquad (\mathrm{m^2/s})$$

- ρc_p is the **heat capacity** of a material (J/m^3). c_p is the specific heat (J/kg°C)
- The thermal diffusivity represents how fast heat diffuses through a material → Propagation velocity.
- A material that has a high thermal conductivity or a low heat capacity will have a large thermal diffusivity.
- The larger the thermal diffusivity, the faster the propagation of heat into the medium.

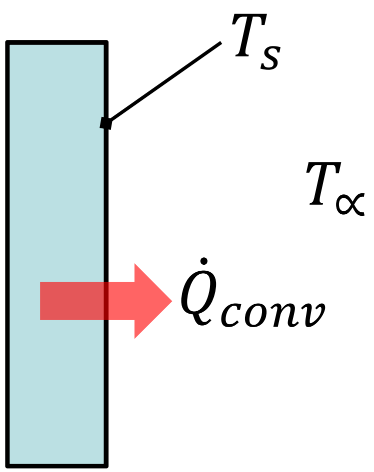
4.1.5 Empirical Laws of Heat Transfer

Thermal Diffusivity: $\alpha = \dfrac{k}{\rho c_p}$

- A small value of thermal diffusivity, α means that heat is mostly **absorbed** by the material and a small amount of heat will be **conducted** further.
- The value of α ranges from 0.14×10^{-6} m²/s for water to 149×10^{-6} m²/s for silver, which is three order of magnitude higher.

Material	α, m²/s*
Silver	149×10^{-6}
Gold	127×10^{-6}
Copper	113×10^{-6}
Aluminum	97.5×10^{-6}
Iron	22.8×10^{-6}
Mercury (l)	4.7×10^{-6}
Marble	1.2×10^{-6}
Ice	1.2×10^{-6}
Concrete	0.75×10^{-6}
Brick	0.52×10^{-6}
Heavy soil (dry)	0.52×10^{-6}
Glass	0.34×10^{-6}
Glass wool	0.23×10^{-6}
Water (l)	0.14×10^{-6}
Beef	0.14×10^{-6}
Wood (oak)	0.13×10^{-6}

❑ Newton's Law of Cooling



$$\dot{Q}_{conv} = h\,A\,(T_s - T_\infty)$$

h : *convection heat transfer coefficient* in **W/m²°C** or **Btu/hft²°F**

A_s: The surface area through which convection heat transfer takes place

T_s : Surface temperature

T_∞: The temperature of the fluid sufficiently far from the surface

4.1.5 Empirical Laws of Heat Transfer

Convection heat transfer coefficient

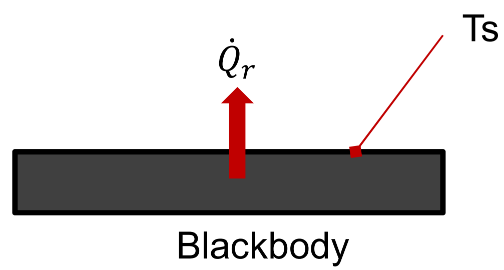
$$\dot{Q}_{conv} = h\,A\,(T_s - T_\infty)$$

- The convection heat transfer coefficient *h* is not a property of the fluid.
- It is an experimentally determined parameter whose value depends on:
  - surface geometry,
  - nature of fluid motion,
  - properties of the fluid, &
  - bulk fluid velocity.

Type of convection	h, W/m^2 · °C*
Free convection of gases	2–25
Free convection of liquids	10–1000
Forced convection of gases	25–250
Forced convection of liquids	50–20,000
Boiling and condensation	2500–100,000

Stefan-Boltzmann Law

- The maximum rate of radiation that can be emitted from a surface at temperature T_s (in K or R) is given by the **Stefan–Boltzmann law:**



$$\dot{Q}_r = \sigma\, A_s\, T_s^4$$

σ =*Stefan–Boltzmann constant* = 5.67×10^{-8} W/m^{2}K^4

- The idealized surface that emits radiation at this maximum rate is called a **blackbody.**
- The radiation emitted by all real surfaces is less than the radiation emitted by a blackbody at the same temperature, and is expressed as

