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High-salinity water desalination using VMD

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ABSTRACT

This research focuses on vacuum membrane distillation (VMD) using high-concentration NaCl aqueous solutions as feed. A new membrane module was investigated to improve water desalination and experiments were carried out using a commercial polypropylene (PP) membrane with a pore size of 0.2 μm. In order to enhance performance of VMD in desalination and to get more flux, effects of operating parameters on the performance were studied. Water fluxes were measured at different feed temperatures, feed concentrations, vacuum pressures and flow rates. The new configuration provides better mixing and this increases heat and mass transfer coefficients, and as a result, reduces temperature and concentration polarization effects.

1. Introduction

Today, pollution of water sources creates considerable problems for water treatment. A principal objective of wastewater treatment is removal of contaminants to such degree so that the effluents can be reused for industrial or municipal purposes. For this reason, the application of several mutually supplementary technologies is required in wastewater treatment.

Membrane technology is quickly becoming a preferred method of technology in wastewater treatment and water reuse industries and the importance of membrane processes in wastewater treatment is continuously growing. Membranes were found their place in wastewater treatment in the early 1990s. Although wastewater treatment using membranes is the newest form of membrane treatment technology, it is also becoming the most popular method. In recent years, membrane technologies such as microfiltration (MF), ultrafiltration (UF), nanofiltration (NF) and reverse osmosis (RO) have become more attractive for water treatment compared with conventional clarification methods. Wastewater treatment using membranes is experiencing stable growth, with projections exceeding a 15% annual growth up to the year 2010. Practically all membrane categories can be found in wastewater treatment and water reuse; however, MF and RO are the most representatives in this area [1,2].

It is clear that additional water sources are required to meet the expanding demand for clean potable water on a global scale. Desalination has been known as a popular and well-argued alternative. With increasing demands for fresh water around the world, seawater and brackish water desalination technology has been developing quickly in the past years. A wide variety of desalination technologies effectively remove salts from salty water, producing a water stream with a low concentration of salts and another with a high concentration of remaining salts. The most common, modern methods of desalination are thermal (distillation or evaporation) and membrane processes. Selection of a desalination process depends on site specific conditions, including salt content of water, economics, and quality of water needed by end users, and finally local engineering experiences and skills [2].

Several new processes have been developed for water desalination in recent years. One of them is membrane distillation (MD). MD combines use of both thermal distillation and membrane process and differs from other membrane technologies in those driving force for desalination is the difference in vapor pressure of water across the membrane, rather than total pressure. The process is a temperature-driven membrane operation which allows obtaining fresh water also from highly concentrated aqueous solutions. Since it operates on principles of vapor–liquid equilibrium, 100% (theoretical) of ions, macromolecules, colloids and other non-volatile components can be rejected, while RO can only reach a desalting efficiency of 95–98%. MD is not limited by concentration polarization phenomena as it is the case in pressure driven processes and contrary to RO, a high-salt concentration can be achieved in MD [3,4]. Since MD fluxes are not very sensitive to salinity, this is up to 9-fold lower than the highest obtained in the reported MD experiments [5]. Also, effectiveness of salt separation during

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MD is relatively constant and the purity of distillate is practically independent of feed concentration [4].

The main advantages of MD lie in its simplicity and need for only small temperature differentials to operate. MD probably has its best application in desalting saline water where inexpensive low-grade thermal energy is available, such as from industries or solar collectors [6].

In MD process, volatile components of the feed evaporate through the membrane pores, therefore, presence of the vapor phase in the pores is a necessary condition for this process. For solution containing non-volatile solutes only water vapor is transferred through the membrane. The efficiency of such separation processes depends on volatility of permeating components, MD operating conditions, membrane characteristics and MD configurations used [7–9].

The membranes for MD are hydrophobic, allowing water vapor (but not water liquid) to pass. Polymers such as polypropylene (PP), polytetrafluoroethylene (PTFE), and polyvinylidenefluoride (PVDF) are commonly employed in preparation of the membranes for MD applications [5,6].

