Teaching

MASS TRANSFER AND FILTRATION USING CROSSFLOW REVERSE OSMOSIS AND NANOFILTRATION:
An Experiment for the Undergraduate Unit Operations Lab

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Water is a limited resource. Less than 1% of water on the planet is fresh and easily accessible, and it is projected that, by 2050, one-third of the global population will be without a secure source of clean drinking water.[1] These circumstances have prompted research into techniques that augment the amount of available fresh water through water reuse and desalination. Membrane separations have become a popular method of desalination due to recent advancements in the field coupled with the relatively low energy requirement compared to thermally driven desalination. With mass transfer, separations, and process engineering at the core of their curriculum, chemical engineers are uniquely suited to design optimized separation processes involving membranes if given the opportunity to learn about their operation. It is therefore imperative that we integrate membrane separations into the undergraduate chemical engineering (CHE) curriculum to prepare our students to tackle these grand challenges with new technologies.

In all ABET-accredited chemical engineering programs, a laboratory course is required to provide hands-on experience to students who have completed their core CHE coursework. Many CHE programs, including the Department of Chemical, Materials, and Biochemical Engineering (CMBE) at the University of Connecticut (UCONN), have been updating their laboratory curricula to more accurately represent modern technologies. The undergraduate CHE Laboratory at UCONN contains only two separations experiments: a pilot-scale double-effect evaporator and a 20-stage distillation column.

These thermal separation methods have value as classical chemical engineering approaches. These techniques, however, are becoming obsolete in certain sectors of industry. Today's employers demand knowledge of newer separation methods from recent graduates. As membrane separations become more commonly employed, students require practical experience with a system that teaches key membrane separations concepts while reinforcing mass transport fundamentals. For this reason, a membrane separations experimental module

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was created for the CHE Laboratory course at UCONN. One component of this module is a crossflow reverse osmosis (RO) system.

Previously published studies on RO experimental development usually describe dead-end filtration systems.[2,3] These systems operate in a batch mode, using a pressure vessel to force water through the membrane. Dead-end filtration systems lack the ability to tightly control hydrodynamics, temperature, and water recovery, and are also subject to more serious concentration polarization. Other RO experiments employ commercial crossflow membrane modules.[4] It is often difficult and costly to change the membranes in these systems, however, limiting the variety of membranes that can be tested. The system described in this paper is a crossflow RO system designed to mimic the conditions of an industrial membrane module while permitting a wide array of controllable variables. This system allows the students to observe change in membrane performance with changing hydrodynamic and fluid characteristics.

This experiment seeks to introduce students to the vital membrane performance parameters: permeability and selectivity. Sometimes referred to collectively as permselectivity, these parameters are used to appropriately select a membrane for any particular separation challenge. Although this experiment focuses primarily on desalination, an understanding of these key performance metrics cuts across separation disciplines and applies to any liquid, gas, or biological separation.

During the experiment, students will calculate the hydraulic permeability and salt rejection of several commercial RO or nanofiltration (NF) membranes and compare their values to the manufacturer's specifications. This experiment is also designed to reinforce mass transfer boundary layer theory through an examination of concentration polarization (CP). Students will learn about the complex interplay between salt rejection, flux, and CP, and think critically about possible applications for each membrane, considering each one's permeability and selectivity. The students will be asked to defend their conclusions, forcing them to think critically about the key design factors in RO desalination (feed water quality, product water quality and quantity, and operating pressure/power requirement).

The system described in this paper was designed to be mobile, robust, and easy-to-use. Test cells were designed such that small, single-use membrane coupons can be changed quickly between tests to permit the evaluation of multiple types of membranes. Furthermore, given the length of an individual test, multiple cells in series were needed to ensure data reproducibility, permitting students to obtain three flux measurements for every pressure they test and expediting the generation of data. Due to the relatively short channel length, pressure drop across each cell is negligible. Finally, the system was mounted to a modified cart to allow demonstrations outside of the undergraduate laboratory. This system has been used for demonstrations to the Membrane Separations class at UCONN and to visiting high school students as part of UCONN's Exploring Engineering (E²) summer program. While a cart-mounted system has this added benefit, it is not essential to the functionality of this system.

EXPERIMENTAL OVERVIEW

A diagram of the cart-mounted RO system layout is presented as Figure 1. Pre-cut, pre-wet commercial membrane coupons are sealed into each of the test cells, and the feed tank is filled with deionized (DI) or saline water. After a brief equilibration period (30 minutes) at high pressure, students measure permeate flow rate and conductivity. This process is repeated at multiple pressures for pure water and at multiple flow rates for saline water. Using this data, hydraulic permeability (A) and salt rejection (%R) are determined for each tested membrane. Boundary layer phenomena are also considered. The results are compared to the manufacturer's published specifications.
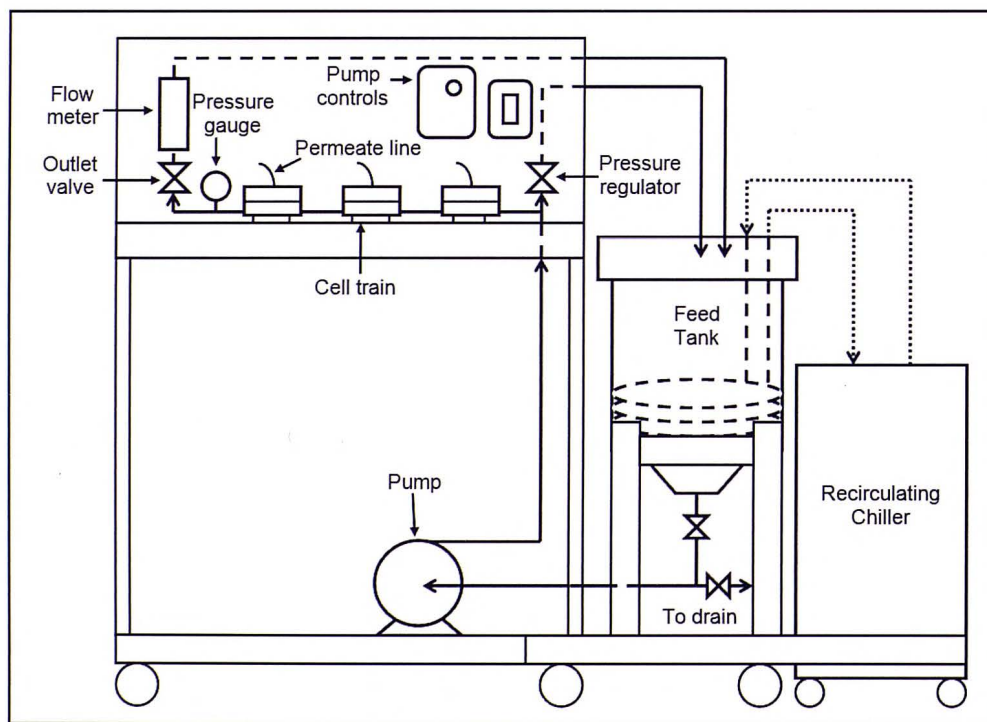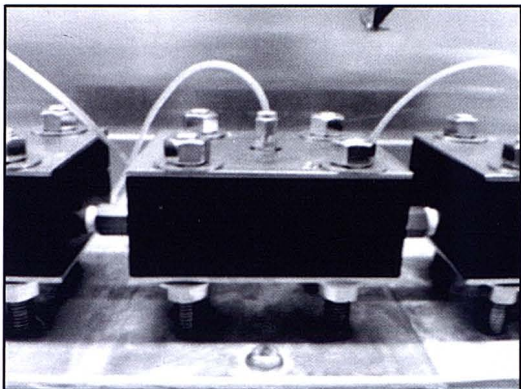

Figure 1. Schematic flow diagram of the crossflow reverse osmosis system.

Students are typically able to perform hydraulic permeability and salt rejection tests in approximately two hours for an NF membrane and three hours for a brackish water (BW) RO

Figures 2. *Photographs of reverse osmosis test cell (a, above) when closed, (b, below) when opened. The open cell shows the feed channel (top) and the permeate collector (bottom). This permeate collector is a sintered stainless steel plate (Mott Corporation).*
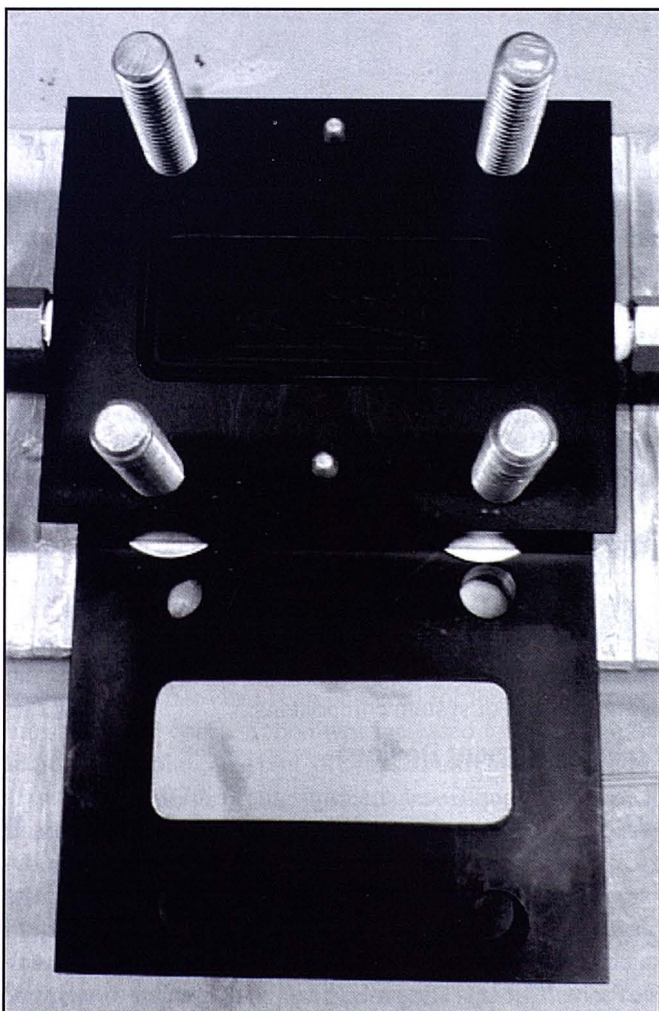
membrane. The length of this experiment can be extended by introducing more independent variables or different membranes. Prior to the experiment at UCONN, students read an instructional manual[5] and meet with a teaching assistant for system operation guidance. The RO system, as described, allows for control of many independent variables beyond membrane type and operating pressure, including crossflow rate, solute type, solute concentration, and temperature.

REQUIRED EQUIPMENT

I. Membrane Selection

Flatsheet membranes have been graciously provided by Dow Water & Process Solutions for this experiment. Specifically, the BW30, NF90, and NF270 membranes were selected to provide students a wide range of membrane permselectivity.[6-9] Dow's seawater (SW) membranes could be used as well, but the low hydraulic permeability makes tests prohibitively long at the pressures tested with this system (up to 400 psi). RO membranes from other manufacturers are also appropriate. This experiment requires only small membrane coupons (approximately 8 in² per cell) that can be discarded after use.

II. Cell Design

The membrane cells are each composed of two halves fabricated from black delrin and supported with stainless steel plates. The bottom half contains a crossflow channel, with dimensions 3" long by 1" wide by 1/8" deep, fed via threaded ports drilled into the sides of each cell. Surrounding the channel is a Viton O-ring (3" OD, 1/8" thick, McMaster) seated in a groove, which serves to seal the cell and prevent leaking. The top of the cell houses permeate collector that prevents damage to the membrane at high pressure. This collector is made of sintered stainless steel from Mott Corporation (Farmington, CT). The collected permeate flows through a 1/8" threaded fitting inserted into the top of each cell. These fittings are connected to lengths of flexible PVC tubing for easy collection. The two halves are placed on threaded stainless steel rods that are mounted to a stainless steel base plate, which can easily be affixed to a cart. Washers and nuts are used to support and seal the cell. Photographs of a sample cell are included in Figures 2. Detailed cell schematics are available upon request. If fabrication facilities are unavailable, pre-made cells with a similar design can be purchased from Sterlitech, General Electric, or Separation Systems Technology.

