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Vacuum Membrane Distillation for Desalination of Ground Water by using Flat Sheet Membrane

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Abstract**—**The possibility of producing drinking water from brackish ground water using Vacuum membrane distillation (VMD) process was studied. It is a rising technology for seawater or brine desalination process. The process simply consists of a flat sheet hydrophobic micro porous 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 and natural ground water. The influence of operational parameters such as feed flow rate (30 to 55 l/h), feed temperature (313 to 333 K), feed salt concentration (5000 to 7000 mg/l) and permeate pressure (1.5 to 6 kPa) on the membrane distillation (MD) permeation flux have been investigated. The maximum flux reached to 28.34 kg/m^2 h at feed temperature, 333 K; vacuum pressure, 1.5 kPa; feed flow rate, 55 l/h and feed salt concentration, 7000 mg/l. The negligible effects in the reduction of permeate flux found over 150 h experimental run for salt water. But for the natural ground water application over 75 h, scale deposits observed on the membrane surface and 29% reduction in the permeate flux over 75 h. This reduction can be eliminated by acidification of feed water. Hence, promote the research attention in apply of VMD for the ground water purification over today's conventional RO operation.

Keywords**—**VMD, hydrophobic PTFE flat membrane, desalination, ground water

I. Introduction

With increasing global population, the gap between the supply and demand for water is widening and is reaching such alarming levels that in some part of the world, it is passing a threat to human existence [1]. The U.S. geological survey found that 96.5% of earth's water is located in seas and oceans, and 1.7% of earth's water is located in the ice caps. Approximately 0.8% is considered to be fresh water. The remaining percentage is made up of brackish water, slightly salty water found as surface water in estuaries and as groundwater in salty aquifers [2].

Ground water is generally less susceptible to contamination and pollution when compared to surface water bodies. The desalination of the available saline water has become a suitable alternative, which is widely used worldwide [3-5]. 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 [6,7]. The well established seawater and brackish ground water desalination technologies, no doubt, can be employed to produce large amounts of good quality water at a cost that as of today appears to be reasonably quite competitive, but the main drawback of all such processes still remaining to be resolved is the high energy consumption [8].

MD is a thermal, vapor-driven transportation process through micro porous and hydrophobic membranes. MD is applied a non-isothermal membrane process in which the driving force is the partial pressure gradient across a membrane that is porous, not wetted by the process liquid. In this process saline water is heated to increase its vapor pressure, which generates the difference between the partial pressure at both sides of the membrane. Hot water evaporates through non-wetted pores of hydrophobic membranes, which cannot be wetted by the aqueous solutions in contact with and only vapor and non-condensable gases should be present within the membrane pores. The passing vapor is then condensed on a cooler surface to produce fresh water [9-12].

The potential applications of MD are production of high purity of water, concentration of ionic, colloid or other non-volatile aqueous solutions and removal of trace volatile organic compounds from wastewater. Various applications are involved in MD such as desalination of seawater or brackish water, environmental cleanup, water-reuse, food, medical etc. All these characteristics make MD process received worldwide attention from both academia and industry in the last decade. Furthermore, The MD process offers some advantages: (1) can be performed at lower operating pressure and lower temperatures than the boiling point of feed solution, (2) requires lower vapor space, (3) is unlimited by high osmotic pressure and fouling, (4) permits very high separation factor of non-volatile solute, (5) has potential applications for concentrating aqueous solutions or producing high-purity water, and (6) can use any form of low –grade waste heat or be coupled with solar energy systems which makes it attractive for production of potable water from brackish water in arid regions. These advantages make MD more attractive than other popular separation processes. [7, 13-16].

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

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(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 [7, 17, 18].

This study proposes VMD process, in which a feed solution is brought into contact with one side of a micro porous 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 [17-21].

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 by many. 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 [22, 23]. In this study, performance of VMD operating for desalination of ground water was investigated.

II. EXPERIMENTAL

The experimental process simply consists of a flat sheet hydrophobic micro porous PTFE membrane (Millipore) and diaphragm vacuum pump without a condenser for water recovery or trap as shown in fig. 1. The typical characteristics of the membrane are summarized in Table I. The membrane was located in 25 mm diameter plate type of module prepared from PVC material. The diameter of inlet and outlet is 6 mm. The aqueous feed solution of about 5000 to 9000 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. The feed temperature and downstream pressure was varied between 313 and 333 K, and 1.5 and 6 kPa respectively. Also, the natural ground water application was done by using the same module and membrane. All the VMD experiments were carried out for 1-2 h and after almost 1 h; the flux reaches equilibrium (steady state).

