WELCOME

HEAT TRANSFER & MASS TRANSFER

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INTRODUCTION

- Several important chemical engineering concepts in Bioprocess Engineering are transport phenomena (fluid flow, mixing, heat and mass transfer), unit operations, reaction engineering, and bioreactor engineering.

INTRODUCTION

- Metabolic activity of cells generates a substantial amount of heat in fermenters; this heat must be removed to avoid temperature increases.
- Most fermentations take place in the range 30-37°C in large-scale operations, cooling water is used to maintain the temperature usually to within 1°C.
- Small-scale fermenters have different heat exchange requirements; because the external surface area to volume ratio is much greater and heat losses through the wall of the vessel more significant, laboratory-scale units often require heating rather than cooling.
- Many enzyme reactions also require heating to maintain optimum temperature.

TWO TYPES OF COMMON HEAT TRANSFER APPLICATION IN BIOREACTOR OPERATION

- In situ batch sterilization of liquid medium.
- In this process, the fermenter vessel containing medium is heated using steam and held at the sterilization temperature for a period of time; cooling water is then used to bring the temperature back to normal operating conditions
- Temperature control during reactor operation. Metabolic activity of cells generates heat. Some microorganisms need extreme temperature conditions (e.g. psycrophilic, thermophilic microorganisms)

EQUIPMENT USED FOR HEAT EXCHANGE IN BIOREACTORS

- Jacketed vessel, external coil, internal helical coil, internal baffle-type coil, and external heat exchanger.
- External jacket and coil give low heat transfer area. Thus, they are rarely used for industrial scale.
- Internal coils are frequently used in production vessel; the coils can be operated with liquid velocity and give relatively large heat transfer area. But the coil interfere with the mixing in the vessel and make cleaning of the reactor difficult. Another problem is film growth of cells on the heat transfer surface.
- External heat exchanger unit is independent of the reactor, easy to scale up, and provide best heat transfer capability.

