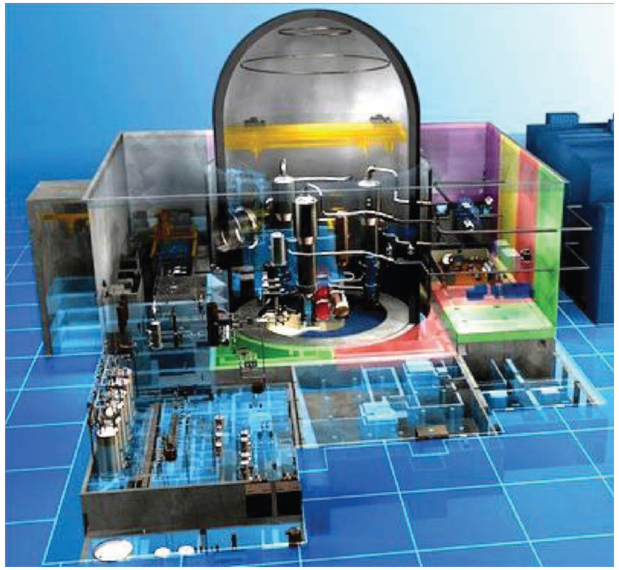
Basics of Heat Transfer



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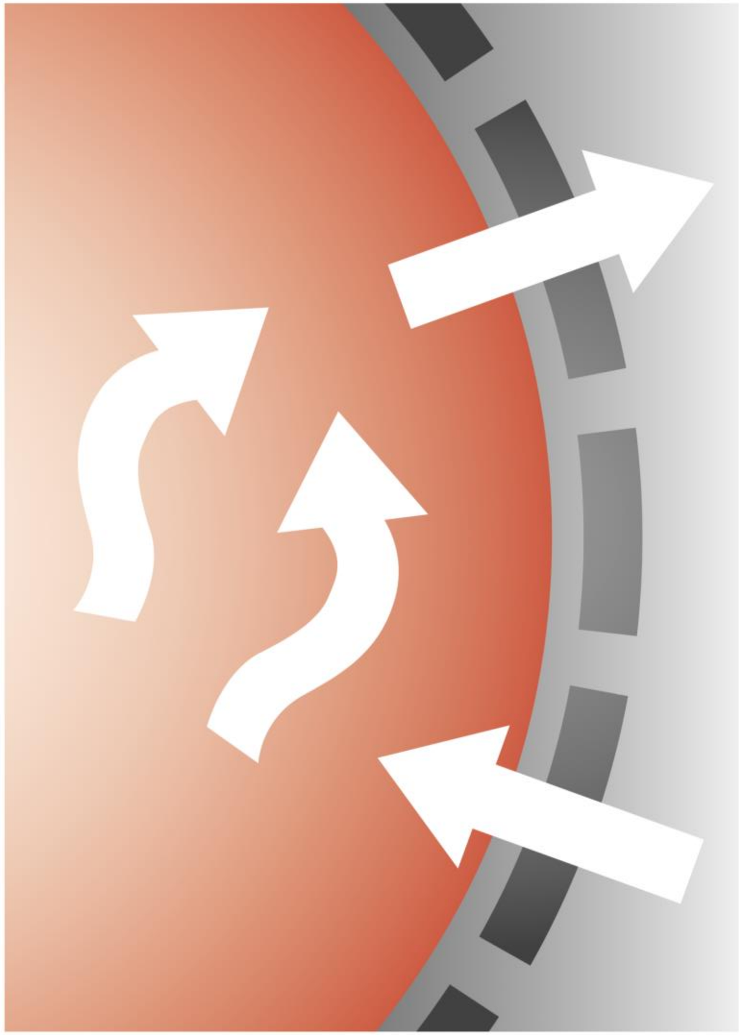
Objectives of topic

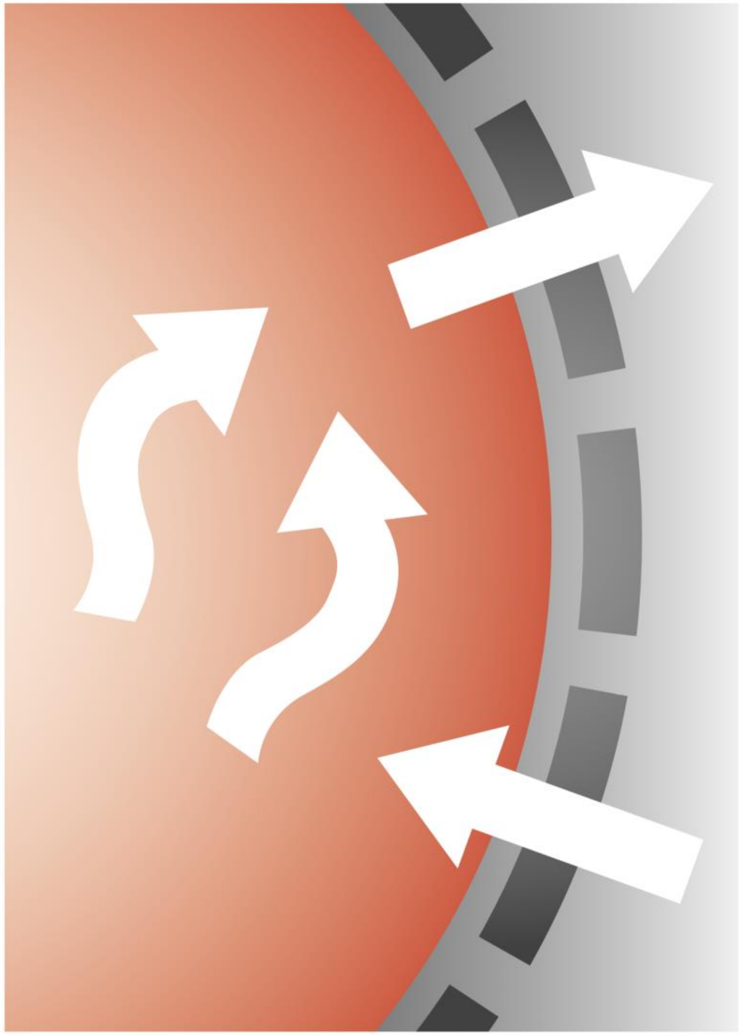
- Understand the fundamental concepts and principles that underlie heat transfer processes
- Calculate the heat transfer rates

What and How ?

