EXPLORING THE POTENTIAL OF ELECTRODIALYSIS

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Electrodialysis is an electrochemical membrane separation technique for ionic solutions that has been used in industry for several decades.[1] It can be used in the separation and concentration of salts, acids, and bases from aqueous solutions, the separation of monovalent ions from multivalent ions, and the separation of ionic compounds from uncharged molecules. It can be used for either electrolyte reduction in feed streams or recovery of ions from dilute streams.[2-4] Industrial applications encompass several industries and include the production of potable water from brackish water, removal of metals from wastewater, demineralization of whey, deacidification of fruit juices, and the removal of organic acids from fermentation broth.[1,2-5] Additional examples of the applications of electrodialysis are given in Table 1.

As a selective transport technique, electrodialysis uses an ion-selective membrane as a physical barrier through which ions are transported away from a feed solution. An energy-intensive phase change is unnecessary, in contrast to the common separation techniques of distillation and freezing.[6] The use of an organic solvent, as is often required with other selective transport techniques such as liquid extraction, is avoided with electrodialysis. In addition, electrodialysis is typically performed under mild temperature conditions, making it particularly attractive for food, beverage, and pharmaceutical applications that deal with heat liable substances.

In typical chemical engineering undergraduate curricula, students are exposed to traditional separations methods with a heavy emphasis on operations such as distillation, extraction, and absorption. The need for incorporation of membrane technology into the chemical engineering curriculum has attracted recent attention.[7-9]

The membrane separation processes mentioned above employ "traditional" driving forces such as concentration and pressure gradients, in contrast to electrodialysis, which uses electrical potential to drive the separation. The first treatment of electrodialysis in the educational literature appeared in 1931.[10] In this work, Kendall and Gebauer-Fuelnegg present three reasons why electrodialysis remains among the "neglected methods" of organic chemistry: 1) its treatment in textbooks is inadequate, 2) its advantages and applicability are not generally recognized, and 3) simple and efficient types of electrodialyzers are not generally available. While bench-scale electrodialysis equipment is now readily available from various manufacturers, electrodialysis is not commonly addressed in chemical engineering curricula, due primarily to the first two reasons presented above. Several reference books include excellent treatment of electrodialysis theory and applications,[1,3-5,11] but this material is not easily "distilled" into material that can be introduced in the undergraduate classroom or laboratory, particularly if the professor has limited experience with membrane separations.

Increasing interest in electrochemical education is reflected by recent publications that address electrochemical reactors for synthesis and pollution control.[12-17] Kendall and Gebauer-

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Fuelnegg[10] made a strong case for inclusion of electrodialysis in the chemistry curriculum and described inexpensive laboratory set-ups for simple and rapid laboratory investigations. Literature that specifically explores electrodialysis in chemical engineering and chemistry education is scarce, however. Garcia-Garcia, *et al.,* have developed an exciting experiment for the desalting of an amino acid solution using electrodialysis as an alternative to precipitation using organic solvents.[18]

This paper describes a hands-on investigation of electrodialysis that introduces the basic principles and applications of electrodialysis technology. The effects of various process operating conditions on the system performance are explored experimentally. Emphasis is given to data analysis and engineering calculations related to rate of ion transfer, Faraday's law, efficiency, energy consumption, and separation performance. These experiments can be implemented in core chemical engineering courses such as unit operations and separation processes, or in elective or graduate-level courses in green/environmental engineering, wastewater treatment, electrochemical engineering, pharmaceutical engineering, and food engineering. Through these experiments, students are not only exposed to an innovative membrane separation experiment, but they also gain a greater knowledge of experimental skills and calculations relevant to the membrane field.