III. Key System Components

The feed tank selected was a 5-gal Easy Drain cylindrical tank with stand from McMaster-Carr (Princeton, NJ). Reinforced PVC tubing joins the feed tank to the Multi-Speed Diaphragm Pump purchased from Wanner Engineering (Minneapolis, MN). A drain is installed in this line to facilitate system cleaning. The pump drive is equipped with a variable speed controller that regulates the pump diaphragm frequency. The variable speed pump permits tests in the RO, NF, and ultrafiltration (UF) pressure regimes (although only NF and RO regimes are tested during this experiment). A high-pressure
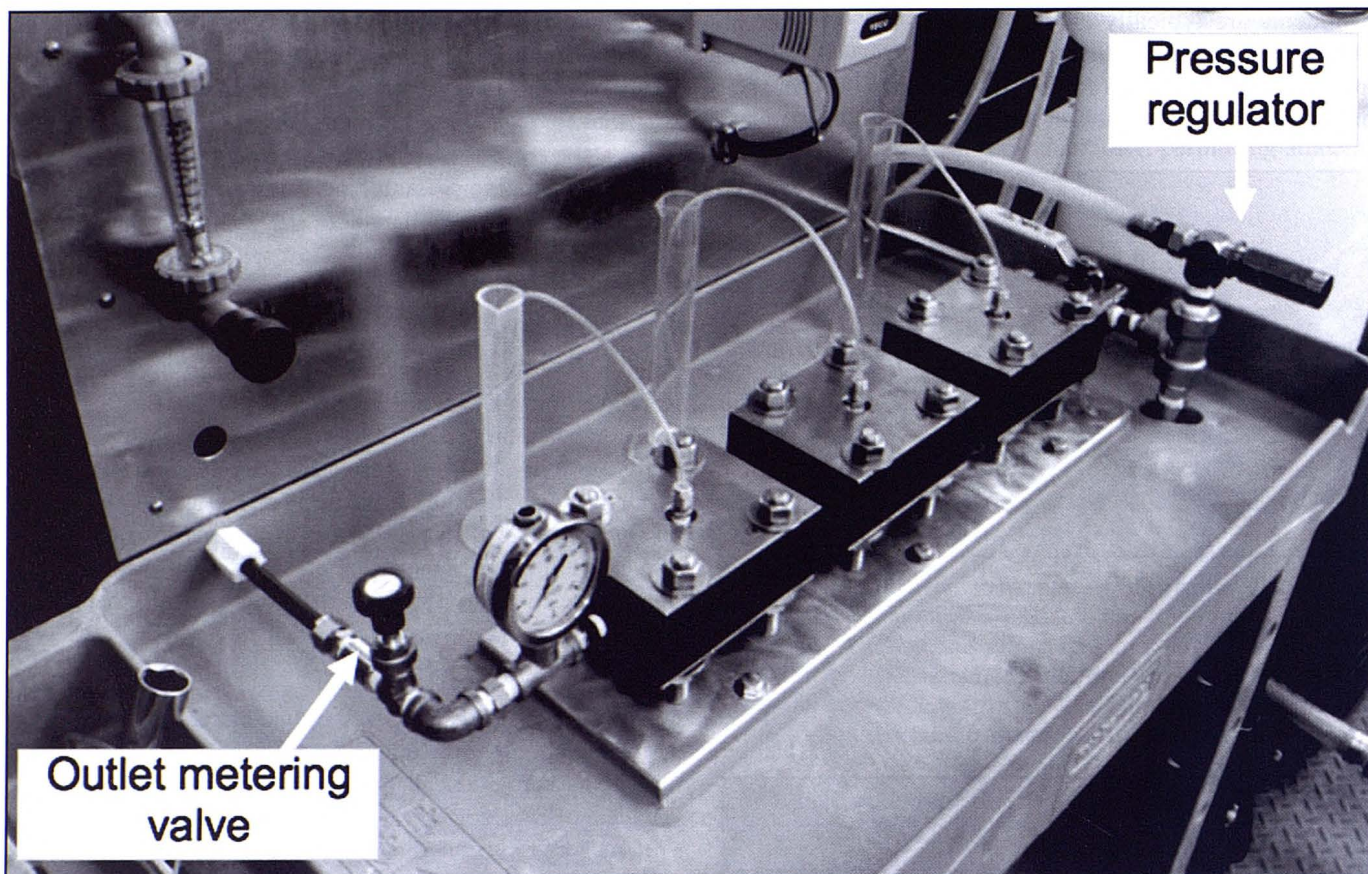
Figure 3. Membrane cell train with bypass pressure regulator and outlet valve labeled.

stainless steel braided hose (McMaster) connects the pump outlet to a stainless steel tee through the surface of the cart. This tee is connected to the first cell. System pressure and fluid flow rate are regulated by a pair of valves. The first is a front pressure regulator (50-500 psi, Wanner), which is installed on the aforementioned tee directly before the cell train and functions as a bypass valve. The second valve is a Swagelok SS-4L2 metering valve (Connecticut Valve and Fitting Co., Norwalk, CT), which regulates the flow of liquid that leaves the cell train. The effluent from this valve flows through a panel-mountable flow meter (0-1 gpm, McMaster). Liquid leaving the bypass regulator and flow meter are returned to the tank via tubing joined with quick-disconnect fittings to permit easy system flushing. A glycerin-filled pressure gauge (0-400 psi, McMaster) is installed between the membrane train and outlet valve. Figure 3 is a photograph of the membrane train with the two valves labeled. These valves are essential to optimal function of this system as they allow pressure and flow rate to be manipulated independently. An air purge port was also installed to allow the user to purge the system of residual water after cleaning. Filtered air is recommended to prevent oil or other particulates from contaminating the system. System temperature is maintained using a Neslab ThermoFlex 1400 recirculating chiller (Fisher) that has been integrated into the system through a coiled length of 316 stainless steel

tubing that resides in the feed tank. The recirculator ensures temperature consistency by dissipating any heat generated by the pump during operation.

