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Evaluation Of Commercial Pervaporation Membranes For Desalination Of Saline And Brackish Waters

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EVALUATION OF COMMERCIAL PERVAPORATION MEMBRANES FOR
DESALINATION OF SALINE AND BRACKISH WATERS.

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Master's Program in Environmental Engineering

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Dean of the Graduate School

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Dedication

To God, casualty, or destiny. However you want to call it.

To my parents and siblings.

To my friends, living far in the distance and close to the heart.

To my mentors, professors, instructors, bosses and coaches that bet on me.

EVALUATION OF COMMERCIAL PERVAPORATION MEMBRANES FOR
DESALINATION OF SALINE AND BRACKISH WATERS.

by

ANDRES FERNANDO SANCHEZ SANDOVAL, B.S., E.I.T.

THESIS

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If I were to write my acknowledgements to God, it would be longer than the thesis itself. Him and I know what His input was in this work. He does know my heart.

I daresay as well, that nothing I am today would have been possible without my family. Their unconditional support has enabled me to be in a position where I know dreams, desires, and goals can only be achieved through hard work and persistence and the constant use of imagination. I cannot thank them enough for all they are and all I am because of them.

One final acknowledgment I would like to share. It is ancient wisdom that still holds truth today:

“As is a tale, so is life: not how long it is but how good it is, is what matters” -Lucius Annaeus Seneca

Abstract

Pervaporation is a solution separation method that occurs by vapor transport through a selective membrane. As the need to provide drinking water to the growing population increases, pervaporation has potential merit as an alternative desalination technology, especially for water with very high salinity.

To our knowledge, there are no commercially available pervaporation membranes made specifically for desalination applications. Thus, the membranes PERVAP 4100 and PERVAP 4101 manufactured by DeltaMemAG were tested to evaluate their performance in desalination. Because the driving force in pervaporation is the difference in vapor pressure between the feed side and the permeate side of the membrane, the commercial membranes were tested with feed temperatures of 40°, 60°, and 80°C and with a constant permeate temperature of 5°C. Aqueous sodium chloride feed solutions were tested with nominal mass fractions of 0.6%, 3%, 6% with conductivities of 10, 50 and 100 mS/cm at 25°C, respectively. In total, 18 experiments were performed (nine experiments per membrane). For each experiment, permeate mass and conductivity were measured, and flux, rejection, and recovery were calculated. For all experiments, the conductivity reduction exceeded 97.5%, and 11 of the 18 experiments resulted in conductivity reduction greater than 99.7%. Salinity removal was not observed to be correlated with feed temperature or feed salinity. Flux ranged from approximately 0.03 kg m⁻² hr⁻¹ to 9.79 kg m⁻² hr⁻¹ and was positively correlated with feed temperature and negatively correlated with feed salinity.

Based on these results research is needed to optimize the fabrication of pervaporation membranes for desalination purposes. Specifically, pervaporation desalination could be more competitive by increasing the water flux.

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Chapter 1. Introduction

1.1. BACKGROUND

From the total water of the world, only 3% is fresh water, and only 0.5% of the total water on earth is available fresh water (Bureau of Reclamation, 2017). The growing population and change in the environment have increasingly complicated the procurement of safe drinking water. A key component to improve the reliability and affordability of drinking water supply is to diversify the portfolio of water supply technologies (UN-Water, 2015).

In the United States, 25% of the fresh water used is comes from groundwater (Mandler, 2017) Fresh water may also be produced from seawater, by using a desalination process. In simple words, desalination is the action of reducing the amount minerals and salts from the water (AMTA, 2016). Since the 1980's membrane technologies have been evolving to expand their application in desalination and beyond, and the two leading desalination technologies are reverse osmosis (RO) and distillation (Ashley, 2009).

1.2 RELEVANT DESALINATION TECHNOLOGIES

RO is the most popular desalination technology in the United States (Carter, 2015). RO operates by applying a mechanical pressure to the feed stream to yield permeate, and the applied pressure is proportional to the feed salinity. However, RO membranes have physical limitations in that applying too much pressure the membranes will break the membrane. This means that there is a limit to the feed salinity that RO can treat (Davis, 2010). Moreover, greater pressure translates into more energy demand, which increases costs (Mericq, Laborie, & Cabassud, 2010).

Membrane distillation (MD) and vacuum membrane distillation (VMD) both use non-wetted (hydrophobic) porous membranes (Vane, 2017). The difference between MD and VMD is that the VMD utilizes a vacuum pump on the permeate side of the membrane (Li & Sirkar, 2005).

The main limitation of MD systems is that the porous membranes are susceptible to wetting and fouling, which allow feed solution to contaminate the product stream (Naidu et al., 2016).

1.3 PERVAPORATION

Pervaporation is a separation process by which water vapor from the feed solution is transported through a non-porous membrane due to a difference in vapor pressure between the feed and the permeate side of the membrane (Burn et al., 2015, Ahmad & Lone, 2012).