- From the study of thermodynamics, you have learned that energy can be transferred by interactions of a system with its surroundings.
- These interactions are called work and heat.
- However, thermodynamics deals with the end states of the process during which an interaction occurs and provides no information concerning the nature of the interaction or the time rate at which it occurs.
- The aim of this topic is to extend thermodynamic analysis through the study of the *modes* of heat transfer and through the development of relations to calculate heat transfer *rates.*



What and How ?



- **TEMPERATURE, *T*** – The measure of the average kinetic energy of each individual molecule in a substance.
- **INTERNAL (THERMAL) ENERGY, *U*** – The kinetic energy of all the molecules in a system added together.
- **HEAT, *Q*** – It's the energy that is transferred between systems, when they are at different temperatures.
- 1 kcal = 1000 cal = 4.186 kJ
- 1 Joule is the energy needed to increase the temperature of 1kg of water by 1 °C.
- The flow of heat changes the temperature of a system.
- How much heat flows to change the temperature of a system depends on mass and specific heat of the substance.
- The more mass of a system, more heat is required to change the temperature (in order to change the average KE of all the atoms).
- **SPECIFIC HEAT, *c*** – Is a measure of how well a substance stores heat, the higher specific heat, more energy needed to change the temperature.
- In thermodynamics, you study the heat required to change the temperature of a system, while considering phase changes.

What and How ?

A simple, yet general, definition provides sufficient response to the question: What is heat transfer?

Heat transfer (or heat) is thermal energy in transit due to a spatial temperature difference.

Whenever a temperature difference exists in a medium or between media, heat transfer must occur.

What and How ?

We refer to different types of heat transfer processes as ***modes***.

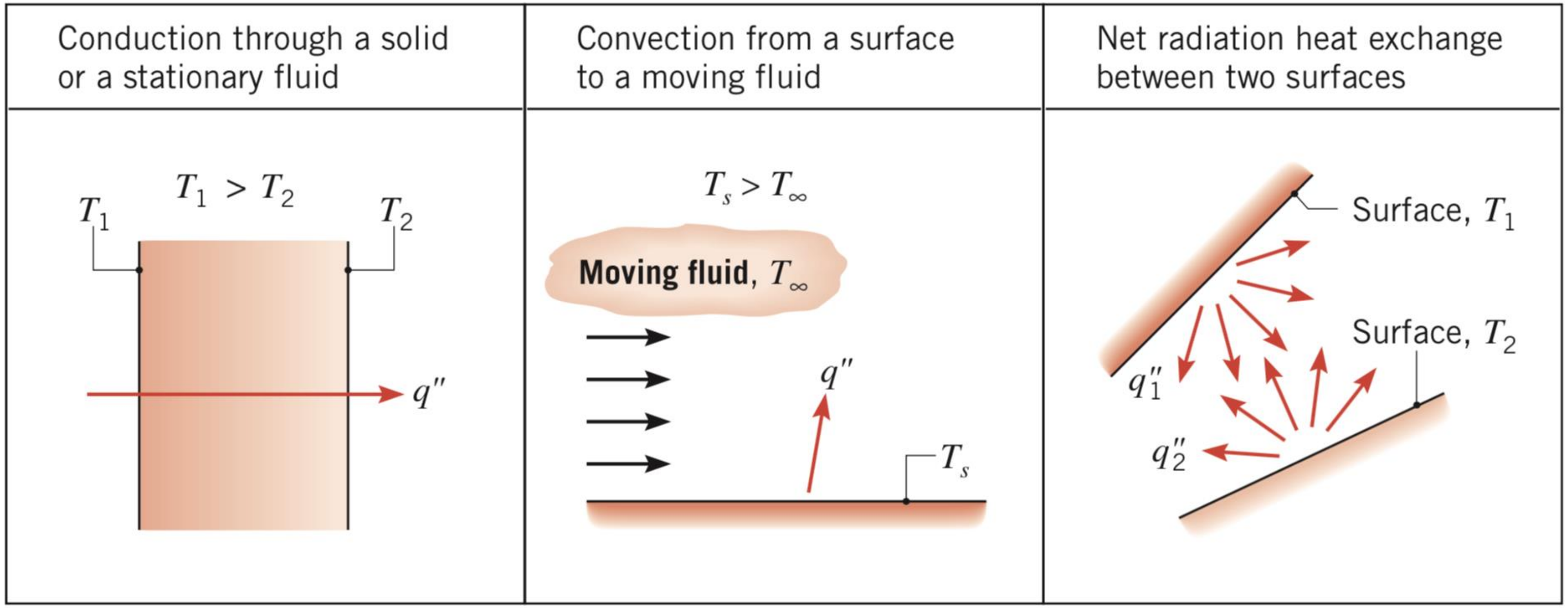


FIGURE 1.1 Conduction, convection, and radiation heat transfer modes.

What and How ?

CONDUCTION: Heat transfer that occur between a stationary medium (solid or liquid in contact) when they are at different temperatures.

CONVETION: Heat transfer that will occur between a surface and a moving fluid when they are at different temperatures.

RADIATION: All surfaces of finite temperature emit energy in the form of electromagnetic waves. In the absence of an intervening medium, there is net heat transfer by radiation between two surfaces at different temperatures.

