Seawater desalination by vacuum membrane distillation (VMD)

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Abstract

In this work, the desalination of saline water (seawater and high-concentration NaCl solution) with different salt concentrations experiments was performed by using vacuum membrane distillation (VMD). Hydrophobic micro porous polypropylene (PP) hollow fiber membrane was used. Effect of various operating conditions such as feed inlet temperature ranged between 45 and 65 °C, salt concentration (i.e., 35000-100000 ppm), and feed flow rates (i.e., 0.3, 0.4, 0.5, and 0.6 l/min) on permeate flux has been investigated. It is found that the highest permeation flux was obtained with higher feed inlet temperature and flow rate, and low salt concentration. The highest permeate flux has attained equal to 65.8 (Kg/m^2.h), at feed concentration of 35 g/l, temperature 65˚C, feed flow rate of 0.6 (l/min) and 665 mmHg vacuum pressure, where water purity was about 99.99%. It was found the permeation flux obtained in this study was higher than the outlined in the literature.

1. Introduction

It is obvious that two-thirds of the Earth is covered by water but only 1% of this water is available as fresh water (drinking water). Seawater desalination to provide human drinking water is becoming a suitable solution to fresh water shortage in many countries [1].

Gulf countries suffer from a lack of water, thus the need arises to use a novel methods for seawater desalination. One of these novel methods used nowadays was membrane distillation (MD). In membrane distillation (MD) process, water vapor passes through a membrane from a hot feed brine solution, and then condenses on the other side. This method involves four configurations to condense the vapor: Direct contact membrane distillation (DCMD), Air gap MD (AGMD), Sweeping gas MD (SGMD), and Vacuum MD (VMD). In order to use the membrane in application of membrane distillation the characteristics of the membrane should be in the following specification: porous membrane; non-wettable by the liquids diffusion; the vapor-liquid equilibrium must not be altered by the membrane; one surface of the membrane might be in direct contact with the liquids to be separate [2].

The advantages of using VMD compare with other membrane distillation techniques or configurations is due to the many reasons for example; working at lower operating temperatures for production of pure water, lower energy cost and higher efficiency and the most important reason is produced higher water vapor flux through the membrane under suitable vacuum pressure at the permeate stream [3-7].

In this work, polypropylene (PP) hollow fiber commercial membrane was used for seawater and high-concentration desalination by VMD process. Effect of different operating conditions such as feed temperature (i.e., 45-65 °C), feed concentration (i.e., 35000 to 100000 ppm), and feed flow rate (i.e., 0.3-0.6 l/min) on permeate flux were studied. Moreover, the permeation flux obtained in this study was compared with that reported in the literature.

2. Experimental work

Figure 1 and Figure 2 show the photograph picture and schematic diagram of the experimental setup of the vacuum membrane distillation (VMD) process, respectively. In the VMD process the feed solution was introduced in the lumen side of the hollow fiber membrane by a peristaltic pump(longer pump BT100-IF, DG-2(6/10))at a flow rate controlled by a control valve. While the water vapour could be withdraw by a vacuum pump ((Speedivac) model (ISP30C serial no 002290)) made in England) at 665 mmHg throughout the shell side of the membrane module and condensed using (Tamson TLC3 recirculating chiller)at a maintained temperature of 10˚C and collected in a glass trap. However, the prepared seawater in a 500 ml glass tank was heated by a water bath, (meditech, DK-8Axx), for different temperatures such as (i.e., 45-65 °C). The inlet and outlet temperatures of the feed streams were measured by a computerized heating control system as shown in Figure 1 and Figure 2.Regarding the hollow fiber membrane module, the PP and PVDF-HFP hollow fiber membranes were packed in a stainless-steel tube with effective length of 18 cm and outer diameter of 10mm, connected to a Swagelok tube fitting (θ 10 mm) on each end. Then, the hollow fiber membranes sealed with an epoxy resin (Euxi 50KII-hardener). The characteristics of the hollow fiber membranes are summarized in Table 1.

