J. Water Environ. Nanotechnol., 3(2): 128-140 Spring 2018

ORIGINAL RESEARCH PAPER

Effects of operating parameters in sweeping gas membrane distillation process: Numerical simulation of Persian Gulf seawater desalination

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Received: 2017.12.02 Accepted: 2018.01.19 Published: 2018.04.30

ABSTRACT

In this communication, an advanced, simultaneous mass and heat transfer model has been developed to take a meticulous glance on the influences of different parameters on Persian Gulf seawater desalination using Sweeping Gas Membrane Distillation (SGMD) technique. This essay focuses on the increasing the distillate flux by investigation of the physical properties and feed temperature of the sweeping gas membrane distillation on the seawater desalination. The effects of operating parameters, including feed temperature, salt concentration, sweeping gas temperature, and heat transfer coefficient on the distillate flux of the Persian Gulf seawater have been investigated. The effect of feed temperature on temperature polarization has also been studied. By increasing the feed temperature from 25 °C to 60 °C, the temperature polarization increases and the polarization coefficient (TPC) decreases; for instance, for membranes with PP, the TPC decreases from 0.95 to 0.905. By increasing the feed temperature, higher fluxes are achieved for both the gas velocities. Therefore, by increasing the feed temperature from 50 °C up to 80 °C, the distillate flux grows 9 times. Also, the distillate flux for membrane with PVDF as polymer increased from 0 to 4.2 by increasing the feed temperature from 40 °C to 70 °C. The model predictions show a small error of 3.6% with the experimental data reported in literature which indicates the reliability of simulated results.

Keywords: *Distillate flux; Numerical simulation; Seawater; Sweeping gas membrane distillation (SGMD); Temperature polarization*

How to cite this article
Asghari M, Dehghani M, Riasat Harami H, Mohammadi AH. Effects of operating parameters in sweeping gas membrane distillation process: Numerical simulation of Persian Gulf seawater desalination. J. Water Environ. Nanotechnol., 2018; 3(2): 128-140. DOI: 10.22090/jwent.2018.02.004

INTRODUCTION

Membrane distillation (MD) is one of the pioneer and most usable processes in brine treatment which is a thermally driven desalination process which is a combination evaporation of water and a hydrophobic porous membrane [1-3]. MD process includes phase separation and needs a heating source. Given that the temperature of feed solution is quite low, the freely available grades of wasted heat from different industries could be utilized as the energy source. It can desalinate the feed solution with very high salinity (higher than 10,000 mg/L of total dissolved solid), including the heavy salty water from reverse osmosis process or industrial wastewater (where reverse osmosis cannot be applied) [4-7]. Therefore, there is a great opportunity for MD processes in distillation and purifying water from waste streams. Regardless of

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the advantages, numerous issues in MD process still require fundamental understanding, optimization and solutions, such as: wetting, the permeance, fouling and scaling.

In addition to feed temperature and salinity, the membrane mass transfer coefficient is mostly determined by the characteristics of the membrane materials, such as porosity, tortuosity and thickness. Previous studies have attempted to correlate the preparation parameters of membranes to the MD flux, therefore, qualitative characterization of the membrane morphology was then utilized as a descriptive controlling factor for the MD performance [8-11].

Some studies have been undertaken to control the membrane performance by improving the pores size and the substrate structure [12-16]. Besides, the surface hydrophobicity of the membrane also affects the flux, which led to a simple correlation between the membrane porous morphology, pore size and size distribution which are very important factors influencing the MD performance [17-20]. This process has four major configurations which are introduced and discussed in the literature, comprehensively [21]. Significant progress has been observed for the last years [22-25], the development and selection of suitable MD systems still remain challenging.

Therefore, it is essential to provide some quantitative guidelines based on performance for comparing MD membranes from different materials to better selection and design MD membranes. As mentioned earlier, the MD process includes four major configurations which are: direct contact MD (DCMD), air-gap MD (AGMD), sweeping gas MD and vacuum MD (VMD) (SGMD) [25]. Among them, SGMD and DCMD are the least and the most investigated configurations, respectively [26]. Detailed information studies of MD configurations have been discussed in literature in the last decades. SGMD process has been used for different purposes including wastewater treatment [27, 28], alcohol-water separation [29], and brine concentration [30].