When selecting piping, tubing, and other fittings for the RO system, it is critical that all wetted parts resist corrosion, which could foul membranes or result in leaks. All pressurized components of the system (from the pump to the outlet valves and pressure regulator) should be plumbed using 316 stainless steel fittings and pipe. Any low-pressure areas may be plumbed using nylon or PVC fittings and hose. All major plumbing components (pipe, tubing, and fittings) were purchased from McMaster-Carr, unless otherwise specified. All components were mounted directly to a Rubbermaid cart (McMaster) that had been modified with an aluminum backsplash and angle iron tank stand. Table 1 describes the estimated cost of system components.

IV. Measurement Devices

Permeate is collected directly into 50 mL graduated cylinders (McMaster). The cylinders allow data to be recorded quickly and easily. A stopwatch is used to accurately measure the collection times. When a saline feed is used, the conductivity of the feed and permeate, which correlates to salt concentration, is measured using an Oakton Conductivity Probe (Fisher). The probe must be calibrated to measure

concentration of the selected solute, which is accomplished by testing the conductivity of a serial dilution of a 2000 ppm stock solution of sodium chloride or other salt. A long-stemmed dial thermometer (McMaster) is inserted into the feed tank to monitor feed temperature.

EXPERIMENTAL PROCEDURE

Before an experiment, a membrane sheet was cut into coupons that can fit within the cell and completely cover the o-ring. Gloves were worn whenever membranes were handled so as to minimize damage. RO membranes shipped from Dow are coated with glycerin, which acts as a humectant to prevent drying. The membranes were stored in DI water for at least 24 hours to remove residual glycerin. For longer-term storage, membranes must be kept in a refrigerator to prevent bacterial growth. Two liters of 5-M sodium chloride stock solution were prepared for use as a salinity adjuster during the test. Since the system is pressurized, safety glasses were worn during operation.

To begin a test, the feed tank was filled with 6 L of DI water, although more water may be needed depending on system hold-up volume. While wearing gloves, students loaded membranes and sealed them into each cell with the selective layer facing downward toward the open channel. The chiller was set to 25 °C, in accordance to Dow's published test parameters. This set point may require modification to offset heat generated by the pump and ambient temperature. The pump was activated to purge air from the lines. After a few minutes, the system was pressurized by gradually closing the bypass regulator and outlet valve, alternating valves until the pressure is 300 psi. The system was equilibrated at this pressure for 30 minutes to flush air from the permeate tubes while compressing the membranes to provide uniform hydraulic resistance throughout the test. Longer equilibration times are acceptable but not practical within a laboratory period. After the equilibration period, permeate from each cell was collected in the graduated cylinders over a period of time at a desired pressure. Pressures between 100 and 300 psi are recommended, although students were encouraged to measure flux at the manufacturer's test conditions (70 psi for Dow's NF membranes, 225 psi for Dow's BW membranes). To optimize time spent in the laboratory, only 10 to 20 mL of permeate were collected per cell per pressure and all permeate was returned to the feed tank after volume was recorded. Once permeate flow rates had been observed for three to five pressures, the feed concentration was increased to 2000 ppm by adding stock solution (41 mL of 5-M sodium chloride stock for a 6-L DI water feed). Using stock solution is important since it rapidly mixes in water relative to the dissolution of solid salt. After a brief mixing period, pressure was maintained at the manufacturer's test specification while crossflow rate varied from 0.1 to 0.5 gpm. At each new flow condition, students should wait a few minutes for the fluid in the permeate line to flush out. A sufficient amount of permeate should then be col-

lected in order to measure the conductivity accurately, but total permeate volume should be minimized so that the experiment does not take too long. Once permeate volume and collection time were recorded, permeate and feed solution conductivity were measured, and all permeate samples were returned to the feed. This procedure should be repeated for at least three flow rates. Measurements should be repeated if time allows. Typical testing conditions for experiments performed by students at UCONN are summarized in Table 2.

After gathering all desired data, the tank was drained and refilled with DI water. The bypass and outlet return lines were disconnected and placed in a sink or a bucket with the outlet valve and pressure regulator bypass opened fully. The pump was then set to sufficient speed such that the flow rate was above 0.5 gpm. The tank was refilled with DI water as needed until the effluent conductivity was below 10 microsiemens (μS). If DI water is in short supply, a pre-rinse using tap water may be performed before a polishing DI water rinse. Flushing usually requires approximately 2 gal of water. The system was then purged with filtered compressed air to remove residual water. The cells were opened and the membranes removed to be examined for defects. If another test was to be immediately done, new membrane coupons were inserted and the procedure was repeated.