The volume of the water permeated from hollow fiber membranes within a measured time was used to determine the water vapor permeation flux by using the following equation:

$$Jv=V\times\rho/A\times t \qquad (1)$$

where, Jv is water vapor permeation flux (kg/m^2.hr), V is volume of collected water (l), ρ is water density (kg/m^3), A is effective surface area of the membrane (m^2), and t is water collected time (hr). The salt concentrations of the feed and permeate into and out of the membrane module were measured by a conductivity meter (Model DDS 307 made in Germany). To calculate the salt rejection, the following equation was used:

$$R(\%)=[1-(C_P/C_F)]\times 100 \qquad (2)$$

where R is the salt rejection C_P is the concentration of permeates solution and C_F is the concentration of the feed solution.

3. Results and Discussion

3.1 Effect of feed temperature on permeation flux

Figure 3 shows the effect of feed inlet temperature from 45 to 65°C on the permeation flux for PP hollow fiber membrane using salt solution of 35g/l NaCl, 0.6L/min feed flow rate, and 665mmHg vacuum pressure. It can be seen that the permeation flux increased from 20.82 to 65.80(Kg/m^2.h) with an increase of the feed inlet temperature from 45 to 65 ° C. The driving force is pressure difference between the membranes in VMD. This phenomenon is attributed to the increase of vapor pressure of the liquid feed side as the temperature of the liquid feed increase. This behavior is attributed to the exponential relation between the feed temperature and water vapor pressure according to the Antonione equation. Therefore, increasing vapor pressure results to increase the driving force of mass transfer through the wall of the membrane.

3.2Effect of feed flow rate on permeation flux

The effect of feed flow rates on the permeate flux of PP hollow fiber membrane at 35 g/l NaCl concentration, 55 and 65℃ feed temperature and 665 mmHg vacuum pressure is shown in Figure 4. It can be observed that the permeation flux of PP hollow fiber membrane increase significantly with an increase of flow rate of the feed solution. This behavior is attributed to the increase of the heat transfer coefficient in boundary layer adjacent to the membrane at feed side. Therefore, with increasing of feed flow rate the boundary layer thickness reduced result to enhance the heat transfer coefficient, which in turn lead to increase the heat transfer through the boundary layer and therefore increase the permeate flux. Serena et al. [8] reported that the permeation flux enhanced as the feed flow rate increases due to the decrease of heat and mass transfer resistance in the feed stream side.

3.3Effect of feed concentration on permeation flux

It is well-known that the important condition in water desalination is NaCl concentration. Influence of various salt concentration of the feed inlet solution on the permeation flux of PP hollow fiber membrane at 65 ° C feed temperature, 0.6 l/min feed flow rate and 665mmHg vacuum pressure is shown in Figure 5. It can be noticed that the permeation flux of PP hollow fiber membrane decreases with an increase of salt concentration in feed solution [9]. With higher salt concentration wall layer will be created just apposite to the membrane interface and parallel to thermal boundary layer both layers (i.e., mass and temperature) will act to reduce the temperature and concentration polarization on feed side. This will fatherly acted to reduced the membrane temperature and vapor pressure where pressure difference in return will be hindered the permeate flux. In addition increasing the salt concentration will reduce water activity coefficient in the salt solution as Lawson and Lloyd [10] had pointed out, which decreases the partial pressure of water and accordingly would decrease the vapor driving force across the membrane interface.

Moreover, the behavior of permeation flux as a function of time for salt solution of 35 g/l salt concentration, 65℃ feed temperature, and 665 mmHg is shown in Figure 6. It can be noticed that the permeation flux increased within the first 50 min of the VMD process. Then, the permeation flux is became approximatly constant during the time of the VMD process.

Finally, a comparison between the permeation flux of the PP hollow fiber membranes obtained in this study and that reported in the literature for VMD process is shown in Table 2. It was found that the permeation flux obtained in this study is higher than that observed by a wide range of the data reported in the literature. In terms of water quality that permeated through the memrane, the average value of electrical conductivity was measured as 3.5 μS/cm.

