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Performance of Air Gap Membrane Distillation for Desalination of Ground Water and Seawater

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Abstract**—**Membrane distillation (MD) is a rising technology for seawater or brine desalination process. In this work, an air gap membrane distillation (AGMD) performance was investigated for aqueous NaCl solution along with natural ground water and seawater. In order to enhance the performance of the AGMD process in desalination, that is, to get more flux, it is necessary to study the effect of operating parameters on the yield of distillate water. The influence of operational parameters such as feed flow rate, feed temperature, feed salt concentration, coolant temperature and air gap thickness on the membrane distillation (MD) permeation flux have been investigated for low and high salt solution. the natural application of ground water and seawater over 90 h continuous operation, scale deposits observed on the membrane surface and reduction in flux represents 23% for ground water and 60% for seawater, in 90 h. This reduction was eliminated (less than 14 %) by acidification of feed water. Hence, promote the research attention in apply of AGMD for the ground water as well as seawater desalination over today's conventional RO operation.

Keywords**—** MD, ground water, seawater, AGMD.

I. Introduction

WATER is the source of life, the basis of human survival, and the principal material base to guarantee the economy substantial development of a country. The fresh water scarcity is a growing problem all over the world because only 1% of earth's water is fresh water available for human to drink. Both rapid population growth and the impairment of existing freshwater sources cause many reasons to turn to the alternative sources of water such as wastewater, brackish water and seawater will gain importance compared to more traditional water sources. In order to bridge the wide gap between the availability and the demand for freshwater, desalination of the available saline water has become a suitable alternative, which is widely used worldwide [1-6]. Among various desalination technologies, membrane distillation (MD) is supposed to have a great potential due to low energy requirement, low operational pressure and temperature, and low-cost alternative to conventional technologies such as reverse osmosis (RO) and distillation. [7-10]

MD for water desalination is a membrane technique for separating water vapor from a liquid saline aqueous solution by transporting through the pores of hydrophobic membranes, made mainly of polypropylene (PP), polytetrafluoroethylene (PTFE), and polyvinylidene fluoride (PVDF). Various types of methods may be employed to impose a vapor pressure difference across the membrane to drive a flux. The permeate side may be a cold liquid in direct contact with the membrane, called direct contact membrane distillation (DCMD) or a condensing surface separated from the membrane by an air gap called air gap membrane distillation (AGMD) or a sweep gas blown across the membrane called sweep gas membrane distillation (SGMD) or vacuumed called vacuum membrane distillation (VMD). Because AGMD and DCMD do not need an external condenser, they are best suited for applications where water is the permeating flux. SGMD and VMD are typically used to remove volatile organic or dissolved gas from an aqueous solution [8, 11-13].

This study proposes AGMD process, in which only the feed solution is in direct contact with the membrane. The permeate is condensed on a cold surface. There is an air gap situated between the membrane and the cold surface to reduce energy losses by heat conduction through the membrane. The main drawback of the air gap is that it is also an additional resistance to mass transfer. Air gap MD is suitable for all direct contact MD applications. However, it is also suitable to separate other volatile substances such as alcohols from an aqueous solution [6, 14]. In this study, performance of AGMD for desalination of ground water and seawater was investigated experimentally using flat membrane and determining the optimal operating conditions.

II. Experimental

The experimental process simply consists of a flat sheet hydrophobic micro porous PTFE membrane (Millipore) fixed in the PVC pipe (25 mm), feed compartment (150 x 25 mm) and cooling compartment (150 x 25 mm) as shown in Fig. 1. The typical characteristics of the membrane are summarized in Table I. The effective area of the membrane was 3.6 cm^2. The permeate vapor diffused through the membrane and condensed due to contact with the cooling plate. The permeated liquid was collected in a graduated cylinder and the volume of permeates collected was noted with regular

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intervals of time and the collected samples were analyzed simultaneously. The inlet temperature of the hot feed and coolant were maintained constant throughout the experiment. The two types of aqueous feed solution such as lower concentration, 2 to 6 g/l and higher concentration, 25 to 35 g/l NaCl in pure water were prepared and continuously fed to the membrane module from a reservoir by using a pump.

The effect of various operating parameters, such as the feed and coolant temperatures, feed flow rate, feed concentration, and air gap thickness for lower salt concentration solution (ground water) as well as higher salt concentration solution (seawater) were studied under a continuous feed flow. Also, the natural ground water and seawater application was studied by using the same module and membrane. All the AGMD experiments were carried out for 3-4 h and after almost 3 hr; the flux reaches equilibrium (steady state).

