5. Filtration

5.1 Filtration Principles

Filtration

- **Filtration**
  - Separation of particulate or solute components in a fluid suspension or solution
  - Separation by size difference
  - Flowing under a pressure differential through a porous medium
- **Types**
  - Conventional or dead-end filtration
    - The fluid flows perpendicular to the medium
    - Results in a cake of solids deposition on the filter medium
    - Used for removal of cells
      - Purification of secreted biomaterials, sterilization
  - Crossflow filtration
    - The fluid flows parallel to the medium
    - Minimization of the buildup of a cake
    - Usage
      - Separation of cells
      - Concentration of cells
      - Removal of cell debris after cell lysis
      - Concentration of protein solutions
      - Exchange or removal of salts in a protein solution
      - Removal of viruses

Types of Filtration

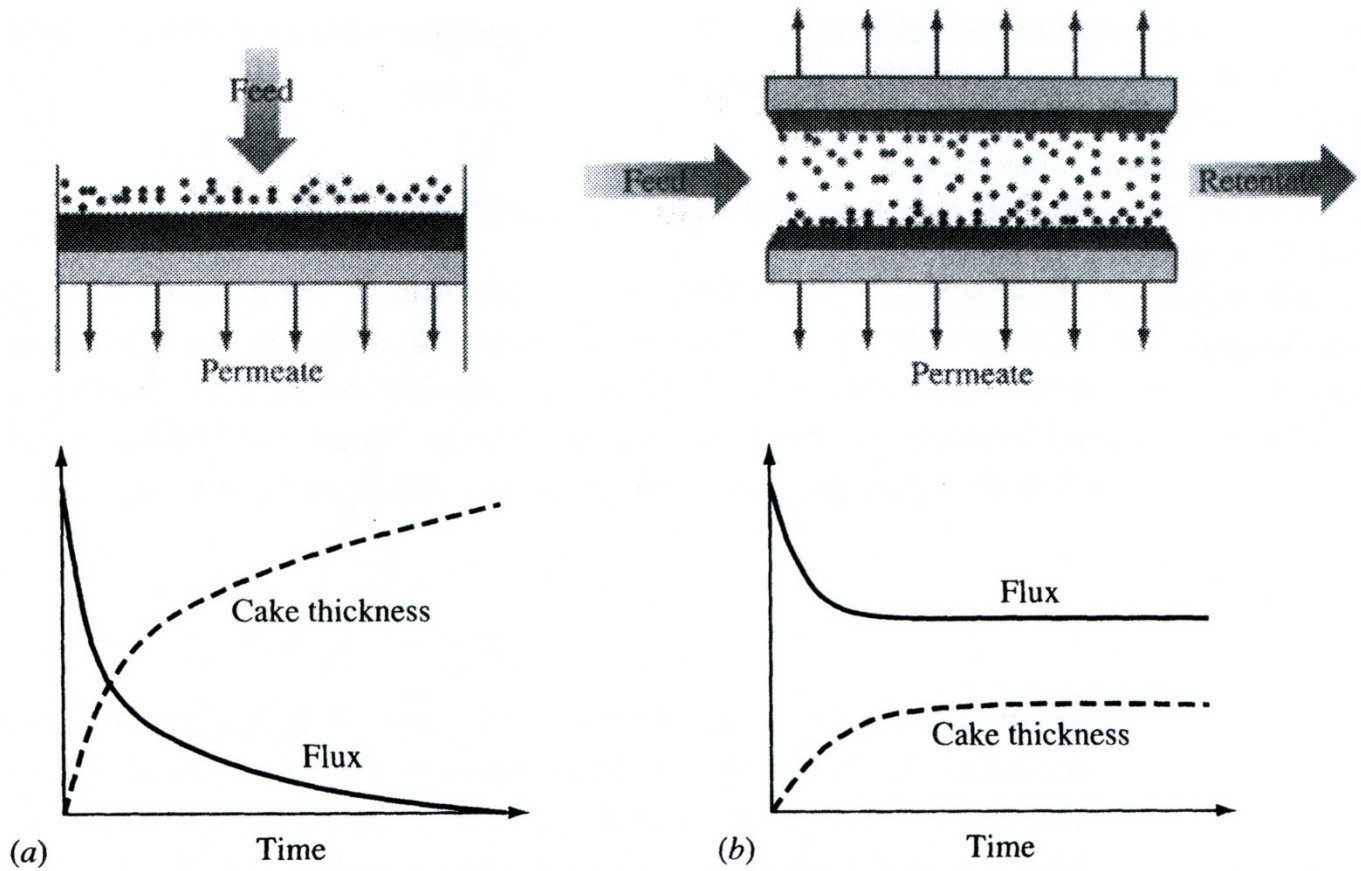


Figure 4.1 Schematic diagrams for (*a*) dead-end or conventional filtration and (*b*) crossflow filtration. For dead-end filtration the thickness of the solids buildup increases and the permeate flux decreases with time, ultimately reaching zero. In crossflow filtration the feed can contain either a soluble or a solid solute, which becomes concentrated at the membrane surface; the permeate flux reaches a constant value at steady state.

