Modes or Mechanisms of Heat Transfer

Basic Concepts and Laws

Introduction

- The transfer of energy in the form of heat occurs in many chemical and other types of processes.
- Heat transfer often occurs in combination with other separation processes, such as drying, distillation, burning fuel, and evaporation.
- The heat transfer occurs because of a temperature-difference driving force and heat flows from the high- to the low-temperature region.

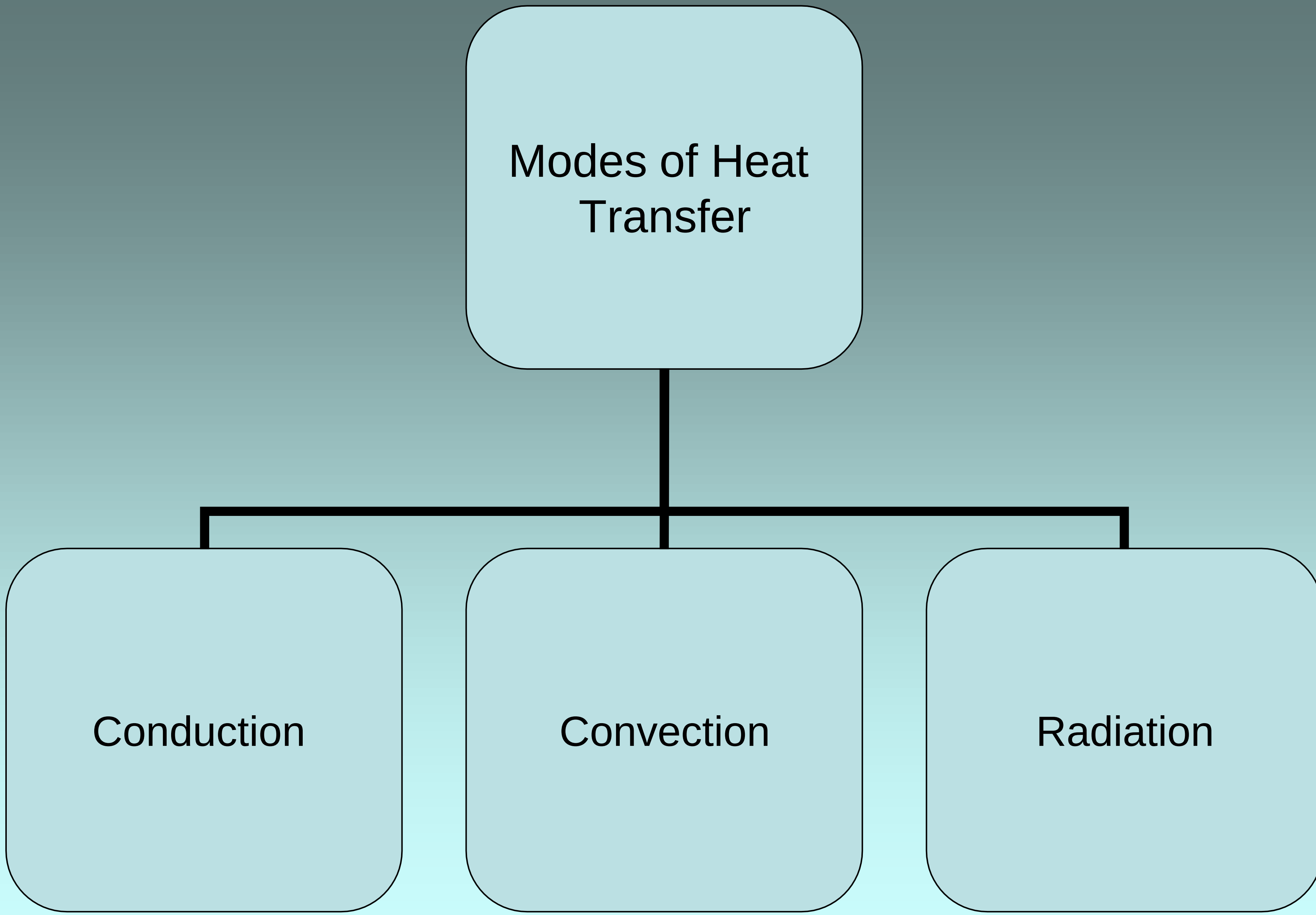
Heat

Sensible

$$Q = m\, c_p\, \Delta T$$

Latent

$$Q = m\, \lambda$$

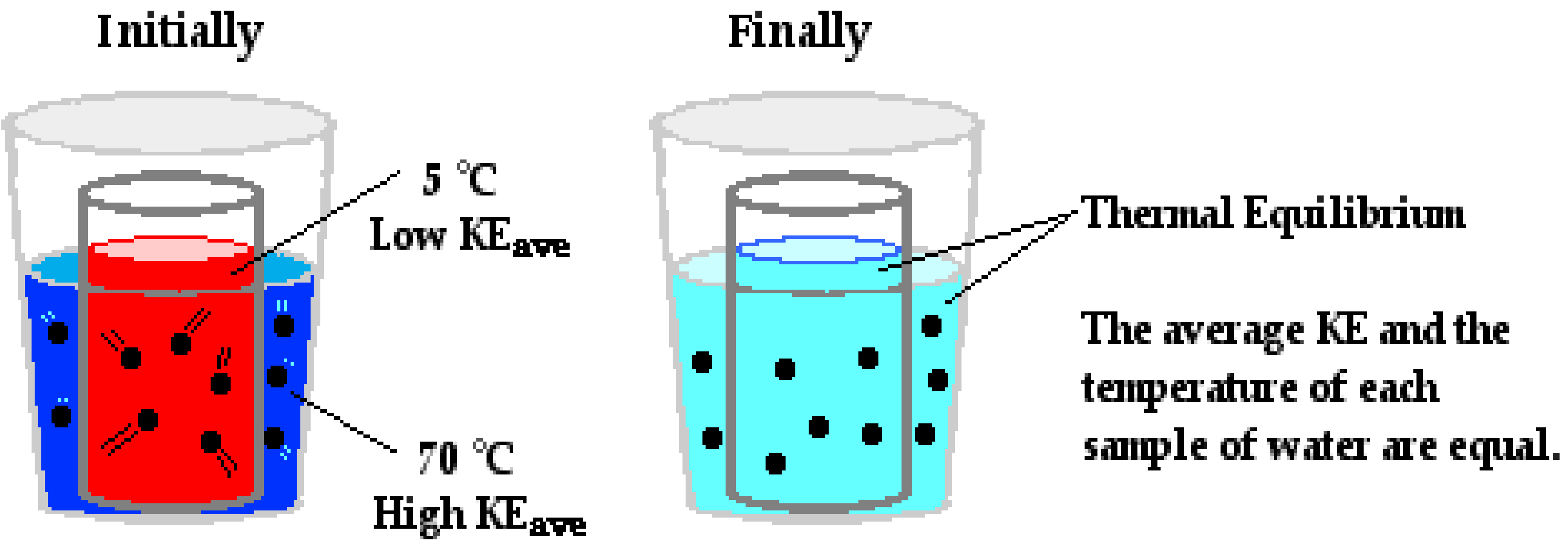

Modes of Heat Transfer
Conduction
Convection
Radiation

Conduction

- When heat is transferred by the energy of motion between adjacent molecules, heat transfer by conduction is said to take place.