Physical Mechanisms

As engineers, it is important that you understand the ***physical mechanisms*** which underlie the ***heat transfer modes*** and that you be able to use the ***rate equations*** that quantify the amount of energy being transferred per unit time.

Conduction

- **Conduction** may be viewed as the *transfer of energy from the more energetic to the less energetic particles* of a substance due to interactions between the particles.
- ***Higher temperatures are associated with higher molecular energies*.** When neighbouring molecules collide, as they are constantly doing, a transfer of energy from the more energetic to the less energetic molecules must occur.
- In the presence of a temperature gradient, energy transfer by conduction must then occur ***in the direction of decreasing temperature*.**
- *Example:* The exposed end of a metal spoon suddenly immersed in a cup of hot coffee is eventually warmed due to the conduction of energy through the spoon. On a winter day, there is significant energy loss from a heated room to the outside air. This loss is principally due to conduction heat transfer through the wall that separates the room air from the outside air.

Conduction

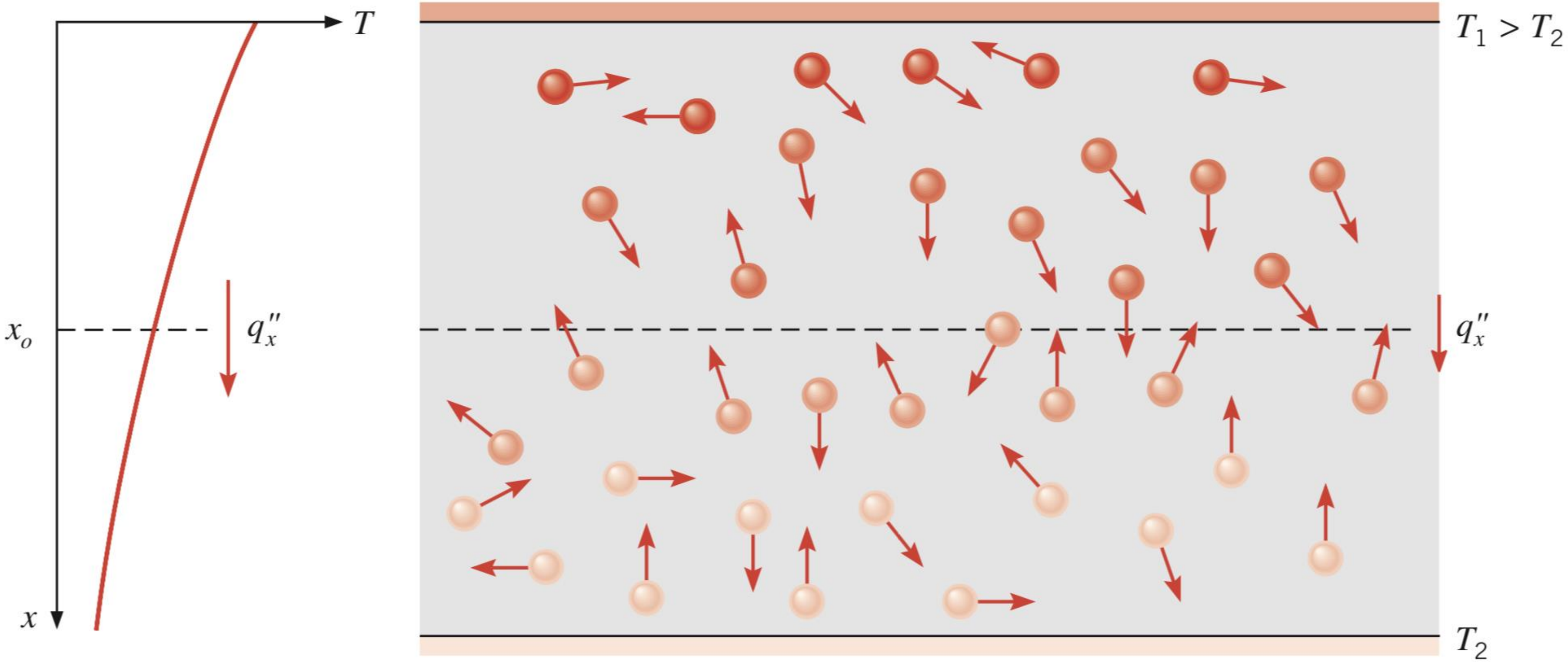
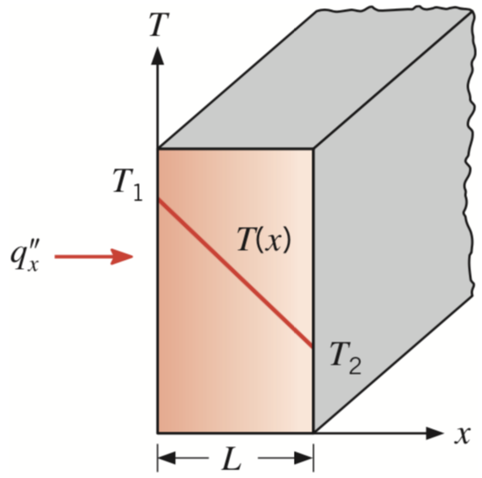


FIGURE 1.2 Association of conduction heat transfer with diffusion of energy due to molecular activity.