Figure 1 Photograph picture of the experimental setup of VMD process

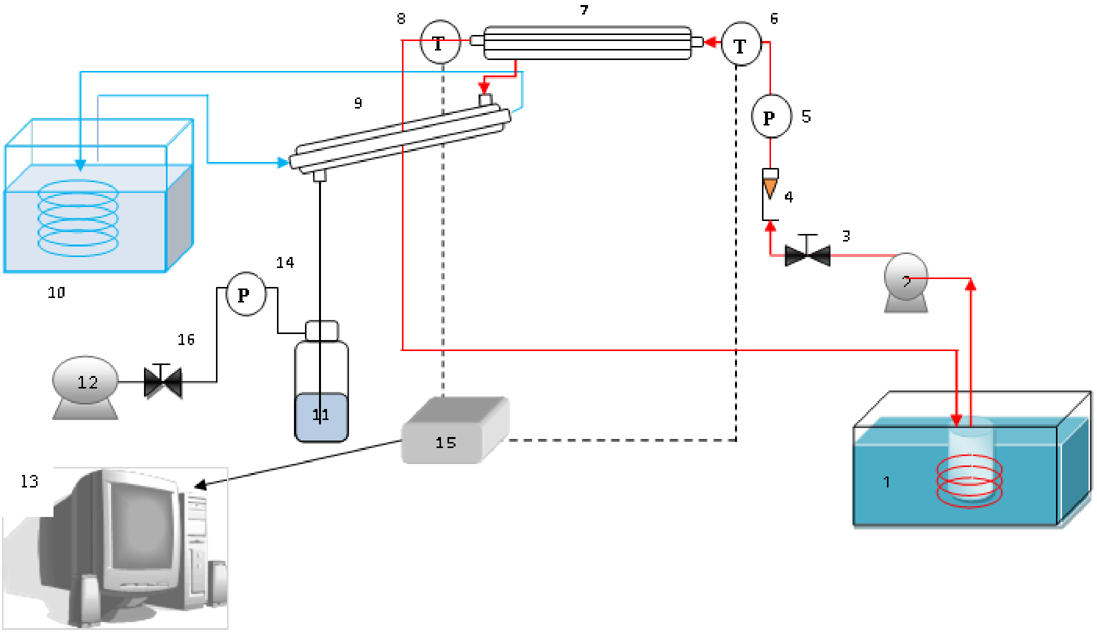

Figure 1 Schematic diagram of the experimental setup of VMD process

1. Water path, 2. Peristaltic pump, 3, 16.Valve, 4.flowmeter, 5, 14.Pressure gage, 6, 8.thermometer, 7.Hollow fiber module, 9.condenser, 10.chiller, 11.permeate trap, 12.Vacuum pump, 13.PCI, 15.data acquisition

Table 1: The characterization of PP hollow fibers

No. of fiber	1
Out diameter (mm)	2.7
Inside diameter (mm)	1.8
Configuration	Hollow fiber
Membrane materials	PP [ACCUREL; PP S6/2 Membrana GmbH
Thickness (mm)	0.45
Porosity Ɛ %	70
Housing diameter (mm)	9
Effective fiber length L (cm)	18
Contact angle ˚	103
Membrane area (mm^2)	1017.875

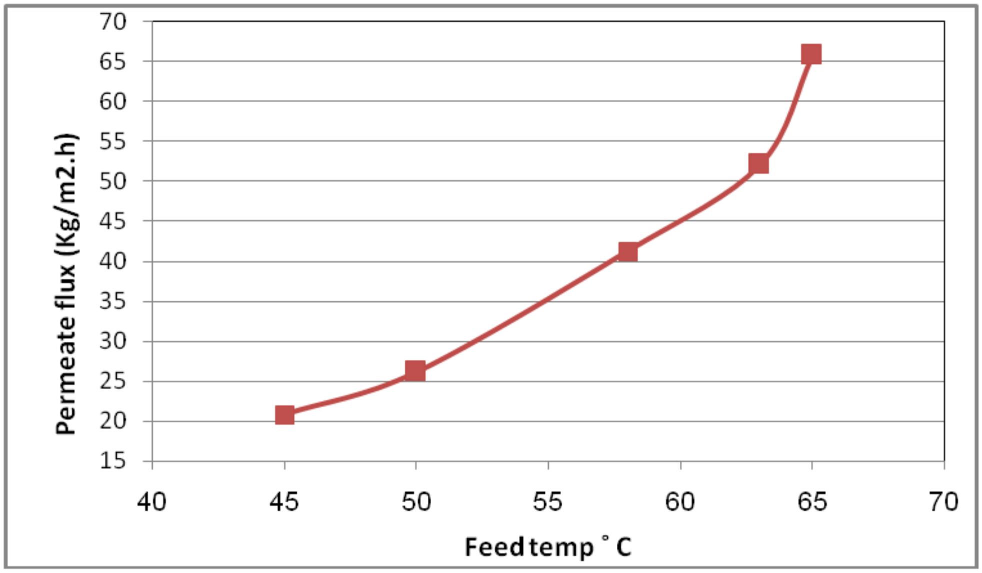

Figure 3 Effect of feed inlet temperature on permeate flux of salt solution of 35 g/l NaCl, 0.6 l/min feed flow rate, 665 mmHg vacuum pressure