- Conduction is transport of heat by statistical molecular movement, i.e. medium is stationary.
- This type takes place in solids and fluids in rest.
- In gases, molecules which have greater energy and motion ‘hotter molecules’ impart energy to the adjacent molecules which are at lower energy levels.
- In solids and liquids the previous mechanism also takes place. Moreover, in metallic solids, heat transfer takes place by ‘free electrons’.

Kinetic Energy

- ✓Vibrating K.E
- ✓Translation K.E



Kinetic Energy

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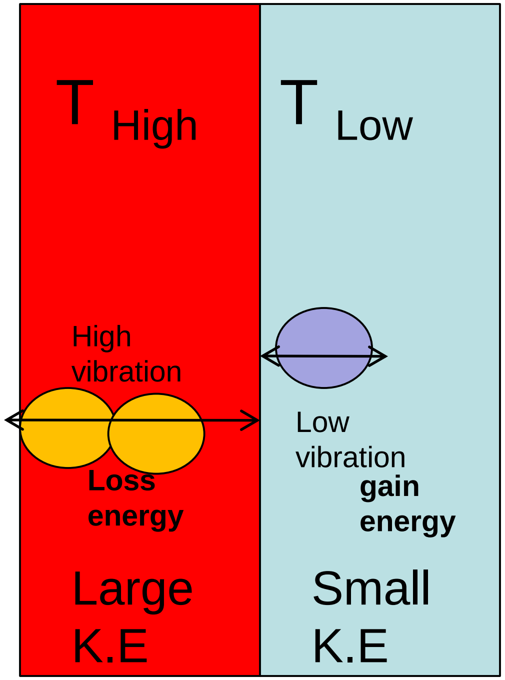
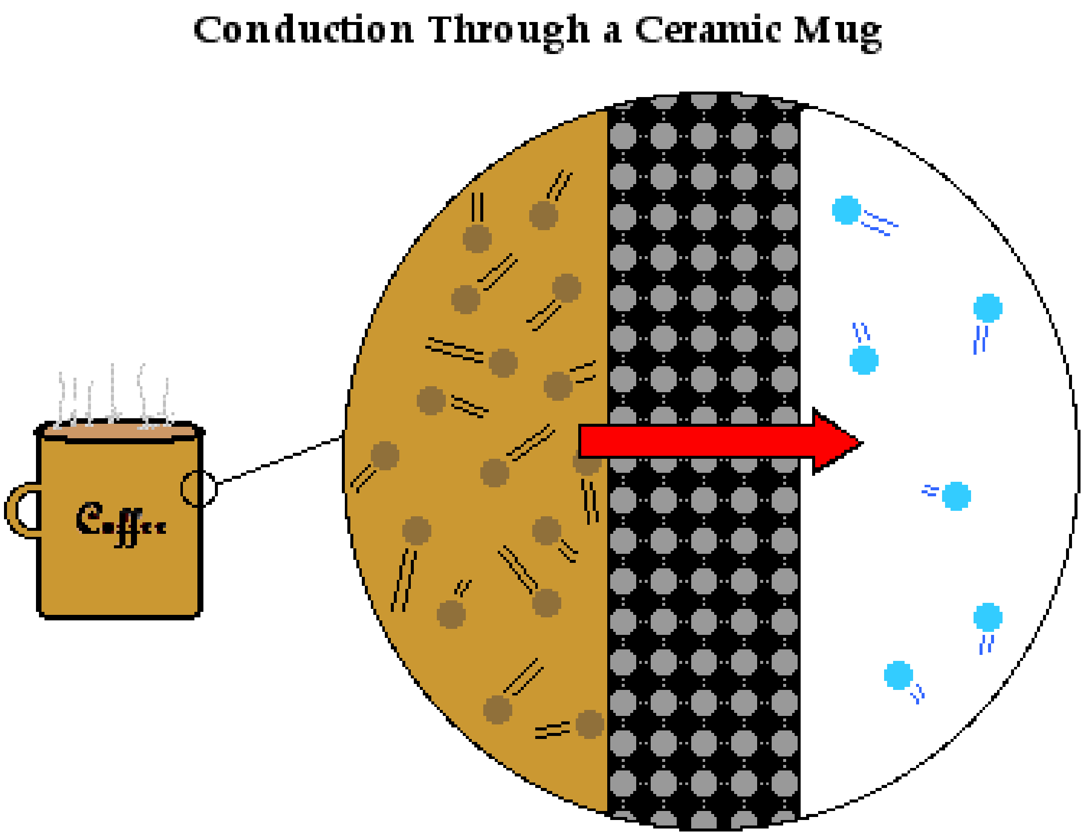


2 metal Blocks at different temperatures

Conduction Through The Bulk of an Object



Coffee particles with a higher average kinetic energy collide with the container wall and transmit their energy to the surroundings.