The most contemporary uses of pervaporation are: organic solvent dehydration, separation of organic mixtures, and removal of volatile organic compounds from solutions containing water (Liang et al., 2015). Pervaporation has the advantage to effectively dehydrate mixtures with many components, as long as these components have different boiling points (PERVATECH, 2014). Still pervaporation is not a common technology used for desalination purposes.

The main difference between pervaporation and MD systems is the type of membrane. In MD systems, a porous membrane is used, whereas in pervaporation, a dense (non-porous) membrane is used (Khayet & Matsuura, 2004).

1.4 GOALS AND OBJECTIVES

The goal of this research was to evaluate the desalination performance of two commercially available pervaporation membranes, DeltaMem AG PERVAP 4100 and PERVAP 4101, on brackish and saline waters by observing their behavior of salt rejection and water flux at three feed temperatures (40°C, 60°C, and 80°C) and at three feed conductivities at 25°C (10 mS/cm, 50 mS/cm, and 100 mS/cm).

Chapter 2. Methodology

2.1 EXPERIMENTAL PERVAPORATION DESALINATION SYSTEM

An experimental (laboratory-scale) pervaporation desalination system was assembled as shown in **(Figure 2.1)**. The feed flow was constant at 700 mL/min using a Cole-Parmer Pump Drive model 75225, which provided a cross-flow velocity of approximately of 12 cm/s to mitigate the effects of the concentration polarization factor (Crittenden, Trussell, Hand, Howe, & Tchobanoglous, 2012). The rotameter used to measure the flow was from Gilmont instruments with a range of 0 to 1300 cubic mL/min of water. The heater used to heat the feed flow was Fisher Scientific Isotemp Immersion Circulator Model 7300, and the feed bath was 3.5 L. The temperature inside the membrane unit was measured using a temperature meter OMEGA HH806AW that was connected to the inside of the membrane unit. The feed was constantly heated and mixed with the recirculated concentrate.

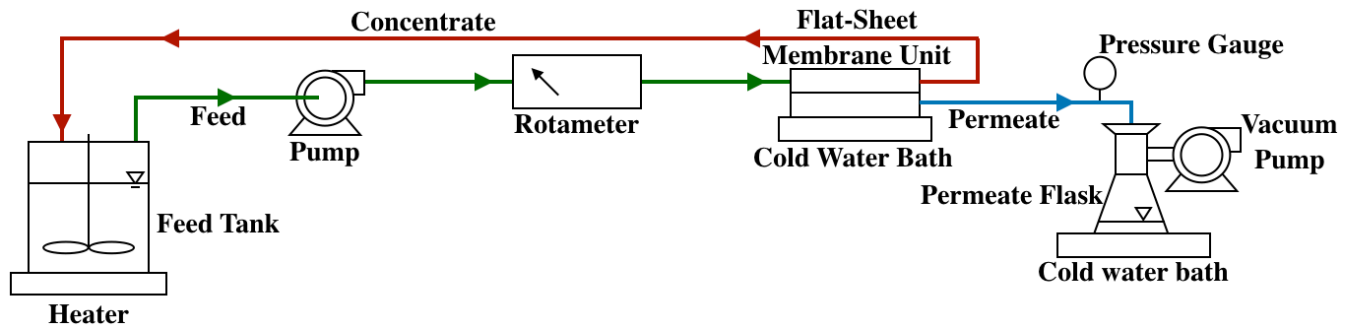


Figure 2.1 Pervaporation system schematic diagram

The flat-sheet membrane unit shown in **Figure 2.2** was a Sterlitech SEPA CF Cell. The feed spacer had a thickness of 0.9 mm and a porosity approximately of 70%. The feed-concentrate plate was on top, and the permeate plate was on the bottom, facilitating its submerging into the cold-water bath.

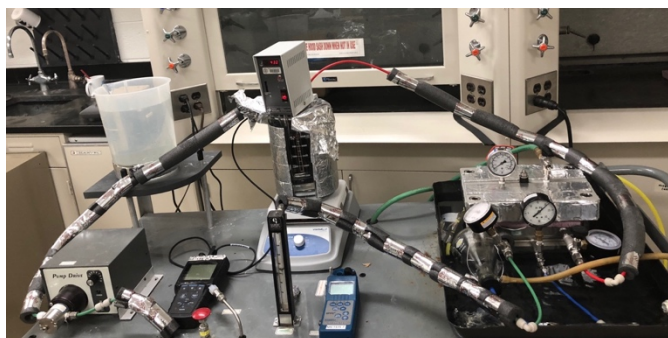


Figure 2.2 Experimental laboratory system

The total dimensions of the tested membranes were of 19.6 cm by 14.5 cm, and the effective area of the tested membranes was 140.2 cm² (14.6 cm by 9.6 cm). The permeate side of the membrane unit was constantly submerged in a cold-water bath at a temperature of 5°C to condense permeate.

The cold bath was continually cooled using a ThermoScientific chiller model HAAKE SC 150 and HAAKE A40 controller. The water was recirculated at 5°C.