Literature review on SGMD process

In the study of Huang *et al.* [31], a hollow fiber membrane tube bank (HFMTB) was prepared for SGMD process. A HFMTB with an in-line arrangement was used for sweeping air membrane distillation. In mentioned HFMTB, the salty water flowed inside the fiber tubes, while the sweeping air flowed between the tube holes in a counter flow configuration. Heat and water vapor can be swapped through the membranes. The vapor transferred from the hot saline side through the membranes was taken away by the sweeping air flow out from the HFMTB. The conjugate heat and mass transfer in the tube bank were then investigated in that study. It was found that the effects of the different pitch-to-diameter ratios on the sweeping air side basic data were much larger than those on the brine side. Shukla *et al.* [32] investigated the use of porous metal hollow fibers in sweeping gas membrane distillation. Various stages were covered, starting from membrane synthesis up to the testing of a pilot scale membrane module. The pore surface of the metal fibers was made hydrophobic using functionalization with polydimethylsiloxane or stearic acid. In another study, Karanikola *et al.* [33] used hollow fiber SGMD module and test it at various air and salt-water flow rates and temperatures. A model based on heat and mass transport was developed to predict permeate production rates. The dependence of permeate production rate on brine temperature, air flow rate and brine flow rate was also simulated in this work. Numerical simulations did support the selection of membrane characteristics and air and brine flow conditions for optimal performance in water desalination. Condensation was then predicted to occur on the air side of the membrane due to saturation of the sweeping gas and is accounted for in the model. In the absence of condensation, temperature profiles in the module could not be predicted correctly. In the study of Khayet *et al.* [34], a central compositional orthogonal design were applied for modeling and optimization of SGMD process. The effects of the operational parameters, liquid temperature, gas temperature, liquid flow rate and gas flow rate and their binary interactions on the membrane distillate flux (i.e. permeate flux) were investigated. As it reveals from these studies, different studies are presented on the SGMD systems and the operating parameters.

However, there are no studies on the SGMD feed temperature and physical properties and also on simultaneous mass and heat transfer modeling of SGMD processes. Also, there is no specific study on the Persian Gulf sea water purification using SGMD process. The Persian Gulf is certainly one of the most vital bodies of water on the planet, as gas and oil from Middle Eastern countries flow through it, supplying much of the world's

energy needs. The refineries and petrochemical industries, which produce a lot of waste heat and are located close to the Persian Gulf, would be able to use the enhanced process to produce distilled water from seawater. The wider application of the desalination process could be used by companies to produce distilled water for industrial processes. In this essay, a simultaneous mass and heat transfer model has been developed to improve the usability of the SGMD process for Persian Gulf seawater desalination. The main purpose and novelty is to increase the distillate flux by investigating physical properties, the feed flux, temperature of the seawater by SGMD process.

MODEL DEVELOPMENT

SGMD is a non-isothermal membrane process and hydrophobic porous membrane that is employed as a barrier separating hot feed solution and cold permeate. Water vapor is generated at the membrane and the hot feed interface, diffusing across the membrane, and condensed at the permeate side and finally swept by the sweeping gas. Heat and mass transfer occurs simultaneously. In order to enhance the performance of SGMD in desalination, a simultaneous heat and mass transfer model in SGMD system has been developed and validated with experimental data. The model has been solved numerically using MATLAB and on the non-linear equations. With the aim of enhancing the mass transfer coefficient, a non-stationary gas barrier has been applied which reduces the heat loss [35]. Some assumptions are considered for the proposed model which are:

- A steady state SGMD system.
- There is no pressure gradient for the sweeping gas [36, 37].
- Constant velocity of the sweeping gas (due to the stable condition of the membrane) [34].
- Vapor condensation occurs inside the condenser, and not in the membrane's pores [37].
- Water vapor is just carried by the sweeping gas out to the condenser [37].
- There is no heat loss to the environment [36].

Fig. 1 shows a short-term summary of the procedure followed by the numerical method based on a MATLAB program.

The total heat transfer in the SGMD process contains different terms. First, convective heat transfer from the bulk (feed side) to the surface of membrane which can be written as follow [38]:

$$Q_h = h_f (T_b - T_1) \quad (1)$$

where, h_f represents the coefficient of convective

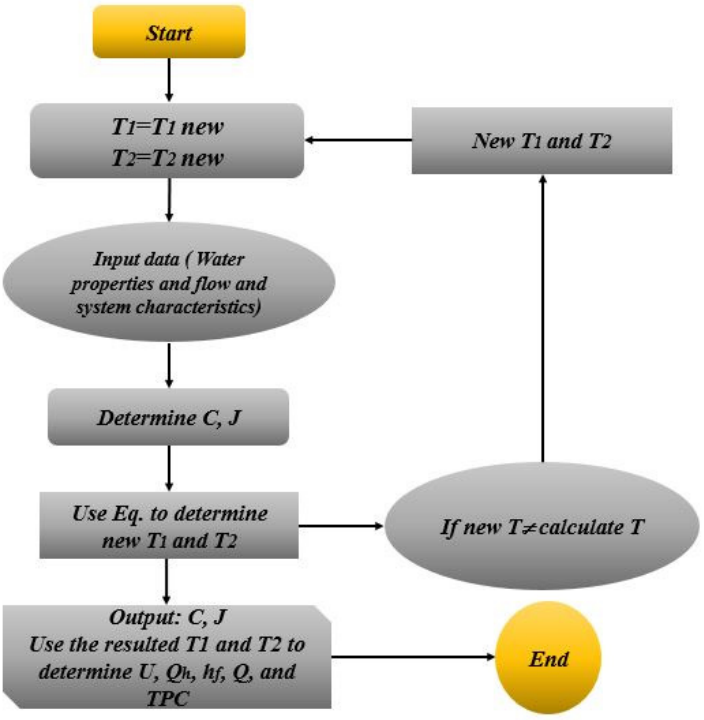

Fig. 1: The MATLAB flowchart of this study.