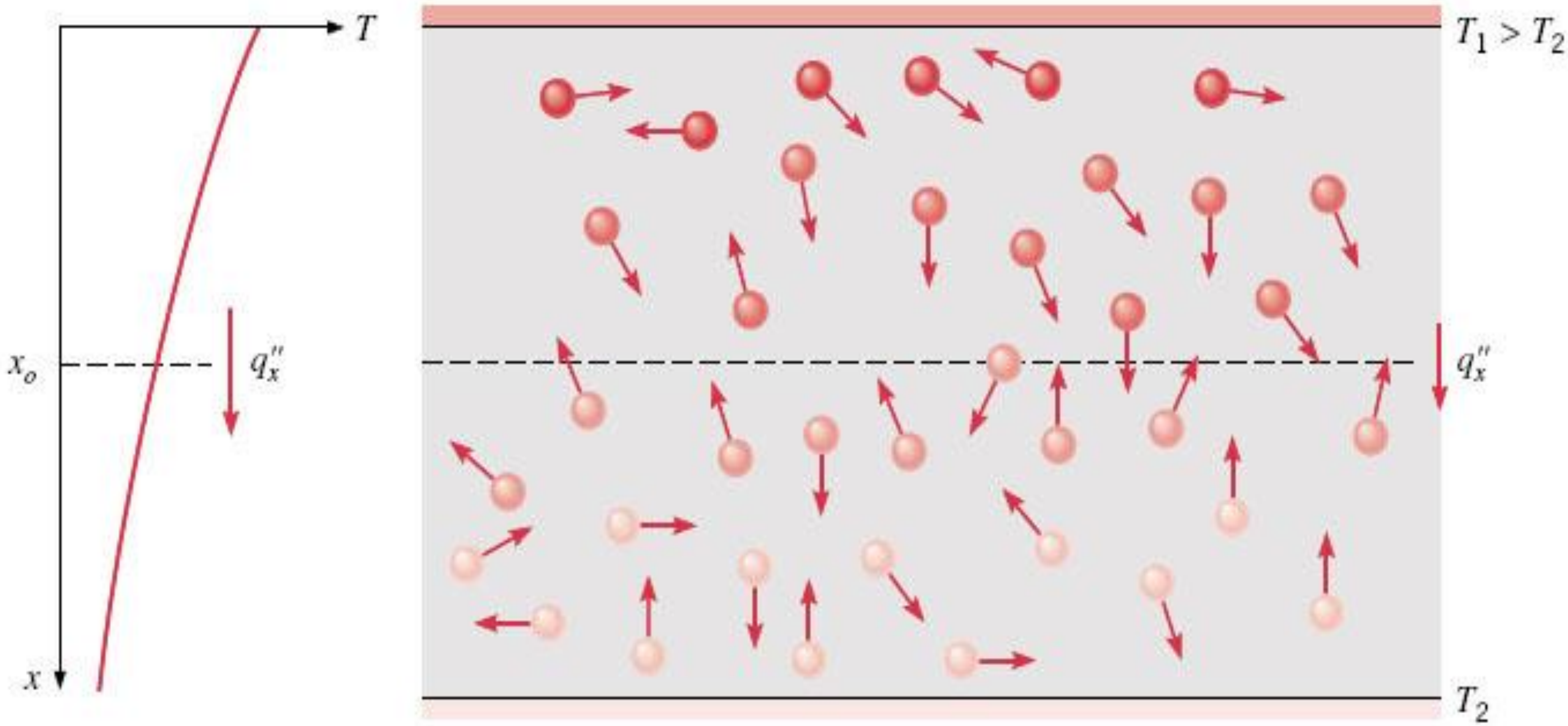
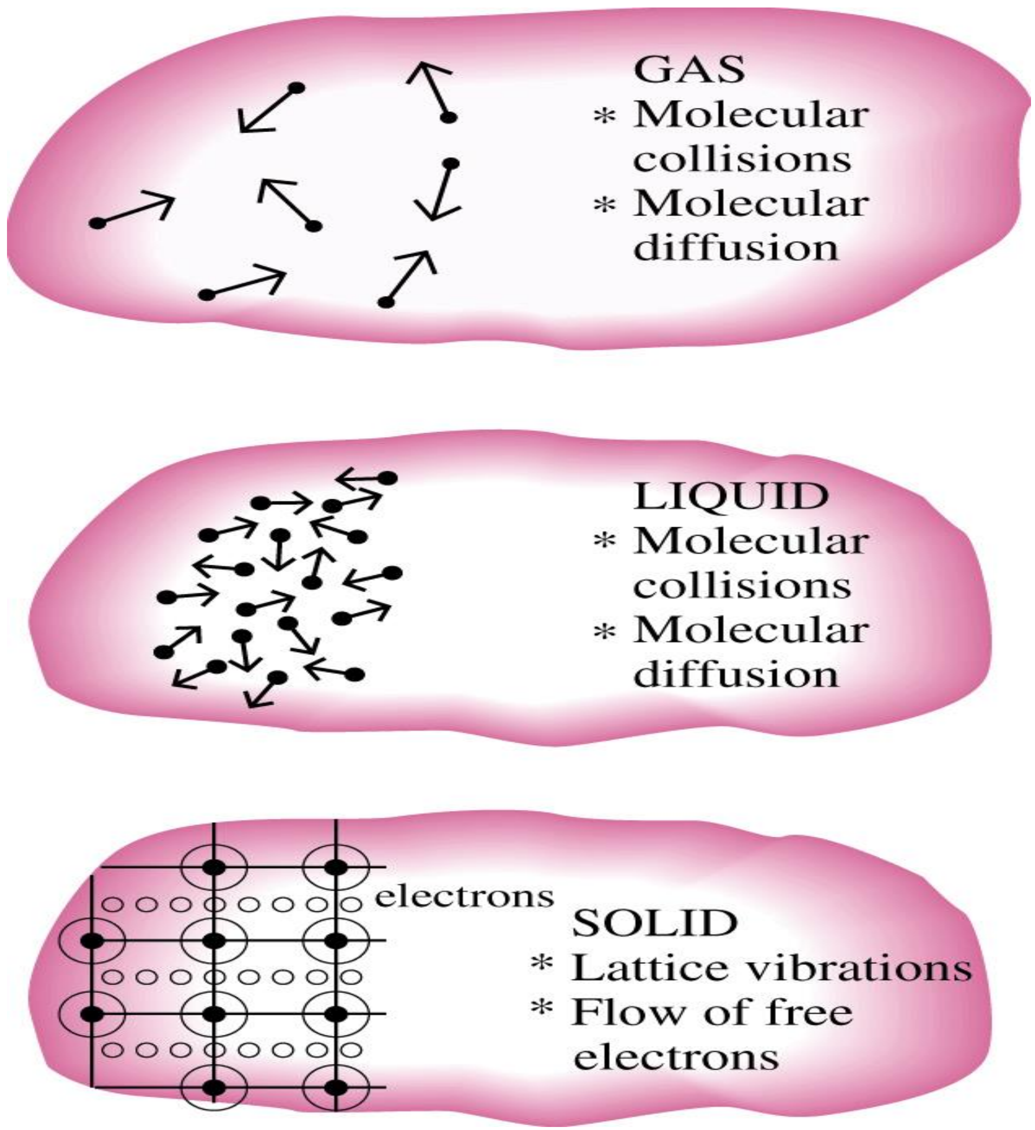