TABLE I
MEMBRANE CHARACTRISTICS

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):

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

Where V is volume of freshwater (l); ρ is density of freshwater (kg/l); A is effective membrane area (m^2) and t is the running time. 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):

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

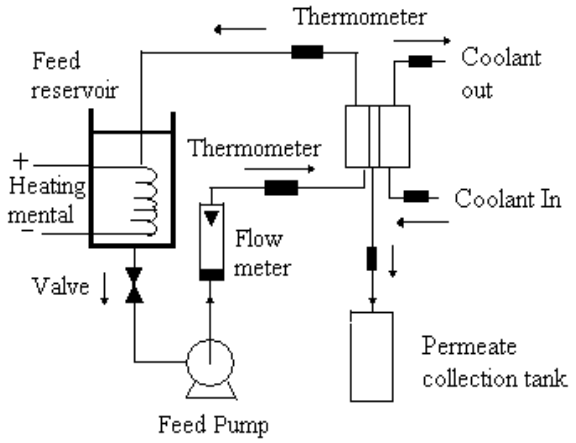

Fig. 1 Experimental setup of AGMD

III. RESULTS AND DISCUSSION

A. Effect of feed concentration

The experiments were performed for different concentration of salt in the feed water such as ground water 2 to 6 g/l and seawater 25 to 35 g/l. Fig. 2 show the effects of feed concentration on permeate flux at feed flow rate, 50 l/h, feed temperature, 333 K, coolant temperature, 288 K, air gap thickness, 1.2 mm. The results show that increasing of feed concentration of salt slightly decreases permeation flux due to influence of salt concentration on activity coefficient of water. The reduction in the permeate flux for ground water was less than 6 % when increasing salt concentration from 2 g/l to 6 g/l and for seawater, it was less than 18 % when increasing salt concentration from 25 g/l to 30 g/l. But the reduction is high means up to 54 % when increasing salt concentration from 2 g/l to 35 g/l. Hence, the result shows the permeate flux depend on the type of feed water but the nominal effect of feed salt concentration on the permeate flux. Because increasing feed salt concentration only marginally decreases vapor pressure of water. The permeate flux of ground water was found higher than the seawater.

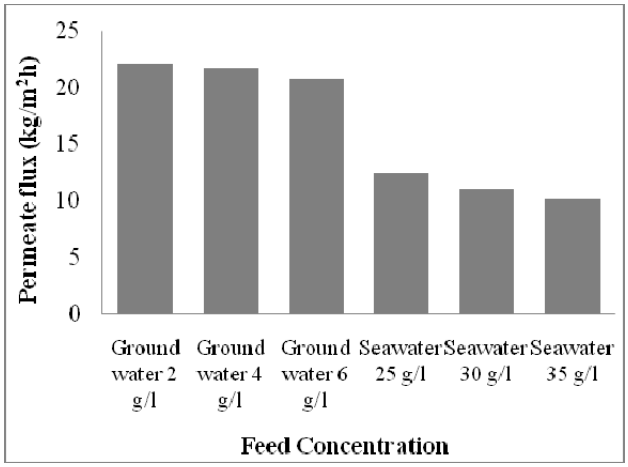

Fig.2. Effect of feed concentration at feed temperature, 333 K, feed flow rate, 50 l/h, coolant temperature, 288 K

According to Roult's law, in aqueous solution increasing salt concentration leads to the reducing of water vapor pressure and consequently driving force across the membrane. When salts are present in the feed solution at high concentration, an additional boundary layer develop at membrane surface, parallel to the temperature and velocity boundary layers. This concentration boundary layer, together with the temperature boundary layer further reduces the driving force for vaporization. Enhanced turbulence in the feed stream reduces both boundary layers and improves VMD performance. Due to reducing of water vapor pressure and increasing of resistance in transfer process, which is reduces the permeation flux. It indicates that AGMD is more suitable for seawater and groundwater purification

B. Effect of feed flow rate

The effect of feed flow rate was studied under the conditions of a constant initial concentration of ground water (4g/l) and seawater (30 g/l), feed temperature of the hot water (333 k) coolant temperature (288 K) and air gap thickness of the module (1.2 mm). The changes in the permeate flux of ground water and seawater with respect to the various feed flow rates are shown in Fig. 3. The permeate flux increases rapidly with increasing feed flow rate and permeate flux of ground water was greater than seawater by 45 %.

