How Pressure Drop and Feed Concentration Affects the Performance of Reverse Osmosis

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Abstract

Reverse osmosis is an important separation process in chemical engineering mainly utilized for the creation of potable water from impure water. In this experiment, a permeable membrane was used to separate salt from impure water using a closed loop system, and the conductivities of the permeate and retentate streams were analyzed in order to obtain the rejection coefficient, the water permeability coefficient, and the salt permeability coefficient. The coefficients obtained, shown in Tab. 1, demonstrate that they vary greatly, which was unexpected. This is attributed to not waiting for steady state to be reached when collecting the data as well as using an inaccurate flowmeter. In the future, it would be best to record the data at steady state and use a more accurate method of measuring the flow rate, such as using a graduated cylinder and stopwatch simultaneously. By doing so, better results can be obtained and more concrete conclusions can be drawn with respect to the desired coefficients.

1 Introduction

Reverse osmosis is one of the many types of separation processes often used in chemical engineering. Reverse osmosis is the process in which a permeable membrane is used to separate impurities that are in contaminated water in order to obtain safe, potable water. Consequently, it is an imperative separation process since it leads to the acquisition of purified water that can be made readily available to the general population. In general, the process of removing unwanted particles from impure water is known as desalination; reverse osmosis happens to be one of the common types of desalination processes prevalent in industry currently. Beforehand, reverse osmosis was not the premier method of creating purified water. Distillation was the desired method of choice, but once membrane technology evolved in the 1980s, it became more efficient and cost-effective to use reverse osmosis instead.[1] Thus, reverse osmosis' advantages became apparent and began to dominate the water purification business.[1] It is used in various aspects in the chemical engineering field but some parts of industry where they're particularly used are in the meat and sugar industries. In regards to the meat industry, the processes used in this field produce a lot of wastewater, which is harmful to the environment.[2] Thus, reverse osmosis is used to purify the water in order to recycle it and use it once again in chemical plants for the meat industry.[2] In regards to the sugar industry, reverse osmosis is used to save energy in the creation of concentrated sugar thin juice for the development of sugar.[3] Since evaporation is known to use a lot of energy, reverse osmosis is used as an alternative since it uses less energy, which drives down both costs and risks of environmental issues.[3] As seen in these two examples, reverse osmosis is proven to be a prominent separation process in the chemical engineering field.

2 Background

Reverse osmosis represents a separation of the concentration from the solvent and solute. The key designs of reverse osmosis have considerable effects that are based on how the semi-permeable plates are modeled. Determining which plates to use for a reverse osmosis system is essential in order to successfully separate concentrations of solvent and solute efficiently. Using semi-permeable membranes that are not appropriate for the designated model will result in irrelevant data in the results.

Determining which models to utilize for a membrane will result in different parameters, such as area, flow rate, volume of concentration, and more. The different types of models can be as simple as the semi-permeable membranes being a flat sheet to as complex as a spiral-wound membrane. Generally, the size of membranes affect most of the parameters; however, some models are more appropriate to use compared to others in finding the concentration rates between the solvent and solute.[4] Across different types of membranes, there can be some similar data results, such as data for concentration, which can also play an important role since increasing the concentration itself from the initial feed stream would increase the flux for the solute.[5] Although most models can apply the similar results, not all industries use the same model with the reverse osmosis process. Some industries would prefer having different models and parameters that will be appropriate for the data they need for their own experiments. For instance, chemical industries actually use a spiral-wound membrane for its wide area in order to provide multiple steps to find the rejection of pH levels of molecular compounds.[6] Another example is the use of flat sheet membranes to observe the data for the rejection of solute concentrations using specific models such as the combined film theory-solution-diffusion model (CFSD).[7] Overall, the reverse osmosis process relies on the different models of semi-permeable membranes to achieve the desired data.

