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Experimental study of thermal performance in air gap membrane distillation systems, including the direct solar heating of membranes

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HIGHLIGHTS

- Novel heating configuration whereby solar flux is absorbed directly onto the membrane.
- Experimental evaluation of reducing pressure of the air gap in AGMD.
- Non-dimensional scaling parameter to compare systems of different sizes.

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ABSTRACT

Membrane distillation (MD), a thermally driven membrane technology which runs at a relatively low pressure and withstands high salinity feed streams, has shown potential as a means of desalination and water purification. This paper focuses on the air gap MD (AGMD) process experimentally with the goal of demonstrating and predicting means of improving the energy efficiency of AGMD systems. In particular, a novel configuration which delivers solar radiation directly to the membrane is investigated using a composite solar-absorbing membrane. The use of reduced pressure in the air gap, for lower diffusion resistance, was also explored. A parameter to relate the performance of a bench-scale experiment with similar membrane and gap size to a production system was developed through the application of previously developed models. Small scale experiments were conducted to verify performance for the novel solar powered configuration and the effect of reduced gap pressure. Experiments demonstrated the efficacy of a solar absorbing membrane to improve the thermal performance of the cycle beyond heating an opaque surface in contact with the feed stream. The results also establish a benefit from the deformation of the membrane into the air gap as a result of hydraulic pressure.

1. Introduction

Membrane distillation is a separation process in which a hot feed stream is passed over a microporous hydrophobic membrane. The temperature difference between the two sides of the membrane leads to a vapor pressure difference that causes water to evaporate from the hot side and, pass through the pores to the cold side. The vapor is pure water which can be condensed. This process has application to desalting water. Compared to reverse osmosis, MD does not require a high pressure feed, and can process very high salinity brines. Compared to other large thermal processes, it can be easily scaled down. Demonstrated pilot plants have been used at a small scale (0.1 m^3/day), including stand-alone systems disconnected from municipal power or water networks [1–4].

MD systems can be used in many configurations; direct contact (DCMD), air gap (AGMD), vacuum (VMD), and sweeping gas (SGMD). All of these configurations can be applied to seawater and brackish water desalination [5,6];however, those most commonly used for desalination are DCMD, AGMD, and VMD. In AGMD, an air gap separates the membrane from a cold condensing plate which collects vapor that moves across the gap. Air gap systems have been tested experimentally. AGMD in particular offers promise as a desalination technology with high energy efficiency as it has favorable heat transfer characteristics. The insulation properties of the air gap prevent direct thermal loss between hot and cold sides and the built in condenser surface allows fluid to be condensed at the local saturation temperature instead of being mixed and condensed at the mean saturation temperature as in a VMD system. Creative design improvements and optimization could potentially make AGMD competitive with more established thermal desalination systems.

Most research on MD desalination focuses on maximizing membrane flux, or vapor produced per unit area of membrane. However some studies have examined energy efficiency for experimental plants at the 0.1 m^3/day scale [1,2,4]. Additionally, more recent MD desalination studies have also examined energy efficiency experimentally [1,7,8]. Numerous studies have examined flux in experimental settings [9–13]. However, using membrane flux as a proxy for thermal

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Nomenclature

Roman Symbols

A	Area [m^2]
B	Membrane distillation coefficient or membrane flux coefficient [kg/m^2 Pa s]
C	Simplified Antoine Equation constant
c_p	Specific heat capacity at constant pressure [J/kg K]
d_{gap}	Air gap width [m]
D_{w-a}	Diffusion coefficient of water in air [m^2/s]
h	Specific enthalpy [J/kg]
h_t	Convective heat transfer coefficient [W/m^2 K]
h_{fg}	Latent heat of evaporation [J/kg]
I	Solar Irradiation Flux [W/m^2]
J	Vapor flux through membrane [kg/m^2 s]
$\dot{m}$	Mass flow rate [kg/s]
M_w	Molecular weight of water [kg/mol]
P	Total pressure [Pa]
p	Partial pressure [Pa]
$\dot{Q}$	Heat flow [W]
q	Heat flux [W/m^2]
$\overline{R}$	Universal gas constant [K]
$\overline{T}$	Mean temperature [K]
T	Temperature [K]
x	Mole fraction
z	Lengthwise coordinate [m]

