Chapter 1

Essential Concepts

1.1 What and How?

- ***Heat Transfer*** (or heat) is thermal energy in transit due to a spatial temperature difference.
- Three modes of heat transfer: conduction, convection, and radiation (Fig. 1.1)

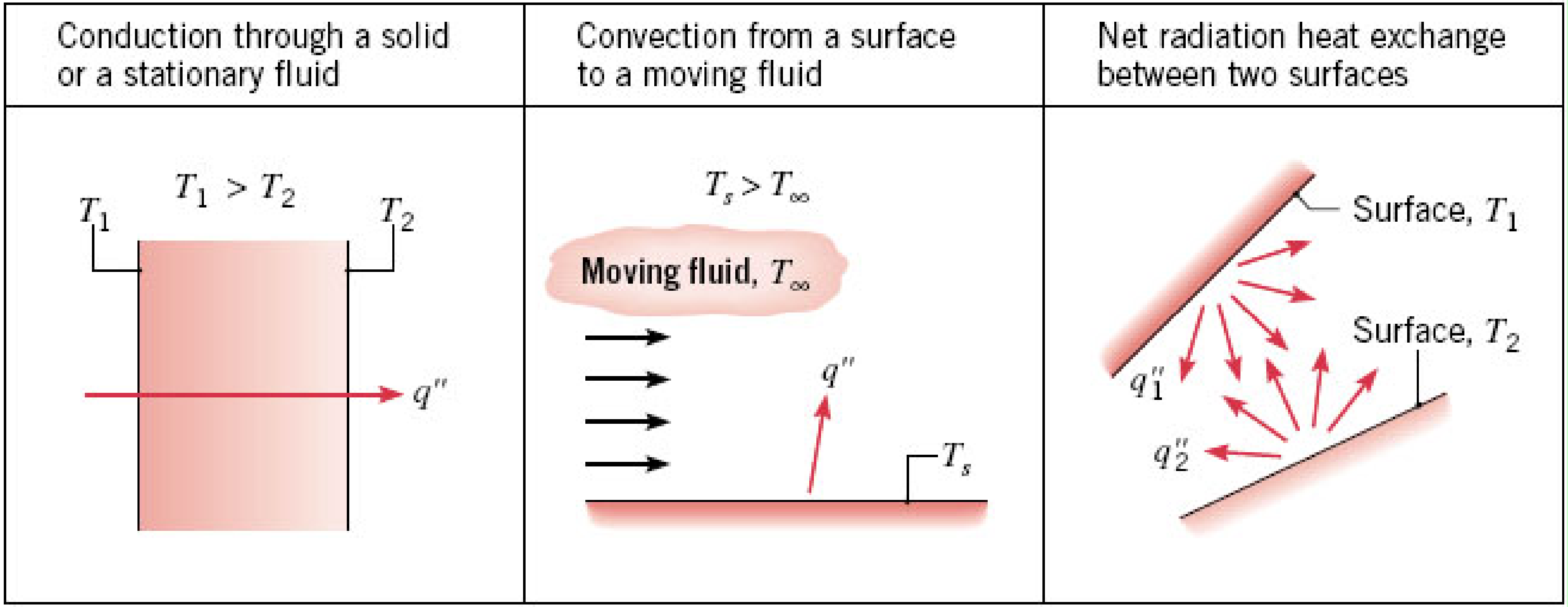

FIGURE 1.1 Conduction, convection, and radiation heat transfer modes.

