Physical unit processes II

Physical unit processes II

Physical processes used for solid/liquid separation

- Depth filtration
- Membrane filtration
- Flotation

Mixing

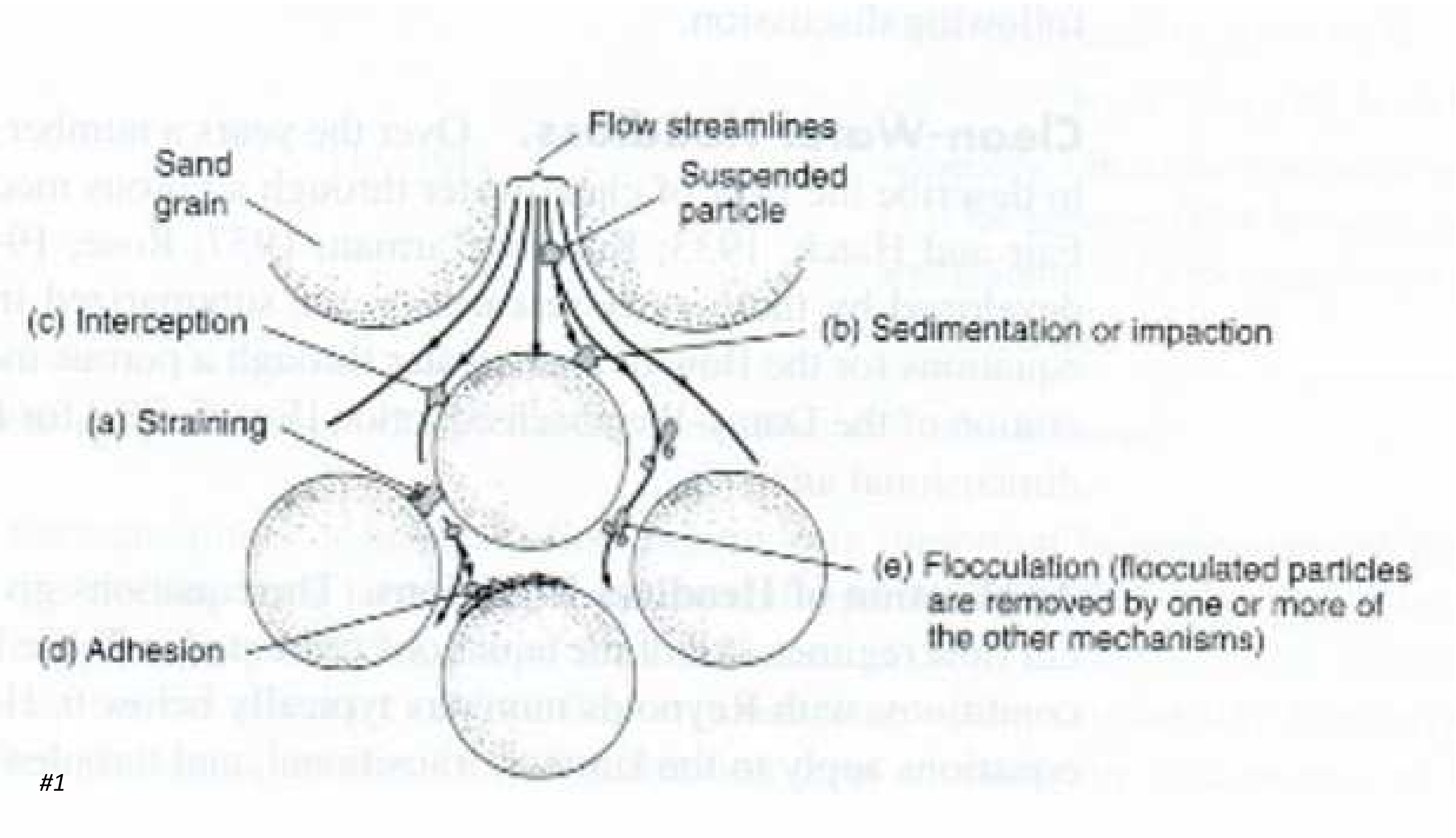
- Fundamentals
- Types of mixers

Filtration

- **Often applied as a tertiary (advanced) treatment method to further treat the secondary treatment effluent in order to**
  - meet standards
  - reduce loading to the water body
  - reuse the treated water [e.g., recreational use, toilets, (indirect/direct) potable use]

- **Depth filtration**
  - Usually sand filters, anthracite coal, dual- or multi-media
- **Membrane filtration**
  - Smaller opening size than surface filtration
  - Microfiltration, ultrafiltration, nanofiltration, reverse osmosis

Depth filtration - Particle removal mechanisms



#1

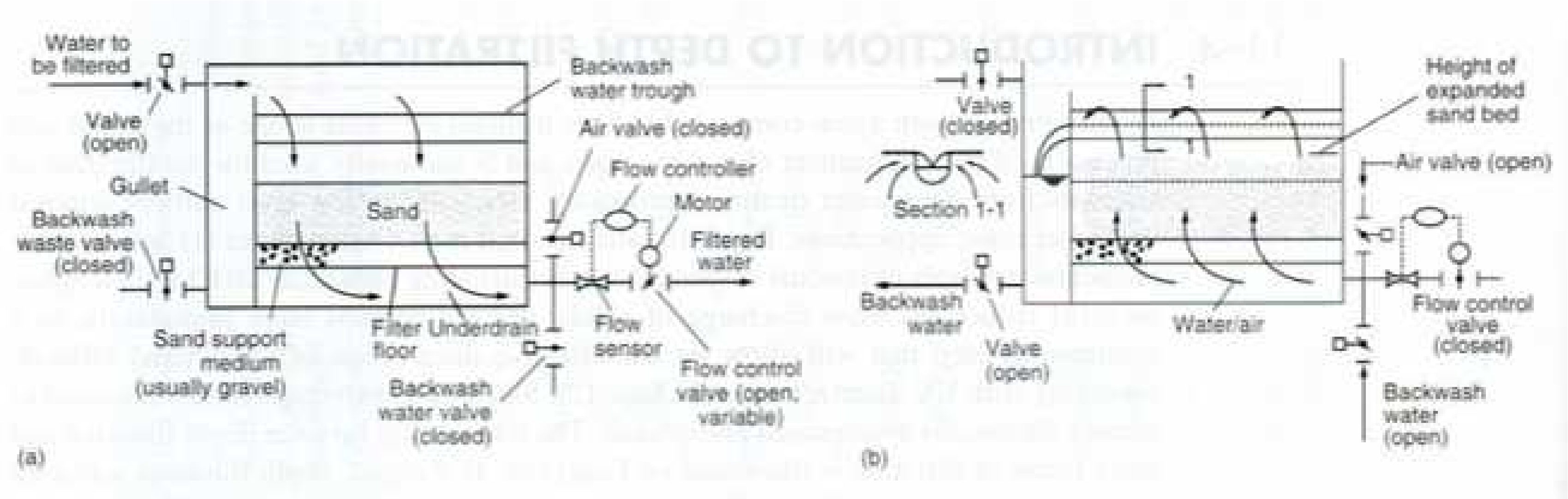
Depth filtration - Particle removal mechanisms

- **Straining**
  - Mechanical : particles larger than the pore space are strained out mechanically
  - Chance contact: particles smaller than the pore space are trapped within the filter by chance contact
- **Sedimentation or impaction**
  - Heavy particles that do not follow the flow streamlines are removed when they come in contact with the surface of the filtering medium
- **Interception**
  - Particles that move along in the streamline are removed when they come in contact with the surface of the filtering medium

Operation of depth filter

- **Filtration-backwash cycle**

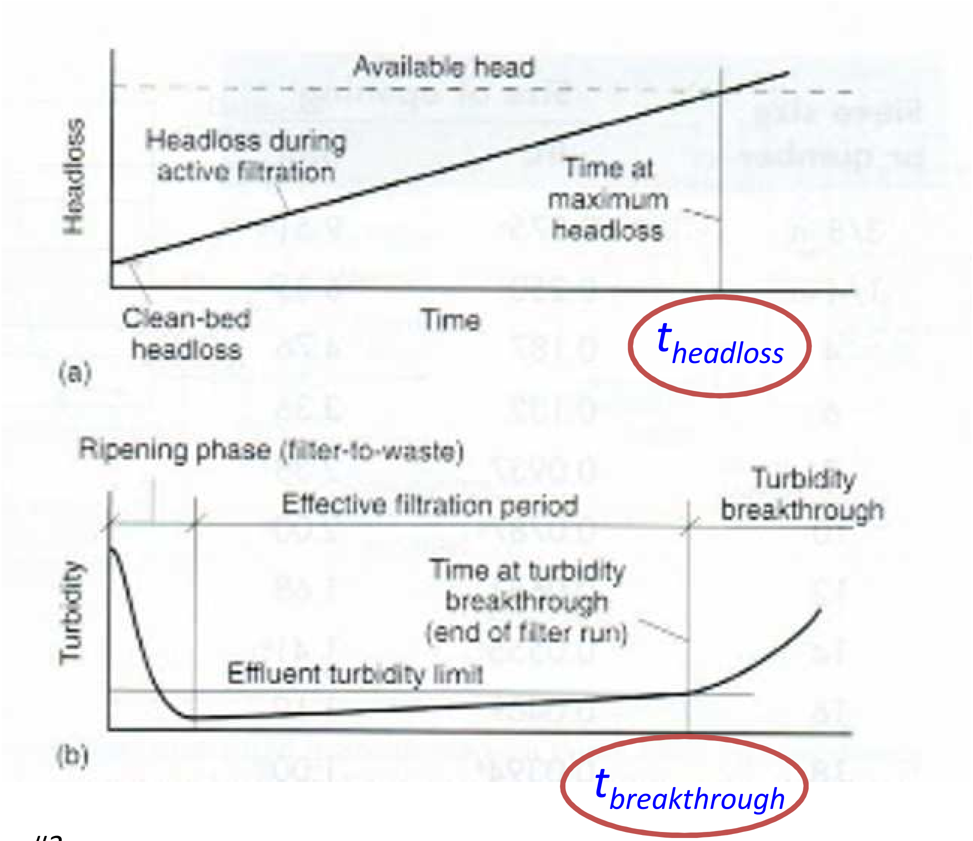
#2



<Filtration> <Backwash>

Headloss buildup and effluent quality

- **Headloss buildup and effluent quality**



  - The shorter of the $t_{headloss}$ and $t_{breakthrough}$ will be the time for backwash cycle
  - Optimized design: design the filter such that

$$t_{headloss} \approx t_{breakthrough}$$

#3

Membrane filtration - Terminologies

- **Terminologies**
  - **Feed water**: influent water supplied to the membrane system for treatment
  - **Permeate**: the liquid that has passed through the membrane
  - **Retentate**: The portion of the feed water that does not pass through the membrane
  - **Flux**: The rate at which permeate flows through the membrane