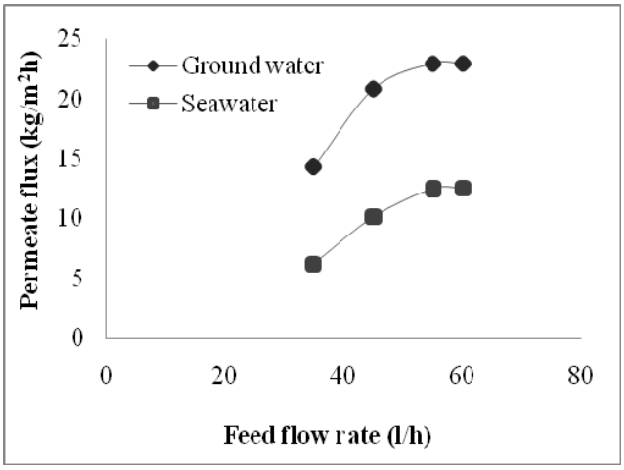

Fig.3. Effect of feed flow rate at feed temperature, 333 K, coolant temperature, 288 K and air gap thickness, 1.2 mm

The efficient method for flux enhancement is to provide highly turbulent flow across the both membrane faces. This is achieved by driving feed and permeates streams at high flow rates. The formation of the temperature boundary layer is mainly brought about by the water vaporization on the membrane surface. At a given temperature, the Reynolds number increases with an increasing feed flow rate, which causes the enhanced mixing of the flow channels to develop the turbulence. Due to this, the temperature polarization coefficient, heat transfer coefficient to increase. Hence, the vapor transfer resistance through the membrane is decreases and permeation flux increases. After 55 l/h feed flow rate, no effect was found on the permeation flux for both feed water. Salt rejection was greater than 99.9 % throughout all the experiments.

C. Effect of feed temperature

The feed temperature plays an impotent role on permeation flux in MD performance. Fig. 4 is showing the effect of feed temperature on permeation flux at fixed concentration of seawater (30 g/l) and ground water (4 g/l), feed flow rate, 55 l/h and coolant temperature, 288 K. The results show the water vapor flux is a function of feed temperature. The permeate flux increased with increasing feed temperature from 313 K to 333 K. It is widely understood that application of a temperature difference across a AGMD 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 AGMD 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

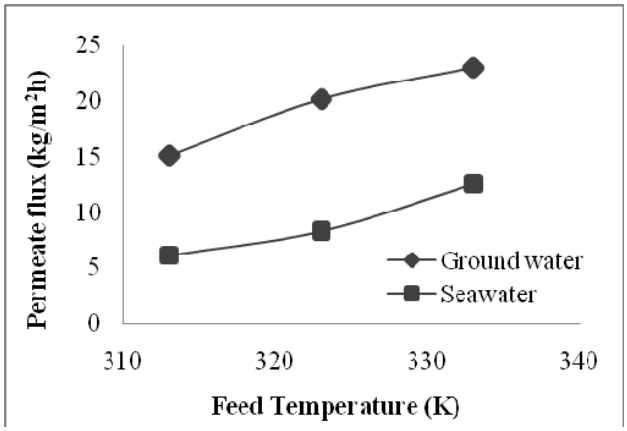

Fig.4. Effect of feed temperature at feed flow rate, 55 l/h, coolant temperature, 288 K and air gap thickness, 1.2 mm

force. So the optimization of feed temperature is an effective way to get high water vapor flux. The permeation flux was reached 22.98 kg/m^2 h of ground water and 12.48 kg/m^2 h of seawater when the operating conditions are: feed temperature, 333 K; feed flow rate, 55 l/h; coolant temperature, 288 K; and air gap thickness, 1.2 mm.

