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Comparative study of the performance of a locally manufactured membrane and the commercial one in vacuum membrane distillation of brackish water

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ABSTRACT

The aim of this work is to manufacture a hydrophobic membrane from recycled polymers by the TIPS method and to test it on the vacuum membrane distillation device by comparing its performance with those of the commercial membrane. The results obtained clearly show that the two membranes have almost similar performance. In addition, we studied the effect of operating conditions (feed temperature, vacuum pressure, feed salinity) on the permeate flow obtained. The experimental results show that the increase in the feed temperature leads to the increase in the production of pure water which is tested by the conductimeter. In the studied temperature range of 50°C–80°C, the water permeation flow can be increased exponentially, in this case the possibility of using renewable energy such as solar or geothermal for the vacuum membrane distillation (VMD) operation unit favorised this new technology so we win economically and environmentally. Indeed desalination using solar energy coupled with membrane techniques is considered as a very interesting alternative for the drinking water production, especially for rural areas and arid. Also, the permeate flow decreases with increasing feed salt concentration and gradually decreases with increasing permeate pressure due to the loss of the driving force through the membrane. The permeate water flow goes from 5.89 to 0.9 kg/h m^2 when the vacuum varies from 10,000 to 20,000 Pa. In this study, a global recovery factor of 89% can be obtained by coupling RO and VMD, salt rejection was 99% and the permeate conductivity was less than 100 (μS/cm).

Keywords: Vacuum membrane distillation (VMD); Reverse osmosis (RO); Brine; Hydrophobic membrane; Recycled polymers; Performance comparison

1. Introduction

In recent decades, the sharp increase in the world's population and the need for people to adopt better living conditions has led to a dramatic increase in the consumption of polymers (mainly plastics). The materials appear intertwined with our consumer society where it would be difficult to imagine a modern society without plastics that have found a myriad of uses in fields as diverse as household appliances, packaging, construction, medicine, automotive and aerospace electronics and components [1].

A continuous increase in the use of plastics has led to an increase in the amount of plastics ending up in the waste stream, which has motivated a greater interest in recycling and reusing plastic. This is because the volume of polymer waste such as rubber from tires and polyethylene terephthalate (PET) bottles is increasing at a rapid rate. It is estimated that 1,000 million tires reach the end of their useful life each year and 5,000 million more are expected to be thrown away regularly by the 2030. As for the annual consumption of PET bottles is over 300,000 million units. The majority are simply buried. On the recovery

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and recycling of plastics. There are several options to recycle plastics: reuse, mechanical recycling and chemical recycling [2].

Reuse: The most common examples of reuse are with glass containers, where milk and beverage bottles are returned to be cleaned and reused. Reuse is not widely practiced in relation to plastic packaging and plastic products in general tend to be thrown away after first use. However, there are examples of reuse in the marketplace. For example, a number of detergent manufacturers market refill pouches for bottled wash liquids and fabric softeners. Consumers can refill and therefore reuse their plastic bottles at home, but in all of these cases, the epic early reuse of plastic bottles and containers does not last long in food applications.

Mechanical recycling: also called physical recycling. The plastic is crushed and then reprocessed and compounded to produce a new component that may or may not be the same as its original use. *Chemical recycling*: polymer waste is recycled as an oil /hydrocarbon component in the case of polyolefins and monomers in the case of polyesters and polyamides, which can be used as raw materials for the production of new polymers and the petrochemical industry, or in pure polymers using chemical solvents [3].

In the other hand, the world suffers from a big problem of shortage of drinking water in many countries. Given the importance of the ocean's water resource, which makes up about 70.8% of the Earth's surface, seawater desalination represents a promising solution. Several desalination techniques have been developed, the best known and most widely used of which is reverse osmosis (RO), including 15,900 desalination plants operational in 2018 in 177 different countries. This leads to large volumes of saline discharges to the sea and a large number of old reverse osmosis membranes rejected to nature, which disturbs the balance of the natural environment [1].

From where the idea to recycle these membranes which are based on polymers and to reuse them to manufacture again hydrophobic membranes intended for the vacuum membrane distillation (VMD) to over concentrate the brine of the RO which has high salinity producing pure water and minimizing the enormous quantities of brine released into nature which threatens flora and fauna. By consequently, we win economically and ecologically. In addition, in this work we present the main characteristics of VMD as well as its basic principles and to study the effect of the operating parameters on the flow of pure water produced. Researchers' efforts to couple VMD with solar power and their cost estimates are reviewed as well.