5.1.1.Conventional Filtration

- **Darcy's law**
  - $J = 1/A \cdot dV/dt = \Delta p / (\mu_0 R)$ (1)
    - J : transmembrane fluid flux
    - V: volume of filtrate
    - T: time
    - A: cross-sectional area of exposed filter medium
    - Δp: pressure drop through the bed of solids (medium + cake)
    - μ_0 : viscosity of the filtrate
    - R: resistance of the porous bed
  - $R = R_m$ (medium)+ R_c (cake) (2)
  - $R_c = \alpha \rho_c (V/A)$ (3)
    - α : specific cake resistance
    - ρ_c : mass of dry cake solids per volume of filtrate
  - $1/A \cdot dV/dt = \Delta p / \{ \mu_0 [\alpha \rho_c (V/A) + R_m] \}$ (1) + (2) + (3) = (4)
  - Integration of (4)
  - $t/(V/A) = (\mu_0 \alpha \rho_c)/ (2\Delta p) \cdot (V/A) + \mu_0 R_m / \Delta p$

Filtration of *Streptomyces* cells

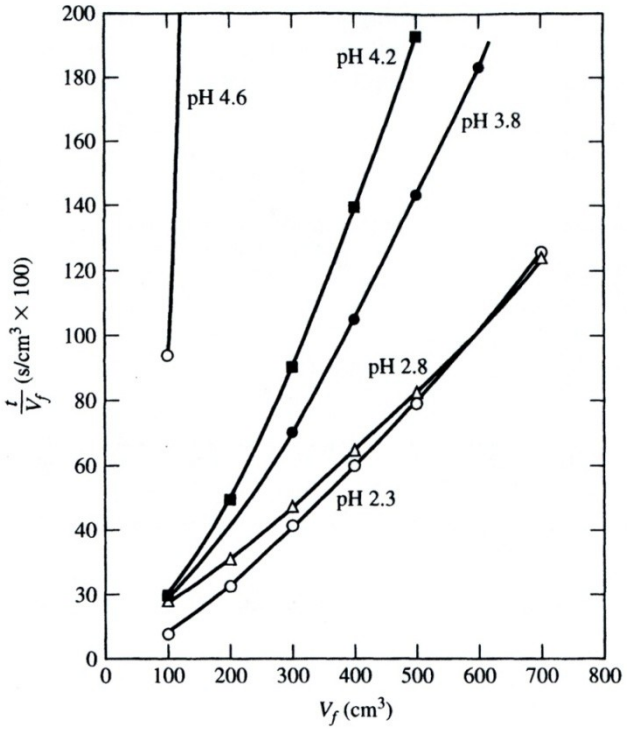


Figure 4.2 Filtration data for *Streptomyces griseus* broth with $\Delta p = 2.0$ bar. The filter medium was of cotton cloth, and diatomaceous earth filter aid was added to the broth. (Data from S. Shirato and S. Esumi, "Filtration of a culture broth of *Streptomyces griseus*" *J. Ferment. Technol. (Japan)*, vol. 41, p. 87, 1963.)

