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Water and air gap membrane distillation for water desalination – An experimental comparative study

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A B S T R A C T

Experiments are conducted to compare and contrast the performance of Water Gap Membrane Distillation (WGMD) and Air Gap Membrane Distillation (AGMD) designs under different operating and design variables. The membrane module is designed to work on both designs exchangeably. The effects of feed flow rate, feed temperature, gap width, coolant flow rate, feed concentration, and the material of membrane supporting plate on the permeate flux are investigated experimentally. The temperatures inside the gap are measured to evaluate the changes in performance in relation to the gap temperature. Results showed that the water gap design enhances the permeate flux significantly. The increase is flux ranges between 90% and 140%, mainly depending on the feed temperature, when using the water gap as compared to the air gap. The temperature inside the water gap is lower than that of the air gap under the same operating conditions. Having a liquid interface on the cold side of the membrane increases the evaporation in feed side, maintains lower gap temperature, promotes the condensation process, and thus enhances the flux. Increasing the gap width reduces the flux, particularly at higher temperature. However, the water gap is found to be less sensitive to gap increases compared to air gap. It is recommended to use brass plate for supporting the membrane with the water gap, regardless of the gap width. On the other hand, with the air gap, the material thermal properties become less effective as the gap increases. A clear decrease in the flux is recorded with increases of the feed concentration due to the effect of concentration polarization on the feed side of the membrane. A salt rejection factor up to 99.98% is achieved with both air and water gaps.

1. Introduction

Resources of fresh water are limited and the demand is gradually increasing due to human activities. Desalination of sea and brackish water is the only solution of fresh water shortage in many regions in the world. Membrane distillation (MD) is an emerging thermal-membrane desalination technology [1–3]. In membrane distillation, a hot, saline feed stream is passed over a micro-porous hydrophobic membrane. The temperature difference between the two sides of the membrane leads to a vapor pressure difference that causes water vapor in the hot feed side to pass through the membrane pores and condense either on the cold side of the membrane or in an external condenser. The hydrophobicity of the membrane keeps the liquid from passing through the pores due to surface tension, while the water vapor is allowed to pass through. The technique offers the attractiveness of operation at atmosphere pressure and low temperatures (40–90 °C) and has the theoretical ability to achieve 100% salt rejection. This means that industrial waste energy and/or solar collection systems can be used directly to produce distillate. There are basically four types of membranes configurations namely: Direct Contact Membrane Distillation (DCMD), Air Gap Membrane Distillation (AGMD), Sweeping Gas Membrane Distillation (SGMD), and Vacuum Membrane Distillation (VMD). In all the MD configurations the feed solution is in direct contact with the hydrophobic membrane. However, the design of the cold side of the membrane and the way the permeate is collected is different for each configuration.

Air gap membrane distillation configuration is suited for water desalination and the removal of volatile compounds from aqueous solutions [4–6]. The membrane module includes a gap of stagnant air between the membrane and a condensation surface or plate within the membrane module. The difference in temperature between the cold surface and the feed solution is the driving force for the water evaporation at the hot liquid/vapor interface formed at the feed surface of the membrane [2,3,6]. Due to temperature differences in the air space, natural convection in the air gap transports the vapor through the membrane to the condensation surface. The air gap within the membrane module reduces the heat

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loss by conduction through the membrane, which increases the efficiency of the MD process. On the other side, the vapor has to cross the air barrier and thus the flux is reduced depending on the effective width of the air gap. The permeate flux drops with the increase of nonvolatile solute concentration due to the decrease of the water vapor pressure. Increasing the salinity of the feed water adds another resistance to mass transfer through the membrane by developing an additional concentration boundary layer at the membrane surface. Compared to the temperature polarization effect, the contribution of the concentration polarization is considered small [7]. The effect of feed temperature on the AGMD performance has been investigated in numerous studies [8,9]. The rate of evaporation and permeate flux are exponentially increased by increasing the feed temperature. The heat loss due to conduction through the membrane decreases by raising the temperature of the feed. It is possible for the AGMD to reduce the temperature and concentration polarization effects by increasing the feed flow rate to create turbulent flow regime; which in turn increases the permeate flux. Numerous studies reported that the sensitivity of the permeate flux of an AGMD unit to the coolant temperature is low [3]. An important factor that affects the performance of an AGMD module is the width of the air gap. The permeate flux increases with reducing the air gap width, which can be attributed to the increase in the temperature gradient inside the vapor space [10,11].

