Lecture 19

ELECTRODIALYSIS

Course: Water Reuse

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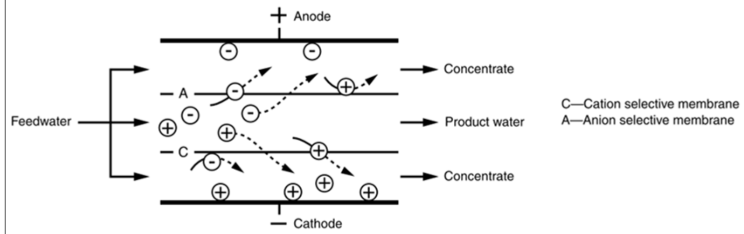
What is electrodialysis?

- Electrodialysis (ED) is an electrochemical separation process in which mineral salts and other ionic species are transported through ion-selective membranes from one solution to another under the driving force of an electric potential.



ED setup

- The key to the ED process is the ion selective membranes. Ion exchange membranes that allow passage of positive ions (e.g. Na+) are called cation membranes. Membranes that allow passage of negative ions (e.g. Cl-) are called anion membranes.
- When a DC voltage is applied, the electrical potential created becomes the driving force to move ions. Meanwhile hydrogen gas (H_2) evolves from the cathode and oxygen gas (O_2) evolves from the anode to maintain charge neutrality during operation.

Cell pairs

- A set of adjacent components consisting of a diluting compartment spacer, an anion membrane, a concentrating compartment spacer, and a cation membrane is called a cell pair. Electrolysis stacks can contain hundreds of cell pairs.
- Anions attempting to migrate to the anode will pass through the adjacent anion membrane but will be stopped by the first cation membrane they encounter. Cations trying to migrate to the cathode will pass through the cation membrane but will be stopped by the anion membrane.

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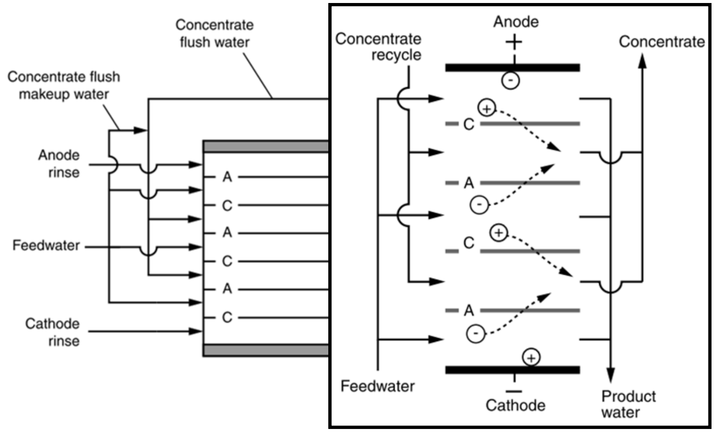
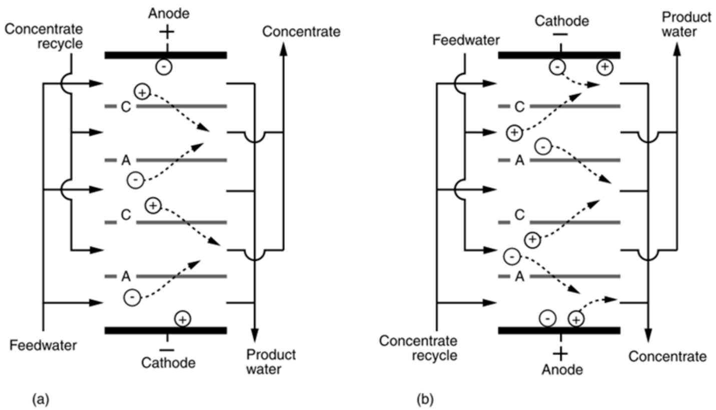
ED stack schematic



ElectroDialysis Reversal (EDR)

- An EDR unit operates on the same principle as ED technology, except that EDR is "self-cleaning" and uses periodic reversal of the DC polarity.
- Polarity reversal causes the concentrating and diluting flow streams to switch after every cycle. Fouling or scaling are thus removed, sending fresh product water through the compartments filled previously with concentrated waste streams.
- Product water is not collected during a short interval of time following reversal.



