Heat Transfer: Physical Origins and Rate Equations

Chapter One
Sections 1.1 and 1.2

- What is heat transfer?

Heat transfer is thermal energy in transit due to a temperature difference.

- What is thermal energy?

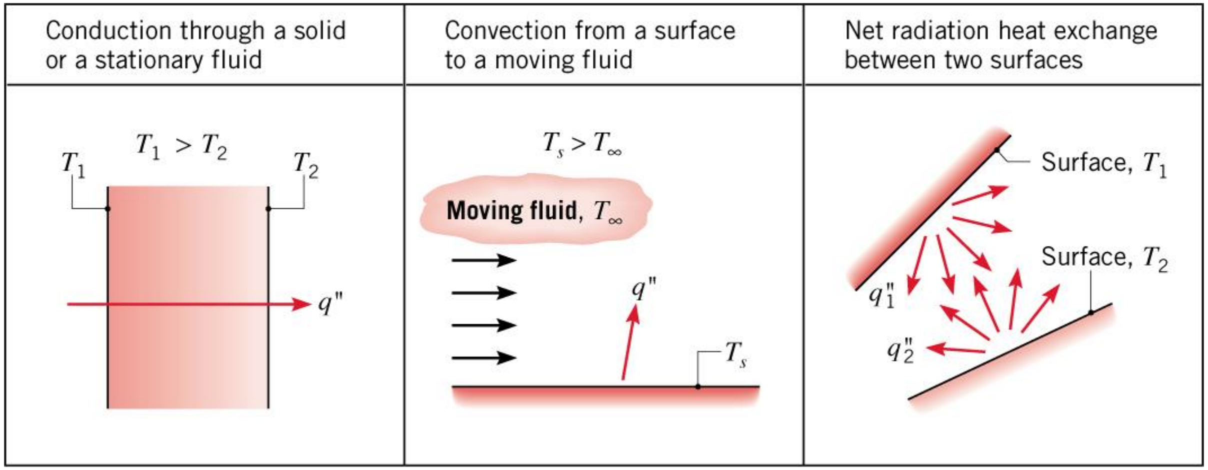
Thermal energy is associated with the translation, rotation, vibration and electronic states of the atoms and molecules that comprise matter. It represents the cumulative effect of microscopic activities and is directly linked to the temperature of matter.

DO NOT confuse or interchange the meanings of Thermal Energy, Temperature and Heat Transfer

Quantity	Meaning	Symbol	Units
Thermal Energy+	Energy associated with microscopic behavior of matter	U or u	J or J/kg
Temperature	A means of indirectly assessing the amount of thermal energy stored in matter	T	K or °C
Heat Transfer	Thermal energy transport due to temperature gradients		
Heat	Amount of thermal energy transferred over a time interval $\triangle t > 0$	Q	J
Heat Rate	Thermal energy transfer per unit time	q	W
Heat Flux	Thermal energy transfer per unit time and surface area	q''	W/m^2

+
$U \rightarrow$ Thermal energy of system
$u \rightarrow$ Thermal energy per unit mass of system

Modes of Heat Transfer



Conduction: Heat transfer in a solid or a stationary fluid (gas or liquid) due to the random motion of its constituent atoms, molecules and /or electrons.

Convection: Heat transfer due to the combined influence of bulk and random motion for fluid flow over a surface.

Radiation: Energy that is emitted by matter due to changes in the electron configurations of its atoms or molecules and is transported as electromagnetic waves (or photons).

- Conduction and convection require the presence of temperature variations in a material medium.
- Although radiation originates from matter, its transport does not require a material medium and occurs most efficiently in a vacuum.

Heat Transfer Rates

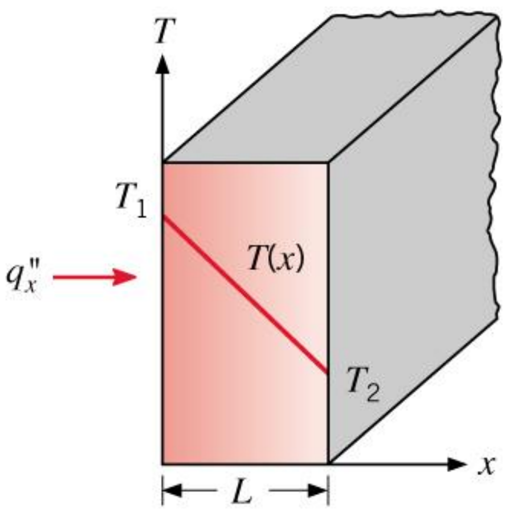
Conduction:

General (vector) form of Fourier's law:

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

Heat flux W/m^2 — Thermal conductivity $W/m \cdot K$ — Temperature gradient $°C/m$ or K/m

Application to one-dimensional, steady conduction across a plane wall of constant thermal conductivity:



$$q''_x = -k\frac{dT}{dx} = -k\frac{T_2 - T_1}{L}$$

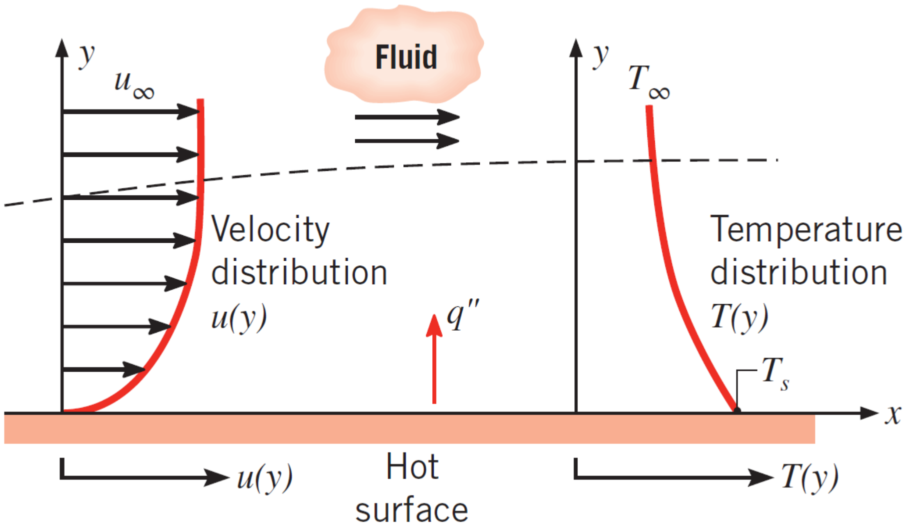
$$q''_x = k\frac{T_1 - T_2}{L} \qquad (1.2)$$

Heat rate (W): $q_x = q''_x \cdot A$

Heat Transfer Rates

Convection

Relation of convection to flow over a surface and development of velocity and thermal boundary layers:



Newton's law of cooling:

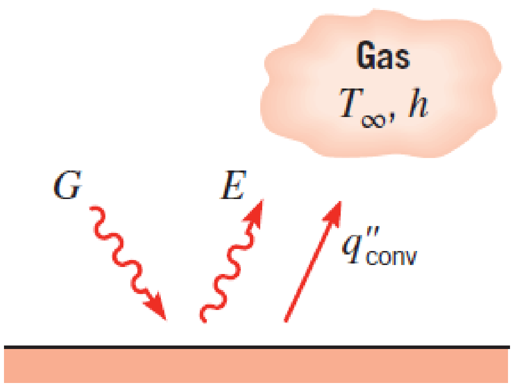
$$q'' = h\left(T_s - T_\infty\right) \qquad (1.3a)$$

h: Convection heat transfer coefficient $(\mathrm{W/m^2 \cdot K})$

Heat Transfer Rates

Radiation

Involves radiation emission from the surface and may also involve the absorption of radiation incident from the surroundings (irradiation, G), as well as convection $\left(\text{if } T_s \neq T_\infty\right)$.



Surface of emissivity ε, absorptivity α, and temperature T_s

Energy outflow due to emission:

$$E = \varepsilon E_b = \varepsilon \sigma T_s^4 \tag{1.5}$$

E: Emissive power $\left(\text{W/m}^2\right)$

ε: Surface emissivity $\left(0 \leq \varepsilon \leq 1\right)$

E_b: Emissive power of a blackbody (the perfect emitter)

σ: Stefan-Boltzmann constant $\left(5.67 \times 10^{-8}\ \text{W/m}^2 \cdot \text{K}^4\right)$