FIGURE 1.2 Association of conduction heat transfer with diffusion of energy due to molecular activity.

Conduction

The mechanisms of heat conduction in different phases of a substance



Convection

- It takes place through bulk transport and the mixing of macroscopic hot and cold particles of a fluid.
- It also includes the transfer of heat between a solid surface and a fluid.
- Convection heat transfer is of two parts:

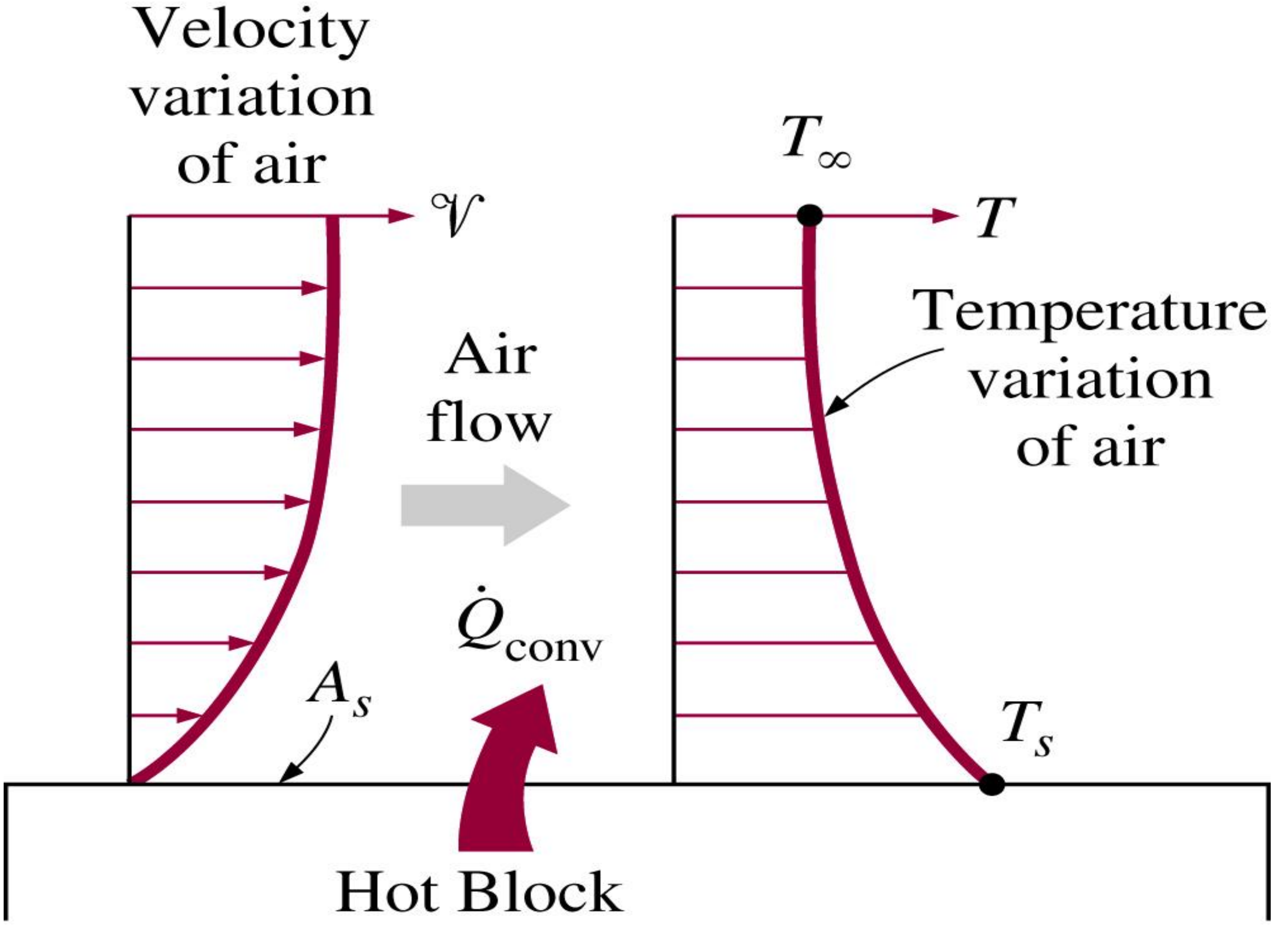
  i) forced convection heat transfer, where fluid is forced over a surface by any mechanical means (such as pumps, compressors and fans).

ii) Natural or free convection i.e driven by density differences resulting from (buoyancy forces) temperature gradient.

- In either case, convection may be turbulent or laminar depending on conditions.
- Examples of heat transfer by convection are:

1. Cooling or heating of fluids in heat exchangers
2. Cooling of cup of coffee by blowing over the surface.
3. Baking a cake in a gas oven.

