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THE EFFECT OF TEMPERATURE AND SALT CONCENTRATION ON SALT REJECTION AND PERMEATE FLUX OF A VACUUM MEMBRANE DISTILL ATION UNIT USING FLAT SHEET MEMBRANE

Adel Fayez Gaid[1,] Minerva Edward[2], Khaled Zaher Abdallah[2] Heba Abdallah[3]

[1] Graduate Student, Project Department Manager, Arab Organization for Industry, Egypt.

[2] Sanitary and Environmental Engineering Division, Public works Engineering Department, Faculty of Engineering, Cairo University, Egypt.

[3] Chemical Engineering & Pilot Plant Department, Engineering Research Division, National Research Centre.

ABSTRACT

Vacuum Membrane Distillation (VMD) is one of the membrane distillation (MD) categories which is a technology that depends on creating a pressure difference between the two sides of a membrane using vacuum pressure on the outlet side of the membrane module. A lab-scale VMD system was constructed and operated to study the effect of temperature and salt concentration on salt rejection and permeate flux of the VMD unit with constant feed flow rate and vacuum pressure. The used membrane was a hydrophobic polyethersulfone flat sheet membrane: effective diameter 0.25 m, effective area 0.049 m^2, pore size 0.2-0.4 µm and membrane thickness 120-160 µm. Permeate flux and salt rejection were measured. Results showed an increase in permeate flux from 15kg/m^2.h to 25 kg/m^2.h and in salt rejection from 74% to 80%with the increase in feed water temperature from 40°C to 70°C at salt concentration 5000 ppm ,flow rate 1L/m and vacuum pressure 0.4 bar and the decrease in permeate flux from 15 kg/m^2.h to 6 kg/m^2.h and in salt rejection from 74% to 67% with the increase in feed water salt concentration from 5000 ppm to 30000 ppm at temperature 40°C with the same flow rate and vacuum pressure.

KEYWORDS: VMD, HYDROPHOBIC MEMBRANE, SALT REJECTION, POLYETHERSULFONE MEMBRANE.

1. INTRODUCTION

Water desalination has become one of the main sources of potable water in Egypt due to the increasing water demand for different usages while there is possible decrease in Egypt's share in Nile water.

Membrane separation and thermal desalination processes are the major seawater desalination technologies used worldwide. For thermal desalination, the main drawbacks the high energy consumption which increases the cost of potable water production. While for membrane separation processes, whether reverse osmosis(RO), electrodialysis(ED), and MD, membrane fouling, scaling and concentration polarization leads to a loss in the permeate flux with time (Cabassaud, and Wirth,2003 and Alklaibi,and Lior, 2005).

MD is a thermal desalination process operated at a temperature lower than the water boiling temperature, the driving force is the pressure difference created between the feed and permeate sides (Min Guan, 2013). The hydrophobic membrane allows vapor to pass while preventing the residual seawater from passing to the permeate side. MD has some advantages over other desalination processes including high salt rejection, low-cost, and less sensitivity to the variations in salt concentration. There are many membrane distillation configurations; each configuration is different from the others in the methods of creating the pressure difference between the two sides of the membrane module and the methods of vapor condensation (Pangarkaret al., 2011). Figure1 shows the different configurations of MD (El-Bourawi et al., 2007 andLi, and Tian, 2009).

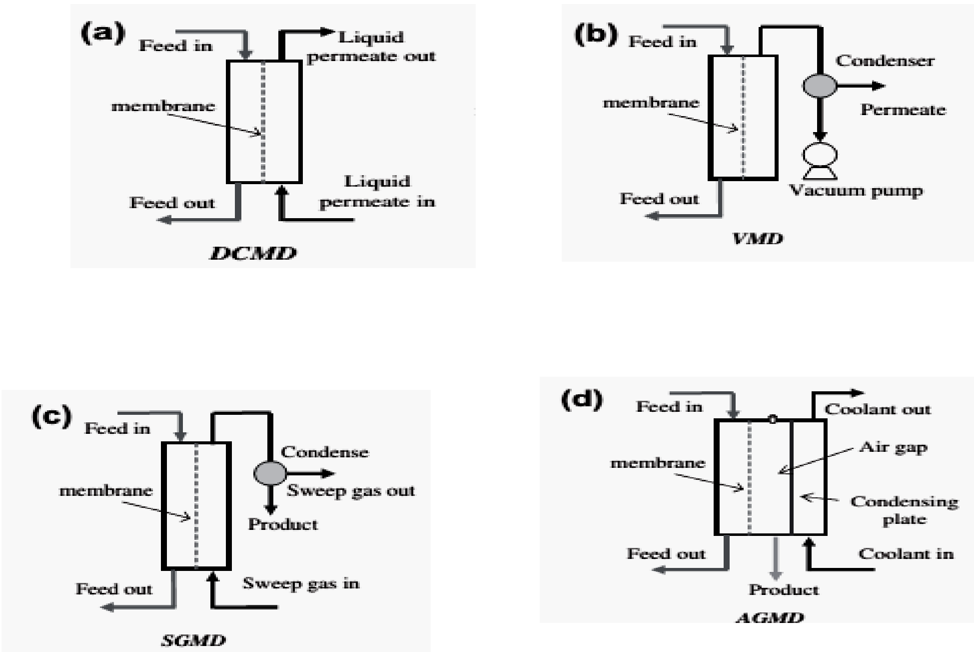

Figure (1) the configurations of the MD (http://emis.vito.be/techniekfiche).

Direct Contact Membrane Distillation (DCMD): the feed water is in contact with the hot side of the membrane, the permeate side of the membrane is in direct contact with a cold liquid, the vapor passes through the hydrophobic membrane according to the pressure difference and condenses inside the membrane module (Lagana et al., 2000).

Air Gap Membrane Distillation (AGMD): the feed water is in contact with the hot side of the membrane, the vapor passes through the hydrophobic membrane crossing the air gap to condense over the cold surface inside the membrane module.

Sweeping Gas Membrane Distillation (SGMD): the feed water is in contact with the hot side of the membrane, the gas used in the permeate side of the membrane module sweeps the vapor outside the membrane module to condenser unit.

Vacuum membrane distillation (VMD): the hot feed water is pumped into the feed side of the porous hydrophobic membrane while the other side of the membrane is subject to vacuum pressure, which allows the feed water to boil at temperature lower than the water boiling temperature, and the vapor is transferred from one side to the other side through the hydrophobic membrane (Alklaibi, and Lior, 2005).

VMD operating cost is much lower than the cost of other thermal desalination processes because the temperature used is below the water boiling temperature. The results of an earlier research conducted by the authors using flat sheet membranes with a feed salt concentration range from 5000 ppm to 30000 ppm showed that the VMD energy consumption lessthan that of an RO unit. Also, the VMD can produce higher permeate flux at a higher temperature but higher energy consumed. This is why it suggested using solar energy to lower the energy consumed cost (Cabassaud**,** and Wirth**,** 2003, Alklaibi**,**and Lior, 2005, Fayez**,** et al., 2016 andGuan, 2013).

The advantages of the VMD that:

- Low operating pressure (0.1-30 kPa) compared to other membrane separation processes (Chiam, and Sarbatly, 2013 and Wang, and Chung, 2015).
- Low operating temperature due to using low pressure (http://emis.vito.be/techniekfiche andAlsalhy, 2014).
- Small footprint.

- Smaller vapor space is needed because the vapor is directly transferred to the outlet side according to the pressure difference.
- VMD requires minimum maintenance compared with the other desalination processes (VMD Less sensitive to fouling due to large pore size) (Alsalhy, 2014).
- Membranes used in VMD have a larger pore size (0.2-1μm) thus; they are less subjected to fouling or scaling (Li, and Tian. 2009).
- VMD is able to treat highly salt concentrated feed solutions with high salt rejection percentage as vapor is little affected by salt concentration (Tang, et al., 2000, Gryta, 2012, Guan 2013, Wang, and Chung, 2015, and Alsalhy, 2014).

The aim of this research is to evaluate the membrane properties, to study the effect of operating temperature and salt concentration on the salt rejection and permeate flux of a VMD unit using polyethersulfone flat sheet membrane.

2. Membrane Preparation for the Experimental Unit

2.1. Materials and Membrane Preparation

The used PES membranes were manufactured in the National Research center (NRC) by the immersion precipitation method. A polymer solution was prepared using PES and DMAC and adding PEG for membrane's pore forms. The solution temperature was adjusted at 22°C and mechanically mixed with 800 rpm for 12 hr. The membranes were cast on a glass plate and the coagulation of the membrane appears in a gelatinous water bath.

