Civil and Environmental Research
ISSN 2224-5790 (Paper) ISSN 2225-0514 (Online)
Vol.8, No.1, 2016
www.iiste.org

The Effect of Operating Conditions on the Performance of a Vacuum Membrane Distillation Unit Using PES Flat Sheet Membrane

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Abstract

The desalination of seawater is considered a promising source of potable water in Egypt. Vacuum Membrane Distillation (VMD) is a new separation technology based on the evaporation of saline water through hydrophobic porous membranes by applying vacuum pressure on the permeate side of the membrane to desalinate brackish or seawater. A lab scale experimental model was constructed and operated using hydrophobic polyethersulfone flat sheet membrane (PES) with effective area of 0.049 m^2, pore size 0.2-0.4 µm and thickness 120-160 µm. Salt concentration ranging from 5000 ppm to 35000 ppm aqueous NaCl. Resultant permeate flux was measured for the following operating conditions: feed flow temperature (40-50-60-70 °C), flowrate (1-1.2-1.4-1.6 L/min), and vacuum pressure (0.2-0.3-0.4-0.5 Bar). Results showed an increase in permeate flux due to increased temperature, flow rate and vacuum pressure, while it decreased with the increase in salt concentration. The flux value obtained reached 15 $kg/m^2.hr$ at T= 40°C, vacuum pressure= 0.4 bar, TDS= 5000ppm, and flow rate 1 L/min, while it reached 29 $kg/m^2.hr$ at T= 70°C, vacuum pressure= 0.5 bar, TDS= 35,000 ppm, and flow rate 1.6 L/min. Electric power consumed by the system reached 0.612 Kwh at T=70°C, TDS =5000ppm, vacuum pressure = 0.4 bar, and feed flow rate 1 L/min.

Keywords: VMD, desalination, vacuum pressure, hydrophobic membrane.

1. Introduction

Water desalination has become a promising source of potable water in Egypt with the constant increase in water consumption for different usages and the expected decrease of its share in Nile water.

Water desalination is divided into two major categories: thermal desalination and membrane separation processes. For thermal desalination, the major drawback is the high energy cost. As for the membrane separation processes with their different types such as reverse osmosis (RO), nanofiltration (NO), ultrafiltration (UF), and microfiltration (MF), their principal limitations are the membrane fouling and scaling, and concentration polarization which cause a loss in the permeate flux with time (Klaibi & Lior 2004).

Membrane distillation (MD) is a new development in the membrane technologies addressing the above mentioned problems, it was first developed in the 1960s (Klaibi & Lior 2004). The main concept of membrane distillation is based on creating a difference in pressure between the two sides of the membrane by heating the feed flow, thus increasing the vapor pressure on the feed side. Only vapor is allowed to pass through a porous, hydrophobic membrane and it is allowed to condense on the colder side of the membrane resulting in fresh water (Klaibi & Lior 2004).

The main benefits of MD is the lower operating pressure (0.1-30 kPa) (Chiam & Sarbatly 2013) compared to other membrane separation processes. As membranes used in MD have larger pore size (0.2-1µm) (Li & Tian 2009), they are less subjected to fouling and scaling. Also, the lower operating temperature compared to thermal desalination processes, as operating temperature is below water boiling point (30-90 °C) (Chiam & Sarbatly 2013). As will be discussed later, MD has proven to be able to treat highly concentrated feed solutions with high salt rejection percentage. Different configurations of MD are developed using the above mentioned concept: Direct Contact Membrane Distillation (DCMD), Air Gap Membrane Distillation (AGMD), Sweep Gap Membrane Distillation (SGMD), and Vacuum Membrane Distillation (VMD) (Li & Tian. 2009, and Chiam & Sarbatly 2013). Figure 1 shows the different configurations of MD.