TABLE 1
Estimated Cost of System Components

Component	Supplier	Approx. Cost
Recirculating chiller	Fisher Scientific	$3,000
Pump & controller	Wanner Engineering	$2,500
Three test cells	n/a	$1,500
Cart & tank	McMaster	$250
Meters & gauges	McMaster	$200
Valves	Swagelock, Wanner	$350
Tubing & piping	McMaster	$600
Conductivity probe	Fisher Scientific	$600
Total		**$9,000**

TABLE 2
Typical Operating Conditions for RO Experiments

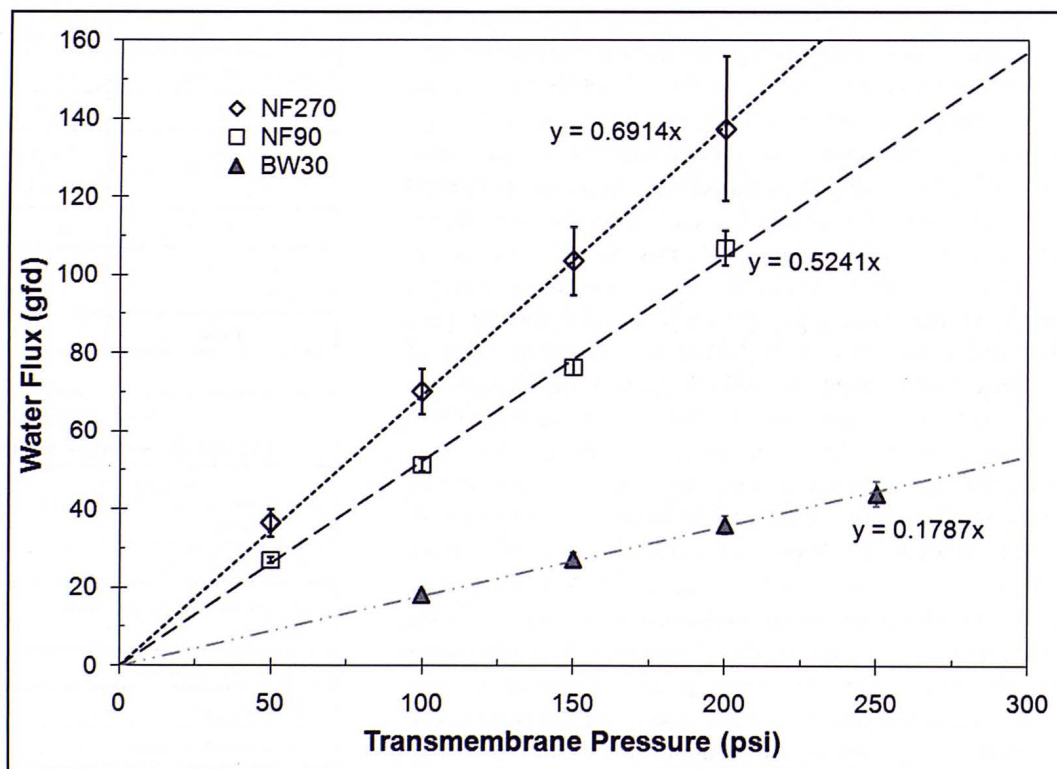| Variable	Typical Value/Range
Temperature	25 °C
Initial feed volume	6 L DI water
High-pressure equilibration time	30 min
Feed concentration	0 ppm NaCl, 2000 ppm NaCl
Hydraulic pressure	0 – 300 psi
Hydraulic flow rate	0.1 – 0.5 L/min

Due to the system's versatility, there are numerous other independent variables for students to explore if time permits. For pure water or saline water, students can explore the impact of temperature on flux and salt rejection. Temperatures can range from 15 to 35 °C. For saline water tests, the effect of solute concentration and solute type on observed salt rejection and CP can be examined. Other recommended solutes include magnesium sulfate and calcium chloride. Crossflow rate can also be held constant during salt rejection tests, varying pressure to increase and decrease flux. Furthermore, other commercial membranes can be tested.

TYPICAL RESULTS AND DISCUSSION

The relevant variables that differentiate RO membranes are hydraulic permeability (A) and salt rejection (%R). Salt permeability coefficient (B) can be used instead of %R, although rejection is generally a more pragmatic performance metric. In order to facilitate student analysis, it can be assumed that the feed solution is dilute. Therefore, the feed is an ideal solution with density and viscosity equivalent to that of pure water. Solute diffusivity can be approximated using the Nernst-Haskell equation.[10] The solution properties do not change appreciably during the test since the system is run at 0% recovery (all permeate is returned to the feed tank) with a constant feed concentration. For a thorough overview of RO theory and calculations, refer to the textbooks of Mulder and Baker.[11,12]

Flux is determined by normalizing the measured volumetric flow rate of permeate by the surface area of the membrane. Flux is typically reported in gallons per square foot per day (gfd) or liters per square meter per

hour (lmh). Once fluxes have been determined for each cell at a given pressure, students will average the three flux values and calculate the standard deviation. Using these average fluxes and standard deviations, pure water flux is plotted vs. operating pressure in accordance with the generalized flux equation below:

$$J_w = A(\Delta P - \Delta \pi) \quad (1)$$

where J_w is water flux, A is the hydraulic permeability constant, ΔP is the transmembrane hydraulic pressure, and $\Delta \pi$ is the transmembrane osmotic pressure. As permeate pressure is atmospheric, ΔP equals the gauge system operating pressure, and $\Delta \pi$ is zero for pure water feeds. Figure 4 presents a summary of pure water flux data gathered by several groups of students using this system, presented with linear trend lines and standard deviation error bars. Note that students should report the units of A—the slopes of these lines—in either gfd/psi or lmh/bar. This portion of the experimental analysis teaches students that, in general, NF membranes (NF270 and NF90) are more permeable than RO membranes (BW30).

TABLE 3
Experimentally Observed Hydraulic Permeability (A) and Manufacturer's Reported A Value Range

Membrane Name	Calculated A value, pure water (gfd/psi)	Calculated A range, salt water (gfd/psi)	Manufacturer's A range (gfd/psi)
NF270	0.82	0.82 – 1.02	0.45 – 0.72
NF90	0.43	0.44 – 0.52	0.36 – 0.58
BW30	0.18	0.17 – 0.19	0.12 – 0.13

Figure 4. Pure water flux vs. pressure for various NF and RO membranes from Dow Water & Process Solutions. Trend line slopes correspond to hydraulic permeability, A. Error bars indicate one standard deviation. Note that 1 gfd is approximately 1.7 l/m² hr.