Membrane Materials

The common materials used in membranes are: polytetrafluoroethylene (PTFE), polypropylene (PP), or polyvinylidenefluoride (PVDF) (El-Bourawiet al., 2007and Pangarkar, et al., 2010)these materials are hydrophobic and made from polymers that have low surface energy (Wang, and Chung, 2015). As for membrane modules, they are either flat sheet or hollow fiber membranes as shown in Figure2 (Ku and Lee, 2014).

Figure (2) (A) Flat sheet membrane. **(B) Hollow fiber**

In this research work, Polyethersulfone (PES) from BASF Chemical Company and Dimethylacetamide, polyethylene glycol from Sigma Aldrich Company. Different saline water solutions prepared using commercial NaClin tap water.

2.2. Determination of Membrane Properties

The performance and efficiency of the VMD process are directly affected by the membrane properties such as pore size, porosity, thickness, tortuosity, membrane morphology, wetting, swelling, and hydrophobicity.

2.2.1. Membrane Pore Size and Porosity

The membrane's pore size can affect the VMD performance: the permeate flux and the liquid evaporation increase with the increase in the pore size (Gryta, 2012). On the other hand, the increase in pore size causes an increase in wettability, thus, small pore size should be chosen (Bourawi et al., 2007, and Khayat, 2011). Moreover, the membrane porosity defined as the average percent ratio between the total volumes of the pores to the total volume of the membrane (Chiam, and Sarbatly, 2013). The evaporation surface area and permeates flux increase with the porosity increase (Susanto, 2011), a 15% change in porosity leads to permeate flux change about 13% (Soni et al., 2008).

The pore size and porosity of the prepared membranes determined using the Brunauer-Emmett-Teller (BET) method using at least two cycles of adsorption and desorption of nitrogen, BET apparatus is of a model (ChemBET-3000,Quantachrome) Chemisorption's analyzer for a different area, the analysis was conducted at the NRC, Giza, Egypt. Samples of known weights of the membrane were cut into long strips and placed in a glass column of the apparatus, dried and degassed by heating at 80° C for 3 hours.

The average of three measurements for the internal surface of the prepared hydrophobic PES membrane ranges from10.5m²/g to11.5m²/g, and the average diameters of the pores of membranes were from 0.2 to 0.4 µm. The membrane porosity was from 70% to 75%.

2.2.2. Membrane Thickness

Membrane thickness is inversely proportional to the permeate flux and directly proportional to salt rejection and conductive heat loss. The thickness of prepared membranes determined using digimatic micrometer. The prepared membrane's thickness ranged from 100 to 150 µm.

2.2.3. Membrane Tortuosity

The membrane tortuosity defined as average percent ratio between the effective pore lengths and membrane thickness or the pore structure deviation from the cylindrical shape, the increase of membrane tortuosity leads to lower permeate flux. The tortuosity can be determined by Macki–Meares equation (Abdullah et al 2012), where:

$$\tau = \frac{(2-\varepsilon)^2}{\varepsilon} \qquad \textbf{(1)}$$

Where, the ε is membrane porosity, τ is membrane tortuosity.

The tortuosity of prepared membranes was from 1.6 to 2.

2.2.4. Scanning Electron Microscopy (SEM)

Scanning electron microscopy (SEM) was used to study the morphology of PES membranes. The cross-sectional snapshots of the membrane were taken using a JEOL 5410 scanning electron microscope (SEM) and conducted at a voltage of 10 kV.

Figure (3) show the cross section of prepared PES membrane which shows a spongy porous structure of the membrane without any appearance of fingerlike porous in sub-layer.