FUNDAMENTALS

The principle that governs electrodialysis is an electrical potential difference across an alternating series of cation and anion exchange membranes between an anode and a cathode. The feed solution containing both positive and negative ions enters the membrane stack to which a voltage is applied, thus causing the migration of the ions toward their respective electrodes. The cation exchange membranes allow the transfer of cations but inhibit the transfer of anions. Conversely, anion exchange membranes allow the transfer of anions but inhibit the transfer of cations. The result is alternating compartments containing streams of dilute ion concentration (diluate) and streams rich in ion concentration (concentrate) exiting the stack. An ionic rinse solution is circulated past the electrodes to maintain conductivity of the membrane stack while preventing potentially corrosive ions from the feed solution from contacting the electrodes. This concept is illustrated in Figure 1 with a feed solution of a salt (C^+A^-) in aqueous solution.

The electrodialysis membrane stack comprises electrodes and membranes separated by gaskets and spacers. The spacers are turbulence-promoting support mesh used to create the compartments through which the solutions flow. Uniform flow distribution and prevention of internal leakage through spacer and gasket design are critical to system performance. Stack design is discussed by Strathmann.[3]

Material balances can be written for streams entering and exiting the membrane stack, as ions are transported from the feed stream to the concentrate stream. The molar rate of transfer of an ionic species to a stream passing through the mem-

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TABLE 1
Industrial Applications of Electrodialysis

Electrolyte reduction
- Potable water from brackish water
- Nitrate removal for drinking water
- Boiler water, cooling tower water, effluent steam desalting
- Cheese whey demineralization
- Fruit juice deacidification
- Sugar and molasses desalting
- Potassium tartrate removal from wine
- Blood plasma protein recovery
- Demineralization of amino acid solutions in the food industry
- Acid removal from organic products

Electrolyte recovery
- Edible salt production from seawater
- Ag(I) salts from photographic waste
- Zn(II) from galvanizing rinse water
- Organic salts from fermentation broth
- Amino acids from protein hydrolysates
- Salts, acids, and alkali from industrial rinse waters

Miscellaneous
- Conversion of organic salts into acid and base (bipolar membrane ED)
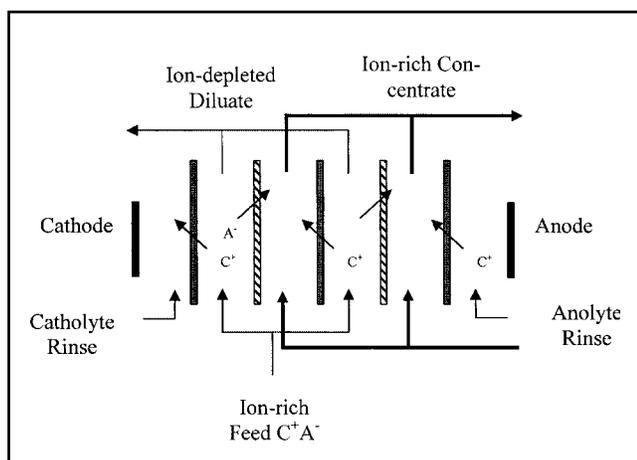- Salt splitting

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Figure 1. The principles of electrodialysis.

brane stack is

$$\dot{m}^i = F_2^i C_2^i - F_1^i C_1^i \qquad (1)$$

where the subscript 2 is the stream exiting the stack and 1 is the stream entering the stack, superscript i represents either the feed or concentrate stream, F is volumetric flowrate, and

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The electrodialysis sytem is easy to operate and the students can perform the suggested experiments in a typical undergraduate laboratory period. The experiments can be used in a variety of undergraduate classes, including a unit operations laboratory or separations course.

C is concentration of the species being transported. In batch recirculation mode, the streams exiting the stack are returned directly to the well-mixed reservoir vessels. The solutions in the reservoir vessels are then fed to the stack. The unsteady-state material balance on the reservoir vessel is

$$\frac{d}{dt}\left(V^i C_1^i\right) = F_1^i C_1^i - F_2^i C_2^i \qquad (2)$$

Equating Eqs. (1) and (2) yields an expression for the molar rate of change in the reservoir vessels in terms of measured reservoir volume V^i and concentration

$$\dot{m} = -\frac{d}{dt}\left(V^i C_1^i\right) \qquad (3)$$

Transfer of ions to and from the rinse solutions does take place, and this rate of transfer is found by an overall balance on the three streams (feed, rinse, and concentrate):

$$\dot{m}^r + \dot{m}^c + \dot{m}^f = 0 \qquad (4)$$

Electrodialysis is commonly performed in either constant-voltage or constant-current mode. Calculations relating voltage and current to power consumption and efficiency are of critical interest, and basic equations that will be used for process evaluation are presented here.

