Permeate flux in air gap membrane distillation for seawater desalination

S. ROCHD, L. SALAMA, K.EL GHAZAOUY, S. MIZANI, H. ZERRADI, M. EL Marsi, R. MOULTIF, A. DEZAIRI*, Laboratory of condensed matter, faculty of sciences Ben M’sick (URAC.10), University Hassan II of Casablanca, Morocco
* aouatif.dezairi@univh2c.ma ; a.dezairi@gmail.com

Abstract: Membrane distillation (MD) is a thermally driven process since only vapor molecules are transported through porous hydrophobic membranes. This process leads to the separation into different desired phases. Air gap membrane distillation (AGMD) is considered one of the most used configurations of the membrane distillation. In this work, the impacts of NaCl concentration, porosity, and membrane pore size on the production of the flux have been investigated. The results have been carried using polynomial approximations through MATLAB. These latter are in agreement with the experiments.

Keywords: Desalination, Membrane, Distillation, Air gap, NaCl concentration, Diffusion, Pore size, porosity.

1. Introduction:

Freshwater is becoming an increasingly scarce global resource, and its availability is expected to influence the long-term wealth and well-being of nations [1]. Furthermore, the common use of unhealthy water in developing countries is estimated to be causing 80-90% of all diseases and 30% of all deaths [1]. As a definition, MD is a thermally driven process, in which only vapor molecules are transported through porous hydrophobic membranes. The liquid feed to be treated by MD must be maintained in direct contact with one side of the membrane without penetrating its dry pores unless a trans-membrane pressure higher than the membrane liquid entry pressure is applied. The hydrophobic nature of the membrane prevents liquid solutions from entering its pores due to the surface tension forces. As a result, liquid/vapor interfaces are formed at the entrances of the membrane pores. Various MD modes differing in the technology applied to establish the driving force could be used [2-3]. A variety of methods may be employed in MD, such as direct contact membrane distillation (DCMD) in which the membrane is in direct contact with liquid phases in both sides [4-6]. Then, the air gap membrane distillation (AGMD) in which an air layer is interposed between the membrane and the condensation surface [7-8]. At that time, a vacuum membrane distillation (VMD) where a vacuum is applied to increase or establish the vapor pressure difference between the membrane sides and the condensation takes place in an external condenser [9-10]. At that point, sweeping gas membrane distillation (SGMD) in which a stripping gas is used on the cold side to sweep the permeate away, with Condensation in a separate device[11-15]. At this juncture, it is worthwhile to underline that the membrane technique is considered promising since it takes place at temperatures range (30 to 90) °C and could use the solar energy [16]. A survey of the state-of-the-art of membrane distillation (MD) and it is various and detailed applications was presented by Alklaibi and Lior [17]. Not far, Ding et al presented a model for predicting the rate of mass transfer in a membrane distillation unit to direct contact (DCMD) [18]. Other researchers, including Meindersma [19], Guijt [20], Payo [15], and Chouikh [21,22] worked on AGMD, but no one of them used solar as the energy source. Likewise, many authors have studied three different types of mass transfer modes through the membrane and possible combinations of this type [23, 24].
Also, Morteza Asghari and Rochd studied the effect of the thickness of the membrane in three different types of mass transfer [24-25]. An experience in the effect of feed saline concentration on permeate flux was studied by Dahiru [26]. At the sometimes, Lucy Mar Camacho [28] have studied the effect of pore size in the production of flux. Furthermore, many other authors produced a simulation with aspen plus in the effect of porosity [29-34]. Thus, the objective of this work is to study the effect of NaCl concentration, porosity, and membrane pore size on the production of the flux. The present article is organized as follows: In Section 2, we present the mechanism of mass transfer. In Section 3, the results and discussion. In section 4, the conclusion.