Here, we show the use of a tubular membrane and the effect with the flux of both the solute and the solvent streams. In addition, we will be adjusting the salt concentration for the initial feed stream to collect data to see the change of conductivity for both streams. The salt concentration was adjusted and recorded multiple times, as well as evaluated using the parameters of the influx streams based off of the equations used in Hung et al.[8]

3 Theory

The reverse osmosis lab aims to filter the salt from the feed of contaminated water. Using the given membrane, the data for both water and salt flux will be obtained. The equation of the area of the membrane is given as:

$$a = \pi(d_o - d_i)hn \tag{1}$$

where a is the area of the cylindrical tube of the membrane, d_o and d_i are the outer and inner diameters of the tube respectively, h is the height, and n is the number of layers the membrane has. In addition, the change of the osmotic pressure is needed to calculate the amount of pressure needed for the prevention of inflow to occur. The equation is:

$$\Delta\pi = \beta RT\Delta C_s = \beta RT(C_f - C_p) \tag{2}$$

where $\Delta\pi$ is labeled as the osmotic pressure, β is the amount of solute that is dissolved, R is the ideal gas constant, T is the temperature, ΔC_s is the change of the solute concentration traveling up and down the membrane, and C_f and C_p are the concentrations of the feed and permeate streams respectively.[8] Using osmotic pressure, flux of both water and the solute can be found. The water flux equation,

$$J_w = \frac{Q_p}{a} = A(\Delta p - \Delta\pi) \tag{3}$$

where J_w is the water flux, A is the water permeability coefficient, Δp is the operating pressure, and $\Delta p - \Delta\pi$ is the driving force, can be used to find A.[8] Similarly, the solute flux equation,

$$J_s = J_w C_p = B\Delta C_s = Br_j C_f \tag{4}$$

where J_s is the dissolved solute flux in through the membrane, B is the salt permeability coefficient, and r_j is the salt rejection coefficient, can be used to find B.[8] Finally, the salt rejection coefficient r_j, given as

$$r_j = 1 - \frac{C_p}{C_f} = \frac{C_f - C_p}{C_f} = \frac{\Delta C_s}{C_f}, \tag{5}$$

can be solved by using the concentration of both the feed and permeate stream; this coefficient can be thought of as the separation efficiency of the membrane.[8]

4 Methods

A feed of contaminated water was pumped from a tank and sent to a semipermeable membrane in a closed loop system, which led to purified water leaving as the permeate stream and impure water leaving as the retentate stream. Two parameters were varied in order to examine their effects on the conductivity. The first of these was the pressure drop within the membrane, which was varied between 2 - 6 bar. In turn, this varied the flow rates of the permeate and retentate streams as well. The second parameter that was varied was the salinity of the feed water, which was varied between 1000 - 3500 ppm. This was done by either diluting the tank with DI water or adding more salt to it. In order to obtain the conductivity, probes were placed at the end of the exiting streams and used to record and measure their conductivities in $\mu\mathrm{S\,cm^{-1}}$.

5 Results and Discussion

The rejection coefficient was plotted for different salinity levels at varying operation pressures as seen in Fig. 1. At 2929 ± 200 ppm, the average r_j value is equal to 0.97 ± 0.04 and generally increases with operating pressures as expected from Hung et al.[8] This is expected for a low salinity level as this allows the membrane to more easily separate salt from the water, while increasing operational pressure increases the driving force for separation and thus the membrane can be more efficient. However, at 2891 ± 200 ppm and 2572 ± 200 ppm the r_j actually decreases to 0.96 ± 0.04 and 0.91 ± 0.04, respectively, while still mostly increasing as operational pressure increases. r_j is not expected to decrease as salinity levels decrease because less solute in the inlet feed stream would mean the membrane can more easily separate the salt from the water and thus less likely for salt to be able to pass through the membrane. Therefore, it would be more reasonable to see r_j increase with decreasing salinity levels, which was not the case here. Although there are some data r_j points in the 2929 ppm and 2572 ppm that decrease, this can be attributed to the error of the measuring devices, such as the flow meter (which was mentioned to be inaccurate), used throughout the experiment.