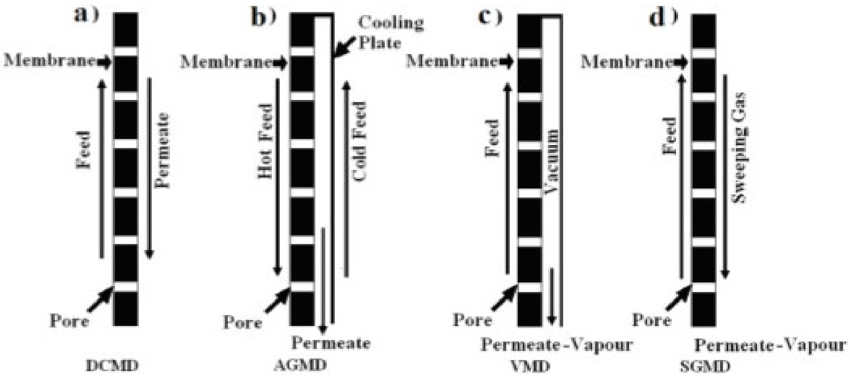


Figure. 1. Different Configurations of MD http://www.mdpi.com/water/water-05-00094/article_deploy/html/images/water-05-00094-g001-1024.png

The Vacuum Membrane Distillation (VMD) is a thermally driven process where a heated feed solution is brought in contact with one side of a hydrophobic microporous membrane while vacuum pressure is applied on the other side allowing the passage of vapor from one side to the other (Klaibi & Lior 2004). Figure 2 shows a schematic presentation of the VMD concept.

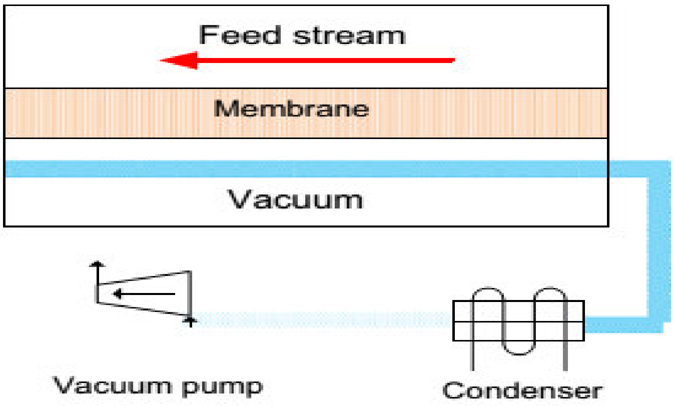


Figure 2. Description of the principle of VMD separation process. http://m.c.lnkd.licdn.com/mpr/mpr/AAEAAQAAAAAAAANrAAAAJDY4NTNjYjhlLTg4ZDctNGY0ZS04NzU2LTVlZjY3NDliZDc0MQ.jpg

Compared to thermal desalination cost, the VMD cost is expected to be much lower as the temperature necessary for VMD is below the water boiling point. RO units used in seawater desalination have an estimated energy consumption of 12 kWh/m^3. An experimental research was conducted on hollow fiber PVDF membranes with salt concentration 1500 ppm to 30,000 ppm. Results showed that VMD energy consumption can be almost as in RO units at the same permeate flux at low temperature using highly porous membrane. It can produce higher flux rates at higher temperature but the energy cost will increase. The use of solar energy can compensate this increase (Cabassaud & Wirth 2003).

The objectives of this research were to determine the optimum operating conditions for the VMD experimental setup used, mainly the temperature as it is the main parameter governing the behavior of the system and to assess its performance at low temperatures. Also, to determine the membrane contact angle, the scanning of the used membrane before and after the experiment and, to estimate the power consumed by the setup.

1.2 Membranes

1.2.1 Membranes' Properties

Membranes' characteristics and properties highly effect the VMD system performance and efficiency. The main parameters to be considered while selecting the membrane are: pore size, porosity, tortuosity, and thickness. Usually pore size ranges are 0.2-1 µm (Li & Tian 2009) is preferred for VMD as the mass transfer increases with the increase in pore size. Large pore size membrane will also reduce the polarization effects.

Porosity is defined as the volume of pores /total volume of membrane. With high porosity, we have larger evaporation surface area and lower membrane thermal conductivity, and its values are recommended to be 6-85% (Li & Tian. 2009).

As for membrane thickness, its ranges are 60-260 µm (Li & Tian 2009), the increase in the thickness of membrane decreases the flux because the mass transfer resistance increases (Gryta 2012).

Membrane tortuosity defined as pore length/membrane thickness, the increase in tortuosity decreases

flux (mass transfer).
The equation of the flux is as follows:

$$J= \mathcal{E}\Delta\ dp^{\varphi}/ \tau\Delta\delta \qquad (1)$$

Where
J= flux, Ɛ = porosity, dp = pore size, φ= constant factor, τ= tortuosity, δ = thickness (Chiam, & Sarbatly 2013).

1.2.2Membrane wetting and swelling.