The cell voltage and current within a membrane stack are related through Ohm's Law

$$\mathscr{V} = I \yen R \qquad (5)$$

where $\mathscr{V}$ is the voltage (V), I is the current (A), and R is the resistance of the membrane stack (   ). The resistance of the membrane stack is due to the friction of the ions with the membranes and the aqueous solution while being transferred from one solution to another.[5] At high voltages, the system does not follow Ohm's Law, and the interested reader is re-

ferred to standard texts such as Mulder[1] for the description of other regimes.

The power consumption necessary for the removal of ions from the feed solution is proportional to the current and the stack resistance. The necessary power, P(J/s), is represented by

$$P = I^2 R \qquad (6)$$

This equation does not account for power necessary to pump the feed, rinse, or diluate streams.[1]

Combination of Eqs. (5) and (6) results in a power expression in terms of measured variables voltage and current, and the number of membrane pairs in the stack, n,

$$P = \mathscr{V} nI \qquad (7)$$

Current is the rate of charge passed through the stack

$$I = \frac{dc}{dt} \qquad (8)$$

where c = charge passed (Coul) and t is time (s). For a system operated at constant voltage, the power consumption will change throughout the run as the current changes. The power is defined as the rate of energy consumption

$$P = \frac{dE}{dt} \qquad (9)$$

To determine the total energy consumed in time t, Eqs. (7) and (8) are substituted into Eq. (9), which is integrated from time 0 to t to obtain

$$E = n\mathscr{V} c \qquad (10)$$

The efficiency of the membrane stack is a measure of the system's ability to use the current effectively in the removal of ions. The minimum (theoretical) charge, c_{min}, required to transfer m moles of ions through the membrane stack is expressed by Faraday's Law

$$c_{min} = zm\mathscr{F} \qquad (11)$$

where z is the valence and $\mathscr{F}$ is Faraday's Constant (96,500 c/mol). The efficiency, h, of the stack compares the minimum theoretical charge to the actual charge required to transport ions through a stack having n membrane pairs[3]

$$h = \frac{c_{min}}{nc} \qquad (12)$$

An efficiency of less than one indicates that not all of the charge passed by the electrodialysis system was used to transfer ions from one stream to another. Potential causes of a less-than-perfect efficiency include less-than-perfect ion selectivity of the membranes, the potential of parallel current paths within the membrane stack, and the transfer of water

molecules by osmosis and ion hydration.[6] The efficiency will change with feed and concentrate solution concentrations throughout a batch run, since the rates of water transfer by osmosis and ion hydration are concentration-dependent.[3]

In an electrodialysis system with the feed stream containing monovalent and divalent ions, the selectivity of a specific membrane of one ion over another can be calculated. The selectivity, a, is taken to be the ratio of the number of moles transferred from the feed vessel of each ion j and k, m^j and m^k.[19]

TABLE 2
Basic Features of the Electrodialysis System

Cell body • *Polypropylene*

Number of membranes • *10 pairs*

Individual effective membrane area • *0.1 m²*

Spacers • *Polypropylene mesh, 0.75 mm intermembrane gap, 2.0 mm electrode chamber gap*

Gaskets • *Epoxy-Cured EPDM*

Anode • *Platinized titanium*

Cathode • *316 stainless steel*

Reservoir • *Custon 2-L glass*

Conductivity/Temperature measurement • *Amel K-1 glass, polypropylene probes with Amel SIRIO meters*

Charge, Current, Voltage, Temperature, Flow measurement/ display • *The Boss electrochemical process control system*