Generally, MD process is characterized by different embodiments designed to impose a vapor pressure difference between the two membrane sides in order to drive vapor across the membrane. Lowering the vapor pressure at the permeate side can be accomplished in different ways: (a) direct contact MD (DCMD); (b) air gap MD (AGMD); (c) sweeping gas MD (SGMD); and (d) vacuum MD (VMD). Each one of these MD configurations has its own advantages and disadvantages depending on the feed solution to be treated [6].

Mass transfer through the membrane in the latter may be enhanced by applying a vacuum or a low pressure on the permeate side. This configuration combines two advantages: a very low-conductive heat loss with a reduced mass transfer resistance. This process allows to reach higher partial pressure gradients and thus higher fluxes, in comparison with other MD configurations [10]. In VMD, evaporation occurs in the feed (liquid) side directly, and the membrane does not interfere with the selectivity associated with the vapor–liquid equilibrium. In contrast, pervaporation process depends mainly on using a dense membrane, which alters the vapor–liquid equilibrium [10,11]. In this process, the downstream pressure is reduced below the equilibrium vapor pressure, so that a convective transport mechanism is dominant for mass transfer. Due to the low-pressure values existing in the permeate (gas) side, molecular mean free path of the permeants is considerably larger than pore size of the membranes typically used in MD processes, so as a consequence, mass transfer through the membranes is generally dominated by Knudsen mechanism [12].

The literature reports on the MD studies usually describe experiments for low-concentration solutions [3,6,13–16]. Only a few papers deal with the studies performed using VMD for high-concentration solutions due to its complexity [17,18]. The complexity may caused by changes of many operating parameters, such as decrease of the feed vapor pressure, increase of the feed viscosity and penetrate pressure, which decreases evaporation efficiency.

In this work, the influence of some operating conditions such as temperature, vacuum pressure, flow rate, and concentration on desalination for high-concentration NaCl solutions by VMD was studied. The main objective of this research, beside feasibility study of using VMD for such high-concentration solutions and by flat sheet membrane, was investigation of operating conditions effects in a systematic manner. By this method the portion of each factor on permeate flux can be obtained. To optimize the design of an existing process, it is necessary to identify which factors have the greatest influence and which values produce the most consistent performance. A commonly applied statistical method, analysis of variance (ANOVA), was used to analyze the results of the experiments and to determine how much variation each factor contributes. By studying the main effects of each factor, the general trends of the influencing factors, can be characterized. The characteristics can be controlled, such that a lower or a higher value in a particular factor produces the preferred result. Thus, the levels of influencing factors, to produce the best results, can be predicted.

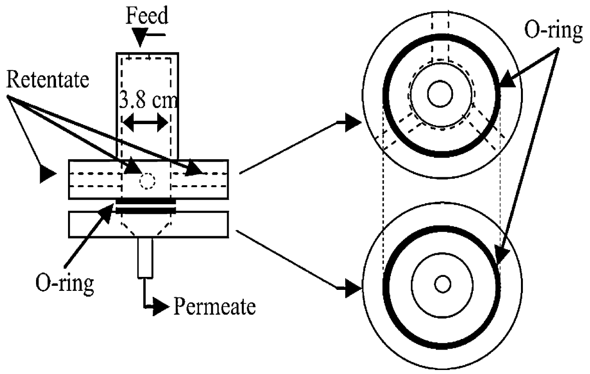

Fig. 1. Membrane module.

2. Experimental

Experiments were carried out using a flat sheet PP membrane from Membrana (Germany). A cross flow membrane module made from Teflon was used in the experiments (Fig. 1) [19]. Effective area of the membrane in the module was 9.1 cm^2. Membrane properties are reported in Table 1. The schematic representation of VMD setup is shown in Fig. 2. The feed was continuously fed to the membrane module from a feed tank, sufficiently large to keep the concentration nearly constant. The membrane flux was measured by collecting the permeate in a condensation trap. Feed composition and temperature were considered as constant values within the module. One important consideration in the setup was that feed pump was not able to flow the small required flow rates in this research, so the excess flow should be bypassed. The bypass flow had a significant influence on feed temperature. Because of bypass flow, the

Table 1
Properties of the flat sheet PP membrane.