heat transfer and can be calculated as follow:

$$h_f = 1.86k_l\left(\frac{RePr}{d_h^2}\right) = 0.116k\left(Re^{\frac{2}{3}} - 125\right)Pr^{\frac{1}{3}}\left[\frac{1+\left(\frac{d_h}{L}\right)^{\frac{2}{3}}}{d_h}\right] \quad (2)$$

In Eq. 1, Q_h is the heat flux which is provided by the circulative hot feed to the membrane surface, T_b and T_1 are the bulk and the membrane's surface temperatures, respectively. k_l is the feed thermal conductivity, d_h is the feed channel hydraulic diameter and L is the module length.

The Nusselt (Nu) number can be calculated for laminar regime and also the turbulent one as follows [39, 40]:

$$Nu = 0.13\,Re^{0.64}Pr^{0.38} \qquad Re<2100 \qquad (3)$$

$$Nu = 0.13\,Re^{0.8}Pr^{0.33} \qquad Re>2100 \qquad (4)$$

and

$$Re = \frac{\rho v d_h}{\mu}$$

$$Pr = \frac{C_p\mu}{k_l} = \frac{\upsilon}{a}$$

where ρ, ν and d_h are the fluid density, velocity and hydraulic diameter of the feed in hot channel of the SGMD module, respectively. Moreover, μ is the viscosity of hot fluid in the feed channel, and a and C_p are the thermal diffusivity and the specific heat capacity, respectively. The sweeping gas heat transfer coefficient could be expressed as follow [41]:

$$h_a = 0.206(\frac{k}{d_h})(Re\cos\propto)^{0.63}Pr^{0.36} \quad (5)$$

where α is the yaw angle, which can change from 0° to 90° for pure cross-flow to parallel flow, respectively. Since there is no heat generation or consumption through the SGMD module, the total heat transfer could be written as:

$$h_f(T_{bf} - T_f) = J\lambda + \frac{\varepsilon K_g + (1-\varepsilon)k_m}{\delta}(T_f - T_a) = h_a(T_{ba} - T_a) \quad (6)$$

where T_f, T_{bf}, T_a, T_{ba} are representative temperatures in the feed channel, i.e. on the membrane surface, in the feed bulk, in the distillate side and on the surface of the membrane, and in the sweeping gas bulk, respectively. The λ symbol shows the latent heat of water, and J is the distillate flux.

In the absence of non-condensable gas, the Knudsen diffusion mechanism is the controlling diffusion mechanism [42]. Hence, diffusion over the membrane can be calculated as follows:

$$\mathrm{J} = \frac{4\varepsilon\, d_p\sqrt{\mathrm{M}}}{3x\,\delta_m(2\pi RT)^{1/2}}(P_1 - P_2) \quad (7)$$

and

$$\mathrm{C} = \frac{4\varepsilon\, dp\sqrt{\mathrm{M}}}{3x\,\delta_m(2\pi RT)^{1/2}}$$

where C, ε, d_p, M, x and δ_m are the MD coefficient, the membrane porosity, the pore diameter, water molecular weight, the membrane tortuosity and its thickness, respectively. P_1 and P_2 are the water saturated vapor pressures in the feed and distillate channels, respectively. The C parameter is also related to the membrane characteristics and the feed temperature, as well [43].

When vapor molecules pass a distance longer than the membrane thickness, the pore tortuosity can be measured as follow [44]:

$$x = \frac{2-\varepsilon}{\varepsilon}$$

Moreover, using the partial pressure (P_I), the vapor pressure of pure component (water) (p_i^0), the activity coefficient (ξ_i) and the liquid molar coefficient (x_i) (in non-ideal mixtures), the VLE (vapor-liquid equilibrium) value can be calculated as follow [44]:

$$P_1 = P_i^\circ x_i \xi_i \quad (8)$$

where the vapor pressure of pure component (p_i^0) can be calculated by using the well-known Antoine's equation [45].

$$P_i^\circ = \exp[A_1 - \frac{B}{C+T}] \quad (9)$$

As mentioned earlier, there is a temperature difference between two sides of the membrane. Hence, the conductive heat transfer occurs cross the membrane thickness [38]:

$$Q = \frac{k_{em}}{\delta_m}(T_1 - T_2) + JH_v \quad (10)$$

where H_v is the enthalpy of the vapor molecules (i.e. water) (which can be calculated by Eq. 12), k_{em} is the membrane average thermal conductivity, T_1 is the temperature of membrane surface in the feed channel, and T_2 is the temperature of membrane surface in the distillate channel. In the aforementioned equation (Eq. 10), the first term mentions the conductive heat transfer and the second one mentions the water latent heat.