2.2 TESTING PROTOCOL

Two commercially available pervaporation membranes were tested to evaluate their potential for desalination applications: PERVAP 4100 and PERVAP 4101 by DeltaMem AG. The objectives of this research were to test the desalination sensitivities to temperature and feed salinity. Neither of the membranes were created for the purpose of desalination. PERVAP 4100 and PERVAP 4101, containing polyvinyl alcohol, were made for dehydration applications. The maximum temperature for long term operation is 100°C (Yave, 2017). Further information can be found in **Appendix 6**. Each membrane was tested with three feed solutions at three different temperatures. After the desired feed temperature was achieved, the permeate vacuum was turned

on, and the timer was started. Each test lasted 5 hours. The permeate vacuum maintained an average vacuum pressure of 23 inches of mercury (Wang, Li, Bolto, Hoang, & Xie, 2016).

Synthetic sodium chloride (NaCl) solutions were prepared with nominal conductivity of 10, 50, or 100 mS/cm at 25°C, with a corresponding mass fraction of approximately 0.6%, 3%, and 6%, respectively. Solutions were prepared with the appropriate sodium chloride concentration (D. D. Lide, 2011) at 25°C \pm 0.1°C with the temperature correction in a beaker of 3.5 L. The selected concentrations simulated a range of salinity from brackish water, seawater, and saline water (*e.g.*, produced water). For reference, the conductivity of seawater is approximately 50 mS/cm (D. R. Lide, 2001).

Table 2.1 Relation between sodium chloride solution concentrations, conductivity and density

Mass Fraction	Concentration at 25°C (mol/L)	Conductivity at 25°C (mS/cm)	Density of solution at 25°C (kg/L)
0.57%	0.09761	10	1.003
3.04%	0.53234	50	1.023
6.26%	1.12045	100	1.049

The membranes were tested at three feed salinities and at three temperatures: 40°C, 60°C and 80°C. The reason for testing the membranes at these specific temperatures was based on the observation that the vapor pressure of pure water approximately doubles every 20°C in the range from 0°C to 80°C (Flowers, Theopold, Langley, & Robinson, 2015).

In order to start a test, it was necessary to wait for the membrane unit to achieve and maintain the desired temperature on the feed side (40°C, 60°C and 80°C). The maximum measured time to achieve stable flow was 18 minutes.

After each test, the mass of the collected permeate was measured using a Mettler Toledo XS16001M mass balance. Since the permeate was collected at a temperature of 5°C, it was warmed to 25°C to measure its conductivity using a ThermoScientific ORION STAR A329 conductivity meter with an Orion 013005MD probe both by ThermoScientific and a Myron L Ultrameter II. The conductivity meters were calibrated using standard KCl solutions at conductivities of 70, 700, and 7000 $\mu\text{S}/\text{cm}$.

2.3 CALCULATION OF SALINITY, REMOVAL, PERMEATE FLUX, AND HYDRAULIC RECOVERY

The density of a sodium chloride solution was calculated by regression for mass fraction (0 to 22.6%) and molar concentration (0 to 4.5 mol/L) data from Rogers & Pitzer, (1982) as shown in (Fig 2.1). These empirical regressions had a maximum error of 0.02%.

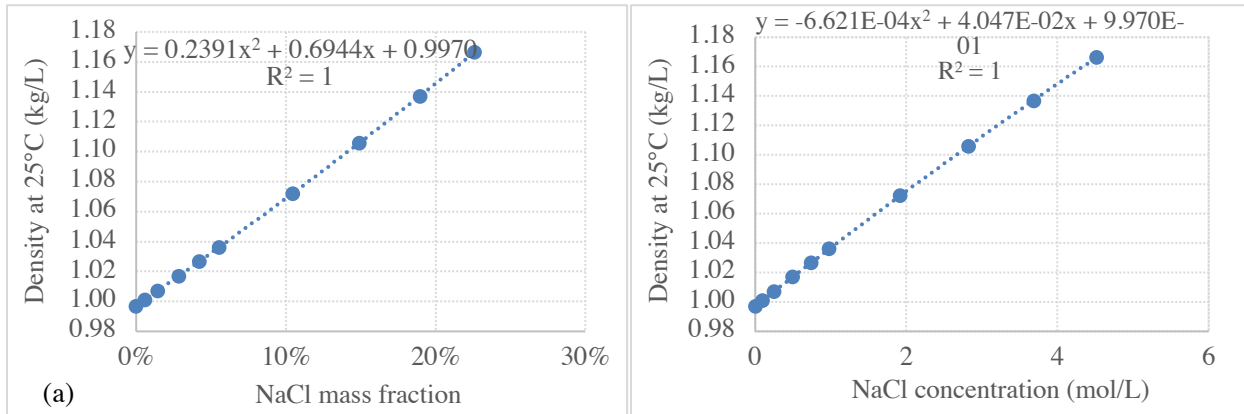


Figure 2.3 Sodium chloride density at 25°C versus (a) mass fraction and (b) molarity.