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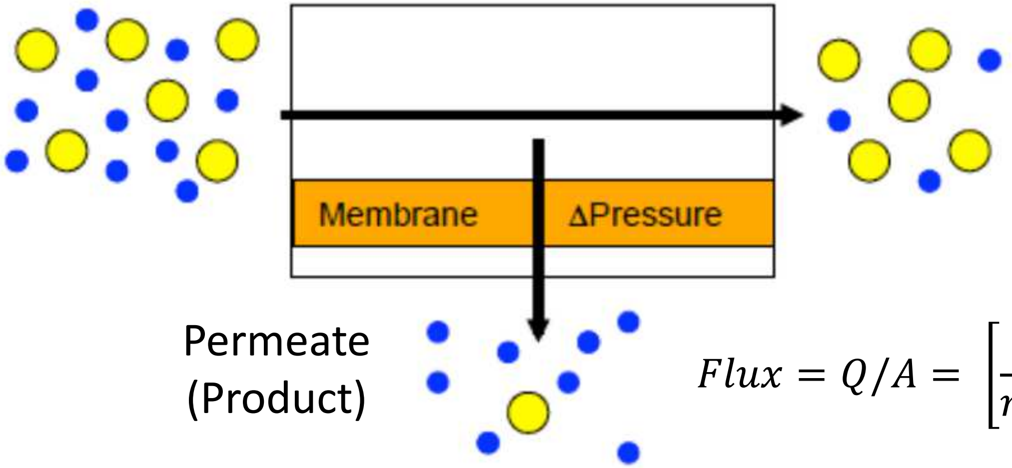
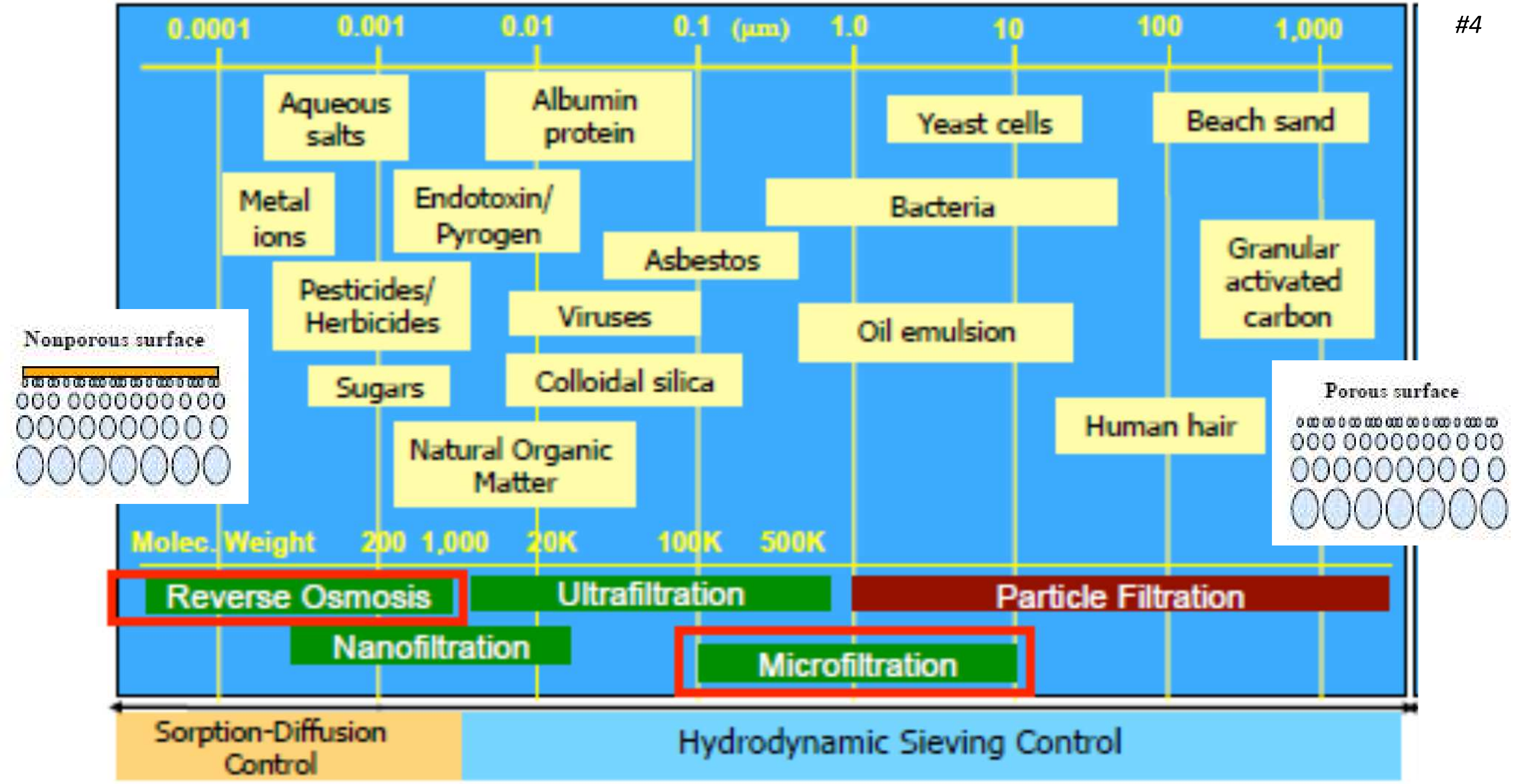


$$Flux = Q/A = \left[\frac{volume\ permeate}{membrane\ area\ \times time}\right]$$

Membrane filtration - classification

#4

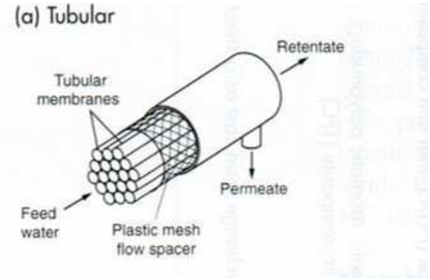


RO/NF: nonporous membrane
Diffusion-like process

MF/UF: porous membrane
Straining-like process

Membrane configuration (1)

#5



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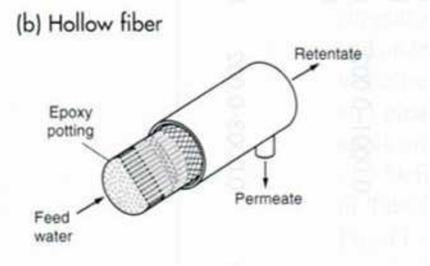
- **Tubular**
  - Membrane is cast on the inside of a support tube and the tubes are placed in a pressure vessel
  - Feed water is pumped through the tube and the permeate is collected outside
  - Tube diameter 6-40 mm

#5

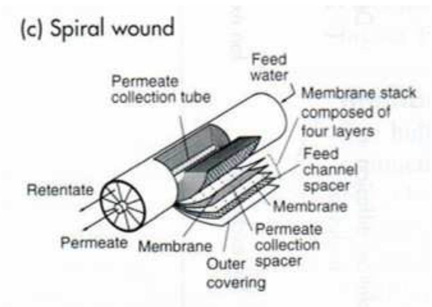


#7

- **Hollow fiber**
  - A module consists of a bundle of hundreds to thousands of hollow fibers
  - Inside diameter 35-45 µm, outside diameter 90-100 µm

Membrane configuration (2)