Type	PP Accurel 2E
Pore size, µm	0.2
Porosity, %	75
Thickness, µm	163

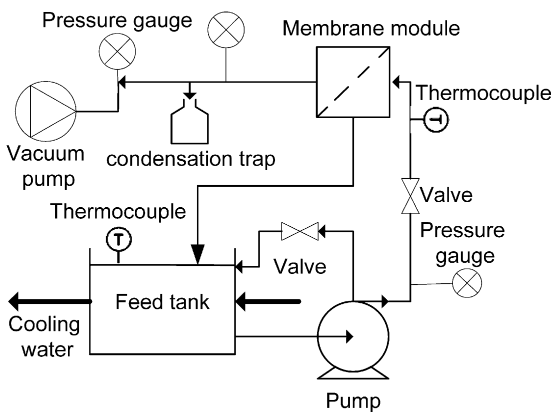

Fig. 2. Schematic diagram of VMD setup.

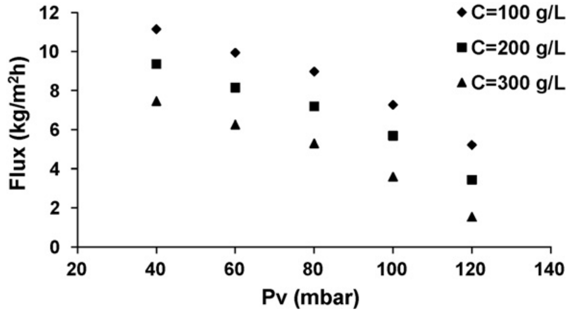

Fig. 3. Effect of vacuum pressure on permeate flux at different concentration ($T = 40\,^{\circ}C$ and $Q = 30$ mL/s).

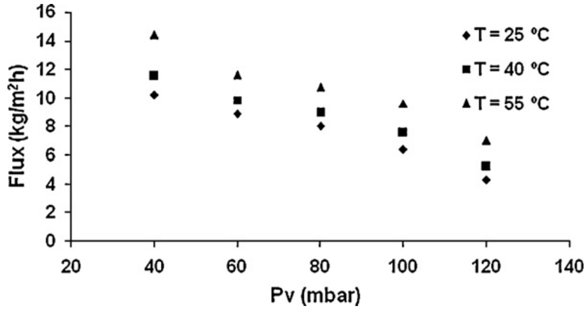

Fig. 4. Effect of vacuum pressure on permeate flux at different temperature ($Q = 30$ mL/s and $C = 100$ g/L).

pump heats the feed and it is needed to cool it to control the temperature, so the feed tank was equipped with cooling water coil.

3. Results and discussion

VMD experiments were performed using NaCl aqueous solutions. Based on the literature [9–18], temperature, vacuum pressure, flow rate and concentration were chosen as the four factors to be investigated. Levels of the factors are as follows: temperature (25, 40 and 55 °C); vacuum pressure (40, 60, 80, 100 and 120 mbar); flow rate (15 and 30 mL/s); concentration (100, 200 and 300 g/L). Electrical conductivity of the MD permeates were measured using a conductimeter (CRISON GLP 32).

In Figs. 3–7, effects of operating conditions on permeate flux is represented. Based on previous studies, it was found that vacuum pressure is the most important factor [9,17]. Thus, in most figures permeate flux was plotted as a function of vacuum pressure. A very important parameter in water desalination is salt concentration of the feed. Experiments were carried out for different concentrations of NaCl (100, 200 and 300 g/L).

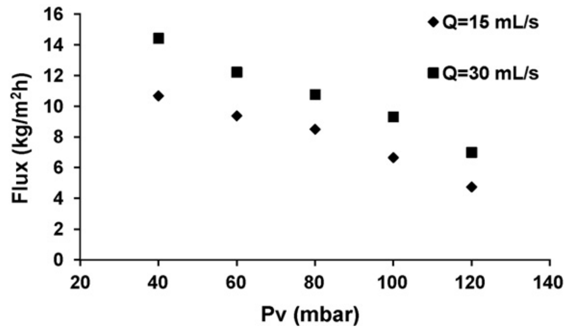

Fig. 5. Effect of vacuum pressure on permeate flux at different flow rate ($T = 55\,^{\circ}C$ and $C = 100$ g/L).