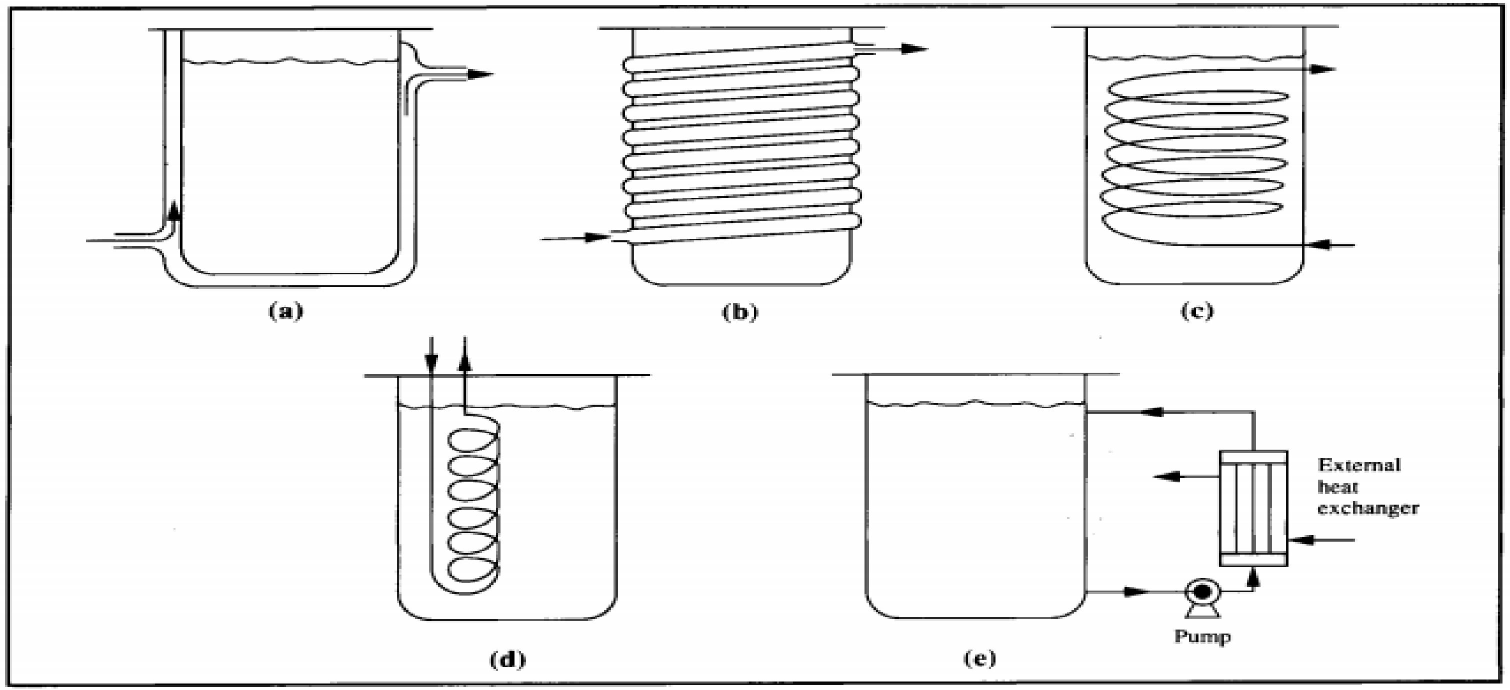
HEAT EXCHANGERS IN FERMENTATION PROCESSES

- Double-pipe heat exchanger
- Shell and tube heat exchanger
- Plate heat exchanger
- Spiral heat exchanger

HEAT EXCHANGERS IN FERMENTATION PROCESSES

- The fermenter may have an external jacket (Figure a) or coil (Figure b) through which steam or cooling water is circulated.
- Alternatively, helical (Figure c) or baffle (Figure d) coils may be located internally. Another method is to pump liquid from the reactor through a separate heat-exchange unit (Figure e).

Figure 8.1 Heat-transfer configurations for bioreactors: (a) jacketed vessel; (b) external coil; (c) internal helical coil; (d) internal baffle-type coil; (e) external heat exchanger.



MECHANISMS OF HEAT TRANSFER

- Heat transfer occurs by one or more of the following three mechanisms.
- **(i)Conduction.** Heat conduction occurs by transfer of vibrational energy between molecules, or movement of free electrons. Conduction is particularly important with metals and occurs without observable movement of matter.
- **(ii) Convection.** Convection requires movement on a macroscopic scale; it is therefore confined to gases and liquids. Natural convection occurs when temperature gradients in the system generate localised density differences which result in flow currents. In forced convection, flow currents are set in motion by an external agent such as a stirrer or pump and are independent of density gradients. Higher rates of heat transfer are possible with forced convection compared with natural convection.
- **(iii) Radiation.** Energy is radiated from all materials in the form of waves; when this radiation is absorbed by matter it appears as heat. Because radiation is important at much higher temperatures than those normally encountered in biological processing, it will not be mentioned further.

MASS TRANSFER

- Mass transfer occurs in mixtures containing local concentration variations.
- Mass-transfer processes are responsible for movement of molecules through the water until equilibrium is established and the concentration is uniform.
- Mass is transferred from one location to another under the influence of a concentration difference or concentration gradient in the system.
- There are many situations in bioprocessing where concentrations of compounds are not uniform; we rely on mechanisms of mass transfer to transport material from regions of high concentration to regions where the concentration is low.
  - Ex. -supply of oxygen in fermenters for aerobic culture ,
  - extraction of penicillin from fermentation liquor using organic solvents such as butyl acetate.

MASS TRANSFER

- Mass transfer plays a vital role in many reaction systems.
- When distance between the reactants and site of reaction is greater, rate of mass transfer is more likely to influence or control the conversion rate.
- Such as oxygen transfer i.e. gas –liquid mass transfer.
- Liquid-solid mass transfer can also be important in systems containing clumps, pellets, flocs or films of cells or enzymes.
- In these cases, nutrients in the liquid phase must be transported into the solid before they can be utilized in reaction.
- Unless mass transfer is rapid, supply of nutrients will limit the rate of biological conversion .
- In a solid or quiescent fluid, mass transfer occurs as a result of molecular diffusion.
- In different circumstances , convective mass transfer occurs.

MOLECULAR DIFFUSION

- Molecular diffusion is the movement of component molecules in a mixture under the influence of a concentration difference in the system.
- Diffusion of molecules occurs in the direction required to destroy the concentration gradient.
- If the gradient is maintained by constantly supplying material to the region of high concentration and removing it from the region of low concentration, diffusion will be continuous.
- The rate of diffusion can be enhanced by increasing
  - the area available for mass transfer,
  - the concentration gradient in the system,
  - and the magnitude of the diffusion coefficient.