#5

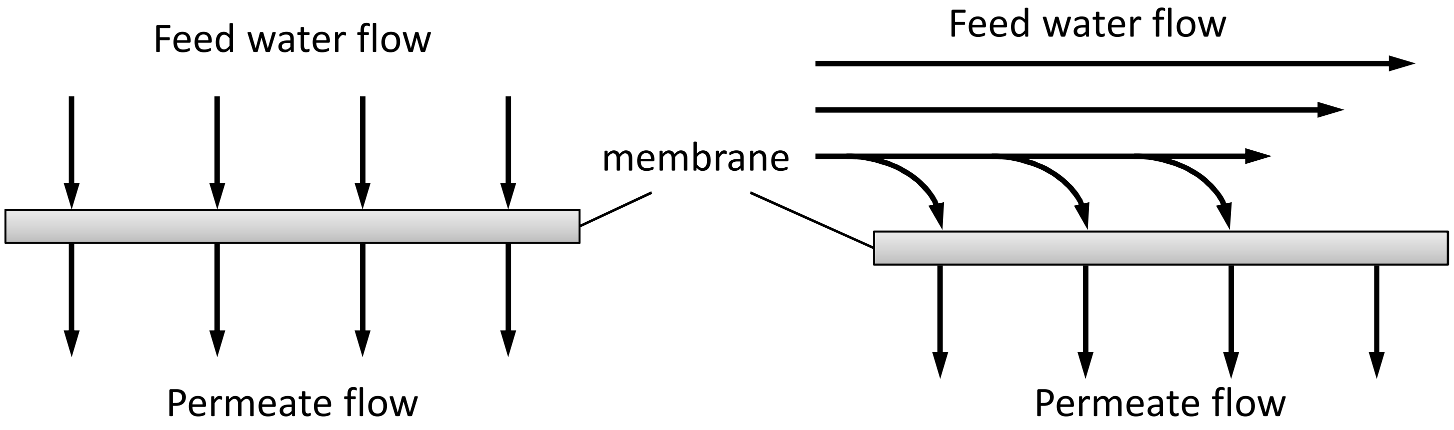


#8

- **Spiral wound**
  - Flat membrane sheets are rolled into a tight circular configuration
  - A flexible permeate spacer is placed between two flat sheets
  - Membrane is sealed on the three side; the open side is connected to a perforated pipe

Driving force: pressure

- Apply either hydraulic pressure or vacuum
- MF & UF: cross-flow or dead-end modes
  - **Cross flow mode**
    - The feed water is pumped parallel to the membrane surface (at a high velocity to control fouling by the shear force)
  - **Dead-end mode**
    - The feed water is directed toward the membrane surface
    - All water applied to the membrane passes through the membrane



Reverse osmosis

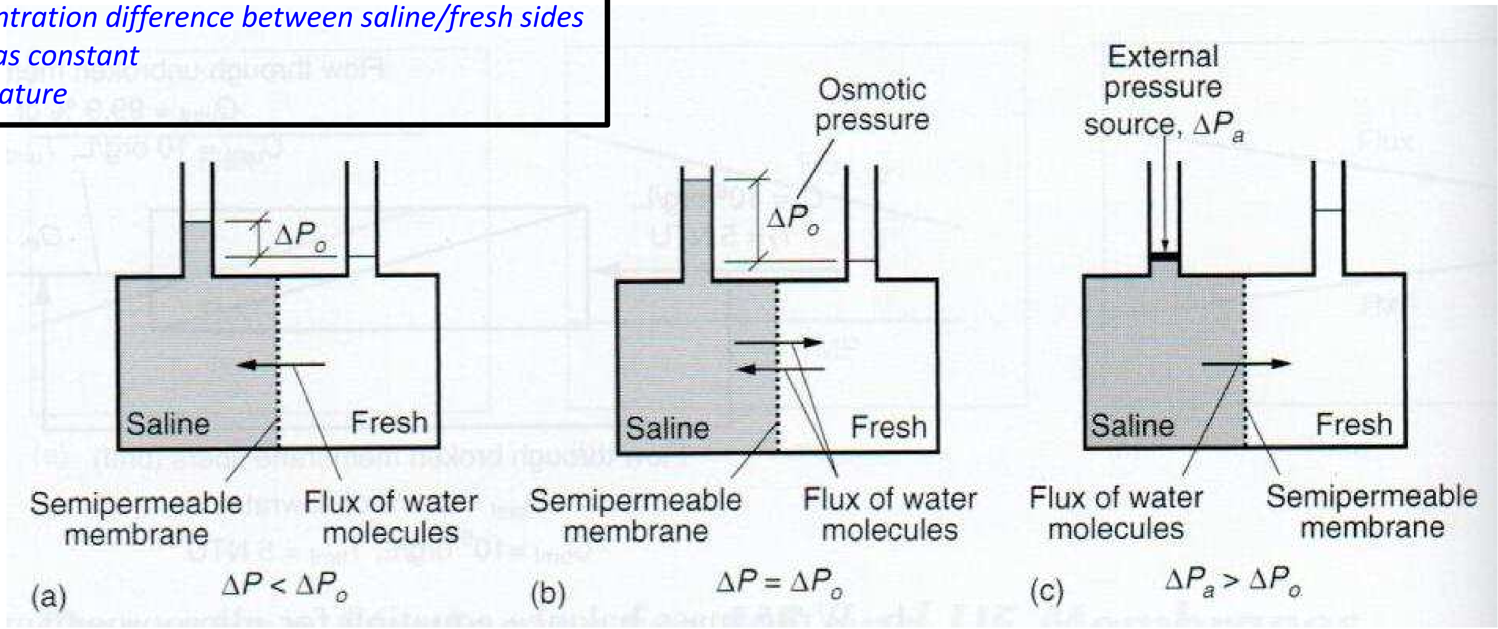
- **Produces retentate (concentrate) that usually has x2 or more salt concentration than the feed water**

Osmotic pressure

$$\Delta P_o \approx \Delta c \cdot RT$$

Δc = concentration difference between saline/fresh sides
R = ideal gas constant
T = temperature

#9



Osmosis
Water moves from low salt conc. → high salt conc.

Osmotic equilibrium
No net water movement

Reverse osmosis
Water moves from high salt conc. → low salt conc.

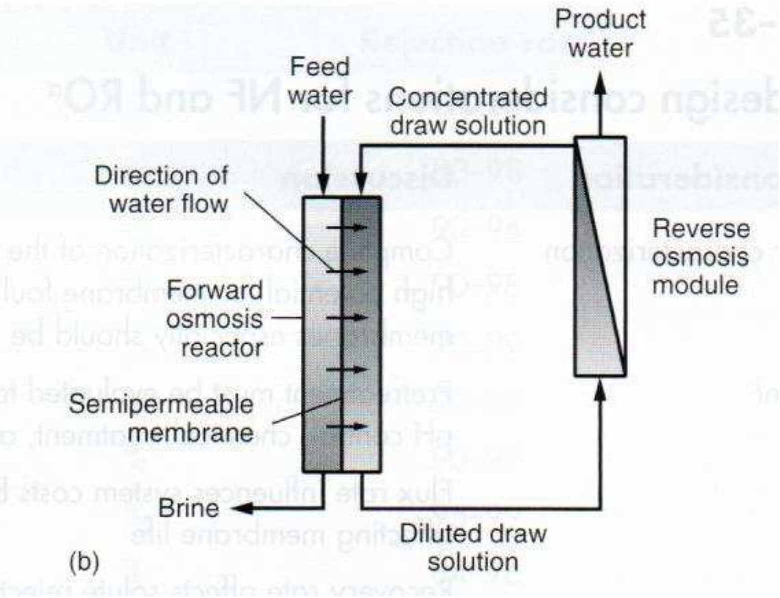
Membrane fouling

- **Particulate fouling**
  - Particles clog the membrane pores
- **Scaling**
  - As chemical constituents in the feed water are removed at the surface of a membrane, their local concentration increases
  - Concentrations of some of the constituents will increase beyond their solubility limits and will be precipitated on the membrane surface
  - Especially critical for RO
- **Organic fouling**
  - Many natural organic matter (NOM) are sticky – accumulate on the membrane surface
  - Fouling is accelerated by forming stable organic/inorganic particulate matter
- **Biological fouling**
  - Elevated concentrations of organic matter and nutrients on the membrane surface → favorable for microbial growth
  - Biofilm formed on the membrane surface

Forward osmosis

- **A membrane technology getting recent interest**
  - RO: High energy consumption for pressurizing the feed water
  - **FO: Uses natural osmotic pressure with minimal pressure application**
  - **Use a more concentrated solution (draw solution) to recover water from the feed water**
  - Principal requirement of the draw solution
    - Osmotic pressure should be greater than the feed solution
    - Must be easy to reconcentrate after being diluted by the water from the feed solution
    - NaCl is a common salt used for draw solution: easy to reconcentrate, no scaling problems