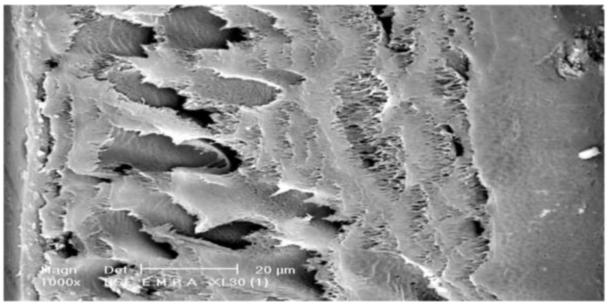

Figure (3) Crosssection of the Membrane

2.2.5. Measuring Contact Angle and Membrane Hydrophobicity

The hydrophobic properties of the membrane allow only the water vapor to pass through it and in the same time completely prevent the residual seawater to pass. The water surface tension affects the passage of water through the membrane. To check the membrane hydrophobic properties, the contact angle between a water drop and the membrane surface measured where it's an important indicator for membrane's hydrophobicity and wetting: if the contact angle is bigger than 90°, the liquid does not wet the membrane and has high hydrophobic properties, if the contact angle smaller than 90°, the liquid wets the surface (Menget al., 2014). Treated water used for the contact angle measurement by the sessile drop method. The measurements were carried out four times for each membrane sample and the average values were reported.

The contact angle was measured several times and the average contact angle for the used membrane was (85° ± 2°). Figure4 indicates the shape of a water droplet in the contact angle measurement of the used hydrophobic membrane.

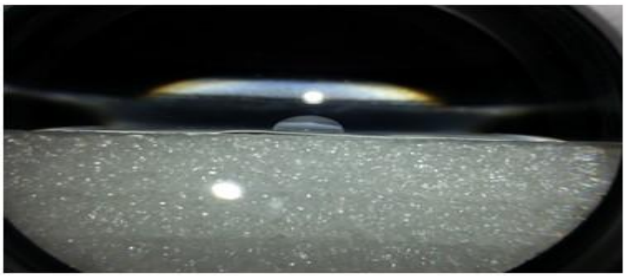

Figure (4) water droplet in contact angle measurement.

2.2.6. Membrane Wetting and Swelling

Membrane wetting means that the feed water penetrates the pores of the membrane reducing pores area, and decreasing permeate flux. Membrane swelling means that the feed pressure is greater than Liquid Entry Pressure (LEP) of the membrane which leads to increase of pores area, increase in the permeate flux and a decrease in salt rejection (Chiam, and Sarbatly, 2013). LEP can be estimated from Eq. (2):

$$\Delta P = P_f - P_p = \frac{-2\beta\gamma_1 Cos\theta}{r_{\max}} \quad (2)$$

Where P_f and P_p are the hydraulic pressure on the feed and permeate side, β is a geometric pore coefficient (equal to 1 for cylindrical pores), $\gamma_l$is liquid surface tension, θ contact angle and r max is the largest Pore size.

LEP is an important membrane characteristic; the definition of LEP is the pressure difference at which the liquid penetrates into the largest pores of the hydrophobic membrane. The feed solution must not penetrate the membrane pores. Accordingly, the pressure applied should not exceed the LEP (Abdullah et al., 2012), where the feed solution penetrates the pores of the hydrophobic membrane. LEP is directly related to feeding concentration and the organic solutes presence where for example the presence of Alcohols can reduce the LEP.

LEP also depends on the contact angle and the surface tension of the membrane, the surface tension of pure water was 72 mn/m at 25°C. For the used membrane the calculated LEP was from 20 to 45 KPa. Where high pore size, high surface energy and low surface tension for the feed solution lead to a low LEP value.

3. Calculation of VMD Performance

3.1 Permeate Flux

The membrane performance indicated according to permeate flux and salt rejection. Equation (3) used in permeates flux calculation as follows (Tanget al., 2009,Alsalhy, 2014).

$$J = w / A{*}T \quad (3)$$

Where,

J; permeate flux (kg/ m^2 .hr), w; weight of treated water (kg), A; effective area of membrane (m^2) and T is running time (h).

3.2 Salt Rejection

Determine salt rejection using equation (4) asfollows (Pangarkar et al, 2010, MinGuan, 2013, and Menget al., 2014)

$$R = (1 - C_p / C_f) \times 100\% \quad (4)$$

Where, R; salt rejection, C_f**,** feed concentration (ppm) and C_p; permeate concentration (ppm).

4. THE EXPERIMENTAL WORK

4.1. Experimental Setup

The experimental lab scale model was constructed and operated using the VMD system in the Aircraft Factory; Arab Organization for Industrialization in the period from 8/2014 till 4/2015 for a total period of 8 months. Figure5shows a schematic of the model while Fig. 6 shows the photo of the equipment used in the model. Polyethersulfone membrane was prepared in the NRC, Egypt; feed water used was a synthetic NaCl solution using concentrations ranging from 5000 to 30000 ppm, the vacuum pressure was created by using a vacuum pump with a constant value of 0.4 bars and the flow rate with a constant value of 1 l/min. Table 1 show the description of the main equipment used in the experimental model.