Pumps • *March model BC-3CP-MD centrifugal, polypropylene and ceramic with viton o-rings*

Flow sensors • *Teflon impeller style, Cole-Parmer Model U-33110-05*

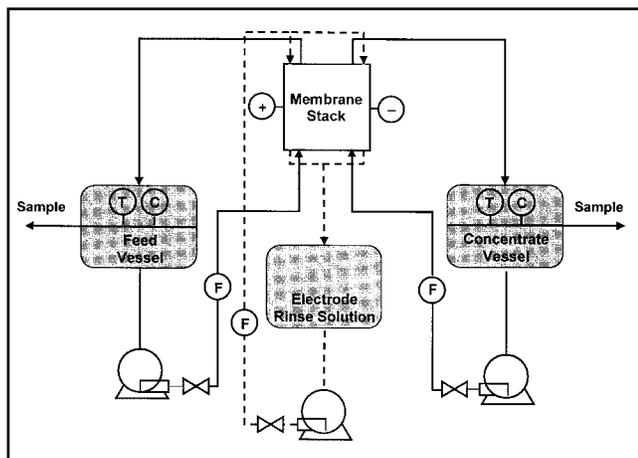**Tubing, compression fittings, valves** • *Polypropylene, 1/2-inch diameter*

Figure 2. Scheme of the experimental electrodialysis system employed for the separation runs. T, C, F are Temperature, Conductivity, and Flowrate on-line analyzers.

$$a = \frac{m^j}{m^k} \qquad (13)$$

Equation (13) is applicable when the ion species j and k are equal in the feed vessel. In a batch electrodialysis system, the feed concentrations change with time, and Eq. (13) for overall selectivity throughout the run is used to quantify the selective transport of ions.

There is a wide range of important theoretical concepts and practical issues related to electrodialysis that are beyond the scope of this paper. Selective transport theory is presented in various references[3,5,6] and Strathman[5] offers a practical treatment of design and cost estimates that would allow estimation of membrane area and required energy for a desired plant capacity. Additional practical considerations of electrodialysis operations include limiting current density, boundary layer effects, and concentration polarization, osmosis, and electroosmosis effects. For treatment of these topics, the reader should consult references 1,3,4,5,6, and 11.

ELECTRODIALYSIS SYSTEM DESCRIPTION

The laboratory-scale electrodialysis system in our experiments was purchased from Electrosynthesis Corporation in Lancaster, New York. The major components of the system are the electrodialysis cell, an electrochemical process control unit, and system instrumentation. The basic features of the electrodialysis system in our laboratory are summarized in Table 2. The entire system was purchased for approximately $30,000. A perfectly adequate electrodialysis system could be constructed for well under $10,000 by purchasing a fabricated electrodialysis cell for about $3,200 (electrodes, cell body, membranes, gaskets, and spacers) and assembling the other components and instrumentation in-house.

The Electrosynthesis Model ED-1 electrodialysis cell features a platinum-on-titanium anode and 316 stainless steel cathode, polypropylene cell body, and individual membrane area of 0.01 m². Multiple pairs of membranes allow a total membrane area up to 0.2 m². The cell stack includes turbulence-promoting mesh spacers and gaskets. A photograph of the electrodialysis cell is shown in Farrell, *et al.,*[20] in this issue of *CEE* (Figure 2b).

The Boss Model 710 electrochemical process control system features a digital coulometer, digital temperature monitor, four independent pump and flow control loops, and digital indicators for temperature, cell potential, current, process charge, and setpoints. Safety features include process shutdown for exceeding flow, voltage, temperature, or charge limits.

The system is fully instrumented with in-line conductivity/

temperature probes (K-1, AMEL, Milan, Italy), programmable microprocessor conductivity/resistivity indicator (model SIRIO, AMEL s.r.l., Milan, Italy), Teflon impeller flow sensor (model U-33110-05, Cole Parmer, Vernon Hills, IL) with ratemeter/totalizer (model DP78A, Omega Engineering, Inc., Stamford, CT). Determination of cation concentrations for mixed monovalent-divalent cation solutions was made using ion selective electrodes (divalent cation electrode Model 93-32 and ammonium electrode model 93-18 with sensing module, Thermo Orion, Beverly, MA).