1.2 Physical Origins and Rate Equations

1.2.1 Conduction (diffusion of energy due to temperature gradient)

- gas, liquid--due to random molecular motion (or diffusion)
- solid--due to lattice vibration and/or motion of free electrons

Rate equation: Fourier's law (from observation)

Vector: $$\vec{\mathbf{q}}'' = -k\nabla T$$

1-D: $$q_x'' = -k\frac{dT}{dx} \quad (1.1)$$

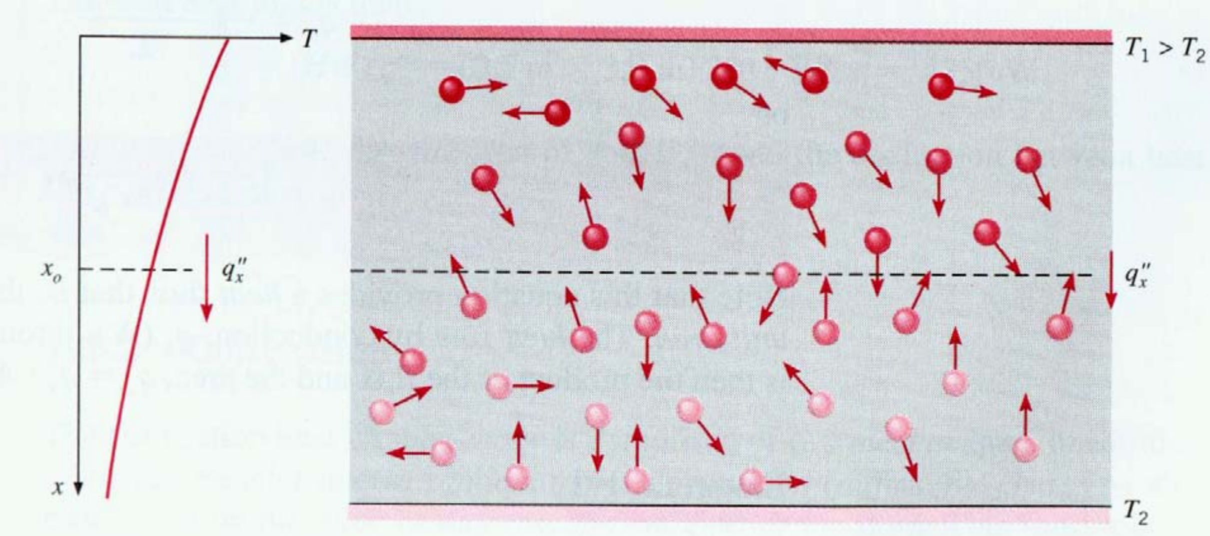

FIGURE 1.2 Association of conduction heat transfer with diffusion of energy due to molecular activity.

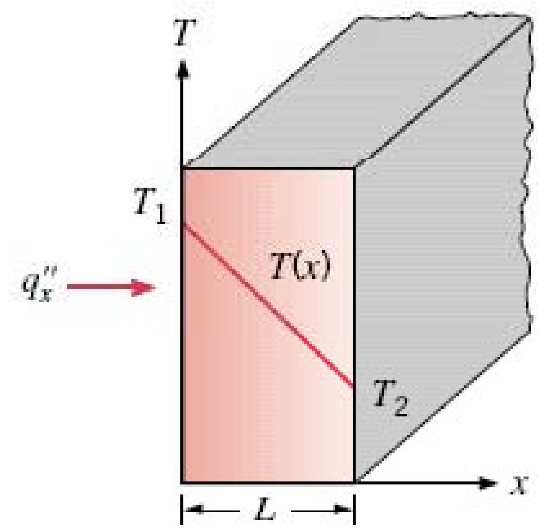

FIGURE 1.3 One-dimensional heat transfer by conduction (diffusion of energy).

- **1.2.2 Convection**

--due to bulk (macroscopic) motion of the fluid in addition to the random molecular motion (diffusion) (Fig. 1.4). Convection H.T. is a combination of conduction within the fluid and energy transport due to fluid motion itself→knowledge of fluid mechanics is essential.