TABLE I
MEMBRANE CHARACTERISTICS

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

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

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

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 concentration of ionic species in the feed water (C_1, mg/l) and in freshwater (C_2, mg/l) were calculated by the water analysis kit. The percentage removal (% R) of the species was calculated from eq. (2):

$$R = \frac{C_1 - C_2}{C_1} x100 \quad (2)$$

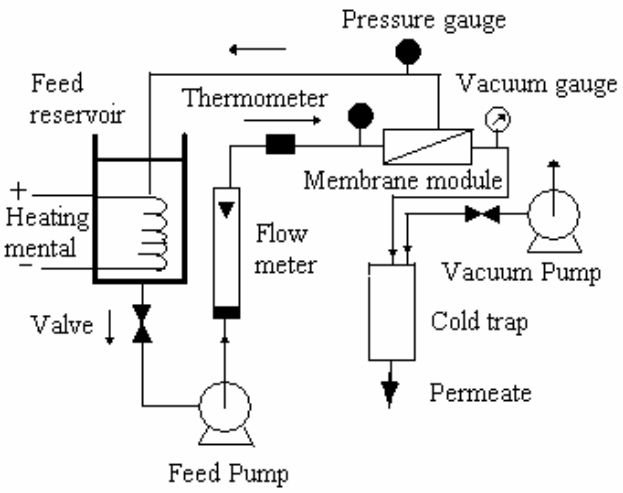

Fig. 1 Experimental setup of VMD

III. RESULTS AND DISCUSSION

A. Effect of feed flow rate

The experiments were performed for 7000 mg/l salt solution, 1.5 kPa permeate pressure and 313 K, 323 K and 333 K feed temperature, the effect of feed flow rate on permeation

flux was shown in fig. 2 and found the positive effect on permeate flux for increasing feed flow rate from 30 to 55 l/h. After 55 l/h feed flow rate, no effect was found on the permeation flux. Salt rejection was greater than 99.9 % throughout all the experiments.

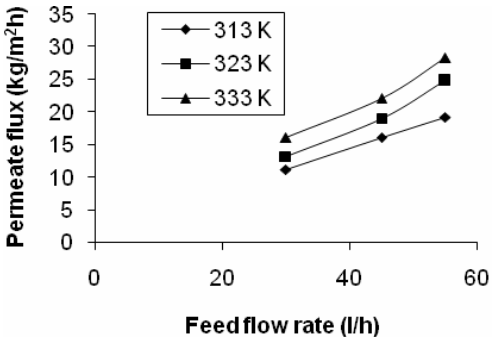

Fig. 2 Effect of feed flow rate at salt conc.= 7 g/l and Permeate pressure = 1.5 kPa

The feed temperature plays an impotent role on permeation flux in VMD performance. The fig. 2 showed the water vapor flux is a function of temperature also. 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 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.

For 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. 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 which is more obvious when the bulk feed temperature higher.

B. Effect of permeate pressure

Fig. 3 show the positive effect of permeates pressure on permeation flux at different values of feed temperature. The result shows that the flux increases with decreasing vacuum side pressure for a given operational conditions. The permeate flux is increases from 1.5 kPa to 6 kPa at constant feed flow rate, 55 l/h and salt concentration, 7000 mg/l. The temperature is varying from 313 K to 333 K and found the higher permeate flux at high feed temperature obviously.

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 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 pore 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 permeation flux was reached 28.34 kg/m^2 h when the operating conditions are: feed temperature, 333 K; vacuum pressure, 1.5 kPa; feed flow rate, 55 l/h and feed concentration, 7000 mg/l.

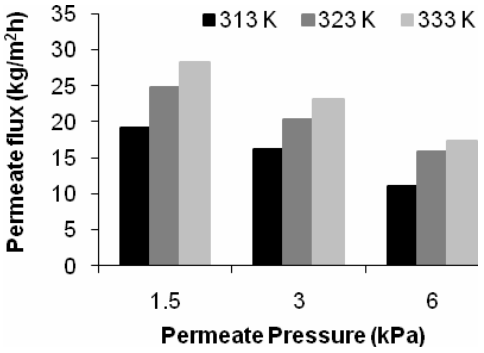

Fig. 3 Effect of permeate pressure at salt conc., 7 g/l, and flow rate, 55 l/h

C. Effect of feed concentration

The experiments were performed for different concentration of salt in the feed water, when the vacuum pressure was 1.5 kPa. Fig. 4 shows the effects of feed concentration on permeate flux at feed flow rate 55 l/h and the feed temperatures 333 K.