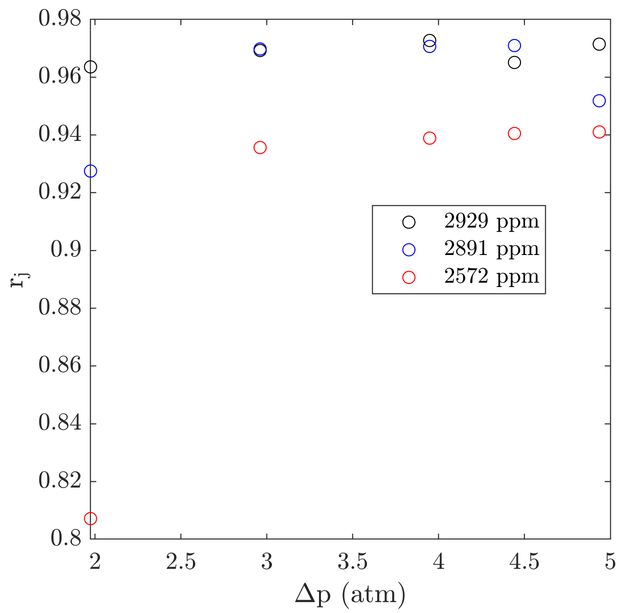

Figure 1: The figure shows r_j at three different salinity levels at varying operational pressures. As the salinity levels decrease the r_j decreases. Error bars were omitted for clarity since they are too large.

The water flux was plotted for different salinity levels at varying driving force pressures as seen in Fig. 2. A was found by fitting a best fit line through the data and the resulting slope was A. For 2929 ppm, $A = 0.015 \pm 0.003$ which is expected for A since it will be a small positive number as seen in Hung et al.[8] This is due to the water flux slowly increasing as the driving force increases, since more water is able to pass through the membrane. However, for 2891 ppm and 2572 ppm level, A decreases to $A = -0.01 \pm 0.06$ and $A = 0.01 \pm 0.02$, respectively. The decrease in A is not expected as A should be increasing with lower salinity levels due to less salt being needed to separate from the water and coupled with the increasing driving force, more water should be forced through the membrane. Therefore, it would be reasonable to see A increase as salinity decreases, but this was not the case here. In addition, at 2891 ppm, A decreases towards a negative value due to two outlying data points. Also, negative driving forces appear at 2929 ppm and 2891 ppm. This is not expected as A and driving force can never be less than 0. This would mean the system is not working properly and the flow of water would be going towards the opposite direction, which would not purify the water and make this system obsolete. The negative values can be attributed to the error of the measuring devices as discussed beforehand with r_j.

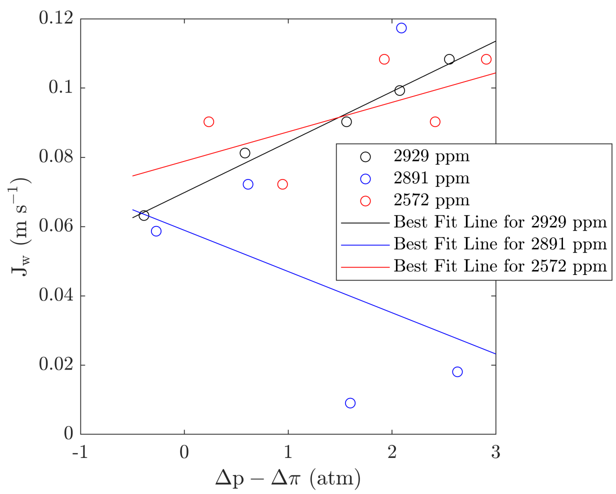

Figure 2: The figure shows the water flux at three different salinity levels at varying net driving forces. As the salinity levels decrease the A decreases. Error bars were omitted for clarity since they are too large.