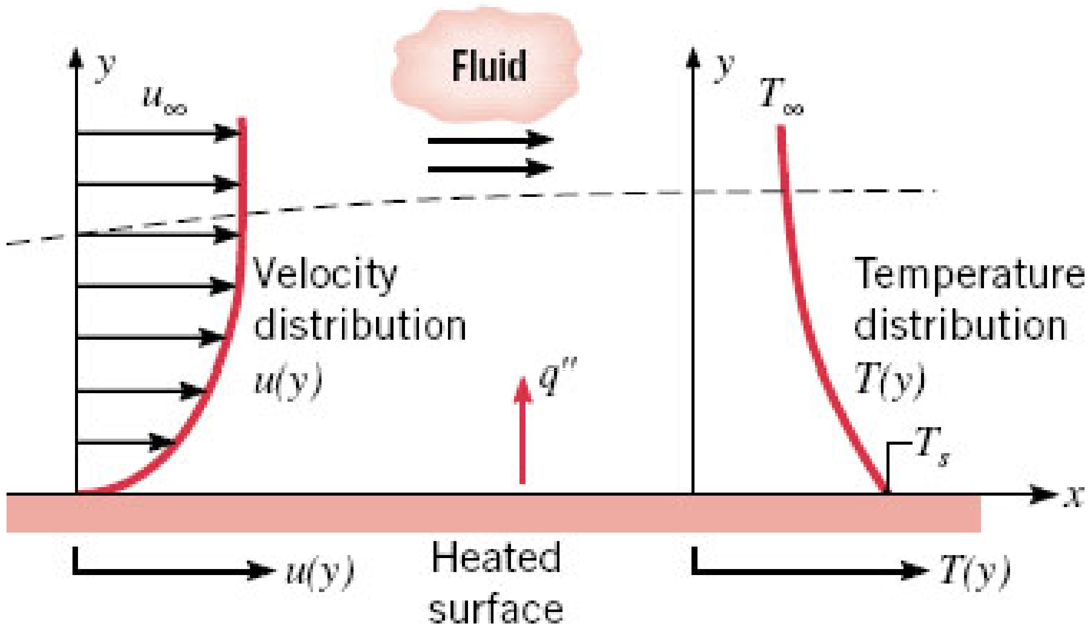

FIGURE 1.4
Boundary layer development in convection heat transfer.

Classification: (Fig. 1.5)

- forced convection
- free convection
- mixed (forced and free) convection
- convection due to boiling or condensation--latent heat exchange in addition to sensible energy exchange