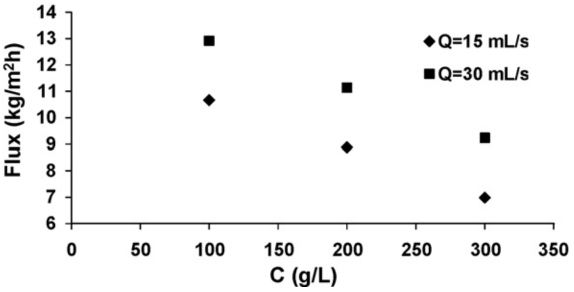

Fig. 6. Effect of concentration on permeate flux ($T = 55\,^{\circ}C$ and Pv = 40 mbar).

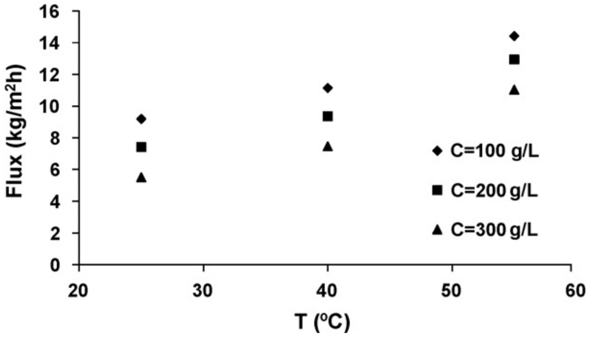

Fig. 7. Effect of temperature on permeate flux (Pv = 40 mbar and $Q = 30$ mL/s).

As can be seen (Fig. 3), at constant flow rate and temperature, increasing vacuum pressure decreases VMD performance. At constant vacuum pressure, permeate flux decreases with increasing salt concentration. This reduction is due to the influence of salt concentration on activity coefficient of water. The flux decline due to concentration enhancement is acceptable: it represents less than 35% when the concentration increases from 100 to 300 g/L. Results in other studies [13,14,17] showed total flux declines of 13–28% for MD systems operated at feed concentrations of 30–120 g/L NaCl. Dissolved compounds reduce the vapor pressure of solvent in aqueous solutions. Therefore, as salt concentration of the feed increases, the vapor pressure of water decreases and this results in a lower driving force for evaporation.

At high-salt concentrations, an additional boundary layer develops next to the membrane interface, parallel to the temperature boundary layer. This concentration boundary layer, together with the temperature boundary layer further reduces the driving force for evaporation. Enhanced turbulent cross flow reduces both boundary layers and improves VMD performance (Figs. 5 and 6). Increasing of permeate flux with flow rate (Reynolds number) indicates importance of the polarization effects in the system. In other words, increasing of permeate flux with flow rate is due to the reduction of temperature and concentration boundary layers thicknesses.

One of the most significant advantages of the MD process for desalination is relatively minimal effect of feed salt concentration on performance of the system. In VMD, increasing feed

Table 2
Parameters of the statistical analysis.

Factor	Sum of squares	Variance	*F*	*P*
Temperature	23.032	11.516	96.451	12.027
Vacuum pressure	107.849	53.924	451.625	57.851
Flow rate	16.870	8.435	70.644	8.775
Concentration	40.693	20.346	170.406	21.346
Error	1.074	0.119		

Table 3
Operating conditions and permeate fluxes in MD of NaCl solutions, as obtained in several studies.

Reference	Configuration	Membrane material	Pore size (μm)	Temperature (°C)	Vacuum pressure (mbar)	Flow rate (mL/s)	NaCl concentration (g/L)	Permeate flux (kg/(m² h))
[5]	AGMD	PVDF	0.45	90	–	75	1	26
[21]	AGMD	PTFE	0.2	45	–	83	30	5
[22]	AGMD	PTFE	1	75	–	63	3	28
[17]	DCMD	PVDF	0.45	50	–	20	58	28
[21]	DCMD	PTFE	0.2	45	–	55	30	40
[5]	DCMD	Teflon	–	50	–	–	5.8	5
[23]	DCMD	PP	0.73	75	–	63	35	70
[17]	VMD	PVDF	0.2	25	10	–	300	0.36
[15]	VMD	PP	0.074	60	79	42	35	3
[20]	VMD	–	0.2	75	1	70	300	50
This work	VMD	PP	0.2	55	40	30	100	14.41
	VMD	PP	0.2	55	40	30	200	11.13
	VMD	PP	0.2	55	40	30	300	9.23

Table 4
Summary of the results achieved in some VMD tests in terms of energy consumption ($T = 55\,^{\circ}$C and NaCl concentration = 100 g/L).