4.2. Experimental Procedures

The feed solution was added to the heated water tank, the heater temperature was adjusted to the corresponding temperature of each run temperature. The heated water was pumped to the feed water tank and then to the membrane module with the required constant flow rate. In the same time, the vacuum pump was operated with the required constant vacuum pressure, as well as the condenser. The treated water was collected in the permeate water tank, the volume of the collected water was measured and the salt concentration then the permeate flux was calculated according to Eq.3 and salt rejection according to Eq.4. The experiments were conducted in duplicate and the average results were calculated. The previous steps were repeated for each run according to the temperature and salt concentration according to Table 2.

Table1. Experiment equipment.

No.	Equipment	Specification
1	Heated water tank	30 liters tank equipped with heater and thermostat.
2	thermometer	Measure temperature in the range of 0°C - 120°C
3	Feed water tank	30 liter capacity.
4	Pump	pump with max head = 1.5 m, maximum flow rate = 850 l/h.
5	Membrane module	Membrane diameter: 0.25m, Area: 0.049 m^2, pore size: 0.2-0.4 µm and thickness :100-150 µm.
6	Condenser	Fan with diameter 0.25 cm and cooling pipes.
7	Water trap	Vertical pipe equipped with inlet and outlet opening with diameter 0.2 m, volume 25 liter.
8	Vacuum pump	0.5HP, 60 HZ, 1725 rpm, capacitor start, automatic thermal overload
9	Vacuum meter	Measure pressure from 0.0 to – 1.0 bar.
10	Treated water tank	30 liter capacity.
11	Control panel	To control the operation of the equipment.

Table (2) Experimental runs operating conditions and results.

Run No.	**Temperature (°C)**	**Vacuum pressure (bar)**	**Flow rate L/min**	**Salt Concentration (ppm)**	**Permeate flux ($kg/m^2.h$)**	**Out let salt**	**Salt rejection %**
1	40°C	0.4	1	5000	15	1300	74
2				10000	13	2900	70
3				15000	10	4650	68
4				30000	6	9900	67
5	50°C			5000	18	1200	75
6				10000	14	2700	72
7				15000	12	4350	71
8				30000	8	9000	70
9	60°C			5000	23	1100	78
10				10000	18	2400	75
11				15000	15	3750	74
12				30000	10	8100	73
13	70°C			5000	25	1000	80
14				10000	21	2200	77
15				15000	18	3450	76
16				30000	12	7500	75

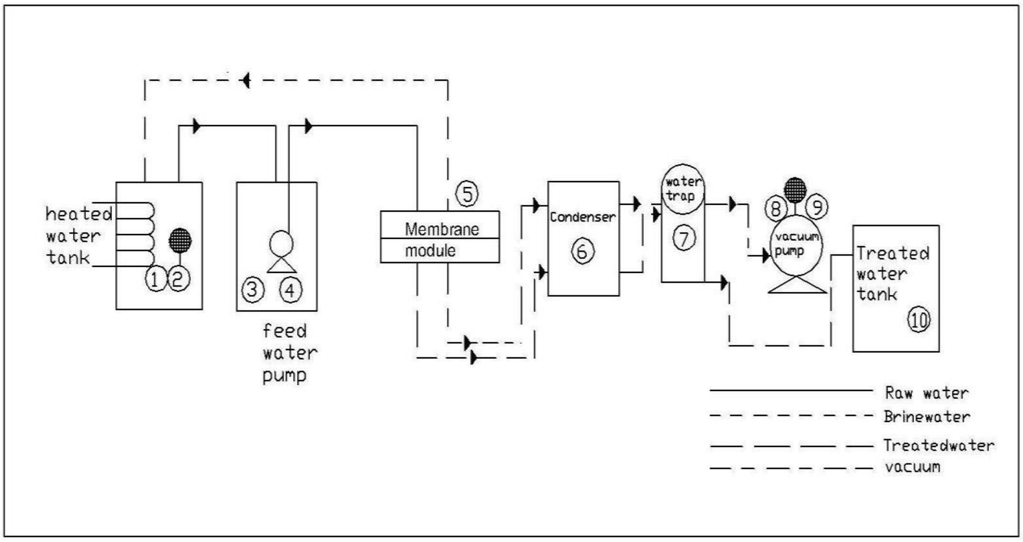

Figure (5)Experimental Setup (Fayez et al.,2016).

