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Performance evaluation of vacuum membrane distillation for desalination by using a flat sheet membrane

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ABSTRACT

Vacuum membrane distillation (VMD) process received a great deal of attention by many investigators because of its promising applications in several separation areas. It is a rising technology for seawater or brine desalination process. The process simply consists of a flat sheet hydrophobic microporous PTFE membrane and diaphragm vacuum pump without a condenser for the water recovery or trap. In this work, VMD performance was investigated for aqueous NaCl solution. In order to enhance the performance of the VMD process in desalination, that is, to get more flux, it is necessary to study the effect of operating parameters on the yield of distillate water. The influence of operational parameters such as feed flow rate, feed temperature, feed salt concentration and permeate pressure on the membrane distillation (MD) permeation flux have been investigated. The VMD performance showed that this device could reach a desalting degree of 99.99% which was not affected by feed concentration. The membrane distillation flux reached 14.62 kg/m^2 h at 333 K bulk feed temperature, 1.5 kPa permeate pressure, 54 l/h feed flow rate, and 30,000 mg/l feed concentration. With these chosen operating conditions, experiments with concentrated salt water showed a permeate flux decreases with time, but these reduction is less than 14% over a long term experimentation. However, this fouling is reversible and easily removed by a water washing. This study promotes the research attention in apply of VMD for over-concentrated salt water means rejected brines of reverse osmosis process.

Keywords: VMD; Hydrophobic PTFE flat membrane; Desalination; MD

1. Introduction

The freshwater scarcity is a growing problem all over the world because only 1% of earth's water is fresh water available for human to drink. Both rapid population growth and the impairment of existing freshwater sources cause many regions to turn to the ocean as a source of fresh water. In order to bridge between the wide gap between availability and the demand for fresh water, desalination of the available saline water has become a suitable alternative, which is widely used worldwide [1–3]. Several kinds of desalination methods are being applied in removing salts from seawater to achieve water salinity lower than 500 mg/l for drinking water, which has restricted by the World Health Organization [4,5]. Among various desalination

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technologies, membrane distillation (MD) is supposed to have a great potential due to low energy requirement, low operational pressure and temperature, and low-cost alternative to conventional technologies such as reverse osmosis (RO) and distillation. The potential application of MD process for production of high purity water, concentration of ionic, colloid or other non-volatile aqueous solutions and removal of trace volatile organic compounds from waste water [6–9].

MD for water desalination is a membrane technique for separating water vapor from a liquid saline aqueous solution by transporting through the pores of hydrophobic membranes, made mainly of polypropylene (PP), polytetrafluoroethylene (PTFE), and polyvinylidene fluoride (PVDF). Various types of methods may be employed to impose a vapor pressure difference across the membrane to drive a flux. The permeate side may be a cold liquid in direct contact with the membrane, called direct contact membrane distillation (DCMD) or a condensing surface separated from the membrane by an air gap called air gap membrane distillation (AGMD) or a sweep gas blown across the membrane called sweep gas membrane distillation (SGMD) or vacuumed called vacuum membrane distillation (VMD). Because AGMD and DCMD do not need an external condenser, they are best suited for applications where water is the permeating flux. SGMD and VMD are typically used to remove volatile organic or dissolved gas from an aqueous solution [5,7,10].

This study proposes VMD process, in which a feed solution is brought into contact with one side of a microporous membrane, and vacuum is pulled on the opposite side to create a driving force for mass transfer. When feed is a water containing salts, the water is a vaporized close to the pores and then passes as a vapor through the membrane pores. Permeate condensation take place outside the module. VMD can be characterized by the following steps: vaporization of the more volatile compounds at the liquid–vapor interface and diffusion of the vapor through the membrane pores according to a Knudsen mechanism [7–11].

Compared with conventional separation techniques, VMD is found economically to be comparable with respect to the separation costs of the membrane alternatives such as pervaporation. Hence, recently VMD has become an active area of research. Most of the researchers studied the use of VMD in the removal of trace gases and volatile organic compounds from water and it has also been proposed as a means for the sea water desalination. Also, the major advantage is to reduce the environmental impact of rejected brines of reverse osmosis technology, means to reduce the brine volume and disposal [12,13]. In this study, performance of VMD operating for desalination was investigated.