The average thermal conductivity of the applied membranes can be measured as follow [22]:

$$k_{em} = \varepsilon k_a + (1-\varepsilon)k_m \quad (11)$$

where k_a and k_m are the thermal conductivities of the sweeping gas and the applied membrane material, respectively. Enthalpy of water vapor molecules in the temperature range of 273 to 373 °C can be calculated as follow [46]:

$$H_v = 1.7535\,T + 2024.3 \quad (12)$$

where the standard units for H_v and T are $kJkg^{-1}$ and *K*, respectively.

For small values of the water partial vapor pressure, the mass transfer flux for the distillate side can be calculated as follow [47]:

$$J = \frac{C D_{AB} M_v}{\delta_a}(y_1 - y_2) \quad (13)$$

where δ_a, D_{AB} and M_v are the boundary layer thickness of the sweeping gas on the membrane surface, the molecular diffusion coefficient of water molecules (in the vapor phase) into air and the water molecular weight, respectively. Moreover, y can be calculated as follow based on the vapor pressure item [47]:

$$y = \frac{p_v}{p} \quad (14)$$

where P is the total pressure of the sweeping gas stream. Combining Eq. 13 and 14, the mass transfer flux for the distillate side would be:

$$J = \frac{D_{AB}\,M_v}{\delta_a\,R\,T_{avg}}(P_1 - P_2) \quad (15)$$

where T_{avg} is the average temperature in the distillate side and R is the global gas constant. Subsequently, D_{AB} of the water vapor molecules into the sweeping gas stream (i.e. air) can be calculated as follow [47]:

$$D_{AB} = \frac{1.895 \times 10^{-5} T_{avg}^{2.072}}{P}$$

Numerical analysis of the SGMD model

The mass and heat transfer models have been numerical dissolved to determine the effects of operation parameters on permeation flux in the SGMD process of Persian Gulf seawater desalination. The obtained results have been validated with experimental data collected from literature [34]. The proposed model has been developed using MATLAB software for three different polymeric membranes namely polyvinylidene difluoride (PVDF), polytetrafluoroethylene (PTFE) and polypropylene (PP), all with the porosity of 75%, thickness of 600 µm and nominal pore size of 0.2 µm. Operating variables, including the feed velocity of 0.8 m/s, the feed temperature of 50 °C and the sweeping gas velocities of 6.3 and 11.3 m/s, have been investigated. The module's length and width of 21.5 cm and 16.5 cm have been investigated, respectively [48]. The conductive heat transfer coefficients (at 296 K) for the membranes are as follow [49]:

- PP: 0.11 – 0.16 ($W.m^{-1}.K^{-1}$)
- PVDF: 0.17 – 0.19 ($W.m^{-1}.K^{-1}$)
- PTFE: 0.25 – 0.27 ($W.m^{-1}.K^{-1}$)

RESULT AND DISCUSSION

In this work, a numerical model has been used to predict the performance of a SGMD system for seawater desalination purpose. The impact of operating parameters (which were mentioned earlier) have been studied. Moreover, the influence of feed temperature has also been investigated to examine the temperature polarization effect. The results obtained by the developed model have been validated with the experimental results reported in the literature. Table 1 displays the Persian Gulf seawater characteristics [50].

Effect of sweeping gas film thickness, tortuosity, membrane thickness and heat transfer coefficient on the distillate flux

Fig. 2.a shows the influence of the depth of the distillate channel on the distillate flux. As it is observed, distillate flux decreases with increase of

Table 1: The analysis of the Persian Gulf seawater studied in this work [50].

Item	Value	Unit
Na^+	14985	ppm
Cl^-	27272	ppm
SO_4^{2-}	3667	ppm
Mg^{2+}	1940	ppm
Ca^{2+}	1231	ppm
K^+	581	ppm
SiO_2	0.30	ppm
Mn^{2+}	0.12	ppm
Fe^{2+}	0.054	ppm
NH_4^-	0.05	ppm
TSS	46.7	ppm
TDS	48000	ppm
pH	8.7	-
Conductivity @ 20°C	65000	µS/cm

channel's depth in the cold side. In other words, thicker gas film (more depth distillate channel) can be translated to the higher mass transfer resistance against the distillate flux. In order to overcome the proposed mass transfer resistance, further to distillate channel depth reduction, higher gas flow can be investigated as one of the most effective strategies. Shirazi and co-workers observed and comprehensively discussed the effect of sweeping gas flowrate [27]. Authors concluded that higher sweeping gas flowrate as well as smaller channel depth in the cold side can significantly increase the distillate flux [27]. Moreover, it was concluded in another work [51] that higher sweeping gas flowrate in the SGMD mode is more effective than that of the cold stream flowrate in the DCMD mode.

Tortuosity is one of the important structural features of porous membranes [52]. In case of MD membranes, subsequently, tortuosity is an effective parameter on the distillate flux [53]. The tortuosity itself is a function of the membrane thickness, as well. To the best of our knowledge, there is no specific data in open literature for tortuosity factor of the investigated membranes in this study; however, for similar membranes, the manufacturers reported a tortuosity factor in the range of $2 < \tau < 14$ [54]. In most of MD studies, the tortuosity factor of 3 is assumed for modeling and predicting the distillate flux, regardless of what the MD mode is [55].

