Al-Khwarizmi Engineering Journal, Vol. 14, No.2, June, (2018)
P.P. 116- 122

Al-Khwarizmi Engineering Journal

Desalination of Highly Saline Water Using Direct Contact Membrane Distillation (DCMD)

Salah S. Ibrahim* **Noor A. Mohammad Ameen****
, Department of Chemical Engineering / University of Technology/Baghdad- Iraq*
**Email: nourayad2017@yahoo.com

(Received 10 0ctober 2017; accepted 20 December 2017)
https://doi.org/10.22153/kej.2018.12.005

Abstract

In this work, laboratory experiments were carried out to verify direct contact membrane distillation system's performance in highly saline water desalination. The study included the investigation of various operating conditions, like feed flow rate, temperature and concentration of NaCl solution and their impact on the permeation flux were discussed. 16 cm^2 of a flat sheet membrane module with commercial poly-tetra-fluoroethylene (PTFE) membrane, which has 0.22 µm pore size, 96 µm thickness and 78% average porosity, was used. A high salt rejection factor was obtained greater than 99.9%, and the permeation flux up to 17.27 $kg/m^2.h$ was achieved at 65°C for hot feed side and 20°C for cold side stream.

Keywords: *Membrane distillation, Desalination, DCMD process.*

1. Introduction

The supply and demand for sweet water were progressively increasing throughout the last two decades. Commercially, desalination of saline water is achieved by either membrane or thermal methods. Thermal process typically involves saline water boiling or evaporation then collecting resultant distillate, examples of such process are multi-effect desalination and multistage flashing while membrane process produces fresh water from the saline water using reverse osmosis (RO) principle at a high pressure [1]. Membrane distillation (MD) is a conjunction of the two processes and can be defined as a thermal membrane process resulting from simultaneous mass and heat transfer phenomena across a hydrophobic microporous membrane [2]. The temperature gradient between liquid-vapor interfaces will generate a pressure difference across the membrane sides which represent the driving force of the process [3]. The process starts when the solution is evaporated alongside the membrane boundary layer after heated to a specific temperature in the feed side. The pure water is produced at the cold side by condensing the vapor which passed through the dry pores of the membrane [4]. At each pore entrance a liquid-vapor interface is created due to the membrane hydrophobic nature that inhibits the liquid solution from penetrating into the pores [5].The ability of membrane to operate at lower operating temperatures (30-80 °C) is considered the main advantage of membrane technology than conventional distillation (>100 °C) and lower operating pressures (<100 kPa) than conventional membrane processes that are driven by pressure like in reverse osmosis (>10 bar) [6]. Fouling is occurring less in MD than other membrane processes such as, reverse osmosis because of the membrane pore size is greater than that used in RO process [7]. MD can be operated with the solar energy as a substitution energy sources. Membrane distillation has four principal configurations which are classified depending on the method used to withdrawn the vapor that formed in the hot side of the membrane [8]: (1) Direct contact membrane distillation using cooled water for the purpose of condensing vapor at permeate side directly inside the membrane module [9]. (2) Vacuum membrane distillation (VMD) employing a vacuum pump at the permeate side to pull the volatile molecules from feed solution. The water vapor condenses in the membrane unit or in a separate condenser [10]. (3) Air gap membrane distillation (AGMD) using a stationary air hole at the permeate side between the condensation surface and membrane layer. The vapor condenses within the membrane module [11]. (4) Sweeping gas membrane distillation (SGMD) utilizing a chilly inefficient gas for sweeping the vapor molecules from the cold side, and the condensation happens at the outer membrane unit [12]. The MD process has a competitive advantage for the desalination of brackish and sea waters [13]. In addition, MD is considered efficient operation for removing heavy metals and also the organic components from waste and watery solutions [7]. However, MD has some disadvantages for example low production rate of distilled water in comparison for desalination technologies such RO. The permeation flux is high sensitive to temperature and concentration of the inlet conditions owing to the fact of temperature and concentration polarization phenomenon. Also, heat wasted by conduction is relatively large.