When a solute is present in the feed, the $\Delta\pi$ term in Eq. (1) is not zero. Furthermore, due to boundary layer effects, the osmotic pressure of the feed solution changes near the membrane interface. This phenomenon, illustrated in Figure 5, is known as concentration polarization (CP). Salts that are rejected by the membrane accumulate near the membrane surface while gradually diffusing back into the bulk solution. The relative rates of convection and diffusion dictate concentration of solute at the membrane interface. As a result, a steady state concentration gradient is established in which a bulk feed concentration, C_b, and a feed-side membrane interface concentration, C_m, are specified. For a thorough explanation of CP, refer to the review paper written by Sablani, et al.[13] A simple mass balance for flow of salt into and out of the boundary layer can be integrated into the following form:

$$\frac{C_m - C_p}{C_b - C_p} = \exp\left(\frac{J_w}{k}\right) \qquad (2)$$

where C_p is the concentration of solute in the permeate and k is the mass transfer coefficient which, according to film theory, is equal to molecular diffusivity divided by boundary layer thickness. The mass transfer coefficient can be determined using Sherwood number ($Sh = kd_h/D$) correlations available from a variety of sources.[10,14] The empirical Sherwood correlations presented to students in this experiment were provided by Mulder[11] for both laminar and turbulent flow in a channel, presented below:

$$Sh_{laminar} = 1.85\left(Re \cdot Sc \cdot d_h / L\right) \qquad (3)$$

$$Sh_{turbulent} = 0.04\left(Re^{0.75} \cdot Sc^{0.33}\right) \qquad (4)$$

where Re is the Reynolds number, Sc is the Schmidt number, d_h is the hydraulic diameter of the channel, and L is the channel length. For the flow rates mentioned previously, the system usually operates in transition flow, and the results of the two Sherwood correlations are averaged. Once C_m is known, CP modulus (C_m/C_b) can be reported; for RO, the CP modulus is always greater than 1. The osmotic pressures of
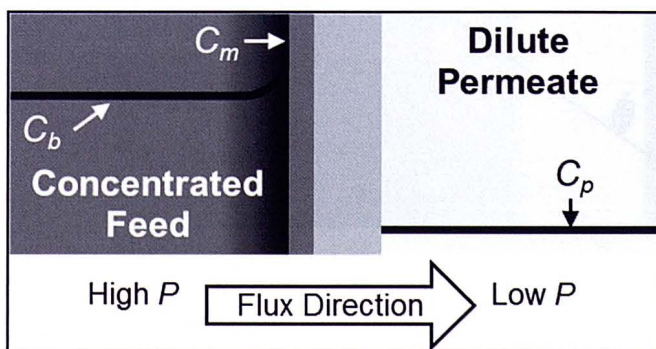

Figure 5. *Illustration of concentration polarization. The black line indicates the concentration of solute in solution.*

the permeate solution, bulk feed solution, and feed solution at the membrane interface can now be calculated using the idealized van't Hoff equation, shown below:

$$\pi = iCRT \qquad (5)$$

where i is the moles of ions produced by the dissolution of one mole of the solute, C is the molar solute concentration, R is the gas constant, and T is the temperature. This equation, which indicates a linear relationship between concentration and osmotic pressure, is valid for dilute solutions. Thus, for relatively dilute solutions, the C_m, C_b, and C_p terms in Eq. (2) can be replaced with π_m, π_b, and π_p, the osmotic pressures of the solution at the feed-side membrane interface, bulk feed, and permeate, respectively.

During experimental analysis, students can be asked to ensure that the water permeability constant is the same for the pure water and saline feeds. To use Eq. (1), however, the students cannot use the observed osmotic pressure gradient ($\Delta\pi_{obs} = \pi_b - \pi_p$) to accurately evaluate A, as the term does not account for CP effects. Therefore, only the effective osmotic pressure gradient ($\Delta\pi_{eff} = \pi_m - \pi_p$) should be considered. When plotting flux vs. driving force ($\Delta P - \Delta\pi_{eff}$), the data should be linear with a slope equal to the hydraulic permeability constant (A) and an x-intercept at zero, similar to the pure water test results. Table 3 compares A values calculated by one group of students based on pure water tests, saline water tests, and Dow's published performance values. Students should be able to observe that A values do not appreciably change in the presence of salt. Discrepancies can be attributed to minor performance differences between individual membrane coupons.

A more advanced analytical method is flux prediction, which combines Eqs. (1), (2), and (5) as follows:

$$J_w = A\left[\Delta P - \left(\pi_m - \pi_p\right)\right] \qquad \text{from Eq. (1)}$$

$$\pi_m - \pi_p = \left(\pi_b - \pi_p\right)\exp\left(\frac{J_w}{k}\right) \qquad \text{from Eq. (2) \& (5)}$$

$$J_w = A\left[\Delta P - \left(\pi_b - \pi_p\right)\exp\left(\frac{J_w}{k}\right)\right] \qquad (6)$$

Eq. (6), which is a nonlinear algebraic equation, can then be solved for water flux, J_w, using the experimentally observed feed concentration and hydraulic pressure along with the previously determined pure water permeability constant and mass transfer coefficient. Figure 6 is a parity plot of observed saline water feed flux data vs. water flux predicted by boundary layer theory at various crossflow rates and constant pressure. The film theory model fits the data well for these membranes. This portion of the analysis is an excellent demonstration of key aspects of boundary layer theory. If flow rate is varied during a saline water test, the mass transfer coefficient will increase with Reynolds number, resulting in a thinner boundary layer, lower CP modulus, and increased flux and rejection. If pressure is increased at constant crossflow rate, it is expected the boundary layer will grow as flux is increased and salt is forced against the membrane, increasing CP modulus and lowering observed salt rejection. The analysis also permits students to check the accuracy of their data against film theory and published data, forcing them to critically consider sources of error, such as erroneous assumptions, data misinterpretation, or poor data acquisition techniques.

