CHG 2314
Heat Transfer

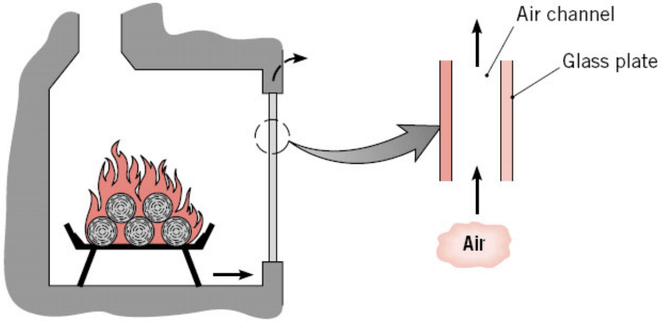
Part 1

Basic Concepts of Heat Transfer

- Physical origins and rate equations
- Application of thermodynamics

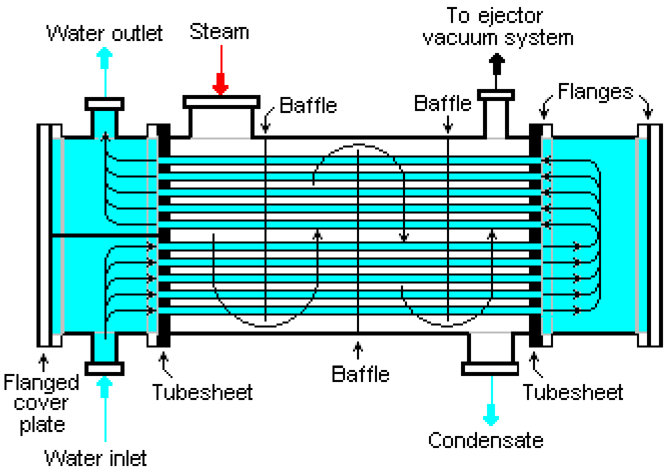
Introduction

- 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 is commonly encountered in engineering systems and other aspects of life



Introduction

- Engineering heat transfer deals in general with two types of problems:
  - ***Rating problems*** – calculating rates of heat transfer at a specific temperature difference for an existing problem
  - ***Sizing problems*** – determination of the size of a system in order to transfer heat at a specified rate for a specified temperature difference



What is the condensation rate of steam at a given flow rate of cooling water which is available at certain temperature in a given heat exchanger?

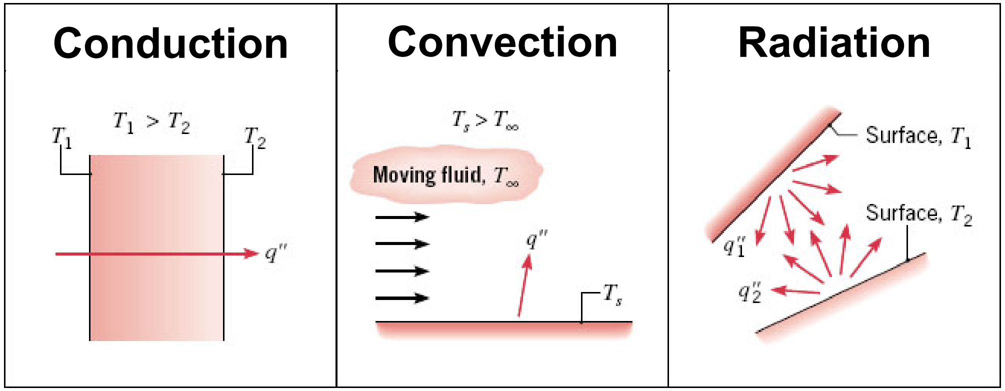
What should be the thickens of insulation to prevent a worker's injury on accidental contact with a pipe surface?

Nomenclature

- **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''	$\mathrm{W/m^2}$

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).

NB1: Conduction and convection require the presence of temperature variations in a material medium.

NB2: Although radiation originates from matter, its transport does not require a material medium and occurs most efficiently in a vacuum.

