Separation Processes

ChE 4M3

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- if you let us know about **any errors** in the slides
- **any suggestions to improve the notes**

All of the above can be done by writing to

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or anonymous messages can be sent to Kevin Dunn at

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If reporting errors/updates, please quote the current revision number: 219

Administrative issues

- Assignment 2 solutions are posted now
- Project topics are posted. Due by 12 November 2013
    1. Treatment of dissolved solids in fracking wastewater
    2. Removing CO_2 from a gas phase stream of mixed hydrocarbons
    3. Removing non-valuable particulate solids (dust) from a gas-phase stream
    4. *Challenge Project*: design and operation of a device or method to create drinking-quality water in a region of hardship
        - water is not easily accessible, and is contaminated
        - electricity is not readily available
        - consumers of the water would have little/low money to pay for your water
        - the device/method must not require technical sophistication to operate

Membranes

[Flickr: 21182585@N07/2057883807]

[Flickr: 21182585@N07/3574729377]

Quick activity

On a sheet of paper write

- bullet points *and/or*
- draw a diagram *and/or*
- describe

"what you know about membranes"

References

- Perry's Chemical Engineers' Handbook, 8th edition, chapter 20.
- Wankat, "Separation Process Engineering", 2nd edition, chapter 16.
- Schweitzer, "Handbook of Separation Techniques for Chemical Engineers", chapter 2.1.
- Seader, Henley and Roper, "Separation Process Principles", 3rd edition, chapter 14.
- Richardson and Harker, "Chemical Engineering, Volume 2", 5th edition, chapter 8.
- Geankoplis, "Transport Processes and Separation Process Principles", 4th edition, chapter 7 (theory) and chapter 13.
- Ghosh, "Principles of Bioseparation Engineering", chapter 11.
- Uhlmann's Encyclopedia, "Membrane Separation Processes, 1. Principles", DOI:10.1002/14356007.a16_187.pub3

Why use membranes?

Some really difficult separations:

- finely dispersed solids; density close to liquid phase; gelatinous particles
- dissolved salts must be removed
- non-volatile organics (e.g. humic substances)
- biological materials: sensitive to the environment
- biological materials: aseptic operation is required
  - cannot centrifuge
  - cannot sediment

It is usually worth asking:

How does nature separate?

- energy efficient
- effective
- maybe slow?

Why use membranes?

Relatively new separation step ("new" meaning since 1960 to 1980s)

- often saves energy costs over alternative separations
  - ambient temperature operation
- often easier to operate and control

[Henk Koops' slides, GE Water and Process Technologies]

Modules:

- feed stream split into parallel units
- easier to maintain and replace parts
- can be expanded as needs grow

Challenges in membrane design

Challenges that still remain:

- withstanding high pressure differences but still have a thin membrane
- dealing with fouling and cleaning
- increasing selectivity (separation factor) for specific application areas
- uniformity of pore sizes
- temperature stability (e.g. steam sterilization)

