Lecture 18

DISSOLVED SOLIDS REMOVAL (2)

Course: Water Reuse
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هدایت الکتریکی

- بین جامدات محلول و هدایت الکتریکی آب رابطه ای وجود دارد که وابسته به ماهیت یون ها، درجه حرارت و دیگر عوامل است
- به صورت **حدودی**: $TDS=K*EC_{25}$

$$EC_{25} = EC_t[1 + 0.022(25 - t)]$$

Water type	Typical EC_{25} (μS/cm)	*K* factor
Distillate	1–10	0.50
RO permeate	300–800	0.55
Seawater	45,000–60,000	0.70
Reject brines	65,000–85,000	0.75

TDS and EC

Origin	Salinity (g · L⁻¹)
Baltic Sea	17
Black Sea	22 to 25
Atlantic and Pacific Oceans	32 to 38
Mediterranean Sea	37 to 40
Red Sea	40 to 47
Dead Sea	270

Water type	Approximate EC (μS/cm) at 25°C
Ultra-pure water	0.05–0.5
Distilled waters	1–10
Rain waters	5–50
Potable waters	50–1000
Brackish waters	2000–20,000
Saline waters	20,000–40,000
Seawaters	40,000–60,000
Brines	60,000→

Water Flux Rate

the flux of water through the membrane is a function of the pressure gradient:

$$F_w = k_w(\Delta P_a - \Delta\Pi) = \frac{Q_p}{A}$$

where F_w = water flux rate, L/m²·h
k_w = mass transfer coefficient for water flux (involving temperature, membrane characteristics, and solute characteristics), L/m²·h·bar
ΔP_a = average imposed pressure gradient, bar

$$= \left[\frac{P_f + P_r}{2}\right] - P_p \qquad \text{(Note: 1 bar} = 10^5 \text{ Pa)}$$

$\Delta\Pi$ = osmotic pressure gradient, bar

$$= \left[\frac{\Pi_f + \Pi_r}{2}\right] - \Pi_p$$

P_f = inlet pressure of feedwater, bar
P_r = pressure of retentate stream, bar
P_p = pressure of permeate water, bar
Π_f = osmotic pressure in feedwater, bar
Π_r = osmotic pressure in retentate, bar
Π_p = osmotic pressure in permeate, bar
Q_p = permeate stream flow, L/h
A = membrane area, m²

Mass (solute) flux rate

Mass (Solute) Flux Rate

Some solute passes through the membrane in all cases. Solute flux can be described adequately by an expression of the form:

$$F_s = k_s \Delta C_s = \frac{(Q_p)(10^{-3}\ m^3/L)C_p}{A} \quad (9\text{-}5)$$

where F_s = mass flux of solute, g/m²·h

k_s = mass transfer coefficient for solute, m/h

ΔC_s = solute concentration gradient across membrane, g/m³

$$= \left[\frac{C_f + C_r}{2}\right] - C_p$$

C_f = solute concentration in feed stream, g/m³

C_r = solute concentration in retentate (concentrate) stream, g/m³

C_p = solute concentration in permeate stream, g/m³

Q_p = permeate stream flow, L/h

Recovery Ratio

The permeate recovery ratio, r, which is the conversion of feedwater to permeate (product water), is defined as:

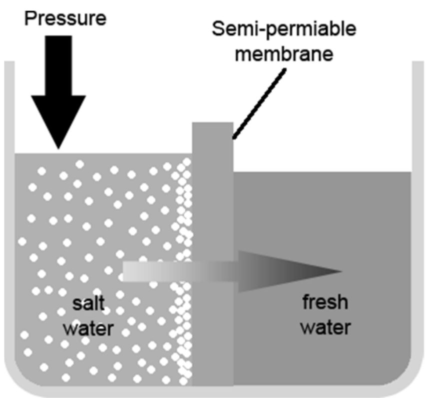
$$r, \% = \frac{Q_p}{Q_f} \times 100 \quad (9\text{-}6)$$

where Q_p = permeate stream flow, L/h, m³/h, or m³/s

Q_f = feed stream flow, L/h, m³/h, or m³/s

- With increased recovery, the required feedwater flow is reduced, the pressure will increase (stronger pump), and the brine will be more concentrated.
- The pressure is a complex function of recovery ratio, feedwater salinity, temperature, and the permeate flux of the membrane. The power requirement of the high pressure pump is proportional to the flow and pressure.

Concentration Polarization



Example

EXAMPLE 9-2. Determine Membrane Performance for TDS Reduction in Reclaimed Water.