2. Mechanism of mass transfer:

The numerical solution methodology employed in this work is described in detail in some of our recent studies [24]. In order to study the mass transfer in this method, the models cited in our previous work have been used, which are Knudsen diffusion, viscous diffusion, and molecular diffusion. Thus, to get rid of the problem of the infinity of solutions, the polynomial approximation has been used. At this point, the three types of mechanisms of mass transfer are presented to show the importance and the equations governing each kind of mechanism.

- **Knudsen diffusion:** is based on the collisions between molecules and the-wall [24], this type of distribution is important in the systems with high temperature and pressure [31].

\[
J_K = K_K (P_{hm} - P_{mg})
\]  

With:

\[
K_K = \frac{2 \varepsilon r_p}{3 \tau \delta_m} \frac{8M_s}{\pi RT_m}
\]  

- **Molecular diffusion:** is based on the collision between the molecules [24], this type of distribution is important in the systems of intermediate temperature and pressure [31].

\[
J_{M,S} = K_{M,S} (P_{hm} - P_{mg})
\]  

With:

\[
K_{M,S} = \frac{\varepsilon pD_{ molecules} M_s}{\pi \delta_m RT_m P_a}
\]  

- **Viscous diffusion:** is based on both types of collisions [24], and this type of distribution is also useful in the systems of low temperature and pressure [31].

\[
J_p = K_p (P_{hm} - P_{mg})
\]  

With:

\[
K_p = \frac{1}{8 \gamma_s} \frac{r_p^2 \varepsilon P_m M_s}{\tau \delta_m RT_m}
\]

To throw more light into the effect of the reduction of vapor pressure caused by the dissolved species, Raoul’s law [26] proposed the following equation

\[
P_{hm} = (1-C_s) P_v
\]
With:

\[ C_s = \frac{x V_{\text{Solution}}}{M_{\text{NaCl}}} \]

\[ = \frac{x V_{\text{Solution}}}{M_{\text{NaCl}} + n_{\text{water}}} \]

(8)

Where: \( x \) is the concentration of NaCl, the number of moles of water \( n_{\text{water}} \) is 55.6 moles for 1 liter, \( M_{\text{NaCl}}=58.44\text{mol/l} \), and \( C_s \) is the mole fraction of solute or salinity. The difference in the partial pressure of the saturated vapor of both sides of the membrane may be calculated from the law of Antoine [15] using the following equation:

\[ p_v = \exp(23.328 - \frac{3841}{T-45}) \]

(9)

The average temperature of the membrane is given by the following equation [22]

\[ T_m = \frac{T_{wb} + T_{wg}}{2} \]

(10)

Furthermore, Qtaishat et al [27] proposed the expression of the amount of steam/air: \( P Dv/a \) (Pa.m\(^2\).s\(^{-1}\)) depending on the temperature [25]

\[ PD_{v/a} = 1.985 \times 10^{-5} T^{2.072} \]

(11)

With: \( P \) is the total pressure, and \( D_{v/a} = \frac{k_v}{\rho_v C_p} \) is a coefficient of vapor diffusion in the air

\[ D_{v/a} = \frac{k_v}{\rho_v C_p} \]

(12)

3-Results and Discussion:

Based on the present numerical approximations, reliable simple predictive graphics have been presented permitting the estimation of the flux as a function of NaCl concentration for different temperatures. The modelisation using numerical approximations in the figures 1, 2 and 3 were carried with the following input data: \( K_m = 0.05\text{Wm}^{-1}\text{K}^{-1} \); \( \delta_m = 4.10^{-4}\text{m4} \); \( \varepsilon = 0.75 \); \( \tau = 1.5 \); \( r_p = 0.11\mu\text{m} \). When the temperature is fixed, and the molar fraction \( x \) is swept between \([0; 30]\)g/l the following results are observed:
Figure 1: The variation of the flux depending on the NaCl concentration using the molecular mechanism at different temperatures and comparing the results obtained with the experience of Dahiru. [26].
ERROR: ioerror
OFFENDING COMMAND: imagemask
STACK: