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

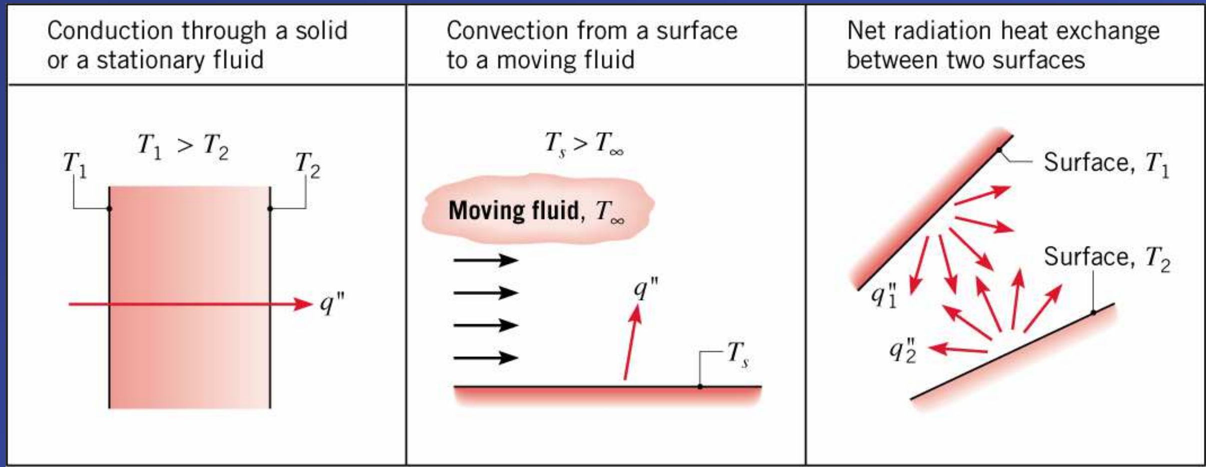
Quantity	Meaning	Symbol	Units
Thermal Energy+	Energy associated with microscopic behavior of matter	U or u	J or J/kg
Temperature	A means of indirectly assessing the amount of thermal energy stored in matter	T	K or °C
Heat Transfer	Thermal energy transport due to temperature gradients		
Heat	Amount of 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:

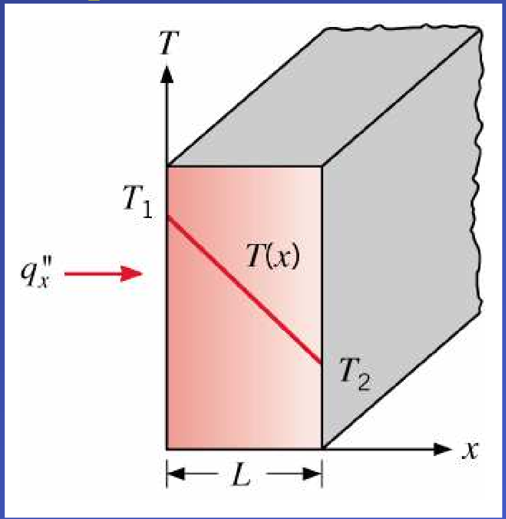
$$\vec{q''} = -k \nabla T$$

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:



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

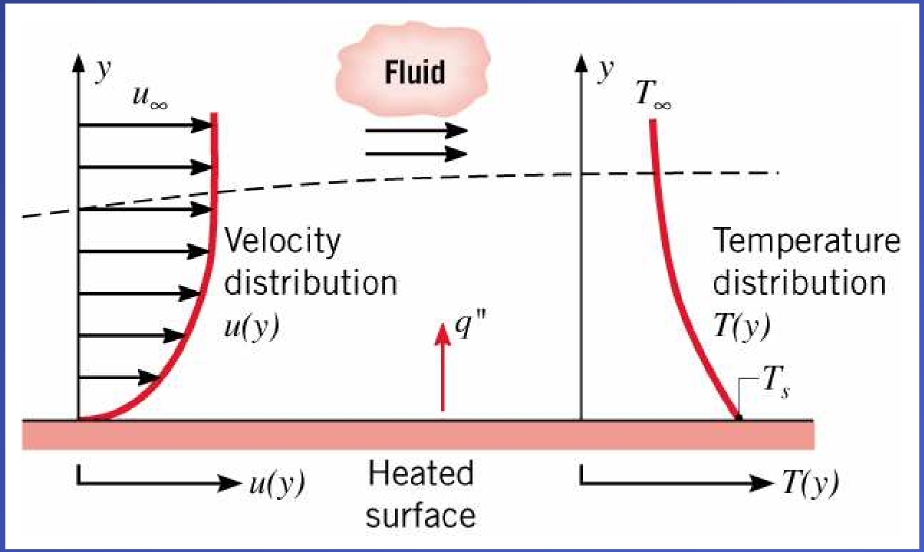
$$q''_x = k \frac{T_1 - T_2}{L} \qquad (1.2)$$