The second key membrane performance metric is selectivity, often reported as observed percent salt rejection (%R) for RO. Rejection—the percentage of feed solute retained by the membrane—can be calculated using the following equation:

$$\%R = \left(1 - \frac{C_p}{C_b}\right) \times 100\% \tag{7}$$

An additional means of quantifying selectivity is the calculation of intrinsic salt rejection ($\%R_{int}$), which accounts for concentration of solute at the membrane interface. This rejection value can be calculated as follows:

$$\%R_{int} = \left(1 - \frac{C_p}{C_m}\right) \times 100\% \tag{8}$$

These rejections are compared to those published by Dow, accounting for the manufacturer's error limits, shown in Figure 7. The intrinsic rejection values are always greater than the observed rejection values, as the calculation accounts for CP effects and provides a more accurate measure of how much salt a membrane is capable of retaining. The observed rejection results are slightly lower than the published values, likely due to microscale defects that unavoidably form as membranes are shipped, cut, and loaded into the system. Minor defects may also form near the o-ring seals. The results, however, are within the limits of acceptable error as reported by Dow. This aspect of the experiment demonstrates the trade-off between membrane permeability and selectivity. The most permeable membrane, the NF270, also has the poorest salt rejection. The inverse is true of the BW30, the least permeable membrane. Understanding this relationship is essential when selecting membranes for an RO process and is a critical aspect of understanding membrane separations.

All data presented in this manuscript were generated by senior-level chemical engineering students using the experimental apparatus as a part of the CHE laboratory curriculum. Students were expected to obtain accurate hydraulic perme-

Figure 6. Parity plot of experimentally observed water flux and water flux predicted by film theory model with 2000 ppm NaCl feed at various crossflow rates. NF membranes evaluated at 70 psi, and BW membrane was evaluated at 225 psi. Error bars indicate one standard deviation. Note that 1 gfd is approximately 1.7 l/m² h.
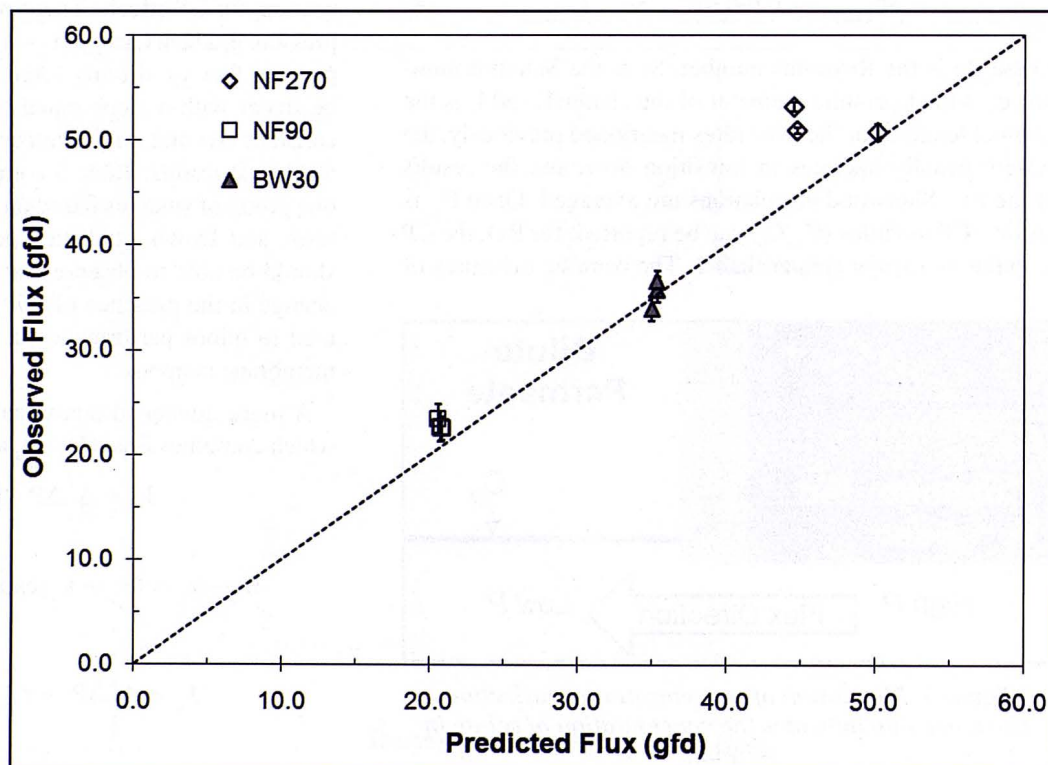
ability constants and salt rejection values for each membrane while generating reasonable CP moduli. They were to observe the trade-off between selectivity and permeability and determine the impact of operating conditions, such as pressure and flow rate, on overall membrane performance. Based on written and oral lab reports, the majority of students who performed this experiment were able to meet these goals. Some of the first student groups to use the equipment cited cell leakage as a possible source of error. Placing thicker o-rings in the cells remedied this problem.

The versatility of this system has enabled its use outside of the unit operations laboratory. We have used this system to provide a brief introduction to membrane separations as part of UCONN's Exploring Engineering (E²) Summer Program, which is aimed at teaching rising high school juniors and seniors about various facets of engineering. Using food coloring instead of sodium chloride in the feed, the system was used to introduce the students to basic membrane separations while teaching them the value of making assumptions (in this case, that osmotic pressure generated by the food coloring is negligible). Furthermore, this system has been successfully implemented as a demonstration in UCONN's Membrane Separations course for senior undergraduates and graduate students. The experiment was used to introduce students to more advanced aspects of RO, generating data from which students could calculate hydraulic permeability, salt rejection, and CP modulus.

CONCLUSIONS

This paper has described the design and use of a versatile reverse osmosis system that has been implemented in the chemical engineering senior laboratory capstone course at the University of Connecticut. Students learn the fundamental performance variables critical to membrane separations, namely permeability and solute rejection. Furthermore, the concentration polarization aspect of this experiment introduces students to a complex mass transport problem while reinforcing mass transport boundary layer theory.