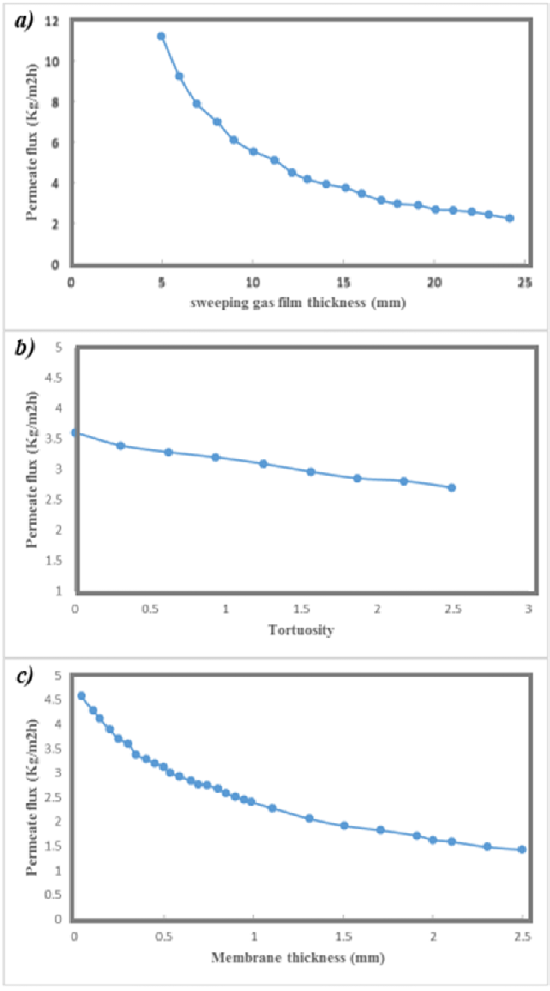

Fig. 2: Effect of a) distillate channel depth (i.e. in the cold side of SGMD) width of sweeping gas band, b) tortuosity, c) membrane thickness on permeate flux.

Fig. 2.b shows the effect of membrane tortuosity on the distillate flux. As could be observed, while the tortuosity factor changes, the distillate flux (i.e. *J*) maintaines fairly constant.

Membrane thickness can be investigated as an emerging parameter which significantly affects the MD process performance. As the MD procedure is a thermally driven one, thicker membranes may perform better when the conductive heat transfer cross the membrane is highlighted [4]. On the other hand, higher membrane thickness can dramatically increase the mass transfer resistance of vapor molecules [22]. As a consequence, the effect of membrane thickness on the distillate flux is a worthy parameter to study. Fig. 2.c shows the effect of membrane thickness on the distillate flux of the investigated membranes. As can be observed, the distillate flux reduces with increase the membrane thickness.

As can be seen in Fig. 3.a, increasing the heat transfer coefficient increases the distillate flux. Increasing the heat transfer coefficient can reduce the heat transfer resistance, and it can lead to a reduction of temperature gradient, as well. As a result, there is not a meaningful temperature difference between the feed bulk and the membrane surface (i.e. in the hot side). Consequently, for the water molecules, higher saturated vapor pressure can be provided and then the driving force increases, exponentially. All these facts can lead to higher distillate flux (see Fig. 3.a).

Effect of feed properties on the distillate flux

Fig. 3.b shows the influence of the seawater feed temperature on the distillate flux for three proposed hydrophobic membranes (e.g. PP, PTFE and PVDF membranes). As can be observed, the distillate flux increases by the feed temperature. This is a well-known behavior for the all MD configurations and

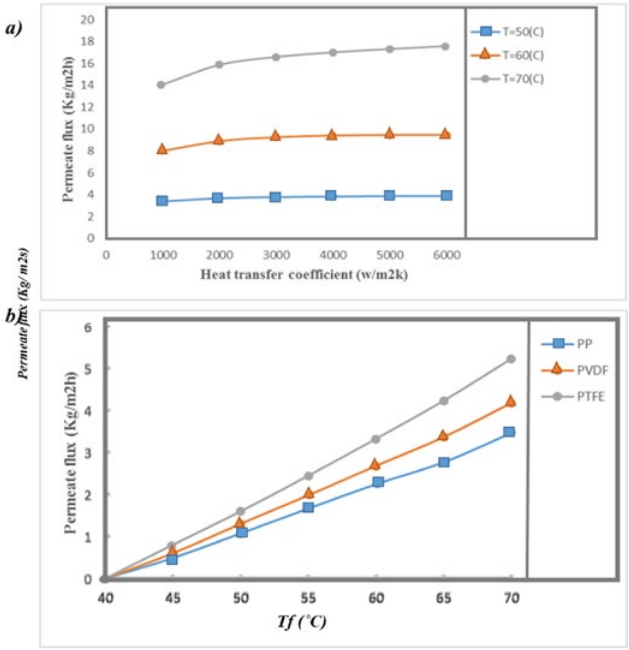

Fig. 3: a) The heat transfer coefficient influence on the distillate flux, b) Effect of feed temperature on the distillate flux for the three hydrophobic membranes.