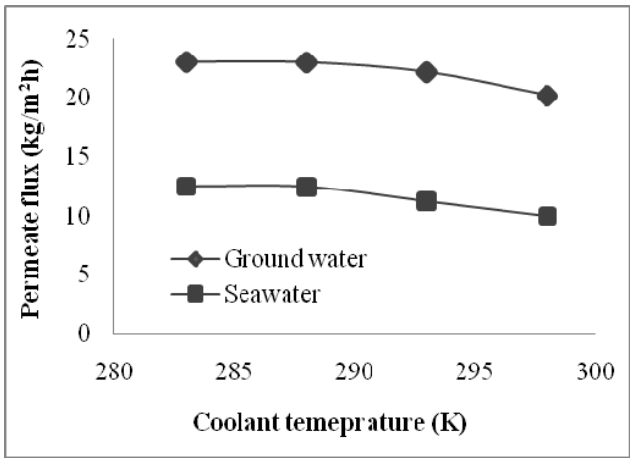

Fig.5. Effect of coolant temperature at feed flow rate, 55 l/h, feed temperature, 333 K and air gap thickness, 1.2 mm

D. Effect of coolant temperature

The vapor pressure difference is the driving force which is induced by the temperature difference in the MD operation. Hence, in AGMD operation the permeate side temperature is very important at constant feed temperature. The effect of

coolant temperature were studied by varying the cold-side temperature between 283 K and 298 K at a constant feed temperature, feed flow rate and feed concentration of ground water and seawater. The results of permeate flux is shown in Fig. 5. The flux of both feed did not change significantly with the coolant temperature. This result can be attributed to the fact that decreasing the temperature difference between the hot and cold sides reduced the vapor pressure gradient. However, the changes in the flux were nominal means less than 12 % and 19 % for ground water and seawater respectively.

E. Effect of air gap thickness

Air gap thickness is a major role plays in AGMD performance. Because air gap is an additional resistance to mass transfer added in the AGMD process [13, 14]. The air gap thickness was varied from 1.2 mm to 3.2 mm using gaskets. The effect of the air gap thickness were studied at constant feed concentration of ground water (4 g/l) and seawater (30 g/l), feed flow rate (55 l/h), feed temperature (333 K), and coolant temperature (288 K). The results are shown in the Fig. 6. The permeate flux was significantly reduced due to increasing air gap thickness in the module at permeate side for both feed because of the higher mass transfer resistance is air gap thickness. So, the minimum air gap thickness is the positive effect on the performance of AGMD process.

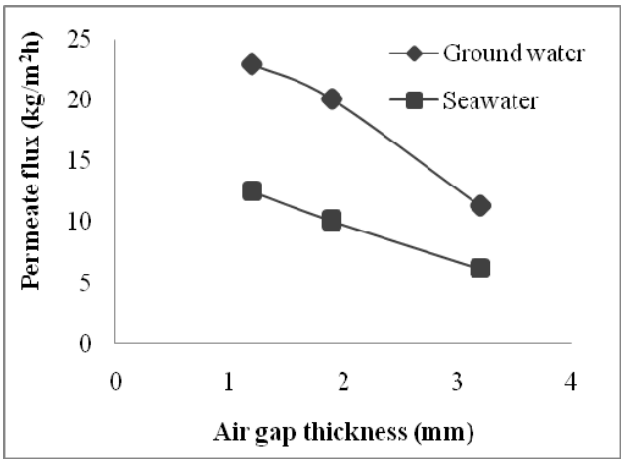

Fig.6. Effect of air gap thickness at feed flow rate, 55 l/h, feed temperature, 333 K and coolant temperature, 288 K

F. Application of natural ground water and seawater

The application of AGMD on the natural ground water and seawater were performed with the feed flow rate, 55 l/h; feed temperature, 333 K; coolant temperature 288 K; air gap thickness, 1.2 mm. The analysis of the feed and permeate water were done presented in Table II. Results found that all the species removed by AGMD were found, >98 % which meets the World Health Organization (WHO) standards. The ground water was taken from Sinnar region (Nashik, India) and seawater was from Mumbai region (India). The sample was taken after 5 h experimental run.

The experimental results of long term experimentation shown in fig. 7 demonstrate that the direct application of the natural ground water and seawater as a feed for AGMD 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 21.87 kg/m^{2}h which was decline to 16.93 kg/m^{2}h for ground water and 12.11 kg/m^{2}h to 4.89 kg/m^{2}h for seawater over 90 h continuously at constant operating conditions. The flux decreases represents 23% for groundwater