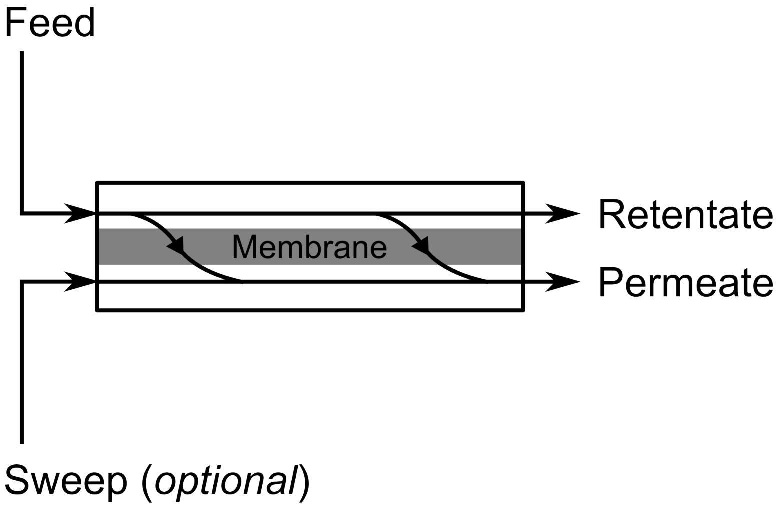
Market size

TABLE 20-16 Membrane Market in 2005

Segment	$M/yr Size	Applications	Characteristics
Dialysis	~2,000	Medical	Mature growing 5%
Reverse osmosis	~500	Water treatment	Growing 10%
Microfiltration	~500	Water, food, pharm.	
Ultrafiltration	~400	Water, food, pharm.	Growing 10%
Gas separation	~500	Nitrogen	
Electrodialysis	~100	Water	
Pervaporation	~5	Solvent/water	Nascent
Facilitated transport	0	None	In development

[Perry's: chapter 20, 8ed]

Let's formalize some terminology



[Seader, Henley and Roper, p 501]

More terminology

semipermeable: partially permeable, e.g. your skin allows certain size particles in, but not others

mass separating agent: the membrane itself

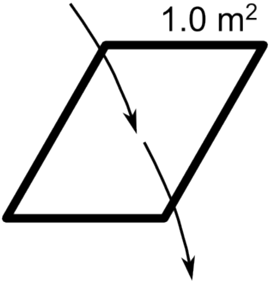
energy separating agent: the applied pressure (pressure drop)

$$\text{porosity} = \frac{\text{area of open pores}}{\text{total surface area}}$$

What is flux?

The (volumetric) or (molar) or (mass) flow per unit time for 1 unit of area

- $J = \text{flux} = \dfrac{\text{transfer rate}}{\text{transfer area}}$
- e.g. 42 $\text{mol.s}^{-1}.\text{m}^{-2}$
- never simplify the units: write 13 $\left(\text{m}^3.\text{s}^{-1}\right).\text{m}^{-2}$
- you may, and probably should, omit the brackets: 13 $\text{m}^3.\text{s}^{-1}.\text{m}^{-2}$
- do not write 13 m.s^{-1}



General principle

For a given unit area, we want the highest flux possible (at the lowest possible cost)

Membrane classification

Table 8.1. Classification of membrane separation processes for liquid systems

Name of process	Driving force	Separation size range	Examples of materials separated
Microfiltration	Pressure gradient	10–0.1 μm	Small particles, large colloids, microbial cells
Ultrafiltration	Pressure gradient	<0.1 μm–5 nm	Emulsions, colloids, macromolecules, proteins
Nanofiltration	Pressure gradient	~1 nm	Dissolved salts, organics
Reverse osmosis (hyperfiltration)	Pressure gradient	<1 nm	Dissolved salts, small organics
Electrodialysis	Electric field gradient	<5 nm	Dissolved salts
Dialysis	Concentration gradient	<5 nm	Treatment of renal failure

[Richardson and Harker, p 438]

Transport through a membrane

Why study theoretical models?

All forms of membrane applications rely to some extent on the same equation **structure**. The details will change.

Will allow us to:

- troubleshoot problems with the process
- predict expected impact of improvements/changes to the process
- used for crudely sizing the unit (order of magnitude estimates)

Examples you will be able to solve

1. how long should we operate unit at constant ΔP to achieve desired separation?
2. what is the mass transfer coefficient through the lab membrane?
3. what pressure drop (and therefore pump size) do I expect?
4. how many cassettes (area) does this application require?