Convection
Heat transfer from a hot surface to air by convection



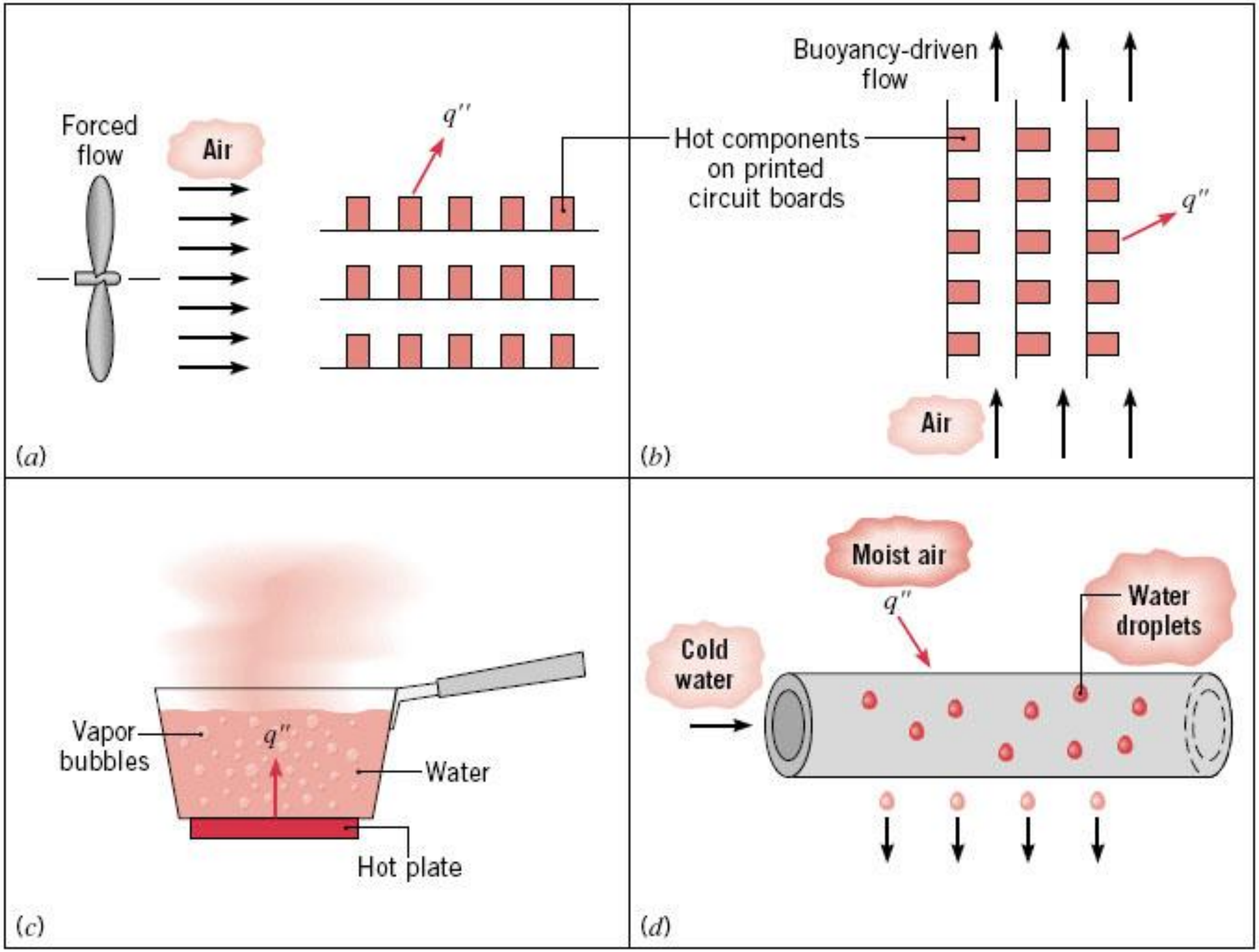


FIGURE 1.5 Convection heat transfer processes. (*a*) Forced convection. (*b*) Natural convection. (*c*) Boiling. (*d*) Condensation.

Radiation

- Radiation is a transport of heat by electromagnetic waves; similar to the transport of electromagnetic light waves .
- No physical medium is required. It can take place in a vacuum.
- Hence, radiation heat transfer is governed by the same laws that govern the transfer of light.
- Solids and liquids have the tendency to absorb the radiation that is being transferred through them, therefore, radiation is of primary importance in the transfer of heat through gases and space.

- Examples of radiation heat transfer are:

I. The transfer of heat from the sun to the earth.

II. Cooking of food over electric coil radiators.

III. Heating of tubes in a furnace.

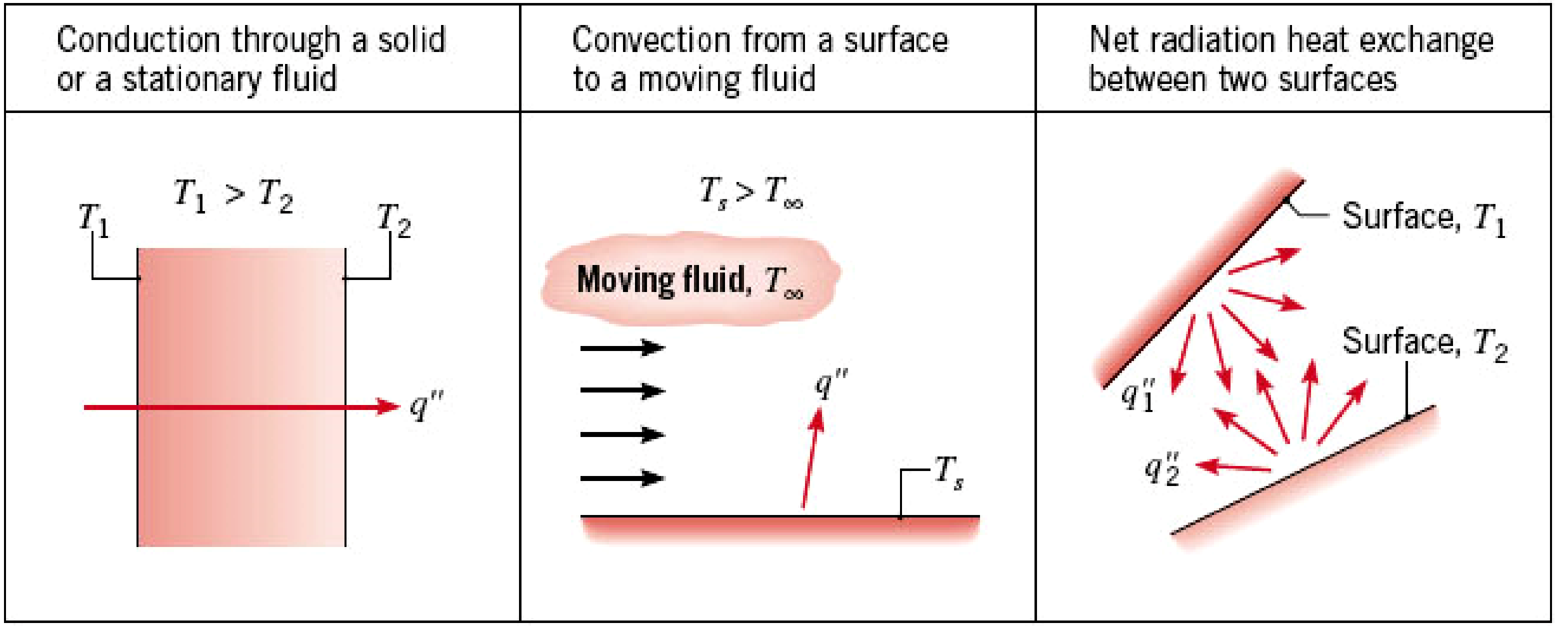


FIGURE 1.1 Conduction, convection, and radiation heat transfer modes.

- Conduction and radiation are the two basic modes of heat flow; convection can be regarded as conduction with fluid in motion.

- It is very difficult to completely isolate one mechanism from the others. But if one mode is dominant, the others may be neglected.

Rate Equations

Conduction

- Fourier's Law

❑ The rate equation of heat transfer by conduction cannot be derived from the first principles. However, it is based on experimental observations made by Biot and named after Fourier.

❑ The Fourier law states that the rate of heat flow by conduction in a given direction is proportional to:

a) the gradient of temperature in that direction, dT/dx

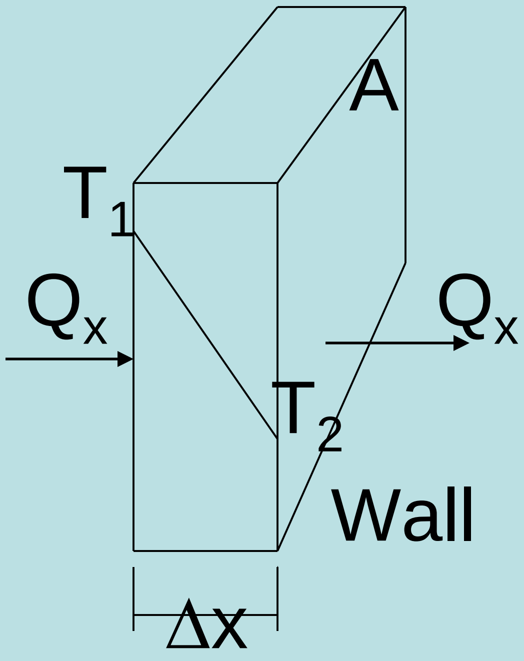
b) the area normal to the direction of heat flow, A

Then

$$q_x = -k\,A\,\frac{dT}{dx}$$

Where k is the proportionality constant called the thermal conductivity.

<u>For 'S.S' linear temp. gradient</u>



$$Q_x = -k\ A\ \Delta T/\Delta x$$

$$Q_x = k\ A\ (T_1 - T_2)/\Delta x$$

Or

$$q''_x = k\ (T_1 - T_2)/x$$

Where q''_x is the heat flux or the heat rate per unit area

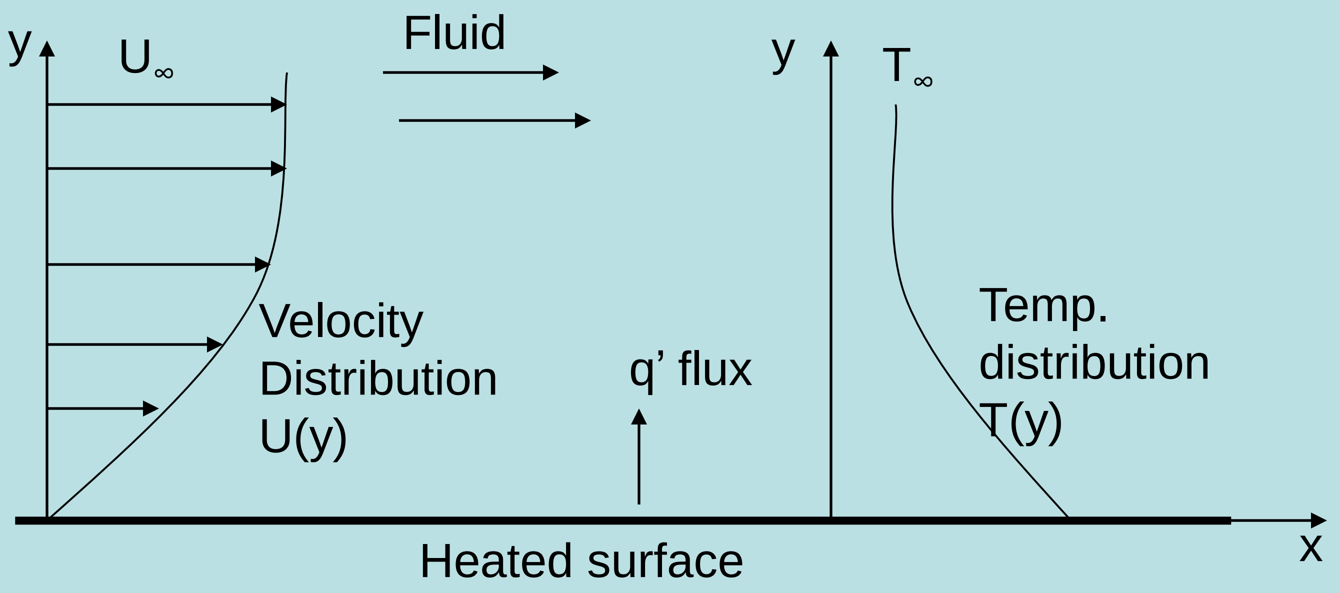
Problem 1

The wall of an industrial furnace is constructed from 0.15-m-thick fireclay brick having a thermal conductivity of 1.7 W/m · K. Measurements made during steady-state operation reveal temperatures of 1400 and 1150 K at the inner and outer surfaces, respectively. What is the rate of heat loss through a wall that is 0.5 m 1.2 m on a side?