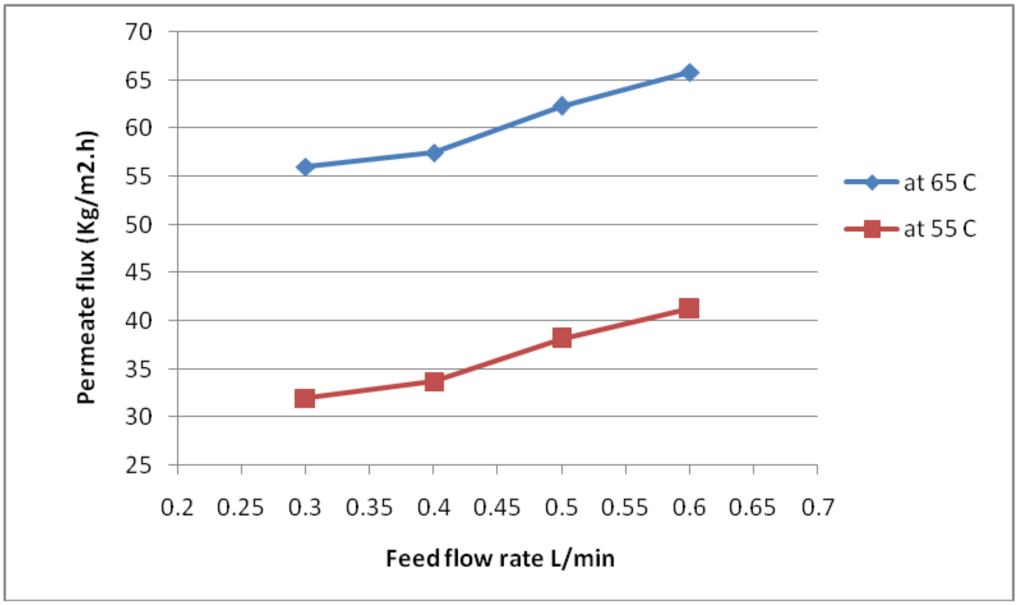

Figure 4 Effect of feed flow rate on permeate flux for solution of 35 g/l NaCl concentration, 65˚C feed temperature and 665 mmHg vacuum pressure

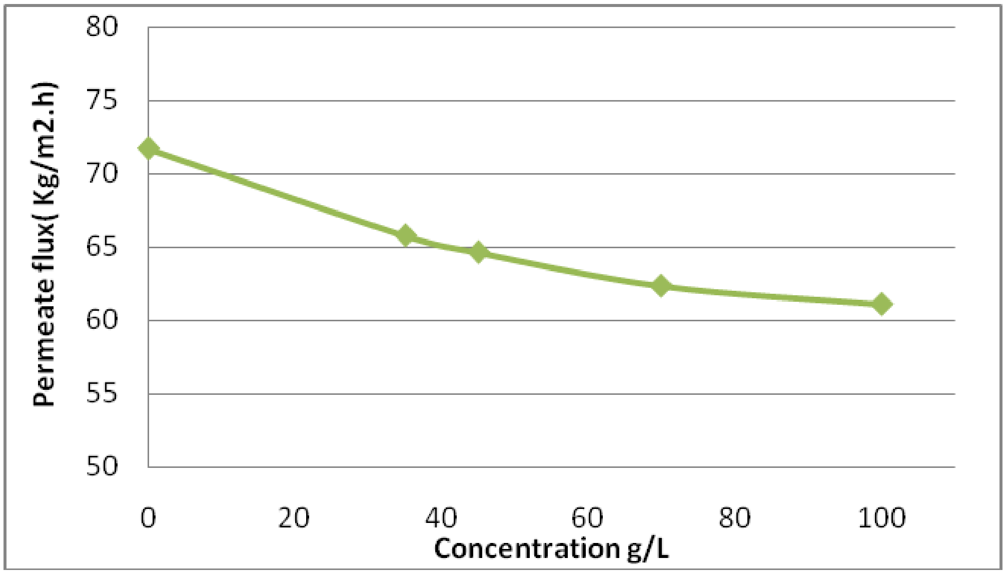

Figure 5 Effect of different feed concentration on permeate flux at 65˚C feed temperature, 0.6 l/min feed flow rate and 665mmHg vacuum pressure