In this context VMD has been a subject of numerous studies focusing on the ground, underground, brackish and seawater desalination with moderate permeate flux. For example, Alsalhy et al. [4] studied the effect of operational conditions, such as feed temperature, feed concentration and vacuum pressure on the permeate flux obtained. They improve that the permeate flux increased with increasing feed temperature for all salt concentrations in fact the permeation flux for solution with 35 g/L feed concentration increased by about 26% when the feed temperature Increased from 45°C to 50°C. The permeate flux increased by about 98% when the feed temperature increased from 45°C to 57°C. Also their results indicate that the permeate flux decreases with the increase in the vaccum pressure on the permeate side and the increase in the feed concentration. Xu et al. [5] used polypropylene (PP) hollow fiber membrane for desalination of seawater by VMD and studied the effect of operating conditions, such as feed temperature and desalting degree, on the permeate flux. More recently, Mohammadi and Safavi [6] investigated a new membrane module to improve the desalination of high concentration NaCl aqueous solution by using VMD process. The effect of operating parameters on the membrane performance was also studied. All studies determine that the salt rejection is about 99.98%–99.99% in all cases.

2. Vacuum membrane distillation

2.1. Working principle

MD has developed into four different configurations, differing by the method employed to impose the vapor pressure difference across the membrane. The permeate side of the membrane may consist of a condensing fluid in direct contact with the membrane (DCMD), a condensing surface separated from the membrane by an air gap (AGMD), a sweeping gas (SGMD), or a vacuum (VMD). In MD desalination, the heated seawater is in direct contact with one side of the membrane.

Salts and organic matter stay in the feed while pure water diffuses through the membrane. The VMD is one of the most favorable MD configurations. In this process, the vapor is removed by exerting a vacuum pressure on the permeate side of the membrane, which is kept just below the saturation pressure of the volatile components in the hot feed. In this case, the membrane is placed between the hot supply and a vacuum chamber. The vapor is recovered outside the membrane module by a condenser in which the cold water circulates [7,8].

The existence of the vacuum on the permeate side allows for a higher partial pressure gradient and imposes additional driving force on the process. This technology achieves a higher distillation production rate compared to other MD configurations [9,10].

In addition, the vacuum space results in negligible heat loss by conduction, which is a notable advantage of VMD. However, the vacuum level must be carefully managed because LEP can be exceeded, which leads to the phenomenon of membrane wetting [11].

2.2. Commercial membranes used for membrane

The membranes used for the distillation modules present the key to this process; one of the most pressing problems hindering the commercialization of MD is the lack of high performance and well-structured membranes. Therefore, in order to materialize MD as a feasible industrial technology, the manufacture of advanced membranes is investigated.

These membranes are mainly made of polymers having the characteristics required for an optimized MD process, in particular: resistance to wettability (high hydrophobicity), minor tendency to clogging, high porosity, thermal stability, low thermal conductivity, ease of manufacture, etc.

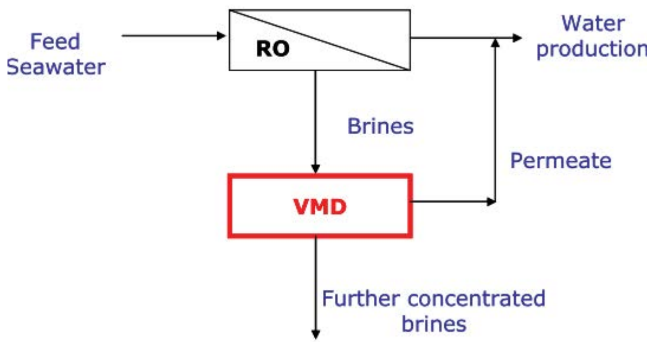

Fig. 1. Seawater desalination by RO coupled to VMD process.

MD Popular commercial membranes for the MD process are generally prepared using polypropylene (PP), polytetrafluoroethylene (PTFE), polyeehylene (PE) and polyvinylidene fluoride (PVDF) which have been applied in scale experiments of the laboratory. Among these commercial membranes, PTFE, with a surface energy of the order of 9–20 N/m, offers the best hydrophobic characteristics, while exhibiting respectable thermal and chemical stability during operations [12–14].

However, the manufacture of PTFE membranes can only be achieved by difficult methods of sintering, rolling or melt extrusion [15]. PP membranes, with a surface energy of 30.0 103 N/m, are also very crystalline, offering low material and manufacturing costs [10]. The major drawback of this membrane is its poor performance and thermal instability under severe operating conditions. PVDF membranes, with a surface energy of 30.3 103 N/m, have received the most attention from researchers in the literature due to their satisfactory stability, high solubility and ease of manufacture and treatment.

These membranes used in several MD configurations and their properties using plate-and-frame and hollow fiber modules were investigated and reviewed extensively in literature recently [10,13,16,17].

2.3. Advantages

Compared to other desalination processes, MD has several advantages. First, it is theoretically possible to remove 100% of ions, colloids and macromolecules. Second, MD technology presents an excellent option for boosting economic viability regarding the feasibility of implementing solar operating systems, which use an inferior and environmentally friendly thermal power source. This is because the MD operates in moderate temperature conditions, typically 60°C–80°C, which makes it perfect for solar collectors [18,19]. The mild operating conditions, along with the use of highly resistant MD membranes, reduce the susceptibility to fouling and scaling, a major drawback of membrane-based operations, reducing maintenance costs [20]. In addition, the fact that the membrane distillation process is not driven by absolute pressure, as is the case with reverse osmosis, and due to the larger membrane pores compared to other membrane techniques, the risk of clogging is reduced, eliminating the need for chemical pre-treatment of the water before entering the modules [20,21]. Also, MD gives a very high purity distillate which, unlike conventional distillation, does not suffer from the entrainment of non-volatile contaminants for that the performance of DM is not affected by the salt concentration in the diet [22]. Given the multitude of advantages of the MD process, its applications are not limited to the field of desalination alone. In the food industry, MD is applied when temperature sensitive materials are involved such as newspapers and juice concentration. It is also used in pharmaceutical fields, in the extraction of organic components such as alcohols from dilute aqueous solutions, in the treatment of waste water, for example, textile or nuclear waste and even in the recovery of crystalline products from effluents).

2.4. Treatment of RO and thermal desalination brines

Drinking water becomes an inaccessible resource despite that 70% of the Earth's surface is covered with water, but almost all of this water is unusable for human consumption. Fresh water is therefore a scarce resource and its distribution is uneven across the globe given the availability of salt water which represents 97% of the earth's water the most used is reverse osmosis (>60%). Indeed, in the world 95 million m^3 of fresh water are produced every day in 2018. But this water production has a negative impact on the environment in this context the desalination of sea water produces 141, 5 million m^3/d of brine, often loaded with toxic pollutants. The UN alerted public opinion in early 2019 to this problem, faced with the increasing development of desalination technologies with large volumes of discharges. Consequently, the management of brine is becoming more and more of a concern. The usual way of treating brines is to throw back into the sea for good in agricultural environments, sometimes which has a considerable impact on the environment and which threatens flora and fauna. For this reason, the discharge becomes more and more difficult. By further overconcentration, the amount of brine can be reduced and can be used for salt recovery. The recovery rates of conventional technologies for seawater desalination are 30%–50% for RO and 15%–50% for MSF/MED. With further treatment with MD, this recovery rate can increase up to 89% [23].

3. Materials and method

3.1. Materials

We manufactured in our Laboratory of Energy, Water, Environment and Process at National School of Engineers of Gabes (ENIG) a hydrophobic membrane from recycled polymers by the TIPS method (Thermally Induced Phase Separation) in order to apply it to the vacuum membrane distillation. VMD experiments were performed using a pilot unit shown schematically in Fig. 2 and its characteristics are detailed in Table 1.

This unit is made up of:

- Flat sheet membrane
- Vacuum pressure gauge (0–1 bar) before and after condenser
- Adjustable safety valve
- Glass water condenser

Fig. 2. Pilot unit of VMD.

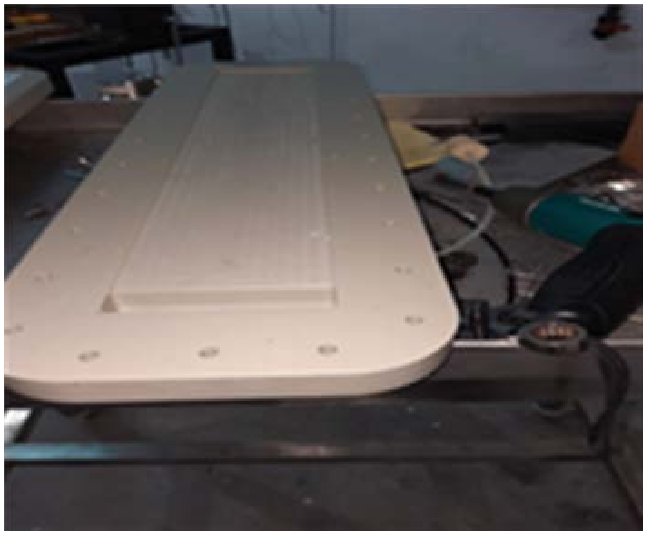

Fig. 3. Flat sheet membrane.