Energy absorption due to irradiation:

$$G_{\text{abs}} = \alpha G \tag{1.6}$$

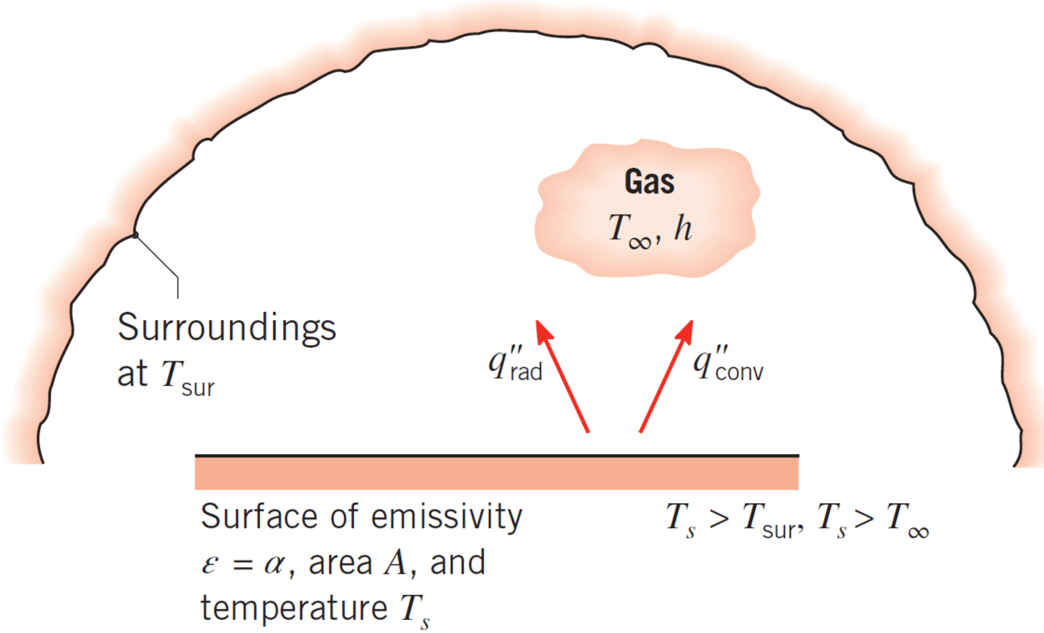
G_{abs}: Absorbed incident radiation (W/m^2)

α: Surface absorptivity $\left(0 \leq \alpha \leq 1\right)$

G: Irradiation $\left(\text{W/m}^2\right)$

Heat Transfer Rates

Irradiation: Special case of surface exposed to large surroundings of uniform temperature, T_{sur}



$$G = G_{sur} = \sigma T_{sur}^4$$

If $\alpha = \varepsilon$, the net radiation heat flux from the surface due to exchange with the surroundings is:

$$q''_{rad} = \varepsilon E_b(T_s) - \alpha G = \varepsilon\sigma\left(T_s^4 - T_{sur}^4\right) \quad (1.7)$$

Heat Transfer Rates

Alternatively,

$$q''_{\text{rad}} = h_r \left(T_s - T_{\text{sur}}\right) \tag{1.8}$$

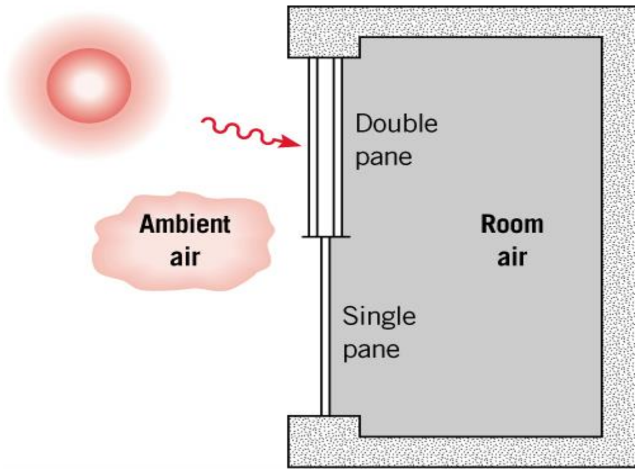
h_r: Radiation heat transfer coefficient $\left(\text{W/m}^2 \cdot \text{K}\right)$

$$h_r = \varepsilon\sigma\left(T_s + T_{\text{sur}}\right)\left(T_s^2 + T_{\text{sur}}^2\right) \tag{1.9}$$

