Desalination 376 (2015) 94–108

Contents lists available at ScienceDirect

Desalination

journal homepage: www.elsevier.com/locate/desal

Experimental and theoretical investigation on water desalination using air gap membrane distillation

A. Khalifa [a,*], D. Lawal [a], M. Antar [a], M. Khayet [b,c]

[a] King Fahd University of Petroleum & Minerals, Mechanical Engineering Department, Dhahran 31261, Saudi Arabia
[b] Department of Applied Physics I, Faculty of Physics, University Complutense of Madrid, Av. Complutense s/n, 28040 Madrid, Spain
[c] Madrid Institute for Advanced Studies of Water (IMDEA Water Institute), Calle Punto Net No. 4, Alcalá de Henares, 28805 Madrid, Spain

HIGHLIGHTS

- Comprehensive experimental and theoretical studies on AGMD
- Effects of main operating and design variables
- Feed temperature and air gap width are main controlling variables
- Theoretical results agree with experimentally measured values
- Evaporation efficiency and temperature polarization are investigated

ARTICLE INFO

Article history:
Received 9 May 2015
Received in revised form 17 August 2015
Accepted 20 August 2015
Available online 5 September 2015

Keywords:
Water desalination
Air gap membrane distillation (AGMD)
Performance evaluation
Experimental investigation
Theoretical modeling
Efficiency analysis

ABSTRACT

Membrane Distillation (MD) is a thermally driven membrane separation technique that is used for water desalination by separating water vapor from feed salty/brackish water using micro-porous hydrophobic membrane. Comprehensive experimental and theoretical studies on the performance of an air gap membrane distillation (AGMD) system are presented. The effects of main operating and design variables on the permeate flux are reported. The design of the AGMD module and the experimental setup are presented in details. PTFE membranes of two different pore sizes are characterized and tested. Results show that the system performance is highly affected by changes in both feed temperature and air gap width. Increasing the feed temperature from 40 °C to 80 °C increases the flux by 550% to 750%, depending on the other operating variables. A maximum of 130% rise in flux, approximately, was achieved when the air gap width was decreased from 7 mm to 3 mm. The maximum permeate flux obtained from the current AGMD system is 71.1 kg/m^2 hr. The measured salt rejection factor is above 99.9% that emphasizes the suitability of the AGMD system for desalination of high concentration feeds. A theoretical model based on the analysis of heat and mass transfer is developed to predict the permeate flux and to study the system efficiency. The theoretical model is validated by comparing the permeate flux with experimentally measured values where a maximum deviation of 15% is observed. The evaporation efficiency of the AGMD module and the temperature polarization coefficient are thoroughly investigated theoretically at different operating parameters.

1. Introduction

Due to urbanization and population rise, the gap between the demand and supply of potable water is ever increasing. In some arid and semi-arid areas, desalination remains the viable solution to water scarcity problem. The market for water desalination is increasing in Gulf Co-operation Council (GCC) countries as the populations grow, drought conditions worsen, and water demand per capita increases [1]. The quest for more and better fresh water production has consistently put researchers in search for superior and most efficient potable water production technology. The emergence of Membrane Distillation (MD) technology contributed in the research for seawater desalination. Membrane distillation differs from other membrane technologies in the sense that the driving force for permeation is the vapor pressure difference, rather than the total pressure of water across the membrane. The membrane materials used for membrane distillation are hydrophobic in nature. Since MD has the theoretical ability to attain 100% salt rejection and can be operated at low temperatures (40 °C–90 °C) and at atmosphere pressure, low-grade energy like solar and waste energy can be used for MD water desalination [2].

* Corresponding author.
E-mail address: akhalifa@kfupm.edu.sa (A. Khalifa).

http://dx.doi.org/10.1016/j.desal.2015.08.016
0011-9164/

Air gap membrane distillation (AGMD) has been used for seawater desalination. In an AGMD configuration, the temperature difference across the hydrophobic membrane creates partial pressure difference which encourages water molecules to evaporate at the hot feed side to permeate through the membrane pores. The vaporized water then diffuses through a stagnant air gap situated between the membrane and a condensation plate where it condenses at a lower temperature to produce distilled water [3]. Factors affecting the performance of air gap membrane distillation were investigated experimentally by several researchers. However, many inconsistencies in results are found in the open literature regarding the performance of the AGMD system (e.g. values of flux and behavior trends). Pangarkar and Sanean [4] experimentally investigated the performance of air gap membrane distillation for aqueous NaCl solution, natural ground water and seawater. The effect of operating parameters such as the feed flow rate, the feed temperature, the feed salt concentration, the coolant temperature and the air gap thickness on the permeation flux was studied. Scale deposits observed on the membrane surface reduced the permeate flux by about 60% and 23% when the both natural seawater and ground water were used as feed solutions. Using two-hollow-fiber-sets based compact membrane device, Singh and Sirkar [5] experimentally investigated influence of operating parameters and membrane types and properties on the performance AGMD system.