The general equation

$$\frac{\text{transfer rate}}{\text{transfer area}} = \text{flux} = \frac{\text{(permeability)(driving force)}}{\text{thickness}} = \frac{\text{driving force}}{\text{resistance}}$$

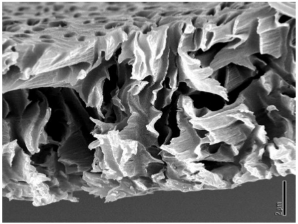
Symbolically:

$$\rho_f \frac{Q_p}{A} = \frac{\rho_f}{A} \cdot \frac{dV}{dt} = J = \frac{\text{(permeability)(driving force)}}{L} = \frac{\text{driving force}}{R}$$

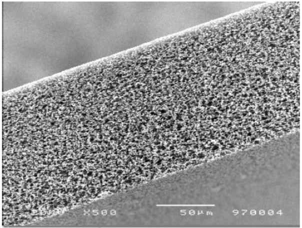
- permeance $= \dfrac{\text{permeability}}{L} = \dfrac{1}{\text{resistance}} = \dfrac{1}{R} =$ "mass transfer coeff"
- permeance: easier to measure
- permeance units: depend on choice of (driving force) and J
- resistance $= f$(thickness, viscosity, porosity, pore size)
- we will specifically define resistance in each case

Microfiltration

- 0.1 μm to 10 μm retained mainly by sieving mechanism
- conventional filters: not effective below $\sim 5\ \mu$m
- microfiltration membranes: generally symmetric pores
- polysulfone membrane
- (surface) porosity as high as $\epsilon = 0.8$
- driving force $= \Delta P$: 100 to 500 kPa
- high fluxes at low TMP (trans-membrane pressure)
- application areas:
  - yeast cells harvesting
  - wine/beer/juice clarification
  - bacteria and virus removal
  - air filtration
  - cytology: concentrate up cells



symmetric open structure



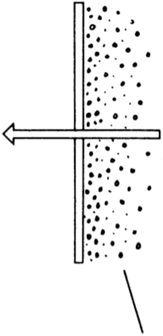
symmetric spongy structure

[Henk Koops' slides]

General modelling equation applied

$$\frac{\rho_f}{A} \cdot \frac{dV}{dt} = \text{Flux} \quad = J = \frac{\Delta P}{\mu \left(R_m \ell_M + R_c L_c \right)}$$

$$\frac{\rho_f}{A} \cdot \frac{dV}{dt} = \text{Flux} \quad = J = \frac{\Delta P}{\mu \left(R'_m + R'_c \right)}$$

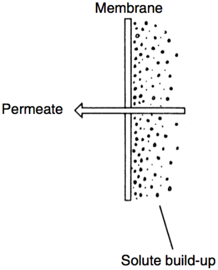


J	$[\text{kg.s}^{-1}.\text{m}^{-2}]$	permeate flux
μ	$[\text{kg.m}^{-1}.\text{s}^{-1}]$	permeate viscosity
ΔP	$[\text{Pa}] = [\text{kg.m}^{-1}.\text{s}^{-2}]$	TMP varies for different applications
R_m	$[\text{m.kg}^{-1}]$	resistance through membrane (small)
R_c	$[\text{m.kg}^{-1}]$	resistance through cake (large)
ℓ_m	$[\text{m}]$	membrane thickness
L_c	$[\text{m}]$	effective cake thickness
ρ_f	$[\text{kg.m}^{-3}]$	fluid density

[Illustration from Richardson and Harker, Ch8]

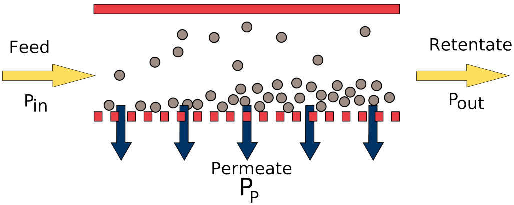
Flow patterns for microfiltration

Dead-end flow



- only for very low concentration feeds
- else becomes rapidly clogged
- air filtration and virus removal applications

Cross-flow (TFF)



- TFF = tangential flow filtration
- main purpose?
  - microfiltration: tends to have cake build up
  - cross-flow induces shearing to erode cake
  - reduces cake resistance, R'_c
  - $\Delta P = \dfrac{P_{\text{in}} + P_{\text{out}}}{2} - P_{\text{P}}$