Conduction

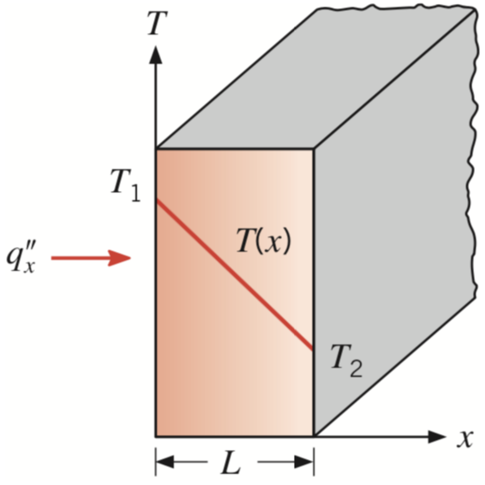


$$q''_x = -k\frac{dT}{dx}$$

FIGURE 1.3 One-dimensional heat transfer by conduction (diffusion of energy).

- For heat conduction, the rate equation is known as **Fourier's law**.
- The **heat flux** q" (W/m^2) is the heat transfer rate in the x-direction per unit area perpendicular to the direction of transfer, and it is proportional to the temperature gradient, dT/dx, in this direction.
- The parameter **k** is a transport property known as the **thermal conductivity** (W/m^2.K) and is a characteristic of the wall material.
- The minus sign is a consequence of the fact that heat is transferred in the direction of decreasing temperature.

Conduction



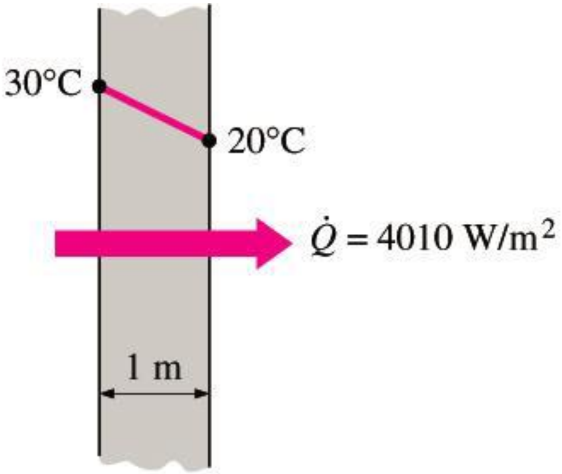
$$q''_x = -k\frac{dT}{dx} \xrightarrow{\text{steady-state conditions}} q''_x = -k\frac{T_2 - T_1}{L}$$

FIGURE 1.3 One-dimensional heat transfer by conduction (diffusion of energy).

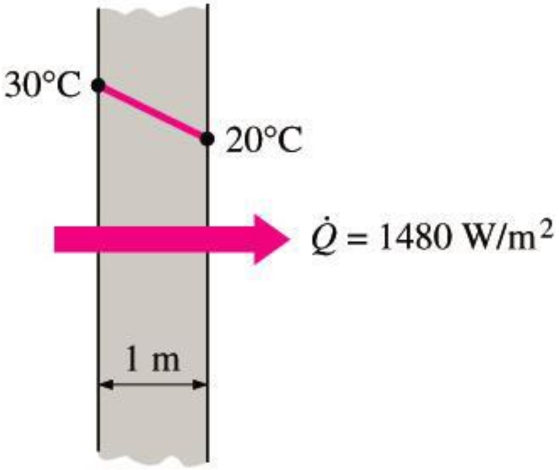
$$q''_x = k\frac{T_1 - T_2}{L} = k\frac{\Delta T}{L}$$

Note: The equation provides a heat flux, that is, the rate of heat transfer per unit area (W/m^2). The heat rate by conduction, q_x (W), through a plane wall of area A is then the product of the heat flux and the area, $q_x = q''_x \cdot A$.

Conduction



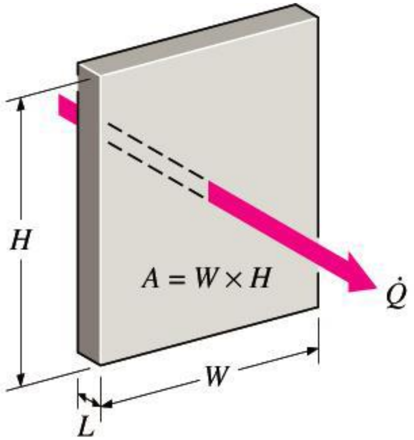
(a) Copper (k = 401 W/m·°C)



(b) Silicon (k = 148 W/m·°C)

$$q_x = -Ak\frac{dT}{dx}$$

In heat conduction analysis, *A* represents the area *normal* to the direction of heat transfer.



The rate of heat conduction through a solid is directly proportional to its thermal conductivity.

Exercise 1

A plane wall made of a material with thermal conductivity of 1 W/m.K is used as a thermal barrier between a hot chamber and atmosphere. The temperature of the wall on the hotter side is 250 °K while that on the colder side is 30 °K. Determine the rate of heat transfer across the wall, if the wall is 1 m x 1 m x 0.1 m.

Thermal Conductivity

$$q_x \propto A \frac{\Delta T}{\Delta x} \qquad\qquad q_x = kA \frac{\Delta T}{\Delta x}$$

- The **proportionality** is converted to an equality by introducing a **coefficient** that is a measure of the **material behavior**

- **SOLIDS:** Thermal energy transports by

1) lattice vibration waves;
2) free electron movements.
Metals use both modes, non-metallics use lattice vibration only.

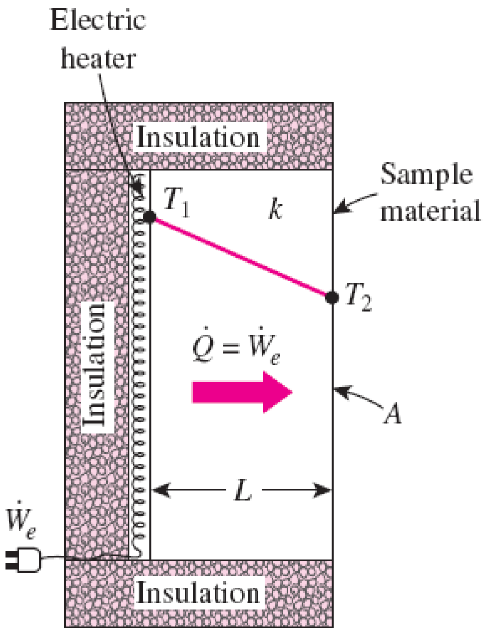
- **LIQUIDS:** Thermal energy transports by kinetic energy exchanges – molecules are closely spaced, with strong molecular force field.