The expressions in Fig 2.3 were used to calculate mass fraction for conductivities at 25°C in the range of 0.013 mS/cm to 138.6 mS/cm (Vanysek, 2012) (Landolt & Börnstein, 1960), as shown in Fig 2.4. The regression equation shown in Fig. 2.4 was used to convert the measured

feed and permeate conductivities to mass fraction with a maximum error of 8%. For further calculation details refer to **Appendix 4**.

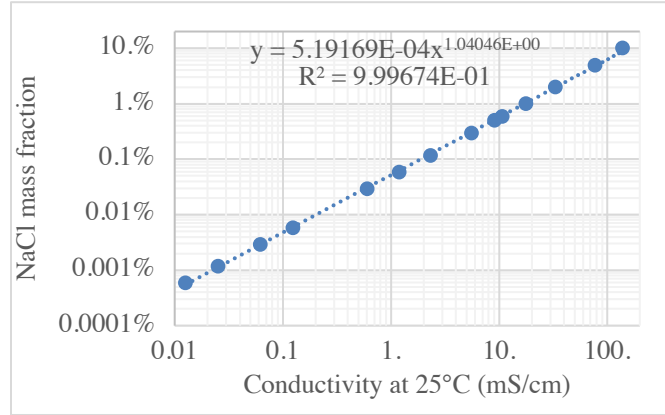


Figure 2.4 Sodium chloride mass fraction versus electrical conductivity at 25°C

The salt removal (R), was calculated for each experiment with **Eq. 2.1**, where c_{perm} is the sodium chloride concentration in mass fraction. The hydraulic recovery (r) of each test was calculated with **Eq. 2.2** where the m_{perm} is the mass of water that pass through the membrane. The flux (J) the was calculated using **Eq. 2.3** (Crittenden et al., 2012), where A_{mem} refers to the effective area (m^2) of the membrane and Δt as the total time for the test.

$$R = 1 - \frac{c_{perm}}{c_{feed}} \quad \text{Eq. 2.1}$$

$$r = \frac{m_{perm}}{m_{feed}} \quad \text{Eq. 2.2}$$

$$J = \frac{m_{perm}}{A_{mem}\Delta t} \quad \text{Eq. 2.3}$$

The vapor pressures of the saline/brackish solutions were calculated according to their NaCl concentration (D. R. Lide, 2001).

By using the densities of the solutions, Raoult's Law was applied (Sawyer, McCarty, & Parkin, 2003):

$$P_i = X_i P^o \quad \text{Eq. 2.4}$$

Where:

P_i = Vapor partial pressure

X_i = Mole fraction

P^o = Vapor pressure in pure form

The calculated vapor pressure of the brackish/saline solutions is provided in **Table 2.2**, as well as the difference in vapor pressure between the feed side and permeate side.

Table 2.2 Vapor pressures of feed and permeate solutions.

Feed Conductivity at 25°C (mS/cm)	Mass Fraction	Feed $P_{\text{vapor}} (P_i)$			Permeate P_{vapor}	$\Delta P_{\text{vapor}} (\text{atm})$		
		40°C	60°C	80°C	5°C	40°C	60°C	80°C
10	0.57%	0.072	0.196	0.465	0.009	0.064	0.187	0.457
50	3.04%	0.071	0.192	0.457	0.009	0.063	0.184	0.449
100	6.26%	0.070	0.189	0.449	0.009	0.061	0.180	0.440

Chapter 3. Results and Discussion

3.1 PERFORMANCE OF THE MEMBRANES

For 11 of 18 experiments, the conductivity reduction was greater than 99.7%, and the salt removal exceed 97.5% for all experiments, as shown in **Fig. 3.1**. (All experimental data are listed in **Appendix 1** and **Appendix 2**). No significant correlation was observed between salt removal and flux. All experiments yielded a hydraulic recovery less than 20%.

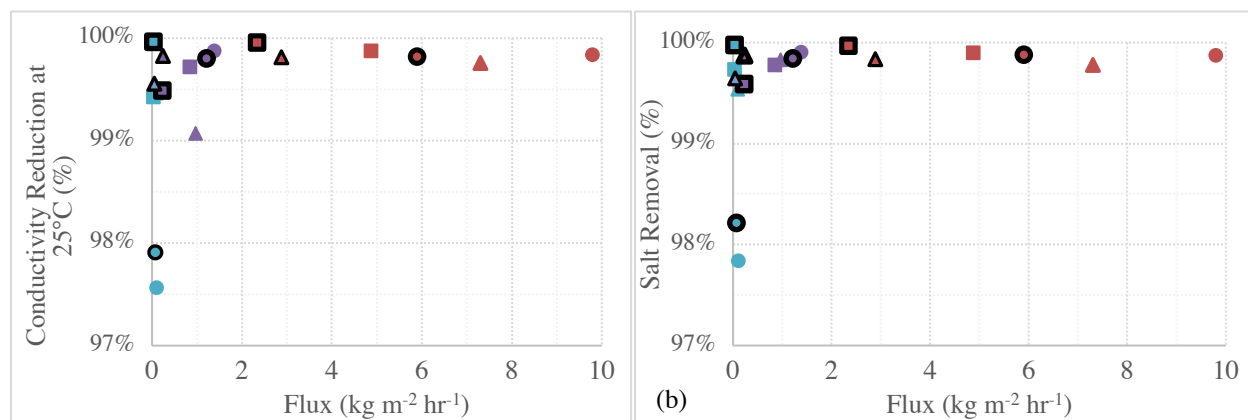


Figure 3.1 (a) Conductivity reduction and (b) Salt Removal vs average permeate flux