- **t/(V/A) vs. V/A curve**
  - Not perfectly straight
  - Increase in slope with the volume filtered
    - Increase in α as the cake is compressed
- **Specific resistance of cake vs. pressure drop across the cake**
  - $\alpha = \alpha' (\Delta p_c)^s$
    - Δp_c : pressure drop across the cake
    - α', s : empirical constants
    - S: cake compressibility factor (0 ~1)
      - 0: no compression (e.g. sand)

Washing of the Filter Cake

- **$R' = (1-E/100)^n$**
  - R' : the weight fraction of solute remaining in the cake after washing
    - R'=1.0 before washing
  - E: the percentage wash efficiency
    - 35% ~ 86%
  - n: the volume of wash liquid (V_w) / volume of liquid in the unwashed cake (V_r)

- **$t_w/t_f = 2\, V_w/V_r \cdot V_r/V_f = 2nf$**
  - V_f : filtrate volume
  - t_f : filtration time
  - t_w : wash time

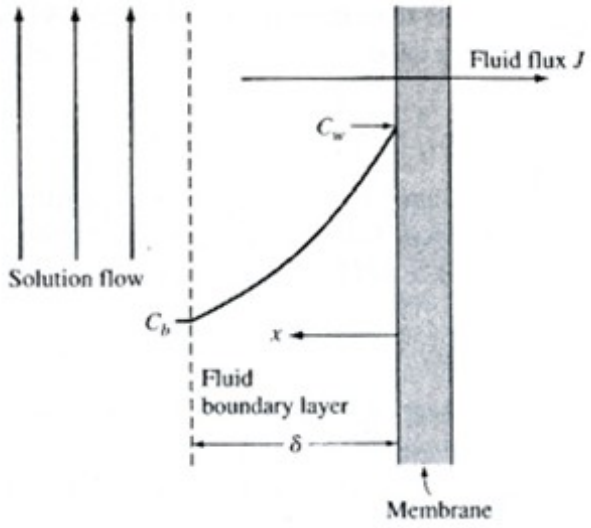
5.1.2.Crossflow Filtration

- **Classification**
  - Filtration of soluble components
    - Ultrafiltration membrane
      - Smaller molecules than the cut off size of membrane will pass through the membrane
      - Gel layer: accumulation of proteins on the membrane surface
      - Increase in osmolarity near the membrane surface : solvent gradient against the applied Δp
  - Filtration of insoluble components
    - Microfiltration membrane
      - Formation of a cake on the surface

Dissolved Species

- **Concentration polarization**
  - Higher solute concentration at the membrane surface (c_w) than in the bulk (c_b)

- **At steady state of mass transfer across membrane**
  - $Jc = - \mathcal{D}\, dc/dx$
    - J : transmembrane fluid flux
      volume/ (length^2 • time)
    - c : concentration of the solute
    - $\mathcal{D}$: diffusion coefficient of solute
  - $J = \mathcal{D}/\delta \ln (c_w / c_b)$
    - δ : boundary layer thickness
  - $c_w / c_b = exp\ (J\delta / \mathcal{D}) = \exp (J/k)$
    - $\mathcal{D} / \delta$: mass transfer coefficient k
    - c_w / c_b : polarization modulus
      - high c_w / c_b can cause formation of the solids of gel layer on the membrane surface



