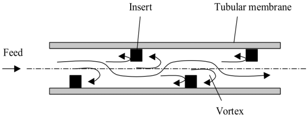
Fouling

- Process feed pretreatment is important.
- e.g. in bio area: prefiltration, pasteurisation to destroy bacteria, or adjust pH to prevent protein precipitation
- Backflushing mostly restores permeation rate (opens pores)
- Can also use pulsated/oscillating feed flows
- Consider adding tube inserts



- Inject air: *sparging* with oxygen or nitrogen
- Oscillating electrical field works on certain feeds
- Chemical cleaning is eventually required [long time], e.g.:
  - flush with filtered water
  - recirculate/back-flush with a cleaning agent at high temperature
  - rinse to remove the cleaning agent
  - sterilize by recirculating weak chlorine solution at high temps
  - flushing with water to remove sterilizing solution

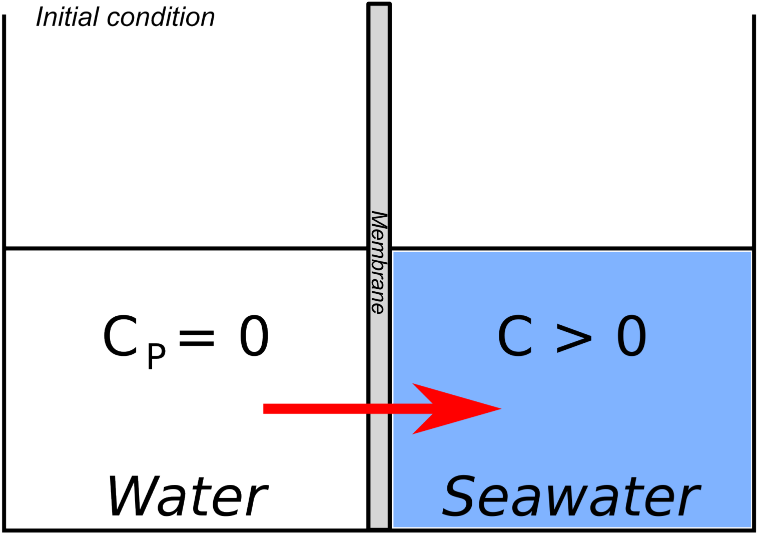
Video

http://www.youtube.com/watch?v=YIMGZWmh_Mw: How spiral membranes are made

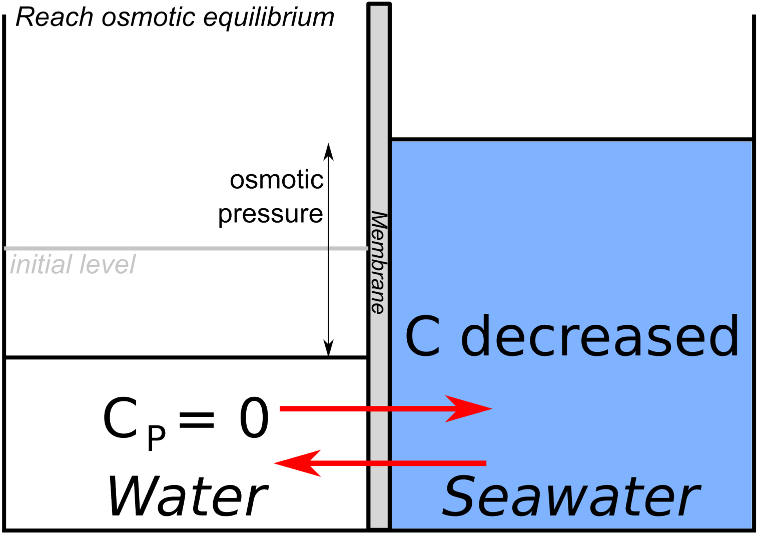
Reverse osmosis

- One the most requested topics (start of the term!)
- One of the largest membrane markets by $ size
  1. Dialysis
  2. Reverse osmosis (water treatment)
- What is osmosis? [Greek = "push"]
- Then we look at reverse osmosis (RO)
- Applications of RO
- Modelling RO

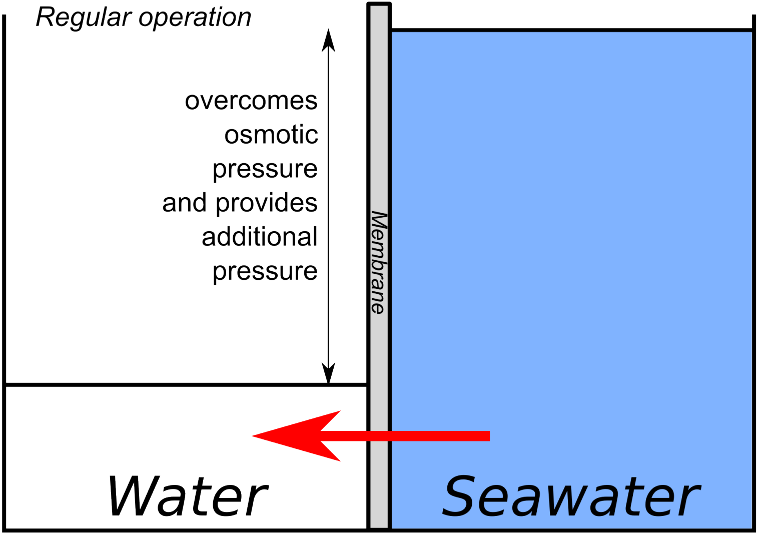
Osmosis principle



Osmosis principle



Reverse osmosis principle

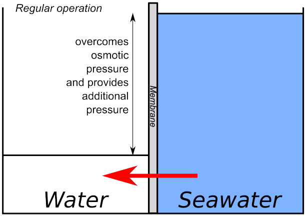


(Reverse) Osmosis principle

- Assume solute barely passes through membrane ($C_p \approx 0$)
- but solvent passes freely: this is why we call it a *semipermeable membrane*
- Chemical potential drives pure solvent (water) to dilute the solute/solvent (mixture).
- This *solvent flux* continues until equilibrium is reached
  - solvent flow to the left equals solvent flow to the right
  - results in a pressure difference (head)
  - called the *osmotic pressure* $= \pi$ [Pa]
  - a thermodynamic property $\neq f$(membrane)
  - a thermodynamic property $= f$(fluid and solute properties), e.g. temperature, concentration, pressure