Membrane A was observed to be $47\% \pm 23\%$ greater flux than Membrane B. Flux was observed to decrease substantially with increasing feed salinity, as shown in **Fig 3.2**. Increments of feed mass fraction (0.6% to 3% and 3% to 6%) decreases the flux on an overall average of $84\% \pm 66\%$. The behavior of increasing feed salinity on the PERVAPTM membranes was very similar to behavior of the three layer thin film nanofibrous pervaporation composite mebrane, which also showed that increasing NaCl concentration decreaced the flux (Liang, Pan, Li, Giannelis, & Cao, 2014). Furthermore PERVAPTM membranes' contain polyvinyl alcohol which makes the behavoir comparable to increasing silica content. Increasing silica concentration decreases the flux of sol-gel derived polyvinyl alcohol hybrid membranes (Xie et al., 2011)

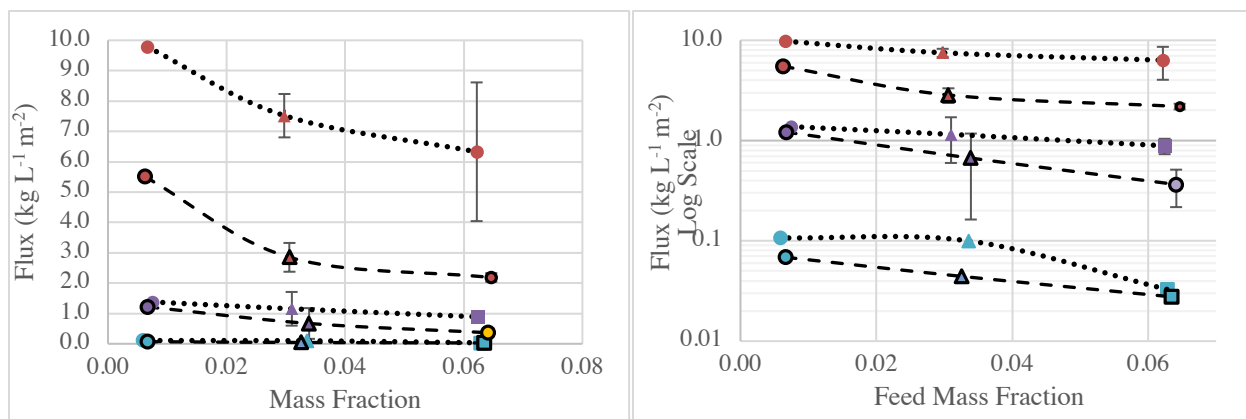


Figure 3.2 Sensitivity of average permeate flux to feed (a) conductivity and (b) concentration

Average permeate flux was observed to increase 90% with the difference in feed and permeate vapor pressure (Δp_{vap}) of the three nominal feed temperatures as shown in **Fig. 3.3**, which is assumed due to an increase in membrane phase solubility and diffusivity associated with the increase in temperature. Both PERVAP™ membranes showed similar behavior to polyetheramide-based polymer pervaporation membranes with respect to vapor pressure and flux correlation (Zwijnenberg, Koops, & Wessling, 2005).

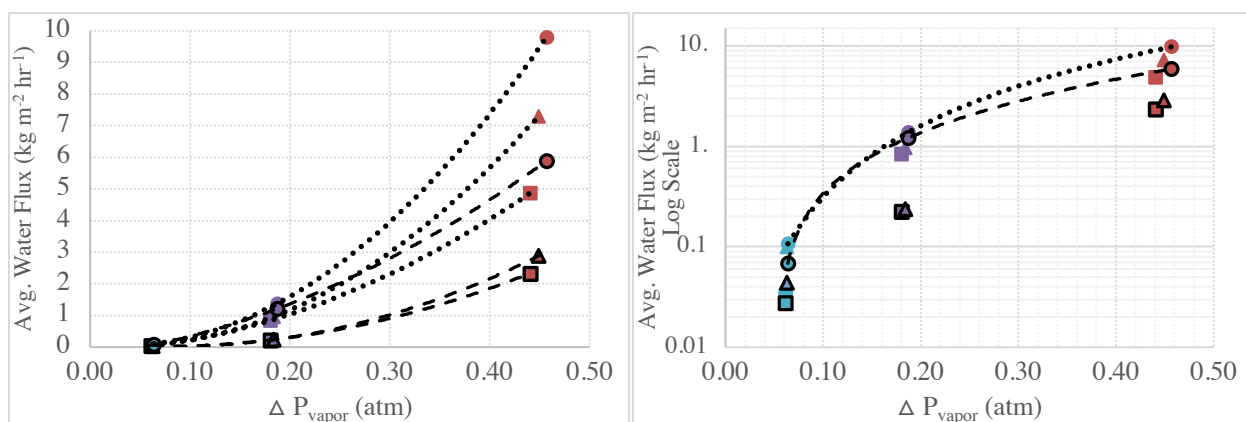


Figure 3.3 Sensitivity of average permeate flux to calculated difference in vapor pressure:
(a) linear scale and (b) logarithmic scale.