Heat transfer rates

- **Conduction** – Fourier’s law of heat conduction (1822)
  - General (vector) form of Fourier’s law

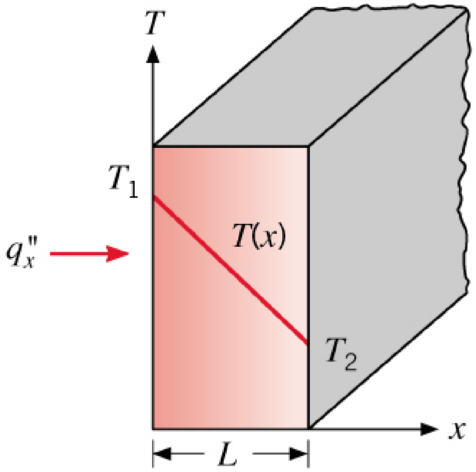
$$\vec{q}'' = -k\underbrace{\vec{\nabla} T}$$

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**



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

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

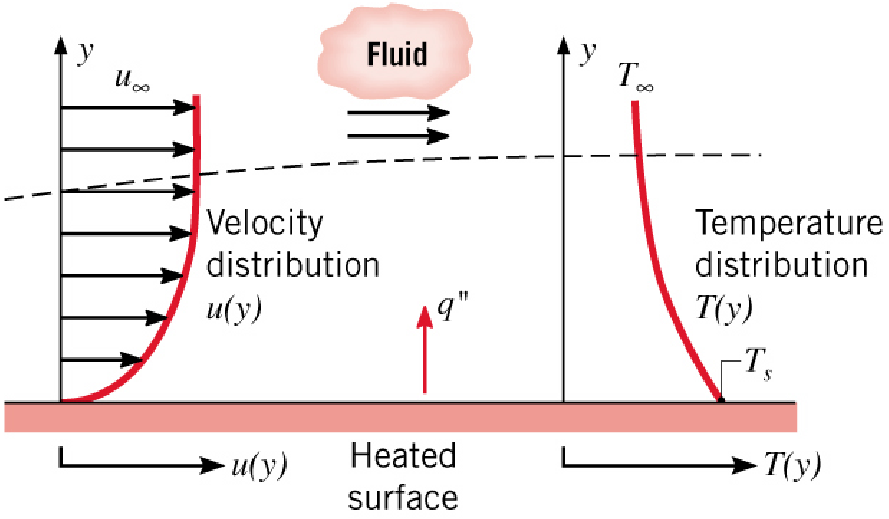
Heat rate (W): $q_x = q''_x \cdot A$

***A* is <u>perpendicular</u> to the vector of heat flow**

***L* is <u>parallel</u> to the vector of heat flow**

Heat transfer rates

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



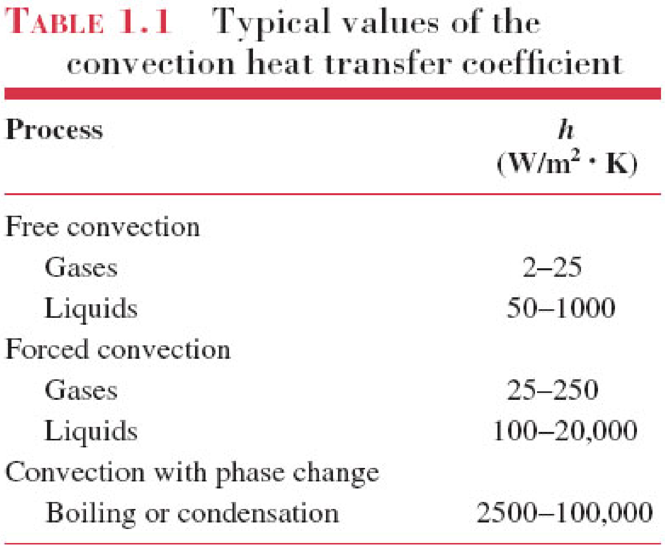


TABLE 1.1 Typical values of the convection heat transfer coefficient

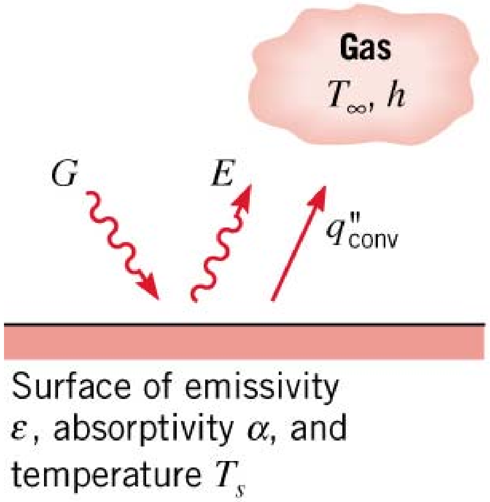
Process	h ($W/m^2 \cdot K$)
Free convection	
Gases	2–25
Liquids	50–1000
Forced convection	
Gases	25–250
Liquids	100–20,000
Convection with phase change	
Boiling or condensation	2500–100,000