Schematic of electrodialysis reversal (EDR) process: (a) negative polarity and (b) positive polarity. Because the polarity is reversed, the anode and cathode rinse similar to ED is not needed.

EDR for brackish water

- Electrodialysis reversal systems are able to reduce dissolved ions in process streams containing 10,000 to 12,000 mg/L of total dissolved solids.
- However, because of energy requirements, EDR is better suited for the treatment of brackish water in the range from 1000 to 5000 mg/L.
- As a rule of thumb, it takes about 1 kWh to remove a kilogram of salt. Typical removal rates can range from 50 to over 90% (series required for high removals)

Example

- At what TDS is the energy required by the EDR process for producing $1m^3$ of permeate, equal to the energy required by RO for producing $1m^3$ of permeate? Compare permeate TDS.

- For EDR assume:
  - 1 kWh is used for the removal of each kg of TDS
  - The recovery is: $Recovery_{\%} = -2*TDS_{feed,(g/L)} + 95$
  - The rejection is 85%

Example (cont)

- For RO assume:
  - The energy used is $Energy_{kWh/m3} = 0.05*TDS_{feed,(g/L)} + 1.8$
  - The recovery is: $Recovery_{\%} = -1.6*TDS_{feed,(g/L)} + 90$
  - The rejection is 98%

Solution

- For this example, the excel software can help greatly. For simplicity, we assume 100 m^3 of water is entering the system for both technologies.

- NOTE: This example is grossly oversimplified and many factors are not considered, it can only give a general understanding.

Solution - EDR

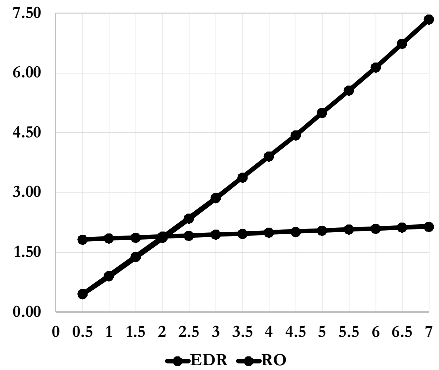
Feed water volume (m3)	Feed TDS (g/L)	Rejection %	kg salt removed	volume water produced (m3)	kWh/m3 product	TDS of product (g/L)
			(=B4*C4*D4/100)	(=B4*(-2*C4+95)/100)	(=E4/F4)	(=(B4*C4-E4)/F4)
100	0.5	85	42.5	94	0.45	0.080
100	1	85	85	93	0.91	0.161
100	1.5	85	127.5	92	1.39	0.245
100	2	85	170	91	1.87	0.330
100	2.5	85	212.5	90	2.36	0.417
100	3	85	255	89	2.87	0.506
100	3.5	85	297.5	88	3.38	0.597
100	4	85	340	87	3.91	0.690
100	4.5	85	382.5	86	4.45	0.785
100	5	85	425	85	5.00	0.882
100	5.5	85	467.5	84	5.57	0.982
100	6	85	510	83	6.14	1.084
100	6.5	85	552.5	82	6.74	1.189
100	7	85	595	81	7.35	1.296

Solution - RO

Feed water volume (m3)	Feed TDS (g/L)	Rejection %	kg salt removed	volume water produced (m3)	kWh/m3 product	TDS of product (g/L)
			(=B4*C4*D4/100)	(=B4*(-1.6*C4+90)/100)	(=0.05*C3+ 1.8)	(=(B4*C4-E4)/F4)
100	0.5	98	49	90	1.83	0.011
100	1	98	98	89.1	1.85	0.022
100	1.5	98	147	88.2	1.88	0.034
100	2	98	196	87.3	1.90	0.046
100	2.5	98	245	86.4	1.93	0.058
100	3	98	294	85.5	1.95	0.070
100	3.5	98	343	84.6	1.98	0.083
100	4	98	392	83.7	2.00	0.096
100	4.5	98	441	82.8	2.03	0.109
100	5	98	490	81.9	2.05	0.122
100	5.5	98	539	81	2.08	0.136
100	6	98	588	80.1	2.10	0.150
100	6.5	98	637	79.2	2.13	0.164
100	7	98	686	78.3	2.15	0.179

