Experimental evaluation and modeling of internal temperatures in an air gap membrane distillation unit

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HIGHLIGHTS

- Experimental and theoretical study of an air gap membrane distillation unit
- Membrane and cooling plate temperatures were measured.
- Vapor diffusion coefficient in the air gap is evaluated from internal temperatures.
- Model without free parameters has reasonable correspondence with experiment.

ARTICLE INFO

ABSTRACT

Membrane distillation is a separation process that involves transfer of heat and vapor through a porous hydrophobic membrane. It can be employed for thermal desalination of water by low grade heat obtained, for instance, from low temperature solar collectors. An experimental and theoretical study of an air gap membrane distillation unit is presented. This unit was built from an insulating material to reduce losses, and has a plane parallel geometry. Temperatures are measured at different points in the unit, as well as flow rates and distillate production, to evaluate the different enthalpy flows. In particular, the internal temperatures surrounding the air gap, namely the membrane and cooling plate temperatures, are measured. From these temperatures the diffusion coefficient for vapor in the air gap is evaluated. Experiments are carried out for different values of saline solution temperature and flow rate. A one dimensional heat and mass transfer model with no free parameters is proposed. Temperatures predicted by the model are compared to the experimental results. The correspondence between measured and predicted temperatures is near to 5% accuracy, although the trends of the curves differ somewhat. Possible improvements to the model are discussed.

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1. Introduction

Fresh water demand in arid zones is a current problem around the world. Usually these areas have plentiful of solar radiation, making solar technologies an attractive option for fresh water production. In particular, technologies that use low temperature reject heat or solar heat are very attractive [1,2,32–35]. One of the technologies for solar desalination is membrane distillation (MD) [3,2]. MD is a separation process that involves transfer of heat and vapor through a porous hydrophobic membrane. One of the faces of the membrane is in direct contact with a hot saline solution. Even though water cannot pass through the pores, because of the hydrophobic nature of the membrane, the volatile component, the water vapor, can. Vapor enters the pores because of the partial pressure gradient occurring across the membrane, and comes out at the other side, where it is recovered and condensed.

Four different configurations are used to carry out this process [4]: direct contact membrane distillation (DCMD), where fresh water sweeps the other face of the membrane, to remove the distillate; sweeping gas membrane distillation (SGMD), where a gas is used for this purpose; vacuum membrane distillation (VMD), where a light vacuum is applied to the opposite side of the membrane; and air gap membrane distillation (AGMD), where a condensing plate, cooled by a cold water flow, is located parallel to the membrane. The gap between the membrane and the condensing plate is filled with air, through which the vapor diffuses from the former to the latter. In all cases, the resulting product from the evaporation/condensation process in the MD unit is fresh water.

One of the advantages of the AGMD configuration is the low parasitic conductive heat losses through the cell, due to the presence of air between the membrane and the condenser plate. However, there is a tradeoff, because this air space leads to an increased mass transfer resistance and reduces the permeate flow [5]. Nevertheless, AGMD is considered the most versatile configuration, showing a great potential for the implementation of MD in the future [6]. Several publications have

addressed the study of the basic MD mechanisms [7–28]. Some recent review studies [29–31] report a number of significant experimental data and modeling approaches on MD processes.

Different experimental works have elucidated the influence of the parameters of the process in the amount of distillate produced per unit membrane area in AGMD systems. For instance, it has been found that the hot side temperature has an exponential effect on the increase of the permeate volume [8–17]. An increase in concentration produces a subtle drop in the permeate flow [9,11,12]; for instance, about 16% reduction in permeate flow occurs when the feed concentration is increased from 20,000 to 50,000 ppm at a constant temperature [8]. The feed flow rate causes an increase of the permeate volume, because high flow rate minimizes the boundary layer resistance and the heat transfer coefficient is increased [22,23]. In some cases it has been observed that the increase is asymptotic [6,10–12]. Several authors report a linear relationship between air gap width and the distillate flow [4,22]. However, when the width is less than 1 mm, a significant effect on the distillate flow occurs [9,13].

There have been several works proposing theoretical models to describe the AGMD configuration [14,16,19,22–26]. These models can be classified into different categories: from rigorous, detailed CFD and mass transfer models, like the one from [14,16,18], to simplified linearized models like those of [19,22–26]. It has been found that the natural convection heat flow is practically suppressed if the air gap thickness is kept below 4–5 mm, leading to a great reduction of parasitic heat losses due to convection, and to reduced mass transfer resistance at the same time.

One dimensional heat transfer models seem like a good approximation for many AGMD configurations, as the lateral sizes of the membrane and condensing plate are much larger than their separation and respective thicknesses, and the suppression of convection leads to nearly one dimensional heat transfer. On the other hand, mass transfer is a complicated interaction of different vapor transport mechanisms [14]. The simpler models attempt a linearization of these processes [22]. This kind of models is very interesting from the practical engineering design point of view, however it has been pointed out that they may be not very accurate [31].