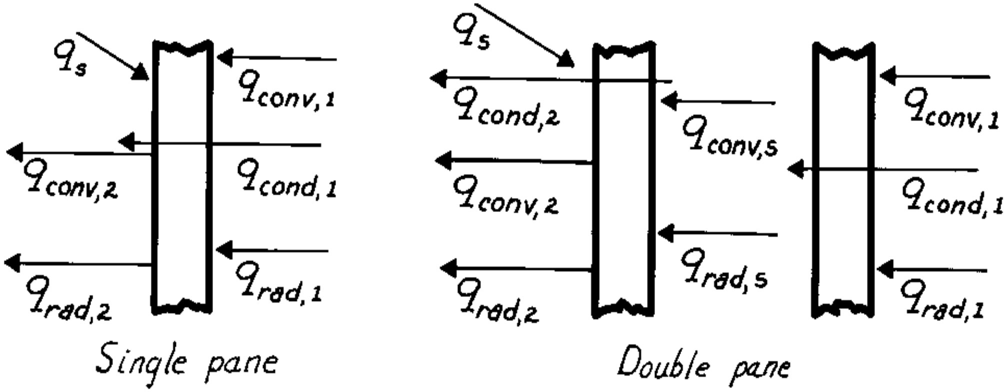
For combined convection and radiation,

$$q'' = q''_{\text{conv}} + q''_{\text{rad}} = h\left(T_s - T_\infty\right) + h_r\left(T_s - T_{\text{sur}}\right) \tag{1.10}$$

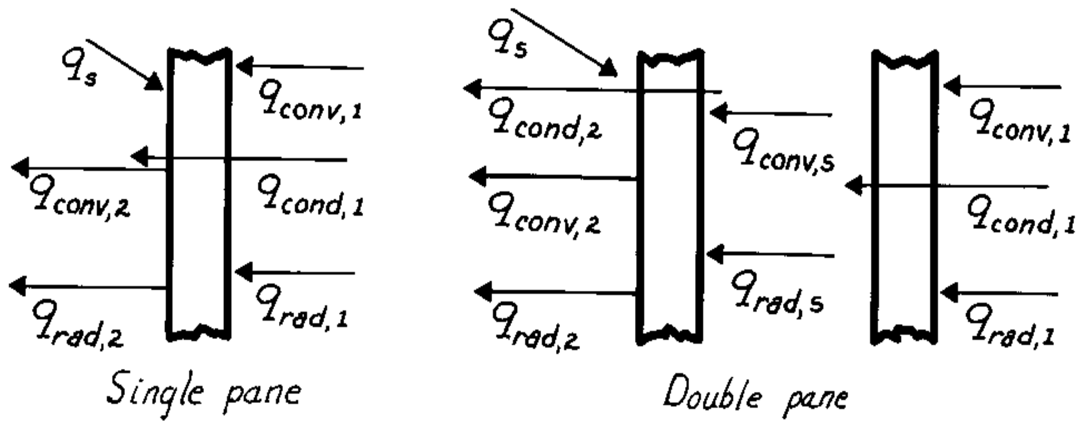
Problem 1.63(a): Process identification for single-and double-pane windows



SCHEMATIC:



Problem: Process Identification (cont.)



$q_{conv,1}$ Convection from room air to inner surface of first pane

$q_{rad,1}$ Net radiation exchange between room walls and inner surface of first pane

$q_{cond,1}$ Conduction through first pane

$q_{conv,s}$ Convection across airspace between panes

$q_{rad,s}$ Net radiation exchange between outer surface of first pane and inner surface of second pane (across airspace)

$q_{cond,2}$ Conduction through a second pane

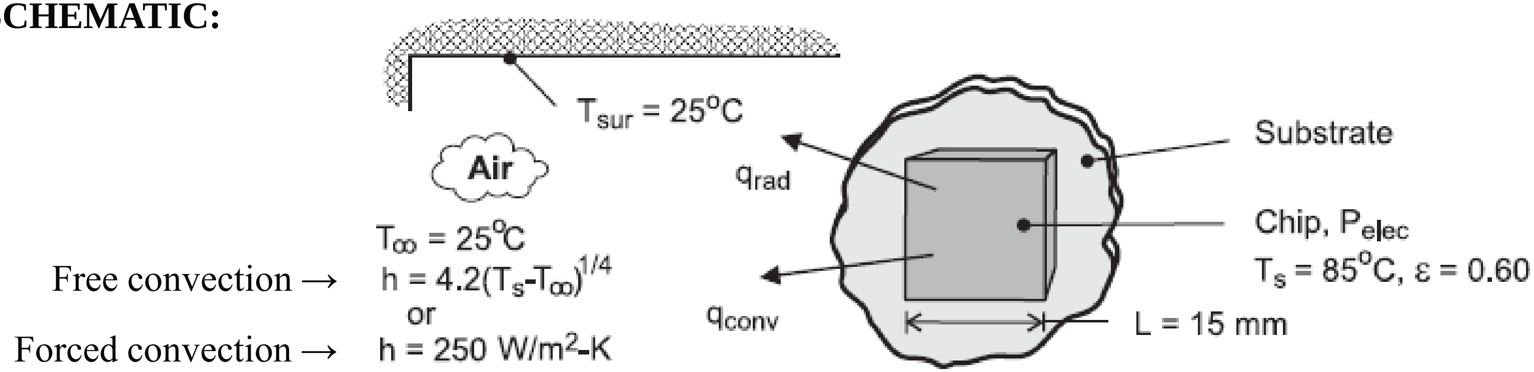
$q_{conv,2}$ Convection from outer surface of single (or second) pane to ambient air

