Effect of Feed Temperature on the Performance and Properties of the NF270 Membrane

By

John O Bolaji

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In Partial Fulfillment of the Requirements for the Degree of
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ABSTRACT

An experimental study was done to explore the effect of feed water temperature on the properties and performance of nanofiltration membranes. The NF270 membrane was selected for this study, in which two temperatures of feed solution were passed through the membrane and water flux and salt rejection were measured.

Results from fitting with experimental data show that water flux increased 23% and salt rejection changed minimally from 25°C to 40°C. A numerical fitting method used the experimental data to determine the parameters of the membrane: pore radius, effective active layer thickness, and volumetric charge density. From 25°C to 40°C, the fitted parameters showed a 29% increase in pore size, and an 84% increase in effective active layer thickness; volumetric charge density increased in magnitude by approximately 64%. Pre-compaction and pre-soaking the membrane in alcohol are two separate membrane pretreatment procedures that showed significant effects on the performance of the membrane.

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1. Introduction

Pressure-driven membrane-based water purification processes include reverse osmosis (RO), nanofiltration (NF), ultrafiltration (UF), and microfiltration (MF). These processes use membranes that differ mainly in the size of the pores through which solution passes, which defines what type of solutes are filtered by that membrane, as shown in Figure 1 [1] [2]. Reverse osmosis membranes, believed to have no pores or negligibly small pores, essentially filter out everything except for water, including monovalent and multivalent ions, viruses, bacteria, and suspended solids. Nanofiltration membranes filter out everything but water, monovalent ions, and some multivalent ions. Ultrafiltration membranes do not filter out monovalent or multivalent ions. Microfiltration membranes, with the largest pore size, allow most solutes to pass through except for large particles such as bacteria and suspended solids.

<table>
<thead>
<tr>
<th></th>
<th>Water</th>
<th>Monovalent Ions</th>
<th>Multivalent Ions</th>
<th>Viruses</th>
<th>Bacteria</th>
<th>Suspended Solids</th>
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<td>Ultrafiltration</td>
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<td>Reverse Osmosis</td>
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</table>

Figure 1: Rejection capabilities of various filtration types. Green indicates the type of solute passes through the membrane. Red indicates the solute is rejected by the membrane. Yellow indicates some types of the solute pass, while others of the same type are rejected.
Nanofiltration membranes are a relatively new type of membrane that have pore sizes of approximately 1 nm [3]. Due to the range of pore size, effects such as membrane charge are key in determining the filtration performance of these membranes, in contrast to other membranes listed previously [4]. Due to the complexity of these membranes and the interplay of different effects that determine their rejection performance, nanofiltration membranes offer many different areas of exploration, including the effect of feed temperature on their performance and characteristics. The results of such studies would be beneficial to evaluating the behavior of NF in a setting such as a conventional thermal desalination process where feed water goes through stages at different temperatures [5][6].

To the best of the present author's knowledge, no single work containing the experimental investigation of the NF270 membrane, along with fitting of membrane parameters as a function of temperature, has been published. This work aims to gain understanding of the performance of the NF270 membrane at two different temperatures in terms of water flux and salt rejection. The experimental data will then be used to fit the parameters of the membrane: pore radius and effective active layer thickness (structural parameters), and the membrane charge (electrical parameter), which can be used to predict the performance of the studied membrane under a large range of flow conditions and feed solutions at the given temperatures, thereby making multiple experiments unnecessary.
2. Background

Rejection ratio and water flux through the membrane are two important measures of membrane performance for given operating conditions. The rejection ratio is defined as

\[ R = 1 - \frac{C_p}{C_f} \]  

where \( C_p \) is defined as the concentration, in mol/L, of the bulk permeate solution and \( C_f \) is defined as the concentration of the bulk feed solution. Water flux through the membrane, in m/s, is defined as

\[ J_w = \frac{\Delta m}{\rho \ast A \ast \Delta t} \]  

where \( \rho \) is the density of the solution, \( A \) is the active area of the membrane, and \( \Delta m \) is the mass of the solution passed through the membrane during time \( \Delta t \). For the well-mixed 0.1 M solution of NaCl used in these experiments, the salt concentration is assumed to be the same for each drop of solution and is 5.5% of the solution by weight. Therefore, due to possible differences in concentration between drops of solution, the maximum uncertainty in assuming the measured \( \Delta m \) of the solution is equal to the \( \Delta m \) of the water in equation (2) is at most 5.5%. Effective pressure is the difference between applied pressure and osmotic pressure defined as