- Relative humidity measurement
- Chilled water pump isothermal ice water tank 0–50 lph
- Vacuum volumetric pump
- Flask 500 mL in pyrex glass
- Electronic scale 0–1,000 g
- Stainless steel 316 storage tank 50 L, with VDF stirrer,
- Thermocouple $T = 90°C$, 0–500 lph
- Flowmeter 0–500 lph in-line
- Water thermometer upstream
- Module pressure gauge 0–6 bar
- Hygrometer
- Water upstream module flowmeter 0–500 lph after module online thermometer water after module 0–6 bar water pressure gauge after module.

The membrane used in this unit is a flat sheet, hydrophobic membrane made from polypropylene. These dimensions are 11 cm × 50 cm with a surface area of 0.055 m^2 as shown in Fig. 3.

3.2. Vacuum membrane distillation method

This VMD unit designed to desalinate either seawater, brackish water or reverse osmosis discharge is a hybrid process combining both a thermal process and a membrane process. The feed solution is heated by means of a thermostatic bath equipped with a temperature controller with an accuracy of ±0.1°C. During the experiments, the feed was stirred continuously at atmospheric pressure and temperature can reach 90°C.

A transmembrane pressure difference is generated by a vacuum pressure on the permeate side of a hydrophobic membrane. The volatile molecules, here water, thus evaporate at the hot liquid/vapor interface and cross the membrane in gaseous form then recondensation takes place outside the membrane module using a condenser.

The condensate mass obtained will be weighed immediately on a balance with a reading uncertainty of 0.001 g, every hour to examine the flow variation. The partial permeate flux "J_i" of component "i" is calculated using the following expression:

$$J_i = \frac{m_i}{\left(A\Delta t\right)} \tag{1}$$

where m_i is the total mass of water vapor passing through the membrane. A is the effective area of the membrane and Δt is the operating time.

Table 1
The different elements of the VMD unit and their characteristics

Designation	Amount	Characteristics	Mark	Origin
Module PP	01	0.05 m^2	AQUASTILL	Netherlands
Motor-pump	01	Stain less steel, 400 lph	NURET	Italy
Chilled water pump	01	1,200 lph, centrifugal	HYDOR	Spain
Heat resistance	01	1,900 W, 220 V stainless steel 316	PPM	Tunisia
Vacuum pump	01	50 lpm, 25 µm	ROTHENBERG	Germany
Brackish water tank	01	Stainless steel 316 L, 50 l	PPM	Tunisia
Ice water tank		Stainless steel 316 L, 50 l	PPM	Tunisia
Conductivity meter	01	0–2,000 µs/cm	ROC	Taiwan

3.3. Effects of operating conditions and discussion

The operational conditions can significantly influence VMD process efficiency. In order to examine the performance of the VMD process, several tests was carried out and the effects of the operating parameters on the yield of permeate water were assessed. Three parameters at different levels were studied in the present work, namely feed temperature in the 50°C–80°C range, vacuum pressure of 0.1–0.3 bar and feed concentration ranging from 40 to 100 g/L.

3.3.1. Temperature effect

The first parameter that we acted on is the salted water temperature, in fact we vary the temperature from 50°C to 80°C and each time we measure the condensing water flow rate as shown in Table 1. The results show that the feed temperature is very sensitive operating parameters which significantly influence permeate flow (Fig. 4). The increase in the feed temperature leads to an increase in production. In the range of studied temperature from 50°C to 80°C, the condensate flow rate can be increased exponentially by raising the feed temperature as a consequence of the increase in the thermal driving force: the saturated water vapor pressure increase significantly with temperature. The use of renewable energy such as solar, geothermal favorised this new technology.

3.3.2. Permeate pressure effect

Fig. 5 shows the effect of vacuum pressure on the system performance. As shown in this figure, Permeate flow passes from 5.89 to 0.27 kg/h m^2 when the vacuum varied from 0.1 to 0.3 bar. Indeed, the water permeate flow decreased gradually with increasing pressure because of the loss of the driving force across the membrane: the more difference between permeate-side membrane pressure and water saturated vapor pressure at system temperature, the more the driving force of VMD process. The energy to create the vacuum represents only 2% of the total energy.