The results show that increasing of feed concentration of salt from 5000 mg/l to 7000 mg/l, slightly decreases permeation flux. This reduction was less than 3 % means it is negligible when increasing salt concentration. Hence for the groundwater, the effect of feed concentration on the performance of VMD is negligible. But when feed was

seawater (using the same module in the previous publication [24]), means feed concentration increases up to 35000 mg/l, the reduction was increases up to 48% due to the Roult's law [24]. Hence, one of the most significant advantages of the VMD process for desalination is the relative nominal effect at lower feed salt concentration on the performance of the system.

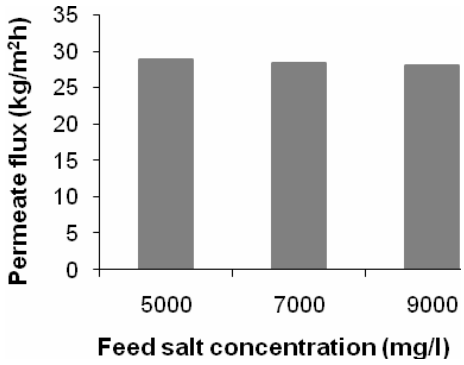

Fig. 4 Effect of feed concentration at feed flow rate,55 l/h, and permeate pressure,1.5 kPa

D. Membrane fouling

In long term experimentation, the salt concentration of 7000 mg/l was used as feed for the flat sheet VMD apparatus and was operated continuously for approximately 150 h. Fig. 5 shows the flux profile at both high and low temperature of 333 K and 313 K respectively. The higher temperature generated initial flux of 28.34 kg/m^2 h which declined to 24.89 kg/m^2 h over 150 h at 55 l/h feed flow rate and 1.5 kPa permeate pressure. However, the lower temperatures produced a flux of 16.29 kg/m^2 h, which declined to 13.84 kg/m^2 h at 55 l/h feed flow rate and 3 kPa permeate pressure. The minor flux decrease with time is observed during the experiments. Flux decrease represents 12 % and 15 % respectively in 150 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. During the process the minor scale deposit was observed on the membrane surface fouling. At every time the salt rejection was high 99.99%. After 150 h, the water washing was done and flux again increases to 27.91 kg/m^{2}h and 15.88 kg/m^{2}h respectively. Really, the MD flux initial and after water washing show a variation of less than 2%. Hence, the fouling phenomenon in VMD is highly reversible and can be easily removed by a water washing.

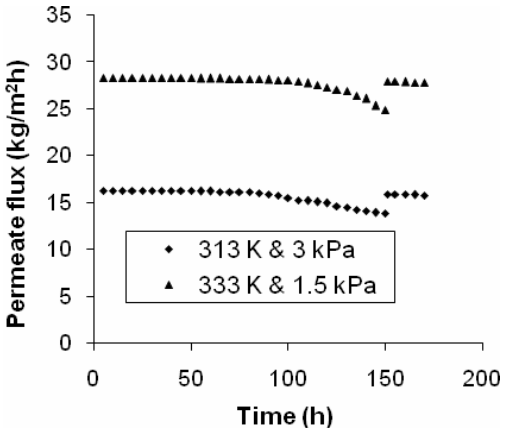

Fig. 5 Time-variation of permeate flux at feed flow rate,55 l/h, and feed salt conc., 7 g/l

E. Application of natural ground water

The application of VMD on the natural ground water was performed with the feed flow rate, 55 l/h and feed temperature, 333 K. The analysis of the feed and permeate ground water were done presented in Table II. Results found that all the species removed by VMD were found, >99 % which meets the World Health Organization (WHO) standards. The ground water was taken from Sinnar region (Nashik, India). The sample was taken after 2 h experimental run.