Solution - comparison

	Energy kWh/m3		TDS g/L	
Feed TDS	EDR	RO	EDR	RO
0.5	0.45	1.83	0.08	0.011
1	0.91	1.85	0.16	0.022
1.5	1.39	1.88	0.24	0.034
2	1.87	1.90	0.33	0.046
2.5	2.36	1.93	0.42	0.058
3	2.87	1.95	0.51	0.070
3.5	3.38	1.98	0.60	0.083
4	3.91	2.00	0.69	0.096
4.5	4.45	2.03	0.78	0.109
5	5.00	2.05	0.88	0.122
5.5	5.57	2.08	0.98	0.136
6	6.14	2.10	1.08	0.150
6.5	6.74	2.13	1.19	0.164
7	7.35	2.15	1.30	0.179



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Design calculations

Power Requirements for Ion Transfer

The current required for ED can be estimated using Faraday's laws of electrolysis. Because one Faraday of electricity will cause one gram equivalent of a substance to migrate from one electrode to another, the number of gram equivalents removed per unit time is given by:

$$\text{Gram eq/unit time} = Q(N_{inf} - N_{eff}) = Q\Delta N \qquad (9\text{-}17)$$

where $\text{gram/eq} = \dfrac{\text{Mass of solute, g}}{\text{Equivalent weight of solute}}$

Q = product flowrate, L/s

N_{inf} = normality of influent (feed), g-eq/L

N_{eff} = normality of effluent (product), g-eq/L

ΔN = change in normality between the influent and effluent, g-eq/L

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Design calculations

The corresponding expression for the current for a stack of membranes is given by:

a localized deficiency of ions may occur on the surface of the membrane, causing a condition called polarization. Polarization should be avoided as it results in high electrical resistance leading to excessive power consumption.

$$i = \frac{FQ(N_{inf} - N_{eff})}{nE_c} = \frac{FQ\Delta N}{nE_c} \qquad (9\text{-}18)$$

Where i = current, A

F = Faraday's constant = 96,485 A·s/g-eq = 26.80 A·h/g-eq

n = number of cell pairs in the stack

E_c = current efficiency, % (expressed as a decimal)

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Current density and normality

- Current density is defined as the current in milliamperes that flows through a square centimeter of membrane perpendicular to the current direction.
- Normality is the concentration of a solution based on the number of gram equivalents of a solute per liter of solution. A solution containing one gram of equivalent weight per liter is referred to as normal.
- The ratio of CD to N (CD/N) is of importance. High values of the CD/N ratio are indicative that there is insufficient charge to carry the current.

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Power consumption

- The resistance of the water, R, must be determined experimentally. Once R and the current flow, i, are known, the power required as per Ohm's law:

$$P = E \times i = R(i)^2$$

Where P = power, W
E = voltage, V
= R × i
R = resistance, Ω
i = current, A

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Example

EXAMPLE 9-4. Determine Power Requirements and Membrane Area for ED Treatment of Reclaimed Water.

Determine the power and area required to reduce the TDS content of 4000 m^3/d of a reclaimed water to be used for industrial cooling water. Assume the following data apply.

1. Use an ED unit comprised of 500 cell pairs
2. Influent TDS concentration = 2500 mg/L (~ 0.05 g·eq/L)
3. TDS removal efficiency = 50%
4. Product water flowrate = 90% of feed stream
5. Current efficiency = 90 percent
6. CD/N ratio = (500 mA/cm^2)/(g·eq/L)
7. Resistance = 5.0 Ω

