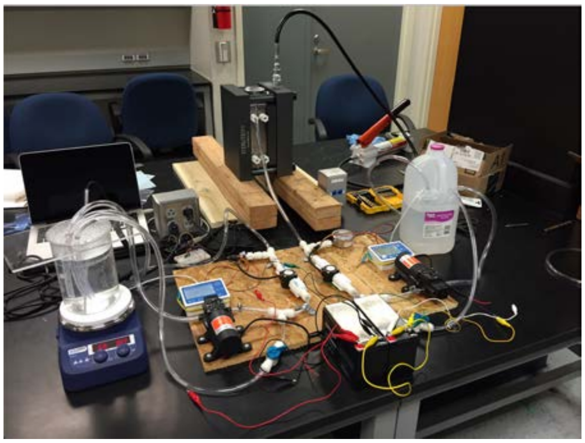
Air Gap Membrane Distillation

EGR 482: Senior Design Project



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1 Abstract

Membrane Distillation is a thermally driven technique used for desalination in which water vapors from brackish water travels through a hydrophobic membrane. In this process, heat and mass transfer are the main driving forces. Air gap membrane distillation is a technique in which an air gap is added to the system. After mechanically modifying a test cell used for forward osmosis to a test cell that can be used for air gap membrane distillation, the operating parameters were varied to see how they affected the permeate flux. A membrane with a 0.45 µm pore size was used and an air gap of 5.6 mm was maintained throughout the experimentation process. The temperature of the hot saline solution was varied from 50°C to 70°C and as a result the flux increased by 373%. Additionally, the permeate flux increased by 110%when the hot feed flow rate was increased from 2.0 L/min to 3.4 L/min. The rejection rate stayed very consistent, regardless of the operating parameters, staying above 99%. At optimum conditions, which was when the temperature was at 70°C and a flow rate of 3.4 L/min, the flux reached its highest value of 14.3 kg/m² hr.

2 Introduction

Fresh water is a very sought after resource. Although abundant in fundamental composition, most of it is not considered fresh water safe for human consumption. Roughly 70% of the world is covered by water; unfortunately only about 2.5% is considered fresh water, while the rest is saline ocean-based water [1]. Of that 2.5 percent however only 1 percent is easily available for consumption, reducing the amount of usable freshwater globally to about 0.007 percent. The amount of fresh water available isn't necessarily reducing in quantity, since it tends to recycle itself through evaporation and precipitation which eventually allows us to gather the water once again. However the population that depends on fresh water consumption for bathing, drinking, and cooking is increasing rapidly. This in turn has forced the research and development of new ways in which to create fresh water in sustainable ways.

Current methods of water filtration or desalination include processes that are very high in energy consumption. The most common processes used for desalination include thermal, electrical, and pressure [2]. The energy intensive nature of the more conventional methods of desalination forces research in novel areas of desalination. The purpose of this project was to investigate and aid in the development of a relatively novel method of desalination called Air Gap Membrane Distillation. Specifically the development of a bench-sized system that allows the further research and testing was the objective.

Air Gap Membrane Distillation falls under the process known simply as Membrane Distillation (MD). MD is a thermally driven separation process in which only water molecules flow through a microporous hydrophobic membrane [4]. Within MD there are four different configurations that all function on the premise of MD however each focuses on manipulating either the heat or mass transfer efficiency. Direct Contact Membrane Distillation (DCMD) shown on the far left in figure 1 represents the most commonly researched method of MD, however for the purposes of this report we will be focusing on the attributes and characteristics inherent to AGMD. The theory behind the driving mechanisms and efficiency of AGMD will be covered before our particular design approach to developing a bench-sized system is discussed.

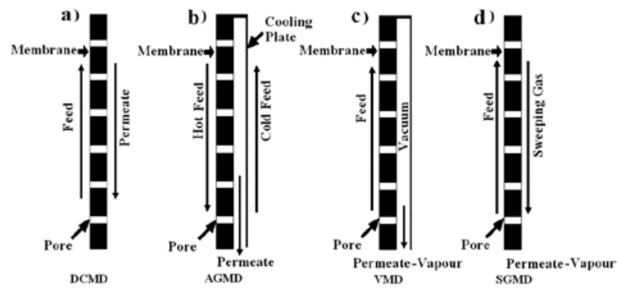

Figure 1: MD Configurations

3 Theory

Within an AGMD test cell there is heat and mass transfer occurring simultaneously. The hot side of the test cell has a heated saline solution circulating through its inlet and outlet ports while it fills a channel with the hot saline solution. This solution is flowing over a hydrophobic microporous membrane with a Liquid Entry Pressure (LEP) higher than that of the saline solution flowing over it. This prevents the water molecules from permeating through the membrane and only allows the fresh water vapor molecules to do so. On the other side of the membrane there is an air gap that was designed to be a certain thickness. On the opposing side of the membrane and the air gap an aluminum plate was introduced to allow the water vapor molecules that are diffusing through the membrane and across the air gap to condense and form fresh water droplets. The water droplets were then collected.

3.1 Heat Transfer

The heat transfer begins as the heat flux from the hot saline solution is being transferred to the exposed membrane area through convective terms. Heat is transferred through the membrane by means of conduction. The heat proceeds through the condensation plate through means of conduction and finally through to the cold circulating solution by means of convection. The theoretical calculations of these processes can be modeled using an engineering equation solver very accurately, however for the purposes of this project we will focus on the development of the bench-sized system.

3.2 Mass Transfer

The mass transfer occurring within the system is very important to the overall rate of the permeate flux. The permeate flux is represented by the equation shown below.

$$Jw = Bw(Pmf - Pcd) \qquad (1)$$

The equation shown above determines the amount of permeate flux flowing through the membrane which will eventually condense on the condensation plate. The rate of this flux is dependent upon the overall mass transfer coefficient represented as Bw and the difference between the hot saline side vapor pressure denoted by Pmf and the vapor pressure occurring within the air gap Pcd. The reason why the heat transfer within the system is so important is because it relates to the amount of vapor pressure that is driving permeate through the membrane. This is further explained or rather proven by the approximation of vapor pressure, which is done using Antoine's equation shown below.

$$Pv(T) = \exp(23.1964 - \frac{3816.44}{T-46.13}) \qquad (2)$$

This equation allows us to relate the relationship between temperature and vapor pressure. The higher the temperature the higher the vapor pressure, allowing the difference in vapor pressure between the hot saline side and air gap to be higher when the temperature in the feed solution is increased.

4 System Design

4.1 Design

A test cell, Sepa CF Cell, designed for forward osmosis was provided by Sterlitech Corporation. As a result, modifications had to be made to the test cell in order to make it useable for air gap membrane distillation. The two main components that needed to be added to the test cell were the condensation plate and the spacer plate. There were also 3 gaskets added: one before the membrane, one in between the membrane and the spacer plate, and one in between the spacer plate and the condensation plate, in order to ensure water tightness. The condensation plate was in contact with the cold feed side of the test cell.

4.2 Condensation Plate

The condensation plate was machined out of a 1/16" (1.5875 mm) thick sheet of aluminum and was cut to the same size as the test cell. There were also four holes punched into the aluminum sheet in the same location as the pins that were on the test cell. This was done to ensure that the condensation plate did not move within the test cell. The main reasons for choosing an aluminum plate as opposed to a different material were the relatively low cost and its high thermal conductivity. The thermal conductivity was a main factor since the condensation plate needs to be able to stay cold so that the vapor molecules traveling across the membrane can condense on the plate, forming purified water droplets.

4.3 Spacer Plate Design

The most important component of design in terms of allowing the conversion of the forward osmosis test cell to become an AGMD test cell was the spacer plate. The spacer plate was 3/16” (4.7625 mm) thick and was made out of PMMA. The reasons for choosing PMMA was its relatively low cost and its ease of manufacturing. There was also a 3” diameter circle cut out of the center of the spacer plate, creating our effective membrane area of 7.068 in^2 (179.5 mm^2). This effective membrane area is the area of the membrane where the vapor molecules are allowed to pass through. The 3” circular design was chosen for a couple reasons. First was the ease of manufacturing. The circle was a relatively easy shape to cut out of the Plexiglas. Also, there was concern that if another shape was chosen, such as a square, that there would be some flooding within the air gap because some of the droplets would not be able to fall to the bottom. The design was chosen as a result of the 3.75”×5.75” channel that is located in the center of the test cell. Due to the width of the channel, the 3” diameter circle machined in the spacer plate was designed so that the entire effective membrane area was located within the channel. There was also a ¼” channel cut into the condensation plate side of the spacer plate. This channel was machined so that the water droplets that formed on the spacer plate would be able to drop to the bottom of the test cell, eventually collecting in a beaker. The air gap thickness was something that was taken into consideration throughout the entire design process. The air gap is a huge factor when it comes to the flux. The smaller the air gap, the smaller the mass transfer resistance in the system resulting in a larger flux. The air gap was 7/32” in (5.56 mm) thick, which was made up of a combination of the thicknesses of the spacer plate as well as the 2 gaskets on either side of the spacer plate.

4.4 Membrane

Flat sheet membranes acquired from Sterlitech was used for all of the testing. The membranes used were aspire laminated, hydrophobic PTFE membranes with a polyester backing. These membranes are especially effective when a very high rejection rate is required. The thickness of the membranes was 6 to 10 mil (15-25 mm) and the pore size was 0.45 µm. As has been discussed previously, the vapor molecules travel through the pores in the membrane, across the air gap, finally condensing on the condensation plate. One of the main reasons that these membranes are so effective is the pressure required for both air and liquid to pass through the membrane. Only 0.004 psi is required for air to permeate through the membrane. On the other hand, 21 psi of pressure is required for liquid to permeate through the membrane. As a result, these Sterlitech membranes provided an extremely high rejection rate.

4.5 Auxiliary Components and Instrumentation

There were many additional components added outside of the test cell to ensure desirable operating conditions. The test cell itself was placed inside a hydraulic press which was connected to a hand pump to increase or decrease the pressure applied to the test cell, both of which were also provided by Sterlitech. The purpose of the hydraulic press was to eliminate leaking within the cell. On both the hot and cold side, there was a pump, tee valve, ball valve, flow meter, and pressure gauge. The pumps were 12V with a maximum flow output of 4.3 L/min. However, the highest range achieved was approximately 3.4 L/min. The tee valve and ball valve worked to manipulate the flow rate to the desired value. The flow meter and pressure gauge was used to measure their respective variables as the water was going into the test cell. Unique to the hot side was a hot plate as well as a heating element to ensure the temperature of the saline solution stayed constant at the desired temperature. The temperature of the cold feed side was measured at various time intervals using a salinity probe which had a temperature setting. As the temperature of the cold side rose, ice was added to maintain the water at 20°C, which is room temperature. The temperature of the hot saline solution was also measured using a type K thermocouple attached to an Agilent 34970A system. Based on the values given by the Agilent system, the hot plate was adjusted in order to maintain the temperature of the hot water. The test cell itself had to be raised and placed vertically so that the water droplets could fall down the channel of the spacer plate and collect in a beaker that was placed below.

5 Results and Discussion

5.1 Results

In this section, the experimental work conducted during this project will be discussed. The manipulation of two main parameters was done in order to observe and further prove their relationship with the permeate flux created. These two parameters were the temperature of the feed solution and the feed flow rate. The manipulation of these two variables was done with a total of six experiments. Three experiments were focused on the manipulation of feed temperature while the remaining three focused on the manipulation of feed flow rate.

5.1.1 Effect of Feed Temperature on Permeate Flux

The effect of feed temperature is very significant in regards to permeate flux. The chart below illustrates the parameters that remained constant while three separate experiments were ran with temperatures of 50 C, 60 C, and 70 C.

Experiment	Varied Parameters	Constant Parameters
1-3	**Feed Temperature** **50°C-70°C**	**Feed Flow rate** **3L/min**
		Cold Flow rate **3L/min**
		Air Gap **5.6mm**
		Salinity **40ppt**

Figure: Feed Temperature Experiments

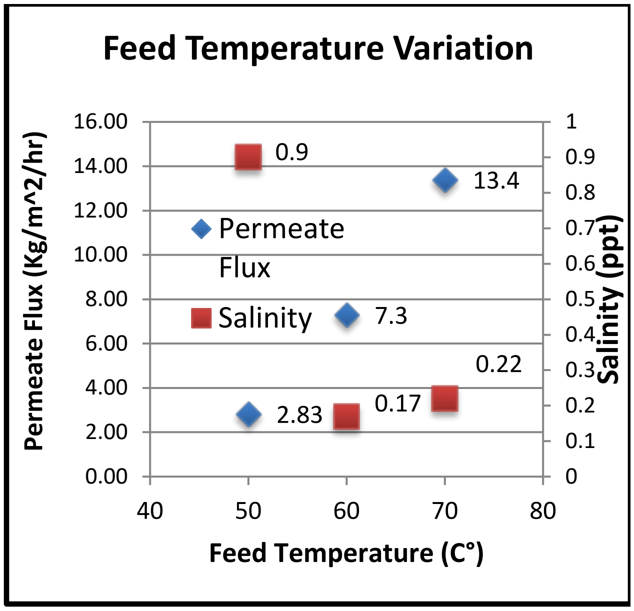

Figure: Results of Feed Temperature Variation

The chart depicted above represents the results from varying the feed temperature. As is very apparent from the results there an exponential increase in permeate flux when the feed temperature is increased, in our case by 10 C for each data point. This resulted in a total permeate flux increase from 50 C to 70 C of 373%. At 50 C permeate flux was 2.83 while a permeate flux of 13.4 was reached at 70 C. The chart also represents the salinity of permeate collected. As mentioned the initially salinity of water was maintained at 40 parts per thousand prior to running all experiments. There does seem to be one outlier in the data represented by the 0.9 ppt obtained in the 50 C experiment, however we attribute this to a possible contamination of the permeate.