- **GASES:** Same as liquids, but loosely spaced molecules and weaker force field.

Thermal Conductivity

A high value for thermal conductivity indicates that the material is a good heat conductor, and a low value indicates that the material is a poor heat conductor or *insulator*.

A simple experimental setup to determine the thermal conductivity of a material.



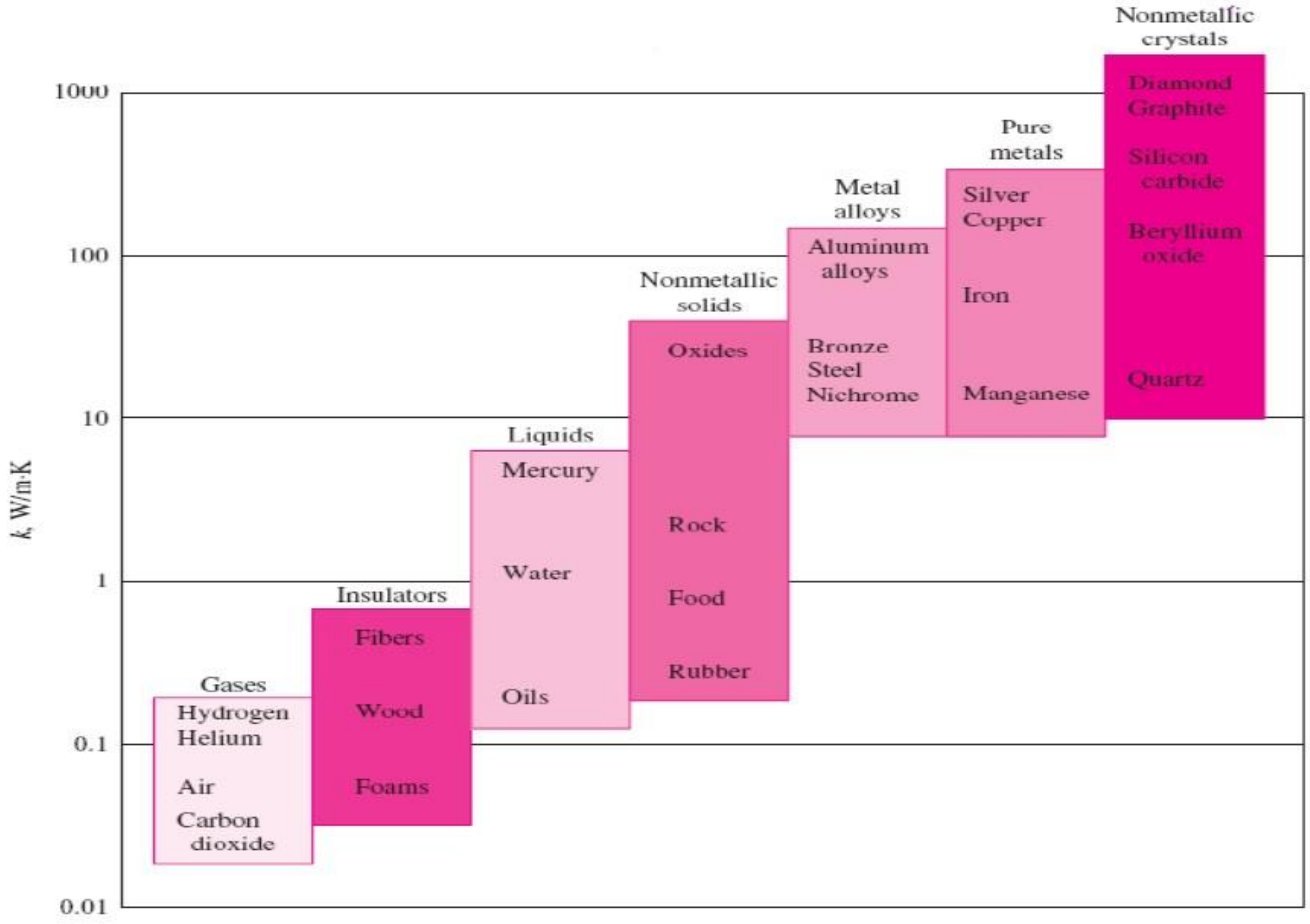
$$k = \frac{L}{A(T_1 - T_2)} \dot{Q}$$

The thermal conductivities of some materials at room temperature

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)	0.607
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

Thermal Conductivity

- **The thermal conductivity of various materials at room temperature.**
- **Pure crystals and metals have the highest thermal conductivities, and gases and insulating materials the lowest.**



Convection

- **Convection** heat transfer mechanism can be described as energy transfer occurring within a fluid due to the combined effects of conduction at the fluid-solid interface and bulk fluid motion.