Membrane wetting occurs as the feed liquid penetrates inside the membranes' pores, this negatively influences the VMD process. As for membrane pore swelling, it causes that a larger interface area of the membrane is exposed to the vapor, this results in increased permeate flux but decreased salt rejection (Chiam & Sarbatly 2013).

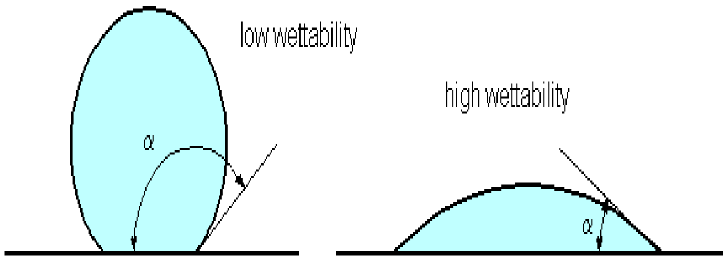
1.2.3Membrane Materials and Module

Membranes' materials used for MD are usually made of polymers that have low surface energy such as: polytetrafluoroethyelene (PTFE), polypropylene (PP), or polyvinylidenefluoride (PVDF). PTFE is thought to have the lowest surface energy (Wang & Chung, 2015). Those materials are also hydrophobic. Polyethersulfone (PES) is largely used in membrane separation processes. It is characterized by its hydrophobicity that is considered an advantage for MD processes while it is disadvantage for membrane processes as it increases fouling (Chiam & Sarbatly 2013).

As for the membranes' module, several commercial membranes are available: the flat sheet, hollow fiber, capillary and tubular forms (Klaibi & Lior 2004, Chiam & Sarbatly 2013, and Wang & Chung 2015)

1.2.4 Membrane contact angle

Contact angle measurement of membranes is considered to be an important parameter for membrane characterization and indirect indication of the hydrophobicity and flux behavior. As shown in Fig.3, the contact angle of a certain liquid with a certain solid surface indicates its degree of wettability: if α > 90°, the liquid doesn't wet the surface, and if α < 90°, the liquid wets the surface.



1.3 Permeation and Permeation selectively

1.3.1 Permeation flux

The flux in the experiment is given by the equation

$$J = V^{*}\rho\ /A.T \qquad (2)$$

where J = flux ($kg/m^2 \cdot h$),
V= Volume of water (L)
ρ = density of water (kg/L)
A = membrane effective area(m^2) ,
And T = time of the experiment (hr) (Pangarkar *et al* 2011)

1.3.2 Permeation selectively.

Salt rejection ratio was calculated for the experimental work by using the equation :

$$R = CF- CP\ /\ CF \qquad (3)$$

where R= salt rejection ,
CF= feed concentration (ppm),
CP = permeate concentration (ppm) (Pangarkar *et al* 2011).

1.4 Process Operating conditions

The flux of VMD increases with the increase of feed flow temperature, vacuum pressure, and flow rate, while it decreases with the increase of salt concentration (Li & Tian 2009, and Chiam & Sarbatly 2013). The water vapor flux is highly sensitive to the feed temperature, thus VMD is expected to operate at higher feed temperature with high permeates pressure and highly permeable membrane.

VMD was tested using a flat sheet membrane and a diaphragm vacuum pump without a condenser, for the desalination of NaCl aqueous solution and natural ground water. Membrane pore size was 0.22µm, porosity 70%, thickness 175 µm. maximum permeate flux reached 28.34 kg/m^2.hr at feed flow temperature = 60°C, vacuum pressure 0.15 bar, feed flow 5 L/hr and salt concentration 7000 mg/l (Pangarkar *et al* 2011).

Polypropylene (PP) hollow fiber commercial membrane with pore size 0.2 m was tested for seawater desalination using VMD. Permeate flux reached 65.8 kg/m^2.hr at salt concentration 35000 ppm, feed flow temperature=65°C, feed flowrate 0.6 L/min and vacuum pressure = 665 mmHg. A decrease in permeation flux was observed (1.75-15.65%) when the salt concentration increased from 35000 ppm to 100000 ppm (Alsalhy 2014).

A flat PTFE membrane 0.02 m^2 with pore size 0.1µm, porosity 55%, thickness 60 µm, was tested for the removal of MIBK from aqueous solution, at feed flow 69.44 mL/sec, vacuum pressure (10.67, 12, 13.33, 14.67) kPa, temperature (34.8, 43.3, 47.8, 52.5, 55 °C), the results showed that the increase in the temperature and feed flowrate caused an increase in removal efficiency, also reducing the pressure in the permeate side caused in increase in removal efficiency (Tang *et al* 2000) .