Figure (6) Experiment equipment photo (Fayez et al., 2016)

5. Results and Discussions

Experimental runs, operating conditions and results are shown in Table 2.

5.1. Experimental Unit Performance

5.1.1. Effect of temperature on permeate flux

Table 2 shows the results and Figures 7, and 8 illustrate them, it can be concluded that the increase in temperature from 40°C to 70°C, at feed concentration 5000 ppm, constant vacuum pressure 0.4 bar and constant flow rate 1 L/min, leads to an increase in the permeate flux from 15 kg/m^2.hr to 25 kg/ m^2.hr, i.e. an increase about 66.67%.The increase in temperature from 40°C to 70°C, at feed concentration 10000 ppm, with the same conditions, leads to an increase in permeate flux from 13 kg/ m^2.hr to 21 kg/m^2.hr, i.e. an increase of about 61%.The increase in temperature from 40°C to 70°C, at feed concentration 15000 ppm, with the same conditions, leads to an increase in permeate flux from 10 kg/ m^2.hr to 18 kg/m^2.hr, i.e. an increase about 80%. The increase in temperature from 40°C to 70°C, at feed concentration 30000 ppm, with the same conditions, leads to an increase in permeate flux from 6 kg/ m^2.hr to 12 kg/m^2.hr, i.e. an increase of about 100 %, These results are explained as follows: the increase of feed water temperature leads to an increase in vapor pressure of water at the feed side and thus increase the driving force of mass transfer.

5.1.2. Effect of temperature on salt rejection

Figure8 illustrates the effect of temperature on the salt rejection, it can be concluded that the increase in temperature from 40°C to 70°C at feed concentration 5000 ppm, constant vacuum pressure 0.4 bar and constant flow rate1 L/min, leads to an increase in salt rejection from 74%, to 80% respectively. The increase in temperature from 40°C to 70°Cat feed concentration 10000 ppm, leads to an increase in salt rejection from 70% to 77 % respectively. The increase in temperature from 40°C to 70°C at feed concentration 15000 ppm, leads to an increase in salt rejection from 68% to 76% respectively. And the increase in temperature from 40°C to 70°C at feed concentration 30000 ppm leads to an increase in salt rejection from 67%, to 75% respectively. These results are interpreted as follows: the increase of feed temperature leads to an increase in vapor pressure of water at the feed side and thus increase the driving force of mass transfer and decrease the salt concentration of permeate flux.

5.1.3. Effect of Feed Concentration on permeates flux

The results are shown in Table 2 and illustrated in Figures 9 and 10, it can be concluded that at feeding temperature 40°C, the increase in feed concentration from 5000ppm to 10,000ppm, 15,000 ppm, and 30,000ppm at constant vacuum pressure and flow rate, leads to a decrease in permeate flux from 15 kg/ m^2.hr, to 13, 10 and 6 kg/ m^2.hr respectively. At feeding temperature 50°C, the increase in feed concentration from 5000ppm to 10,000ppm, 15,000 ppm, and 30,000ppm, with the same conditions, leads to a decrease in permeate flux from 18 kg/ m^2.hr, to14, 12 and 8 kg/ m^2.hr respectively. At feeding temperature 60°C, the increase in feed concentration from 5000ppm to 10,000ppm, 15,000 ppm, and 30,000ppm, with the same conditions, leads to a decrease in permeate flux from 23 kg/ m^2.hr, to 18, 15 and 10 kg/ m^2.hr respectively. And at feeding temperature 70°C, the increase in feed concentration from 5000ppm to 10,000ppm, 15,000 ppm, and 30,000ppm, with the same conditions, leads to a decrease in permeate flux from 25 kg/ m^2.hr, to 21, 18 and 12 kg/ m^2.hr respectively These results are explained as follows: the increase in salt concentration lead to decrease the water vapor pressure, increase of resistance in transfer and decrease the driving force across the membrane.