Chapter 4. Conclusion

4.1 GENERAL CONCLUSIONS

Two commercially available pervaporation membranes were tested: DeltaMem AG PERVAP 4100 and PERVAP 4101. For 16 of 18 experiments, the conductivity reduction was greater than 99%, and 16 out of 18 exceed 99.5% of salt removal. This very high salt rejection makes pervaporation promising for desalination of seawater, produced waters, and other high-salinity streams. Salt passage was observed to have a weak correlation with flux.

The PERVAP 4100 membrane yielded approximately 47% greater flux than the PERVAP 4101 membrane. For both membranes, the average water fluxes were observed to decrease with increasing feed salinity at about 84% average. Finally, the fluxes increased 90% on average with increasing feed temperature at the three nominal temperatures used.

4.2 FUTURE WORK

Further experimentation should be performed with the current pervaporation membranes using real brackish and saline water, as well as concentrate from desalination plants, to determine ion selectivity.

The water flux observed in this research is not competitive with reverse osmosis, but at the time of this writing, no commercially available pervaporation membranes were found that were manufactured specifically for desalination purposes. Future research should focus on developing pervaporation desalination membranes with high rejection and competitive flux.

Pilot pervaporation studies should be performed with alternative heat sources such as waste heat recovered from industrial process, solar heating, or geothermal brackish water.

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List of Mathematical Symbols

ΔP_{vapor} = Difference in Vapor Pressure

J = Flux

P_i = Vapor partial pressure

P^0 = Vapor pressure in pure form

R = Salt Removal

r = hydraulic removal

X_i = Mole fraction

ΔP_{vapor} = Difference in Vapor Pressure

Appendix

APPENDIX 1 PERFORMANCE OF THE COMMERCIAL MEMBRANE PERVAP 4100 (MEMBRANE A)

Experiments Membrane A		Feed Temp (°C)	Δ P_{vapor} (atm)	Feed Conducti vity at 25°C (mS/cm)	Feed Mass Fracti on	Flu x (kg m ⁻² hr ⁻¹)	Permeate Conducti vity (mS)	Perme ate Mass Fractio n	Conducti vity reduction at 25°C (%)	Salt Remov al	Recover y (%)
□	1	40	0.06	100.30	6.2745 %	0.0 3	0.336 5	0.01672 %	99.43%	99.73 %	0.07 %
	2	60	0.18	99.80	6.2420 %	0.8 4	0.279 4	0.01378 %	99.72%	99.78 %	1.69 %
	3	80	0.44	99.40	6.2160 %	4.8 7	0.127 8	0.00611 %	99.88%	99.90 %	9.75 %
Δ	4	40	0.06	55.00	3.3580 %	0.1 0	0.312 5	0.01548 %	99.47%	99.54 %	0.20 %
	5	60	0.18	50.88	3.0967 %	0.9 7	0.111 5	0.00530 %	99.07%	99.83 %	1.93 %
	6	80	0.45	48.97	2.9759 %	7.3 0	0.136 75	0.00655 %	99.76%	99.78 %	14.61 %
○	7	40	0.06	10.28	0.5865 %	0.1 1	0.257 7	0.01266 %	97.56%	97.84 %	0.21 %
	8	60	0.19	12.92	0.7439 %	1.3 8	0.015 86	0.00070 %	99.88%	99.91 %	2.76 %
	9	80	0.46	11.47	0.6573 %	9.7 9	0.018 24	0.00081 %	99.84%	99.88 %	19.61 %

APPENDIX 2 PERFORMANCE OF THE COMMERCIAL MEMBRANE PERVAP 4100 (MEMBRANE B)

Experiments Membrane B		Feed Temperature (°C)	ΔP_{va} por (atm)	Feed Conductivity at 25°C (mS/cm)	Feed Mass Fraction	Flux (kg m ⁻² hr ⁻¹)	Permeate Conductivity (mS)	Permeate Mass Fraction	Conductivity reduction at 25°C (%)	Salt Removal (%)	Recovery (%)
□	10	40	0.06	101.30	6.34 %	0.03	0.03280	0.00148 %	99.97%	99.98%	0.06%
	11	60	0.18	102.40	6.41 %	0.23	0.52000	0.02629 %	99.49%	99.59%	0.53%
	12	80	0.44	103.20	6.46 %	2.33	0.04076	0.00186 %	99.96%	99.97%	4.36%
Δ	13	40	0.06	53.40	3.26 %	0.04	0.23610	0.01156 %	99.56%	99.64%	0.09%
	14	60	0.18	55.50	3.39 %	0.24	0.09600	0.00453 %	99.83%	99.87%	0.47%
	15	80	0.45	50.30	3.06 %	2.88	0.10410	0.00493 %	99.82%	99.84%	5.77%
○	16	40	0.06	11.65	0.67 %	0.07	0.24330	0.01193 %	97.91%	98.21%	0.14%
	17	60	0.19	11.68	0.67 %	1.22	0.02334	0.00104 %	99.80%	99.84%	2.43%
	18	80	0.46	10.94	0.63 %	5.89	0.01677	0.00074 %	99.82%	99.88%	11.79 %

Appendix 3 Calculations of Density and mathematical error.