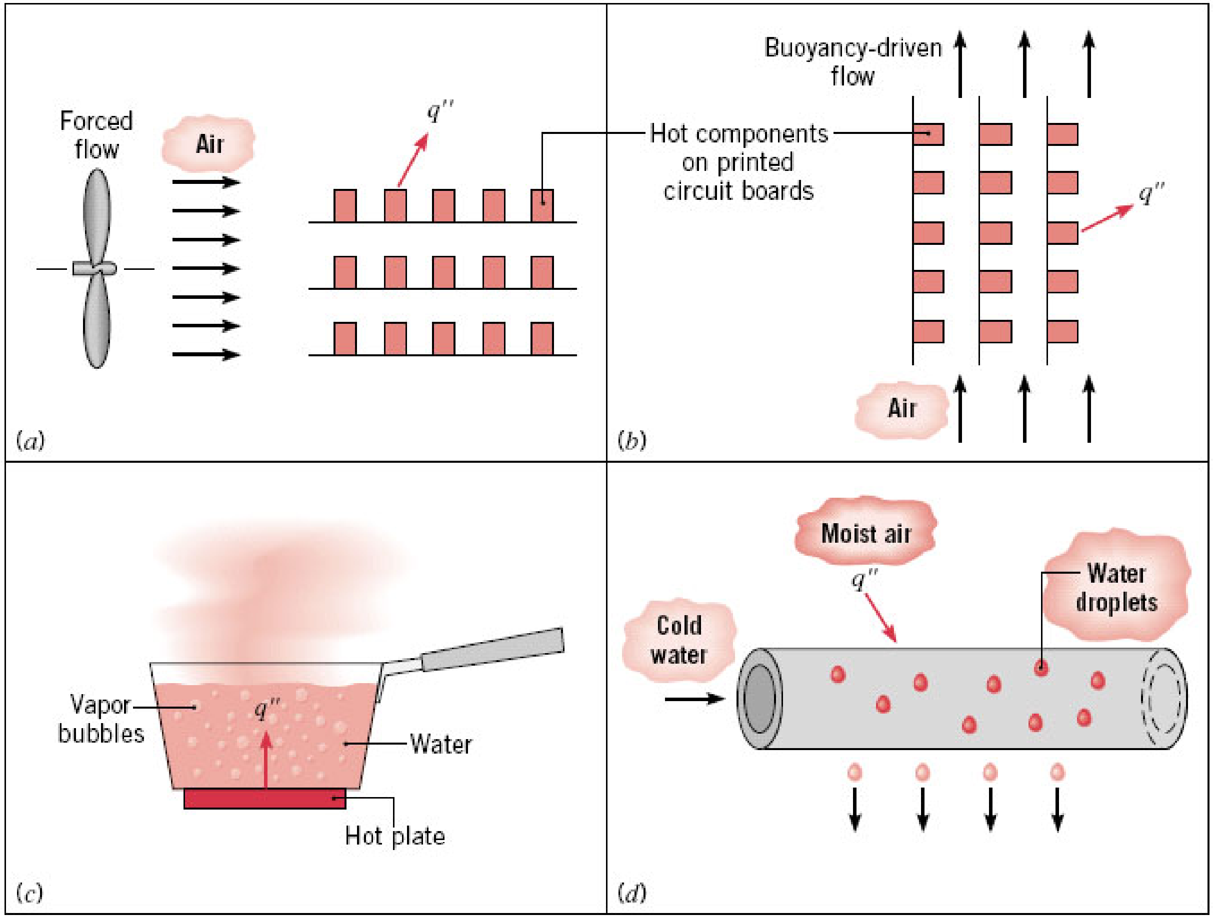

FIGURE 1.5 Convection heat transfer processes. (a) Forced convection. (b) Natural convection. (c) Boiling. (d) Condensation.

Thermodynamic data of water at 300K:

$c_{p,liq}$=4.18 kJ/kgK, $c_{p,vap}$=1.91 kJ/kgK; h_{fg}=2437 kJ/kg

The equivalent ΔT~2437/4.18=583K for liq. water; ~1276K for vapor

- **Rate equation**: Newton's law of cooling (empirical)

$$q'' = h(T_s - T_\infty) \ , \qquad (1.3a)$$

h=convection heat transfer coeff.

=f (fluid properties,flow conditions,surface geometry)

TABLE 1.1 Typical values of the convection heat transfer coefficient

Process	h ($W/m^2 \cdot K$)
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

1.2.3 Radiation

--exchange of energies emitted from matters at finite temperatures

- The surface emissive power of a *blackbody*: Stefan-Boltzmann law (from theoretical analysis)

  $E_b = \sigma T_s^4$, σ--Stefan-Boltzmann constant

- The emissive power of a real surface:

  $E = \varepsilon \sigma T_s^4$, ε--emissivity of the surface, $0 \leqq \varepsilon \leqq 1$