5.1.4. Effect of Feed Concentration on salt rejection

Table 2 and Figures 9 and 10 illustrate the results, it can be concluded that the increase in feed concentration from 5000ppm to 10,000ppm, 15,000 ppm, and 30,000ppm at temperature 40°C, constant vacuum pressure and flow rate, leads to a decrease in salt rejection from 74%, 70%, 68% and 67% respectively. The increase in feed concentration from 5000ppm to 10,000ppm, 15,000 ppm, and 30,000ppm at temperature50°C, with the same conditions, leads to a decrease in salt rejection from 75%, to72%, 71% and 70% respectively. The increase in feed concentration from 5000ppm to 10,000ppm, 15,000 ppm, and 30,000ppm at temperatur60°C, with the same conditions, leads to a decrease in salt rejection from 78%, 75%, 74% and 73% respectively. The increase in feed concentration from 5000ppm to 10,000ppm, 15,000 ppm, and 30,000ppm respectively at temperature70°C, with the same conditions, leads to a decrease in salt rejection from 80%, to77%, 76% and 75% respectively. These results are explained as follows: the increase in salt concentration lead to decrease the water vapor pressure, increase of resistance in transfer and decrease the driving force across the membrane and increase of salt concentration of permeate flux.

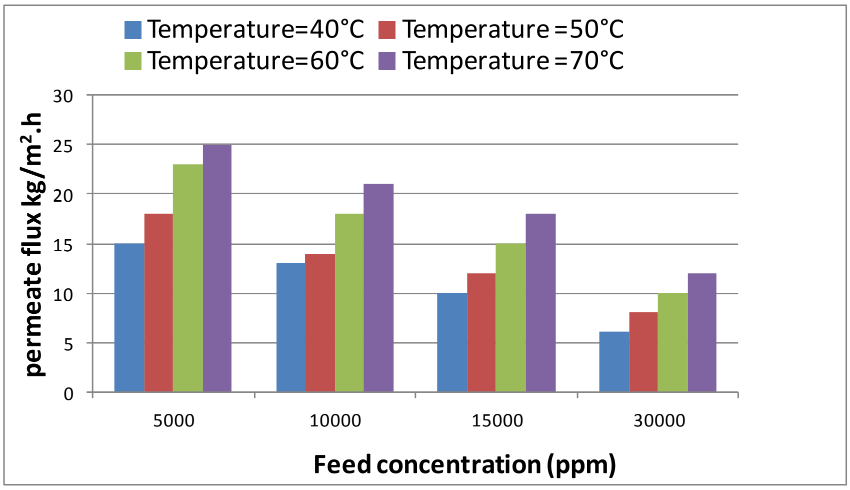

Figure 7Relation between permeates flux and feed concentration at different temperature values, Constant flow rate = 1 L/min, and constant vacuum pressure =0.4 bar.

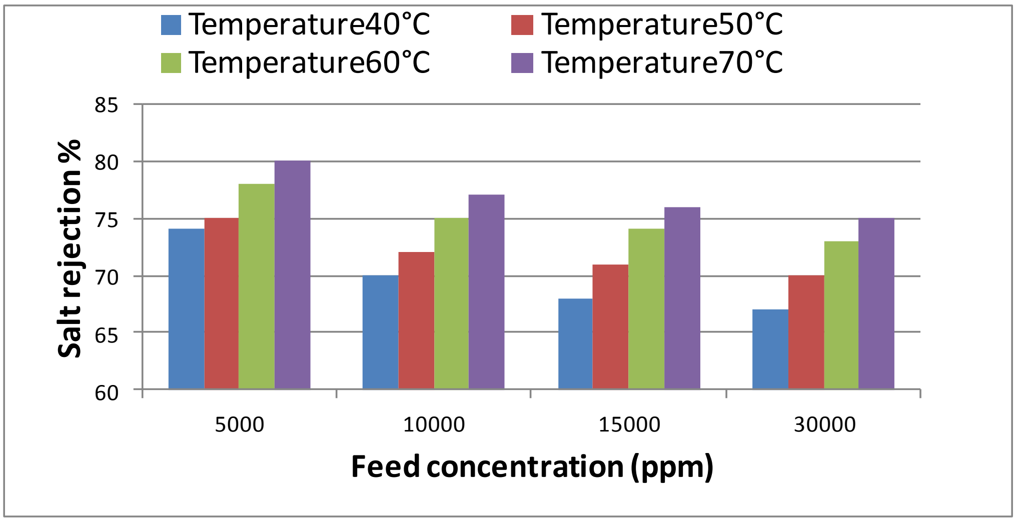

Figure 8:Salt rejection and feed concentration at different temperature values, flow rate = 1 L/min, and vacuum pressure =0.4 bar