2. Experimental Setup and Program

2.1 Experimental Setup

An experimental model was built and operated in Arab Organization for Industry – Aircraft factory, for a period of 8 month from August 2014 to April 2015. A schematic diagram of the experimental setup is shown in Fig.4, while Fig. 5 shows a photo of it. The solution used in the experiments is a synthetic NaCl solution with salt concentration 5000 - 35000 ppm**.** The experimental setup is composed of the following components indicated in Table 1.

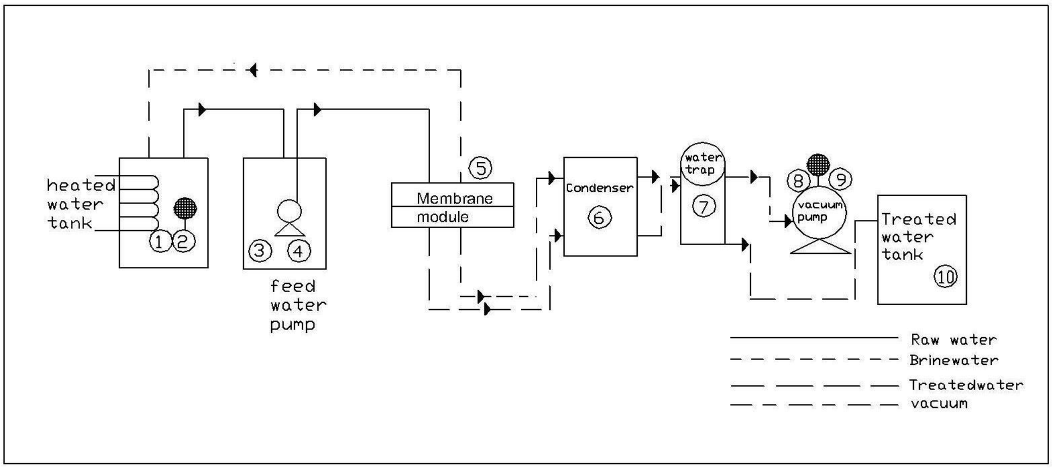


Figure 4. Schematic Diagram of the VMD experimental setup.

Figure. 5. Photograph of the VMD experimental setup.

Table 1. Experiment Equipments

No.	Equipment	Specification
1	Heated water tank	Heated water tank volume 30 liters with heater and thermostat which operates and stops at adjusted temperatures which ranges from 0°C to 120°C.
2	Temperature meter	It measures temperature from 0°C to 120°C.
3	Feed water tank	Volume 30 liter.
4	Pump	An aquarium pump, max. head = 1.5 m, max. flowrate = 850 l/h, 50, HZ = 50, .and 1.5 WT.
5	Membrane module	Two steel flanges treated with epoxy paint. They include the PES membrane with diameter (0.25m) area (0.049m^2), pore size range from 0.2-0.4 µm and thickness range from (120-160 µm).
6	Condenser	Fan 0.25 m diameter with cooling pipes.
7	Water trap	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 (0.0– 1.0) bar
10	Treated water tank	Volume 30 liter.
11	Control panel	To control the operation of the equipment (4 outlets)with overload – Not shown in figure.

2.2 Experimental Procedures

1. Fill the heated water tank with the aqueous NaCl solution prepared synthetically with the specified concentration for each run of the experimental work.
2. For the first run, set the heater temperature at 40 °C and make sure that the heater stops when the temperature of feed water reaches 40 °C.
3. Transfer the heated water to the feed tank from which it is pumped to the membrane module. The valve on the outlet of the pump was adjusted to determine the required flowrates.
4. Operate the vacuum pump with specified pressure and operate the water condenser,
5. Measure the amount of collected treated water. Measurements of the permeate flux were duplicated and average values were calculated.
6. Repeat the previous steps for each run with the conditions specified in table 2.