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:

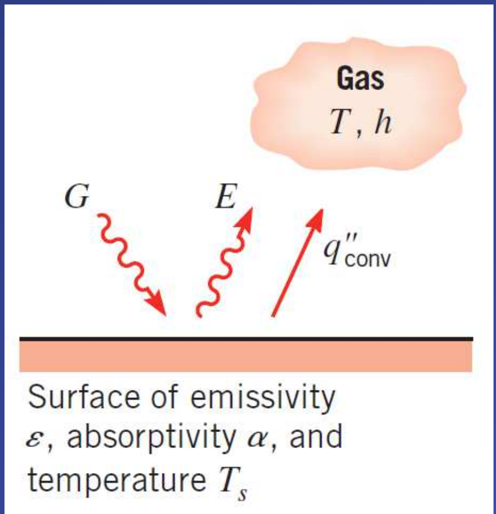
$$q'' = h\left(T_s - T_\infty\right) \qquad (1.3a)$$

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

Heat Transfer Rates

Radiation

Heat transfer at a gas/surface interface involves radiation emission from the surface and may also involve the absorption of radiation incident from the surroundings (irradiation, G), as well as convection $\left(\text{if } T_s \neq T_\infty\right)$.



Energy outflow due to emission:

$$E = \varepsilon E_b = \varepsilon \sigma T_s^4 \qquad (1.5)$$

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

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

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

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

Energy absorption due to irradiation:

$$G_{\text{abs}} = \alpha G \qquad (1.6)$$

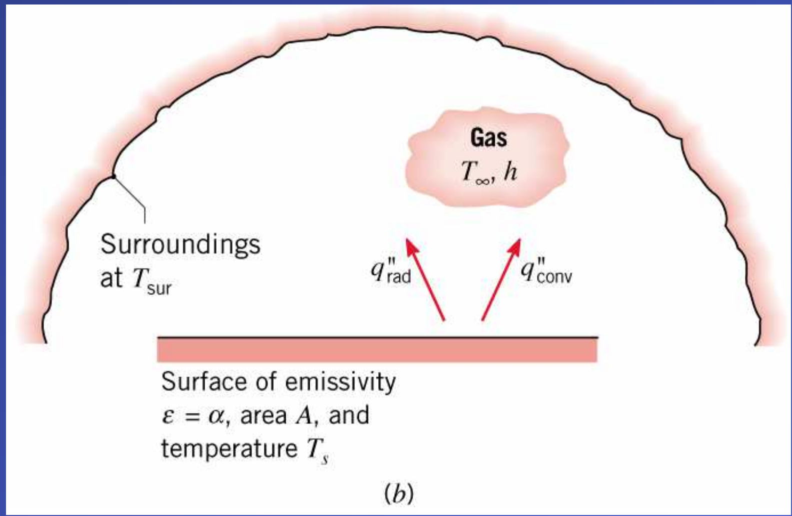
G_{abs} :Absorbed incident radiation$(\mathrm{W/m^2})$

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

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

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:

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

Heat Transfer Rates

Alternatively,

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

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

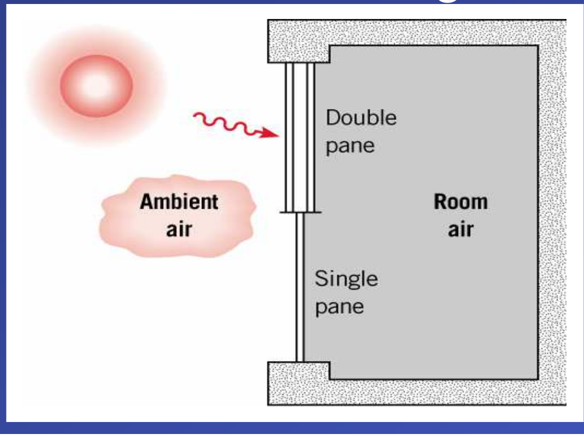
$$h_r = \varepsilon\sigma\left(T_s + T_{\text{sur}}\right)\left(T_s^2 + T_{\text{sur}}^2\right) \qquad (1.9)$$