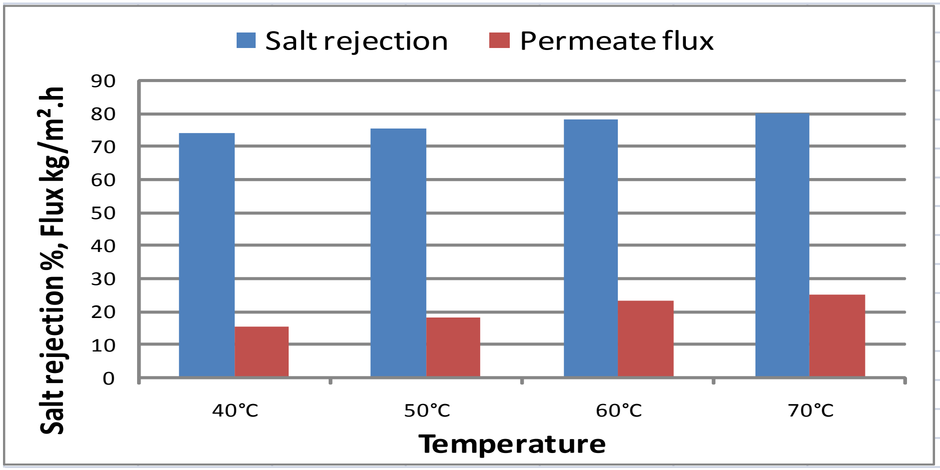

Figure9: Salt rejection and permeate flux at different temperature values, flow rate, vacuum pressure and salt concentration = 5000 ppm.

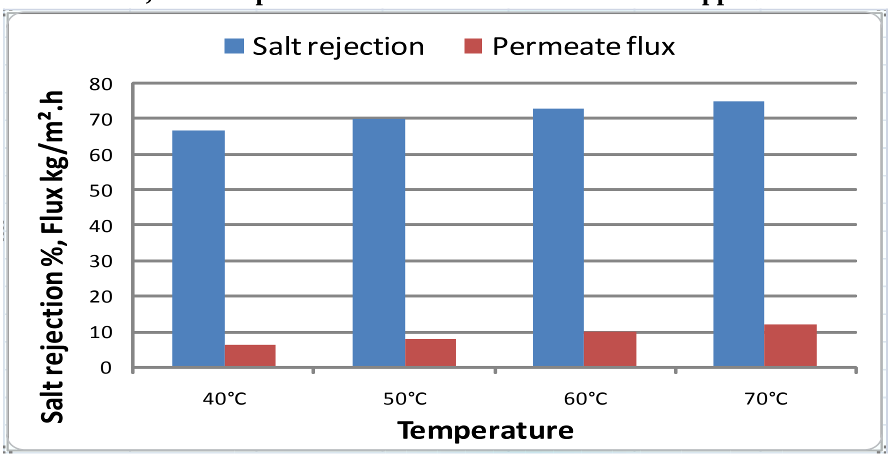

Figure 10:Salt rejection and permeate flux at different temperature values, Flow rate, vacuum pressure and salt concentration= 30000 ppm.

6. CONCLUSIONS

From the results of the experimental work, it can be concluded that the VMD is effective separation process for seawater desalination.

- The permeate flux increases with the increase in feed water temperatures and the decrease of feed water salt concentration.
- The salt rejection increases with the increase in feed water temperature and the decrease of feed water salt concentration.
- The hydrophobic properties of the membranes used in VMD are the most important characteristics of the membranes for the salt rejection results. The hydrophobic membrane used gave satisfactory results in permeate flux but need to improve for salt rejection results (contact angle $85^{\circ} \pm 2^{\circ}$).
- The best salt rejection percentage obtained was 80% at feed concentration 5000 ppm, vacuum pressure =0.4 bar, flow rate= 1 L/min, and temperature= 70 °C. However, at higher TDS= 30,000 ppm, vacuum pressure =0.4 bar, flow rate= 1 L /min, and temperature=40° C, salt rejection was 67%.

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