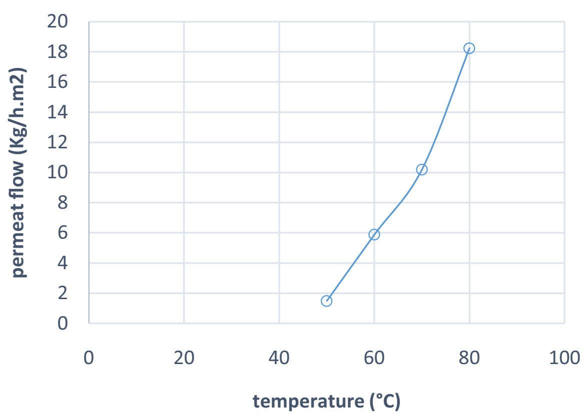

Fig. 4. Variation of permeate flow as a function of feed temperature for a feed salinity of 40 g/L and a vacuum pressure of 0.1 bar

3.3.3. Feed water salinity effect

To determine the effect of the feed water salinity on the condensate flow obtained, tests are carried out for different salinity values as follows: 40, 60, 80, 100, 120, 150, 180 g/L and for this conditions: Salt water temperature = 60°C, Salt water flow = 95 L/h, permeate pressure = 0.1 bar, Cooling water inlet temperature = 16°C, Cooling water outlet temperature = 18°C, Cooling water flow = 195 L/h. The results show that the permeate flow decreases as the salinity increases. The flow decreases from 6 to 5 kg/h m^2 when the salinity passes from 40 to 180 g/L at a temperature of 60°C (Fig. 6). This variation is due to the fact that the solution is more concentrated in salt, which reduces the mass transfer, this reduction can be compensated by modified the operating conditions. However, Fig. 6 clearly shows that the permeate flow decreases with increasing salt concentration, this decrease can be explained by two reasons. First, it causes

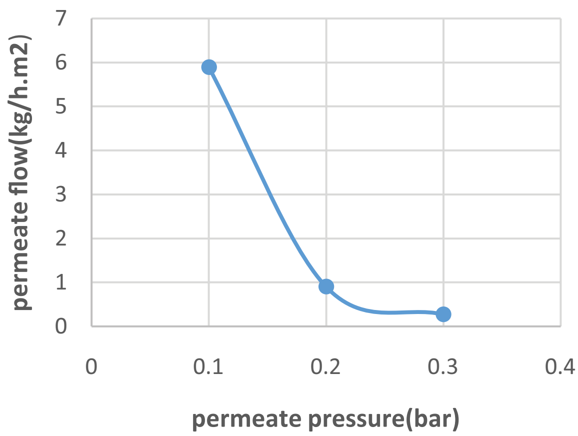

Fig. 5. Variation of permeate flow as a function of permeate pressure for a feed temperature of 60°C and a feed salinity of 40 g/L.

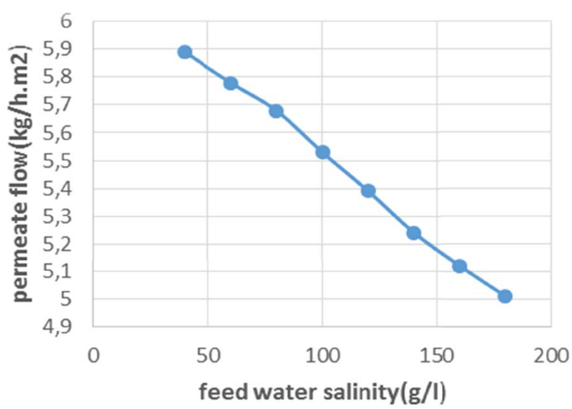

Fig. 6. Variation of permeate flow as a function of feed water salinity for a feed temperature of 60°C and a vacuum pressure of 0, 1 bar.

a drop in the partial vapor pressure in the feed (change in the activity coefficient). The second is an increase in the phenomena of concentration polarization.

We resume that the results with the commercial polypropylene membrane used for desalination of highly saline water via VMD demonstrated that the water permeate flux of about 18.24 kg/m² h was achieved at the operating conditions defined by 40 g/L, 80°C, 0.1 bar (salt feed concentration, temperature, and permeate pressure, respectively), whereas salt rejection was 99% and the conductivity of the permeate was less than 100 (µS/cm).