Ultrifiltration flux vs. Concentration of soultions

- **Estimation of c_w**
  - Intercept at zero flux

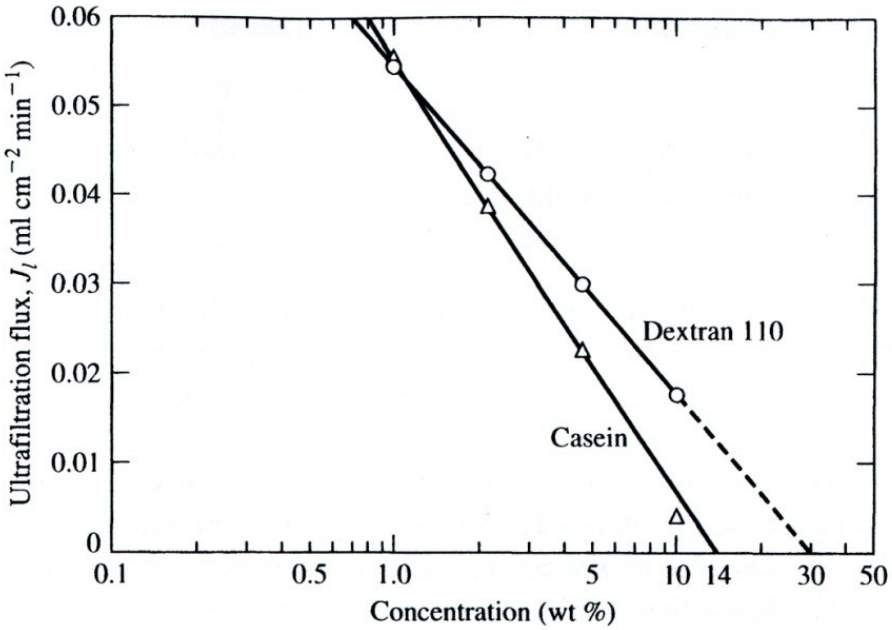


Figure 4.4 Decline in ultrafiltration flux with increasing concentration for solutions of casein and Dextran (MW 110,000). Data were obtained in thin-channel recirculating flow cells. (Data from W. F. Blatt, A. Dravid, A. S. Michaels, and L. Nelsen, "Solute polarization and cake formation in membrane ultrafiltration: Causes, consequences, and control techniques," in *Membrane Science and Technology,* J. E. Flinn, ed., p. 63, Plenum Press, New York, 1970.)

Laminar Flow

- **Leveque or Graetz solutions**
  - k (mass transfer coefficient) = 0.816 $(\gamma_w \mathcal{D}^2/L)^{1/3}$
    - γ_w : fluid shear rate at the membrane surface
    - L : length of the flow channel over the membrane
    - 0.816: applicable for the gel-polarized condition where the solute concentration at the wall is constant
  - γ_w for a rectangular slit of height 2h
    - $\gamma_w = 3u_b/h$, u_b : bulk stream velocity
  - γ_w for a circular tube of diameter D
    - $\gamma_w = 8u_b/D$

Turbulent flow

- **Empirical correlations for turbulent flow**
  - Sh (Sherwood number) = $kD_h/\mathcal{D}$ = f(Re, Sc, L/D_h)
  - $k = \mathcal{D}\,\mathrm{Sh}/D_h$
    - Re (Reynolds number): $D_h\, u_b \rho/\mu$
      - Turbulent flow when Re> 2000
    - Sc (Schmidt number) : $\mu/(\rho\mathcal{D})$
    - D_h: equivalent diameter of the channel = 4(cross-section area/wetted perimeter)
    - ρ : density of fluid
    - μ: viscosity of fluid
  - Typical correlation: $\mathrm{Sh} = 0.082\ \mathrm{Re}^{0.69}\mathrm{Sc}^{0.33}$

Example : Determination of the polarization modulus c_w / c_b

- **Operation condition of ultrafiltration**
  - Flow channel tubes
    - Diameter : 0.1 cm, length : 100 cm
  - $\mathcal{D}$: 9 x 10^{-7} cm^2/s
  - μ : 1.2 cp (centipoise) = 0.012g/(cm s)
  - ρ : 1.1 g/cm^3
  - U_b : 300 cm/s
  - Transmembrane flux (J) = 45L m^{-2} h^{-1}
- **Solution**
  - $Re = D_h u_b \rho / \mu$
  - $Sc = \mu / (\rho \mathcal{D})$
  - $k = \mathcal{D}\,\mathrm{Sh} / D_h$
    - $\mathrm{Sh} = 0.082\ \mathrm{Re}^{0.69}\mathrm{Sc}^{0.33}$
  - $c_w / c_b = exp\ (J / k)$

Effect of concentration polarization to fluid flow

- $J = (\Delta p - \sigma \Delta\pi)/ [\mu_0(R_m + R_p)]$
  - Δp : pressure difference between the bulk fluid and the permeate
  - $\Delta\pi$: osmotic pressure
  - σ : reflection coefficient for the solute
    - 1: no passage, 0: free passage
    - For an ideal dilute solution

      $\Delta\pi = RTc_w$
  - R_p : resistance of the polarized boundary layer, gel layer next to the surface of membrane
  - μ_0: viscosity of the permeate

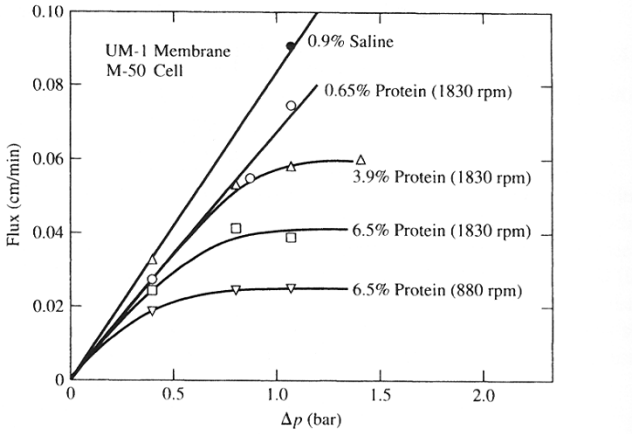


Figure 4.5 Ultrafiltration flux as a function of pressure drop in a stirred cell with varying pr concentration and stirring rate. (Data from E. S. Perry, ed., *Progress in Separation and Purific* vol. 1, p. 318, Wiley, New York, 1968.)