Table 2. Experimental Program and Results

Run No.	**Temperature °C**	**Vacuum pressure(bar)**	**Flow rate L/min**	**Salt Concentration (ppm)**	**Permeate flux (kg/m^2.h)**
1	40	0.4	1	5000	15
2				10000	13
3				15000	10
4				30000	6
5	50	0.4	1	5000	18
6				10000	14
7				15000	12
8				30000	8
9	60	0.4	1	5000	23
10				10000	18
11				15000	15
12				30000	10
13	70	0.4	1	5000	25
14				10000	21
15				15000	18
16				30000	12
17	40	0.4	1	5000	15
18			1.2		18
19			1.4		20
20			1.6		22
21	50	0.4	1	5000	18
22			1.2		22
23			1.4		25
24			1.6		26
25	60	0.4	1	5000	23
26			1.2		26
27			1.4		30
28			1.6		31
29	70	0.4	1	5000	25
30			1.2		30
31			1.4		32
32			1.6		33
33	40	0.2	1	5000	15
34		0.3			16
35		0.4			17
36		0.5			18
37	50	0.2	1	5000	18
38		0.3			19
39		0.4			20
40		0.5			22
41	60	0.2	1	5000	23
42		0.3			25
43		0.4			26
44		0.5			28
45	70	0.2	1	5000	25
46		0.3			27
47		0.4			29
48		0.5			31
49	70	0.5	1.6	35000	29

2.3 Scanning by SEM

Samples of hydrophobic PES membranes were coated with gold to provide electrical conductivity. The micrographs were taken on a JEOL 5410 scanning electron microscope (SEM) operating at 20 kV. Figure 6. (a) indicates the hydrophobic porous PES membrane before the desalination process, while Fig 6 (b) indicates membrane after desalination process, where the precipitated salts on the membrane surface can be noticed.

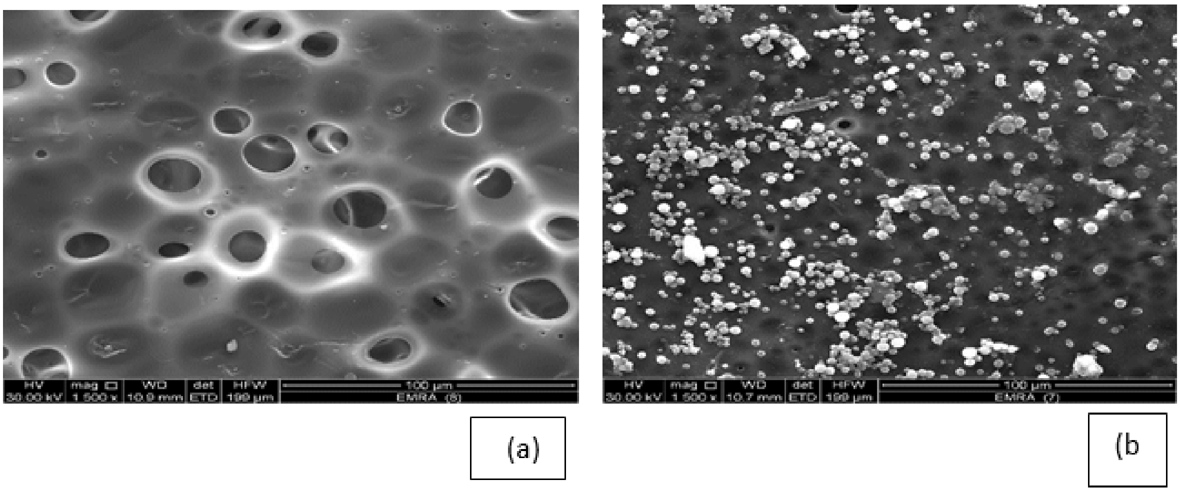


Figure. 6. SEM images for hydrophobic membranes before & after desalination

2.4 Membrane Contact Angle

Contact angle measurement of membranes is considered to be an important parameter for membrane characterization and flux behavior. The membrane contact angle was determined using the sessile drop method. The contact angles were measured several times and then average values were reported. The hydrophobic PES membrane had the contact angle (85 ± 2◦). Fig. 7 indicates the shape of water droplet in the contact angle measurement of the hydrophobic membrane.