Table 1
Membrane characteristics

Material	Hydrophobic PTFE
Pore size, µm	0.22
Porosity, %	70
Thickness, µm	175
Membrane area, cm^2	3.6

2. Experimental

Experiments were performed using a microporous hydrophobic PTFE flat membrane (Millipore). The typical characteristics of the membrane are summarized in Table 1. The membrane was located in 25 mm diameter plate type of module prepared of PVC material. The diameter of inlet and outlet is 6 mm. In all experiments, the aqueous feed solution of about 25,000–35,000 mg/l NaCl in pure water were prepared and continuously fed to the membrane module from a reservoir by using a pump. A flow rate of feed water was measured by the flow meter connected in between the pump and module. A vacuum pump was connected to the permeate side of the membrane module to remove the water vapor flux. Cold trap was used to condense and recover the water permeating vapor. The condensed pure water was collected to calculate the distillate flux. Calibrated vacuum gauge was used to measure the pressure at the permeate side of the module. A schematic view of the setup is presented in Fig. 1. The feed temperature and down stream pressure was varied between 313 and 333 K, and 1.5 and 5 kPa respectively.

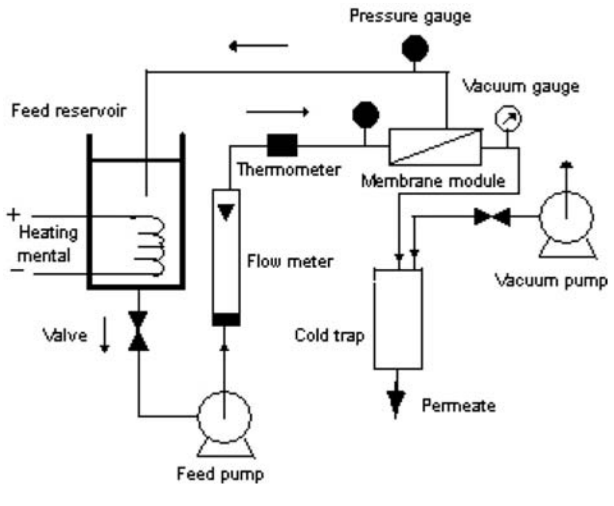

Fig. 1. Experimental setup of VMD.

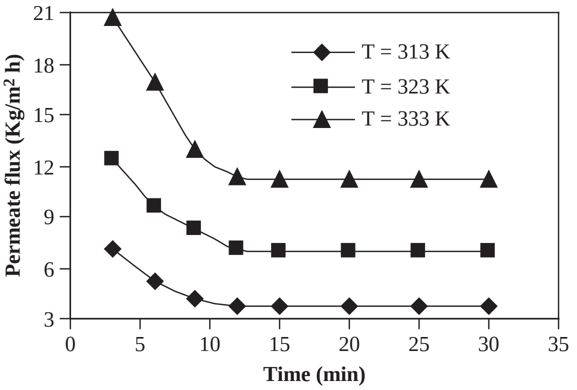

Fig. 2. Variation of flux with time at feed flow rate = 52 l/h, permeate pressure = 3 kPa and feed salt conc. = 30,000 mg/l.

The MD flux (j, kg/m^2 h) is calculated by Eq. (1):

$$j = \frac{V \cdot \rho}{A \cdot t}, \qquad (1)$$

where V is volume of freshwater (l); ρ is density of freshwater (kg/l); A is effective membrane area (m^2) and t is the running time of VMD. The salt concentration in the feed water (C_1, mg/l) and in freshwater (C_2, mg/l) were calculated by the Hg(NO$_3$) titration and conductivity measurement. The desalting degree (η, %) was calculated from Eq. (2):

$$\eta = \frac{C_1 - C_2}{C_1} \times 100. \qquad (2)$$

3. Results and discussion

The VMD experiments were carried out to determine steady state (equilibrium) flux. Figs. 2 and 3 show the variation of flux with time for change in feed temperature and feed flow rate. Each experiment was performed for 30 min and sampling was done after every 5 min. The results show that after almost 12 min, flux reaches equilibrium (steady state). The flux decreases because vapor transfer resistance across the membrane is increases and reaches steady after 12 min. As a result, the next experiments were performed for 30 min and sampling was done twice. All data presented herein were recorded during the second sampling and each test was performed three times, and the average values are presented. The maximum deviation was very less 2%.