Once students analyze their data and determine the permeability and rejection of the membranes, they must think critically about possible applications for each membrane they tested, based on each membrane's permeability and salt rejection. Students must consider vital parameters to the RO desalination process, such as feed water salinity, desired
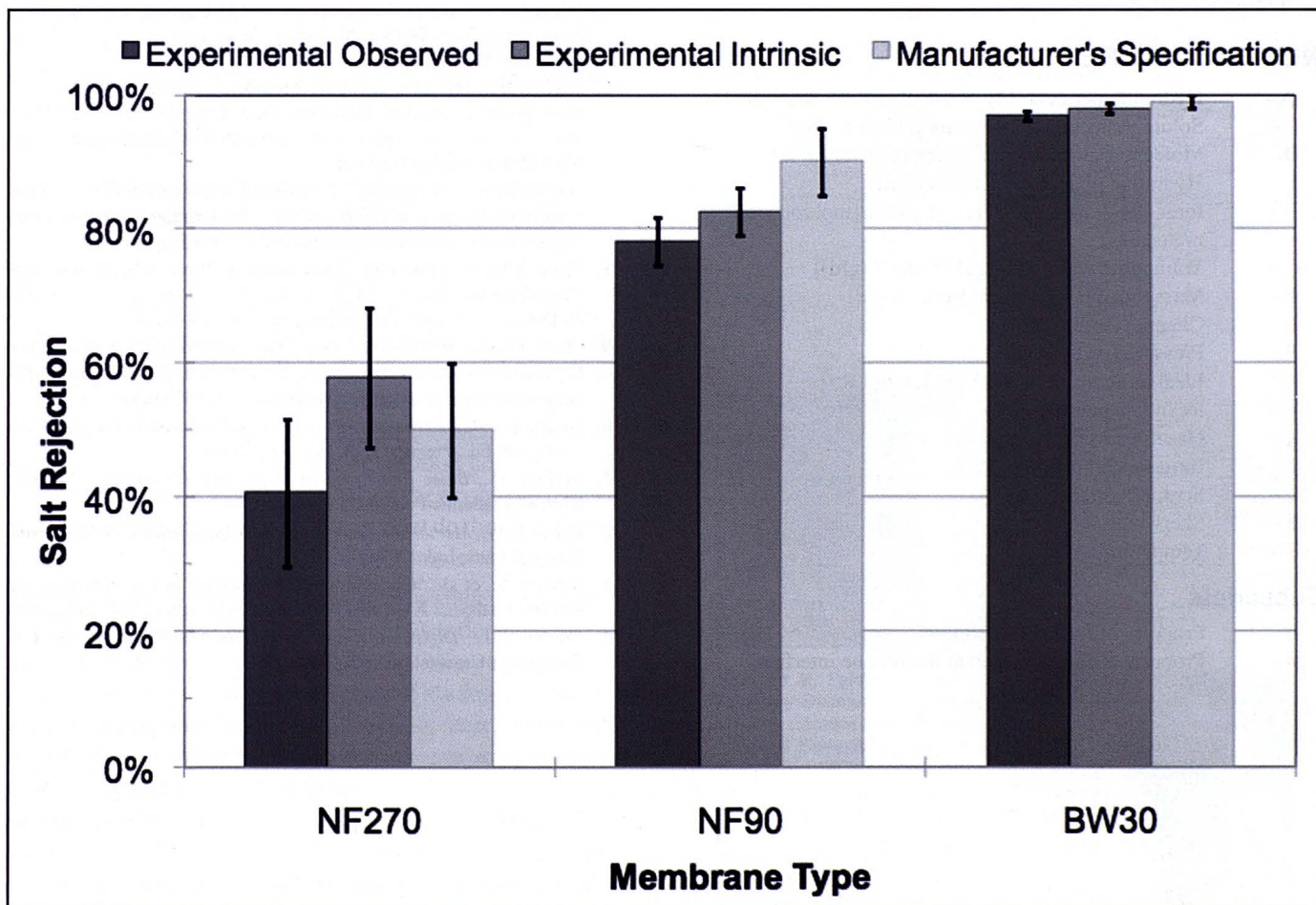

Figure 7. Observed and intrinsic salt rejection of various membranes based on student observations and values reported by the manufacturer. Feed solution was 2000 ppm NaCl. Error bars indicate one standard deviation.

permeate water quality and quantity, and operating power requirements and restrictions. While designed as an experiment for the undergraduate laboratory course, this portable system has curriculum-wide applications, such as providing demonstrations to freshman-through-graduate-level classes in addition to demonstrating a chemical engineering process to prospective students.

ACKNOWLEDGMENTS

NOMENCLATURE

A – Hydraulic permeability constant [gal ft^{-2} day^{-1} psi^{-1}]
C – Solute molecular concentration [mol/L (M)]
D – Molecular diffusivity of solute in water [m^2/s]
d_h – Hydraulic diameter of channel [m]
i – Ionic dissociation constant of solute [mol ions/mol molecules]
J_w – Volumetric water flux [gal ft^{-2} day^{-1} (gfd)]
k – Mass transfer coefficient [m/s, or gfd]
L – Channel length [m]
P – Pressure [psi]
R – Ideal gas constant [1.205 psi L mol^{-1} K^{-1}]
Re – Reynolds number
%R – Observed salt rejection [%]
%R$_{int}$ – Intrinsic salt rejection [%]
Sc – Schmidt number
Sh – Sherwood number
T – Temperature [K]

Subscripts

b – Property of bulk feed solution
m – Property of feed solution at membrane interface
p – Property of bulk permeate solution
eff – Effective conditions at the membrane interface
laminar – Equation for laminar flow
turbulent – Equation for turbulent flow

Greek

μ – Fluid viscosity [kg m^{-1} s^{-1}]
π – Osmotic pressure [psi]
ϱ – Fluid density [kg/L]
υ – Fluid crossflow velocity [m/s]
Δ – Difference evaluated between feed and permeate conditions

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