\[ \Delta P_{eff} = \Delta P_{applied} - \Delta C \ast R \ast T \ast i \]  

where \( \Delta P_{applied} \) is the gauge pressure, \( \Delta C \) is the difference between \( C_f \) and \( C_p \) in mol/L, \( R \) is the universal gas constant = 8.314 J/mol-K, \( T \) is the temperature of the solution in K, and \( i \) is the Van 't Hoff coefficient ~1.8 for NaCl [7]. It should be noted that the osmotic pressure on the feed side is more accurately calculated using the value of concentration near the membrane, \( C_m \), instead of \( C_f \) due to concentration buildup at the surface of the membrane as a result of concentration polarization. However, this value could not be used as it is not an experimentally measureable quantity, hence, the bulk feed concentration can be assumed to be the concentration near the
membrane based on the assumption of a well-mixed solution due to a high Reynolds number. Example calculations to illustrate the use of these equations are detailed in Appendix A.

As mentioned in the previous section, experimental data can be used to fit membrane parameters. The method used in this study follows the procedure outlined by Roy et al. [8]. A set of several different possible pore radii and membrane charge densities over the usual range in nanofiltration (pore radii from 0.3-0.5 nm, charge densities from -1000 to 1000 mol/m³) [4] are input into the code, as well as the experimental rejection ratio, water flux, and effective pressure. Each possible pore radius is used to calculate the membrane active layer thickness according to the equation

$$\delta = \frac{r_p^2 \Delta P_{eff}}{8 \mu f_w}$$

where $\delta$ is the membrane effective active layer thickness, $r_p$ is the pore radius, and $\mu$ is the dynamic viscosity of the solution. Active layer thickness is calculated for each experimental effective pressure, and the average is the value used in the simulation. Each set of pore radius, active layer thickness, and charge density are then used to simulate different values of rejection ratio and water flux for each effective pressure. The combination with the smallest difference between the simulation rejection ratio and the experimental rejection ratio over all six data points are defined as the optimal fitting parameters.
3. Experimental methods

3.1 Experimental setup

A dead-end stirred cell setup was used in which the solution was placed in a 200 mL Amicon (UFSC20001) stirred cell, which contained the tested membrane. An applied pressure forced the feed solution through the membrane, out of the stirred cell, and into a separate collection vial. Compressed nitrogen was used to apply pressure inside the Amicon, and a CONCOA 422 series pressure gauge and regulator were used to control the applied pressure. The stirred cell was positioned on a Thermo-Scientific Cimarec+ (S88854100) magnetic stirrer plate with a digital readout to maintain a well-mixed feed solution. The permeate solution was collected in plastic vials positioned on a Scout Pro (SPJ601) scale connected to a computer to measure the change in mass of the permeate solution over time. A Hach (HQ440D) conductivity meter was used to measure the conductivity of the bulk feed and bulk permeate solutions, from which the concentration could be calculated.

An OMEGA (HSTH-44033-40) thermistor connected to a temperature controller (DP25-TH) was used to measure and control the bulk feed solution temperature. The thermistor measured the temperature of the feed solution contained in the stirred cell, and the controller activated a 75W McMaster-Carr (35765K375) flexible silicone-rubber heater sheet wrapped around the outside of the stirred cell. When the temperature fell below the desired temperature, the controller activated the heater sheet to heat the solution to the desired temperature. This helped to maintain a fixed value of temperature of the feed solution inside the stirred cell. The experimental setup is shown in Figure 2.

The stirred cell lid had only a single inlet used by pressure tubing and no additional inlets for the thermistor, so a special tee junction was made from PVC pipe, reducing bushings, and concrete glue to accommodate both a pressure inlet and thermistor inlet for the lid while still maintaining a pressure tight seal. The heater sheet was attached to the stirred cell with tape to be easily attached and removed from the stirred cell during cleaning and moving membranes between tests. A close view of the stirred cell is shown in Figure 3, and the lid and specialized tee junction are shown together in Figure 4.
Figure 2: The experimental set-up

- Temperature Controller
- Amicon stirred cell
- Heater sheet
- Magnetic stirrer plate
- Base of stirred cell
- Body of stirred cell
- Metal stir bar
- Permeate collection vial
- Scale

Figure 3: Close up view of disassembled Amicon stirred cell without lid
To decide the type of heater sheet needed, estimations of heat flux needed were made based on the water temperatures desired, estimated heat loss to the environment at given temperatures, and minimizing time needed to heat the water to the desired temperature. Example calculations for these estimations are shown in Appendix B. In order to avoid excessive thermal input that could damage or deform the stirred cell, the feed solutions were first raised to the desired temperature on a separate hot plate, then transferred to the stirred cell.

For this study, two temperatures, 25 ± 1.5°C and 40 ± 1.5°C, were chosen to compare membrane performance. A temperature of 30°C was not chosen because the variation of temperature is too high to accurately distinguish between 25°C and 30°C. For each test, the thermistor controller was set to a setpoint 1°C below the desired temperature. When the temperature reached this set point, the heater sheet activated, heating up the system until it again reached the desired temperature. Due to a time lag between the heat output from the sheet and heating of the water, the temperature rose above the desired temperature by 1.0-1.5°C each time the heater sheet turned on. Due to the length of tests, especially for low pressures, and technical limitations of sensor data output for the experimental setup, the actual average temperature was estimated by assuming a repeating temperature profile vs time. The average and standard deviation of the mean of the assumed profile was used to approximate the average temperatures during the tests. An example profile estimation is shown in Appendix C.
3.2 Experimental procedure

NF membranes are manufactured and purchased in large sheets that can be cut to application size. The tested membrane was an NF270 flat sheet membrane purchased from Octochem, Inc. Different areas of the membrane may have slightly varied characteristics, so 3 separate membrane samples, A, C, and D, were cut from the NF270 flat sheet to ensure repeatability of the measured rejection ratio and water flux. The membrane samples were cut using standard paper scissors and a template to ensure correct fit of the membrane in the stirred cell. A sample B was also cut, but a mistake in the cutting lead to leaks around the O-ring of the Amicon, so this sample was not used for the actual experiments. Each membrane was tested with 0.1 M NaCl solution at 25°C and 40°C, and 0.5 M at 40°C. Each concentration was tested at 6 different pressures ranging from 1.5 bar to 4 bar. A concentration of 0.1 M, the lowest concentration that could be measured without significant error using our scale, was selected to compare results with a concentration of 0.5 M, which represents the concentration of seawater. NaCl was selected due to its presence as the main solute in seawater.

The 0.1 M NaCl feed solution was prepared using pure NaCl salt from Sigma-Aldrich and deionized (DI) water by first measuring 7.012 g of NaCl using an Sartorius Practum (124-1S) scale and then adding it to 1.2 L of DI water. The solution was then mixed on the magnetic stirrer plate for approximately 10 minutes, then heated to the desired temperature. The 0.5 M solution was prepared the same way, using 35.06 g of NaCl in 1.2 L of DI water. The stirred cell and membrane being tested were both rinsed thoroughly with DI water to ensure no foreign particles or residual solution from previous experiments were present. The membrane was prepared by soaking it in a 50% alcohol, 50% DI water solution for 5 minutes, then soaking in DI water for 25 minutes. This process may remove air from the membrane and hence improve wettability [9] [10]. One set of tests was done without this procedure for a single membrane to compare the results of the difference in pretreatment, discussed in the results section. 200 mL of the heated solution was then transferred to the stirred cell. Since the stirred cell had an operating volume of 200 mL, six tests would be run before a new solution was prepared.

The concentration of feed solution inside the stirred cell was then recorded by measuring the conductivity of the solution using the Hach conductivity meter and converting the conductivity to a concentration using a conversion constant for conductivity of NaCl in water detailed in Appendix A. These measurements were taken three times and averaged to take into account the
variability of the readings. After recording the feed solution concentration, the stirred cell lid was placed on the body such that the thermistor sensor rested near the center of the body and a short distance above the stir bar. This positioning ensured that the temperature reading would not fluctuate due to proximity to the cell wall. Once the lid was attached, the stirred cell was placed on the magnetic stirrer plate at 370 RPM [11] to ensure a well-mixed solution and a uniform temperature profile of the water. The pressure regulator was then opened to allow compressed nitrogen into the cell and the test began.