- Newton's law of cooling: $$q'' = \mathrm{h}\left(T_s - T_\infty\right)$$

h is the convection heat transfer coefficient ($W/m^2 \cdot K$)

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 ($T_s \neq T_\infty$)



Energy outflow due to emission: (1.5) $E = \varepsilon E_b = \varepsilon \sigma T_s^4$

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

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

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

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

Energy absorption due to irradiation:

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

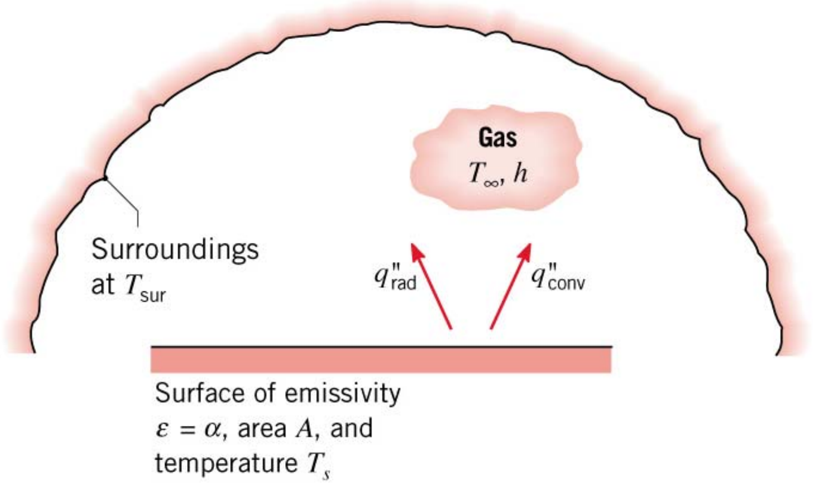
α : Surface absorptivity $(0 \le \alpha \le 1)$

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

Heat transfer rates

Radiation

- Special case of surface exposed to large surroundings of uniform temperature, T_{surr}



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

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

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

- Linearized form of rate equation for radiation

$$q_{rad} = h_r A\left(T_s - T_{surr}\right) \quad (1.8)$$

$$h_r \equiv \varepsilon\sigma\left(T_s + T_{surr}\right)\left(T_s^2 + T_{surr}^2\right) \quad (1.9)$$

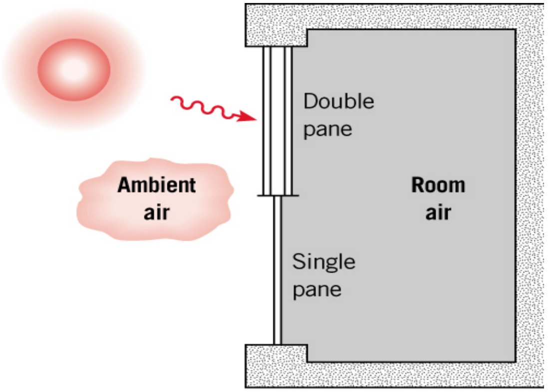
NB: ***h_r*** is a very strong function of temperature

- For combined convection and radiation:

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

Example 1 (problem 1.73a)

Process identification for single-and-double pane windows



Application of thermodynamics in heat transfer

Heat transfer vs. Thermodynamics

- **Classical thermodynamics deals with systems in equilibrium**
  - Thermodynamics deals with the states of systems from a macroscopic view and does not make hypotheses about the structure of matter
  - Thermodynamics allows calculation of the energy required to change the system <u>from one equilibrium state to another</u>
  - Thermodynamics does not provide information about the <u>rate</u> at which the change between states occurs nor about the <u>mechanism</u> of energy flow