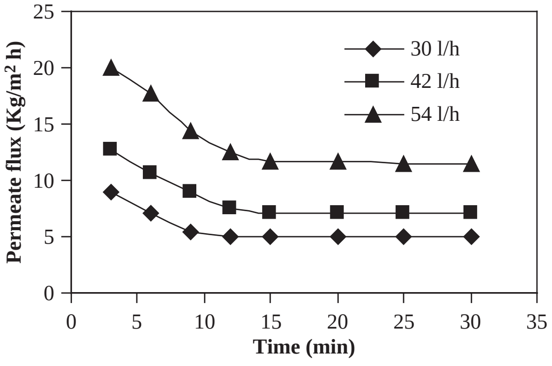

Fig. 3. Variation of flux with time at feed temperature = 333 K, permeate pressure = 3 kPa and feed salt conc. = 30,000 mg/l.

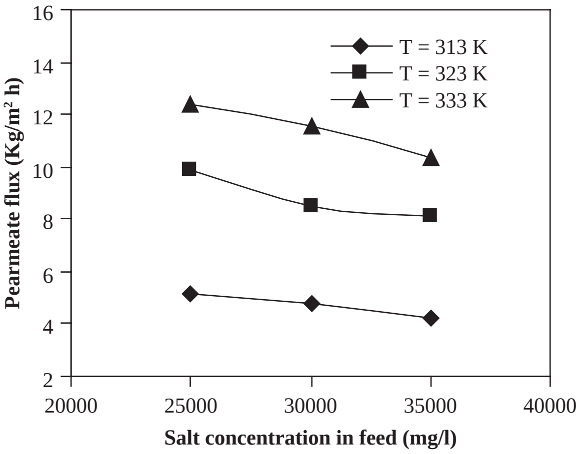

Fig. 4. Effect of feed salt concentration at feed flow rate = 54 l/h.

3.1. Effect of feed concentration

The experiments were performed for different concentration of salt in the feed water, when the vacuum pressure was 3 kPa. Fig. 4 show the effects of feed concentration on permeate flux at feed flow rate 54 l/h and the feed temperatures were 313, 323 and 333 K, respectively. Similarly, Fig. 5 shows the result at feed temperature 333 K and feed flow rates were 30, 42 and 54 l/h, respectively.

The results show that increasing of feed concentration of salt slightly decreases permeation flux due to

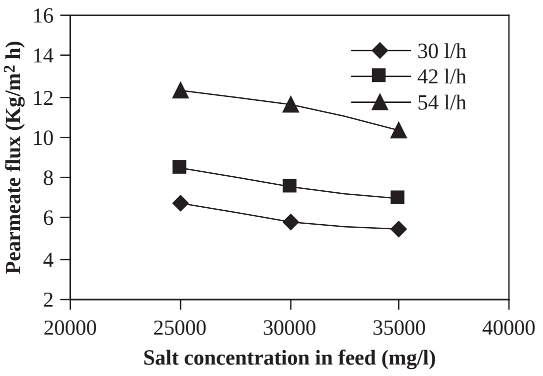

Fig. 5. Effect of feed salt concentration at feed temperature = 333 K.

influence of salt concentration on activity coefficient of water. This reduction was less than 19% when increasing salt concentration from 25,000 to 35,000 mg/l. According to Roult's law, in aqueous solution increasing salt concentration leads to the reducing of water vapor pressure and consequently driving force across the membrane. When salts are present in the feed solution at high concentration, an additional boundary layer develop at membrane surface, parallel to the temperature and velocity boundary layers. This concentration boundary layer, together with the temperature boundary layer further reduces the driving force for vaporization. Enhanced turbulence in the feed stream reduces both boundary layers and improves VMD performance. Due to reducing of water vapor pressure and increasing of resistance in transfer process, which is reduces the permeation flux. It indicates that VMD is more suitable for diluting high salinity brine, which provides a basis for the treatment of a higher concentration of salt water desalination.

One of the most significant advantages of the MD process for desalination is the relative nominal effect of feed salt concentration on the performance of the system. In VMD, increasing feed salt concentration only marginally decreases vapor pressure of water. In RO operations, increased feed salt concentration can substantially reduce the driving force for mass transfer across the membrane and increase the salt passage through the membrane. The operating conditions in RO promote concentration polarization, scaling, compaction of a cake layer, and increased osmotic pressure that leads to reduced performance.

3.2. Effect of feed flow rate

The permeation flux of the salt solution in VMD was influenced by the feed flow condition. The experiments were performed for 30,000 mg/l salt solution, 3 kPa permeate pressure and 313, 323 and 333 K feed temperature, the effect of feed flow rate on permeation flux is shown in Fig. 6.