A wastewater with a TDS concentration of 1500 g/m³ is required to be reclaimed for groundwater recharge by means of surface spreading. RO treatment is required with product water having a TDS of no more than 200 g/m³. A thin film composite membrane is used having a mass transfer coefficient for water flux k_w of 1.0 L/m²·h·bar and a mass transfer coefficient for solute k_s of 5×10^{-4} m/h. The flow rate is to be 150 m³/h. The net operating pressure ($\Delta P_a - \Delta\Pi$) will be 20 bar (2000 kPa). Assume the recovery rate will be 85 percent. Estimate the rejection rate and the concentration of the retentate stream.

Solution

Solution

1. Determine the membrane area required to produce 150 m^3/h of water and the TDS concentration of the permeate.
2. Estimate membrane area using Eq. (9-4).

$$F_w = k_w(\Delta P_a - \Delta\Pi)$$

$$= (1.0\ L/m^2\cdot h\cdot bar)(20\ bar) = 20\ L/m^2\cdot h$$

$$Q_p = F_w \times A,\ Q = r Q_f = 0.85 Q_f$$

$$A = \frac{(0.85)(150\ m^3/h)(10^3\ L/m^3)}{(20\ L/m^2\cdot h)} = 6375\ m^2$$

3. Estimate permeate TDS concentration using Eq. (9-5).

$$F_s = k_s \Delta C = \frac{Q_p C_p}{A}$$

Substituting the definition for ΔC from Eq. (9-5), and solving for C_p yields

$$C_p = \frac{k_s[(C_f + C_r)/2]A}{Q_p + k_s A}$$

Assume $C_r \approx 10\ C_f$ and solve for C_p (Note: If the estimated C_r value and computed value of C_r, as determined below, are significantly different, the value of C_p must be recomputed).

Assume $Q_p = r Q_f$

$$C_p = \frac{(5 \times 10^{-4}\ m/h)[(1500\ g/m^3 + 15{,}000\ g/m^3)/2](6375\ m^2)}{(0.85)(150\ m^3/h) + (5 \times 10^{-4}\ m/h)(6375\ m^2)} = 201\ g/m^3$$

Solution

4. Estimate the rejection rate using Eq. (9-7).

$$R, \% = \frac{C_f - C_p}{C_f} \times 100$$

$$R = \frac{(1500\ g/m^3 - 201\ g/m^3)}{(1500\ g/m^3)} \times 100 = 86.6\,\%$$

5. Estimate the retentate stream TDS by rewriting Eq. (9-10).

$$C_r = \frac{Q_f C_f - Q_p C_p}{Q_r}$$

$$C_r = \frac{(150\ m^3/h)(1500\ g/m^3) - (0.85 \times 150\ m^3/h)(201\ g/m^3)}{(0.15)(150\ m^3/h)} = 8.9 \times 10^3\ g/m^3$$

Operating parameters

Parameter	Unit	Nanofiltration	Reverse osmosis
Flux rate	$L/m^2\cdot h$	10–35	12–20
Operating pressure			
1000–2500 mg/L TDS	kPa	350–550	1200–1800
Seawater TDS	kPa	500–1000	5500–8500

Note: kPa $\times 10^{-2}$ = bar (1 bar = 100 kPa = 10^5 N/m^2).
kPa $\times$ 0.145 = $lb/in.^2$

- Energy consumption of NF and RO for brackish water is typically about 1 kWh/m^3 and 2 kWh/m^3
- For seawater SWRO energy recovery devices are required

بازیافت انرژی

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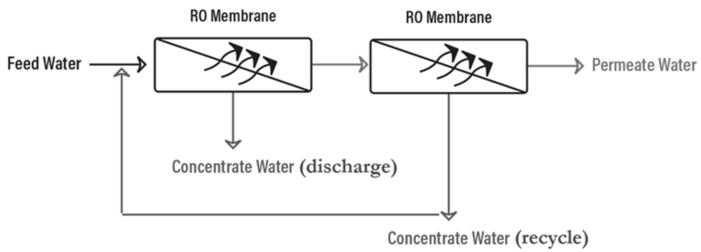
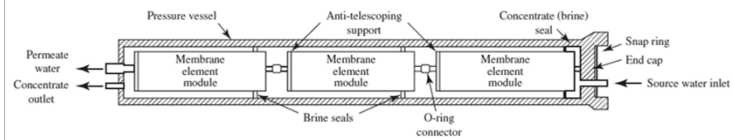
- کارخانه های اسمز معکوس مقدار زیادی برق مصرف می کنند
- به عنوان مثال، برای شیرین سازی آب دریا، حدودا 8-11kWh به ازای هر متر مکعب آب شیرین مصرف میشود
- پس می بایست روش هایی به کار برد، که مقداری از این انرژی را بازیافت کند
- با به کار گیری تجهیزات و طراحی مناسب، مصرف کل کارخانه می تواند به 3-4kWh به ازای تولید هر متر مکعب آب برسد