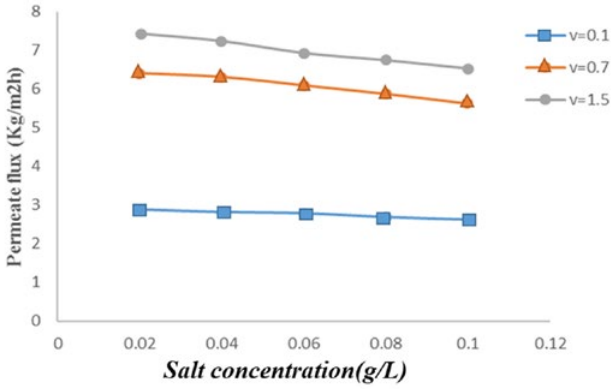

Fig. 4: The effect of salt concentration on permeate flux.

it is in good agreement with the literature [56]. This can be explained based on the well-known Antoine's equation, which claims that higher saturated vapor pressure of volatile molecules could be provided at higher temperature. In other words, higher operating temperature could be translated to more significant driving force for the MD process (see Fig. 3.b).

The effect of feed temperature on the TPC (temperature polarization coefficient) for the generally used membranes (e.g. PP, PVDF and PTFE) in MD process is widely discussed in our earlier studies [44, 49]. For the proposed membranes, the effects of temperature polarization are directly proportional to the thermal conductivity of the polymer material of the membrane itself. It has been shown that temperature polarization coefficients decrease with the feed temperature (T_f). This can be clarified by the fact of higher energy consumption from the vaporization at higher temperatures of the feed [49]. On the other hand, for the membrane material, at much lower thermal conductivity, the influence of the temperature polarization will be reduced due to the less heat

dissipation by membrane surface [44].

Same as other membrane-based separation processes, MD is sensitive to the feed concentration [12]. In fact, further to temperature polarization, the concentration polarization is another important parameter that can decline the MD flux. As could be observed in Fig. 4, by increasing the feed concentration, distillate flux decreases. It is worth noting that the feed flowrate can directly affect the distillate flux by decreasing both temperature and concentration polarization effects. In other words, higher feed flowrates can reduce the effect of temperature and concentration boundary layers.

As mentioned earlier, the MD method is a separation technique which can be thermally developed [4]. Therefore, the feed temperature is among the most important operating variables. Fig. 5 shows the effect of feed temperature on the distillate flux. As can be observed, with increasing the feed temperature, higher fluxes are achieved for both the gas velocities. Increasing the feed temperature from 50 °C up to 80 °C, the distillate flux grows 9 times. This fact can be explained based on the exponential relation between the feed temperature and the vapor pressure which follows the Antione's equation [57]. The result of feed temperature vs. flux has been compared to the results of the study of Shirazi *et al.* [51]. The effect of feed temperature on the permeate flux through SGMD configuration with the process condition of Q_h = 600 mL/min, Q_a = 0.453 Nm^3/h and C = 45 g/L were determined in their study. As it reveals, the results are in good agreements with the experimental results and the slight deviation is because of the operating conditions which had made this deviation.

On the other hand, for all three investigated feed velocities, by increasing the feed temperature distillate flux increases (see Fig. 5), which is in good agreement with the literature [58]. It is worth noting that the more turbulent flow regime in the feed channel can be translated to the lower concentration and temperature polarization effects, which is due to lower boundary layers' effect, as well [59].

Fig. 6.a shows the effects of feed velocity, heat transfer coefficient in the feed channel and temperature and concentration polarizations on the distillate flux. Working under a turbulent regime can provide much more vapor molecules due to higher heat transfer and higher Reynolds number (R_e) [60]. In MD processes, and more specifically in the SGMD mode, the higher vapor molecules are