Suspended Particles 1 : 1 to 30~40 μm

- **Shear-induced diffusion theory (up to 30~40 μm paricles)**
  - Zydney and Colton
  - Shear-induced hydrodynamic diffusion of spherical particles
  - $\mathcal{D}_s = 0.3\ \gamma_w a^2$ (for $0.2 < \Phi < 0.45$)
    - Φ : particle volume fraction in the bulk suspension
    - a: particle radius
    - γ_w : fluid shear rate at the membrane surface
  - Substitution to $k = 0.816\ (\gamma_w\ \mathcal{D}^2/L)^{1/3}$
    - $k = 0.366\ \gamma_w\ (a^4/L)^{1/3}$
      - Stronger dependence on γ_w than dissolved species

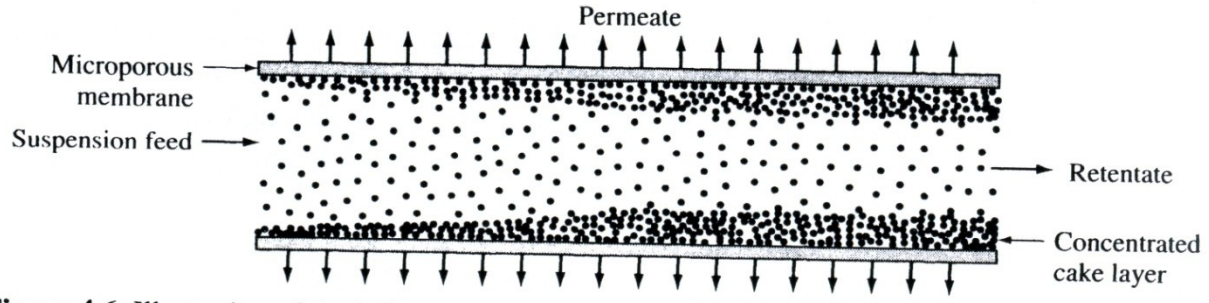


Figure 4.6 Illustration of the buildup of a cake layer at the membrane surface in crossflow filtration with suspended solids in the feed.

Suspended Particles 2 : Inertial lift (larger particles)

- **When Reynolds number based on the particle size is not negligible**
- **For fast laminar flow of dilute suspensions with thin fouling layers**
- **$J = 0.036\rho_0 a^3 \gamma_w^2/\mu_0$**
  - ρ_0: density of permeate
  - μ_0 : viscosity of permeate
  - Strong dependence on particle size and shear rate at the membrane surface

5.2 Filter Media and Equipment

Conventional Filtration

- **Filter media**
  - In biotechnology
    - Woven fabrics : cut off 10 μm
    - Metal fabrics or screens : cut off 5 μm
      - Nickel, copper, brass, aluminum, steel, stainless steel etc.
    - Rigid porous media
      - Sheets and tubes
      - Sintered stainless steel, silica, porcelain, plastics
  - Sterile filtration
    - Membrane filter
      - Cellulose esters, other polymers
      - Pore sizes: 0.22 or 0.45 μm
    - Depth filter
      - Compacted beds of pads of fibrous materials (eg. glass wool)
      - High efficiency particulate air (HEPA) filter
        - » Sterile filtration of air
        - » Collect microbes and other airborne particles

Conventional Filtration

- **Filter aids**
  - Powdered solid improving the filtration operation
  - Properties
    - Highly permeable
    - Chemical resistance
    - Compatibility with the product
  - Applications
    - Mix with the suspention
      - Less compression, faster filtration
    - Precoat the filter
  - Types
    - Diatomite
      - Skeletal remain of diatoms (algae)
      - Mostly silica
    - Perlite
      - A glassy volcanic material
      - Aluminum silicate with some combined water
      - Can be used for rough filtration

Conventional Filtration

- **Equipment**
  - Classification
    - Driving force: pressure, vacuum, gravity
    - Operation: batch, semicontinuous, continuous
  - Types

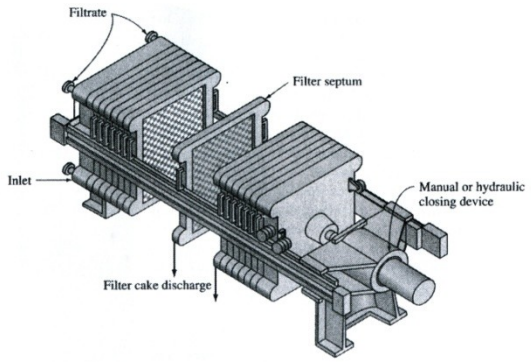


Figure 4.7 Plate-and-frame filter press.