It is difficult to establish firmly the validity of the simplified models in AGMD due to limitations in the experimental information available. Usually models are compared against distillate production and temperature drops in the hot and cold side of the unit [9,19,22,25,28]. No comparisons have been carried out with temperature data measured inside the unit, in particular, the membrane temperatures, due to the difficulties to carry out those measurements.

In the present work an experimental AGMD unit has been built and instrumented to carry out measurements of internal (condensing plate and membrane) temperatures, and several experiments have been carried out. The results from these experiments are compared to a one dimensional theoretical model. To this end, the effective diffusion coefficient for water vapor inside the air gap has been determined from the experimental data, as well as the effective air gap dimensions.

2. Theoretical method

A conceptual scheme of the AGMD system configuration is shown in Fig. 1. At one side of the unit, a warm saline solution flows in direct contact with the porous membrane. Water cannot pass through the membrane, due to the hydrophobic nature of the material, and a water–air interface is formed at the pore entrances. Phase change occurs at this interface, according to the vapor–liquid equilibrium. The resulting vapor diffuses, first through the pores, and then across the air gap, finally condensing and forming a permeate film at the condensing plate.

The temperature difference across the system results in heat conduction and promotes mass transfer. A vapor concentration gradient is generated from the pore entrances to the permeate film, at temperatures
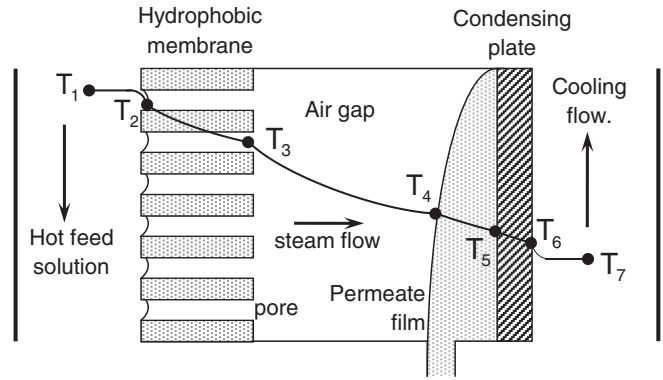

Fig. 1. Conceptual scheme of an AGMD unit.

T_2 and T_4, respectively. The coupling of diffusion and heat conduction gives rise to cross-phenomena called the Soret effect [9].

To model the system, a balance of enthalpy flow conservation in different regions is carried out. Since the characteristic length of the system is much larger than the combined thickness of the membrane, air gap and plate condenser, the heat and mass transfer is considered to occur in one dimension. Moreover, in previous studies [13,14] it has been found that for air gap thicknesses less than 5 mm, the air is practically stagnant. As air gap thickness of the system modeled here is of 2.4 mm, natural convection is neglected in our model.

The equations for the conservation of enthalpy flow are expressed as follows [22], considering that the two transfer mechanisms involved are thermal conduction and mass diffusion: at the membrane

$$h_1(T_1-T_2) + Nc_{pL}\left(\frac{T_1+T_2}{2}-T_0\right) =$$
$$N\left[c_{pL}(T_2-T_0) + \Delta H_V(T_2) + c_{pV}\left(\frac{T_3+T_2}{2}-T_2\right)\right] + \frac{k_m}{l_m}(T_2-T_3)$$
(1)

inside the air gap

$$h_1(T_1-T_2) + Nc_{pL}\left(\frac{T_1+T_2}{2}-T_0\right) =$$
$$N\left[c_{pL}(T_2-T_0) + \Delta H_V(T_2) + c_{pV}\left(\frac{T_4+T_3}{2}-T_2\right)\right] + \frac{k_{gap}}{l_{gap}}(T_3-T_4)$$
(2)

in the permeate film

$$h_1(T_1-T_2) + Nc_{pL}\left(\frac{T_1+T_2}{2}-T_0\right) = h_4(T_4-T_5) + Nc_{pL}\left(\frac{T_4+T_5}{2}-T_0\right)$$
(3)

at the condensing plate

$$h_1(T_1-T_2) = \frac{k_p}{l_p}(T_5-T_6)$$
(4)

in the cooling flow

$$h_1(T_1-T_2) = h_6(T_6-T_7).$$
(5)

The terms proportional to $Nc_p\Delta T$ can be neglected because their contribution to the net enthalpy flow is much smaller than the heat flow by conduction, and diffusion enthalpy flow. With this consideration, the first three equations can be simplified to

$$h_1(T_1-T_2) = N\Delta H_v + \frac{k_m}{l_m}(T_2-T_3)$$
(6)