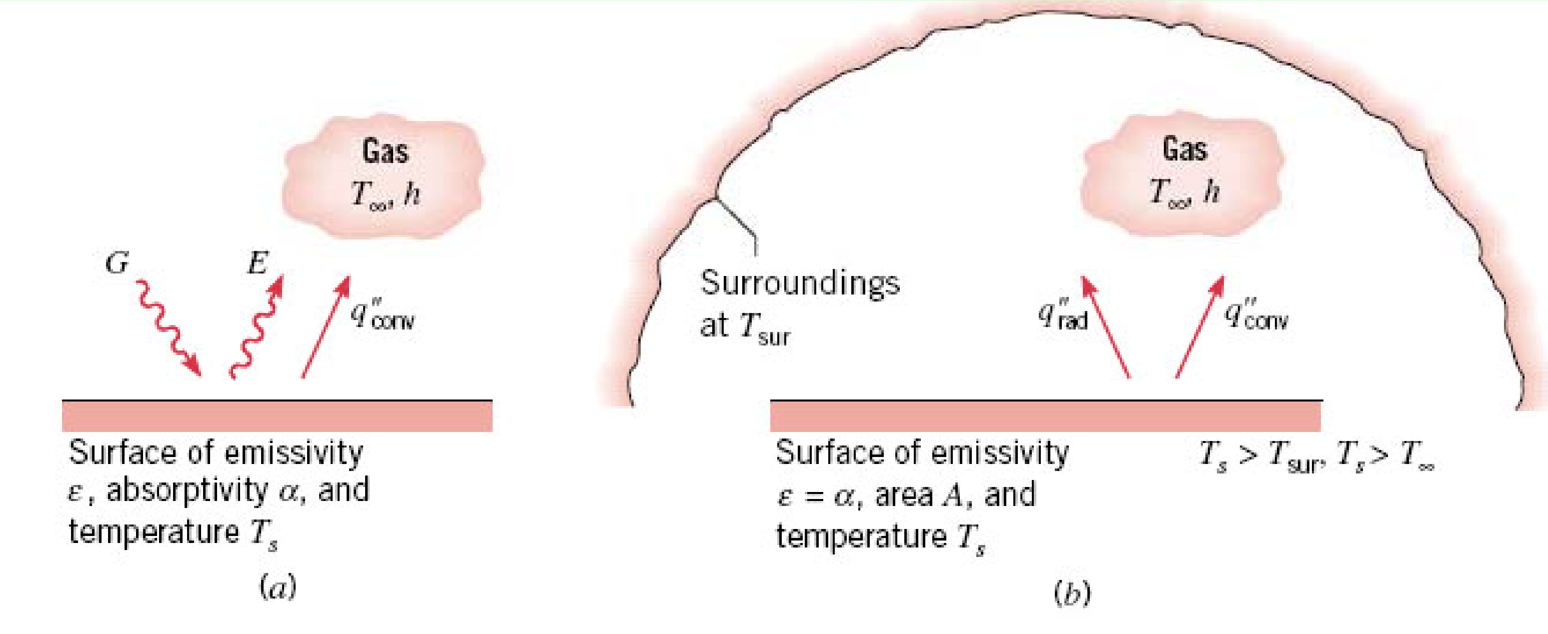

FIGURE 1.6 Radiation exchange: (*a*) at a surface and (*b*) between a surface and large surroundings.

- Irradiation G--the rate of radiation incident on a surface per unit area from its surroundings (Fig. 1.6)
  - The rate at which radiant energy is absorbed per unit area:

    $G_{\text{abs}} = \alpha G$, α--absorptivity of the surface,
- The net rate of radiation heat transfer *from* a gray surface (for which $\alpha = \varepsilon$, as will be shown in Chap. 12):

$$q''_{\text{rad}} = \varepsilon\sigma T_s^4 - \alpha G \approx \varepsilon\sigma(T_s^4 - T_{\text{sur}}^4) \qquad (1.7)$$

if the irradiation is from a large isothermal surrounding at T_{sur}, where G can be approximated by

$$G \approx \sigma T_{\text{sur}}^4$$

- There are many applications for which it is convenient to express the net radiation heat exchange in the form

$$q_{\text{rad}} = h_r A(T_s - T_{\text{sur}}) \qquad (1.8)$$

where h_r is the *radiation heat transfer coefficient*

$$h_r \equiv \varepsilon\sigma(T_s + T_{\text{sur}})(T_s^2 + T_{\text{sur}}^2) \qquad (1.9)$$

EX 1.2

1.2.4 Relationship to Thermodynamics

- Thermodynamics--concerned with equilibrium states of matter
- Heat transfer--inherently a non-equilibrium process, due to the presence of temperature gradient
- Heat transfer, as a result of temperature gradient, is essentially in agreement with the 2nd law of thermodynamics: heat flows from high to low temperature in nature.