$$\dot{Q}_r = \sigma\, \epsilon\, A_s\, T_s^4$$

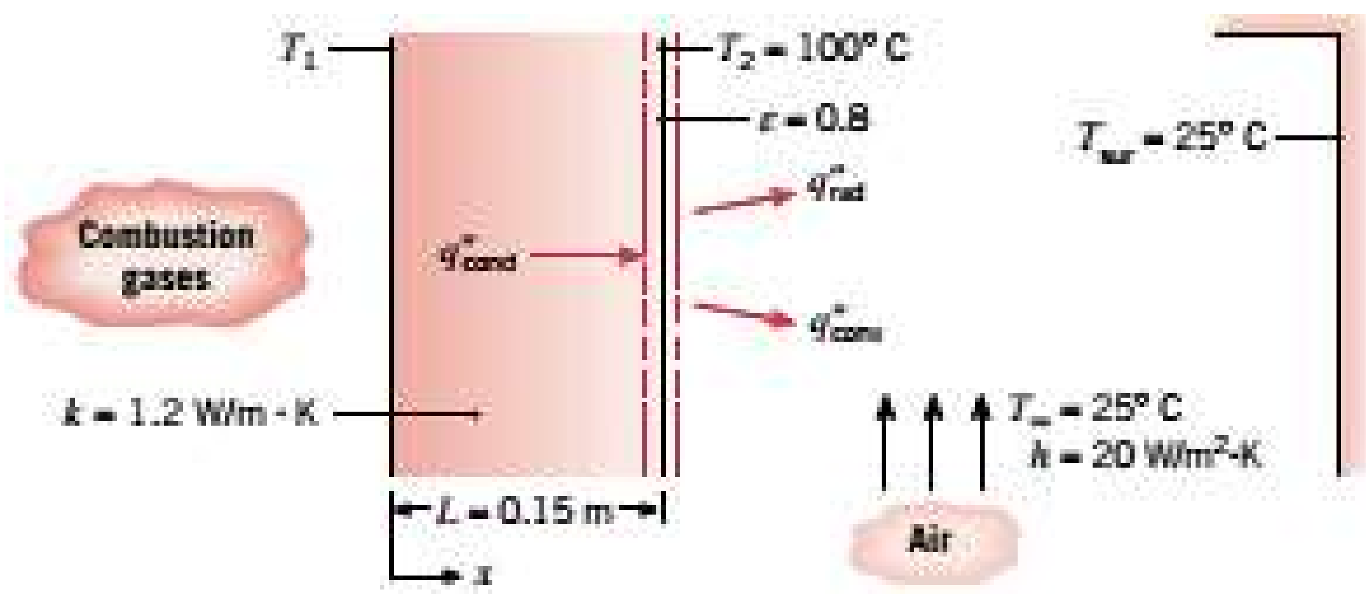
Where, ε is the **emissivity**

❑ Summary of Heat Transfer Processes

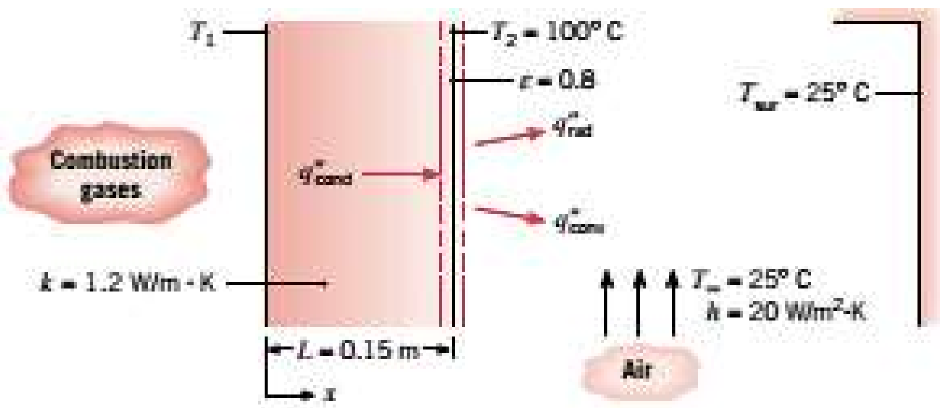
Mode	Mechanism	Empirical Law	Transport Property or coefficient
Conduction	Energy transfer due to molecular/atomic activity	Fourier's Law	Conductivity k (W/m.K)
Convection	Energy transfer due to molecular motion and bulk fluid motion	Newton's Law	Convection coefficient h ($W/m^2.K$)
Radiation	Energy transfer due to electromagnetic waves	Stefan-Boltzmann Law	Emissivity ε (-)

EP#1.2 Multiple heat transfer modes

The hot combustion gases of a furnace are separated from the ambient air and its surroundings, which are at 25°C, by a brick wall 0.15 m thick. The brick has a thermal conductivity of 1.2 W/m.K and a surface emissivity of 0.8. Under steady-state conditions an outer surface temperature of 100°C is measured. Free convection heat transfer to the air adjoining the surface is characterized by a convection coefficient of h = 20 W/m^2.K What is the brick inner surface temperature?



EP#2: Solution



EP#2: Solution