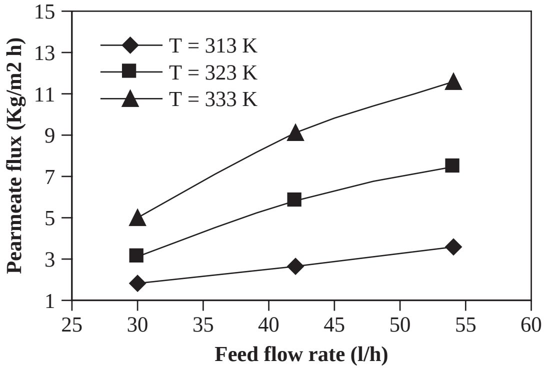

Fig. 6. Effect of feed flow rate at feed salt conc. = 30,000 mg/l, and permeate pressure = 3 kPa.

Water flux of MD system is proportional to the temperature difference at the membrane barrier layer (i.e. at both membrane faces) and the effect of temperature polarization lowers that temperature difference. Therefore, successful MD operation requires an efficient method of moving the hot feed from the heating device to one face of the membrane, and cold permeates to the other. The method of choice is to provide highly turbulent flow across the both membrane faces. This is achieved by driving feed and permeates streams at high flow rates. Due to high vacuum on the permeate side in the VMD system, the temperature of the permeate side is same as the temperature measured at the entrance of the membrane pore means at the feed side membrane surface and the conduction heat transfer across the membrane is negligible relative to other MD configuration. Hence, temperature polarization occurs only in the hot feed. The formation of the temperature boundary layer is mainly brought about by the water vaporization on the membrane surface. Here, the ratio of temperature of film boundary layer at membrane surface to the bulk film temperature represents the extent of temperature polarization in VMD. The flow rate of water increases the enhanced mixing of the flow channels. Due to this, the temperature polarization resistance, heat and mass transfer boundary layer decreases. Hence, the vapor transfer residence through the membrane is decreases and permeation flux increases (Fig. 6), which is more obvious when the bulk feed temperature higher. After 54 l/h feed flow rate, no effect was found on the permeation flux. Salt rejection was greater than 99.9% throughout all the experiments.

3.3. Effect of feed temperature

The feed temperature plays an impotent role on permeation flux in VMD performance. Fig. 7 is showing the effect of feed temperature on permeation flux. The permeate pressure was set at 3 kPa and varied flow rate of feed solution. Also, the effect of temperature at various concentration of feed was expressed in Fig. 4. The permeate flux was more obviously at higher feed flow rate and lower salt concentration.

The results showed the water vapor flux is a function of temperature difference. It is widely understood that application of a temperature difference across a VMD membrane will induce water vapor to pass and some amount of permeate to be generated. Furthermore, developing significant temperature difference should lead to a greater desalination production rates. However the actual driving force for VMD is the vapor

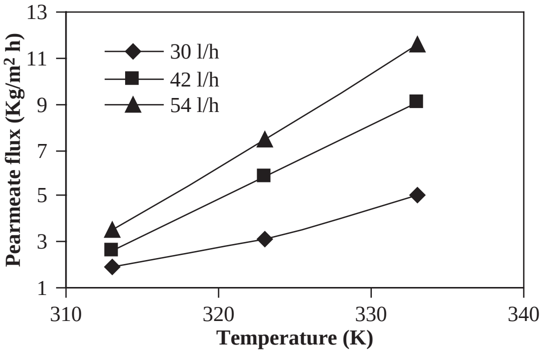

Fig. 7. Effect of feed temperature at feed salt conc. = 30,000 mg/l, and permeate Pressure = 3 kPa.

pressure difference across the membrane, which is induced by this temperature difference. Although increase of feed temperature increases the water vapor pressure and the Reynolds number somewhat, it drastically increases the driving force. So the optimization of feed temperature is an effective way to get high water vapor flux in VMD. The results of Fig. 7 show that the membrane permeation flux increases with increasing the feed bulk temperature at the same operational conditions.

The driving force for VMD also induced by varying the vacuum pressure at permeates side at constant feed bulk temperature. Fig. 8 show the positive effect of permeates pressure on permeation flux at different values of feed temperature. The result shows that the flux decreases with increasing vacuum side pressure for a given operational conditions. Increase of vacuum to the downstream side of the membrane at constant feed bulk temperature increases the vapor pressure of water consequently driving force. Hence the mass flux is depending on the driving force, which is an increase by increasing vapor pressure of water, this is due to decrease in the mass transfer resistance because the transport mechanisms for mass transfer across the membrane is usually based on the Knudsen diffusion, has a vapor pressure difference as a driving force. The influence of air in the membrane pores over the water vapor diffusion through the bore can be neglected in VMD. Also, the low pressure employed prevents the formation of a boundary layer on the permeate side, thus this resistance can be neglected as compared to the RO technique. The presence of reasonably high vacuum on the other side of the membrane in VMD drastically reduces the extent of conductive heat loss from the hot brine. Potentially one can achieve a very high water vapor flux in VMD. The permeation flux was reached 14.62 kg/m^2 h when the operating conditions are: feed temperature, 333 K; vacuum pressure, 1.5 kPa; feed flow rate, 54 l/h and feed concentration, 30,000 mg/l.