Concentration (mol/kg)	Concentration (mass fraction)	Concentration NaCl(g/L)	Concentration (mol/L)	Specific Vol @ 25°C (cm ³ /g)
	0	0	0	
0.1	0.6%	5.82	0.10	0.998834
0.25	1.4%	14.50	0.25	0.992832
0.5	2.8%	28.88	0.49	0.983185
0.75	4.2%	43.11	0.74	0.973932
1	5.5%	57.21	0.98	0.965038
2	10.5%	112.21	1.92	0.93259
3	14.9%	164.95	2.82	0.904339
4	18.9%	215.44	3.69	0.879457
5	22.6%	263.76	4.51	0.857301
Density @ 25°C (g/mL)	Calculated Density (kg/L) by mass fraction	Error	Calculated Density (kg/L) by concentration (mol/L)	Error
0.997048	0.99705	0.00%	0.997048	0.00%
1.001167361	1.00109	-0.01%	1.001069624	-0.01%
1.007219751	1.00710	-0.01%	1.007051025	-0.02%
1.01710258	1.01696	-0.01%	1.016883115	-0.02%
1.026765729	1.02663	-0.01%	1.026543951	-0.02%
1.036228625	1.03612	-0.01%	1.036034133	-0.02%
1.072282568	1.07233	0.00%	1.072314916	0.00%
1.105780023	1.10595	0.02%	1.105999931	0.02%
1.137065257	1.13720	0.01%	1.137242667	0.02%
1.166451456	1.16630	-0.01%	1.166218921	-0.02%

APPENDIX 4 CALCULATIONS OF CONCENTRATION (MASS FRACTION) AS A FUNCTION OF CONDUCTIVITY AT 25°C AND MATHEMATICAL
ERROR.

Concentration (mass fraction)	concentration (mol/L)	Concentration (g/L)	Density (kg/L)	Equivalent Conductivity
				126.39
0.0006%	0.0001		0.99705	125.56
0.0012%	0.0002		0.99706	125.21
0.0029%	0.0005		0.99707	124.44
0.0059%	0.001		0.99709	123.68
0.0293%	0.005		0.99725	120.59
0.0586%	0.01		0.99745	118.45
0.117%	0.02		0.99786	115.7
0.292%	0.05		0.99907	111.01
0.584%	0.1		1.00109	106.69
0.5%	0.086	5.0	1.00053	105.37
1.0%	0.172	10.0	1.00402	102.44
2.0%	0.346	20.2	1.01103	96.01
5.0%	0.883	51.6	1.03237	87.30
10.0%	1.829	106.9	1.06888	75.78
15.0%	2.840	166.0	1.10659	66.22
20.0%	3.920	229.1	1.14549	57.24
25.0%	5.072	296.4	1.18559	48.15

Conductivity @ 20°C (mS/cm)	Conductivity @ 25°C (mS/cm)	Calculated mass fraction	Error
	0.013	0.0005%	-7%
	0.025	0.0011%	-4%
	0.062	0.0029%	-1%
	0.124	0.0059%	1%
	0.603	0.0307%	5%
	1.185	0.0619%	6%
	2.314	0.1243%	6%
	5.551	0.3089%	6%
	10.7	0.6096%	4%
8.2	9.02	0.5119%	2%
16	17.6	1.0262%	3%
30.2	33.2	1.9873%	-1%
70.1	77.1	4.7728%	-5%
126	138.6	8.7847%	-12%
171	188.1		
204	224.4		
222	244.2		

APPENDIX 5 PAIR-WISE COMPARISON OF FLUX

Conductivity mS/cm at 25°C	Flux A 80°C	Flux B 80°C	%Greater	Flux A 60°C	Flux B 60°C	%Greater	Flux A 40°C	Flux B 40°C	%Greater
10	9.79	5.89	40%	1.38	1.22	12%	0.11	0.07	36%
50	7.30	2.88	61%	0.97	0.24	75%	0.10	0.04	56%
100	4.87	2.33	52%	0.84	0.23	73%	0.03	0.03	16%
Mean	7.32	3.70	50.8%	1.06	0.56	53.5%	0.08	0.05	35.8%
Standard Deviation	2.46	1.92	0.10	0.28	0.57	0.36	0.04	0.02	0.20

APPENDIX 6 PERVAPORATION MEMBRANE DATA SHEETS. (PROVIDED BY DELTAMEM AG)

Table 1 Typical application of PERVAP™ membranes

Membrane type	Typical application
PERVAP™ 4100	Standard membrane developed for most dehydration of volatile organic mixtures.
PERVAP™ 4101	Highly cross-linked membrane developed for dehydration of reactions mixtures, up to 50% w/w water.
PERVAP™ 4102	Modified and highly cross-linked membrane for dehydration of volatile organic mixtures containing amines up to 500ppm.
PERVAP™ 4510	High flux membrane specially developed for the dehydration of higher alcohols >C ₃ .
PERVAP™ 4155-XX	Membrane with tailored separation properties suitable for removal of methanol and / or water from volatile organic mixtures.
PERVAP™ 4060	Organophilic membrane to remove organics from aqueous solutions.