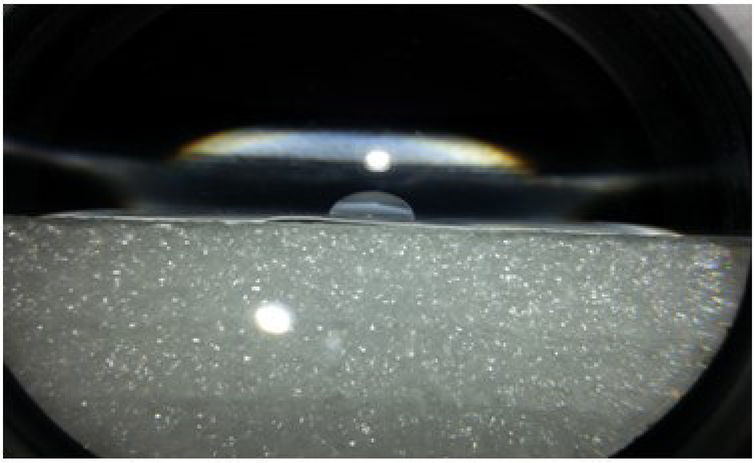


Figure 7. Water droplet on the membrane surface in the contact angle measurement

3. Experimental Work Program and Results

3.1 Results

The results of the experimental work conducted are shown in Figs (8-13). From Fig.8, it can be concluded that the increase in temperature from 40 °C to 70 °C caused an increase in the permeate flux from 15 to 25 kg/ m^2.hr at flow rate = 1 L/min, TDS= 5000ppm and vacuum pressure 0.4 bar, i.e. an increase of about 66.67 %, The same can be observed at different TDS concentrations: for the same flow rate and vacuum pressure, the increase of temperature from 40 °C to 70°C at TDS= 10,000 ppm caused an increase in permeate flux of 61 %, and of 80 % at TDS= 15,000 ppm. As for TDS= 30,000 ppm, the flux increased from 6 to 12 kg/ m^2 .hr i.e. an increase of about 100 %.

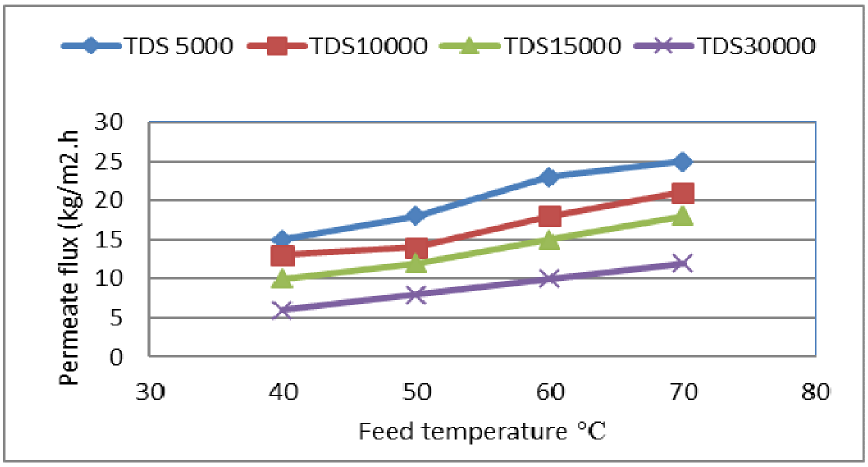


Figure 8.Relation between permeate flux and feed temperature at different TDS values, constant flowrate = 1 L/min, and constant vacuum pressure =0.4 bar.

From the same figure we can observe the effect of TDS on the permeate flux at same temperature, vacuum pressure and flowrate. For example, at 40°C, the increase in TDS from 5000 ppm to 10,000 ppm, 15,000ppm, and 30,000 ppm caused a decrease in permeate flux of 13 %, 33 %, and 60 % respectively.

The effect of flow rate is shown in Fig. 9, at T= 40°C, vacuum pressure = 0.4 bar and TDS=5000 ppm, the increase in flow rate from 1 to 1.2, 1.4, 1.6 L/min caused an increase in the permeate flux of 20%, 33%, and 47% respectively. The same can be observed at 50°C where the % increase reached 22 %, 39%, and 44 % respectively. At 60° C the percentage increase reached 13 %, 30 % and 34 % respectively, and at 70° C , 20%, 28%, and 32% respectively.