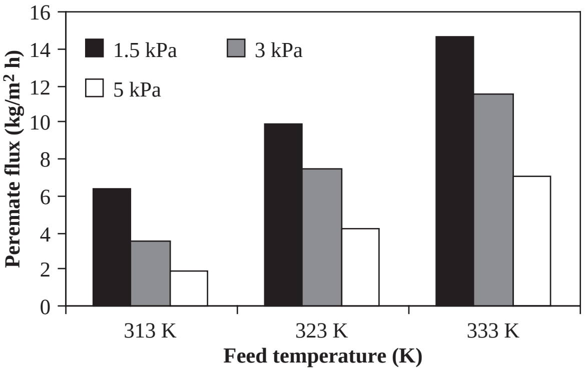

Fig. 8. Effect of feed temperature at feed salt conc. = 30,000 mg/l and feed flow rate = 54 l/h.

3.4. Desalting degree and fouling

Desalting degree or percentage of salt rejected by the membrane is an important factor for VMD. If the membrane is not broken, the desalting degree of VMD can be 100% [8]. The test of desalting degree of VMD was performed for five hrs per day continuously for five days in a week like six month period. The operating parameters were setup at 333 K feed temperature, 54 l/h feed flow rate and 3 kPa permeate pressure. The feed salt concentration was varied from 25,000 to 35,000 mg/l. The water washing of the membrane surface was done after every five hours and permeate flux was measured at every hour.

Throughout six month experimental results are shown in Fig. 9 in terms of water quality, whatever the feed concentrations, negligible traces, i.e., less than 6 mg/l of salt was found in the treated water. The desalting degree of VMD throughout four month experimentation was held above 99.99% and during 5th to 6th month, it was decreased to 99.98%. Hence, in the product water the salt concentration was 3 mg/l up to four

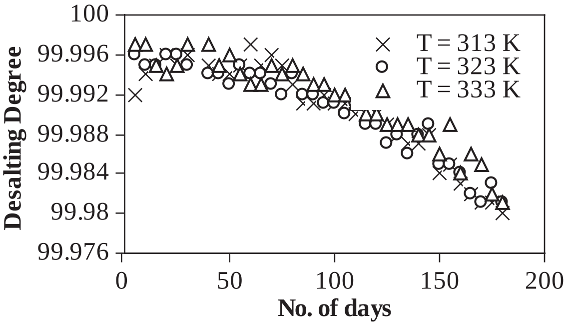

Fig. 9. Percentage rejection of salt by membrane over six month of period.

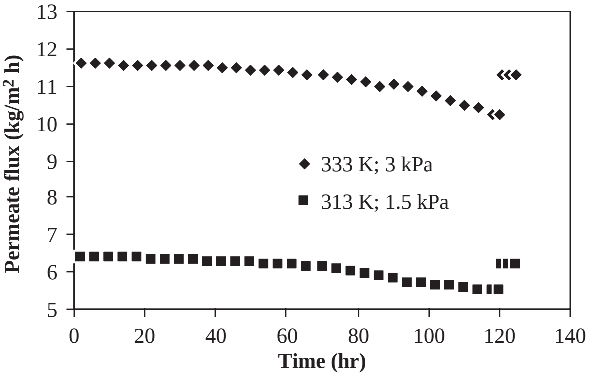

Fig. 10. Time-variation of permeate flux at feed flow rate = 54 l/h and feed salt conc.= 30,000 mg/l.

month and it was increased up to 6 mg/l during 5th to 6th month and meets the requirements of drinking water. During long term run demonstrated no membrane leakages found. The water vapor flux was declined as an average about 1–2% form initial to final steady state value measured after five hours in an every day. This minor reduction also removed by water washing of the membrane surface after every five hours. Hence, the fouling of the membrane was not observed in six month period. But need to study the detailed fouling of the membrane in a continuous long term experiments. The membrane wall thickness was as large as 175 μm to improve the membrane's strength and durability.