Table 2 Compatibility with organic groups

Membrane	PERVAP™ 4100	PERVAP™ 4101	PERVAP™ 4102	PERVAP™ 4510	PERVAP™ 4155-xx
Alcohols. <i>e.g. Methanol, Ethanol, n-Propanol, i-Propanol, Butanols and higher linear paraffin alcohols.</i>	○	○	○	○	○
Ethers including cyclic ethers. <i>e.g. Diethyl ether, Diisopropyl ether, Dioxane, THF.</i>	○	○	○	●	○
Acetates / Esters. <i>e.g. Methyl Acetate, Ethyl Acetate, (Iso)-Propyl Acetate, Butyl Acetate, Pentyl Acetate.</i>	○	○	○	●	○
Ketones. <i>e.g. Acetone, Cyclohexanone, MEK, MIBK.</i>	○	○	○	●	○
Hydrocarbons. <i>e.g. pentane, hexane.</i>	○	○	○	●	○
Others					
Acetonitrile.	○	○	○	●	◐

Table 3 Recommended maximum feed water concentration for dehydration and methanol removal membranes

Maximum water concentration	Membrane type				
	PERVAP™ 4100	PERVAP™ 4101	PERVAP™ 4102	PERVAP™ 4510	PERVAP™ 4155-xx
Up to 20% w/w	○	○	○	○	See Table 4.
Up to 30% w/w	○	○	○	○	See Table 4.
Up to 50% w/w	◐	○	◐	●	See Table 4.
Up to 100% w/w	●	●	●	●	See Table 4.

Table 4 Maximum recommended feed water content for methanol removal membranes

Maximum water concentration	Membrane type					
	PERVAP™ 4155-30	PERVAP™ 4155-40	PERVAP™ 4155-50	PERVAP™ 4155-60	PERVAP™ 4155-70	PERVAP™ 4155-80
Up to 2% w/w.	○	○	○	○	○	○
Up to 5% w/w.	●	◐	○	○	○	○
Up to 10% w/w.	●	●	●	◐	◐	○
Up to 15% w/w.	●	●	●	●	●	◐

Table 5 Compatibility with Impurities

Impurities	Membrane type				
	PERVAP™ 4100	PERVAP™ M 4101	PERVAP™ 4102	PERVAP™ 4510	PERVAP™ 4155-xx
Aldehydes & derivatives <30ppm (as acetaldehyde).	◐	◐	◐	●	○
Organic acids <0.1 % w/w.	◐	◐	◐	●	●
Amines (e.g. MMA) <500 ppm.	●	○	○	●	●
Acetals / Ketals.	◐	◐	◐	●	◐
Special solvents such as DMF, DMSO, NMP, DMAc <0.1% w/w.	◐	◐	◐	●	●
Mineral acids.	●	●	●	●	●
Peroxides.	●	●	●	●	●

PERVAP™ dehydration and methanol removal membranes have limited or no compatibility with the following impurities: mineral acids, halogenated hydrocarbons, peroxides, sulfoxides and some nitriles. Advice should be sought where these impurities are present.

Key and comments

- Compatible.
- ◐ Conditionally compatible.
- Not compatible

Vita

Andres F. Sanchez started his university life in fall 2012 and in December of 2016. He was awarded his bachelor's degree in Civil Engineering from The University of Texas at El Paso (UTEP). During his time as an undergraduate student he was part of several student organizations such as the social fraternity of Phi Delta Theta ($\Phi\Delta\Theta$), Chi Epsilon Honor Society for Civil Engineers and the student chapter of the American Society of Civil Engineers (ASCE). Mr. Sanchez held a summer internship two consecutive summers with the General Contractors company of Construction, Project Management Enterprises LLC (CPME). For the summer of his Senior year he did a Summer Internship with Western Refining in their Environmental Department.

As a graduate student Mr. Sanchez worked as a research assistant for the Center of Inland Desalination Systems laboratory and as teaching assistant for the Department of Civil Engineering at UTEP. He also held the position of master's assistant for 7 months working for the Office of Provost at UTEP. Mr. Sanchez was an active member of the student chapter of Engineers Without Borders (ESW), where he participated in the Disaster Relief Bridge Reconstruction project in Utuado, Puerto Rico. Finally, Mr. Sanchez did a summer internship with El Paso Water under their department of Water Resources.

After completing his master's degree, Mr. Sanchez is planning to look for a job in consulting.

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