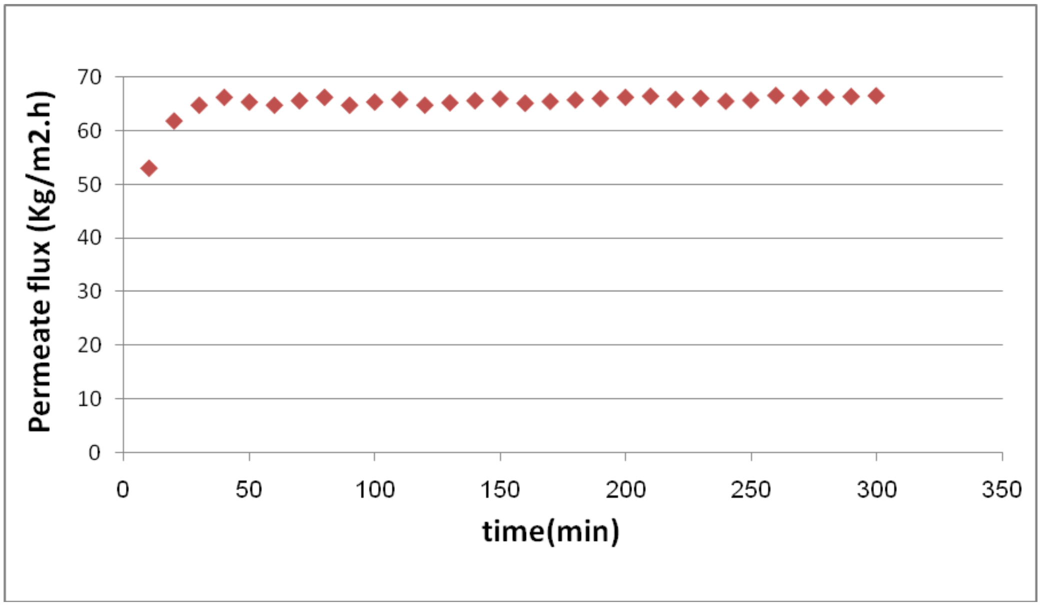

Figure 6 variation of permeate flux as a function of time for salt solution of 35g/l salt concentration, 65℃ feed temperature, and 665 mmHg.

Table 2 Comparison between the permeation flux in this study with the that reported in the literature

Ref	Memb.	ID mm	OD mm	Memb. Thick. mm	porosity %	Avg. pore size (μ m)	Feed Temp. °C	Conc. g/l	Vacuum pressure mbar (abs)	Flux kg/m^2. h
11	PP	1.8	2.6	0.4	70	0.2	65	Pure water	40	19
12	PP	0.028	0.035	-	60	0.1	80	20	239.9	7.8
13	PP	0.33	-	0.15	65	>0.2	85	1	131.1	71
14	PP	1.8	2.6	0.4	70	0.2	65	Pure water	40	30.6
15	PP	1.05	0.61	0.22	55-65	0.2	88	Pure water	300	58
16	PP	0.327	1387	0.53	-	-	55	35	70	5.4
This Work	PP	1.8	2.7	0.45	70	0.2	65	35	131	65.8

4. Conclusions

An experimental study of VMD process was carried out. Influence of feed temperature, feed concentration, and feed inlet flow rate on the permeate flux were studied for sea water (salt water) at 35000 ppm and high-NaCl concentration up to 100000 ppm by using PP hollow fiber membrane. The VMD permeation flux increased with increasing of feed temperature and flow rate. Whereas, the permeation flux of PP hollow fiber decreased with increasing of NaCl concentration in feed solution. The permeation flux obtained in this work was higher than that found in the literature.

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