Vacuum pressure (mbar)	Flow rate (mL/s)	Permeate flux (kg/(m² h))	Energy consumption (W)	Energy consumption/permeate flow rate (kW/(kg/h))
40	30	14.4	320.9	3.50
40	15	12.2	307.3	3.96
60	30	11.6	170.8	2.32
80	30	10.7	115.6	1.70
100	30	9.6	102.1	1.67
120	30	6.9	100.5	2.29
120	15	4.7	91.2	3.05

salt concentration only marginally decreases vapor pressure of water.

Fig. 7 illustrates the performance of VMD at different feed temperatures (25, 40 and 55 °C). As seen, the permeate flux through the PP membrane increases linearly with temperature. This behavior is most likely due to the exponential dependence of water vapor pressure on temperature (considering the Antoine equation) [13]. In terms of maximizing the permeate flux, $T = 55\,^{\circ}$C, Pv = 40 mbar, $Q = 30$ mL/s and $C = 100$ g/L were chosen. Also, it was also worthwhile to compare previously reported MD performance under similar configurations and operating conditions. Table 2 compares permeate flux obtained in this work with other studies.

In terms of water quality, the average value of permeate electrical conductivity was measured as 2.49 μS/cm (while electrical conductivity of distilled water was measured as 3.30 μS/cm). ANOVA was used to determine the factors to what extend influence the permeate flux. Sum of squares (SS), mean square (variance), ratio of factor variance to error variance (F) and contribution percentage of each factor on response (P) are presented in Table 3. The contribution of each factor on the response is presented in Fig. 8. P values of temperature, flow rate and concentration are almost the same and are lower than these that of vacuum pressure. This means that vacuum pressure is the most significant factor.

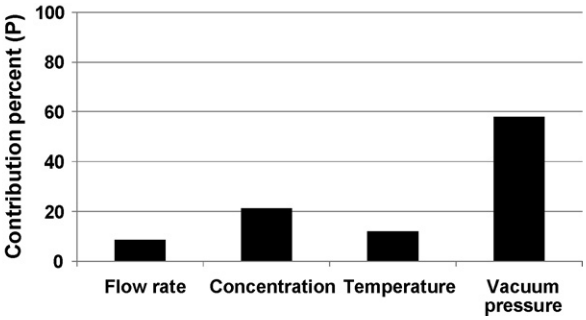

Fig. 8. Contribution of each factor on permeate flux.

In terms of energy consumption, the studies reported in literature on membrane distillation mainly investigate the temperature polarization phenomena, heat efficiency/heat transfer [24–26] and only few studies refer to the energy requirements [5,20,27,28]. Table 4 summarizes the results obtained in terms of energy consumption/permeate flow rate ratio for some of VMD runs. For energy consumptions calculation the heating of the hot stream and the vacuum application at the permeate side were taken into account. The energy consumption considered in the work made referred only to the external heat supply/removal needed, as well as to the vacuum application at the distillate side in VMD, and included the energy consumption of pumps used for re-circulating feed. The energy required for the vacuum pump and the feed pump was considered 210 and 40 W, respectively.

4. Conclusions

An experimental study of VMD process was carried out. Effects of the following parameters on the permeate flux were also studied: temperature, vacuum pressure, flow rate and concentration. For all the experiments, a commercial PP membrane with a pore size of 0.2 μm was employed. VMD performance (measured in terms of water (permeate) flux through the membrane) was observed to increase with increasing feed temperature and flow rate and decreasing vacuum pressure and feed concentration. Salt rejection is always high in MD processes and is not affected by concentration. Average electrical conductivity of the permeates were 2.49 μS/cm. Optimum operating conditions for maximizing the permeate flux are: temperature, 55 °C; vacuum pressure, 40 mbar; flow rate, 30 mL/s and concentration, 100 g/L. At these conditions, obtained permeate flux is 14.4 kg/(m² h).

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