- Unlike thermodynamics, **heat transfer deals with nonequilibrium states**
  - Therefore, principles of heat transfer **<u>cannot</u>** be derived from the basic laws of thermodynamics
  - However, principles of heat transfer **<u>must obey</u>** the laws of thermodynamics

Heat transfer vs. Thermodynamics

- Steady state versus equilibrium processes
  - **Question: Can a steady state process be a non-equilibrium process?**
  - Zeroth Law of Thermodynamics states that when system A is in thermal equilibrium with system B, the following applies:

$$T_A = T_B$$

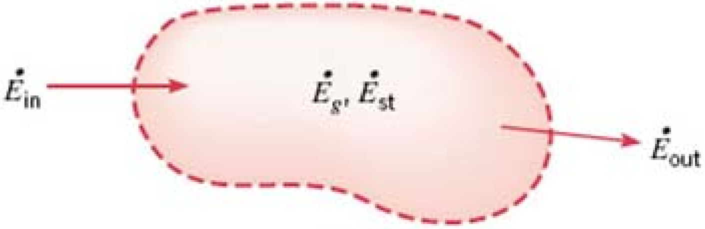
First Law of Thermodynamics

Energy can be neither created nor destroyed but only changed from one form to another

- Since energy must be conserved, once we identify the system boundaries (control surface) we can define the energy balance for a system
- Can be expressed for a time interval (increase in amount of energy stored, ΔE_{st}) or at an instant (rate of increase of energy stored, $\dot{E}_{st}$)

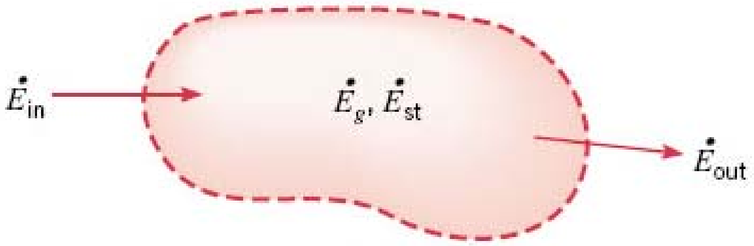
(1.11b) $$\Delta E_{st} = E_{in} - E_{out} + E_g$$

(1.11c) $$\dot{E}_{st} \equiv \frac{dE_{st}}{dt} = \dot{E}_{in} - \dot{E}_{out} + \dot{E}_g$$



Energy terms

- ***Energy inflow*** ($\dot{E}_{in}$) and **energy outflow** ($\dot{E}_{out}$) are the combination of heat transfer modes, i.e. conduction, convection, radiation
- ***Energy generation*** ($\dot{E}_g$) is associated with converting chemical, electrical, nuclear energy into thermal energy
- ***Energy storage*** ($\dot{E}_{st}$) is associated with kinetic, potential and internal energy; in heat transfer problems only internal energy (U) is important

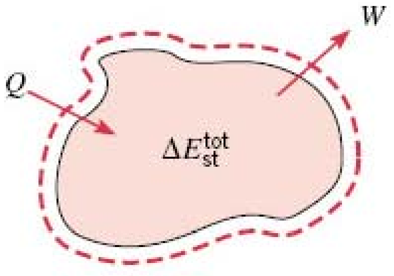


Surface versus volumetric phenomena

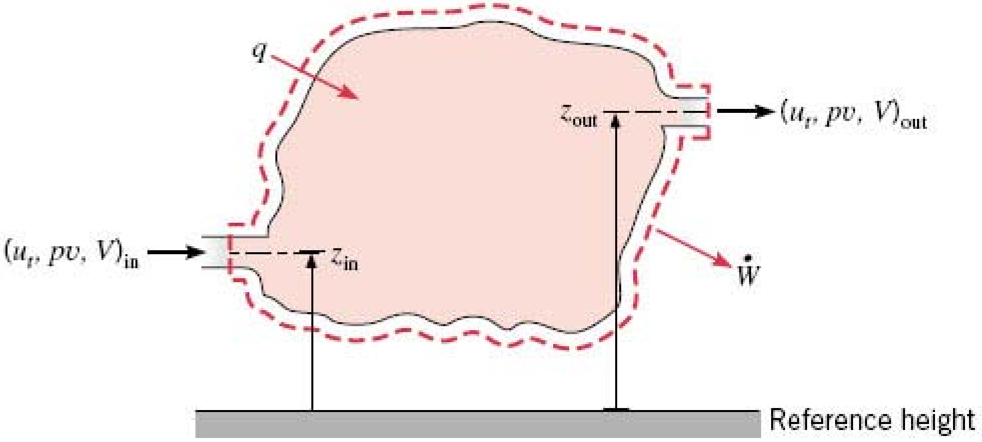
- Energy inflow and outflow terms are surface phenomena
  - They are associated with processes occurring at the control surface
- Energy generation and storage terms are volumetric phenomena
  - They occur in the control volume enclosed by the control surface