2. Transport Mechanisms

Mass and heat transfer are taken place at one time in the MD process. The fluid boundary layers occur neighboring the two hot and cold membrane sides [8].Over the feed side boundary layer, the feed temperature decreases from T_{bf} to the value of T_{mf} when reach the surface of membrane. Evaporation of some water occurs and diffuses through the dry pores of hydrophobic membrane to the permeate side, at the same time; heat transfers across the membrane layer by the conduction. On the other hand, permeate temperature rises from the value T_{bp} over the cold boundary layer and reaches T_{mp} value at membrane surface [14]. The existence of the two boundaries leads to temperature polarization which lowering the trans-membrane temperature. Heat is transmitted in three stages: (1) from feed solution to the surface of membrane by convection. (2) Across the membrane layer by conduction and (3) from membrane surface to permeate side by convection. Transferring of mass in MD usually happens by diffusion and convection of vapor during the porous membrane. The feed solution contains a non–volatile component, with the passage of time the concentration of these components at the surface of the membrane (C_{mf}) becomes much higher than that at the bulk feed (C_{bf}), giving rise to concentration polarization [15]. There are three mechanisms used for describing how the vapor molecules can pass through the membrane pores [14]: (1) Knudsen diffusion (2) Poiseuille- flow (3) Molecular-diffusion. Figure (1) illustrates the DCMD process with concentration and temperature variations.

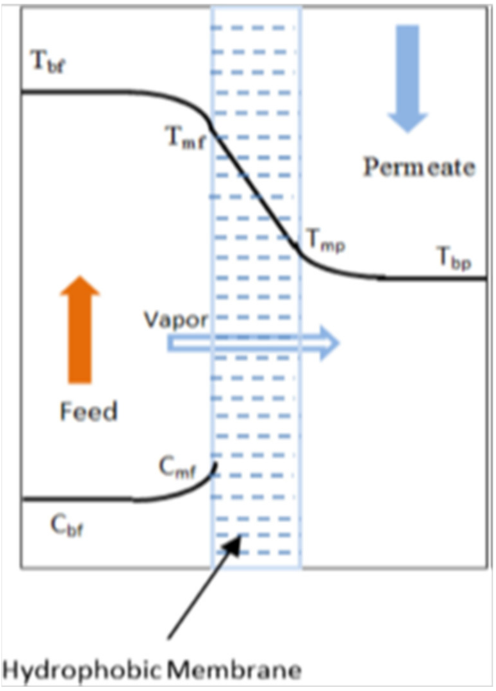


Fig. 1. DCMD process with concentration and temperature variations.

3. Materials and Methods

3.1. Membrane and Membrane Module

DCMD system was equipped with a 0.22 µm flat sheet commercial poly-tetra-fluoroethylene (PTFE) membrane (Membrane, Spain) having a thickness of 96µ m ,78% of average porosity, 1.27 nm roughness and 114 contact angle. Membrane module was designed and constructed in Italy (Delta company, Cosanza, Rende, Italy), and the membrane effective area was 16 cm^2. The module is made of silicones that withstand corrosion by the NaCl solution and has a good heat transfer resistance. Figure (2) shows the membrane module.

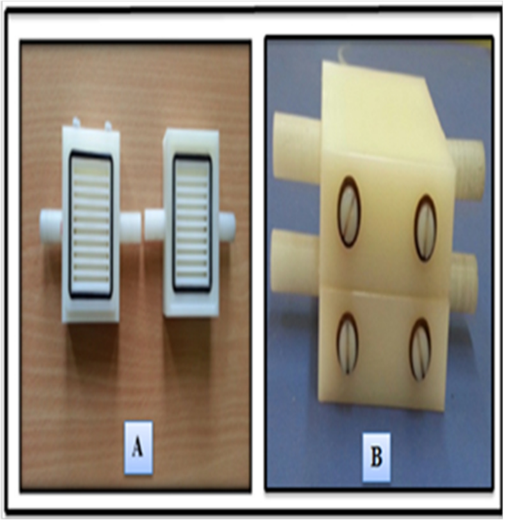


Fig. 2. Membrane module. (A) Inside the module, (B) Outside the module.