DIFFUSION THEORY

- In single-phase systems, the rate of mass transfer due to molecular diffusion is given by Fick's law of diffusion .
- It states that mass flux is proportional to the concentration gradient.

$$J_A = -D_{AB} \frac{dC_A}{dy}$$

- J_A is the mass flux of component A
- C_A is the concentration of component A, and y is distance, dC_A / dy is the concentration gradient, or change in concentration of A with distance.
- The negative sign in above equation indicates that the direction of mass transfer is always from high concentration to low concentration, opposite to that of the concentration gradient.
- The diffusion coefficient D_{AB} is binary diffusion coefficient or diffusivity of component A in a mixture of A and B.
- Its value depends on concentration of both A & B as well as temperature , pressure.
- for example, diffusivity of carbon dioxide in water will be different from the diffusivity of carbon dioxide in another solvent such as ethanol .

Role of Diffusion in Bioprocessing

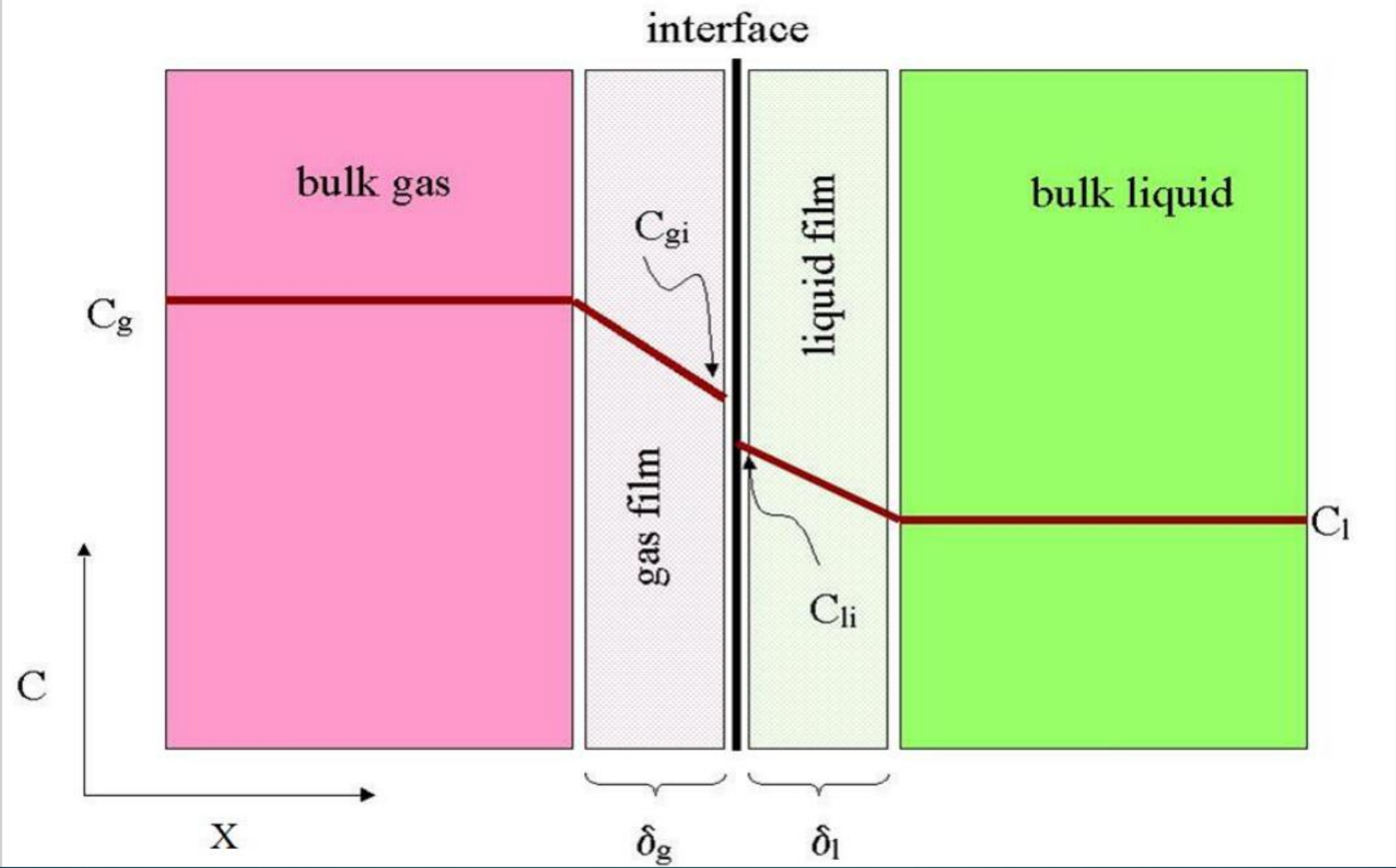
- Fluid mixing is carried out in most industrial processes where mass transfer takes place.
- Areas of bio processing in which diffusion plays a major role are—
- (i) Scale of mixing--Mixing on a molecular scale relies on diffusion as the final step in the mixing process.
- (ii) Solid-phase reaction.-- When cells or enzyme molecules are clumped together into a solid particle, substrates must be transported into the solid before reaction can take place.
- (iii) Mass transfer across a phase boundary. --Mass transfer between phases occurs often in bioprocessing. Oxygen transfer from gas bubbles to fermentation broth, penicillin recovery from aqueous to organic liquid, and glucose transfer from liquid medium into mould pellets are typical examples. When different phases come into contact, fluid velocity near the phase interface is significantly decreased and diffusion becomes crucial for mass transfer across the phase interface.