In order to enhance the performance of the AGMD system, Tian et al. [6] presented an innovative design of an AGMD system. The new design of AGMD configuration was reported to have significantly enhanced water productivity of the system. The AGMD module was built in such a way that the membrane material is in partial contact with the condensation surface. The transport resistance of the air gap was reduced hence improving the system efficiency. A maximum permeate flux of 119 kg/m^2 hr was reported. In an effort to improve the performance of AGMD unit, Khalifa [7] built and tested a module that can have either an air gap or a water gap. It was reported that the increase in flux ranges between 90% and 140%, 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. Other researchers have also made similar attempts to improve the performance of AGMD by replacing air in the gap with liquid [8,9] with significantly different results. Bahar et al. [10] enhanced the system performance by about 50% by replacing the flat coolant plate with channeled one, which improved the heat transfer during condensation. The effect of membrane pore size on permeate flux was investigated [11]. In general, it was reported that membranes with larger pore size produce higher permeate flux. Lawal and Khalifa [12] studied the performance of double-stage AGMD unit at different operating parameters such as feed temperature, feed flow rate, coolant temperature, coolant flow rate and air gap width. Experimental results revealed that the double-stage AGMD unit is capable of achieving a maximum cumulative distillate production of 128.46 kg/m^2 hr, and a single stage flux of 65.81 kg/m^2 hr.

Dehesa-Carrasco et al. [13] investigated the performance of an AGMD unit both experimentally and theoretically. The system was manufactured from an insulated material to minimize heat losses. With the help of temperature and flow rate measurement, the enthalpy and the diffusion coefficient of vapors in the air gap were evaluated. The model predictions and the experimental data showed good match. The differences between measured and predicted temperatures were approximated to 5% accuracy. However, the trends of the model and the experimental data were different and the possible improvements to the model were discussed. Alsaadi et al. [14] developed a one dimensional model based on theoretical equations governing the mechanism for mass and heat transfer process in AGMD. The developed model is reported to be capable of predicting flux in both AGMD modules in counter-current and co-current flow regimes. The model was validated against the experimental data. Comparison showed that the model flux predictions are strongly correlated with the experimental data, with model predictions being within +10% of the experimentally determined values. Then, the model was subsequently used to study and analyze the thermal efficiency and the parameters that improved the AGMD unit. Geng et al. [15] developed an AGMD module with internal heat recovery for water desalination to investigate the impact of AGMD operating parameters. Based on mass and energy balance, a theoretical model was developed to estimate the permeate flux and temperature drop along the membrane. Results revealed that higher permeate flux and temperature drop were observed at the upper part of the module when compared to that of the lower part. Experimental results yielded maximum permeate flux of 5.3 kg/m^2 hr and a gain output ratio of 5.7.

In this paper, detailed experimental and theoretical investigations on the performance of AGMD system for water desalination are presented. Detailed experiments are conducted to provide better understanding of the factors influencing air gap membrane distillation process. A theoretical analysis of heat and mass transfer inside the AGMD module is used to predict the system permeate flux. The theoretical model is validated against the experimental findings. The evaporative (thermal) efficiency and temperature polarization of the system are calculated and discussed at different operating conditions.

2. Theory

Heat and mass transfer take place simultaneously inside the AGMD module. The analysis of heat and mass transfer in AGMD involves convective heat transfer from hot feed solution to the membrane surface, evaporation at the membrane pores' entrance liquid-gas interface, movement of water vapor across the membrane pores, conductive heat transfer across membrane material, water vapor diffusion via the stagnant air gap, vapor condensation over the cooling plate, conductive heat transfer across the condensation plate, and convective heat transfer from cold solution to the condensation plate [16]. Fig. 1 shows a schematic for the heat and mass transfer inside the AGMD module. In modeling the AGMD, the following assumptions are considered: steady state conditions, air trapped within the membrane pore is considered stagnant, constant pressure inside the air gap, and liquid entrance pressure is greater than the pressure at the feed side of the membrane. Within the air gap, mass is transported by diffusion while heat is transferred by conduction and no heat exchange between the system and the surrounding. A film-wise condensation in the air gap is considered on the condensation plate.

2.1. Heat transfer

Referring to Fig. 1, at steady state operation, the heat flux (W/m^2) from the hot solution to the membrane surface is made up of convective term and the diffusive term, given as [2,17,18]:

$$Q_f = \left(h_f + J_w C_{p,f}\right)\left(T_f - T_{mf}\right) \quad (1)$$

where J_w is the permeate flux, h_f is the feed heat transfer coefficient, and $C_{p,f}$ is the specific heat of the feed solution. The convective term is dominant over the heat transfer associated with the mass transfer term in Eq. (1).

The heat transfer from membrane surface to the condensate liquid interface is expressed as:

$$Q_p = h\left(T_{mf} - T_{cd}\right) + J_w H_w \quad (2)$$

where H_w is enthalpy of vaporization of water (kJ/kg), which may be calculated from [2,26] as:

$$H_w = 1.75535\boldsymbol{T} + 2024.3 \quad (3)$$

where T is the absolute temperature in K.