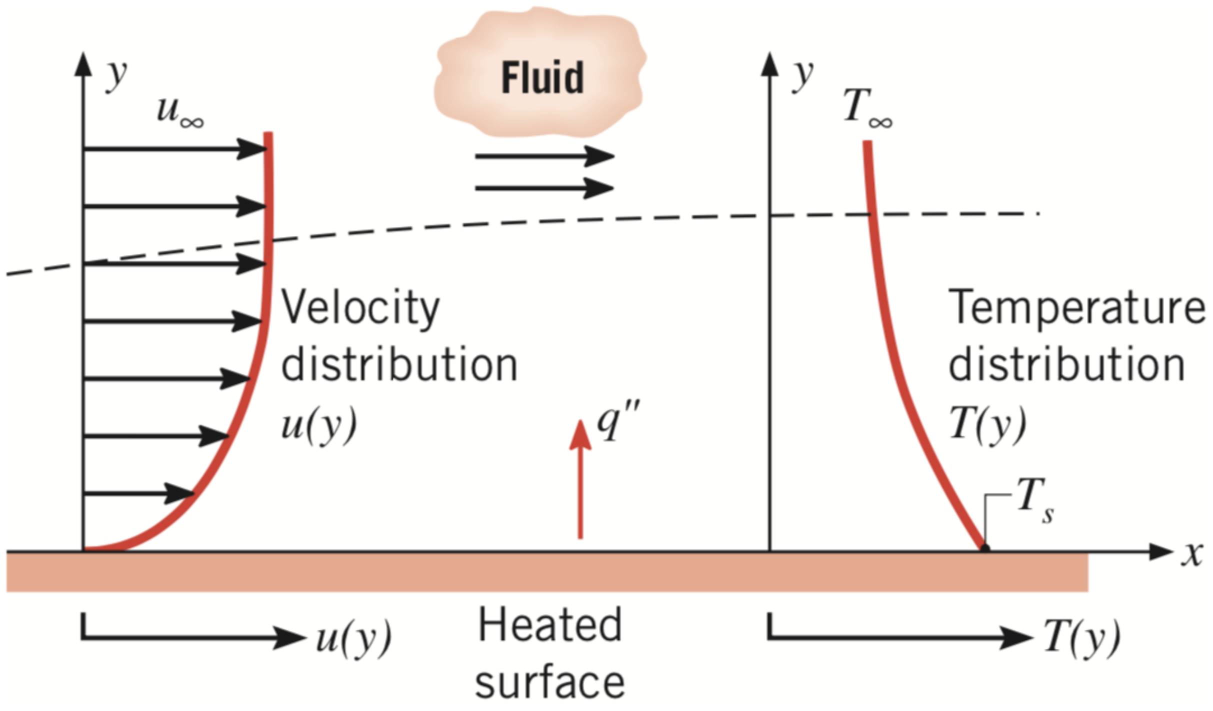


FIGURE 1.4 Boundary layer development in convection heat transfer.

Convection

- Convection heat transfer may be classified according to the nature of the flow:
  - **Forced convection** is when the flow is caused by external means, such as by a fan, a pump, or atmospheric winds.
  - **Free (or natural) convection** is when the flow is induced by buoyancy forces, which are due to density differences caused by temperature variations in the fluid.
  - Convection heat transfer results from fluid motion induced by vapor bubbles generated at the bottom of a pan of **boiling** water.
  - Convection heat transfer by the **condensation** of water vapor on the outer surface of a cold water pipe.