Initially tests were run by first pre-compacting the membrane at the maximum operating pressure for the stirred cell, 5 bar, for 1 hour. However, initial results show that pre-compaction of the membrane can cause discontinuities in the trend of salt rejection at the higher pressures, so this step was removed and applied pressure for each test began at the lowest testing pressure, 1.5 bar, and was only increased. One test was done that went back down to a lower pressure after the highest pressure to determine any hysteresis effect on the membrane due to compaction. The permeate solution was collected in a 20 mL vial on a scale. For initial tests, the first 10 mL of permeate solution was collected as waste to ensure a clean permeate solution and three subsequent 20 mL samples were taken to ensure that the values being taken were steady state values for the behavior of the membrane. The data showed no change in rejection or water flux across the three different 20 mL samples, so further tests measured only one sample to decrease the time of the tests, but still collected the first 10 mL as waste. The concentration of the permeate solution was measured with the same procedure as the concentration of the feed solution.
4. Results from experiments

4.1 Effect of temperature change on membrane performance

As mentioned previously, the rejection ratio and water flux for each membrane sample were measured at six different applied pressures and two values of temperature. The results for the 0.1 M feed solution were averaged across all membrane samples to show the overall effect of the variation of temperature on the performance of the membrane. The results are shown in Figure 5, which compares the rejection ratios and water fluxes at both study temperatures. The increase in water flux can be partially explained by the reduction of solvent viscosity at higher temperature, but the fitting parameters will show how changes in the membrane structure could also contribute to an increase in water flux. Although there are results in literature for NF at different temperatures [12] [13], this study also uses the experimental data to fit the membrane parameters for the temperatures studied and systematically understand the factors that cause changes in the membrane behavior.

![Figure 5: Rejection ratio and water flux averaged across membrane samples for 0.1 M feed solution at 25°C and 40°C](image)

These results indicate that an increase in feed temperature from 25°C to 40°C resulted in a 23% increase in water flux, and a 3% increase in rejection ratio, although within the limits of experimental error the rejection showed minimal change. Thus, taking into account uncertainty, the data shows that increasing the temperature of the feed had a substantial effect on the water flux.
through the membrane, while having a much more minimal impact on the rejection ratio. Figures 6 and 7 show the experimental results for the individual membrane sample rejection ratio and water flux, respectively, and highlight the variability between the different sections of the flat sheet.

Figure 6: Rejection ratio for individual membrane samples for 0.1 M feed solution

Figure 7: Water flux for individual membrane samples for 0.1 M feed solution
Figure 8 shows the results averaged over the membrane samples for the tests done at 40°C for the 0.5 M solution. Due to time constraints, tests for 0.5 M solution at 25°C could not be completed.

Figure 8: Rejection ratio and water flux averaged across membrane samples for 0.5 M feed solution at 40°C
4.2 Effect of temperature change on membrane parameters

Table 1 shows the membrane parameters fitted using the numerical model referenced in the background section. It is shown that increasing the feed solution temperature from 25°C to 40°C caused a 29% increase in pore size, presumably due to thermal expansion, and the effective active layer thickness to increase by 84%; volumetric charge density increased in magnitude by approximately 64%. From experience with the numerical model, pore size is known to be the most sensitive structural parameter that affects rejection ratio. Therefore, the minimal change in rejection ratio observed from these experiments is explained by the increase in magnitude of membrane charge density, which superseded the effect of the increased pore radius. The increase in pore radius, along with a 27% decrease in solvent viscosity between the temperatures considered, is responsible for explaining the increase in water flux.

<table>
<thead>
<tr>
<th>Membrane Parameter</th>
<th>25°C, 0.1 M</th>
<th>40°C, 0.1 M</th>
<th>40°C, 0.5 M</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pore radius (nm)</td>
<td>0.35</td>
<td>0.45</td>
<td>0.35</td>
</tr>
<tr>
<td>Volumetric charge density</td>
<td>-513.33</td>
<td>-840</td>
<td>-880</td>
</tr>
<tr>
<td>(mol/m³)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Effective Active Layer Thickness (µm)</td>
<td>0.380</td>
<td>0.701</td>
<td>0.479</td>
</tr>
</tbody>
</table>

Table 1: Comparison of fitted structural and electrical membrane parameters for different feed solution concentrations, at different temperatures
4.3 Effect of membrane pretreatment on performance

In addition to the effect of feed temperature on the membrane, it was also found that different pretreatment conditions yielded notable changes in membrane performance. Taking into account these effects is essential in order to establish an optimal experimental procedure and give insight to the nature and behavior of the membrane.

Initially tests were done by pre-compacting the membrane at the highest operating pressure of the stirred cell (5 bar), for 1 hour before beginning tests at lower pressures. This process was believed to be necessary to remove impurities from the manufacturing of the membrane and to ensure that the membrane structure and performance during tests were not affected by the increases in pressure [14]. The results for these tests at 25°C are shown in Figure 9. The data shows lower water fluxes at all pressures and a discontinuity in the rejection trends at higher pressures compared to tests without pre-compaction; the rejection increases linearly with pressure, then decreases significantly at 2.25 bar, then begins increasing linearly again. The same trend was seen in the three samples tested. The exact cause and mechanism of this discontinuity in the trend is unclear. Experimental error due to misreading of pressures or misreporting of values at these higher pressure tests is possible, but unlikely. The pressure regulator may have malfunctioned during these tests, but use of the same pressure regulator did not result in similar trends when pre-compaction was not a part of the pretreatment process.

If the trends are not the result of procedural error, there are three hypotheses for the discontinuity in rejection. Firstly, it is possible that upon reaching the higher pressures, the membrane undergoes deformation that decreases the active layer thickness. However the pore size is also expected to decrease when the membrane is compressed by pressure, which would cause the rejection to increase at higher pressures, but instead the data shows reduced rejection at higher pressure. Moreover, the pressure range for these tests was small due to the limitations of the Amicon stirred cell, and it is unexpected for such low pressures to have such an impact [15].

Secondly, the maximum operating pressure of the stirred cell may be lower than the 5 bar stated by the manufacturer, causing a leak in pressure and hence the lower rejection observed, but the water flux did not exhibit a decrease due to the lowered pressure, as would be expected. Thirdly, it is possible that there is leakage around the membrane at the higher pressures causing lower rejection; however, no water leaks were observed during the tests, and it is not clear why pre-compaction would enhance the leakage effect. Since none of these hypotheses is able to entirely
explain the trends observed, the irregularities are attributed to the viscoelastic/viscoelastic plastic behavior known to be shown by NF membranes [15]. This implies that the membrane retains memory of previous treatment, which is observed clearly when the membrane is pre-compacted before use. The underlying mechanisms are not well understood [15]. A next step is to determine the time constant for recovery of the NF membrane, which would be used in future experiments to ensure that tests are done with the membrane when it has recovered from the pressure applied during the previous experiment. The uncertainty in the calculation of the rejection ratio due to multiple instrument readings and instrument accuracy also may show that the trends are actually accounted for within the error bars; further work is necessary to confirm that the trends are not within the error bars.

![Figure 9: Comparison of rejection ratio and water flux with and without pre-compaction of the membrane, averaged across all samples.](image)

A repeatability test was done using membrane sample C, at 40°C with 0.5 M feed solution, by conducting experiments at 0.5 bar pressure intervals up to the highest pressure of 4 bar. Following the 4 bar experiment, the 3.5 bar pressure test was repeated to measure any hysteresis of the membrane that may have occurred. Figure 10 shows the difference between the first test at 3.5 bar and the second test at 3.5 bar following the test at 4 bar. Both rejection and water flux showed minimal change within experimental error for the second 3.5 bar test. On a short time scale, it appears that going to higher pressures did not affect the membrane parameters noticeably.
The effect of pretreating the membrane with alcohol was quantitatively evaluated in an experiment where membrane sample A, was tested with and without the alcohol pretreatment process. Figure 11 shows the difference in results between these two tests. The data shows a clear reduction in rejection ratio and increase in water flux when the alcohol pretreatment is done, which is explained by the removal of air bubbles in the membrane by the alcohol, allowing for an increased flux of salt and water through the membrane. The outlier at the 3.5 bar data point for the test done with alcohol pretreatment is most likely the result of measurement error of the rejection, since the irregularity in the trend is observed only for salt rejection and not for water flux.
5. Summary and Conclusion

This work shows that a temperature increase from 25°C to 40°C for a 0.1 M NaCl feed solution resulted in an increase in water flux by approximately 23% and a minimal change in rejection ratio within the limits of experimental error. This indicates that increasing the temperature can be useful in filtration processes where higher water fluxes are desired without compromising rejection ratio of charged solutes. The experimental data was used to numerically fit structural and electrical parameters of the membrane. The pore radius increased by 29%, effective active layer thickness increased by approximately 84%, and the charge density increased in magnitude by 64% when the temperature increased from 25°C to 40°C. These fitted parameters can be used to predict the performance of the NF270 membrane under different flow conditions and results at the two values of feed concentration considered in this study can be used to derive a relation for membrane charge as a function of concentration [1] [4].