5.1.2 Effect of Feed Flow Rate

For these experiments feed temperature, cold flow rate, air gap and feed concentration were kept constant as shown in Fig.16. We were limited in the amount we could increase the feed flow rate to 3.3L/min due to equipment and budget constraints. As the feed flow rate was increased from 1L/min to 3.3L/min there was a 110% increase in the amount of permeate flux. The feed concentration was controlled at 40ppt and the final permeate flux concentration varied form .03ppt to 0.12ppt. The figure shows that there is no correlation between feed flow rate and the final concentration of the permeate flux. The figure shows that the feed flow rate has a low effect on the amount of permeate flux, when compared to the effect of feed temperature.

Experiment	Varied Parameters	Constant Parameters
4-6	**Feed Flow rate 2L/min – 3.3L/min**	**Feed Temperature 70°C**
		Cold Flow rate 3L/min
		Air Gap 5.6mm
		Salinity 40ppt

Figure: Feed Flow Rate Experiments

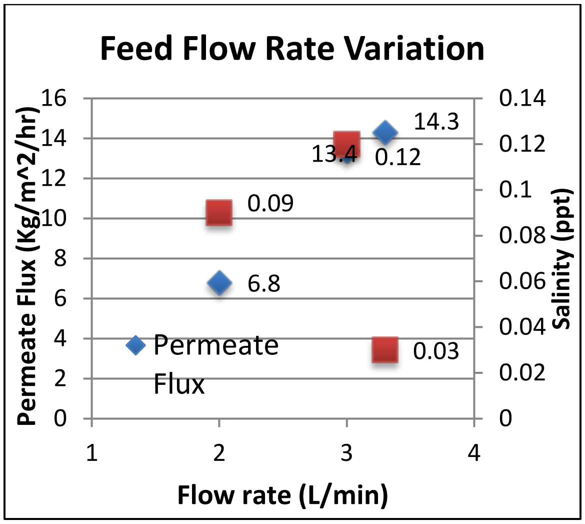

Figure: Results of Feed Flow Rate Variation

5.1.3 IR Camera Thermal Imaging

For the experiments relating to the feed temperature, we took thermal images of the test cell during the experiment as we varied the feed temperature from 50°C to 70°C. We were able to get real time temperature readings inside the cell. As shown in the figure below the feed side from the cold side is easily distinguishable.

Figure: Feed Solution 50C/122F

Figure: Feed Solution 60C/140F

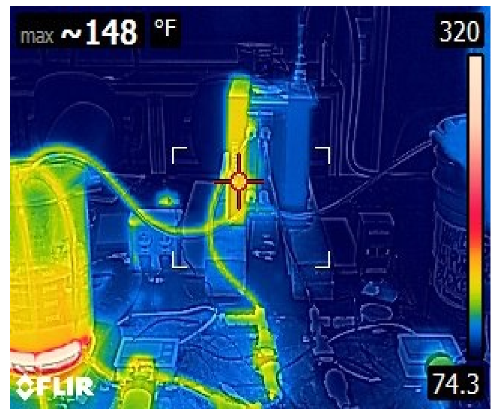

Figure: Feed Solution 70C/158F

6 Conclusions

Experimental data on the studies and experiments for the air gap membrane desalination (AGMD) system are presented. The effect of the feed temperature, feed flow rate and feed concentration on the amount of permeate flux were investigated. The permeate flux increases with the feed temperature and the feed flow rate. However, the permeate concentration has no correlation with feed temperature and feed flow rate. Varying the feed temperature is the most influential parameter, there was a 373% increase in the amount of permeate flux when the feed temperature was increased from 50°C to 70°C. Although the feed flow rate was not as influential as the feed temperature we were still able to get a 110% increase in the amount of permeate flux, when increasing the feed flow rate from 2L/min to 3L/min.

The objective of our project was met we were able to prove the concept of AGMD on a bench scale. All of the experiments we ran with the exception of one outlier had a rejection rate of 98% as shown in Fig.18. We were able to take a solution with a concentration of 40ppt and desalinate it down to under 0.5ppt. In order to put that into perspective we were able to take a solution slightly more concentrated than ocean water and desalinate it to a concentration that is below the accepted standard for freshwater.

7 Acknowledgments

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8 References

[1] "Fresh Water Crisis." *National Geographic*. National Geo, n.d. Web. 1 June 2016. <http://environment.nationalgeographic.com/environment/freshwater/freshwater-crisis/>.

[2] Praise, Tom. "Water Desalination." *Standard.edu*. N.p., 16 Dec. 2012. Web. 12 May 2016. <http://large.stanford.edu/courses/2011/ph240/parise2/>.

[3] Alkhudhiri, Abdullah, Naif Darwish, and Nidal Hilal. "Membrane Distillation: A Comprehensive Review." *Desalination* 287 (2012): 2-18. Web.

- [4] Khalifa, A., D. Lawal, M. Antar, and M. Khayet. "Experimental and Theoretical Investigation on Water Desalination Using Air Gap Membrane Distillation." *Desalination* 376 (2015): 94-108. Web.