#10



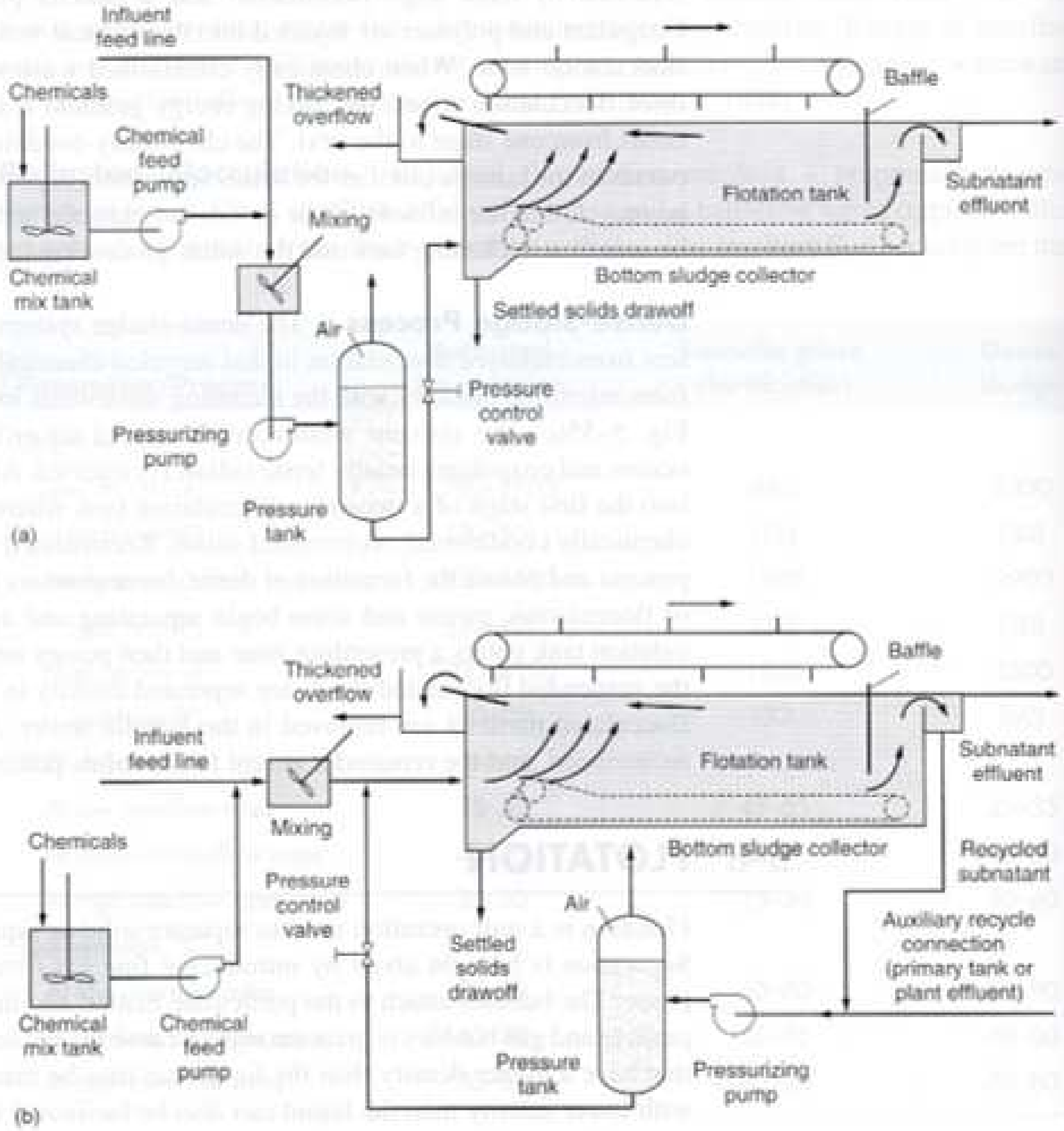
Types of flotation unit processes

- **Two typical types of flotation**
  - Dissolved-air flotation
  - Dispersed-air flotation

- **Dissolved-Air Flotation (DAF)**
  - Air is dissolved in the wastewater under a pressure of several atms (high P → high gas solubility)
  - The gas-laden wastewater then flows to a flotation tank under atmospheric pressure (low P → low gas solubility → generation of fine bubbles)

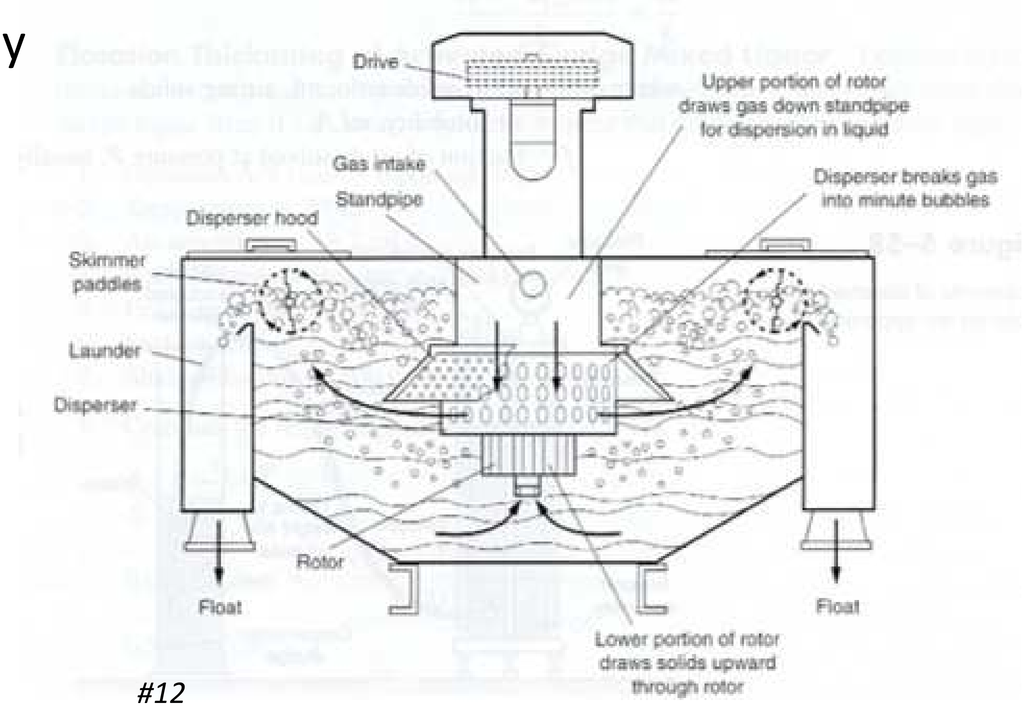
Figure 5-56

Schematic of dissolved-air flotation systems: (a) without recycle in which the entire flow is passed through the pressurizing tank and (b) with recycle in which only the recycle flow is pressurized. The pressurized flow is mixed with the influent before being released into the flotation tank.



Types of flotation unit processes

- **Dispersed-Air Flotation**
  - A revolving impeller forces water through disperser openings and creates a vacuum in the standpipe
  - The vacuum pulls air into the standpipe and mixes it with the water
  - Fine bubbles are created by a mixing force and by the movement of the fluid through a series of cells
  - Less frequently used – mainly used in industrial wastewater treatment



#12

Mixing

- Application of mixing in wastewater treatment
  - Continuous rapid mixing
    - Blending of chemicals with wastewater
    - Blending of miscible liquids
    - Addition of chemicals to sludge and biosolids
  - (Slower) Continuous mixing
    - Keeping the contents of a reactor or storage tanks in suspension (e.g., for biological treatment)
    - Flocculation (after adding coagulants - more common in drinking water treatment!)

The G value

- Velocity gradients and power requirement
  - Mixing can be viewed as a development of velocity gradients among fluid
  - “G value”: average velocity gradient, a measure of mixing intensity

Camp and Stein (1943)

$$\boxed{G = \sqrt{\frac{P}{\mu V}}}$$

G = average velocity gradient (1/s)
P = power requirement (W)
μ = dynamic viscosity (N-s/m^2)
V = reactor volume (m^3)

⇨ The effectiveness of mixing is a function of power input per volume

⇨ Greater power requirement to achieve greater G with the same reactor volume;

Greater power requirement to achieve the same G with the larger reactor volume

Range of retention time and G value for mixing

- rapid mixing: G↑ with small τ
- gentle mixing (flocculation): G↓ with large τ

Process	**Range of values**	
	Retention time	**G value, s^{-1}**
Mixing		
Typical rapid mixing operations in wastewater treatment	5-30 s	500-1500
Rapid mixing for effective initial contact and dispersion of chemicals	<1 s	1500-6000
Rapid mixing of chemicals in contact filtrations processes	<1 s	2500-7500
Flocculation		
Typical flocculation processes used in wastewater treatment	30-60 min	50-100
Flocculation in direct filtration processes	2-10 min	25-150
Flocculation in contact filtration processes	2-5 min	25-200

Mixing

Q: Determine the theoretical power requirement to achieve a G value of 100/s in a tank with a volume of 2800 m^3. Assume that the water temperature is 15°C. What is the corresponding value when the water temperature is 5°C?

Dynamic viscosity values:

15°C: 1.139×10^{-3} N-s/m^2

5°C: 1.518×10^{-3} N-s/m^2

Mixing

$$G = \sqrt{\frac{P}{\mu V}}$$

⇨ $P = G^2 \mu V$

@ 15°C: $P = (100/s)^2 \times (1.139 \times 10^{-3}\ N - s/m) \times (2800\ m^3) = 31900\ W$

$= 31.9\ kW$

@ 5°C: $P = (100/s)^2 \times (1.518 \times 10^{-3}\ N - s/m) \times (2800\ m^3) = 42500\ W$

