Fundamentals of Heat and Mass Transfer

Chapter 1

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Heat Transfer and Thermal Energy (1 of 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.

Heat Transfer and Thermal Energy (2 of 2)

Do not confuse or interchange the meanings of Thermal Energy, Temperature and Heat Transfer

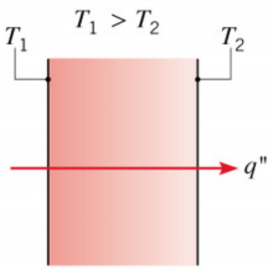
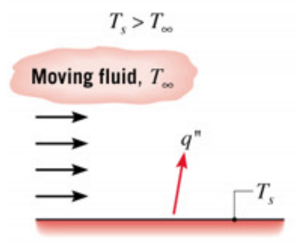
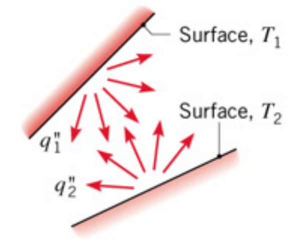
Quantity	Meaning	Symbol	Units
Thermal Energy[+]	Energy associated with microscopic behavior of matter	U or u	J or J/kg
Temperature	A means of indirectly assessing the amount of thermal energy stored in matter	T	K or °C
Heat Transfer	Thermal energy transport due to temperature gradients		
Heat	Amount 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 through a solid or a stationary fluid	Convection from a surface to a moving fluid	Net radiation heat exchange between two surfaces
		

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.

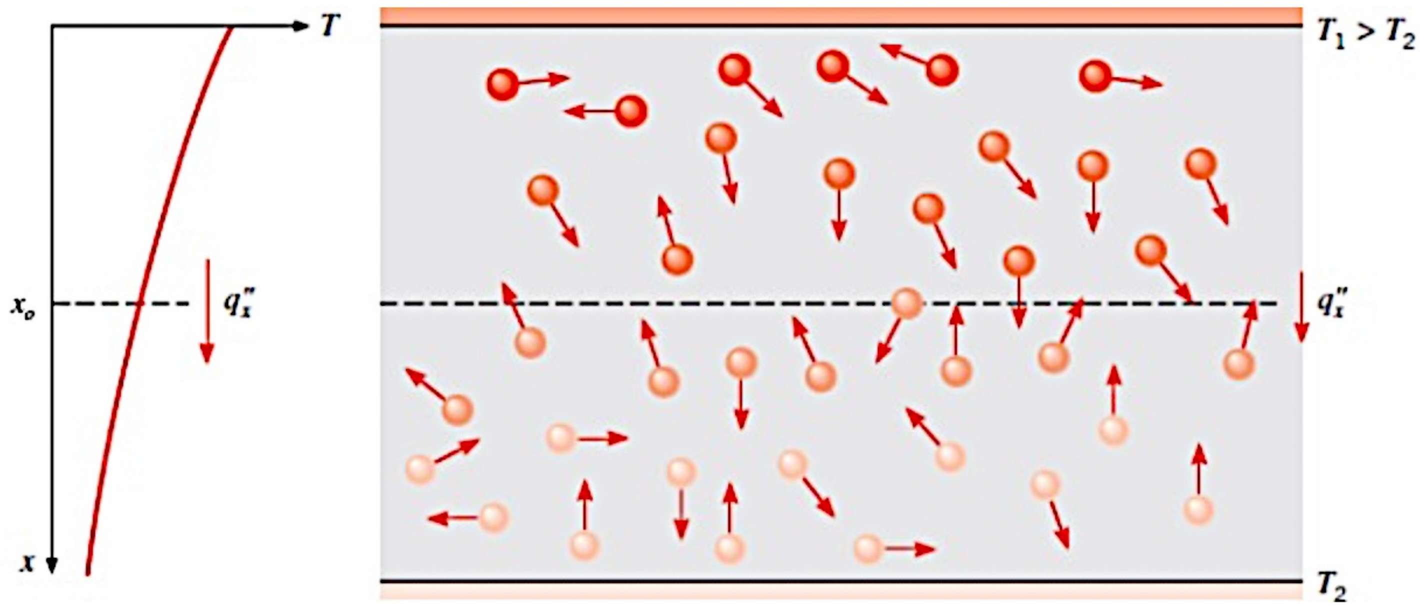
Radiation: Energy that is emitted by matter due to changes in the electron configurations of its atoms or molecules and is transported as electromagnetic waves (or photons).

- 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 (1 of 6)

Conduction:

Transfer of energy from the more energetic to the less energetic particles of a substance due to interactions between the particles.