Closed versus open systems

- In a closed system mass does not flow across the control surface



- In an open system mass can flow across the control surface



Closed systems

- For closed systems containing a fixed mass of solid, the 1st Law of Thermodynamics at an instant becomes:

$$\frac{dU}{dt} = \dot{E}_{in} + \dot{E}_{g} - \dot{E}_{out} - \dot{W}$$

- For incompressible closed systems work is zero; changes in the internal energy (***U***) will manifest as a temperature change of the system. Therefore, the above equation becomes:

$$\rho V c \frac{dT}{dt} = \dot{E}_{in} + \dot{E}_{g} - \dot{E}_{out}$$

where $\boldsymbol{\rho}$, $\boldsymbol{c}$ and $\boldsymbol{V}$ are the density, specific heat (for solids and generally for incompressible fluids, $\boldsymbol{c_p = c_v = c}$) and the volume of the system, respectively

Open systems

- Mass flow across the system boundary provides for the transport of kinetic and potential energy into and out of the system

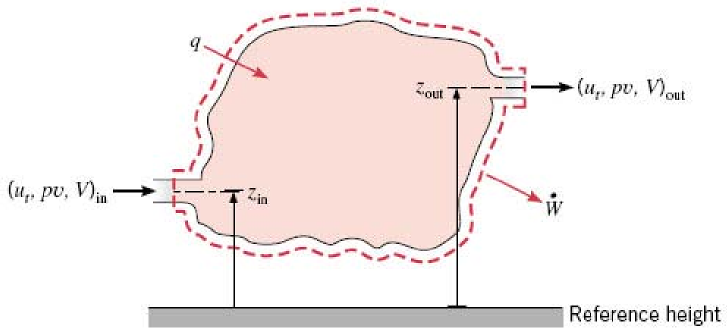


FIGURE 1.8 Conservation of energy for a steady-flow, open system.

  - Referring to the figure, at steady state the 1st Law becomes:

$$\dot{m}\left(u + pv + \frac{V^2}{2} + gz\right)_{in} - \dot{m}\left(u + pv + \frac{V^2}{2} + gz\right)_{out} + q - \dot{W} = 0 \qquad (1.11d)$$

where ***u*** is the specific internal energy; ***pv*** is the specific flow work associated with the work done by pressure forces moving fluid through the system boundaries; ***V*²/2** is the specific kinetic energy; ***W*** is the work done by the system

Open systems

$$(1.11d)\qquad \dot{m}\left(\underbrace{\boxed{u+pv}}_{i}+\cancel{\frac{V^2}{2}}+\cancel{gz}\right)_{in}-\dot{m}\left(\underbrace{\boxed{u+pv}}_{i}+\cancel{\frac{V^2}{2}}+\cancel{gz}\right)_{out}+q-\cancel{\dot{W}}=0$$

- The sum of the specific internal energy and the specific flow work is the specific enthalpy, $\boldsymbol{i = u + pv}$
  - $\boldsymbol{i_{in} - i_{out} = c_p(T_{in}-T_{out})}$