Convection

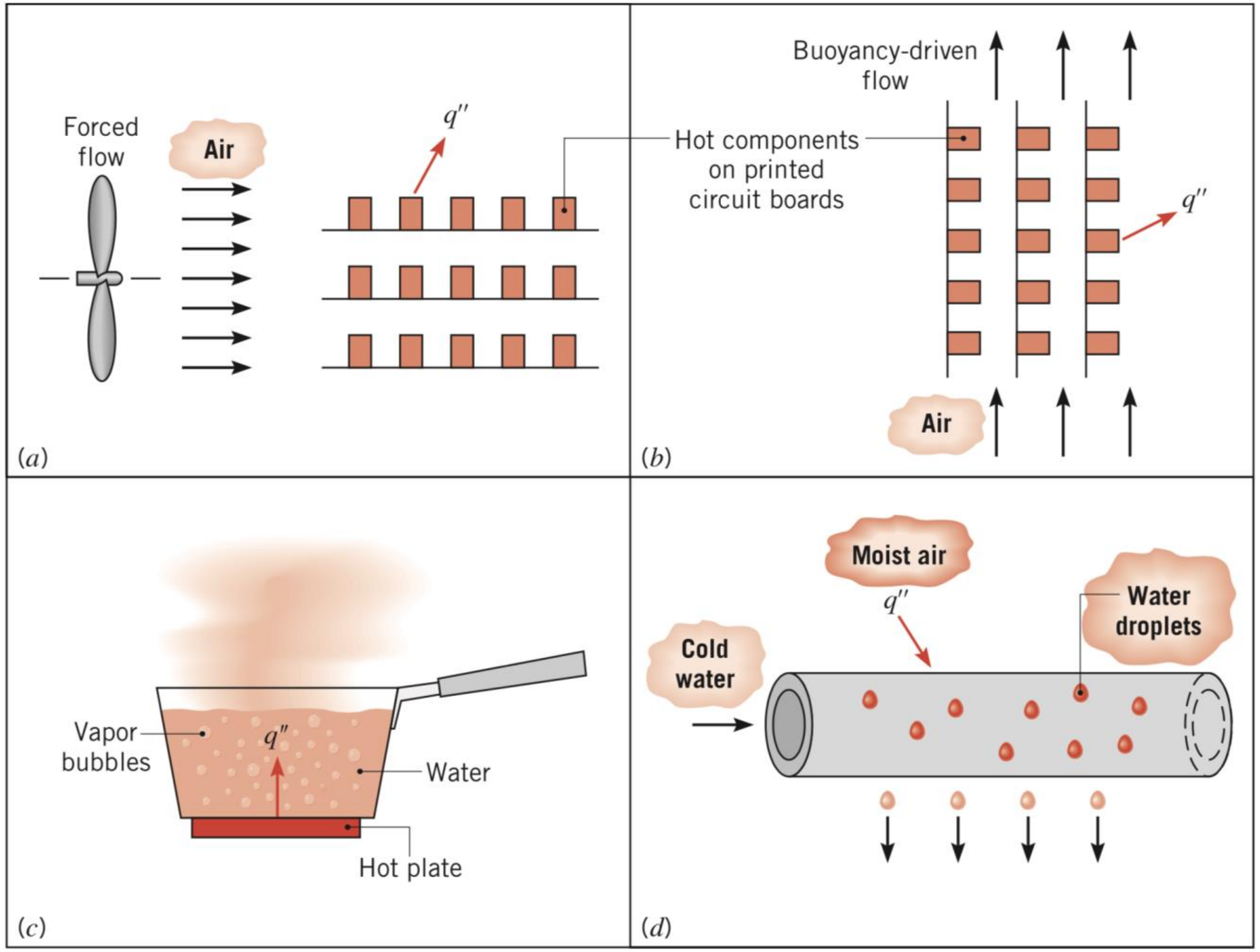


FIGURE 1.5 Convection heat transfer processes. (*a*) Forced convection. (*b*) Natural convection. (*c*) Boiling. (*d*) Condensation.

Convection

Regardless of the nature of the **convection heat transfer process**, the appropriate rate equation is of the form:

$$q'' = h(T_s - T_\infty)$$

- For heat conduction, the rate equation is known as **Newton's law of cooling**.
- *q*" is the heat flux (W/m^2), is proportional to the difference between the surface and fluid temperatures, T_s and T_∞, respectively.
- ***h*** (W/m^2.K) is termed the **convection heat transfer coefficient**. This coefficient depends on conditions in the boundary layer, which are influenced by surface geometry, the nature of the fluid motion, and an assortment of fluid thermodynamic and transport properties.
- The convection heat flux is presumed to be positive if heat is transferred from the surface ($T_s > T_\infty$) and negative if heat is transferred to the surface ($T_\infty > T_s$).

Convection

TABLE 1.1 Typical values of the convection heat transfer coefficient

Process	h (W/m^2 · K)
Free convection	
Gases	2–25
Liquids	50–1000
Forced convection	
Gases	25–250
Liquids	100–20,000
Convection with phase change	
Boiling or condensation	2500–100,000

Exercise 2

A hot cylinder at a temperature of 200 °K is exposed to air at 30 °K. If the heat transfer coefficient is 20 $\mathrm{W/m^2\ K}$, determine the rate of heat transfer per unit area

Radiation

- Radiation is the mode of heat transfer that involves emission and absorption of electromagnetic radiation between two objects placed at different temperatures.
- This mode of heat transfer does not require a material medium and can occur even in vacuum.
- In fact, heat transfer by radiation is fastest (at the speed of light) and it suffers no attenuation in a vacuum. This is how the energy of the sun reaches the earth.

Radiation

- **In heat transfer studies we are interested in *thermal radiation*, which is the form of radiation emitted by bodies because of their temperature.**
- **All bodies at a temperature above absolute zero emit thermal radiation.**
- **Radiation is a *volumetric phenomenon*, and all solids, liquids, and gases emit, absorb, or transmit radiation to varying degrees.**
- **However, radiation is usually considered to be a *surface phenomenon* for solids.**

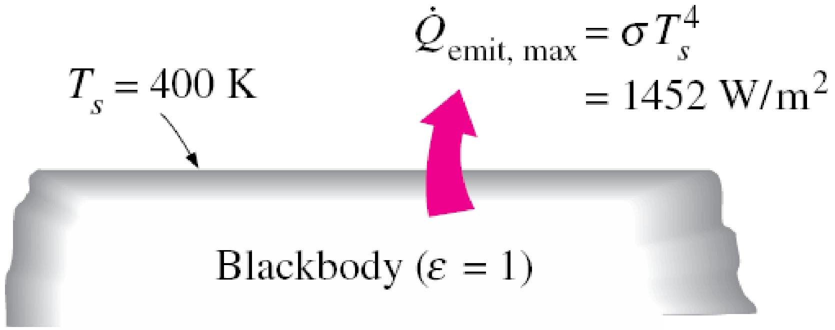
Radiation

Stefan-Boltzmann Law

$$q = Q = \varepsilon \sigma A_s T_s^4$$

$\boldsymbol{\varepsilon}$ – emissivity (1.0 for black body)
$\boldsymbol{T_s}$ – Surface temperature
$\boldsymbol{\sigma}$ – Stefan-Boltzmann coefficient ($= 5.67 \times 10^{-8}\ W/m^2 \cdot K^4$)
$\boldsymbol{A_s}$ – Surface area

Blackbody: The idealized surface that emits radiation at the maximum rate.