The two film theory

- In many cases with gas-liquid transfer we have transfer considerations from both sides of the interface. Therefore, we use the Lewis Whitman (1923) two-film model as described below.

THE TWO FILM THEORY

- The two film theory is a useful model for mass transfer between phase.
- Mass transfer of solute from one phase to another involves transport from bulk of one phase to the interface, and then from the interface to the bulk of the second phase.
- This theory is based on idea that a fluid film or mass transfer boundary layer forms whenever there is contact between two phases.
- According to film theory, mass transfer through the film is solely by molecular diffusion and is the major resistance


interface
bulk gas
gas film
liquid film
bulk liquid
C_{gi}
C_g
C_{li}
C_l
C
X
δ_g
δ_l

The same assumptions apply to the two films as apply in the single Nernst film model. The problem, of course, is that we will now have difficulty in finding interface concentrations, C_{gi} or C_{li}. We can assume that equilibrium will be attained at the interface (gas solubilization reactions occur rather fast), however, so that:

$$C_{li} = \frac{C_{gi}}{H_c}$$

A steady-state flux balance (okay for thin films) through each film can now be performed. The fluxes are given by:

$$J = k_l(C_l - C_{li})$$

and

$$J = k_g(C_{gi} - C_g)$$

assuming that the flux is in the **X** direction, in other words from bulk gas phase to bulk liquid phase.

- Unfortunately, concentrations at the interface cannot be measured so overall mass transfer coefficients are defined.
- These coefficients are based on the difference between the bulk concentration in one phase and the concentration that would be in equilibrium with the bulk concentration in the other phase.

CONVECTIVE MASS TRANSFER

- The term convective mass transfer refers to mass transfer occurring in the presence of bulk fluid motion.
- Molecular diffusion will occur whenever there is a concentration gradient; however if the bulk fluid is also moving, the overall rate of mass transfer will be higher due to the contribution of convective currents.
- Rate of mass transfer is directly proportional to the driving force for transfer, and the area available for the transfer process to take place.
- This can be expressed as:
- Transfer rate $\propto$ (transfer area) × (driving force).
- The proportionality coefficient in this equation is called the mass-transfer coefficient, so that:
- Transfer rate = (mass-transfer coefficient) × (transfer area) × (driving force).

MASS TRANSFER SITUATIONS

- Three mass-transfer situations occur in bioprocessing are
- Liquid-solid mass transfer- Mass transfer between a moving liquid and a solid is important in biological processing in a variety of applications. Transport of substrates to solid-phase cell or enzyme catalysts . The process of dissolving a solid in liquid requires liquid-solid mass transfer directed away from the solid surface
- Liquid-liquid mass transfer between immiscible solvents --Liquid-liquid mass transfer between immiscible solvents is most often encountered in the product-recovery stages of bioprocessing. Organic solvents are used to isolate antibiotics, steroids and alkaloids from fermentation broths; two-phase aqueous systems are used in protein purification. Liquid liquid mass transfer is also important when hydrocarbons are used as substrates in fermentation, e.g. in production of microbial biomass for single-cell protein.
- Gas-liquid mass transfer--Gas-liquid mass transfer is of paramount importance in bioprocessing because of the requirement for oxygen in aerobic fermentations.