The salt flux was plotted for different salinity levels at varying salinity differences between the feed and permeate concentrations as seen in Fig. 3. B was found by fitting a best fit line through the data and the resulting slope was B. At 2929 ppm, $B = 0.1 \pm 0.2$, which is expected for B as it should be a small positive number as seen in Hung et al.[8] This is expected due to the membrane not easily separating large salinity levels of salt in the feed and therefore more salt is passed through the membrane, and ΔC_S increases due to the higher salinity levels in the feed. However, for 2891 ppm and 2572 ppm, B decrease to $B = -0.1 \pm 0.2$ and $B =$

-0.08 ± 0.06, respectively, which is not expected at lower salinity levels. J_s and ΔC_S would be expected to decrease as salinity decreases due to the membrane being able to more effectively separating solutions at lower salinity levels due to less salt being present in the initial feed stream, resulting in positive B values. Thus, it would be expected for B to decrease with lower salinity levels, but this was not the case. In addition, B should not be negative as this would mean the salt is traveling in the opposite direction which would mean the reverse osmosis process is not properly working, similar to what was discussed for A.

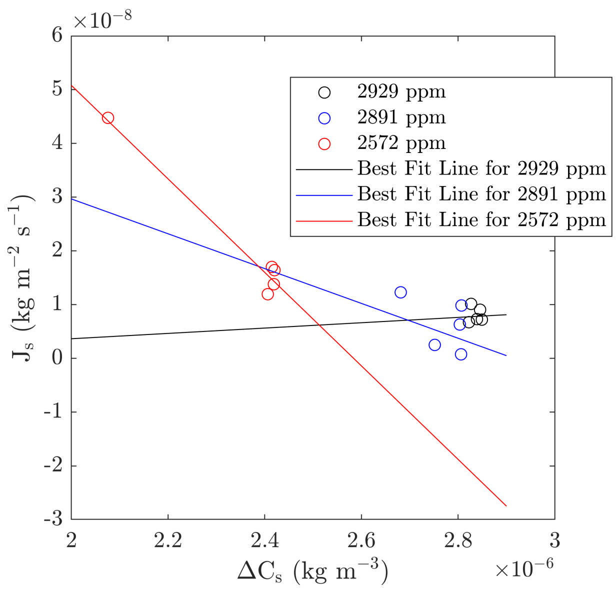

Figure 3: The figure shows rejection coefficient at three different salinity levels at varying operational pressures. As the salinity levels decrease the r_j decreases. Error bars were omitted for clarity since they are too large.

The results mentioned beforehand have been tabulated and provided below in Tab. 1:

Table 1: Important coefficients such as the average r_j, A, and B with their respective errors have been tabulated for easier readability.

ppm (mg L^{-1})	Average r_J	A (m^2 s kg^{-1})	B (m s^{-1})
2929 ± 200	0.97 ± 0.04	0.015 ± 0.003	0.1 ± 0.2
2891 ± 200	0.96 ± 0.04	-0.01 ± 0.06	-0.1 ± 0.2
2572 ± 200	0.91 ± 0.04	0.01 ± 0.02	-0.09 ± 0.06

The main errors such as negative values and opposite expected trends arise when decreasing concentrations, and the reason for this was an error on our part. Initially the reverse osmosis process was started using 2929 ppm that was already at steady state before running the system. However, when testing was finished for 2929 ppm the inlet tank was diluted to lower concentrations. Rather then letting the inlet tank reach steady state after diluting, the reverse osmosis process was run before it had a chance to reach this state. Not letting the system reach steady-state combined with the inaccurate measurement tools led to large fluctuations in the readings. This would explain why expected trends seen in Hung et al.[8] do not appear in this experiment for any trials after the first salinity level of 2929 ppm, but do appear for this salinity level. Therefore, to improve upon the experiment it would be best to give substantial time (10 minutes) when changing salinity levels. In addition, using more accurate measuring devices or methods such as recording the permeate flow rates by using a graduated cylinder and a stopwatch would decrease the uncertainties in our measurements and increase accuracy. These adjustments would then show the expected trends mentioned beforehand and accurately describe the reverse osmosis membrane.