For combined convection and radiation,

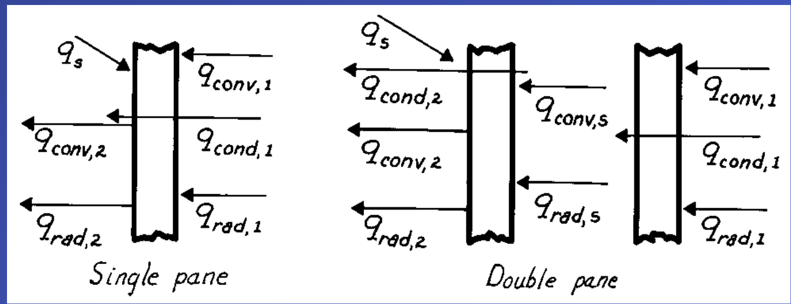
$$q'' = q''_{\text{conv}} + q''_{\text{rad}} = h\left(T_s - T_\infty\right) + h_r\left(T_s - T_{\text{sur}}\right) \qquad (1.10)$$

Process Identification

Problem 1.87(a): Process identification for single-and double-pane windows



Schematic:



$q_{conv,1}$ 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

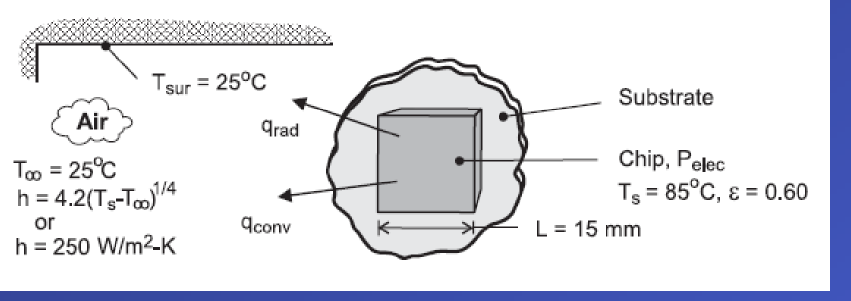
$q_{conv,2}$ Convection from outer surface of single (or second) pane to ambient air

$q_{rad,2}$ 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 1.40: 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) Negligible heat transfer from sides of chip or from back of chip by conduction through the substrate.

Analysis:

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

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

(a) If heat transfer is by natural convection,

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

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

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

(b) If heat transfer is by forced convection,

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

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

Relationship to Thermodynamics

Chapter One
Section 1.3

CONSERVATION OF ENERGY (FIRST LAW OF THERMODYNAMICS)

- An important tool in heat transfer analysis, often providing the basis for determining the temperature of a system.

- Alternative Formulations

  Time Basis:

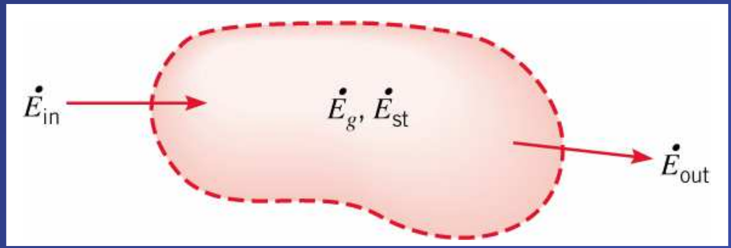
  At an instant
  or
  Over a time interval

  Type of System:

  Control volume
  Control surface

APPLICATION TO A CONTROL VOLUME

- At an Instant of Time:



Note representation of system by a control surface (dashed line) at the boundaries.

Surface Phenomena

$\dot{E}_{in}, \dot{E}_{out}$: rate of thermal and/or mechanical energy transfer across the control surface due to heat transfer, fluid flow and/or work interactions.

Volumetric Phenomena

$\dot{E}_g$: rate of thermal energy generation due to conversion from another energy form (e.g., electrical, nuclear, or chemical); energy conversion process occurs within the system.

$\dot{E}_{st}$: rate of change of energy storage in the system.

Conservation of Energy

$$\dot{E}_{in} - \dot{E}_{out} + \dot{E}_g = \frac{dE_{st}}{dt} \equiv \dot{E}_{st} \qquad \textbf{(1.12c)}$$

Each term has units of J/s or W.

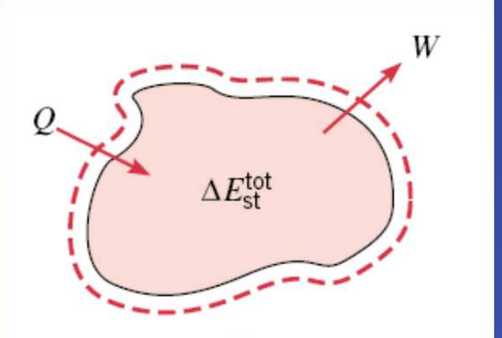
- Over a Time Interval

$$E_{in} - E_{out} + E_g = \Delta E_{st} \qquad \textbf{(1.12b)}$$

Each term has units of J.