- The best example of an open system is a heat exchanger
  - normally there is no external work done on or by a heat exchanger, and changes in kinetic and potential energy are negligible
  - The 1st Law simplifies to:

$$(1.11e)\qquad q=\dot{m}\Delta i=\dot{m}c_p\left(T_{out}-T_{in}\right)$$

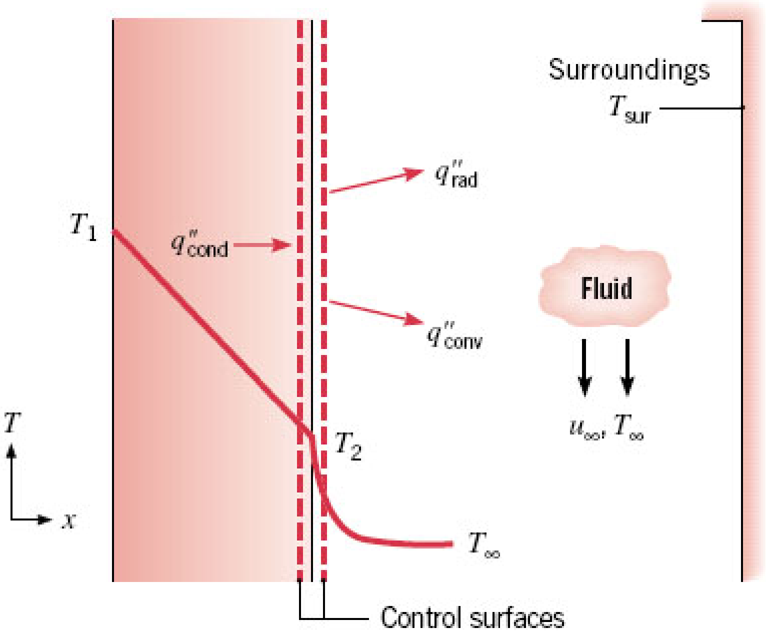
2nd Law of Thermodynamics

- No process is possible whose sole result is the net transfer of heat from a region of lower temperature to a region of higher temperature
- In simple words, the 2nd Law of Thermodynamics in heat transfer determines the direction of heat flow

Surface energy balances

- Surface has no volume
  - Energy cannot be generated or stored within the surface
  - $\dot{E}_g = \dot{E}_{st} = 0$
- Whether or not the system is at steady state, the 1st Law for a surface is expressed by:

$$\dot{E}_{in} - \dot{E}_{out} = 0 \qquad (1.12)$$

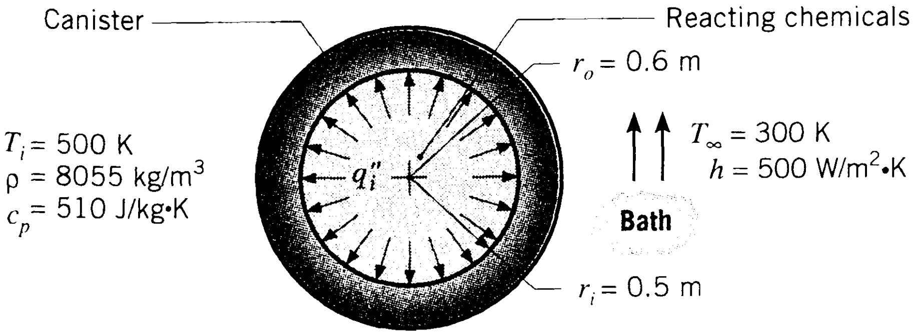


- Application of surface energy balance – evaluation of surface temperature
  - Applying Eq. (1.12) to the figure →
  - Each term can then be expressed using the rate equations

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

Example 2

A spherical, metal canister is used to store reacting chemicals that provide for a uniform heat flux to its inner surface. The canister is suddenly submerged in a liquid bath of temperature $T_\infty < T_i$, where T_i is the initial temperature of the canister wall.



a) Assuming negligible temperature gradients in the canister wall and a constant heat flux , develop an equation that governs the variation of the wall temperature with time during the transient process. What is the initial rate of change of the wall temperature if $q_i'' = 10^5$ W/m^2?

b) What is the steady-state temperature of the wall?

Summary – Part 1

- Heat transfer occurs between systems at different temperatures
  - Three modes of heat transfer: **conduction**, **convection**, **radiation**
  - Heat flux determined by **rate equations** specific to each mode