1.3 The Conservation of Energy Requirement

1.3.1 Conservation of Energy for a Control Volume

EXs 1.3, 1.4, 1.5

1.3.2 The Surface Energy Balance

Fig. 1.9: $\dot{E}_{in} - \dot{E}_{out} = 0 \rightarrow q''_{cond} - q''_{conv} - q''_{rad} = 0$

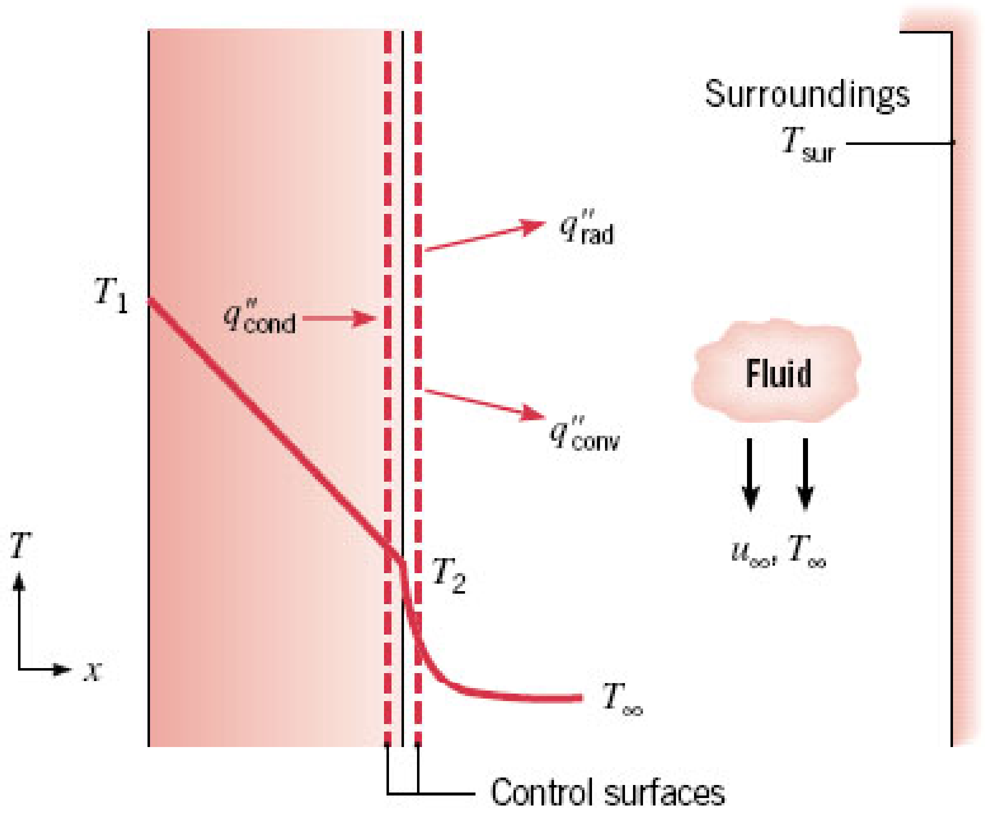

FIGURE 1.9
The energy balance for conservation of energy at the surface of a medium.

EX 1.6

1.3.3 Application of the Conservation Law: Methodology

Read the textbook.

1.4 Analysis of Heat Transfer Problems: Methodology

Read the textbook.

EX 1.7

1.5 Relevance of Transfer

Read the textbook.

1.6 Units and Dimensions

Read the textbook.