A theoretical model for Liquid Gap Membrane Distillation (LGMD) was developed and validated through experiments on a laboratory scale setup [12] and it was observed that the vapor mass flux increases by increasing flow rates (feed or coolant), feed solution temperature, and the membrane length. The flux increases with increases in the feed flow rate and then it becomes almost constant close to a flow rate of 200 L/h. Three possible schemes of the liquid gap membrane distiller are examined for minimal power inputs installation with small productivity [13]. The installation consists of a membrane module assembled from separate liquid gap membrane cells, a heater and a heat exchanger. It has been shown that the value of power input increases directly proportional to the product of volume stream rate and the temperature difference of the streams at the entry to the membrane module. Using different materials inside the gap of membrane distillation design has been studied [14]. It has been observed that employing appropriate materials (like sand, water, and sponge) between the membrane and the condensation plate in an air gap membrane distillation module enhances the water vapor flux significantly. An increase in the water vapor flux of about 200–800% was observed by filling the gap with sand and deionized water at various feed water temperatures. Also, an increase in the water gap width from 9 mm to 13 mm increases the water vapor flux. Another comparative study between air and liquid gap membrane distillation designs is presented by [15] as an application of a porous composite hydrophobic/hydrophilic membrane in desalination. A membrane of hydrophobic (active layer) and hydrophilic (support layer) nature was used. It was reported that a maximum vapor flux increase of only 6.6% is achieved when using the liquid gap as compared to air gap. The LGMD also showed higher thermal efficiency and less internal heat loss as compared to AGMD. When water is used to fill the gap, the configuration is said to be Water Gap Membrane Distillation or WGMD.

In the present work, the performances of AGMD and WGMD are investigated and compared. The effect of feed flow rate, feed temperature, gap width, coolant flow rate, feed concentration, and the material of membrane supporting plate on the permeate flux are investigated experimentally. The temperature inside the air and water gaps is measured to assess the general heat transfer and to evaluate the changes in performance.

2. Experimental setup

The MD module is made of two High-Density Polyethylene (HDPE) compartments with overall dimensions of 200 × 225 mm. One compartment is used for the hot feed water and the other one is for the coolant side. The two HDPE compartments are channeled to have two headers and two flow channels in each of them. The headers (15 × 150 mm) are used to collect the water at channels inlet and outlets. Each channel has dimensions of 60 × 120 mm, with channel depth of 5 mm. Fig. 1 shows an exploded view for the complete assembly.

The hot feed water directly passes over the hydrophobic flat sheet membrane which is supported by a brass perforated plate of 1.5 mm thickness. The perforated part of the support plate gives an effective membrane area of 0.00724 m^2. Another brass plate is used as condensation surface for the vapor passing through the membrane pores to the air gap. The air gap is created by a spacer gasket between the two brass plates (the membrane support and the condensation plates). The gap width can be varied by changing the thickness of the spacer gasket. Cold water with constant inlet temperature flows behind the condensation plate to keep the plate at low temperature to condense the vapor. The assembly parts are held together by two metallic steel frames. The metallic frames help in distributing the pressure of the 14 bolts equally around the module edges to prevent leakage. The condensed vapor (permeate) is collected in a sealed cavity at the bottom of the condensation plate. This cavity leads the permeate out of the module through a small pipe with a valve. In case of using the module with liquid gap rather than air gap, the cavity port is closed by closing its valve and another outlet port at the top of the gap is opened to collect the permeate. Fig. 2 shows the assembly process of the module.

Inlet and outlet pipes are made of stainless steel of size 3/8 in. Pressure and temperature sensors are placed as close as possible to the module (3 cm from module inlets and 8 cm from module outlets) ports for accurate measurements. The pressure at module inlet and outlet is measured for both feed and coolant sides using four pressure gages as shown in Fig. 3. Also, the temperatures of feed water and coolant water are measured at inlets and outlets using four thermocouples. The thermocouples are connected to a data acquisition system (DAQ), model NI 9211, and are monitored/recorded with a Labview code. The flow rates of feed and coolant sides are measured with low flow rate turbine flow meter and rotameter, respectively.

Feed water is heated up to the required set temperature using a thermostat-heating bath. The coolant water is supplied from a refrigerated circulation bath. The module is supported on a simple steel structure with adjustable dimensions for handling the MD system easily. Two thermocouples are inserted from module sides, at midway of the flow channels, to measure the temperature inside the gap. Another thermocouple is inserted to measure the temperature inside the permeate collecting cavity at the bottom of the module gap. A hydrophobic flat PTFE membrane sheet, from Tisch Scientific, is used. The measured membrane characteristics showed that it has a pore size of 379 ± 8 nm (commercially reported as 450 nm) and a total thickness of 153.9 ± 13.6 micrometer. The membrane has an active layer of thickness 6.9 ± 2.0 micrometer and a supporting layer of thickness 141.4 ± 15.8 micrometer. The measured porosity is 80% and the surface contact angle is 140°. The measured membrane liquid entry pressure is 2.4 ± 0.1 bar. The membrane effective area is 0.00724 m^2, based on the opening area of the perforated support plate. The actual applied water pressure for hot and cold sides ranged between 0 and 0.3 bar, depending on the flow rate. However, to test the module for leakage, the module was split at the gap section into two closed cycles. Each cycle was bolted