In addition to the effects of changing temperature, certain membrane pretreatment procedures had a pronounced effect on the water flux and rejection ratio of the membrane; soaking the membrane in a 50% DI water, 50% alcohol solution resulted in a 17% increase in water flux and 18% decrease in rejection. It was shown that hysteresis in the membrane due to repeating tests at a lower pressure immediately after a higher pressure was not large, as reflected in the results of water flux and rejection, although more tests would be needed to confirm this observation. Pre-compaction of the membrane at high pressures before experiments at lower pressures seemed to cause a discontinuity in rejection ratio trends at higher pressures, but the actual mechanism for why this trend occurs is unclear, and can only be attributed to the viscoelastic/viscoelastic-plastic nature of the membrane.

Future work is required to determine the time constant of the viscoelastic property of the membrane to ensure adequate recovery time before reuse. Work to determine the effect of pH and determination of the membrane iso-electric point at different temperatures is necessary. Experiments using feed of actual seawater composition are necessary in order to better simulate the conditions of desalination plants and confirm if the 0.5 M NaCl feed used in these tests was able to correctly provide fitting parameters for seawater composition, as assumed in this study.

The results presented in this study contribute to the understanding of nanofiltration membranes which, due to their range of pore size, are known to exhibit complex properties as a result of the interplay of membrane electrical and structural properties. The experimental results
show the effect of temperature on the two key performance characteristics of the membrane while the fitting parameters provide an understanding of how the membrane itself changes with variation of temperature.
References

Appendix A: Determination of experimental quantities from measured values

Conversion of conductivity to concentration:

Conductivity is measured in μS per cm by the Hach Q440d conductivity meter. The conductivity of the solution is directly proportional to the concentration of charged solutes in the solution. For NaCl, this relation is made through a known constant that converts the conductivity measured into a concentration of NaCl in water. This constant is equal to 0.64 [16]. The resultant concentrations are reported in units of molarity, or moles per liter.

The constant 0.64 is defined as a measure of concentration (in mg of solute per kg of water) per unit of conductivity (μS/cm) such that

\[
1 \text{ } \frac{\mu S}{\text{cm}} = 0.64 \frac{\text{mg, NaCl}}{\text{kg, water}}
\]

\[
= 10790 \text{ } \frac{\mu S}{\text{cm}} = 10790 \times 0.64 \frac{\text{mg, NaCl}}{\text{kg, water}} = 6905.6 \frac{\text{mg, NaCl}}{\text{kg, water}}
\]

Concentration = 6905.6 \frac{\text{mg, NaCl}}{\text{kg, water}} \times \frac{1 \text{g, NaCl}}{1000 \text{mg, NaCl}} \times \frac{1 \text{mol, NaCl}}{58.44 \text{g, NaCl}} \times \frac{1 \text{kg, water}}{1 \text{L, water}} = 0.118 \text{M}

Equation (1): Rejection Ratio:

The rejection ratio is a measure of the membrane's ability to prevent solutes from passing through the membrane. By definition

\[
R = \frac{(C_f - C_p)}{C_f} = 1 - \frac{C_p}{C_f}
\]

where \(C_f\) is the initial bulk feed concentration and \(C_p\) is the bulk permeate concentration. For illustration, for the experiment using ~0.1 M (0.1 M could not be measured exactly due to measurement limitations) feed solution at 25°C at 4 bar,

\[C_f = 0.118 \text{M}, \ C_p = 0.102 \text{M}\]

\[\Rightarrow R = 1 - \frac{C_p}{C_f} = 1 - \frac{0.102}{0.118} = 0.135\]
Equation (2): Water Flux:

The water flux through the membrane is the volumetric flow rate of water per unit membrane area per unit time. The volumetric flow rate is defined as

\[ Q = \frac{\Delta m}{\rho \cdot \Delta t} \]

where \( \Delta m \) is the change in mass of permeate collected in a given amount of time \( \Delta t \), and \( \rho \) is the density of water. It should be noted that the water density is not exactly equal to the solution density due to presence of solute in the solution, however the difference for a well-mixed 0.1 M solution is at most 5.5%, as discussed previously, so water flux is assumed equal to solution flux. For example, if a mass of \( 10^{-4} \) kg solution is collected in 4 seconds through a membrane with area 0.0029 m\(^2\)

\[ \Delta m = 10^{-4} \text{ kg}, \Delta t = 4 \text{ s}, \rho = 1000 \text{ kg/m}^3, A = 0.0029 \text{ m}^2 \]

\[ Q = \frac{10^{-4} \text{ kg}}{1000 \text{ kg/m}^3 \cdot 4 \text{ s}} = 2.5 \times 10^{-8} \text{ m}^3/\text{s} \]

\[ J_w = \frac{Q}{A} = \frac{2.5 \times 10^{-8} \text{ m}^3}{0.0029 \text{ m}^2} = 8.62 \times 10^{-6} \text{ m/s} \]

Equation (3): Effective Pressure:

Effective pressure difference is the difference between the net hydraulic pressure and the net osmotic pressure across the membrane. The net hydraulic pressure is equal to the gauge pressure applied to the membrane since gauge pressure accounts for the cancellation of atmospheric pressure on both sides of the membrane. The net osmotic pressure accounts for the difference in concentrations across the membrane, and is given by

\[ \Delta \Pi = \Delta C \times R \times T \times i \]

where \( \Delta C \) is the difference between bulk feed and bulk permeate concentrations, \( R \) is the universal gas constant, \( T \) is the temperature of the solutions, and \( i \) is the Van 't Hoff coefficient. As mentioned previously, the bulk feed concentration can be assumed to be the concentration near the membrane, \( C_m \), with the assumption of a well-mixed solution and high Reynolds number of the system. For illustration, for the experiment using ~0.1 M feed solution at 25°C at 4 bar,

\[ \Delta C = C_f - C_p = 0.118 \text{ M} - 0.102 \text{ M} = 0.016 \text{ M}, \Delta P_{\text{applied}} = P_{\text{gauge}} = 4 \text{ bar}, \]

\[ R = 8.314 \text{ J/mol K}, T = 313\text{K}, i = 1.83 \text{ for NaCl} \]
\[ \Delta P_{\text{effective}} = \Delta P_{\text{applied}} - \Delta \Pi = \Delta P_{\text{applied}} - \Delta C \cdot R \cdot T \cdot i \]

\[ = 4 \text{ bar} - \left( 0.016 \cdot \frac{\text{mol}}{\text{L}} \cdot 8.314 \cdot \frac{\text{J}}{\text{mol} \cdot \text{K}} \cdot \frac{1000 \text{L}}{\text{m}^3} \cdot 313 \text{K} \cdot 1.83 \right) = 3.26 \text{ bar} \]
Appendix B: Selection of heater sheet

The calculation below shows how the selection was made for a McMaster-Carr heater sheet. The desired wattage was determined by estimating the heat energy, \( Q \), needed to heat 200 mL of water from 20°C to 40°C in 5 minutes, which was the maximum time desired for the heating to take place. The mass considered in the estimation was assumed to be the mass of water in the stirred cell because the heat capacity of the water contained in the stirred cell (835.8 J/°C) is much greater than the heat capacity of the stirred cell plastic, (~60 J/°C). The heat flux required to heat the assembly is given by

\[
\Delta Q = mc_{\text{water}}\Delta T = 200\text{g} \times 4.179 \frac{\text{J}}{\text{g} \cdot \text{°C}} \times 20\text{°C} = 16716 \text{ J}
\]

\[
\Rightarrow \dot{Q} = \frac{\Delta Q}{t} = \frac{16716 \text{ J}}{300 \text{ s}} = 55.72 \text{ W}
\]

where \( m \) is the mass of the water, \( c_{\text{water}} \) is the specific heat of water, \( \Delta T \) is the change in temperature of the water, and \( t \) is the time needed to heat the water. Although a 56 W heater shows sufficient heat flux, a 75 W heater sheet was chosen to account for any unaccounted mass or heat loss.