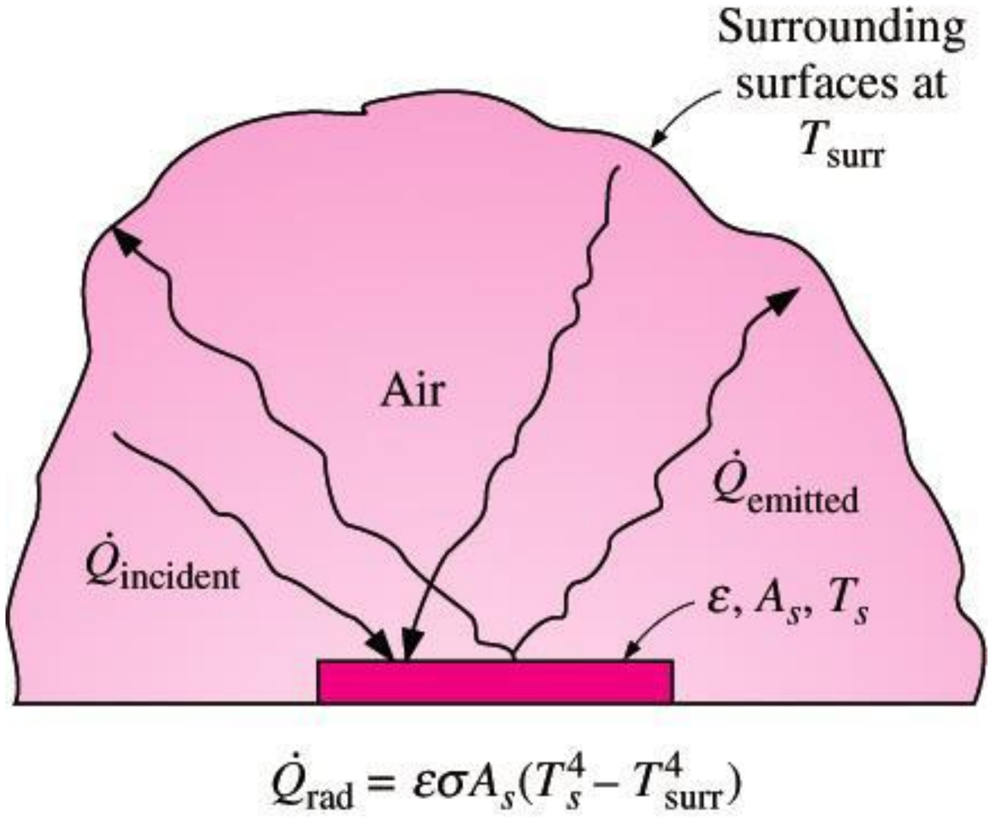


Radiation

When a surface is *completely enclosed* by a much larger (or black) surface at temperature *T*surr separated by a gas (such as air), the net rate of radiation heat transfer between these two surfaces is given by

$$Q = \varepsilon\sigma A_s(T_s^4 - T_{surr}^4)$$

Radiation heat transfer between a surface and the surfaces surrounding it.



Radiation

Emissivity ε : A measure of how closely a surface approximates a blackbody for which ε = 1 of the surface. $0 < \varepsilon < 1$.

Emissivities of some materials at 300 K

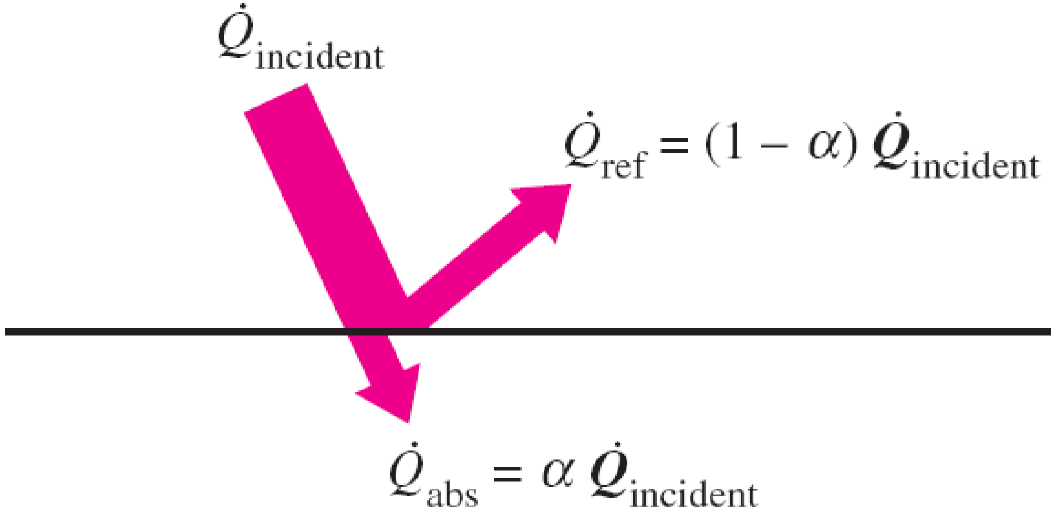
Material	Emissivity
Aluminum foil	0.07
Anodized aluminum	0.82
Polished copper	0.03
Polished gold	0.03
Polished silver	0.02
Polished stainless steel	0.17
Black paint	0.98
White paint	0.90
White paper	0.92–0.97
Asphalt pavement	0.85–0.93
Red brick	0.93–0.96
Human skin	0.95
Wood	0.82–0.92
Soil	0.93–0.96
Water	0.96
Vegetation	0.92–0.96

Radiation

Absorptivity α: The fraction of the radiation energy incident on a surface that is absorbed by the surface. $0 < \alpha < 1$

A blackbody absorbs the entire radiation incident on it (α = 1). Kirchhoff's law: The emissivity and the absorptivity of a surface at a given temperature and wavelength are equal.

$$Q_{absorbed} = Q_{incident}^{\alpha}$$



Radiation

- **Net radiation heat transfer: The difference between the rates of radiation emitted by the surface and the radiation absorbed.**
- **The determination of the net rate of heat transfer by radiation between two surfaces is a complicated matter since it depends on**
  - **the properties of the surfaces**
  - **their orientation relative to each other**
  - **the interaction of the medium between the surfaces with radiation**

Radiation is usually significant relative to conduction or natural convection, but negligible relative to forced convection.

Exercise 3

An overhead 25-m-long, uninsulated industrial steam pipe of 100-mm diameter is routed through a building whose walls and air are at 25 ℃. Pressurized steam maintains a pipe surface temperature of 150 ℃, and the coefficient associated with natural convection is $h = 10\ \mathrm{W/m^2\ K}$. The surface emissivity is ε =0.8.

a) What is the rate of heat loss from the steam line?
b) If the steam is generated in a gas-fired boiler operating at an efficiency of η_f = 0.90 and natural gas is priced at *Cg* = $0.02 per MJ, what is the annual cost of heat loss from the line?

Thank You

Stay safe!