- Special Cases (Linkages to Thermodynamics)

  (i) Transient Process for a Closed System of Mass (*M*) *Assuming Heat Transfer to the System (Inflow) and Work Done by the System (Outflow).*



(*a*)

Over a time interval

$$Q - W = \Delta E_{st}^{tot} \tag{1.12a}$$

For negligible changes in potential or kinetic energy

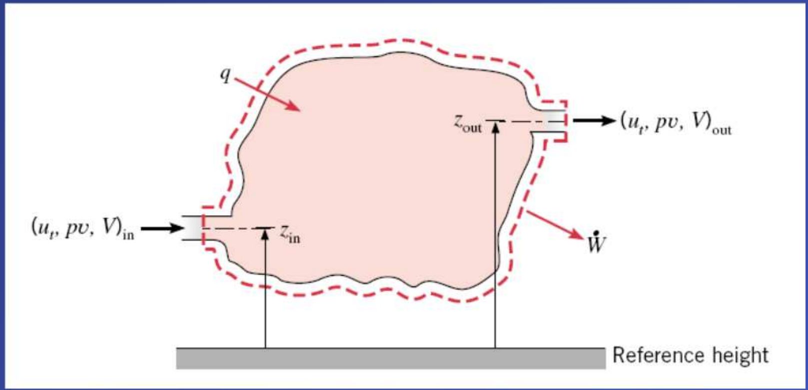
$$Q - W = \underbrace{\Delta U_t}_{\text{Internal thermal energy}}$$

At an instant

$$q - \dot{W} = \frac{dU_t}{dt}$$

Open System

(ii) Steady State for Flow through an Open System without Phase Change or Generation:



At an Instant of Time:

$$\dot{m}\left(u_t + pv + V^2/2 + gz\right)_{in} + q - \dot{m}\left(u_t + pv + V^2/2 + gz\right)_{out} - \dot{W} = 0 \qquad \textbf{(1.12d)}$$

- $(pv) \rightarrow$ flow work
- $(u_t + pv) \equiv i \rightarrow$ enthalpy
- For an ideal gas with constant specific heat:

$$i_{in} - i_{out} = c_p\left(T_{in} - T_{out}\right)$$

- For an incompressible liquid:

$$u_{in} - u_{out} = c\left(T_{in} - T_{out}\right)$$

$$(pv)_{in} - (pv)_{out} \approx 0$$

- For systems with significant heat transfer:

$$\left(V^2/2\right)_{in} - \left(V^2/2\right)_{out} \approx 0$$

$$(gz)_{in} - (gz)_{out} \approx 0$$

THE SURFACE ENERGY BALANCE

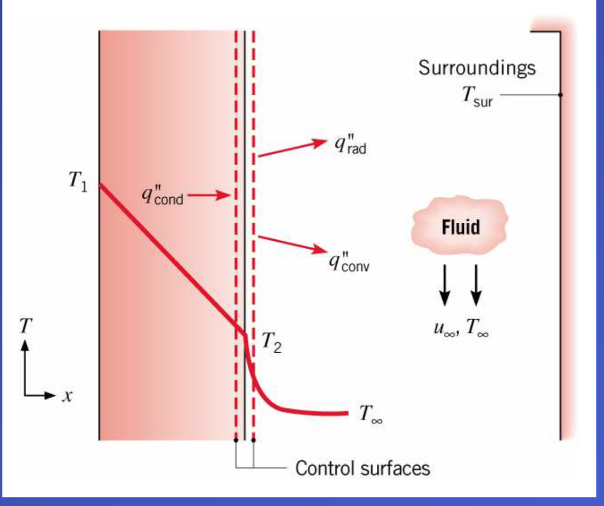
A special case for which no volume or mass is encompassed by the control surface.

Conservation of Energy (Instant in Time):

$$\dot{E}_{in} - \dot{E}_{out} = 0 \qquad (1.13)$$

- Applies for steady-state and transient conditions.
- With no mass and volume, energy storage and generation are not pertinent to the energy balance, even if they occur in the medium bounded by the surface.

Consider surface of wall with heat transfer by conduction, convection and radiation.



$$q''_{cond} - q''_{conv} - q''_{rad} = 0$$

$$k\frac{T_1 - T_2}{L} - h\left(T_2 - T_\infty\right) - \varepsilon_2\sigma\left(T_2^4 - T_{sur}^4\right) = 0$$

METHODOLOGY OF FIRST LAW ANALYSIS

- On a schematic of the system, represent the control surface by dashed line(s).
- Choose the appropriate time basis.
- Identify relevant energy transport, generation and/or storage terms by labeled arrows on the schematic.
- Write the governing form of the Conservation of Energy requirement.
- Substitute appropriate expressions for terms of the energy equation.
- Solve for the unknown quantity.