3.2. Experimental Set-Up and Procedure

Module and all lines of the experimental system were set and well insulated for lowering the amount of heat that loses toward the surrounding environment. The temperatures of the four streams were recorded at the input and output of the both warm and cool channels before the connection points with the membrane module by four thermometers. The mass permeation of clean water was computed by the volume change of distillate cylinder, multiplied by water density and then divided by the membrane area and operating time. The experiments were conducted on a saline solution that was prepared in laboratory with various NaCl concentrations (0, 15, 35, 70 and 100 g/L). The hot feed and the coolant for the DCMD were circulated in counter-current flow method. Experiments were accomplished by using different feed temperatures in the range (45, 50, 55, 60, and 65 °C). The feed flow rate was investigated at various levels changed from 0.3 to 1.07 L/min, while the permeate flow rate was remained constant for the all tests. The diagram of the experimental rig of DCMD is shown schematically in Figure (3).

4. Results and Discussion

In this part, the obtained results of DCMD system are first presented and discussed to illustrate how the membrane's performance is affected by operational conditions.

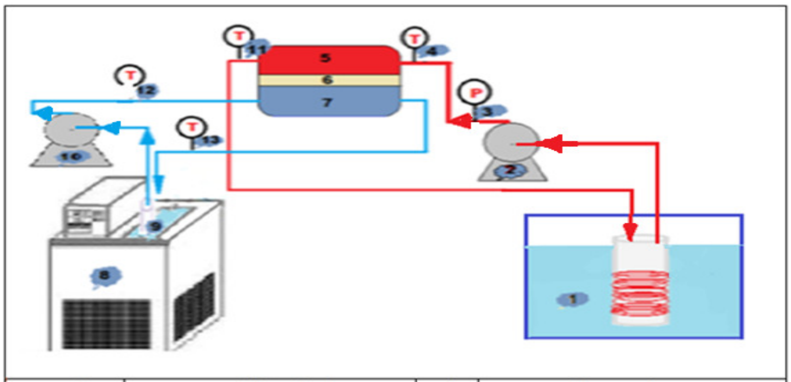
4.1. Effect of feed temperature

Figure (4) exhibits the impact of the hot feed temperature on the distillate production at different concentrations. Temperatures were used from 45 to 65 ° C and they were changed every five degrees at different concentrations (35 and 100 g/L of NaCl), whereas the feed flow rate was preserved fixed at 1.07 L/min. It can be noted that for both salt concentrations, the permeate flux increased with the temperature increasing. This phenomenon can be clarified by increasing the driving force (vapor pressure) as a result of the temperature increase. The vapor partial pressure depends on temperature exponentially, as described by Antoine’s equation [1]:

$$P^{\circ} = \exp\left(A - B/(C + T)\right) \qquad \ldots(1)$$

The production flux was increased by 116.56 % by changing feed temperature from 45°C to 65 °C. Obviously the impact of feed temperature is quite controlling the permeate flux.

Figure (5) offers how the temperature change effects on the percentage of salt rejection and the permeate conductivity for a saline solution with 35 g/L NaCL. It can be seen that the permeate conductivity increases slightly when the temperature increases. This behavior indicates that the feeding temperature has a clear influence on the membrane pore wetting process. The permeate conductivity ranged between (8-12) µS/cm with salt rejection achieved about 99.98%



1	Water bath	6	The membrane
2	Peristaltic pump of feed side	10	Peristaltic pump of permeate side
3	Pressure gage	7	Cold channel
4,11,12,13	Thermometers	8	Chiller
5	Hot channel	9	Glass cylinder

Fig. 3. schematic diagram of the experimental rig of DCMD process.

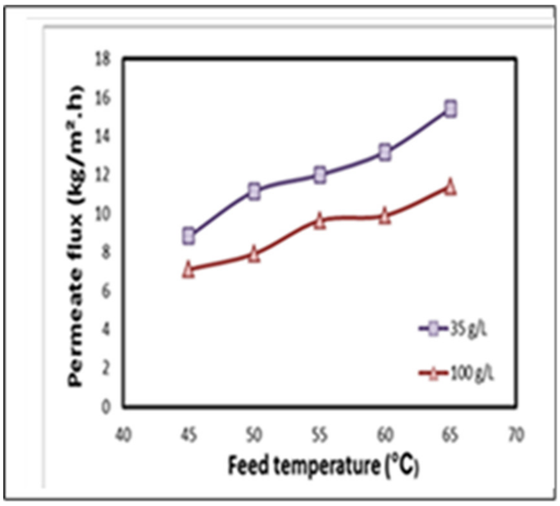


Fig. 4. the impact of feeding temperature on the resulting flux at various concentrations and 1.07 L/min feed flow rate.

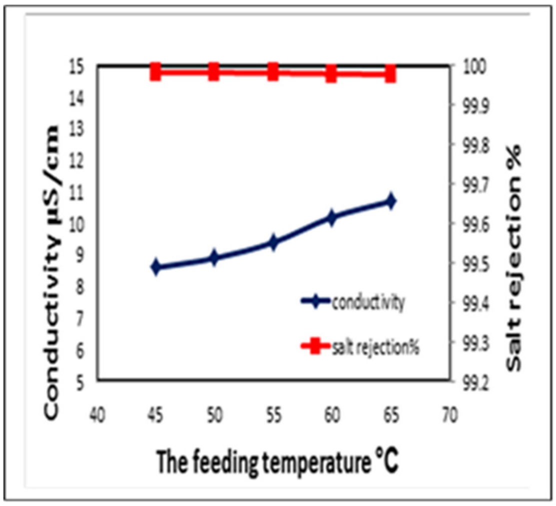


Fig. 5. Effect of the feeding temperature on the permeate conductivity and salt rejection at 35 g/L Nacl, and 1.07 L/min feed flow rate.

4.2. Effect of Feed Flow Rate

Figure (6) manifests the influence of feed flow rate in a range (0.3-1.07 L/min.) on the permeation flux at various temperature levels (45, 55, 65 °C) and fixed concentration 35 g/L of feed salt solution. The permeate flux increased approximately linearly with increasing feed flow rate. The increase in flux is become noticeable when both the feed flow rate and the feed temperature are increased at the same time. When the feed flow rate increased from 0.3 to 1.07 L/min the flux increased about 46.62% at 55 ℃ and 67.1% at 65 ℃ feed temperature. This behavior can be explained through the fact that when feed flow rate increased, the membrane surface temperatures become near to that of the bulk streams, and thus lead to increase the temperature variations across the membrane and enhance the permeate flux.

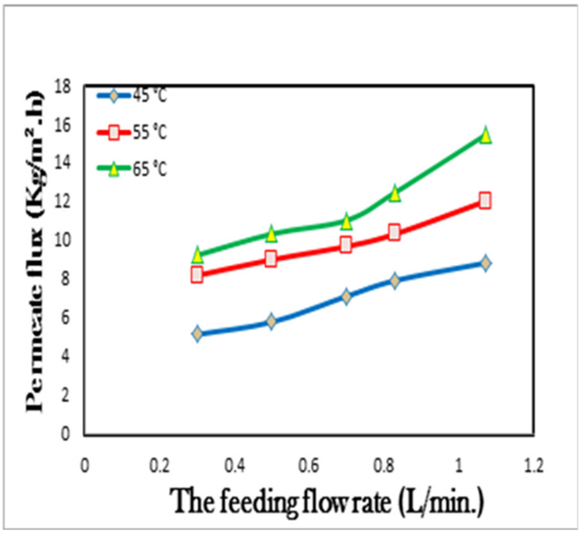


Fig. 6. Influence of feeding flow rate on the permeation flux at different feed temperatures and 35 g/L NaCl feed solution.

4.3. Effect of Feed Concentration

Figure (7) displays the relationship between the feed concentration and the permeation flux. The experimental tests were conducted at many feed concentrations (0, 15, 35, 70, and 100 g/L of NaCl) and different feed flow rates (0.3, 0.7 and 1.07 L/min), while the feed temperature remained constant at 60 °C. The results show that the permeate flux decreased about 23.28% when the feed concentration increased from zero to 35 g/L and 24.91% with the increase of salt concentration from 35 to 100 g/L. The overall ratio of permeate reduction was reached to 42.4% when the feed salt concentration increased from zero to 100 g/L at 1.07 L/min feed flow rate. The low production flux can be explained by the impact of salt on the solution boiling point, the higher concentration of the saline solution leads to higher boiling point and thus reduced the amount of vapor flows across the membrane which led to decrease the permeate flux.

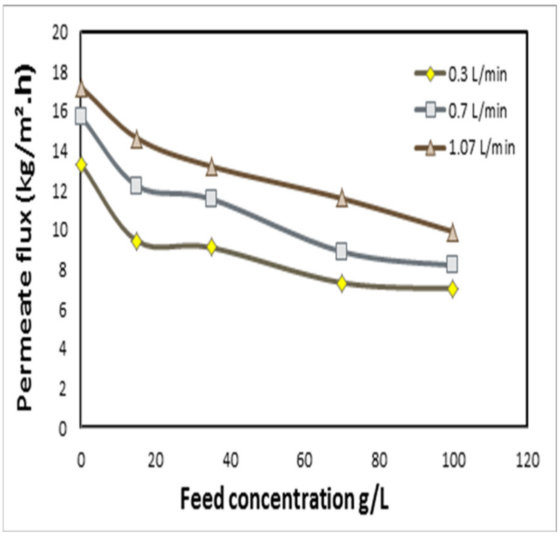


Fig. 7. Effect of feed concentration on the permeation flux for solution at 60 °C feed temperature.

5. Conclusions

1. The permeation flux improved with increasing feed temperature; when feed temperature raised by 20 degrees, the permeate flux increased by 116.56%, that indicates the feed temperature is quite controlling the permeate flux.
2. The permeate flux increased with increasing feed flow rate, the flux increased about 67.1% when the flow rate increased from 0.3 to 1.07 L/min.
3. The permeate flux decreased with increasing concentration of feed solution, the flux decreased about 42.4% when the feed salt concentration increased from zero to 100 g/L.
4. The percentage of salt rejection was reached about 99.98% even at high concentrations.

Notation

Tbp	bulk permeate temperature
Tbf	bulk feed temperature
Tmf	membrane feed side temperature
Tmp	membrane permeate side temperature
Cbf	salt concentration at the bulk feed
Cmf	salt concentration at the feed side
m	of membrane surface
P°	vapor pressure
A,B,C	constants of Antoine's equation
T	temperature

6. References

[1] Bahar, R., "Conversion of saline water to fresh water using air gap membrane distillation (AGMD)", Ph.D. Thesis. University of Singapore, 2010.

[2] Yarlagadda, S., Gude, V., Camacho, L., Pinappu, S. and Deng, S, "Potable water recovery from As, U, and F contaminated ground waters by direct contact membrane distillation process", Journal of Hazardous Materials, 192, PP.(1388-1394), 2011.

[3] Al-Obaidania, S., Curcio, E., Macedonio, F.,Profio, G.,Al-Hinai, H. and Drioli, E, "Potential of Membrane Distillation in Seawater Desalination: Thermal Efficiency Sensitivity Study and Cost Estimation", Journal of Membrane Science,323, PP.(85–98), 2008.