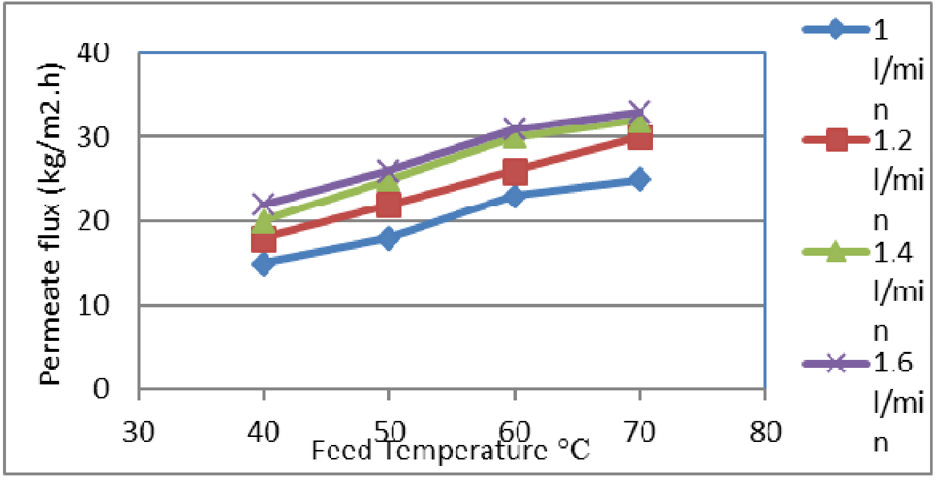


Figure 9. Relation between permeate flux and feed temperature with respect to different flowrate, at constant TDS= 5000 ppm, and constant vacuum pressure = 0.4bar.

The effect of vacuum pressure is shown in Fig. 10, at T= 40°C, vacuum pressure = 0.4 bar and TDS= 5000 ppm, the increase in vacuum pressure from 0.2 to 0.3, 0.4 and 0.5 bar caused an increase of 6.7 %, 13%, and 20 % respectively. The same can be observed at 50°C where the percentage increase reached 5. 6 %, 11 % and 22 % respectively, at 60° C the percentage increase reached 8.7 %, 13 % and 22 % respectively, and at 70° C , 8 %, 16 %, and 24% respectively. It can be noticed that the increase in vacuum pressure had a smaller effect on the increase in permeate flux compared to the increase in temperature or feed flowrate.

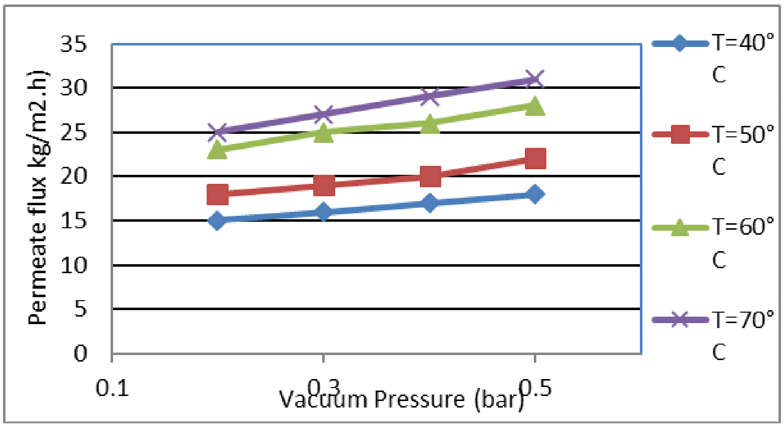


Figure 10. Relation between flux and vacuum pressure with respect to different temperature.

Figures (11-13) summarize the effect of different parameters on the increase in the permeate flux. The increase in salt concentration caused a decrease in the permeate flux as shown in Fig.11, while vacuum pressure and feed flowrate increase caused an increase in permeate flux as shown in Figs. 12 and 13. It can be concluded that the parameter of greater influence is the increase in temperature although it is the main energy consuming item as will be shown in the following section. It can also be noticed that the rate of increase is higher at the lower temperature and decreases as temperature increases.

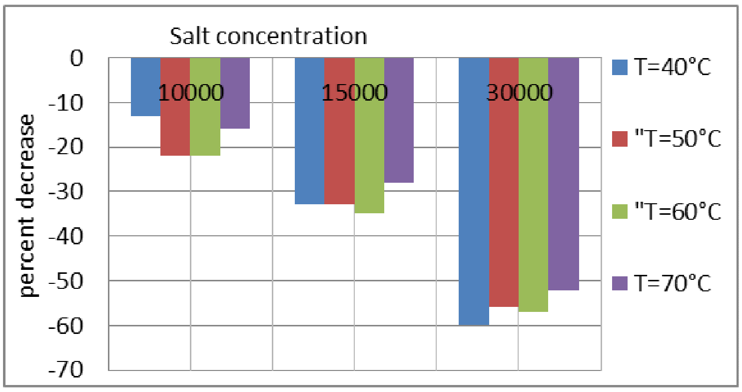


Figure 11. Percentage Increase of Permeate flux with different temperatures and salt concentration.