TABLE II
ANALYSIS OF RAW AND TREATED GROUND WATER

Parameter	Concentration in feed (mg/l)	Concentration in permeate (mg/l)	% Reduction
Ca	286.2	1.1	99.6
Mg	55.3	0.49	99.1
Na	561.7	0.56	99.9
K	4.2	0.02	99.5
Si	1.2	0.01	99.2
Cl^-	1022.1	1.02	99.9
SO_4^{2-}	722.4	2.16	99.7
Fe	1.02	0.01	99
HCO_3^-	174.6	1.57	99.1
NO_3^-	5.7	0.04	99.3
TDS	3920	32	99.2

The experimental results of long term experimentation shown in fig. 6 demonstrate that the direct application of the natural ground water as feed for VMD process resulted in a rapid decline of the permeate flux. This is due to the formation of the deposits on the membrane surface. This scale deposits scattered on the membrane surface would cause pores clogging and pollute the membrane. Therefore, the permeate flux was decreased with the prolongation of operating time. Although the scale deposits polluted with the membrane, the quality of obtained permeate was maintained. The initial flux of 22.07 kg/m^{2}h which decline to 15.67 kg/m^{2}h over 75 h at 55 l/h feed flow rate and 1.5 kPa permeate pressure. The flux decreases represents 29%, in 75 h. The permeate flux was

nearly constant up to 45 h experimental run and after that the flux decline rapidly, means the scale deposits start after 45 h. After 75 h, the water washing was done and flux again increases to 20.84 kg/m^{2}h. Hence, the fouling phenomenon in VMD is highly reversible and can be easily removed by a water washing.

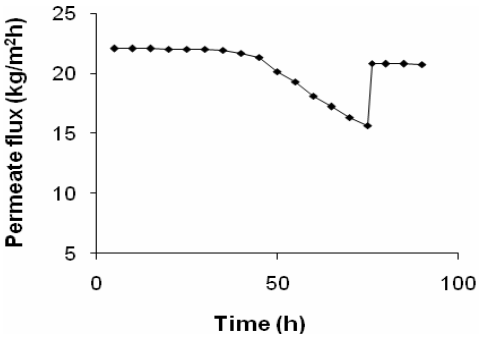

Fig. 6. Time-variation of permeate flux of natural ground water at flow rate, 55 l/h, and feed temperature, 333 K

Fouling and scaling are two important mechanisms that affect stability of MD process and lead to reduce the overall performance. Deposit reports that membrane fouling in MD is less problematic than in other processes due to large pore size, the phenomena is not studied, either experimentally or analytically [25]. But here, in VMD process, the fouling was observed. Hence, in order to eliminate the negative effect of scale deposition on the membrane, VMD process were carried out at the initial feed pH 4.5 adjusted by addition of 0.1 mol/l HCl to the feed. The results of fig. 7 was seen, the acidification of the feed enhances the stability of the process in a significant degree. There was no obvious decline of permeate flux during 75 h continuous operation process. Hence, addition of HCl in water (acidification of feed) was an efficient method to eliminate the negative effect of scale deposits on the surface of the membrane.

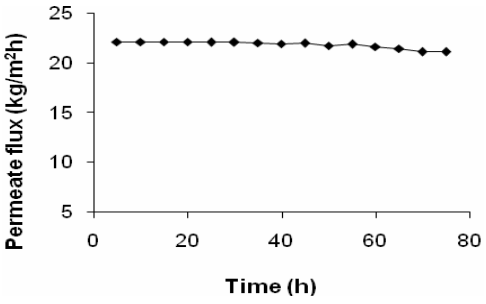

Fig. 7 Time-variation of permeate flux of natural ground water at flow rate, 55 l/h, and feed temperature, 333 K with addition of 0.1 mol/l HCl

IV. Conclusion

The performance of VMD for desalination of ground water by using a flat sheet membrane configuration is presented experimentally. The VMD permeate flux were increased with increasing the feed temperature, 313 K to 333 K, and feed flow rate, 30 l/h to 55 l/h. The water vapor flux was very influenced by the permeate pressure. The permeation flux was highly reduced by increasing permeate pressure from 1.5 kPa to 6 kPa at constant other operating parameters. In all the experiments, the product water was almost distilled water; because negligible trace of salt was found in this for all operational conditions. The permeation flux was reached 28.34 kg/m^2 h when the operating conditions are: feed temperature, 333 K; vacuum pressure, 1.5 kPa; feed flow rate, 55 l/h and feed concentration, 7000 mg/l. 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 15 % with time that may be caused by some salt deposited on the membrane surface but it is negligible and it was easily removed by the water washing. Also, the membrane fouling test in VMD process was done by using natural ground water. The fouling was observed due to the deposition of scale on the membrane surface. The permeate flux was decreased by 29%. This was eliminated by acidification of feed water, the initial pH 4.5 adjusted by adding 0.1 mol/l HCl to feed water. This showed a good scene for the application of flat sheet membranes in the field of ground water purification.

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