Try to solve the problem

Convection

Boundary layer developed in convection heated transfer



The rate of heat flow for a cold fluid, T_∞ passes over a hot surface, T_s as shown in the previous figure is given by:

$$Q = h\,A\,(T_s - T_\infty)$$

Or the convection Heat Flux, q'' , is

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

The previous expression is known as *Newton's law of cooling*, and the parameter h is termed the *convection heat transfer coefficient*.

In general, the determination of h is a very complex problem because h is affected by:

1. The type of flow i.e laminar, turbulent or transitional.
2. The geometry of the body.
3. The physical properties of fluid.
4. The temperature difference.
5. The position a long the surface of the body.
6. Whether the mechanism is forced or free.

Note: h is found experimentally or analytically (for simple shapes)

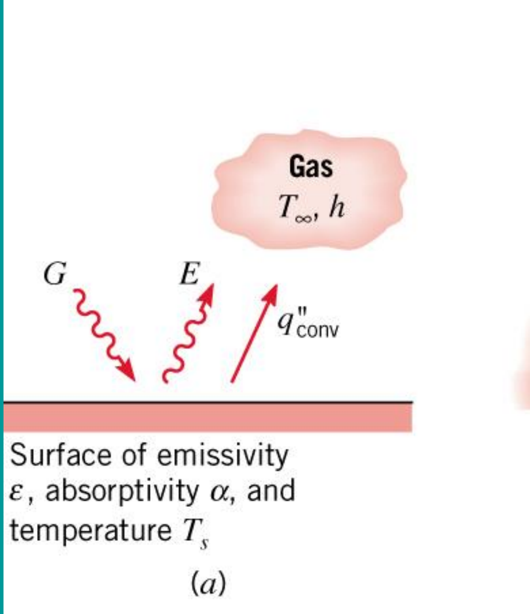
Mean value of h

Since h varies with the position along the surface of the body, for simplicity its mean value over the surface is considered.

Typical values of h

Process	**h, W/m² .K**
Free convection	
Gases	2 - 25
Liquid	50 – 1000
Forced convection	
Gases	25 - 250
Liquid	100 -20,000
Convection with phase change Boiling or condensation	2500 -100,000

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 $\left(5.67\times10^{-8}\,\mathrm{W/m^2 \cdot K^4}\right)$

Energy absorption due to irradiation:

$$G_{abs} = \alpha G$$

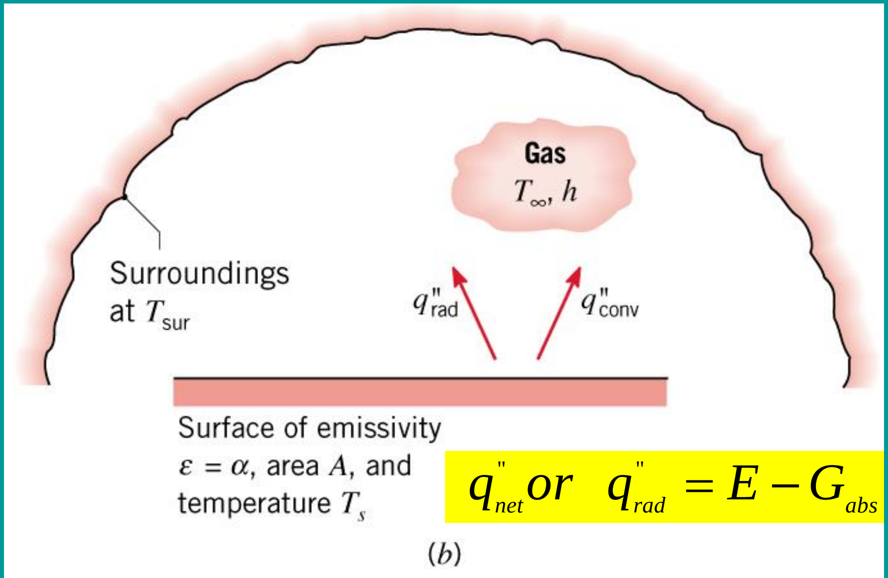
G_{abs} : Absorbed incident radiation $(\mathrm{W/m^2})$

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}



$$q''_{net} \; or \;\; q''_{rad} = E - G_{abs}$$

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

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,

$$q''_{rad} = \mathrm{h}_r \left(T_s - T_{sur}\right) \tag{1.8}$$

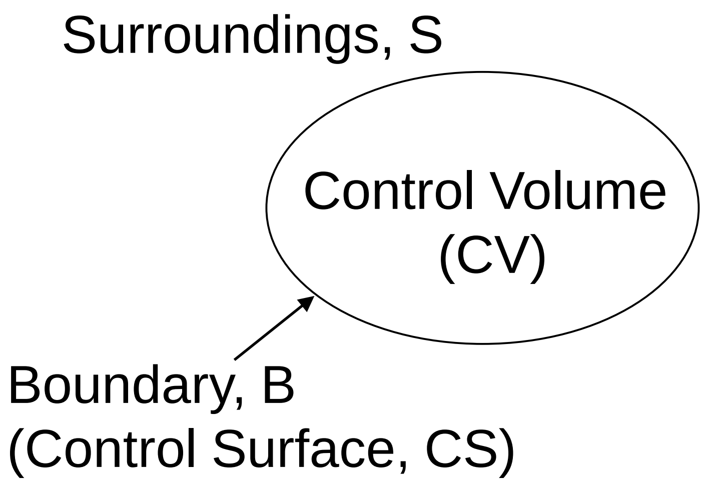
h_r: Radiation heat transfer coefficient $\left(\mathrm{W/m^2 \cdot K}\right)$