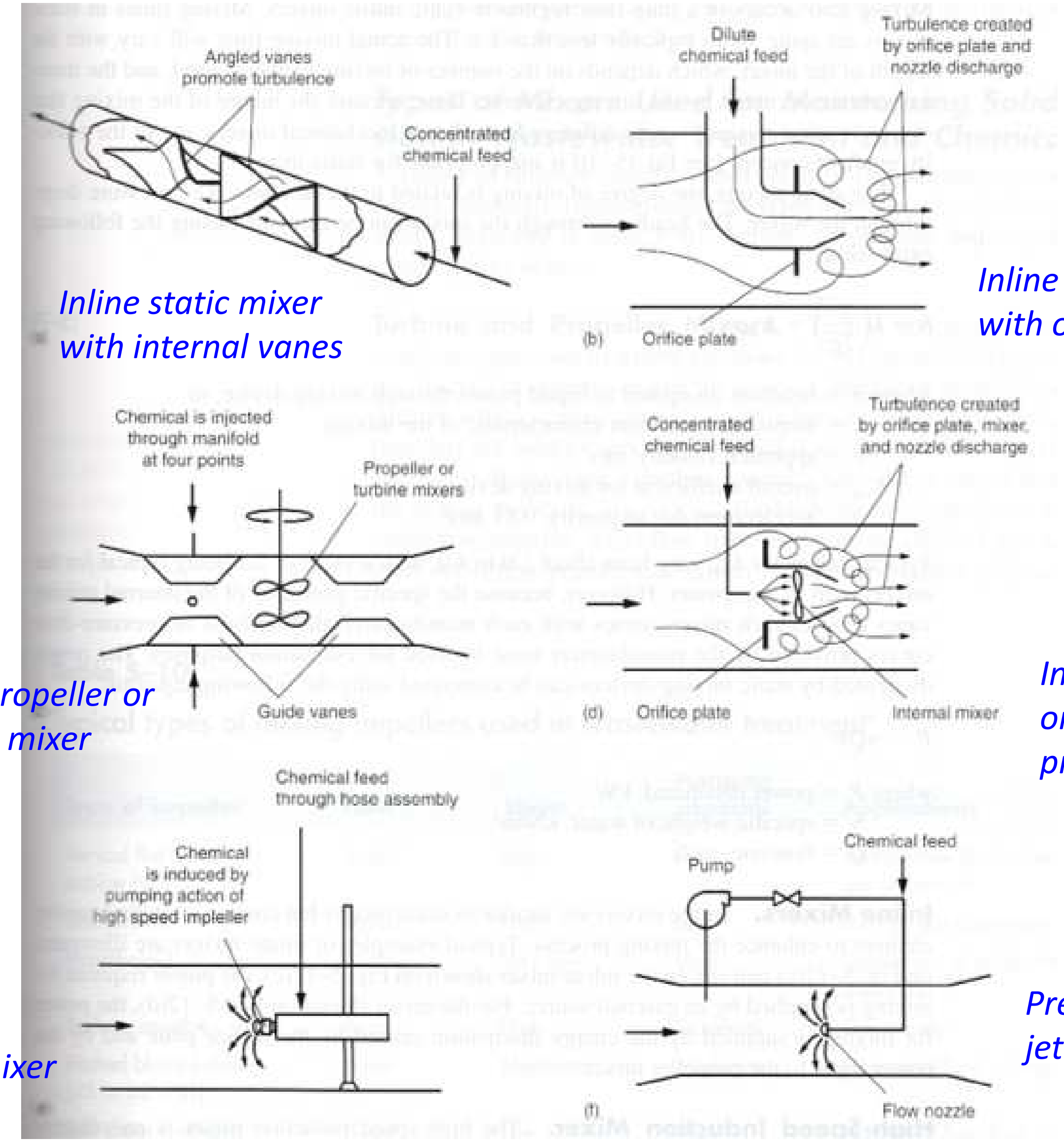
$= 42.5\ kW$

Results indicate that as temperature ↓, viscosity ↑, so more power input is required for the same intensity of mixing

Types of mixers (1)

Typical mixers used for rapid mixing of chemicals

#13



Inline static mixer with internal vanes

Inline static mixer with orifice

Inline propeller or turbine mixer

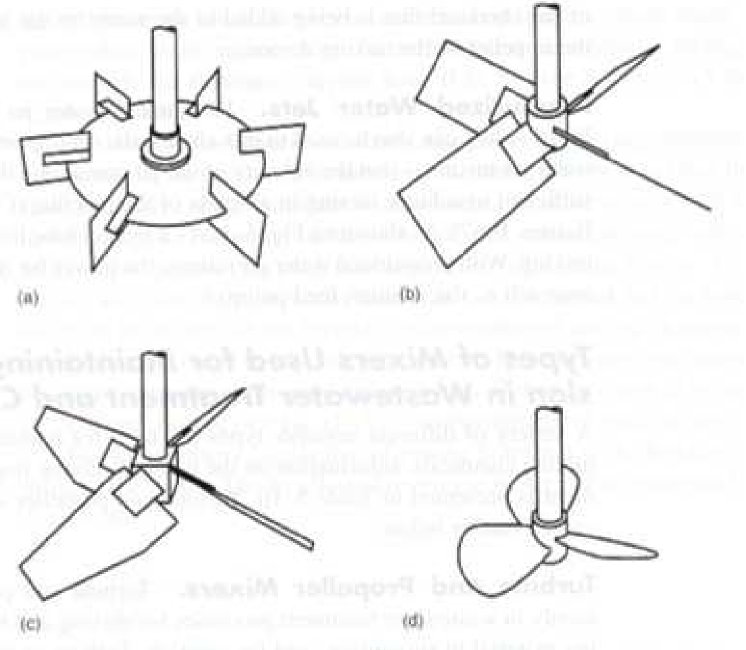
Inline mixer with orifice and internal propeller mixer

High-speed induction mixer

Pressurized water jet mixer

Types of mixers (2)

Mixers for maintaining solids in suspension and chemical blending in reactors: turbine and propeller mixers most common



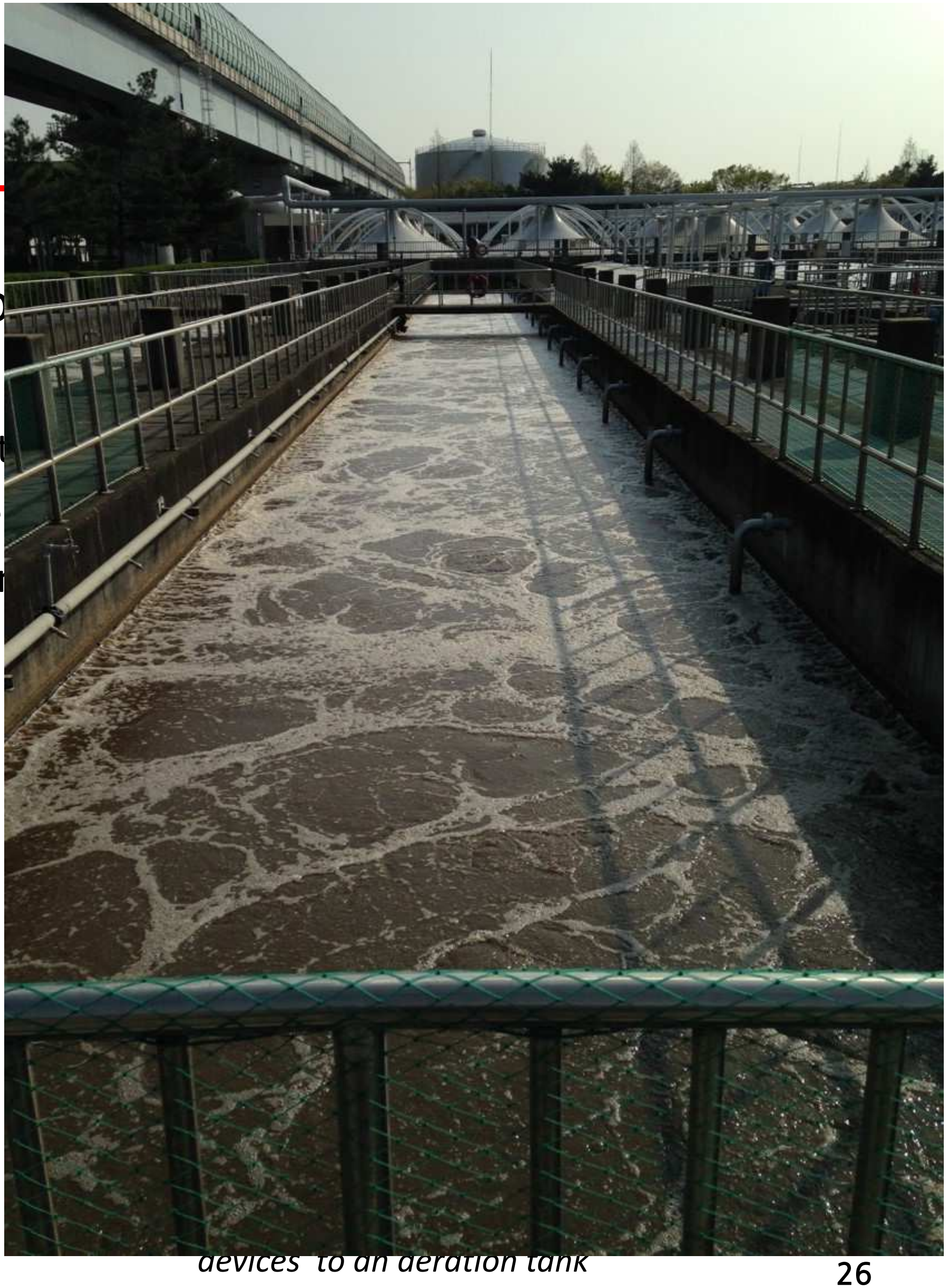
#14

Types of mixers (3)

- Type of mixers used for bio
  - Pneumatic mixing
    - mixing is provided by inject
    - both mixing effect & oxyge
    - used for aeration tank of a