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

Heat Transfer Rates (2 of 6)

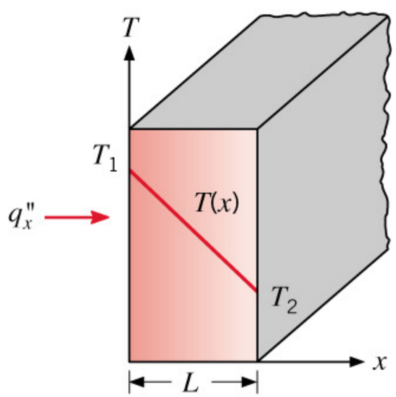
Conduction:

General (vector) form of Fourier's law:

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

Heat flux W/m^2 — Thermal conductivity $\text{W/m}\cdot\text{K}$ — Temperature gradient $^\circ\text{C/m}$ or K/m

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



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

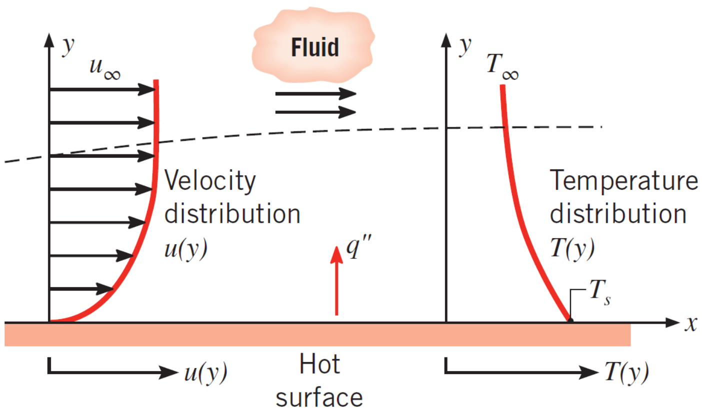
$$q''_x = k\frac{T_1 - T_2}{L} \qquad (1.2)$$

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

Heat Transfer Rates (3 of 6)

Convection

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



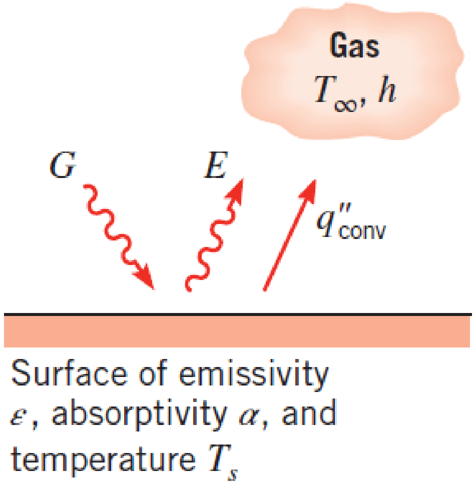
Newton's law of cooling:

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

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

Heat Transfer Rates (4 of 6)

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 (if $T_s \neq T_\infty$).



Energy outflow due to emission:

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

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

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

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

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

Energy absorption due to irradiation:

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

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

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

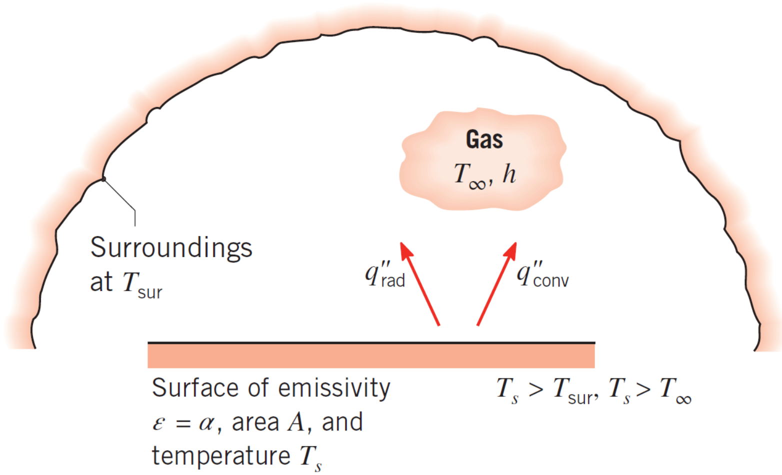
G: Irradiation $\left(\mathrm{W/m^2}\right)$

The emissivity of a surface represents the ratio of the radiation emitted by the surface at a given temperature to the radiation emitted by a blackbody at the same temperature.

A blackbody is defined as a perfect emitter and absorber of radiation.

Heat Transfer Rates (5 of 6)

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 (6 of 6)

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,

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