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Normality calculation reminder

$$mg = \frac{mEq \cdot M}{valence}$$

If the salt is assumed to be NaCl

$$2500 = \frac{mEq \cdot (23 + 35.5)}{1}$$

$$mEq = \frac{2500}{58.5} = 0.043\ Eq$$

If the salt is assumed to be $CaCO_3$

$$2500 = \frac{mEq \cdot (100)}{2}$$

$$mEq = \frac{2500 \cdot 2}{100} = 0.05\ Eq$$

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Solution

1. Calculate the current using Eq. (9-18).

$$i = \frac{FQ\Delta N}{n\,E_c}$$

$$Q = (4000\ m^3/d) \times (1000\ L/m^3)/(86{,}400\ s/d) = 46.3\ L/s$$

$$i = \frac{(96{,}485\ A \cdot s/eq)\ (46.3\ L/s)(0.9)(0.05\ eq/L)\ (0.5)}{500 \times 0.90}$$

$$i = 223\ A$$

2. Determine the power required using Eq. (9-19).

$$P = R(i)^2$$

$$P = (5.0\ \Omega)(223\ A)^2 = 248{,}645\ W = 249\ kW$$

Solution

3. Determine the power requirement per m^3 of treated water.

$$\text{Power consumption} = \frac{(249\ kW)\ (24\ h/d)}{(4000\ m^3/d)(0.9)} = 1.66\ kWh/m^3$$

4. Determine the required surface area per cell pair.
   a. Determine the current density:

$$CD = (500\ mA/cm^2)/(g\ eq/L) \times 0.05\ g \cdot eq/L = 25\ mA/cm^2$$

   b. The required area is:

$$\text{Area} = \frac{(223\ A)(1000\ mA/A)}{(25\ mA/cm^2)} = 8920\ cm^2 = 0.89\ m^2$$

Notes

- The ED process should be protected from particulate fouling by a 10 μm cartridge filter
- A single electrodialysis stack can remove from 25 to 60 percent of the TDS, depending on the feedwater characteristics. Further desalting requires that two or more stacks be used in series.
- Membranes for ED(R) have a life of about 10 years. Effective and timely CIP (cleaning in place) extends the membrane life and improves product quality and power consumption.

Notes

- Cation membranes typically last longer than anion membranes because anion membranes are particularly susceptible to oxidation by chlorine and other strong oxidants
- The anode and cathode last for about 2-3 years, although anode life is usually shorter
- EDR requires less maintenance than RO because of the reversal process, yet RO has other benefits such as better TDS removal.

Typical ED design

Parameter	Unit	Range
Flux rate	$m^3/m^2 \cdot d$	0.8–1.0
CD/N ratio	mA/cm^2	500–800
Membrane resistance, Ω	Ohms	4–8
TDS removal	%	50–94
Current efficiency	%	85–95
Concentrate stream flow	% of feed	10–20
Energy consumption[a]	kWh/m^3	1.5–2.6
Approximate energy per kg of salt removed	$kWh/m^3 \cdot kg$	1–1.2

[a]Based on treating reclaimed water with a TDS concentration in the range from 1000 to 2500 mg/L. Not recommended for TDS concentration values beyond 10,000 to 12,000 mg/L.

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ED(R) vs. RO

Advantages	Disadvantages
Electrodialysis	
• Minimal pretreatment may be required (cartridge filtration is recommended) • Operates at a low pressure • Process is much quieter because high pressure pumps are not required • Antiscalant is not required • Membrane life expectancy is longer because foulants are removed continuously during the reversal process • Requires less maintenance than RO due to reversal process	• Limited to 50 percent salt rejection for a single membrane stack (stage) • Requires larger footprint to produce similar quantity and quality of water if multiple staging is used • Electrical safety requirements • Less experience for wastewater demineralization in the U.S. • Not as effective at removing microorganisms and many anthropogenic organic contaminants

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ED(R) vs. RO

Advantages	Disadvantages
Reverse osmosis	
• RO membranes provide a barrier to microorganisms and many anthropogenic organic contaminants (for the treated portion of the water produced) • More demonstrated experience for wastewater demineralization • RO membranes can remove more than 90 percent of TDS • Source water blending will reduce size of systems • Flexibility to provide higher quality water, if desired	• Requires high pressure to achieve high salt rejection • Requires pretreatment processes to minimize scaling and fouling • Requires chemical addition for MF & RO fouling control • More routine maintenance may be required to maintain performance

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