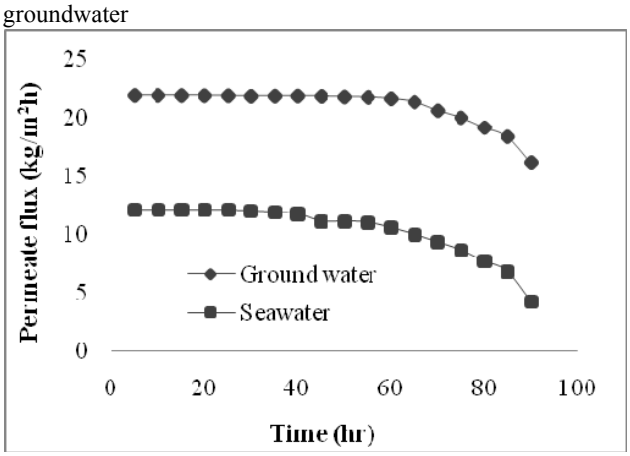

Fig.7. Time variation of permeate flux of natural ground water and sea water at feed flow rate, 55 l/h, feed temperature, 333 K and coolant temperature, 288 K

and 60% for seawater, in 90 h. The permeate flux was nearly constant up to 65 h for ground water and up to 40 h for seawater and after that the flux decline rapidly, means the scale deposits start after 65 h for ground water feed and after 40 h for seawater feed. Due to the higher concentrations of the species in seawater, the deposits on the membrane surface is higher as compared to the ground water.

TABLE II
PERCENTAGE REDUCTION OF PARAMETERS OF GROUND WATER AND SEAWATER

Parameter	% Reduction in ground water	% Reduction in seawater
Ca	99.3	99.1
Mg	98.9	99
Na	99.7	99.8
K	99.5	99.2
Si	98.8	98.7
Cl^-	99.9	99.6
SO_4^{2-}	99.2	NA
Fe	98.3	99.9
HCO_3^-	98.8	NA
NO_3^-	99.1	NA
B	NA	99.9
Br	NA	99.8
TDS	98.6	98.9

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 [15]. But here, in AGMD process, the fouling was observed. Hence, in order to eliminate the negative effect of scale deposition on the membrane, AGMD process were carried out at the initial feed pH 4 adjusted by addition of 0.1 mol/l HCl to the feed. The results of Fig. 8 was seen, the acidification of the feed enhances the stability of the process in a significant degree. There was negligible (<14%) decline of permeate flux for ground water and seawater during 180 h continuous operating 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. Also, there is no effect of acidification on the removal of species from ground water and seawater.

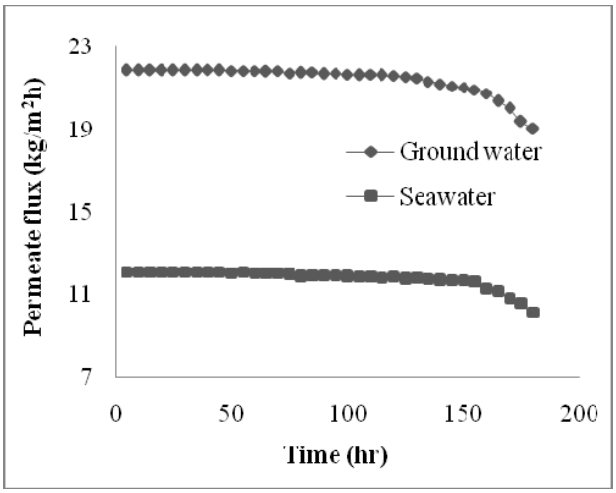

Fig.8. Time variation of permeate flux with maintaining initial pH 4 by adjusting 0.1 mol/l HCl to the feed

IV. Conclusion

The performance of AGMD for desalination of ground water and seawater by using a flat sheet PTFE membrane is presented experimentally. The AGMD permeate flux were increased with increasing the feed temperature, 313 K to 333 K, and feed flow rate, 35 l/h to 60 l/h. It was decreases with increasing coolant temperature, 283 K to 298 K, and an air gap thickness, 1.2 mm to 3.2 mm. The lower salt concentration (ground water) 4 g/l and higher salt concentration (seawater) 30 g/l solutions were used for determining the optimum operating parameters of AGMD process. The permeation flux of the natural ground water and seawater was reached 21.87 kg/m^2 h and 12.11 kg/m^{2}h respectively at the optimum operating conditions are: feed temperature, 333 K; feed flow rate, 55 l/h; coolant temperature, 288 K; and air gap thickness, 1.2 mm. The higher deposits on the membrane surface were observed by seawater as compared to groundwater during 90 h experimental run. This deposition can be removed by the acidification of the feed water, maintain the initial pH 4 adjusted by adding 0.1 mol/l HCl to feed water.

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