Greek Symbols

α	Thermal diffusivity [m^2/s]
δ	Thickness [m]
Ψ	Non-dimensional scaling parameter
ρ	Density [kg/m^3]

Subscripts

a	Air gap
b	Bulk
bot	Bottom temperature
c	Condenser stream
f	Feed
i	Condensate film interface
l	Liquid phase
m	Membrane
p	Permeate
sat	Saturation
top	Top
v	Vapor phase
w	Water (liquid)

performance may not lead to the correct conclusion about overall system performance, as fresh water output and energy consumption can be highly dependent on system configuration, membrane area, system top temperature, and heat recovery from hot brine and condensing vapor. In a complete cycle, the highest flux may not lead the best use of energy, as it often requires high heat inputs and the resulting high vapor flux can increase resistance to heat and mass transfer, driving up energy use.

In this paper, an experiment was devised to test the AGMD system in the context of a complete thermal cycle, with the goal of assessing its energy efficiency. The experiment allows for the assessment of the impact of the AGMD system to improvements in energy efficiency in two ways; by delivering heat directly to the membrane where the water evaporates by means of solar energy as described in previous work [14,15], and reducing resistance to mass transfer be reducing the total pressure in the gap. The results of the experiment can be scaled up to relate them to the performance of a production-scale system through a scaling parameter developed in this study.

The use of direct heating on the membrane to eliminate temperature polarization was experimentally tested by Hengl et al. [16]. Heating was delivered using an electrically resistive metallic membrane which would be impractical to use in a larger scale system. Energy efficiency performance was not measured. Chen and Ho [17] used uniform solar flux to heat the feed stream by placing a solar absorbing surface above the feed stream. This method still retained the temperature polarization effect, but captured the idea of integrating solar collection and desalination into one unit. The feature that strongly distinguishes the system tested in this study from others developed in the past, is a solar absorbing membrane that sits below the water layer. The membrane used in this study is a composite with a hydrophilic polymer such as polycarbonate or cellulose acetate, layered on top of a standard MD membrane material, like Teflon (PTFE). Experimental tests of reducing the pressure inside the membrane gap were attempted previously [18] at very low vacuums (approximately 9/10ths of atmospheric pressure) and only a small enhancement of mass transfer was reported.

2. Experimental scaling

To understand how the energy efficiency performance of a bench-top experimental system relates to that of a large-scale production system of the air gap membrane distillation (AGMD) configuration shown in Fig. 1, it is necessary to know how the system scales with input parameters such as system size, feed mass flow rate, and operating temperature. The model for an AGMD system consists of many equations and is highly nonlinear, depending in large part on exponential functions of temperature and of the permeate flux itself multiplied by the effects of system size. However, it can be simplified using some order of magnitude estimates derived from the numerical solution to the detailed system of equations developed in previous work by the authors [19].

In analyzing the results of the detailed model the following approximations can be made:

- Heat conduction through the membrane, q_m, is negligible. $q_m/J_m h_{fg} < 0.1$. Since the air in the gap has good insulating properties heat fluxes as a result of conductive losses through the membrane are small compared to the energy carried by the latent heat of the vapor.
- The thickness of the liquid condensate layer in the gap, δ, is negligible. $\delta/d_{gap} < 0.15$. This ratio is even lower at the top of the module where there is a small amount of condensed vapor.
- The change in temperature across the gap along the length of the module is small relative to the absolute temperature (in Kelvin) of the vapor in the gap. $(T_{f,b} - T_{c,b})/\overline{T}_{gap} < 0.05$. For the purpose of calculating the vapor concentration in the gap by means of the ideal gas law, the average absolute temperature can be held constant. For this simplified model, it is fixed to $(T_{top} + T_{bot})/2$.

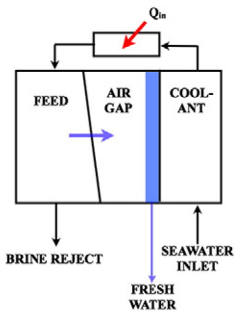

Fig. 1. Schematic diagram of an AGMD system with conventional heating.