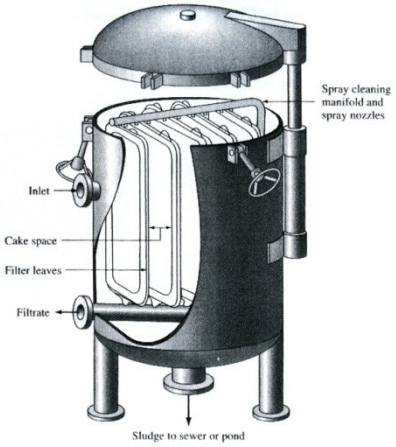


Figure 4.8 Vertical leaf filter.

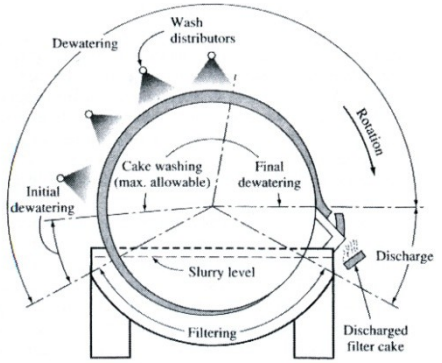


Figure 4.9 Rotary vacuum filter.

Crossflow Filtration

- **Filter media (membranes)**
  - Ultrafiltration (UF)
    - Pore size: 0.001 to 0.1 μm
    - Molecular weight cutoff: 90% rejection
      - MWCO 1kDa to 1,000 kDa
  - Microfiltration (MF)
  - Reverse osmosis (RO) or hyperfiltration membranes
    - Pass only water and a very low flux of solutes
- **Membrane structure**
  - Homogenous
    - Homogenous pore size
  - Asymmetric
    - Thin layer with small pores and thicker layer with larger pores
  - Composite
    - Asymmetric membrane consisting of two different types of material
- **Materials**
  - Polymers
    - Cellulose acetate, polyamide, polyether, polycarbonate,polyester, polypropylene, polyethylene, poly(vinylidene fluoride) (PVDF) etc.
  - Inorganic materials
    - Ceramics, zirconium oxide, borosilicate glass, stainless steel, silver

Crossflow Filtration

- **Equipment**
  - Module
    - Physical unit containing membranes
    - Requirements
      - Mechanical:
        - » Obtain effective separation of the feed and permeate streams
        - » Physical support for the membrane
      - Hydrodynamic:
        - » Minimize pressure drops through the module
        - » Optimize solute mass transfer
        - » Minimize particulate plugging or fouling
      - Economic
        - » Maximize membrane packing density
        - » Minimize manufacturing costs
        - » Easy access for cleaning and membrane replacement
        - » Sufficient chemical resistance and operation lifetime
        - » Incorporate modularity of design for easy scale up, staging, or cascading

Crossflow Filtration

- Types of module
- Hollow fiber
  - Highly resistant to plugging
  - Can be cleaned by backflushing
- Flat plate systems
- Spiral-wound modules
  - Susceptible to fouling
- Rotating cylinder device
  - Rate of mass transfer is determined mainly by the rate of rotation of the inner cylinder (> 300 rpm)
  - High energy demand