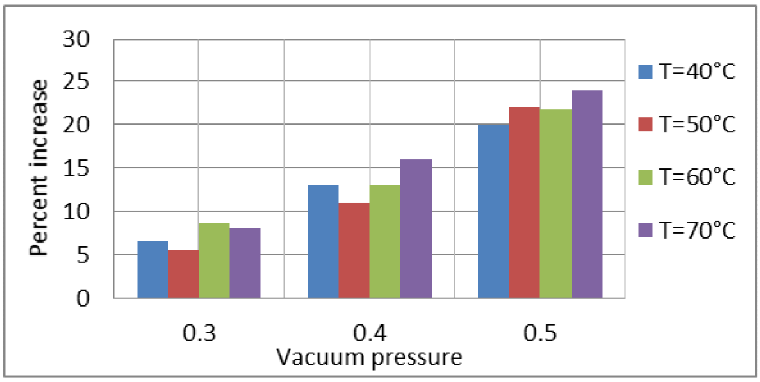


Figure 12. Percentage Increase of Permeate flux with different temperatures and vacuum pressure.

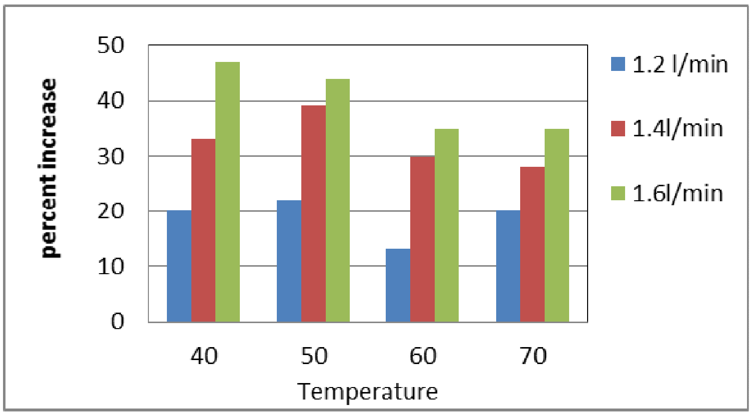


Figure 13. Percentage Increase of Permeate flux with different temperatures and feed flowrate.

3.2 Energy consumption

The energy consumption of the experimental setup was measured in order to have an estimate of the VMD power consumption. Table 3 gives the average values of power consumed. As shown in the table, the biggest portion of energy is consumed in the heating process; it represents about 49 % of the total energy, while the rest is consumed in vacuum pressure generation and in pumping of water between the different parts of the system. Average values of consumption reached 0.612 Kwh and were measured in run 29: T=70°C, TDS =5000ppm, vacuum pressure = 0.4 bar, and feed flow rate 1 L/min.

Table 3. Energy Consumption

Equipment	**Energy Wh**	**Operation time (h)**	**Energy used in kWh**
Water pump	15	1	0.015
Vacuum	375	0.75	0.281
condenser	16	1	0.016
Heater	1200	0.25	0.3
Total power in hour			**0.612**

4. Conclusions

VMD has proven to be a promising efficient separation process for seawater. Results obtained from the experimental work show the following:

- The hydrophobic properties of the membranes used in VMD remains the most important characteristics of the membranes. PES membrane used in this research proved to have high hydrophobicity and gave acceptable results.
- The hydrophobic PES membrane had the contact angle (85 ± 2◦).
- Best value of permeate flux was 33 kg/ m^2.hr, it was obtained at TDS=5000 ppm, vacuum pressure =0.4 bar, flowrate= 1.6 L/min, and temperature= 70 °C. Nevertheless, at higher TDS= 35,000 ppm, vacuum pressure =0.5 bar, flowrate= 1.6 l/min, and temperature=70° C, permeate flux was 29 kg/ m^2.hr.
- The system showed satisfactory results at lower temperature values as the flux reached 15 kg/m^2.hr at T=40 °C , vacuum pressure 0.4 bar, TDS =5000 ppm and flowrate 1L/min.
- It can be concluded that the temperature is the most influential parameter on the performance of VMD, other parameters have less influence on the system's performance.

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