#15

Ceramic disk diffuser

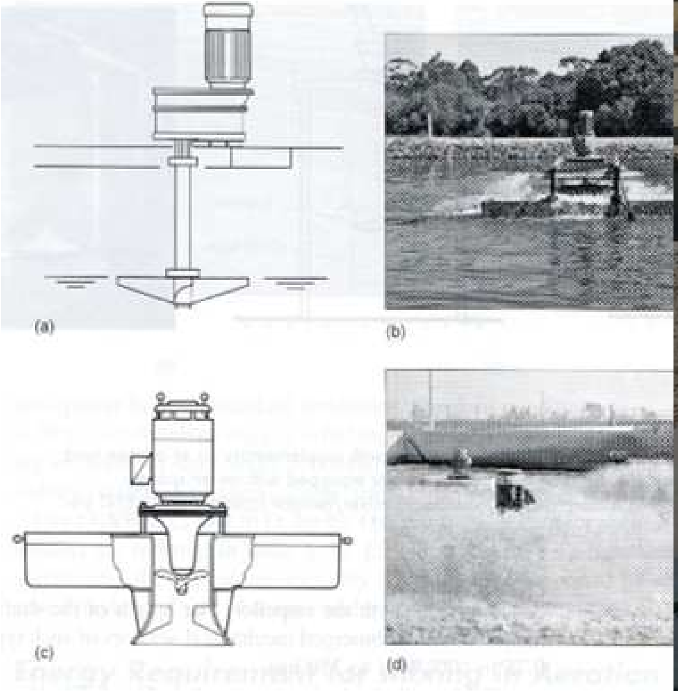


devices to an aeration tank

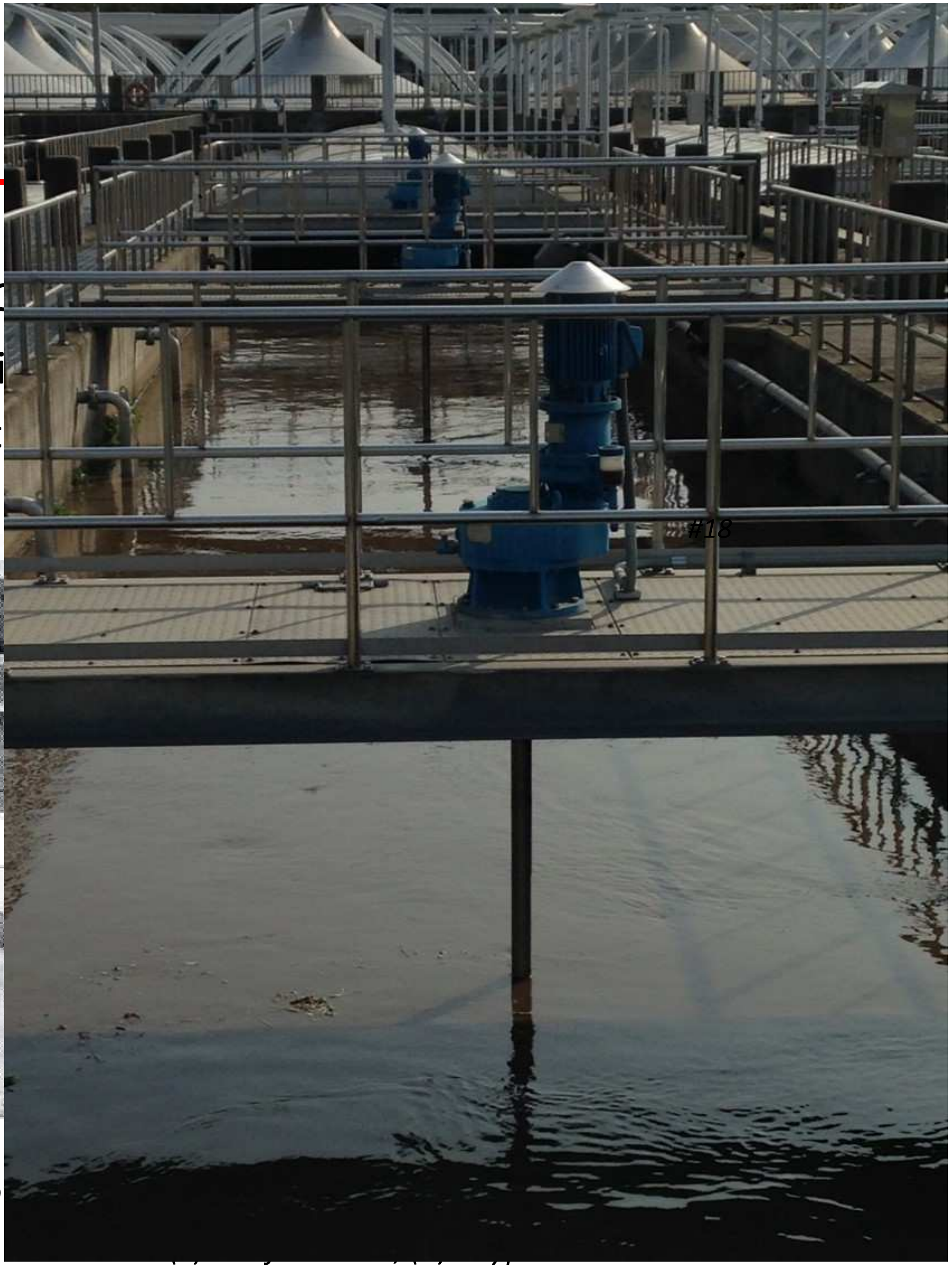
Types of mixers (4)

- Type of mixers used for bio
  - Mechanical aerators and mi
    - for anoxic/anaerobic react

#17



Surface mechanical aerators: (a), (b) – lo speed; (c), (d) – high-speed



#18

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Physical unit processes III

Physical unit processes III

Physical processes utilizing interphase mass transfer

- Gas-liquid mass transfer
- Adsorption
- Ion exchange

Mass transfer processes

- **Phase partitioning**: in multi-phase systems, materials are distributed with some ratio between the phases at equilibrium
  - Recall Henry's law (gas-liquid partitioning): $C_g/C_s = H_u$

ex) At 1 atm, 20°C, the saturation concentration of dissolved oxygen in pure water is 9.08 mg/L (0.208 atm partial pressure of O_2 in gas phase ↔ 9.08 mg/L O_2 in aqueous solution)

Mass transfer processes

- Transfer of material from one homogeneous phase to another
- Interphase mass transfer occurs **towards equilibrium**
- **Time as a factor**: it takes some time for the mass transfer processes to occur such that equilibrium is established

ex) Drying clothes

phase partitioning: moisture wetting the clothes vs. moisture in the ambient air

equilibrium: almost no moisture in the clothes because the amount of ambient air is almost infinite

time as a factor: it takes some time (~1 day) for the clothes to dry

Application of mass transfer in WW treatment

Type of reactor	Phase equilibria	Application
Absorption	Gas → liquid	Addition of gases to water (e.g., O_2), NH_3 scrubbing in acid
Adsorption	Gas → solid	Removal of organics with activated carbon
	Liquid → solid	Removal or organics with activated carbon, dechlorination
Desorption	Solid → liquid	Sediment scrubbing
	Solid → gas	Reactivation of spent activated carbon
Drying (evaporation)	Liquid → gas	Drying of sludge
Gas stripping	Liquid → gas	Removal of gases (e.g., CO_2, H_2S, NH_3, VOCs)
Ion exchange	Liquid → solid	Selective removal of chemical constituents, demineralization

Gas-liquid mass transfer

- **Modeling concentration change by mass transfer**
  - Mass transfer occurs at the interface (surface) -- ***A***
  - Should depend on compound (rate of diffusion) & surface characteristics (calm or turbulent?) -- ***K_L***
  - Should also depend on how far the current state is from equilibrium -- ***(C_s-C)***
  - Flux = (mass transferred) / (area) / (time)

$$F = K_L(C_s - C)$$

F = flux of mass transfer [$ML^{-2}T^{-1}$]

K_L = mass transfer coefficient with liquid as a reference phase [LT^{-1}]

A= area through which mass is transferred [L^2]

C_s = liquid concentration in equilibrium with bulk gas concentration [ML^{-3}]

C = current liquid concentration

Gas-liquid mass transfer

- **Modeling concentration change by mass transfer**
  - When gas concentration is constant, change in liquid concentration is represented as:

$$r_v = \left.\frac{dC}{dt}\right|_{mass\,transfer} = K_L\frac{A}{V}(C_s - C) = K_La(C_s - C)$$

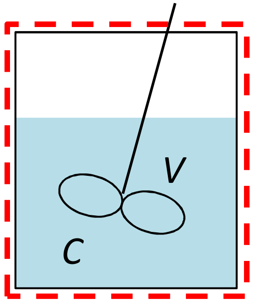
r_v = rate of mass transfer [$ML^{-3}T^{-1}$]

V = bulk liquid volume [L^3]

K_La = volumetric mass transfer coefficient [T^{-1}] – 1st order rate constant

Gas-liquid mass transfer

- **Absorption of gas in a batch reactor**



(rate of accumulation)

= (rate of inflow) – (rate of outflow) + (rate of generation)

$$\frac{dC}{dt} = K_L a(C_s - C_t) \Rightarrow \boxed{\frac{C_s - C_t}{C_s - C_o} = e^{-(K_L a)t}}$$

- **Desorption of gas in a batch reactor**

$$\frac{dC}{dt} = -K_L a(C_s - C) \Rightarrow \boxed{\frac{C_t - C_s}{C_0 - C_s} = e^{-(K_L a)t}}$$

Gas-liquid mass transfer

Q: Secondary effluent is placed in a storage basin for reuse. If the initial DO concentration is 1.5 mg/L, estimate the time required for the DO concentration to increase to 8.5 mg/L due to surface reaeration. The surface area of the storage basin is 400 m^2 and the depth is 3 m. Assume the K_L value for oxygen is 0.03 m/hr. Use the saturation DO concentration of 9.09 mg/L at 20°C.