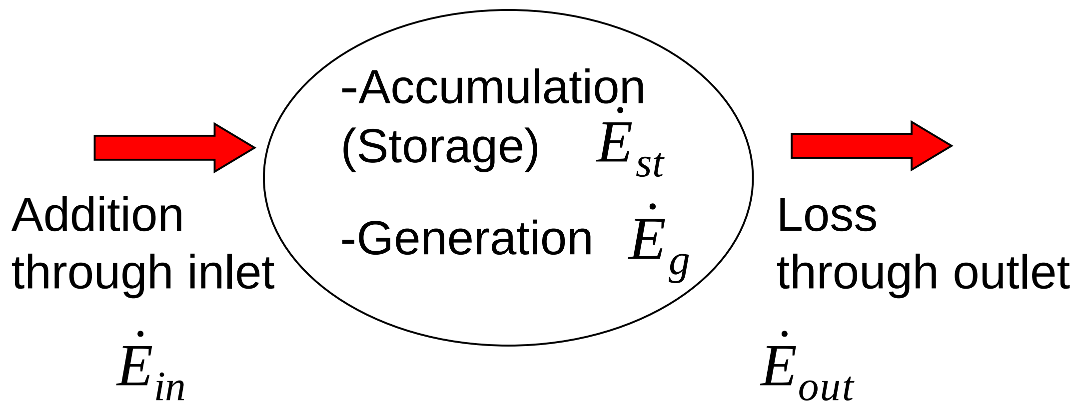
$$\mathrm{h}_r = \varepsilon\sigma\left(T_s + T_{sur}\right)\left(T_s^2 + T_{sur}^2\right) \tag{1.9}$$

For combined convection and radiation,

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

Conservation of Energy





- Energy conservation on a rate basis:

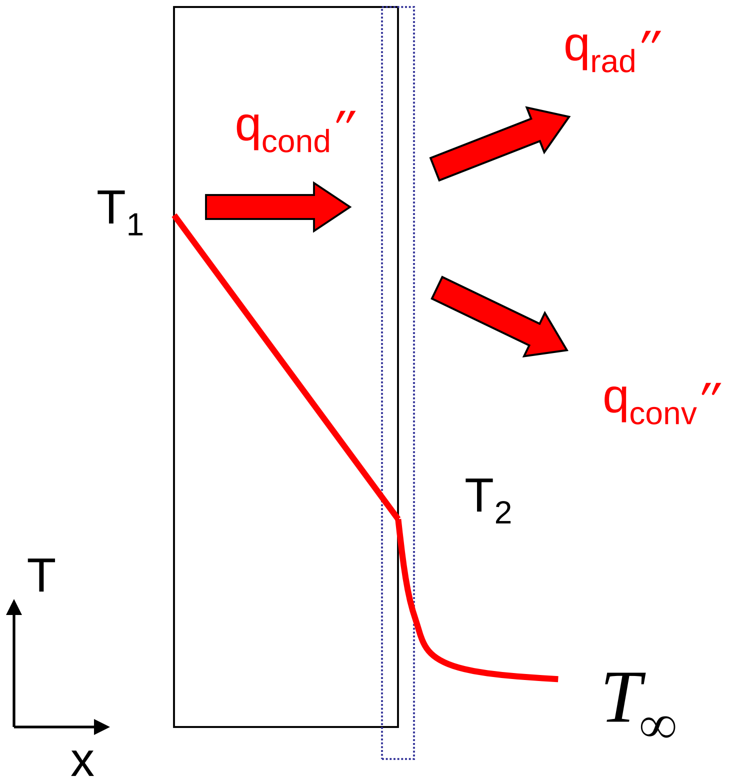
$$\dot{E}_{in} + \dot{E}_g - \dot{E}_{out} = \frac{dE_{st}}{dt} = \dot{E}_{st}$$

Units W=J/s

- ➢ Inflow and outflow are surface phenomena
- ➢ Generation and accumulation are volumetric phenomena

Surface Energy Balance

For a control surface:



$$\dot{E}_{in} - \dot{E}_{out} = 0$$

or

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

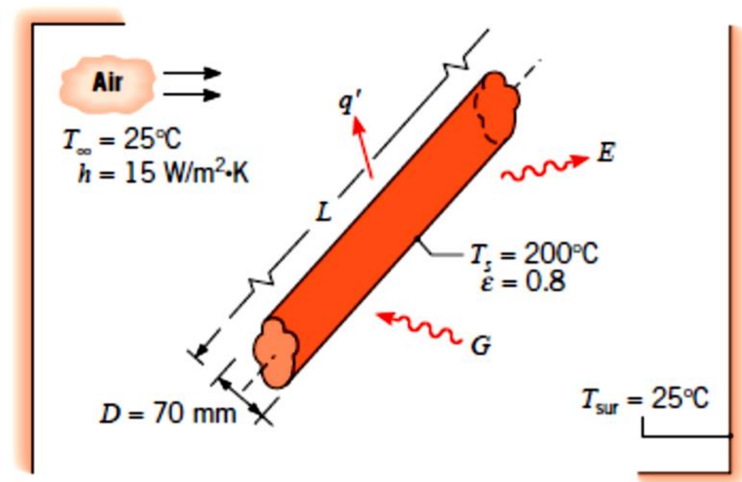
Problem 2

An uninsulated steam pipe passes through a room in which the air and walls are at 25 ° C. The outside diameter of the pipe is 70 mm, and its surface temperature and emissivity are 200 ° C and 0.8, respectively. What are the surface emissive power and irradiation? If the coefficient associated with free convection heat transfer from the surface to the air is 15 $W/m^2 \cdot K$, what is the rate of heat loss from the surface per unit length of pipe?

Solution

Assumptions:

1. Steady-state conditions.
2. Radiation exchange between the pipe and the room is between a small surface and a much larger enclosure.
3. The surface emissivity and absorptivity are equal.



The surface emissive power may be evaluated from Eq. $E = \varepsilon\sigma T_s^4$, while the irradiation corresponds to $G = \sigma T^4_{sur}$. Hence

Try to complete the solution

Continue solution

Heat loss from the pipe is by convection to the room air and by radiation exchange
with the walls. Hence, $q = q_{conv} + q_{rad}$ and with $A = \pi DL$,

$$q = h(\pi DL)(T_s - T_\infty) + \varepsilon(\pi DL)\sigma(T_s^4 - T_{sur}^4)$$

Try to complete the solution