The electrodialysis process is shown schematically in Figure 2, and a photograph of the system is shown in the companion paper by Farrell, *et al.,* (Figure 2a).[20] The system is operated in batch recirculation mode. Continuous and batch modes of operation, along with their relative advantages and disadvantages, are described by Shaffer and Mintz.[6]

ION EXCHANGE MEMBRANES

The performance of ion-permeable membranes used in electrochemical processes depends on several properties. The desirable characteristics of membranes used in electrodialysis applications include[5,21] selectivity between ions of opposite charge, high ionic conductivity, low electrical conduction, long-term chemical stability, mechanical strength, and resistance to fouling. These characteristics are determined by the membr_{j,,}1 matrix polymer and the fixed ionic moiety that effects the ion selectivity of the membrane. Strathmann[5] describes the challenges of optimization of these properties. Polymer materials such as polystyrene, polyethylene, and polysulfone are often chosen for the membrane matrix and are often cross-linked to ensure stability. Fixed ionic moieties such as SO_3^-, COO^-, PO_3^{2-}, HPO_2^-, AsO_3^{2-}, and SeO_3^- are commonly used for cation exchange membranes, and NH_3^+, RNH_2^+, R_3N^+, R_2N^+, R_3P^+, R_2S^+, are common choices for anion-exchange membranes.[5]

There are several manufacturers of ion-selective membranes for a variety of electrochemical process applications. Table 3 provides information on the materials and features of several ion exchange membranes used in electrodialysis applications. Detailed information on membrane manufacturers and membrane characteristics is provided in reference books[3,21] and directly from the manufacturers. Membrane replacement costs are on the order of $100/m^2.

Tokuyama Soda Neosepta® ion-exchange membranes are used in our experiments. Two Neosepta cation exchange membanes, CMX and CMS, were investigated, while the same anion exchange membranes, Neosepta AMX, were used in all experiments. Neosepta AMX and CMX membranes are standard grade, general-purpose polystyrene-based ion exchange membranes. Neosepta CMS membranes have a thin cationic charged layer on the membrane surface that increases the selectivity between monovalent cations (*i.e.,* NH4+) and multivalent cations (*i.e.,* Mg^{2+}). Neosepta membranes have high ionic selectivity, low electric resistance, and a low diffusion coefficient for solute or solvent. They exhibit high mechanical strength and high dimensional stability, and are highly resistant to chemical attack.

EXPERIMENTAL

Ammonium cations and chloride anions are contaminating

TABLE 3
Ion Exchange Membranes Used in Electrodialysis Applications
(Information from References 3, 21, and Membrane Manufacturers)

Manufacturer	Tradename	Material	Special Features	Location
Solvay		Perfluorinated film with fixed pyridine (anion-permeable) or sulfonic acid (cation-permeable)		France
FuMA-Tech		Polyetherketones, polysulfone, polyphenylene oxide		Germany
Tokuyama Soda	Neosepta®	Styrene-divinyl benzene	Robust high mechanical strength; Moderate electrical resistance	Japan
Asahi Glass	Selemiom®	Polystyrene-based	Very low electrical resistance	Japan
Asahi Chemical	Aciplex®	Styrene-divinyl benzene/PVC backing		Japan
Ionics, Inc.		Heterogeneous polystyrene-based/acrylic fabric, with fixed sulfonate (cation-permeable) and quarternary ammonium cations (anion-permeable)	Rugged, low resistance, high selectivity, chemically stable, low fouling	MA, USA
Dupont Co.	Nafion®	Perflourinated sulfuric acid polymer	Cation permeable	NC, USA
Sybron	Ionac®	Heterogeneous resin-PVDF/fabric	High mechanical strength	NJ, USA

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species that are commonly present in industrial process streams. In this investigation, we considered removal of ammonium chloride from an aqueous stream. Experiments were performed to study the effect of the following parameters in the removal of NH_4Cl from water: the initial concentration of the concentrate vessel, the applied cell voltage, and the selection of the membranes. Additional experiments could be conducted to investigate other process parameters such as number of membrane pairs, flow rate, feed concentration, and temperature (within the limits of the membranes). The system performance was evaluated using efficiency, selectivity, power, and energy consumption calculations.