Gas-liquid mass transfer

This is the case of absorption of gas in a batch reactor, so use:

$$\frac{C_s - C_t}{C_s - C_o} = e^{-(K_L a)t}$$

$$t = -\frac{1}{K_L a} \cdot ln \frac{C_s - C_t}{C_s - C_o}$$

$$a = \frac{A}{V} = \frac{1}{H} = 0.33\ m^{-1}$$

$$t = -\frac{1}{(0.03\ mhr) \cdot (0.33\ m^{-1})} \cdot ln \frac{9.09 - 8.5}{9.09 - 1.5} = 258\ hr = 10.8\ d$$

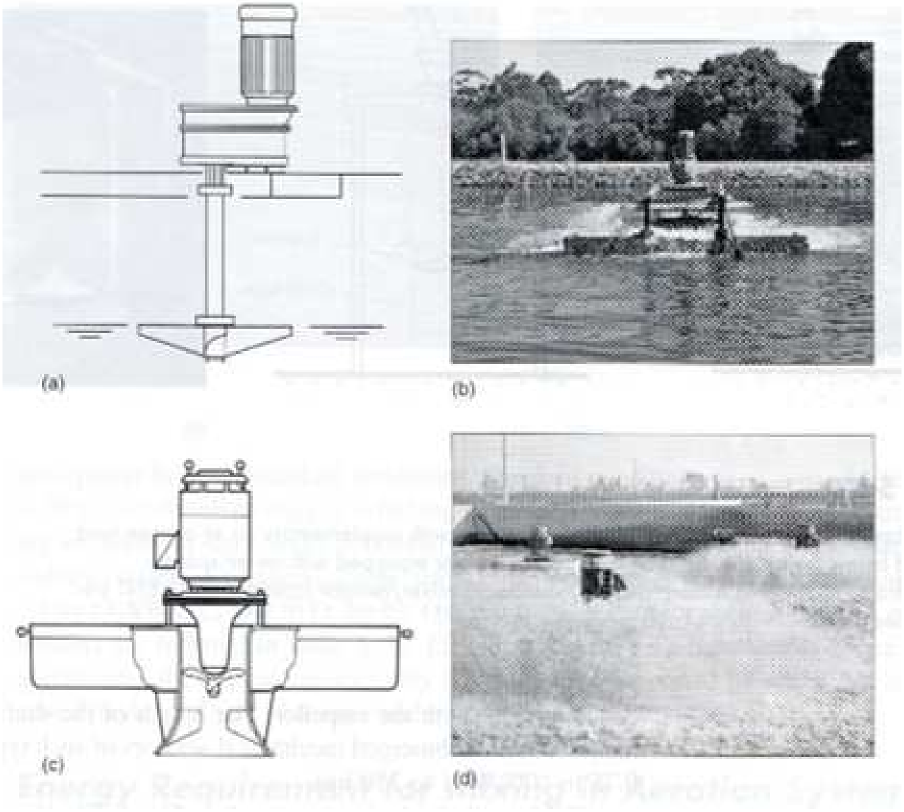
You see it takes a long time for surface reaeration from the atmosphere in the absence of mechanical agitation!

G-L mass transfer ex 1: Aeration

- **Diffused air aeration vs Mechanical aeration**

#1

#2



G-L mass transfer ex 2: Gas stripping

- **Mass transfer of a gas from the liquid phase to the gas phase**

  Recall: $$\frac{dC}{dt} = K_L \frac{A}{V}(C - C_s) = K_L a(C - C_s)$$

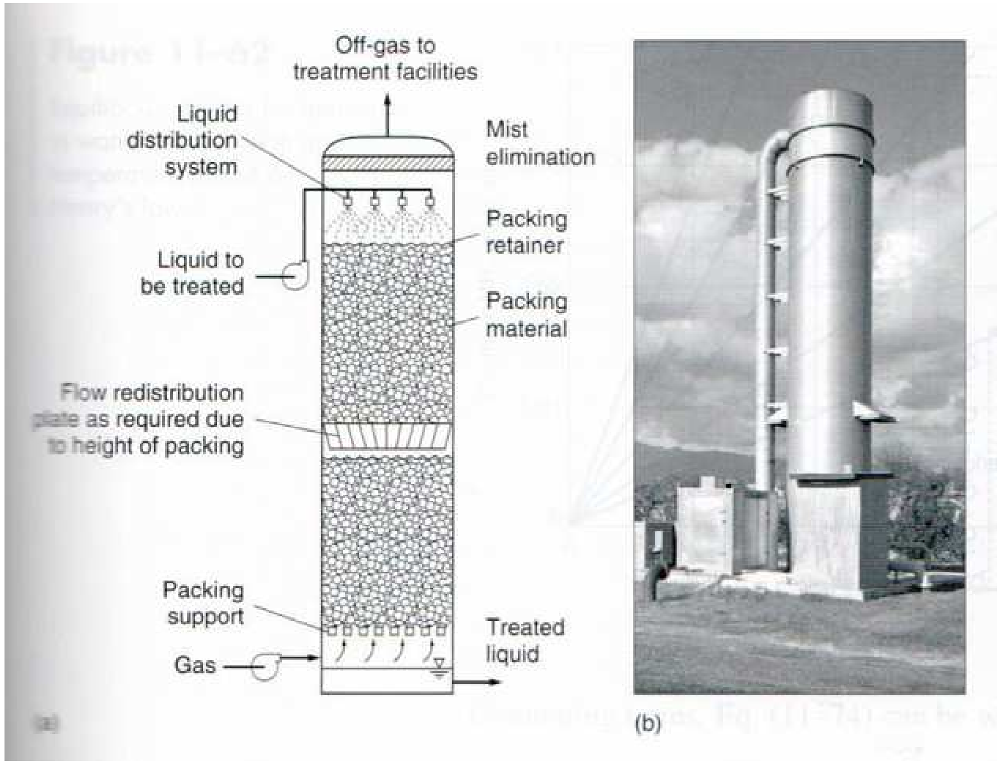
  (for desorption of gas)

- **Stripping (blowing) a contaminant-free gas into the water**
  - Creates large gas-liquid interfacial area for mass transfer
    - Most significant concern in the process design
  - Concentration gradient generated: $C_s \rightarrow 0$

- **Removal of NH_3, odorous gases and VOCs**
  - For ammonia stripping, pH should be raised by addition of lime (why?)

Gas stripping - methods

- **Methods to contact phases**
  - Cocurrent, countercurrent, cross-flow
  - Countercurrent most common



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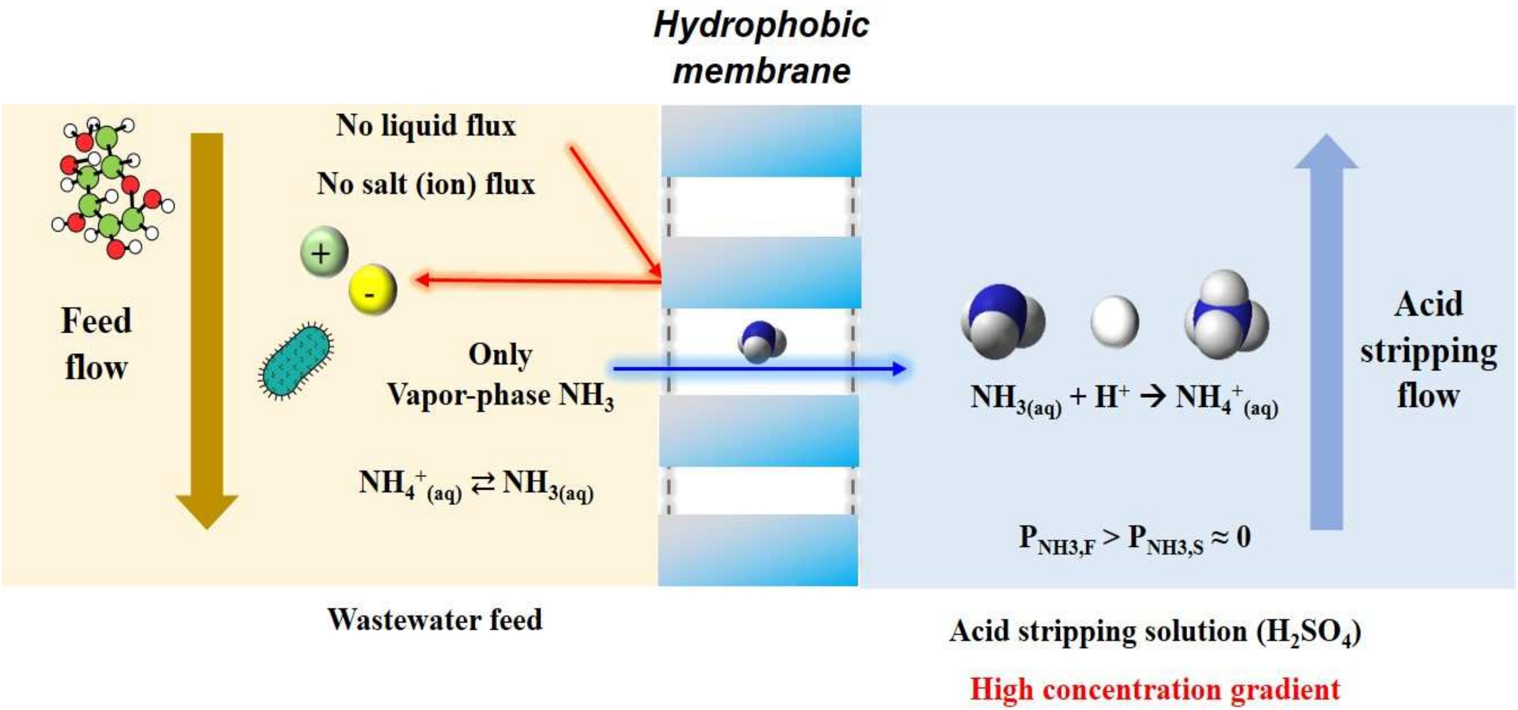
G-L mass transfer ex 3: Gas-permeable membrane

- An emerging technology
  - Gas-permeable membranes have been used for water production from water with high impurities (e.g., RO retentate from seawater desalination)
  - Opportunities to be used for recovery NH_3/NH_4^+ and CH_4 from wastewater



Hydrophobic membrane

Feed flow

No liquid flux

No salt (ion) flux

Only Vapor-phase NH_3

$NH_4^+{}_{(aq)} \rightleftarrows NH_{3(aq)}$

$NH_{3(aq)} + H^+ \rightarrow NH_4^+{}_{(aq)}$

Acid stripping flow

$P_{NH3,F} > P_{NH3,S} \approx 0$

#4

Wastewater feed

Acid stripping solution (H_2SO_4)