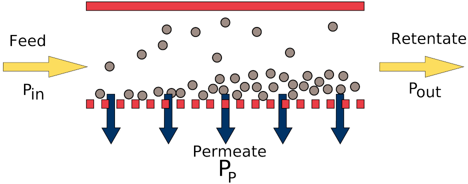
Dead-end flow vs cross-flow geometries

Dead-end flow

- cake thickness increases with time: $L_c(t)$
- implies cake resistance changes with time: $R'_c(t)$
- so for a constant ΔP, implies $J(t)$ falls off

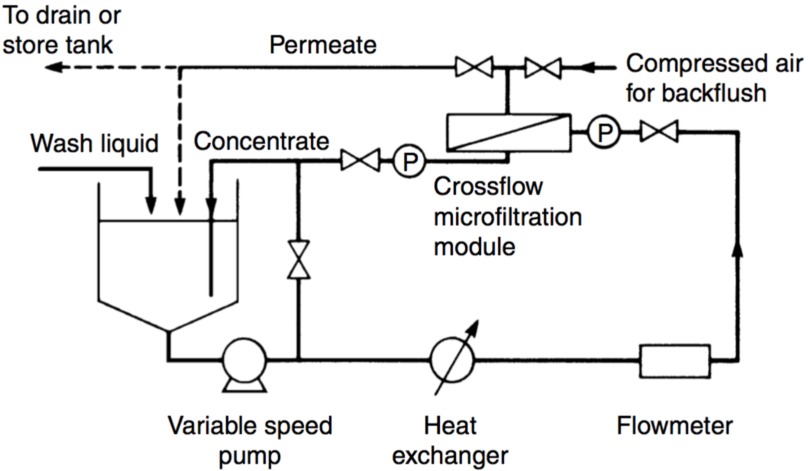
$$J = \frac{\Delta P}{\mu\left(R'_m + R_c L_c\right)}$$

Cross-flow (TFF)



- fluid velocity: 1 to 8 $m.s^{-1}$ tangentially
- keeps mass transfer resistance low
- for a given ΔP: TFF allows us to obtain higher fluxes than dead-end (usually ΔP is 100 to 500 kPa)
- cannot take lab test results with a filter cloth dead-end and apply it to cross-flow situation

Cross-flow flowsheet

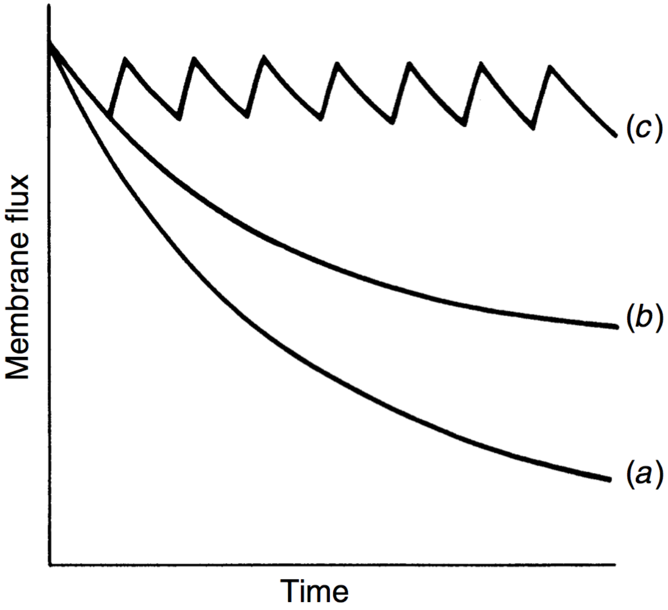


How to pressurize the unit?

1. Supply feed at pressure; valve at retentate to adjust/control ΔP
2. Draw a vacuum at permeate and pull material through membrane

[Illustration from Richardson and Harker, Ch8]

Dealing with fouling



[Richardson and Harker, Ch8]