6 Conclusions

By using a semipermeable membrane, reverse osmosis was performed in order to separate particulates from water and ultimately determine the coefficients of interest. Tab. 1 displays the values for all three of the coefficients at three different salinity levels. As seen in Tab. 1, the values are greatly different than one another. Comparing these values to Hung et al.'s values demonstrates that they are not as expected.[8] Two factors are considered for why this is the case. One of them is the fact that some of the data was not collected at steady state. Instead, it was collected at the beginning while the reverse osmosis system was still adjusting to the changes that were made to it, such as a different salinity level. The second factor that contributed to this variation in coefficient values was the flowmeter itself. The flowmeter was known to be a relatively inaccurate tool for measuring the flow rates, which also led to the data varying greatly. For the future, two improvements can be made for the data collection process. First, waiting for the system to reach steady state is of paramount importance so that the data is as accurate as possible. Second, using a different method of collecting the flow rate should be pursued. Namely, using a graduated cylinder and stopwatch concurrently would be a better way of measuring the flow rate. If these are taken into consideration, better results can be obtained in the future.

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Appendix

1. A Reverse Osmosis Desalination Unit

    - Author(s): Dababneh, A.J.; Al-Nimr, M.A.
    - Year published: 2002
    - Journal name: Desalination
    - 1-3 major accomplishments of this paper:

        (a) Determined how water production would be affected by different parameters such as the height of specific columns in a reverse osmosis system.

2. Treatment of Wastewater from the Meat Industry Applying Integrated Membrane Systems

    - Author(s): Bohdziewicz, J.; Sroka, E.
    - Year published: 2005
    - Journal name: Process Biochemistry
    - 1-3 major accomplishments of this paper:

        (a) Compared different membrane systems to determine which process is the best at purifying wastewater produced by the meat industry.

        (b) Concluded that reverse osmosis was the best membrane system in comparison to coagulation and ultrafiltration.

3. Reverse Osmosis Alternative: Energy Implication for Sugar Industry

    - Author(s): Madaeni, S.S.; Zereshki, S.
    - Year published: 2008
    - Journal name: Chemical Engineering and Processing
    - 1-3 major accomplishments of this paper:

   (a) Utilized reverse osmosis as an alternative method of creating sugar juice for the production of sugar.
   (b) Concluded that reverse osmosis is the preferred process since it reduces energy and economic costs as well as environmental risks.

4. Modeling and Scaleup of Reverse Osmosis Separation
   - Author(s): Van Gauwbergen, D.; Baeyens, J.
   - Year published: 2002
   - Journal name: Environmental Engineering Science
   - 1-3 major accomplishments of this paper:
     (a) Successfully applied different membranes to the reverse osmosis process

5. Modeling the Transient Behavior of an Experimental Reverse Osmosis Tubular Membrane
   - Author(s): Al-haj Ali, M.; Ajbar, A.; Ali, E.; Alhumaizi, K.
   - Year published: 2009
   - Journal name: Desalination
   - 1-3 major accomplishments of this paper:
     (a) Validated the dynamic model of a reverse osmosis using a tubular membrane
     (b) Compared steady-state model with the dynamic model using different designs and parameters

6. Spiral-Wound Membrane Reverse Osmosis and the Treatment of Industrial Effluents
   - Author(s): Bódalo-Santoyo, A.
   - Year published: 2004
   - Journal name: Desalination

- 1-3 major accomplishments of this paper:
  (a) Determined the high and low rejections values of different solutes using a spiral-wound membrane
  (b) Correlated the spriral-wound membrane to with chemical and environmental engineering industries

7. Simultaneous Rejection of Fluoride and Cr(Vi) from Synthetic Fluoride-Cr(Vi) Binary Water System by Polyamide Flat Sheet Reverse Osmosis Membrane and Prediction of Membrane Performance by CFSK and CFSD Models
   - Author(s): Gaikwad, M. S.; Balomajumder, C.
   - Year published: 2017
   - Journal name: Journal of Molecular Liquids
   - 1-3 major accomplishments of this paper:
     (a) Determined the rejection values of the dissolved fluoride solute using flat sheets membrane
     (b) One of the first at the time that was able to perform a reverse osmosis with the finding a rejection on fluoride