To evaluate fouling potential, the salt concentration of NaCl at 30,000 mg/l was used as feed for the flat sheet VMD apparatus and was operated continuously for approximately 120 h. Fig. 10 shows the flux profile at both high and low temperature of 333 and 313 K, respectively. The higher temperature generated the initial flux of 11.6 kg/m^2 h which declined to 10.2 kg/m^2 h over 120 h at 54 l/h feed flow rate and 3 kPa permeate pressure. However, the lower temperatures produced a flux of 6.4 kg/m^2 h, which declined to 5.5 kg/m^2 h at 54 l/h feed flow rate and 1.5 kPa permeate pressure. An inconsequential flux decrease with time is observed during the experiments. Flux decrease represents 12% and 14%, respectively, in 120 h. These decrease of permeate flux is not caused by a reduction of the vapor partial pressure of the feed water, and so of the vapor pressure difference. Really, variation of the partial vapor pressure with time is negligible as temperature and concentration are nearly constant with time in the system. Concentration at the membrane is nearly the same than in the bulk for those operating conditions, and has no influence on the VMD process. The 120 h experimental run shows about 14% decrease of permeate flux between begin and end of the experiments. No apparent significant deposit was observed on the membrane surface fouling. At every time the salt rejection was high 99.99%. After 120 h, the water washing was done and flux again increases to 11.3 and 6.2 kg/m^2 h, respectively. Really, the MD flux initial and after water washing show a variation of less than 3%. Hence, the fouling phenomenon in VMD is highly reversible and can be easily removed by a water washing. Hence, promote the research attention in apply of VMD for over-concentrated salt water means rejected brines of reverse osmosis process. So, further experiments will be performed to study the membrane fouling for highly concentrated seawater.

3.5. Preliminary assessment of energy requirement

VMD desalination plant is operated in conjunction with a power plant or any other source of waste heat, the cost of energy for heating the feed water is negligible and thermally polluted water is used beneficially. Other sources of energy such as renewable solar or geothermal energy could be utilized to heat the feed water [14,15]. As opposed to warm condenser water, use of renewable sources would involve higher capital investment. However, this investment may eventually be paid off by lower operating costs. The VMD operate at low temperatures and low pressure pumps are required as compared to RO process. Low pressure pumps are less expensive in both capital and operating costs. The heat supply to the VMD process can be electricity source; it does not take into account the energy recovery which will occur during vapor condensation nor by energy recovery system.

Table 2 summarizes the results obtained in terms of energy consumption per permeate flow rate for some of VMD runs. For energy consumptions calculation the heating of hot stream and the vacuum application at the permeate side taken into account. This was the

Table 2
Summary of energy consumption achieved in VMD runs (Feed temperature = 333K and feed salt concentration = 30000 mg/l

Flow rate (l/h)	Vacuum Pressure (kPa)	Permeate flux (kg m^{-2} h)	Energy consumption/ permeate flow rate [kW/ (kg h^{-1})]
54	1.5	14.62	3.74
30	1.5	8.73	4.52
54	3	11.56	2.83
30	3	5.15	3.67
54	5	7.06	2.11
30	5	3.17	2.76

preliminary assessment of the energy consumption; the detailed study of energy requirement will be present in the further study.

4. Conclusions

An experimental study of VMD performance for desalination in a flat sheet membrane configuration is presented. When the feed flux is constant, the VMD permeation flux increased with increasing feed temperature. Also, the water vapor flux increased with increasing feed flow rate at constant feed temperature and vacuum pressure. The water vapor permeation flux decline due to concentration enhancement and it was less than 19% when the feed concentration increased from 25,000 to 35,000 mg/l. The water vapor flux was very influenced by the permeate pressure. The permeation flux was highly reduced by 70% by increasing permeate pressure from 1.5 to 5 kPa at constant other operating parameters. In all experiments, the product water was almost distilled water; because negligible trace of salt was found in this for all operational conditions. The permeation flux reached 14.625 kg/m^2 h at 333 K feed temperature, 1.5 kPa permeate pressure, 54 l/h feed flow rate, and 30000 mg/l feed concentration. Salt rejection was high as 99.99% and it was not affected by concentration of feed solution. In the fouling test, the permeate flux was reduced about less than 14% with time that may be caused by some salt deposited on the membrane surface. However, this was easily removed by the water washing. This showed a good scene for the application of flat sheet membranes in the field of high salinity brine and seawater desalination. These preliminary results show the potential interest of the use of VMD for desalination for operating high salt concentration solutions.

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