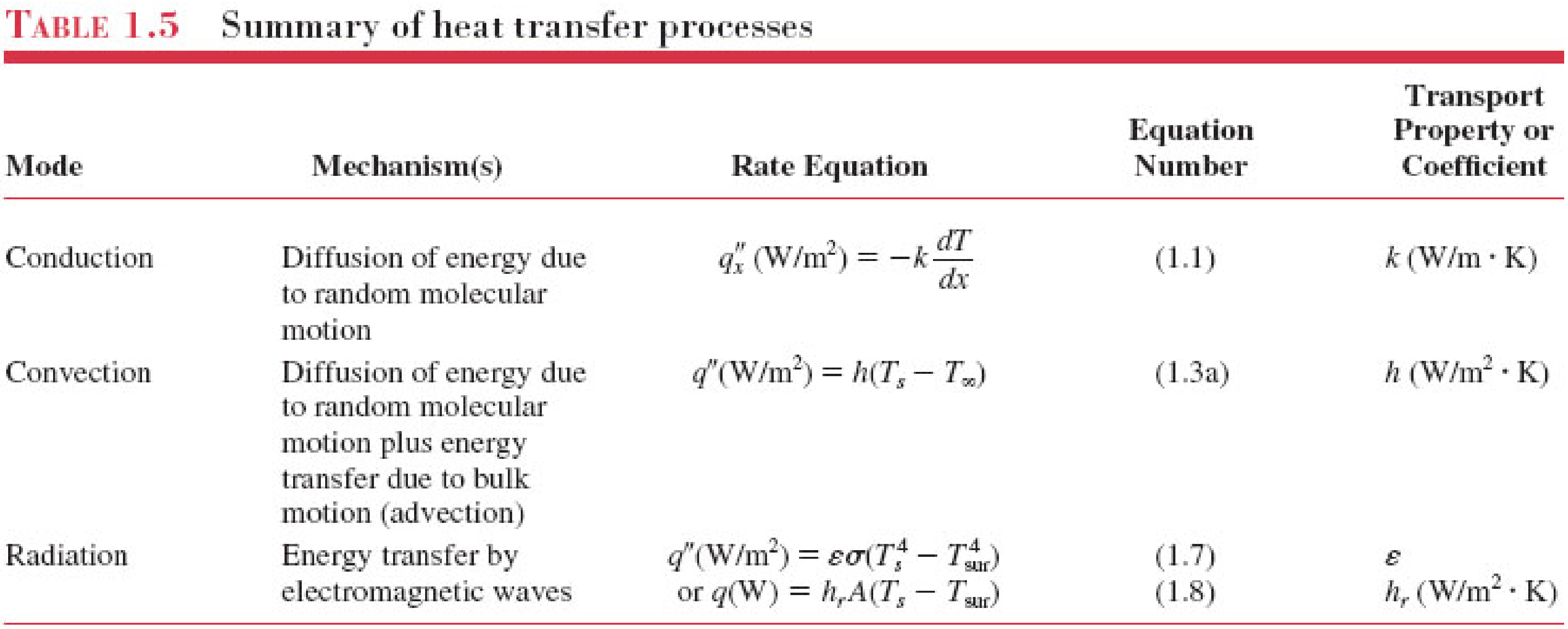


TABLE 1.5 Summary of heat transfer processes

Mode	Mechanism(s)	Rate Equation	Equation Number	Transport Property or Coefficient
Conduction	Diffusion of energy due to random molecular motion	$q''_x\ (\mathrm{W/m^2}) = -k\dfrac{dT}{dx}$	(1.1)	$k\ (\mathrm{W/m \cdot K})$
Convection	Diffusion of energy due to random molecular motion plus energy transfer due to bulk motion (advection)	$q''(\mathrm{W/m^2}) = h(T_s - T_\infty)$	(1.3a)	$h\ (\mathrm{W/m^2 \cdot K})$
Radiation	Energy transfer by electromagnetic waves	$q''(\mathrm{W/m^2}) = \varepsilon\sigma(T_s^4 - T_{\mathrm{sur}}^4)$ or $q(\mathrm{W}) = h_r A(T_s - T_{\mathrm{sur}})$	(1.7) (1.8)	ε $h_r\ (\mathrm{W/m^2 \cdot K})$

Summary Part 1

- First Law of Thermodynamics lets us define **energy balances** for systems
  - Includes energy inflow, outflow, generation, storage
  - **Control surfaces** define the system boundaries
  - Ways energy can cross the boundaries depend on whether the system is **open** (mass can cross the boundary) or **closed**
  - Special case: **surface energy balance**, no generation or storage
- **Combination of energy balance and rate equations used to analyze heat transfer problems**