ترکیب – pass



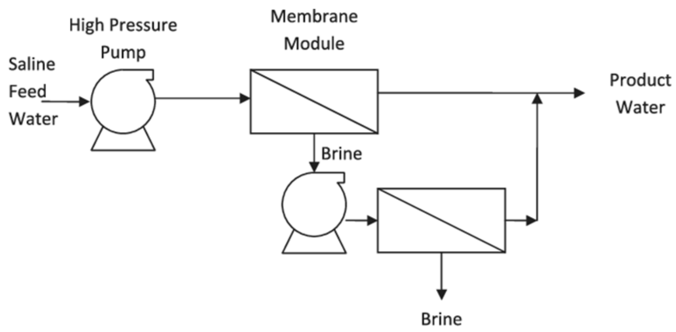
قرارگیری المان ها



کیفیت آب

Pass Streams (mg/L as Ion)						
Name	Feed (Seawater)	Concentrate		Permeate		
		Stage 1	Stage 2	Stage 1	Stage 2	Total
K	380	606.6	758.4	1.09	3.18	1.62
Na	10556	16860	21081	26.71	76.45	39.22
Mg	1262	2016	2523	0.74	2.05	1.07
Ca	400	639.1	799.7	0.23	0.65	0.33
Sr	13	20.77	25.99	0.01	0.02	0.01
CO3	7.06	13.2	17.69	0	0	0
HCO3	140	219.58	272.11	0.6	1.35	0.78
Cl	18980	30305	37896	44.02	125.9	64.62
F	1	1.6	2	0	0.01	0
SO4	2649	4233	5297	0.62	1.7	0.89
CO2	1.77	2.94	3.73	2.05	3.14	2.33
TDS	34388	54916	68673	74.02	211.3	108.6
pH	7.6	7.58	7.63	5.64	5.78	5.69

ترکیب – stage



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Langelier Saturation Index

- Let us define pHs as the pH at which Ca and HCO_3 are in equilibrium with $CaCO_3$:

$$CaCO_3 + H^+ \leftrightarrows Ca^{2+} + HCO_3^-$$

- If the actual pH is lower than the pH_s this would mean that the concentration of H^+ is higher than equilibrium. Thus the above chemical equation will shift to the right (and dissolve calcium carbonate).

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پس تصفیه

- اسمز معکوس گازهای محلول را به مقدار زیاد حذف نمی کند، پس اگر آب ورودی گازهای غیرمطلوب داشته باشد، آب خروجی نیز تا حدودی خواهد داشت (به عنوان مثال سولفید هیدروژن) که باید حذف شود
- آب تولیدی pH اسیدی دارد، قلیاییتش کم است، قابلیت بافر ندارد، و خورنده است
  - پس باید پس تصفیه برای افزایش املاح و کاهش خورندگی انجام دهیم. همچنین برای انتقال در شبکه، ضدعفونی ثانویه می کنیم

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Langelier Saturation Index

- The LSI is the most popular index used
- It is the change in pH required for bringing the water to equilibrium:

$$\text{Langelier Saturation Index (LSI)} = \text{pH} - \text{pH}_s$$

- The values of pH_s can be calculated from reaction kinetics, or by using a variety of different empirical relations with different levels of accuracy

Langelier Saturation Index

- One empirical relation for when the calcium and alkalinity are less than 1000 mg/L as $CaCO_3$:

$$\text{pHs} = \left(10.0754 + 2.432636e^{\left(-\frac{T}{86.89927}\right)} - 0.2006e^{(-0.004624\times\text{TDS})} - \log(\text{Cah}) - \log(\text{Alk})\right)$$

T (^{o}C), TDS (mg/L), Cah (mg/L as $CaCO_3$), Alk (mg/L as $CaCO_3$)

Langelier Saturation Index

- Provides estimate for thermodynamic driving force
- It does not predict "how much" precipitation or dissolution we will have
- Optimum LSI for corrosion protection is slightly positive = slight coating of pipe walls
- LSI is NOT accurate. It does not incorporate corrosion inhibiting chemicals.
- Experts have called for its abandonment but still, it is the most popular index

نرم افزار

- نرم افزارهایی وجود دارد که در طراحی سیستم اسمز مکعوس به کار می رود
- اکثر پارامترهای مربوطه در نرم افزار لحاظ شده است: درجه حرارت، فشار اسمزی، concentration polarization ، نرخ های انتقال جرم، کیفیت آب خروجی، کیفیت پساب و ...
- هر نرم افزار مربوط به یک تولید کننده غشاء است:
- ROSA , IMS Design , Toray DS2