Since the temperature limit of the heater sheet (232°C) was greater than the temperature limit of the stirred cell (125°C), it was necessary to ensure the steady state temperature of the system was lower than the limit for stirred cell. The heater sheet was considered as a thermodynamic system as shown below, where heat flow out of the system is negative. Temperature of the water is equal to temperature of the inner surface of stirred cell, assuming a high heat transfer coefficient on the inner surface of the stirred cell. It was assumed there was negligible heat transfer from the water to the environment through the top and bottom of the system because the conductive heat transfer through the thin side walls is greater than through the thicker lid, and the area of the side walls is greater than the area of the lid.

In the diagram above,

\[
q_{\text{conv}} = (h_c + h_r)A_{\text{heater}}(T_{\text{ambient}} - T_{\text{heater}}), \text{ heat dissipated to the ambient air by convection}
\]

\[
q_{\text{cond}} = \frac{2\pi k_{\text{plastic}}L(T_{\text{heater}} - T_{\text{inner wall}})}{\ln\frac{r_2}{r_1}}, \text{ heat transferred to cell inner wall by conduction}
\]
\[ h_c = 5 \frac{W}{m^2 K}, \text{natural convective coefficient of air,} \]

\[ h_r = 5 \frac{W}{m^2 K}, \text{thermal radiation heat transfer coefficient} \]

\[ A_{heater} = 0.0097 \text{ m}^2, \text{surface area of the heater sheet,} \]

\[ T_{ambient} = 298 \text{ K, ambient temperature,} \]

\[ k_{plastic} = 0.25 \frac{W}{m K}, \text{conductive heat transfer coefficient of plastic} \]

\[ L = 0.12 \text{ m, length of the stirred cell,} \]

\[ r_{out} = 0.069 \text{ m, outer radius, } r_{in} = 0.065 \text{ m, inner radius} \]

\[ T_{water} = 313 \text{ K, } T_{heater} = \text{temperature of the heater sheet} \]

\[ Q = 75 \text{ W, electrical heat flux to the heater sheet} \]

At steady state, the heater sheet and stirred cell are in thermal equilibrium and the electrical heat input to the heater sheet is equal to the heat lost to the environment and the stirred cell.

\[ \dot{Q} = (h_c + h_r)A_{heater}(T_{heater} - T_{ambient}) + \frac{2\pi k_{plastic}L(T_{heater} - T_{inner\ wall})}{\ln \left(\frac{r_{out}}{r_{in}}\right)} \]

The above equation can be solved for the steady state temperature of the heater sheet by rearranging to solve for \( T_{heater} \)

\[ T_{heater} = \frac{\frac{2\pi k_{plastic}L}{\ln \left(\frac{r_{out}}{r_{in}}\right)} + (h_c + h_r)A_{heater}}{\frac{\dot{Q}}{75 \text{ W}} + 10 \frac{W}{m^2 K}(0.0097 \text{ m}^2) + \frac{2\pi \left(\frac{0.25 W}{m K}\right)0.12m}{\ln \left(\frac{0.069m}{0.065m}\right)} 313K} \]

\[ = \frac{2\pi \left(\frac{0.25 W}{m K}\right)0.12m}{\ln \left(\frac{0.069m}{0.065m}\right)} + 10 \frac{W}{m^2 K}(0.0097 \text{ m}^2) \]

\[ = 326.7 \text{ K} = 53.5^\circ C \]

Therefore, the 75 W heater sheet was found to be satisfactory for the experiment because the wattage is able to supply adequate heat flux the solution while maintaining a steady state temperature well below the operating limit of the stirred cell and the heater sheet.
Appendix C: Average temperature estimation

Approximate Temperature Profile:

The average feed solution temperature could not be measured during tests due to limitations of the experimental setup, and therefore the average temperature needed to be analytically determined. Due to rapid heating and gradual cooling, the actual temperature fluctuated above the set point temperature, 24.0°C. Based on this variation in temperature, the average temperature over the setpoint can be estimated as the average value of an assumed triangular profile, as shown in the diagram below:

\[ T_{average} = \frac{\int_{0}^{300} T \, dt}{\int_{0}^{300} dt} + 24^\circ C = \frac{bh}{2b} + 24^\circ C = 25.25^\circ C \]

Where \( b \) is the base of the triangular profile and \( h \) is the height of the triangular profile, 2.5°C. Therefore the average temperature is 25.25 °C.