(Reverse) Osmosis principle

- Osmosis in action:
  - trees and plants to bring water to the cells in upper branches
  - killing snails by placing salt on them
  - why freshwater fish die in salt water and *vice versa*
  - try at home: place peeled potato in very salty water
- If you exceed osmotic pressure you reverse the solvent flow
- Called “reverse osmosis”
- Net driving force in this illustration = ____________________



Typical values of osmotic press

For dilute solutions

$$\pi \approx \frac{nRT}{V_m} = CRT$$

π	[atm]	osmotic pressure
n	[mol]	mols of **ions**: e.g. Na^+ and Cl^-
R	$[m^3.atm.K^{-1}.mol^{-1}]$	gas law constant: 8.2057×10^{-5}
V_m	$[m^3]$	volume of solvent associated with solute
T	[K]	temperature
C	[mol of ions per m^3]	generic concentration

Example

Prove to yourself: 0.1 mol ($\sim$ 1 teaspoon) of NaCl dissolved in 1 L of water at 25°C is **4.9 atm**!

- that's almost 500 kPa
- or almost 50m of head for 5.8 g NaCl in a litre of water
- (recall: 1 atm $\approx$ 10 m of water height)

Other osmotic values

The previous equation is an approximation.

Some actual values:

Substance	Osmotic pressure [atm]
Pure water	0.0
0.1 mol NaCl in 1 L water	4.56
2.0 mol NaCl in 1 L water	96.2
Seawater [3.5 wt% salts]	25.2

- Driving force in membrane separation is pressure difference
- $\Delta P = \pi$ implies we only counteract the osmotic pressure
- Reverse osmosis occurs when we increase $\Delta P > \pi$
- So the net useful driving force applied: $\Delta P - \pi$
- Ultrafiltration ΔP was 0.1 to 1.0 MPa (10 atm) typically
- RO: typical ΔP values: 2.0 MPa to 8.0 MPa, even 10.5 MPa

Let's be a little more accurate

- The solute (salt) passes through the membrane to the permeate side
- $C_p \neq 0$
- There is an osmotic pressure, π_{perm} back into the membrane.
- Correct, net driving force $= \Delta P - \Delta \pi$
  - ΔP is the usual TMP we measure
  - $\Delta \pi = \pi_{\text{feed}} - \pi_{\text{perm}}$
  - $\Delta \pi = C_{\text{ions,feed}} RT_{\text{feed}} - C_{\text{ions,perm}} RT_{\text{perm}}$
  - Even more correctly: $\Delta \pi = C_{\text{ions,wall}} RT_{\text{wall}} - C_{\text{ions,perm}} RT_{\text{perm}}$

Key point

There's a natural limitation here: what if we try to recover too much solvent?

Widest application for RO: desalination

Some quotes:

- "*McIlvaine forecasts that world RO equipment and membrane sales will reach $5.6 billion (USD) in 2012, compared to $3.8 billion in 2008 (actual).*"
- "*Depleting water supplies, coupled with increasing water demand, are driving the global market for desalination technology, which is expected to reach $52.4 billion by 2020, up 320.3% from* **$12.5 billion in 2010**. *According to a recent report from energy research publisher SBI Energy, membrane technology reverse osmosis will see the largest growth, reaching $39.46 billion by 2020.*"

Industrial applications of RO

- demineralization of industrial water before ion exchange
- not primary aim, but RO membranes retain > 300 Dalton organics
- ultrahigh-purity water
  - laboratories
  - kidney dialysis
  - microelectronic manufacturing
  - pharmaceutical manufacturing (purified water)
- tomato, citrus, and apple juice dewatering [$\sim$ 4.5 c/L; 1995]
- dealcoholization of wine and beer to retain flavour in the retentate
- other: keep antifreeze, paint, dyes, PAH, pesticides in retentate; discharge permeate to municipal wastewater

Salt-water reverse osmosis example

- Larnaca, Cyprus [island state near Greece/Turkey]
- Desalination plant: Build, Own, Operate, and Transfer
- 21.5 million m^3 per year
- Seawater intake → flocculation and filtration [why?] → RO → chemical dosing → chlorination
- Energy recovery of ΔP (see http://www.youtube.com/watch?v=M3mpJysa6zQ: novel way of recovering pressure energy)

RO costs [Perry's; 8ed], 1992

TABLE 20-23 Representative RO Process Costs

Costs	Seawater
Operating conditions	
Inlet pressure	6.9 MPa
Flux	25 LMH*
Conversion	40%
Total cost, $/1000 gal	4.7
Capital cost	2.1
Operating cost	2.6
Total capital cost, $/(gal/day)	4.5
Direct costs	3.7
Equipment	3.3
Indirect costs	0.8
Total operating cost, $/1000 gal	2.6
Energy	1.6
Membrane replacement	0.4
Chemicals	0.2
Labor	0.3
Other	0.1

Household RO cost:

- $ 0.015 to $0.07/L