High concentration gradient

Adsorption

- **Removal of substances in solution by accumulation of those substances on a solid phase**
  - Adsorbate: the substance that is being removed from the solution
  - Adsorbent: the material onto which the adsorbate accumulates

- **Applications**

  Removal of:

  - refractory organics
  - residual inorganic constituents (nitrogen, sulfides, heavy metals, etc.)
  - odor compounds

#5

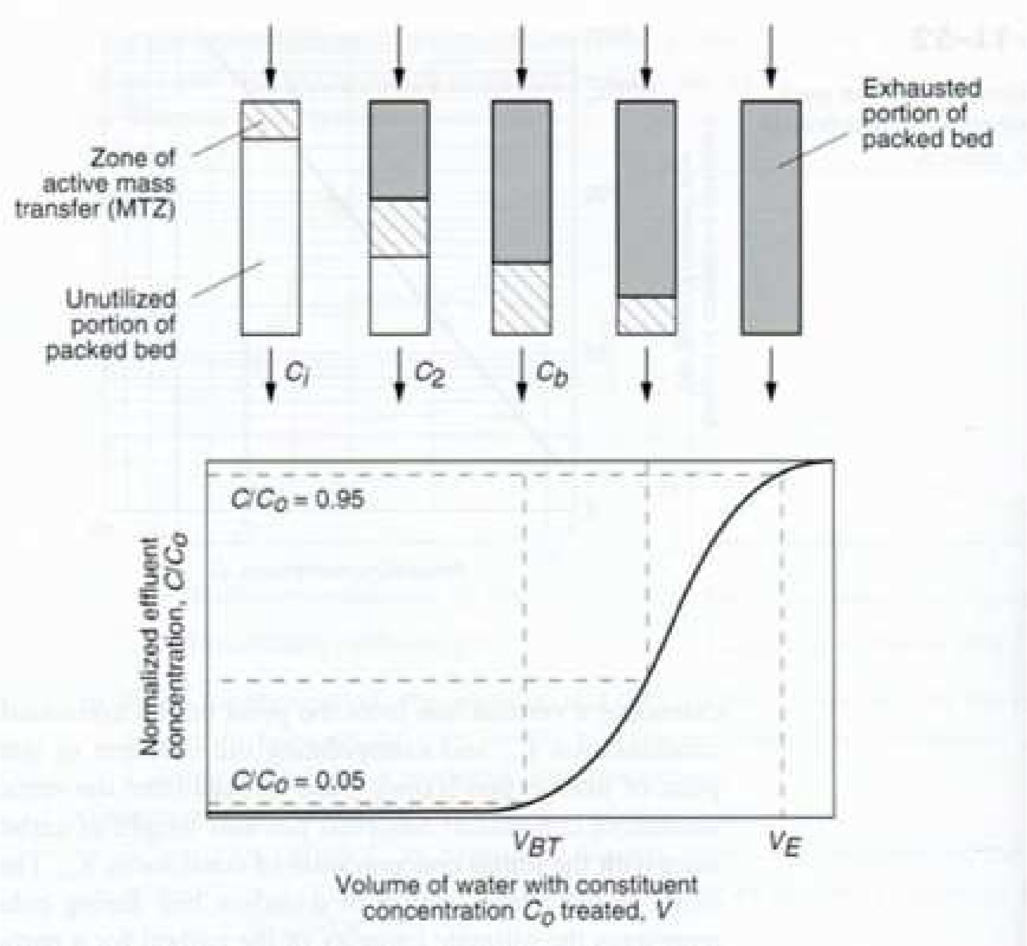
Types of adsorbents

- **Activated carbon**
  - Most common – removal of refractory organics & residual COD
  - Derived by i) pyrolysis of organic materials (wood, coal, coconut, etc.) and ii) activation by steam or CO_2 at high temperatures
  - Two types based on particle size
    - GAC (granular activated carbon): > 0.1 mm, apply in columns
    - PAC (powdered activated carbon): < 0.074 mm, apply in well-mixed contact tanks

- **Granular ferric hydroxide**
  - Ferric hydroxides/oxides have high affinity to many metals and metalloids
  - Applicable for removal of arsenic, chromium, selenium, copper, etc.

- **Activated alumina**
  - May be considered in case of water reuse
  - Removal of arsenic and fluoride

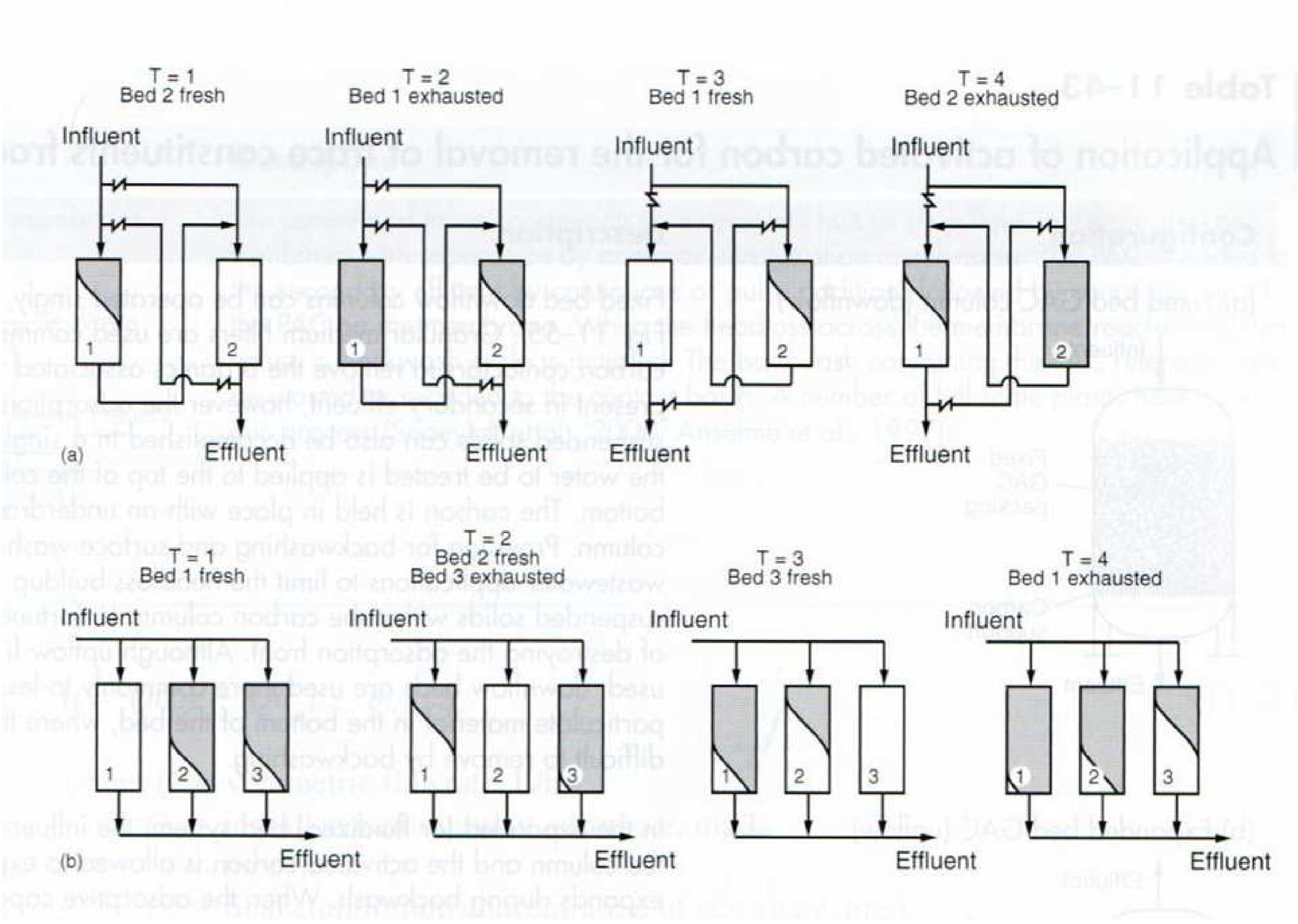
GAC columns: breakthrough curve



#6

- **Mass transfer zone** (MTZ; dashed zone): adsorption is occurring, some adsorbate conc. in pore-water
- Grey zone: GAC exhausted (adsorption equilibrium with influent), no further adsorption
- **Breakthrough** occurs after adding V_{BT} of influent, but **want full usage of the column**!

GAC columns: configurations



#7

Ion exchange

- **A unit process in which ions of a given species are displaced from an insoluble exchange material by ions of a different species in solution**
- **So ions in the solution is exchanged by other ions originating from the insoluble exchange material**
- **Applications**
  - Most common: water softening (Na^+ from exchange material to solution; Ca^{2+} and Mg^{2+} from solution to exchange material)
  - Removal of nitrogen, heavy metals, and TDS
- **Commonly used exchange materials**
  - Natural mineral: zeolite
  - Synthetic material: ion exchange resin

Ion exchange – N & heavy metal removal

- **Nitrogen removal**
  - Remove NH_4^+ or NO_3^-
  - NH_4^+: zeolite or synthetic cation exchange resins
  - NO_3^-: synthetic anion exchange resins

- **Heavy metal removal**
  - Zeolites, synthetic anion and cation resins, chelating resins
  - Some chelating resins are made to have a high selectivity for specific metals (cations – Cu, Ni, Cd, Zn, …)

References

#1) https://www.ysi.com/Product/id-7586200/Ceramic-Disc-Diffuser

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