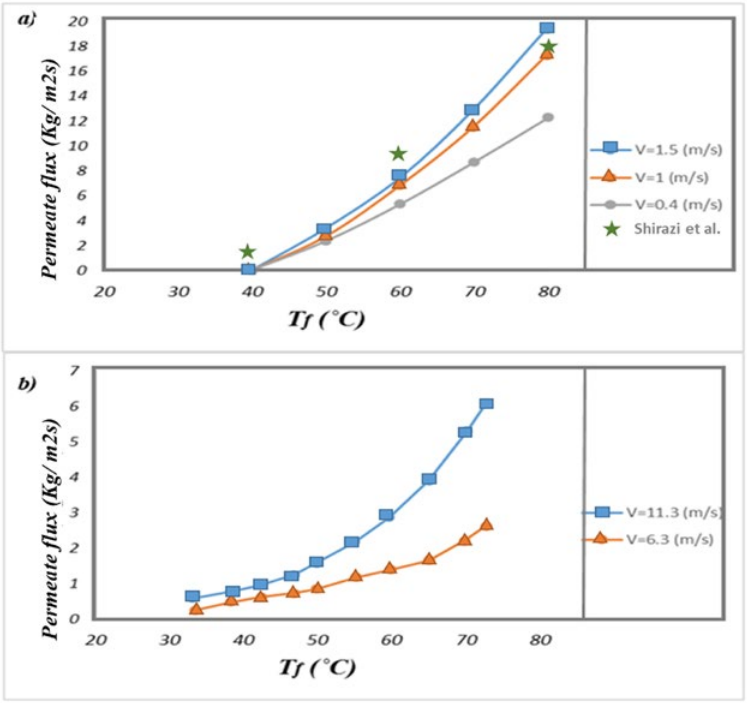

Fig. 5: The effect of feed temperature on permeate flux (a) in three different velocities (0.4,1,1.5 m/s), (b) in two different sweeping gas velocity (6.3,11.3 m/s) feed velocities = 0.1 m/s, temperature = 20 °C. (Flux is multiplied in 10^{-3})

translated to higher distillate flux. In better words, higher input feed velocity (R_e > 2100) causes higher flow intensity and mixing velocity. This means the membrane surface temperature gets closer to the bulk temperature, thereunder the difference of vapor pressure increases.

As mentioned earlier, increasing the feed velocity is an alternative to reduce the temperature/concentration polarization by growing the Reynolds number [61]. While the feed flow intensity is increasing, the hydrostatic pressure which is pushing on the membrane surface should be kept lower than the liquid entry pressure (LEP) of membrane's pores, which keeps the membrane dry.

Effect of feed temperature on the temperature polarization

In all MD configurations, a complicated relevance between heat and mass transfers appears due to unmixed hot channel (boundary layers) in the feed side and on the membrane surface [62]. Due to vaporization of water molecules, the feed temperature on the surface of the membrane is lower than the temperature of feed bulk which causes a temperature gradient adjacent of the membrane surface and in the liquid layer [63]. It is worth quoting that the proposed temperature gradient provides by the latent heat required for the evaporation in membrane surface, i.e. on pores' face. This phenomenon is called the temperature polarization [64, 65]. The effect of feed temperature on temperature polarization is shown in Fig. 6.b. As can be observed, by increasing the feed temperature, the temperature polarization increases and its polarization coefficient (TPC) decreases. This is due to the higher energy consumption of evaporation (higher latent heat) under higher feed temperatures.

Effect of sweeping gas properties and parameters on permeate flux

Fig. 7.a shows effect of the velocity of sweeping gas on the distillate flux. According to the experimental data which were published in the literature [36], increasing the sweeping gas velocity reduces the mass transfer resistance in the distillate channel, as R_e number changes. This achievement is also confirmed experimentally by the study of Shirazi *et al.* [27]. In other words, the distillate flux would be raised by increasing the heat transfer coefficient in the distillate channel. However, based

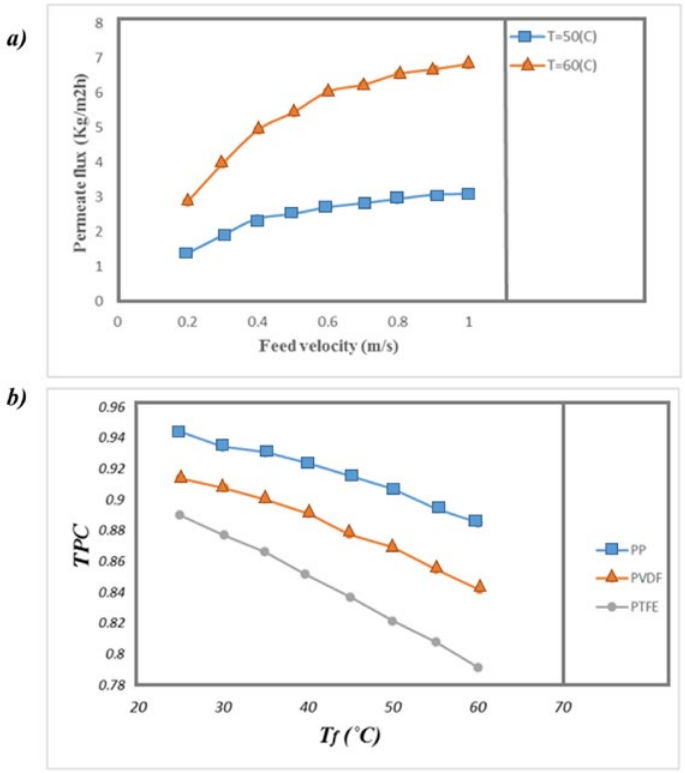

Fig. 6: a) Effect of the velocity of seawater feed on the distillate flux, b) Effect of feed temperature on the temperature polarization.

on the results of this work, it is not appropriate to increase the sweeping gas velocity over than 12 m/s value, due to dramatically distillate flux reduction (see Fig. 7.a).