The membrane stack was constructed with five pairs of cation and anion exchange membranes, with a cation exchange membrane adjacent to each electrode as described above. A solution of 0.5 M ammonium sulfate was used as
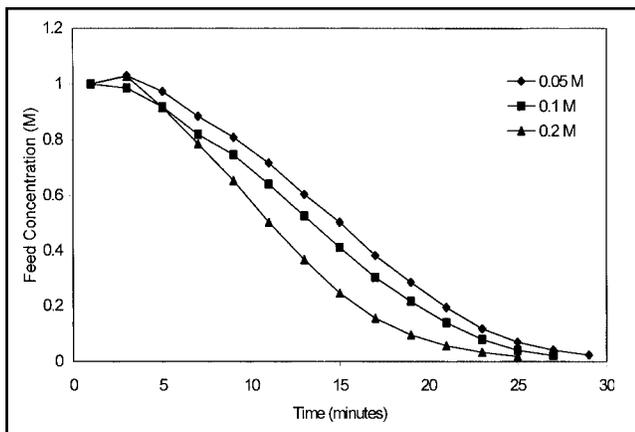

Figure 3. *Effect of initial concentrate concentration at constant voltage. Process operating conditions: 13 V, 1 M feed (initial), AMX/CMX membranes.*
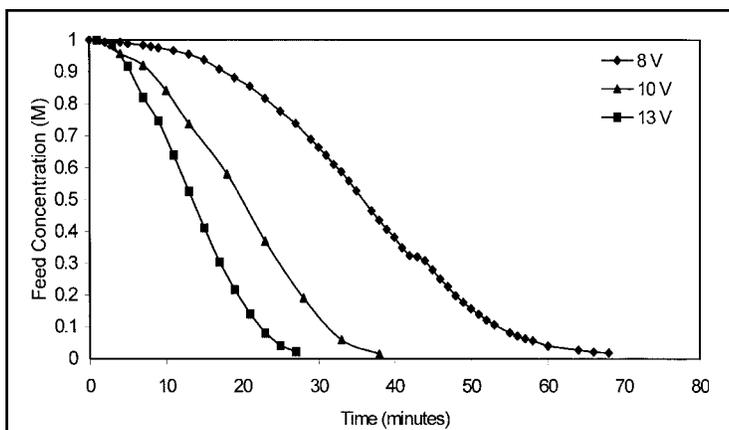

Figure 4. *Effect of voltage on the feed concentration. Process operating conditions: 1 M feed (initial), 0.1 concentrate (initial), and AMX/CMX membranes.*

the anolyte/catholyte rinse solution in order to prevent generation of chlorine or hypochlorite, which would be hazardous. The feed solution was aqueous NH_4Cl or $NH_4Cl/MgCl_2$ with a total initial salt concentration of approximately 1.0 M. The concentrate stream was an aqueous NH_4Cl with an initial concentration between 0.05 and 0.2 M (specified for each run). At the anode, the expected predominant reaction in this system with a neutral solution is the formation of oxygen

$$2\,H_2O_{(l)} \rightleftharpoons O_{2(g)} + 4\,H^+ + 4\,e^- \qquad (14)$$
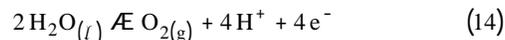
At the cathode, the formation of hydrogen gas is the predominant reaction in neutral solution

$$2\,H_2O_{(l)} + 2\,e^- \rightleftharpoons H_{2(g)} + 2\,OH^-_{(aq)} \qquad (15)$$
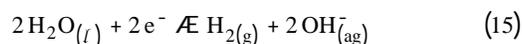
The system was operated in a constant voltage, batch recirculation mode. Flowrates were 0.5 L/min for the feed and concentrate streams, and 0.7 L/min for the combined anolyte and catholyte streams. The following data were collected at regular intervals of ten minutes or less: liquid volume in each vessel, conductivity of each stream, current, charge passed, and temperature. Completion of experiments took between 70 and 90 minutes, depending on the applied voltage and other operating parameters. The experiment was considered complete when the current dropped to approximately 1.0 A. The ion concentrations were determined using conductivity measurements.

Initial concentration of the concentrate vessel is important because it is a key parameter in the resistance of the membrane stack. If the concentrate stream initially has an extremely low ion concentration, water splitting may occur in order to provide the ions necessary to carry the current. (Water splitting generates hydrogen ions and hydroxyl ions, which are capable of migrating through the cation- or anion-selective membranes, respectively; this may result in pH changes in the diluate and concentrate compartments.) Thus, the concentrate stream is usually "primed" with a low electrolyte concentration to facilitate transport of the desired ions from the feed stream. To illustrate this, the system performance is compared using different initial concentrate vessel concentrations. The effect of the initial ion concentration in the concentrate stream is shown in Figure 3.

These runs were performed at a constant voltage of 13 V using a 1.0 M NH_4Cl feed and 0.5 M $(NH_4)_2SO_4$ rinse, and the initial concentrate concentration was varied from 0.05 M to 0.2 M NH_4Cl. The figure shows the decline in the feed ion concentration throughout the course of the runs. The rate of ion transport increases with increasing initial concentrate concentration. At

higher concentrate concentrations, the ionic conductivity of the membrane increases, effecting a higher current for a given voltage drop across the cell stack and thus resulting in a higher rate of transport of the ionic species.

Applied cell voltage is a critical operating condition in electrodialysis processes. As the cell voltage is increased, the ion concentration in the feed vessel is depleted more rapidly, thus reducing the duration of the experiments. Increasing the cell voltage, however, increases the energy consumption of the unit according to Eq. (10). An interesting investigation can be performed by varying the voltage and comparing the system performance and energy consumption.

To study the effect of voltage, the voltage was varied between 8 and 13 volts, based on manufacturer recommendations.[22] The system operated in the Ohmic region within this voltage range. The results of ammonium chloride removal at different voltages are shown in Figure 4, which plots the feed ion concentration throughout the run. This figure shows that at higher cell voltages, the feed ion concentration is depleted more rapidly than at lower cell voltages. As the concentrate concentration increases at the start of the run, the current increases and a higher ion transport rate is observed. This can be observed through the change in the slope of the curves in Figure 4 (about 5-10 minutes into the run).

Using Eqs. (11) and (12), students can calculate the efficiency of the membrane stack in the removal of ions at the various cell voltages. At the conditions shown in Figure 4, overall efficiencies of close to 100% were obtained for the 8 V and 10V runs, while the efficiency of the 13 V run was approximately 85%. The lower efficiency of the 13 V run was accompanied by an increase in temperature due to finite membrane resistance, which could damage the ion-selective membranes if cooling is not provided. Similarly, the calculated energy consumption for the 13 V run was significantly higher than that for the 8 V or 10 V run, as shown in Table 4. The experimental results for efficiency and energy consumption could be used to estimate the energy requirements and membrane area necessary to achieve this deionization task for a given plant capacity and to obtain a rough estimation of process costs.

A third parameter for students to investigate is the type of membrane used in the stack. There are numerous types of specialized membranes available for a variety of separation applications. Some general features of available commercial membranes include size selective, charge selective, and specific-ion selective membranes. The objective of this experiment is to compare the selectivities of two types of cation exchange membranes—a general-purpose membrane (CMX) and a monocation-selective membrane (CMS).

For the purpose of this experiment, divalent cations (Mg^{2+}) and monocations (NH_4^+) were provided in a feed solution of 0.55 M $MgCl_2$ and 0.55 M NH_4Cl. The initial concentrate concentration was 0.2 M NH_4Cl and the system was operated at 10 V. Samples were extracted from the feed and concentrate vessels initially and at ten-minute intervals. They were stored for analysis with ion selective probes.

The monocation-selective membranes reduce the migration of the divalent magnesium ions from the feed vessel to the concentrate vessel. The concentration of the ammonium ions and magnesium ions in the feed vessel can be plotted as a function of time for either set of membranes. Figure 5 shows the slow decline of magnesium ions in the feed vessel in comparison with the rapid decline of the ammonium ions in an experiment with the CMS membranes. Comparing the performance of CMS membranes to CMX membranes, the enhanced retention of magnesium in the feed using the CMS membranes is also shown in Figure 5. (At early times, the expected difference in magnesium ion removal rates for the two membranes is not apparent. This is probably due to sys-

TABLE 4
Comparison of Total Energy Consumption for Runs at Three Different Applied Voltages

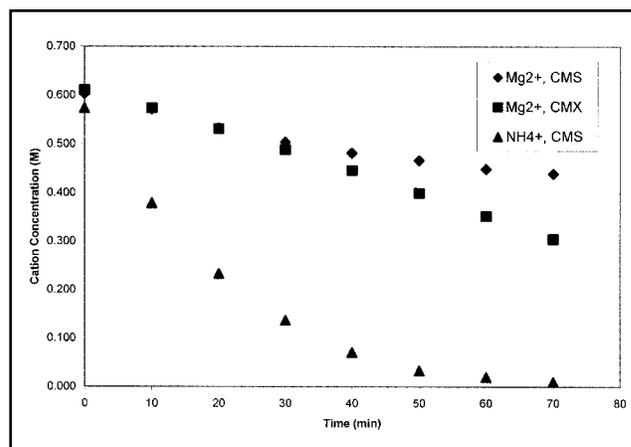| Time (min)	Voltage (V)	Energy Consumption (kJ)
68	8	722
38	10	816
25	13	962

Figure 5. *Removal of ammonium and magnesium ions using CMX and CMS cation exchange membranes. Process operating conditions: 10 V, 0.5 M $MgCl_2$, and 0.5 M NH_4Cl feed (initial), 0.2 M concentrate (initial).*

tem equilibration and run-to-run variations that are most apparent at start-up. The difference in removal rates for the two runs is evident after 20 minutes.)

The overall selectivity throughout the run, for ammonium relative to magnesium, is calculated using Eq. (13), using the total number moles of each ion removed from the feed at the completion of a 70-minute run. The total number of moles of each ion transferred from the feed is determined by integrating Eq. (3) for the duration of the run.

For the general-purpose CMX membrane, the overall selectivity was 1.04, indicating that the average removal rates of ammonium and magnesium are approximately equal. For the monocation-selective membrane, the overall selectivity was 2.8, indicating that the CMS membrane selectively enhances the removal of monovalent ammonium ions from the feed.

CONCLUSIONS

We have developed an experimental investigation of the practical engineering aspects of electrodialysis. Students investigate the effects of operating parameters such as concentrate concentration and applied voltage. Membrane selection is explored through comparison of two cation exchange membranes for the selective removal of competing cations.

Additional experiments could be conducted to investigate other process parameters such as the number of membrane pairs, flow rate, feed concentration, and temperature (within the limits of the membranes). Data analysis and calculations emphasize practical engineering considerations such as energy consumption, efficiency, and selectivity.

The electrodialysis sytem is easy to operate and the students can perform the suggested experiments in a typical undergraduate laboratory period. These experiments can be used in a variety of undergraduate classes, including a unit operations laboratory or separations course. Advanced courses that would be enhanced with electrodialysis experiments are specialized topics courses such as green/environmental engineering, wastewater treatment, electrochemical engineering, pharmaceutical engineering, and food engineering.

ACKNOWLEDGMENTS

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