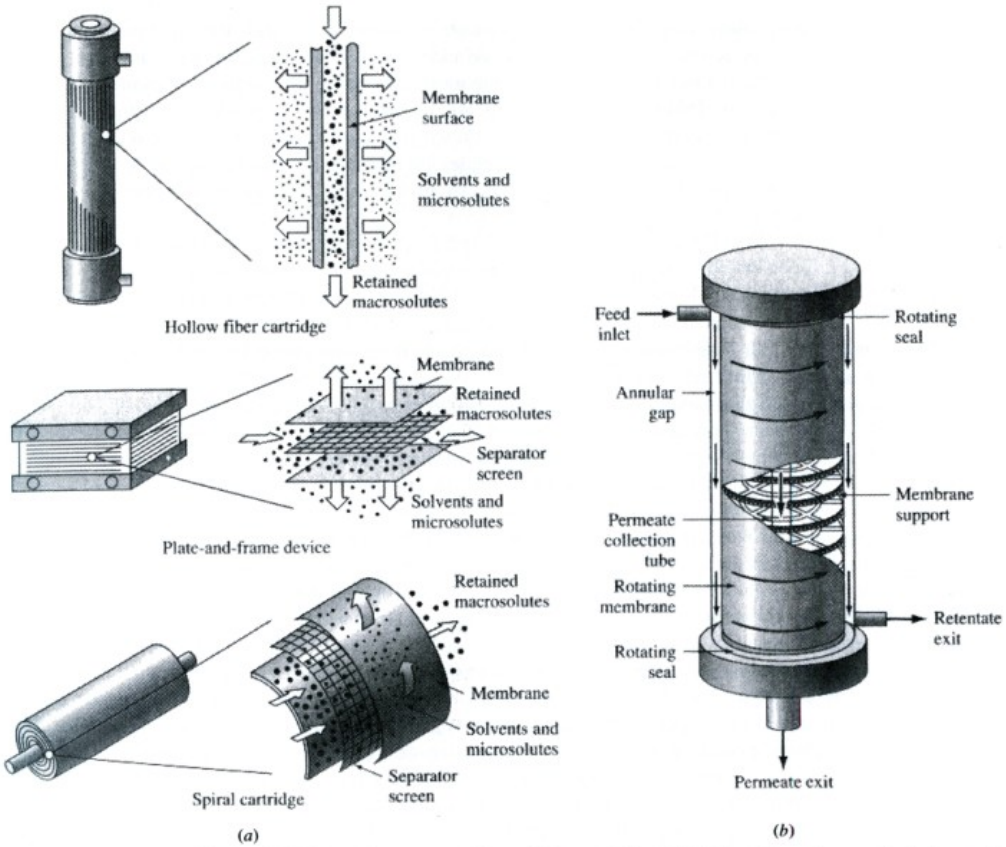


Figure 4.11 Schematic representations of filter modules. (*a*) Hollow fiber, plate, and spiral-wound membrane modules. (*b*) A rotating cylinder module.

Membrane Fouling

- **Result from**
  - Physical and/or chemical interactions between the membrane and various components in the process stream
- **Result in**
  - A decline in the permeate flux
  - A change in the membrane selectivity
- **Proteins are the main contributor to fouling**
  - Protein adsorption to the membrane
    - Can be minimized by using hydrophilic membrane or reducing pore size
  - Protein deposition to the adsorbed protein
  - Protein accumulation by concentration polarization → formation of gel layer
    - Can be minimized by increasing the fluid shear rate

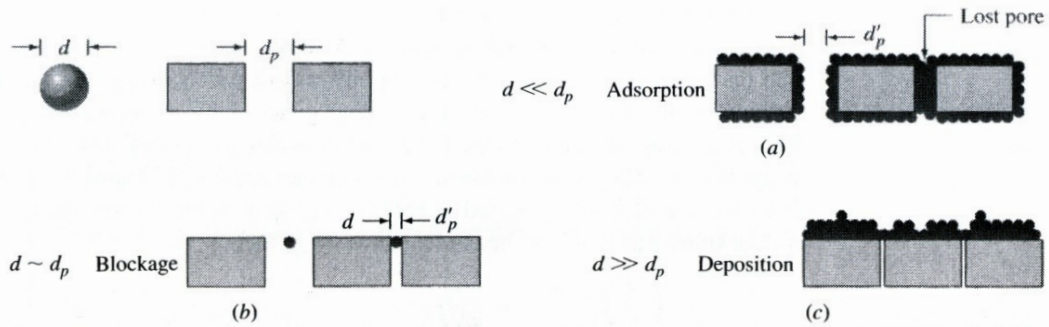


Figure 4.12 Mechanisms of membrane fouling. (*a*) Pore narrowing and constriction. (*b*) Pore plugging. (*c*) Solute deposition and formation of a gel or cake layer. Dimensions: d, protein or particle diameter, d_p, clean pore diameter, d'_p, effective pore diameter in the presence of adsorbed proteins or particles.