[4] Eleiwi, F., Ghaffour, N., Alsaadi, A., Francis, L.,and Laleg-Kirati, T, "Dynamic Modeling and Experimental Validation for Direct Contact Membrane Distillation (DCMD) Process", Desalination,384, PP.(1–11), 2016.

[5] Gryta M., "Influence of polypropylene membrane surface porosity on the performance of membrane distillation process", Journal of Membrane Science, 287, PP. (67-78), 2007.

[6] Cheng, D., Gong, W., and Li, N, "Response Surface Modeling and Optimization of Direct Contact Membrane Distillation for Water Desalination", Desalination, 394, PP.(108–122), 2016.

[7] Alkhudhiri, A., Darwish, N., and Hilal, N, "Membrane distillation: A comprehensive review", Desalination, 287, PP. (2-18), 2012.

[8] Sanmartino, J., Khayet, M., and García-Payo, M, "Desalination by Membrane Distillation", Book, University Complutense of Madrid, Emerging Membrane Technology for Sustainable Water Treatment, PP. (77-109), 2016.

[9] Cath, T., Adams, V., and Childress, A., " Experimental study of desalination using direct contact membrane distillation: a new approach to flux enhancement", Journal of Membrane Science, 228, PP. (5-16), 2004.

[10] My, D., "Membrane Distillation Application in Purification and Process Intensification", MSc Thesis, Asian Institute of Technology, School of Environment, Resources and Development, Thailand, 2015.

[11] Phungsai, P., "Development of Thermo Philic Anaerobic Membrane Distillation Bioreactor", MSc Thesis, Asian Institute of Technology School of Environment, Resources and Development, Thailand, 2013.

[12] El-Bourawi, M., Ding, Z., Ma, R., and Khayet, M., "A Framework for Better Understanding Membrane Distillation Separation Process", Journal of Membrane Science, 285, PP. 4–29, 2006.

[13] Banat, F., "Membrane Distillation for Desalination and Removal of Volatile Organic Compound from Water", Ph.D. Thesis, University of McGill, Canada, 1994.

[14] Dahiru,U., and Khalifa, A., "Flux Prediction in Direct Contact Membrane Distillation", International Journal of Materials, Mechanics and Manufacturing, 2014.

[15] Camacho, L., Dumée, L., Zhang, J., Li, J. and Duke, M., "Advances in Membrane Distillation for Water Desalination and Purification Applications", Water,5, PP.(94–196),2013.

تحلية المياة عالية الملوحة باستخدام غشاء التقطير ذي الاتصال المباشر

صلاح سلمان ابراهيم*　　نور اياد محمد امين**
**، **قسم الهندسة الكيمياوية/ الجامعة التكنولوجية*
**البريد الالكتروني: Nourayad2017@yahoo.com

الخلاصة

في هذا البحث تم عمل تجارب مختبرية لغرض التحقق من اداء غشاء التقطير ذي الاتصال المباشر في تحلية المياه العالية الملوحة. تم دراسة تأثير عوامل التشغيل المختلفة على الأداء و منها درجة حرارة مياة التغذية و معدل جريانها و تركيز الأملاح. تم استخدام وحدة غشاء مسطحة ذو مساحة سطحية (١٦ سم^2) مع غشاء بولي تيترا فلوراثيلين التجاري ذي حجم مسام (٠,٢٢) مايكرون، السمك (٩٦) مايكرون و (٧٨%) معدل مسامية الغشاء. وجد ان نسبة ازالة الأملاح اكبر من ٩٩,٩% و معدل الماء النقي الناتج(١٧,٢٧) كغم/م^2. ساعة عندما كانت حرارة المحلول الساخن (٦٥) درجة مئوية و الماء البارد (٢٠) درجة مئوية.