$q_{rad,2}$ Net radiation exchange between outer surface of single (or second) pane and surroundings such as the ground

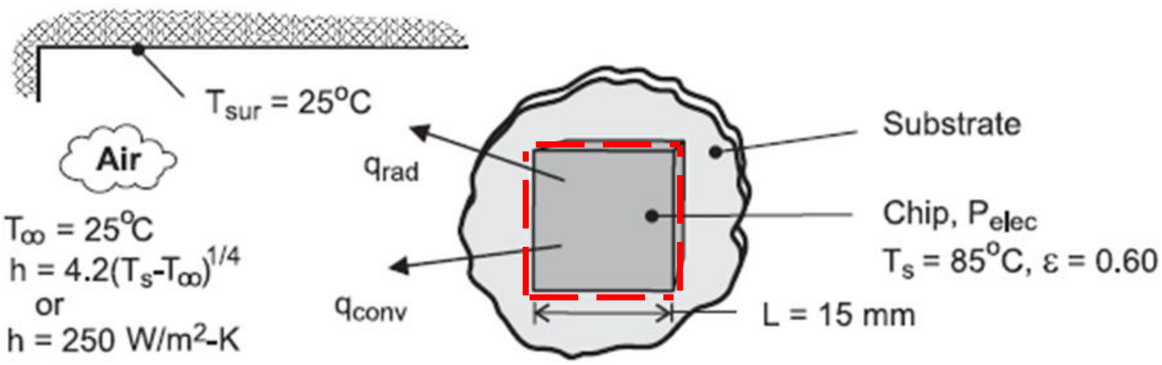
q_s Incident solar radiation during day; fraction transmitted to room is smaller for double pane

Problem 1.35: Power dissipation from chips operating at a surface temperature of 85°C and in an enclosure whose walls and air are at 25°C for (a) free convection and (b) forced convection.

SCHEMATIC:



ASSUMPTIONS: (1) Steady-state conditions, (2) Radiation exchange between a small surface and a large enclosure, (3) $\alpha = \varepsilon$, (4) Negligible heat transfer from sides of chip or from back of chip by conduction through the substrate.



ANALYSIS:

$$P_{\text{elec}} = q_{\text{conv}} + q_{\text{rad}} \quad = hA\left(T_s - T_\infty\right) + \varepsilon A\sigma\left(T_s^4 - T_{\text{sur}}^4\right)$$

$$A = L^2 = \left(0.015\text{m}\right)^2 = 2.25\times10^{-4}\text{m}^2$$

(a) If heat transfer is by free convection,

$$q_{\text{conv}} = CA\left(T_s - T_\infty\right)^{5/4} = 4.2\text{W/m}^2\cdot\text{K}^{5/4}\left(2.25\times10^{-4}\text{m}^2\right)\left(60\text{K}\right)^{5/4} = 0.158\text{W}$$

$$q_{\text{rad}} = 0.60\left(2.25\times10^{-4}\text{m}^2\right)5.67\times10^{-8}\text{W/m}^2\cdot\text{K}^4\left(358^4 - 298^4\right)\text{K}^4 = 0.065\text{W}$$

$$P_{\text{elec}} = 0.158\text{W} + 0.065\text{W} = 0.223\text{W}$$ $<$

(b) If heat transfer is by forced convection,

$$q_{\text{conv}} = hA\left(T_s - T_\infty\right) = 250\text{W/m}^2\cdot\text{K}^4\left(2.25\times10^{-4}\text{m}^2\right)\left(60\text{K}\right) = 3.375\text{W}$$

$$P_{\text{elec}} = 3.375\text{W} + 0.065\text{W} = 3.44\text{W}$$ $<$