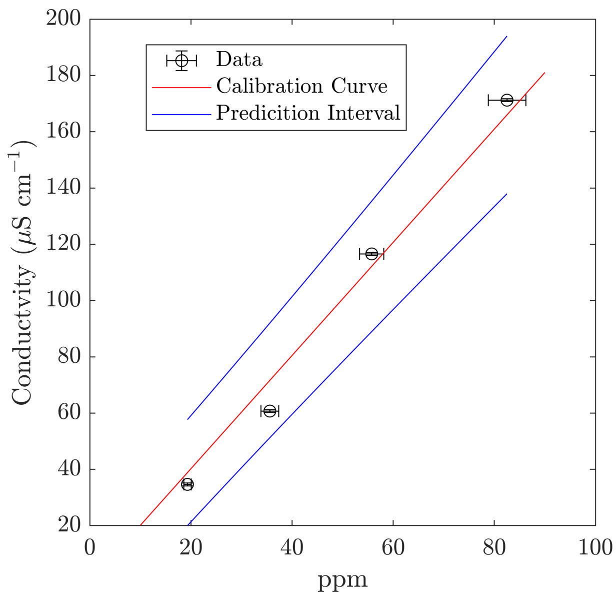

Figure 4: The calibration curve was created for the 0-200 μS cm^{-1} setting on the probe by diluting stock solutions

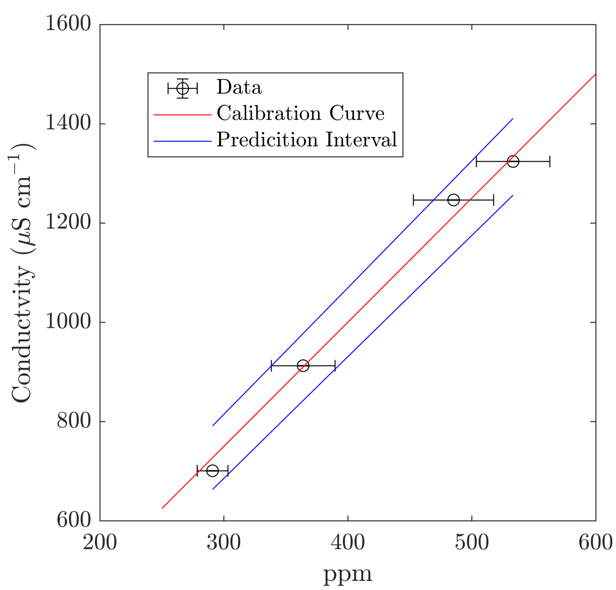

Figure 5: The calibration curve was created for the 0-2000 μS cm^{-1} setting on the probe by diluting stock solutions

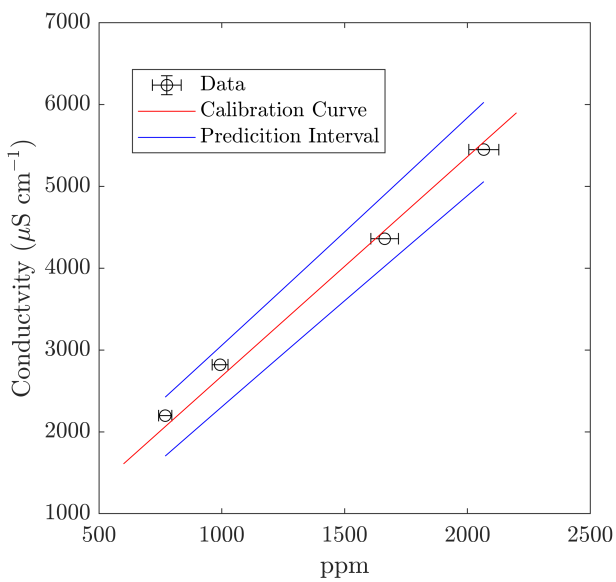

Figure 6: The calibration curve was created for the 0-20000 μS cm^{-1} Siemens setting on the probe by diluting stock solutions