A statistical analysis was used to predict the best value of experimental results. For this reason, square root of mean percent deviation (e) and coefficient of linear correlation (r) equations were used [24].

$$e = \sqrt{\frac{\sum_{i=1}^{n} e_i^2}{N}} \tag{2}$$

$$e_i = \left(\frac{x_i - y_i}{y_i}\right) \times 100 \tag{3}$$

where x_i, y_i and N are the experimental parameters.

Using this formula we obtained an error of 3% for analysis.

3.4. Comparison performances of a locally manufactured membrane and the commercial one in VMD of saline water

We manufactured in our laboratory LEEEP at ENIG a hydrophobic membrane from recycled polymers by the TIPS method (thermally induced phase separation) in order to apply it to the VMD and compared their performances with the commercial one. We tested our prepared membrane on the VMD device for different pressures by setting the temperature at 60°C and the salinity at 40 g/L. The permeate flow rates obtained are collated in Table 2. All VMD experiments were repeated at least twice in order to verify the reproducibility of the measurements.

By comparing the permeate flow obtained by the commercial membrane and by the manufactured membrane we can see that we are almost similar (Fig. 7). This is an encouragement because the polymers used for the manufacture of our membrane are recycled.

4. Conclusion

In this study, commercial polypropylene membrane was used for desalination of highly saline water via VMD and compared to the one made in our laboratory. In this case, the result of the performance comparison of two membranes clearly shows that the manufactured membrane has performances close to those of the commercial membrane, which we encourage because we used recycled polymers for the manufacture.

The effect of operational conditions, such as feed temperature (i.e., 50°C–80°C), feed concentration (i.e., 40–180 g/L), and vacuum pressure (i.e., 0.1–0.3 bar), on hydrophobic membrane performance was studied.

The tests that have been carried out by changing the pressure show the significant effect of the pressure on the condensate flow rate obtained in fact the permeate flow increases with the decrease in the permeate pressure, however, this also leads to an increase in the wettability of the membrane by increasing the transmembrane hydrostatic pressure. It is therefore necessary to work at low vacuum pressure but not too much to avoid membrane wetting.

Indeed, the resulting permeate flow increases with increasing temperature and decreases with increasing salt concentration and permeate pressure. We resume that the results demonstrated that the water permeate flow of about 18.24 (kg/m² h) was achieved at the operating conditions defined by 40 g/L, 80°C, 0.1 bar (salt feed concentration, temperature, and permeate pressure, respectively), whereas salt rejection was 99% and the conductivity of the permeate was less than 100 (µS/cm). We conclude that the coupling of reverse osmosis with VMD will make it possible to reduce the volume of brine and increase its concentration by evaporating the water it contains. The objectives are to achieve a concentration of these brines to facilitate salt crystallization and to increase the efficiency of desalination in order to reduce the pumped volume of seawater, thus reduce its energy consumption.

These preliminary results with highly concentrated waters show the potential interest of using VMD as an

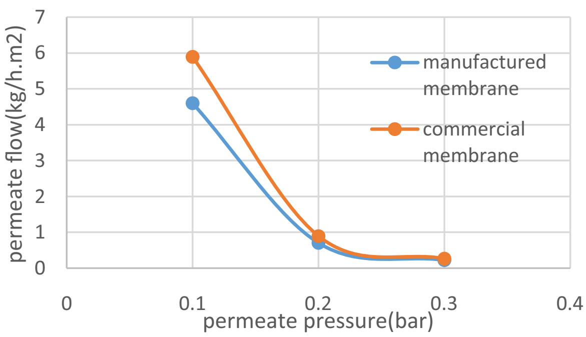

Fig. 7. Comparison between locally and commercial membrane.

Table 2
Permeate flow obtained by locally manufactured membrane in different permeate pressure

Temperature (°C)	Salinity (g/L)	Permeate pressure (bar)	Condensate flow (kg/h m²)
		0.3	0.23
60	40	0.2	0.71
		0.1	4.6

integrated process with RO, indeed an overall recovery factor of 89% can be obtained by coupling RO and VMD. And we aim to apply this technology (VMD) to rural areas where there is no drinking water and electricity when solar or geothermal energy is used as a source of energy.

Symbols

A	—	Effective area of the membrane
e	—	% deviation
J_i	—	Partial permeate flux of component i
m_i	—	Total mass of water vapor
r	—	Linear correlation
Δt	—	Operating time

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