In case of the SGMD process, gas temperature in the range of 10 to 30 °C has been reported in the literature to be used for gas stream in the distillate channel [4, 59]. It should be noted that the sweeping gas temperature can affect the SGMD overall performance. In other words, the lower sweeping gas temperature is, the higher distillate flux will be achieved. Fig. 7.b shows the model prediction for the influence of the temperature of sweeping gas on the distillate flux.

In order to validation of the developed model, its prediction has been compared with the Khayet's experimental data on Persian Gulf seawater desalination [34] (see Fig. 8). As could be observed, the model predictions and the experimental results are well-fitted with the overall error of 3.6%.

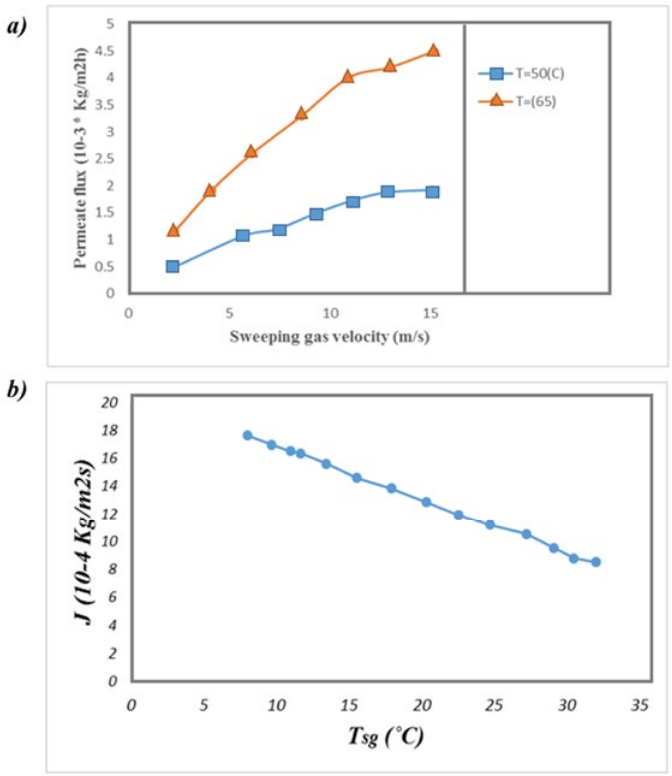

Fig. 7: a) Effect of the sweeping gas velocity in the distillate channel under two constant feed temperatures (feed velocity of υ = 0.10 m/s) on the distillate flux, b) Effect of the temperature of sweeping gas on the distillate flux (J).

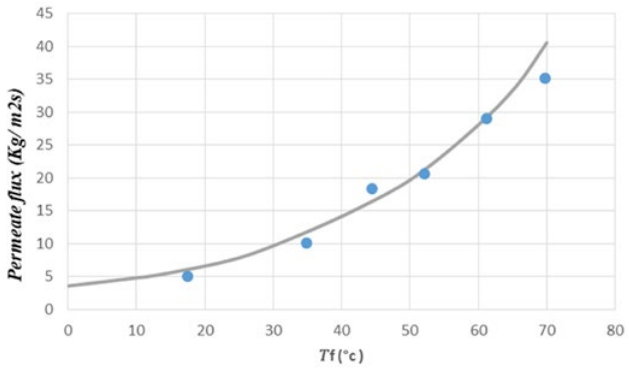

Fig. 8: The model validation with Khayet's experimental data.

CONCLUSION

A theoretical study on the SGMD process has been performed to improve its application in seawater desalination. The effect of operating parameters (including the feed temperature, the membrane's pores tortuosity, the membrane thickness, the heat transfer coefficient, the sweeping gas velocity, the salt concentration, the sweeping gas temperature, the feed velocity and temperature polarization) for three different membrane materials have been studied. Results indicate that the distillate flux increases by increasing the feed temperature. Higher heat transfer coefficient has been found as a positive parameter to achieve higher distillate flux. Moreover, lower pore's tortuosity, higher sweeping gas velocity, up to 12 m/sec however, and higher feed velocity have positive effects on the SGMD performance. By increasing the feed temperature from 25 °C to 60 °C, the temperature polarization increases and the polarization coefficient (TPC) decreases; for instance, for membranes with PP, the TPC decreases from 0.95 to 0.905. Also, the distillate flux for membrane with PVDF as polymer increased from 0 to 4.2 by increasing the feed temperature from 40 °C to 70 °C. On the other hand, decreasing distillate flux is observed with increase the membrane thickness, salt concentration, and sweeping gas temperature. It can also be concluded that the temperature polarization increases with the feed temperature.

ACKNOWLEDGMENT

The Authors are very grateful to Energy Research Institute at University of Kashan for supporting this work.

CONFLICT OF INTEREST

The authors declare that there are no conflicts of interest regarding the publication of this manuscript.

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