1 **Effect of non-woven net spacer on a direct contact membrane distillation performance:**

2 **Experimental and theoretical studies**

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28 **Abstract**

29 This study provides a comprehensive and systematic overview of the fundamental characteristics of heat and

mass transfer in the direct contact membrane distillation (DCMD) process that employs different types of spacers ~~on (i.e., adjacent to)~~ one or both surfaces of the membrane. Detailed theoretical investigations were carried out to demonstrate the effects of spacers adjacent to the membrane surface on heat and mass transfer enhancement in the DCMD with a PTFE/PP composite membrane, complemented with experimental data for model validation. Thus, this work aimed to propose and demonstrate the heat transfer correlation for spacer-filled channels to reliably predict the heat and mass transfer improvement by non-woven net spacers in the DCMD process. The results showed that the permeate flux enhancement by the spacers ranged between 7% – 19% only for the spacer-filled permeate channels and between 21% – 33% only for the spacer-filled feed channels even at higher flow rates, thus indicating lower flux enhancements in the spacer-filled permeate channels. This was because the influence of spacers on flux improvement became more evident at higher temperatures owing to higher temperature polarization. In this study, the maximum flux enhancement of approximately 43% over the empty channels, ~~which~~ was achieved using the thinnest and densest spacer with a hydrodynamic angle of 90°, adjacent to both membrane surfaces.

Keywords: spacer; temperature polarization; heat and mass transfer; flux improvement; desalination

1. Introduction

Membrane distillation (MD) has attracted significant attention in the last few decades as an emerging technology owing to its numerous advantages [1]. The driving force of MD, which is a thermally driven membrane separation process in which a microporous hydrophobic membrane is used, is the partial pressure difference of water vapor at the liquid-vapor interfaces of the membrane caused by the temperature gradient imposed on both interfaces. There are four types of MD configurations, including the direct contact MD (DCMD), air gap MD (AGMD), material gap MD (MGMD), and vacuum MD (VMD) and those are categorized by the condensation scheme inside the module [2]. In the case of DCMD, the temperature gradient results from evaporation and condensation at the liquid-vapor interface on the feed and permeate sides of the membrane, respectively, as well as heat conduction through the membrane. Therefore, the membrane surface temperature differs from its bulk temperature, a phenomenon known as the temperature polarization, thus resulting in a significant loss of the thermal driving force, and in a lower permeation flux. As a result, the performance of MD is affected mainly by temperature polarization rather than concentration polarization [1],

even when treating highly concentrated saline solutions [3]. Reduction in the temperature polarization in MD can be achieved by improving the flow characteristics, such as higher flow rates and turbulence conditions. However, the resulting large pumping energy consumption is not desirable from an economic point-of-view. Moreover, in the case of the composite membrane (double layer), it is necessary to take into account the physical damage, such as the exfoliation of the soft polymer from the membrane owing to the excessively high flow rates. An alternative way to reduce the temperature polarization is the use of a spacer in the flow channel rather than increasing the flow rate [4–7]. Improvement in the flow characteristics may result from the existence of turbulence or eddy currents induced by the spacers. Although a pressure drop can occur in the channel as a result of employing the spacer-filled channels, the total specific energy consumption may be reduced owing to the increase in the water production [8].

Fig. 1. Trend Variation of the number of publications on MD and spacer-filled MD over the last four decades. The orange bars denote the number of publications on “membrane distillation” [4], and purple bars denote publications on “membrane distillation and spacers”.

Such MD processes have several potential advantages: low-operating temperature and hydraulic pressure, a rejection of nonvolatile solute that is almost 100%, low sensitivity to salt concentration and concentration polarization, low-footprint requirements, and potentially high-permeation flux [1]. For these reasons, MD has been regarded as an emerging desalination technology for producing freshwater from seawater and a number of

studies on MD have been conducted in recent years. The growing interest in MD is reflected in the growth rate of scientific publications over the years. Fig. 1 depicts the number of publications on “membrane distillation” (orange bars) between 1980 and 2017 obtained from ScienceDirect (www.sciencedirect.com) and shows an exponential increase over the years [9]. Conversely, the numbers of publications on “membrane distillation” and “spacers” (purple bars) between 1990 and 2017 obtained from Google Scholar (scholar.google.com) are also shown in Fig. 1 demonstrating a minor increase. In addition, Table 1 presents a detailed comparison of research articles on the MD process employing spacer-filled channels since 2000. It is shown that most of the studies have focused on DCMD processes using flat-sheet membranes. In particular, before 2010, a simple, lumped parameter model (i.e., 0D model) that ignored mass, species, momentum, and energy balances in both bulk feed and permeate flows, was mainly used for simulations. Thanks to recent advances in computational power, computational modeling approaches and methods since 2010, both 2D and 3D modeling/simulation studies has been performed using computational fluid dynamics (CFD) to investigate the heat transfer and pressure drop characteristics in spacer-filled MD.

As it can be deduced from the aforementioned literature, despite evident effects of the spacer on the heat and mass transfer enhancement in different MD processes, investigations on spacer-filled MD are still limited in comparison to other MD research topics. Only a few reports have been found to take a closer look into the effect of the spacers on the heat transfer coefficient causing the mass transfer enhancement effect. In addition, despite these many efforts, most of the existing theoretical and experimental studies, which have attributed a 0D and model, a 1D models that only considers heat or heat and mass balance, and a 2D or 3D CFD models that employs a limited computational domain due to high complexity and associated high computational time and cost, based on the lab-scale MD experiments, would be very limited in the performance evaluation of full-scale MD modules. It is important to note that both the pressure loss and the mass transfer enhancement effect of spacers used in full-scale modules can be assessed. Therefore, in regards of the later module design a more reliable and accurate detailed model of spacer-filled MDs is essentially required when evaluating the MD performance.

Table 1 Chronological list of publications on “membrane distillation” and “spacers” in the period of 2000 and 2018.

Year	MD configuration	Methodology	Membrane configuration	Reference
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2000	DCMD	Exp.	Flat sheet	[10]
2001, 2003	DCMD	Exp. / Sim. (0D)	Flat sheet	[11–13]
2003	AGMD	Sim. (2D)	Flat sheet	[14]
2005	AGMD	Exp.	Flat sheet	[15]
2006, 2007	DCMD	Exp. / Sim. (0D)	Flat sheet	[16–18]
2008	DCMD	Exp. / Sim. (1D)	Hollow fiber	[19]
2008	DCMD	Sim. (0D)	Flat sheet	[20]
2009	DCMD	Exp. / Sim. (2D)	Flat sheet	[21]
2010	DCMD	Exp.	Flat sheet	[22]
2011	DCMD	Exp. / Sim. (0D)	Hollow fiber	[23]
2012	DCMD	Exp. / Sim. (1D)	Flat sheet	[24]
2012	DCMD	Sim. (2D)	Flat sheet	[25]
2012	DCMD	Exp. / Sim. (2D)	Hollow fiber	[26]
2012	DCMD	Sim. (3D)	Hollow fiber	[27]
2013	AGMD	Exp.	Flat sheet	[28]
2013	DCMD	Exp. / Sim. (1D)	Flat sheet	[29]
2013	DCMD	Sim. (3D)	Spiral-wound	[30]
2013	AGMD	Exp. / Sim. (1D)	Flat sheet	[31]
2014	VMD	Exp. / Sim. (0D)	Flat sheet	[32]
2014	DCMD	Exp. / Sim. (2D)	Flat sheet	[33]
2015	DCMD	Exp. / Sim. (1D)	Flat sheet	[34]
2015	DCMD	Sim. (3D)	Flat sheet	[35]
2016	DCMD	Exp. / Sim. (1D)	Flat sheet	[36]
2017	DCMD	Sim. (3D)	Flat sheet	[37–40]
2017	DCMD	Exp. / Sim. (3D)	Flat sheet	[41]
2017	DCMD	Exp. / Sim. (0D)	Flat sheet	[42,43]
2017	DCMD	Exp. / Sim. (1D)	Flat sheet	[44]
2017	DCMD	Exp. / Sim. (2D)	Flat sheet	[45]
2018	DCMD	Exp.	Flat sheet	[46]

Therefore, the main objective of this study was to theoretically investigate the influence of spacers adjacent to the membrane on the permeate flux enhancement in the DCMD process with a PTFE/PP composite membrane using a detailed and rigorous theoretical model, an effort that was complemented with experimental

studies for model validation. The developed model took into account the structural characteristics of the composite membrane, the heat and mass transfer mechanism through the membrane, and the mass, species, momentum, and energy balance for both bulk feed and permeate flows in the spacer-filled channels. This study focused on the proposition and assessment of convective heat transfer correlation for spacer-filled channels to achieve a more accurate prediction of heat and mass transfer enhancement based on the use of net-type spacers in the DCMD process. In addition, the performance of the proposed model was compared with an existing heat transfer model to demonstrate the superiority of the model developed in the present work.

2. Experimental

2.1 Composite membrane and characterization

Commercially available hydrophobic microporous composite membranes with an active layer of polytetrafluoroethylene (PTFE) and a scrim-backing support layer of polypropylene (PP) were used in all the experiments. The membranes were characterized for their surface morphologies, thicknesses, average pore sizes, pore size distributions, and water contact angles. The membrane surface morphology was studied using a field emission scanning electron microscopy (Quanta 200 FEG, FEI). The membrane thickness was determined using a digital micrometer (DML 3032, Digital Micrometers). The pore size of the membrane was measured using a porometer (Porolux 1000, IB-FT GmbH) by a wet-up/dry-up method, and the analysis was carried out using an automated capillary flow porometer system software. Porosity was determined by using the method illustrated by Palacio et al. [47]. The water contact angle of the membrane was measured using an optical tensiometer (Attension T301, Biolin Scientific).

As shown in the SEM images (clockwise from top left: 100 $\times$, 500 $\times$, 1,000 $\times$, and 10,000 $\times$ magnifications) in Fig. 2 [34,36], the knot-fibril net structured PTFE active layer (dark gray in the top right of Fig. 2) was partially covered by the PP scrim support layer (white gray). The PTFE active layer was not covered by the PP support layer at the permeate side, which indicated an effective area for diffusion. The latter was expressed by the surface porosity defined as the surface area of the active PTFE layer exposed at the permeate side divided by the total membrane surface area. The surface porosity was found to be equal to 42% using CAD software based on the SEM images. The physical properties of the PTFE/PP composite membrane are shown in Table 2 [34,36,48]. The maximum pore size (or first bubble point) was in the range of $0.77 \pm 0.03 \mu\text{m}$ and the water contact angle was approximately equal to $160 \pm 3^\circ$. It was shown that the composite membrane had an active

layer that was much thinner and more porous than the support layer, which led to a decrease in the mass transfer resistance and to an increase in the heat transfer resistance. However, since a portion of the active layer was covered owing to the presence of the scrim support layer, the effective open area for diffusion was reduced, which may adversely affect the transmembrane flux.

Fig. 2. SEM micrographs of a commercial PTFE/PP composite membrane. Clockwise from top left: 100 $\times$, 500 $\times$, 1,000 $\times$ and 10,000 $\times$ magnifications [34,36] of the imaged membrane sample.

Table 2 Characteristics of the PTFE/PP composite membrane.

Material	PTFE	PP
Thickness *, δ_m (μm)	20 ± 0.4	80 ± 1.6
Porosity *, ε (%)	70 ± 5.0	34 ± 2.4
Mean pore size *, r (μm)	0.5 ± 0.020	0.1 ± 0.004
Liquid entry pressure **, LEP_w (kPa)	207	160

* Measured data, ** Manufacturer's data

2.2 Experimental set-up and procedure

Fig. 3 shows the schematic of a lab-scale DCMD experimental set-up. A flat-sheet DCMD module with flow channel dimensions of 50 mm $\times$ 50 mm $\times$ 3 mm was designed by employing a first-in-last-out (FILO)

configuration that helps achieving better flow uniformity in the channel width direction, leading to an improved DCMD performance, and fabricated using polymethyl methacrylate material. Real seawater filtered with the use of a 10 μm filter was used as the feed solution, whereas deionized water was used as a permeate solution in DCMD experiments with a countercurrent flow configuration. As shown in Fig. 3, temperatures of the feed and permeate streams were controlled using the heater and chiller, respectively. Pressures, temperatures and flow rates of both feed and permeate streams were monitored using appropriate sensors using a National Instruments DAQ device equipped with Lab View software. A composite membrane specimen was mounted in the membrane module and tested for the DCMD process with and without spacers. Evaporation-condensation took place during the DCMD process owing to the transmembrane vapor pressure difference. Increase in the weight at the permeate tank was continuously recorded using a weighing balance (ML3002E, Mettler Toledo) and communicated to the Lab View system. The conductivity of the permeate stream was continuously monitored throughout the process. Water vapor flux (J) was determined using the equation $J = W / At$, where A is the effective area of the membrane, and W is the weight of the permeate collected during a particular time interval t . DCMD performances of the composite PTFE/PP membrane were tested at different feed inlet temperatures in the range of 40 $^{\circ}\text{C}$ – 80 $^{\circ}\text{C}$, while the permeate inlet temperature was maintained constant at 20 $^{\circ}\text{C}$. The system was stabilized for approximately two hours before logging the data. The flow rates of bulk feed and permeate solutions were kept constant at 2.0 L/min and 1.0 L/min, respectively, in all the successive DCMD experiments. The corresponding channel velocities were 2.22×10^{-1} m/s and 1.11×10^{-1} m/s, respectively, for the empty channels.

Fig. 3. Schematic of the lab-scale DCMD experimental set-up.

Table 3 Specifications of the spacers used in this study.

Spacer type	Overall thickness (mils/mm)	Strand count (numbers/in)	Intersection angle (°)	Flow attack angle (°)	Material
I	46/1.17	7	90	45	PP
II	30/0.76	9	90	45	PP
III	20/0.51	16	90	45	PP
IV	13/0.33	29	90	45	Nylon
V	20/0.51	15	60	60	Nylon

Fig. 4. Convention used for the description of spacers.

In this study, water vapor flux was observed during the DCMD process using different spacers which were applied to the feed, permeate, or both sides of the composite membrane. Herein, the use of spacers on both sides of the membrane was accomplished using spacers that had the highest permeate flux improvement when the latter were implemented on the feed or permeate sides. In the experiments, spacers in the DCMD module were installed adjacent to the membrane surface for the following reasons. The first was to provide the flow channel by fixing the position of the membrane, thus preventing significant membrane deformation, and the second was to separate the hydraulic and thermal boundary layer at the membrane surface by employing it as a static mixer enabling an enhanced heat and mass transfer between the bulk stream and the membrane surface. Spacers were provided by DelStar Technologies Inc., USA. Detailed specifications of the spacers used in this study are listed in Table 3, and the convention used for the description of spacers is shown in Fig. 4. It is shown that spacers with a larger number of strands (i.e., thinner filaments) have a smaller mesh aperture size, thus providing lower spacer porosity. All the experiments were performed more than three times with the same operating conditions to demonstrate the reproducibility of the process and the uncertainty in the measured permeate fluxes was found to be less than $\pm 4\%$.

3. Theoretical approach

The detailed theoretical models and solution procedure for the heat and mass transfer through the composite membrane and the transport behaviors on the bulk feed and permeate flows can be found elsewhere [34,36]. For the simulation, thermophysical properties of pure water and seawater were obtained from [49]. Meanwhile, this study focused on the proposition and assessment of convective heat transfer correlation (i.e., Nusselt number) to achieve a more accurate prediction of heat and mass transfer across the boundary layer in the spacer-filled channel.

The heat and mass transfer occurred simultaneously across the feed and permeate boundary layers and through the PTFE/PP composite membrane, as shown in Fig. 5. In particular, the existence of turbulence or eddy currents evoked by the spacers in both channels may yield better flow characteristics in terms of heat and mass transfer. Consequently, the thickness of the thermal boundary layer in the spacer-filled channel became smaller than that in the empty channel, which resulted in membrane interface temperatures closer to the bulk stream temperatures. Thus, temperature polarization will be reduced, and transmembrane fluxes will be enhanced owing to the larger vapor pressure differences through the composite membrane.

Fig. 5. Schematic diagram of temperature polarization in both empty and spacer-filled channels.

Table 4 Heat transfer correlations adopted for the empty and spacer-filled channels.

$$\text{Nu} = \frac{hd_h}{k} = 4.36 + \frac{0.036 \text{Re} \text{Pr} (d_h / L)}{1 + 0.0011 [\text{Re} \text{Pr} (d_h / L)]^{0.8}}, \quad \text{Re} < 2100 \quad (1)$$

Empty channel

$$\text{Nu} = \frac{hd_h}{k} = 0.023 [1 + 6(d_h / L)] \text{Re}^{0.8} \text{Pr}^{1/3}, \quad \text{Re} > 2100 \quad (2)$$

$$\text{Nu} = \frac{hd_h}{k} = k_{dc} 0.023 [1 + 6(d_h / L)] \text{Re}^{0.8} \text{Pr}^{1/3} \quad (3)$$

Spacer-filled channel

$$k_{dc} = c_1 \left(\frac{d_f}{h_s} \right)^{-c_2} |\sin \theta|^{c_3} \exp \left[-c_4 \left| \ln \left(\frac{\varepsilon_{sp}}{0.6} \right) \right|^2 \right] \quad (4)$$

In the present study, for an empty or spacer-filled channel, the convective heat transfer coefficients at the feed and permeate boundary layers for laminar or turbulent flows were determined by using the correlations shown in Table 4. In order to determine the heat transfer coefficient in the spacer-filled channels, the modified Dittus-Boelter's correlation on the flat surface of a fully-developed turbulent flow was implemented, as expressed by Eq. (3) [24,31,34,36,50,51]. It has been known that for the spacer-filled channels, the heat transfer coefficient could be well described by the Nusselt number correlation for fully developed turbulent flow, even at low Reynolds number, less than 300 [24,31,50,51]. Furthermore, the entry length in turbulent flow is much

shorter than laminar flow. This entrance effect becomes insignificant beyond a channel length 10 times the hydraulic diameter of channel, and thus the Nusselt number determined for fully developed turbulent flow can be used approximately for the entire channel. Meanwhile, the maximum hydraulic diameter of the spacer-filled channels considered in this study is about 2.46×10^{-3} m, where the hydrodynamic and thermal entry lengths are approximately half the channel length. As a result, the modified Dittus-Boelter's correlation taking into account the thermal entrance effect was employed to the laboratory-scale MD module in this study, as shown in Table 4.

As aforementioned, the geometric parameters of the spacers employed as turbulence promoters and membrane supports had a significant influence on the heat and mass transfer and on the flow resistance [11–13,24,31,34,36,52]. A non-woven net spacer can be thus characterized by several key parameters, such as the filament diameter (d_f), mesh size (l_m), hydrodynamic angle (θ), spacer thickness (h_s), and spacer porosity (ε_{sp}), as shown in Fig. 4. In this regard, Da Costa et al. [52] suggested the following expression for the spacer factor (k_{dc}):

$$k_{dc} = a \left(\frac{d_f}{h_s} \right)^b f(\theta) f(\varepsilon_{sp}), \quad (5)$$

where $f(\theta)$ and $f(\varepsilon_{sp})$ are the relationships between the spacer factor and hydrodynamic angle and spacer porosity, determined from the experiments. Herein, the spacer porosity can be calculated as

$$\varepsilon_{sp} = 1 - \frac{\pi d_f^2}{2 l_m h_s \sin \theta} \quad (6)$$

for round filaments [34,36,52]. Therefore, in this study, the spacer factor was implemented by the correlation defined in Eq. (4). The channel hydraulic diameter in Eq. (3) is given by

$$d_h = \frac{4 \varepsilon_{sp}}{2(w_c + h_c) / w_c h_c + 4(1 - \varepsilon_{sp}) / d_f}, \quad (7)$$

where w_c and h_c are the flow channel width and height, respectively.

The porosities of the spacers used in this study were in the narrow range of 0.86 – 0.91, as calculated from Eq. (6). Thus, it can be expected that its effect on the DCMD permeate flux may be negligibly small. However, it has been found that the highest permeate flux enhancement can be achieved at a porosity of approximately 0.6 [13]. The four parameters (c_1 , c_2 , c_3 , c_4) in Eq. (4) are estimated using a conjugate gradient method [53] to achieve the best fit between the measured and simulated permeate fluxes. Herein, the coefficient of determination (R-squared) was employed to evaluate the degree of the fit of the heat transfer coefficient

correlation with the measured data, and is given by

$$R^2 = 1 - \frac{\sum_{i=1}^N (J_{exp,i} - J_{sim,i})^2}{\sum_{i=1}^N (J_{exp,i} - \bar{J}_{exp})^2}, \quad (8)$$

where $\bar{J}_{exp} = \frac{1}{N} \sum_{i=1}^N J_{exp,i}$, N is the number of measured permeate flux data, J_{exp} is the measured permeate flux,

and J_{sim} is the predicted mean permeate flux over the membrane length, which is determined as follows,

$$J = \frac{1}{L} \int_0^L J_z dz \quad (9)$$

where $J_z = \varepsilon_s J_{al} + (1 - \varepsilon_s) J_{al-sl}$ is the total local permeate flux across the composite membrane, z is the axial membrane length, ε_s is the surface porosity of the composite membrane mentioned in the second paragraph of Section 2.1, J_{al} and J_{al-sl} are the respective local permeate fluxes through the active PTFE layer and composite PTFE/PP layers [34,36].

In order to examine the thermal efficiency of the DCMD process, the performance ratio (PR) is defined as

$$PR = \frac{1}{L} \int_0^L \eta_z dz, \quad (10)$$

where η_z is the local performance ratio determined as the ratio of the vaporization heat associated with the permeate flux to the heat transferred through the membrane, and given by [34,36]

$$\eta_z = \frac{\varepsilon_s J_z \Delta H|_{al} + (1 - \varepsilon_s) J_z \Delta H|_{al-sl}}{Q_m}, \quad (11)$$

where $\Delta H|_{al}$ and $\Delta H|_{al-sl}$ are the enthalpies of evaporation at the mean temperature through the active layer membrane and the active/support layer membrane, respectively, and Q_m is the heat flux through the composite membrane.

Heat and mass transfer across the boundary layer is perceived as a limiting factor to the transport efficiency of the MD process, and the temperature polarization coefficient (TPC) is extensively used as an index to quantify the fraction of the boundary layer resistance to the overall heat transfer resistance. In the DCMD process, asymmetric polarization phenomena were demonstrated by Khayet et al. [54] who showed that the temperature polarization in the permeate side was lower than that in the feed side. The local global TPC is defined as

$$TPC_z = TPC_{f,z} + TPC_{p,z} - 1, \quad (12)$$

where TPC_f and TPC_p are the local temperature polarization coefficients corresponding to the feed and permeate phases, respectively, and are expressed by [1,54]

$$TPC_f = \frac{T_{m,f} - T_p}{T_f - T_p}, \quad TPC_p = \frac{T_f - T_{m,p}}{T_f - T_p} \quad (13)$$

where T_f and T_p denote the local feed and permeate temperatures at the bulk fluids, respectively, and $T_{m,f}$ and $T_{m,p}$ denote the local liquid-vapor interface temperatures on the feed and permeate sides, respectively. Therefore, the overall global TPC and the overall $TPCs$ corresponding to the feed and permeate phases can be calculated by integrating Eqs. (12) and (13), respectively, over the entire membrane length.

4. Results and discussion

4.1. Model validation with empty channels

Prior to the performance investigation of the DCMD process with the spacer-filled channels, and in order to verify the currently developed in-house computational code, the performance characteristics of the DCMD process without the use of spacers had been examined with respect to the feed temperature at the inlet of the membrane module. The DCMD performances were determined by operating the process at different feed inlet temperatures from 40 °C to 80 °C and at a constant permeate inlet temperature (20 °C). The flow rates of bulk feed and permeate solutions were kept constant at 2.0 L/min and 1.0 L/min, respectively.

Fig. 6 presents the mean permeate flux (measured and predicted) with respect to the bulk feed temperature at an inlet permeate temperature of 20°C using seawater. It was found that with an increase in the inlet feed temperature from 40 °C to 80 °C the measured permeate flux increased exponentially from 17 kg/m²h to 80 kg/m²h as a consequence of a significant increase in the driving force. This change is expected in accordance to Antoine's equation [34,55,56]. With the increase of the feed temperature in the empty channels, the calculated convective heat transfer coefficients increased in the range of 3,410 W/m²K – 3,660 W/m²K for the feed side and in the range of 2,100 W/m²K – 2,120 W/m²K for the permeate side, while the Reynolds numbers varied within the range of 1,730 – 2,900 for the feed side (i.e., the transition from laminar to turbulent flow regime) and in the range of 680 – 850 for the permeate side (i.e., laminar flow regime). It was noted that the model predictions on the permeate flux were in good accordance with the measured results.

Fig. 6. Measured and predicted permeate fluxes with respect to the feed inlet temperature in the DCMD process with the empty channels at the constant inlet permeate temperature of 20 °C. Square and triangle symbols denote the measured and predicted results, respectively.

4.2. Effects of empty and spacer-filled channels on DCMD performance

To demonstrate the influence of the spacers on the DCMD performance, the permeate fluxes for the twelve experimental cases were obtained using the spacers listed in Table 3, which were employed on the feed, permeate, or both sides of the membrane, as shown in columns 1 to 4 in Table 5. The permeate fluxes of the DCMD processes with the spacer-filled channels were then compared to those with empty channels discussed in Section 4.1. In all the experiments, the inlet feed and permeate temperatures were kept at 70 °C and 20 °C, respectively, where the flow rates of bulk feed and permeate streams were kept at 2.0 L/min and 1.0 L/min, respectively.

As a result, the comparison of mean permeate fluxes of DCMD processes with the empty and spacer-filled channels is given in Table 5. The corresponding plot can be observed in Fig. 7, which also illustrates the performance ratio (PR) of each DCMD process defined in Eqs. (10) and (11). The convective heat transfer coefficients for the spacer-filled channels given in Table 4 were evaluated and correlated with the spacer geometries, hydrodynamic angle, and spacer porosity, based on the measured permeate fluxes. With the heat transfer coefficients for the spacer-filled channels obtained via the conjugate gradient method, as listed in Table 6, the best fit between the measured and predicted permeate fluxes was achieved with an R-squared of 0.88 for

Table 5 Comparison of mean permeate fluxes for the empty and spacer-filled channels.

Experimental case	Spacer type	Spacer at feed side	Spacer at permeate side	Measured permeate flux, $J_{exp.}$ (kg/m ² h)	Experimental standard deviation (kg/m ² h)	Predicted permeate flux, $J_{sim.}$ (kg/m ² h)	Relative error between $J_{exp.}$ and $J_{sim.}$ (*) (%)	Permeate flux enhancement** (%)
1	-	No	No	56.81	1.23	59.82	5.30	0.0
2	I	Yes	No	68.69	1.97	70.53	2.68	20.9
3		No	Yes	60.80	2.06	63.44	4.33	7.0
4	II	Yes	No	72.20	3.53	69.89	3.20	27.1
5		No	Yes	61.00	1.32	62.84	3.02	7.4
6	III	Yes	No	74.00	1.15	71.01	3.92	30.3
7		No	Yes	66.00	1.76	63.96	3.09	16.2
8	IV	Yes	No	75.80	1.40	72.85	3.90	33.4
9		No	Yes	67.50	1.89	65.57	2.86	18.8
10	V	Yes	No	71.90	1.81	70.80	1.53	26.6
11		No	Yes	62.50	1.29	63.69	1.90	10.0
12	IV	Yes	Yes	81.20	1.06	83.13	2.34	42.9

* $\left| \left(J_{exp.} - J_{sim.} \right) / J_{exp.} \right| \times 100$, ** $\left| \left(J_{exp.\#i} - J_{exp.\#1} \right) / J_{exp.\#1} \right| \times 100$

Table 6 Values of parameters in the spacer factor obtained by the conjugate gradient method.

c_1	c_2	c_3	c_4
1.923	0.168	0.292	1.601

Fig. 7. Mean permeate flux and performance ratio for the empty and spacer-filled channels. Squares and triangles denote the measured and predicted permeate fluxes, respectively, in which gradients denote the predicted permeate fluxes using Eq. 14 [13], while circles denote the predicted performance ratios. The detailed configurations for the twelve experimental cases are described in Table 5.

Fig. 8. Measured permeate flux versus predicted permeate flux for the empty and spacer-filled channels. The solid line denotes the trend using a linear regression with an R-squared value of 0.8843. The detailed configurations for the twelve experimental cases are described in Table 5.

Fig. 9. Overall temperature polarization coefficient calculated for the empty and spacer-filled channels. Squares, triangles and circles respectively denote the feed, permeate, and feed and permeate sides, respectively. The detailed configurations for the twelve experimental cases are described in Table 5.

all experimental data, as demonstrated by the linear regression shown in Fig. 8. As also depicted in Fig. 7, the predicted data on the mean permeate flux were compared with those calculated from the heat transfer correlation for spacer-filled channels proposed by Phattaranawik et al. [13], which was obtained by correlating with spacer characteristics by multiple linear regressions from experimental results:

$$\text{Nu} = \frac{hd_h}{k} = k_{dc} \left[4.36 + \frac{0.036 \text{Re} \text{Pr} (d_h / L)}{1 + 0.0011 [\text{Re} \text{Pr} (d_h / L)]^{0.8}} \right] \quad (14)$$

where

$$k_{dc} = 1.88 \left(\frac{d_f}{h_s} \right)^{-0.039} (\sin \theta)^{1.33} \exp \left\{ -4.05 \left[\ln \left(\frac{\varepsilon_{sp}}{0.6} \right) \right]^2 \right\}.$$

Here, the maximum relative error between the measured and predicted permeate fluxes for spacer-filled channels was approximately 4% (in case 3) with the heat transfer correlation from the present work, exhibiting good agreement with experimental data, while it was approximately 25% (in case 4) with the correlation suggested by Phattaranawik et al. [13].

The permeate flux enhancement for the different types of spacers ranged between 7% – 19% only for the

spacer-filled permeate channels, and between 21% – 33% only for the spacer-filled feed channels. Lower flux enhancements were obtained with the spacer-filled permeate channels, even though the same spacer was used on the feed or permeate sides. Herein, the effects of flow rate and bulk stream temperature can be regarded as the possible reasons for the aforementioned phenomena, but the influence of the flow rate on the flux enhancement should be excluded. This was because the feed-side flow rate was two times higher over the permeate side, and the enhanced heat transfer in empty channels could be achieved at higher flow rates. Thus, the effect of the spacer on the heat transfer enhancement disappeared at higher flow rates, whereby turbulence was approached [13]. In comparison, the effect of the spacer on improving the permeate flux became more pronounced at higher temperatures with a low temperature polarization coefficient [1,13,55,56], which was the main reason for the lower flux improvements in the spacer-filled permeate channels. It is thus noted that the spacer can play an important role under operating conditions that result in inferior heat transfer or high temperature polarization, i.e., a low temperature polarization coefficient. As illustrated in Fig. 7, the *PRs* were in the narrow range of 0.86 – 0.89 for all experimental cases, indicating that the *PRs* of the spacer-filled feed channels were improved, while the *PRs* of the spacer-filled permeate channels were slightly reduced, as compared to both empty channels (case 1). This was found to be attributed to an increased vaporization heat associated with the flux enhancement and an increased conductive heat loss through the membrane induced by the enhancement of convective heat transfer across the permeate boundary layer [1,36]. Therefore, in this study, the maximum flux enhancement was approximately equal to 43% with the thinnest and densest spacer (type IV) adjacent to both membrane surfaces that had an overall spacer thickness of 0.33 mm, a mesh size of 0.91 mm, and a hydrodynamic angle of 90° (case 12).

The profiles of the temperature polarization coefficients in the empty and spacer-filled channels are presented in Fig. 9. The overall *TPCs* for the spacer-filled feed and permeate channels, *TPC_f* and *TPC_p*, were improved by 11% – 14% and 7% – 14%, respectively, while the overall, global *TPCs* for the spacer-filled channels were increased by 7% – 15% over the empty channels (case 1). It was observed that higher *TPC* enhancements were obtained in the feed channels because the higher temperature polarization in empty channels was achieved at higher temperatures. For the empty and spacer-filled channels the values of *TPC_f* were approximately 1.3 times higher than those of *TPC_p*, mainly owing to a higher flow rate at the feed side, and the *TPCs* were much lower than those of *TPC_f* and *TPC_p* [1]. Meanwhile, the overall *TPC_f*, *TPC_p*, and global *TPC*, for both the spacer-filled channels (case 12) were 10%, 2%, and 28%, higher than the empty channels (case 1),

respectively. The corresponding values were 0.815, 0.588, and 0.402, indicating that approximately 60% of the applied temperature difference was dissipated in both the feed and permeate boundary layers.

Fig. 10 displays the calculated convective heat transfer coefficients across the feed and permeate boundary layers in the empty and spacer-filled channels. Except for the spacer-filled channels at both sides (case 12), the heat transfer coefficients were increased by 64% – 95% only for the spacer-filled feed channels, and by 17% – 37% only for the spacer-filled permeate channels, over the empty channels (case 1). The heat transfer coefficients at both the feed and permeate channels with the type IV spacer (case 12) were respectively equal to 6,704 W/m²K and 2,961 W/m²K, which corresponded to 1.9- and 1.4-fold increases compared to the empty channels (case 1), respectively.

Fig. 10. Convective heat transfer coefficient calculated for the empty and spacer-filled channels. Squares and triangles denote the feed and permeate sides, respectively. The detailed configurations for the twelve experimental cases are described in Table 5.

4.3. Spatial variations in empty and spacer-filled channels

To elucidate the heat and mass transport phenomena for the empty and spacer-filled channels, the axial variations of permeate flux (J_z), performance ratio (PR), temperatures (T_f , $T_{m,f}$, $T_{m,p}$, T_p), velocities (v_f , v_p), and seawater salinity (w), are compared for both configurations as follows: empty (case 1, dashed lines) and spacer-filled (case 12, solid lines) channels, as shown in Fig. 11. In this study, it would be reasonable to compare the

absolute magnitudes of the aforementioned properties for both configurations since their spatial variations were very small owing to the use of small MD modules.

Fig. 11. Predicted profiles of (a) permeate flux and performance ratio, (b) temperature, (c) velocity, and (d) feed seawater salinity along the composite membrane for the empty and spacer-filled channels. Dashed and solid lines denote the empty and spacer-filled channels, respectively.

Fig. 12. Predicted profiles of (a) temperature polarization coefficient and (b) convective heat transfer coefficient along the composite membrane for the empty and spacer-filled channels. Dashed and solid lines denote the empty and spacer-filled channels, respectively.

The results shown in Fig. 11(a) revealed that spacers improved permeate fluxes by approximately 43% compared to the empty channels, and attained values that approximately ranged from 60 kg/m²h to 83 kg/m²h. This was because the heat and mass transfer across the boundary layers was enhanced and the temperature polarization was reduced. The performance ratios exhibited a slight linear decrease along the membrane length for both configurations owing to the decrease in the vaporization heat associated with the permeate flux decline. As depicted in the axial temperature variations in Fig. 11(b), the temperatures at the feed and permeate sides respectively decreased and increased slightly along the flow directions. Herein, it was noted that the liquid-vapor interface temperatures ($T_{m,f}$, $T_{m,p}$) at both the feed and permeate sides for the spacer-filled channels were approximately 3.8 °C higher and approximately 0.5 °C lower, respectively, compared to the empty channels. This resulted in a decrease in the temperature polarization (based on Eqs. (12) and (13)), and a consequent increase in the driving force for permeation, thereby yielding a higher permeate flux (based on Eq. (9)). The corresponding bulk feed and permeate velocity distributions in Fig. 11(c) tended to be similar to those shown in Fig. 11(b). Specifically, decreases and increases along with the flow direction were induced by the vapor permeation through the membrane. It was shown in Fig. 11(d) that as a result of the vapor permeation the salinity of the feed solution increased along the flow direction, and the increasing rate ($\Delta w / \Delta z$) of feed salinity for the spacer-filled channels was approximately 1.3 times higher compared to the empty channels.

The axial distributions of the temperature polarization coefficients (TPC_f , TPC_p , TPC) and convective heat

transfer coefficients (h_f , h_p) calculated for the empty (case 1, dashed lines) and spacer-filled (case 12, solid lines) channels are depicted in Fig. 12. As described above, it was clear that the spacers could provide a significant role in lowering the temperature polarization effect and in enhancing further the heat and mass transfer in MD processes. Furthermore, the influence of the spacers on the improvement of MD flux became more evident at higher temperatures.

5. Conclusions

In this study, the performance of the spacers adjacent to the membrane surface was identified experimentally and theoretically based on the permeate flux enhancement in the DCMD process with a PTFE/PP composite membrane. In the conducted experiments, the permeate fluxes were obtained using five different types of spacers, which were employed on (i.e., adjacent to) one or both surfaces of the membrane, and were then compared to that for empty channels. Detailed theoretical investigations were also performed to develop and demonstrate the heat transfer correlation for spacer-filled channels that could more accurately predict the heat and mass transfer enhancement based on the use of net-type spacers in the DCMD process. The heat transfer coefficients were evaluated and correlated with different spacer geometries, hydrodynamic angles, and spacer porosities using a gradient-based optimization technique. It was noted that the permeate flux enhancement by the spacers were 7% – 19% only for the spacer-filled permeate channels and 21% – 33% only for the spacer-filled feed channels, even at higher flow rates, thereby demonstrating that lower flux improvements could be achieved in the spacer-filled permeate channels. It was evident that the effect of spacers on flux improvement became more prominent at higher temperatures resulting in higher temperature polarization, which was the main cause of the phenomenon described above. At the given conditions, the effect of bulk temperature on temperature polarization was more pronounced than that of mass flow rate. In this study, the maximum flux enhancement was of approximately 43% over the empty channels, which was obtained using the thinnest and densest spacer with a hydrodynamic angle of 90°, adjacent to both surfaces of the composite membrane.

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Nomenclature

A	effective membrane area [m ²]
c_p	specific heat capacity [J/kg°C]
d_f	filament diameter [m]
d_h	hydraulic diameter [m]
h	convective heat transfer coefficient [W/m ² °C]
h_c	channel height [m]
h_s	spacer thickness [m]
$\Delta H _{al}$	enthalpy of evaporation at the mean temperature through the active layer membrane [J/kg]
$\Delta H _{al-sl}$	enthalpy of evaporation at the mean temperature through the active/support layers membrane [J/kg]
J	mean permeate flux [kg/m ² h]
J_z	local permeate flux [kg/m ² h]
k	thermal conductivity [W/m°C]
k_{dc}	spacer factor [–]
l_m	mesh size [m]
L	membrane length [m]
LEP	liquid entry pressure [kPa]
P	pressure [kPa]
PR	performance ratio [%]
Q_m	heat flux through the membrane [W/m ²]
r	mean pore size [m]
t	time [s]
T	temperature [°C]
TPC	temperature polarization coefficient [%]
v	velocity [m/s]
w	seawater salinity [wt%]
w_c	channel width [m]

1	W	collected permeate weight [kg]
2	z	axial coordinate [m]
3		
4	<i>Dimensionless numbers</i>	
5	Nu	Nusselt number, hd_h/k [–]
6	Pr	Prandtl number, $\mu c_p/k$ [–]
7	Re	Reynolds number, $\rho v d_h/\mu$ [–]
8		
9	<i>Greek letters</i>	
10	δ	membrane thickness [m]
11	ε	membrane porosity [%]
12	ε_s	surface porosity [%]
13	ε_{sp}	spacer porosity [%]
14	η_z	local performance ratio [%]
15	θ	hydrodynamic angle [°]
16	μ	dynamic viscosity [kg/ms]
17	ρ	density [kg/m ³]
18		
19	<i>Subscripts</i>	
20	exp	experiment
21	f	feed
22	m	membrane
23	p	permeate
24	sim	simulation
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References

- [1] Y.-D. Kim, K. Thu, N. Ghaffour, K.C. Ng, Performance investigation of a solar-assisted direct contact membrane distillation system, *J. Membr. Sci.* 427 (2013) 345–364.
- [2] A. Alsaadi, L. Francis, H. Maab, G. Amy, N. Ghaffour, Evaluation of air gap membrane distillation process running under sub-atmospheric conditions: Experimental and simulation studies, *J. Membr. Sci.* 489 (2015) 73–80.
- [3] J. Xu, Y.B. Singh, G.L. Amy, N. Ghaffour, Effect of operating parameters and membrane characteristics on air gap membrane distillation performance for the treatment of highly saline water, *J. Membr. Sci.* 512 (2016) 73–82.
- [4] R. Schofield, A. Fane, C. Fell, R. Macoun, Factors affecting flux in membrane distillation, *Desalination* 77 (1990) 279–294.
- [5] Y. Fujii, S. Kigoshi, H. Iwatani, M. Aoyama, Selectivity and characteristics of direct contact membrane distillation type experiment. I. Permeability and selectivity through dried hydrophobic fine porous membranes, *J. Membr. Sci.* 72 (1992) 53–72.
- [6] Y. Fujii, S. Kigoshi, H. Iwatani, M. Aoyama, Y. Fusaoka, Selectivity and characteristics of direct contact membrane distillation type experiment. II. Membrane treatment and selectivity increase, *J. Membr. Sci.* 72 (1992) 73–89.
- [7] L. Martínez-Díez, M.I. Vázquez-González, F.J. Florido-Díaz, Study of membrane distillation using channel spacers, *J. Membr. Sci.* 144 (1998) 45–56.
- [8] S. Soukane, W.M. Naceur, L. Francis, A.S. Alsaadi, N. Ghaffour, Effect of feed flow pattern on the distribution of permeate fluxes in desalination by direct contact membrane distillation, *Desalination* 418 (2017) 43–59.
- [9] N. Thomas, M.O. Mavukkandy, S. Loutatidou, H.A. Arafat, Membrane distillation research & implementation: Lessons from the past five decades, *Sep. Purif. Technol.* 189 (2017) 108–127.
- [10] L. Martínez-Díez, M.I. Vázquez-González, A method to evaluate coefficients affecting flux in membrane distillation, *J. Membr. Sci.* 173 (2000) 225–234.
- [11] J. Phattaranawik, R. Jiraratananon, A. Fane, C. Halim, Mass flux enhancement using spacer filled channels in direct contact membrane distillation, *J. Membr. Sci.* 187 (2001) 193–201.
- [12] J. Phattaranawik, R. Jiraratananon, A. Fane, Heat transport and membrane distillation coefficients in direct

- contact membrane distillation, *J. Membr. Sci.* 212 (2003) 177–193.
- [13] J. Phattaranawik, R. Jiraratananon, A. Fane, Effects of net-type spacers on heat and mass transfer in direct contact membrane distillation and comparison with ultrafiltration studies, *J. Membr. Sci.* 217 (2003) 193–206.
- [14] M.N. Chernyshov, G.W. Meindersma, A.B. de Haan, Modelling temperature and salt concentration distribution in membrane distillation feed channel, *Desalination* 157 (2003) 315–324.
- [15] M.N. Chernyshov, G.W. Meindersma, A.B. de Haan, Comparison of spacers for temperature polarization reduction in air gap membrane distillation, *Desalination* 183 (2005) 363–374.
- [16] L. Martínez, J.M. Rodríguez-Maroto, Characterization of membrane distillation modules and analysis of mass flux enhancement by channel spacers, *J. Membr. Sci.* 274 (2006) 123–137.
- [17] L. Martínez, J.M. Rodríguez-Maroto, On transport resistances in direct contact membrane distillation, *J. Membr. Sci.* 295 (2007) 28–39.
- [18] L. Martínez, J.M. Rodríguez-Maroto, Effects of membrane and module design improvements on flux in direct contact membrane distillation, *Desalination* 205 (2007) 97–103.
- [19] M.M. Teoh, S. Bonyadi, T.-S. Chung, Investigation of different hollow fiber module designs for flux enhancement in the membrane distillation process, *J. Membr. Sci.* 311 (2008) 371–379.
- [20] L. Martínez, J. Rodríguez-Maroto, Membrane thickness reduction effects on direct contact membrane distillation performance, *J. Membr. Sci.* 312 (2008) 143–156.
- [21] T.-C. Chen, C.-D. Ho, H.-M. Yeh, Theoretical modeling and experimental analysis of direct contact membrane distillation, *J. Membr. Sci.* 330 (2009) 279–287.
- [22] C.-L. Liu, Y.-F. Chen, W.-J. Sheu, C.-C. Wang, Effect of flow deflector on the flux improvement in direct contact membrane distillation, *Desalination* 253 (2010) 16–21.
- [23] X. Yang, R. Wang, A.G. Fane, Novel designs for improving the performance of hollow fiber membrane distillation modules, *J. Membr. Sci.* 384 (2011) 52–62.
- [24] J. Zhang, S. Gray, J.-D. Li, Modelling heat and mass transfers in DCMD using compressible membranes, *J. Membr. Sci.* 387–388 (2012) 7–16.
- [25] M. Shakaib, S.M.F. Hasani, I. Ahmed, R.M. Yunus, A CFD study on the effect of spacer orientation on temperature polarization in membrane distillation modules, *Desalination* 284 (2012) 332–340.
- [26] X. Yang, H. Yu, R. Wang, A.G. Fane, Analysis of the effect of turbulence promoters in hollow fiber membrane distillation modules by computational fluid dynamic (CFD) simulations, *J. Membr. Sci.* 415–416

- (2012) 758–769.
- [27] X. Yang, H. Yu, R. Wang, A.G. Fane, Optimization of microstructured hollow fiber design for membrane distillation applications using CFD modeling, *J. Membr. Sci.* 421-422 (2012) 258–270.
- [28] A. Kullab, R. Fakhrai, A. Martin, Experimental evaluation of a modified air-gap membrane distillation prototype, *Desalin. Water Treat.* 51 (2013) 4998–5004.
- [29] A. Tamburini, P. Pitò, A. Cipollina, G. Micale, M. Ciofalo, A thermochromic liquid crystals image analysis technique to investigate temperature polarization in spacer-filled channels for membrane distillation, *J. Membr. Sci.* 447 (2013) 260–273.
- [30] S. Al-Sharif, M. Albeirutty, A. Cipollina, G. Micale, Modelling flow and heat transfer in spacer-filled membrane distillation channels using open source CFD code, *Desalination* 311 (2013) 103–112.
- [31] A. Alsaadi, N. Ghaffour, J.-D. Li, S. Gray, L. Francis, H. Maab, G. Amy, Modeling of air-gap membrane distillation process: a theoretical and experimental study, *J. Membr. Sci.* 445 (2013) 53–65.
- [32] A.S. Alsaadi, L. Francis, G.L. Amy, N. Ghaffour, Experimental and theoretical analyses of temperature polarization effect in vacuum membrane distillation, *J. Membr. Sci.* 471 (2014) 138–148.
- [33] Y.M. Manawi, M.A.M.M. Khraisheh, A.K. Fard, F. Benyahia, S. Adham, A predictive model for the assessment of the temperature polarization effect in direct contact membrane distillation desalination of high salinity feed, *Desalination* 341 (2014) 38–49.
- [34] J.-G. Lee, Y.-D. Kim, W.-S. Kim, L. Francis, G. Amy, N. Ghaffour, Performance modeling of direct contact membrane distillation (DCMD) seawater desalination process using a commercial composite membrane, *J. Membr. Sci.* 478 (2015) 85–95.
- [35] H. Chang, J.-A. Hsu, C.-L. Chang, C.-D. Ho, CFD study of heat transfer enhanced membrane distillation using spacer-filled channels, *Energy Procedia* 75 (2015) 3213–3219.
- [36] J.-G. Lee, W.-S. Kim, J.-S. Choi, N. Ghaffour, Y.-D. Kim, A novel multi-stage direct contact membrane distillation module: Design, experimental and theoretical approaches, *Water Res.* 107 (2016) 47–56.
- [37] H. Chang, J.-A. Hsu, C.-L. Chang, C.-D. Ho, T.-W. Cheng, Simulation study of transfer characteristics for spacer-filled membrane distillation desalination modules, *Appl. Energy* 185 (2017) 2045–2057.
- [38] A. Katsandri, A theoretical analysis of a spacer filled flat plate membrane distillation modules using CFD: Part I: velocity and shear stress analysis, *Desalination* 408 (2017) 145–165.
- [39] A. Katsandri, A theoretical analysis of a spacer filled flat plate membrane distillation modules using CFD:

- Part II: Temperature polarisation analysis, *Desalination* 408 (2017) 166–180.
- [40] M. La Cerva, M. Ciofalo, L. Gurreri, A. Tamburini, A. Cipollina, G. Micale, On some issues in the computational modelling of spacer-filled channels for membrane distillation, *Desalination* 411 (2017) 101–111.
- [41] Y. Taamneh, K. Bataineh, Improving the performance of direct contact membrane distillation utilizing spacer-filled channel, *Desalination* 408 (2017) 25–35.
- [42] A. Hagedorn, G. Fieg, D. Winter, J. Koschikowski, A. Grabowski, T. Mann, Membrane and spacer evaluation with respect to future module design in membrane distillation, *Desalination* 413 (2017) 154–167.
- [43] L. Han, Y.Z. Tan, T. Netke, A.D. Fane, J.W. Chew, Understanding oil wastewater treatment via membrane distillation, *J. Membr. Sci.* 539 (2017) 284–294.
- [44] I. Hitsov, L. Eykens, W. De Schepper, K. De Sitter, C. Dotremont, I. Nopens, Full-scale direct contact membrane distillation (DCMD) model including membrane compaction effects, *J. Membr. Sci.* 539 (2017) 284–294.
- [45] J. Seo, Y.M. Kim, J.H. Kim, Spacer optimization strategy for direct contact membrane distillation: Shapes, configurations, diameters, and numbers of spacer filaments, *Desalination* 417 (2017) 9–18.
- [46] M. Albeirutty, N. Turkmen, S. Al-Sharif, S. Bouguecha, A. Malik, O. Faruki, A. Cipollina, M. Ciofalo, G. Micale, An experimental study for the characterization of fluid dynamics and heat transport within the spacer-filled channels of membrane distillation modules, *Desalination* 430 (2018) 136–146.
- [47] L. Palacio, P. Prádanos, J.I. Calvo, A. Hernández, Porosity measurements by a gas penetration method and other techniques applied to membrane characterization, *Thin Solid Films* 348 (1999) 22–29.
- [48] L. Francis, L. Ghaffour, A.A. Alsaadi, G.L. Amy, Material gap membrane distillation: A new design for water vapor flux enhancement, *J. Membr. Sci.* 448 (2013) 240–247.
- [49] M.H. Sharqawy, J.H. Lienhard V, S.M. Zubair, Thermophysical properties of seawater: a review of existing correlations and data, *Desalin. Water Treat.* 16 (2010) 354–380.
- [50] A.L. Lydersen, *Fluid Flow, Heat Transfer*, John Wiley & Sons, New York, 1979.
- [51] J. Welty, C.E. Wicks, G.L. Rorrer, R.E. Wilson, *Fundamentals of Momentum, Heat, and Mass Transfer*, John Wiley & Sons, New York, 2009.
- [52] A.R. Da Costa, A.G. Fane, D.E. Wiley, Spacer characterization and pressure drop modelling in spacer-filled channels for ultrafiltration, *J. Membr. Sci.* 87 (1994) 79–98.
- [53] Y.-D. Kim, W.-S. Kim, Re-evaluation and modeling of a commercial diesel oxidation catalyst, *Ind. Eng.*

Chem. Res. 48 (2009) 6579–6590.

[54] M. Khayet, M.P. Godino, J.I. Mengual, Study of asymmetric polarization in direct contact membrane distillation, Sep. Sci. Technol. 39 (2005) 125–147.

[55] Y.-D. Kim, K. Thu, S.-H. Choi, Solar-assisted multi-stage vacuum membrane distillation system with heat recovery unit, Desalination 367 (2015) 161–171.

[56] Y.-D. Kim, K. Thu, K.C. Ng, G.L. Amy, N. Ghaffour, A novel integrated thermal-/membrane-based solar energy-driven hybrid desalination system: Concept description and simulation results, Water. Res. 100 (2016) 7–19.

Table captions

Table 1 Chronological list of publications on “membrane distillation” and “spacers” in the period of 2000 and 2018.

Table 2 Characteristics of the PTFE/PP composite membrane.

Table 3 Specifications of the spacers used in this study.

Table 4 Heat transfer correlations adopted for the empty and spacer-filled channels.

Table 5 Comparison of mean permeate fluxes for the empty and spacer-filled channels.

Table 6 Values of parameters in the spacer factor obtained by the conjugate gradient method.

Figure captions

Fig. 1. Variation of the number of publications on MD and spacer-filled MD over the last four decades. The orange bars denote the number of publications on “membrane distillation” [4], and purple bars denote publications on “membrane distillation” and “spacers”.

Fig. 2. SEM micrographs of a commercial PTFE/PP composite membrane. Clockwise from top left: 100×, 500×, 1,000×, and 10,000× magnifications [34,36] of the imaged membrane sample.

Fig. 3. Schematic of the lab-scale DCMD experimental set-up.

Fig. 4. Convention used for the description of spacers.

Fig. 5. Schematic diagram of temperature polarization in both empty and spacer-filled channels.

Fig. 6. Measured and predicted permeate fluxes with respect to the feed inlet temperature in the DCMD process with the empty channels at the constant inlet permeate temperature of 20 °C. Square and triangle symbols denote the measured and predicted results, respectively.

Fig. 7. Mean permeate flux and performance ratio for the empty and spacer-filled channels. Squares and triangles denote the measured and predicted permeate fluxes, respectively, in which gradients denote the predicted permeate fluxes using Eq. 14 [13], while circles denote the predicted performance ratios. The detailed configurations for the twelve experimental cases are described in Table 5.

Fig. 8. Measured permeate flux versus predicted permeate flux for the empty and spacer-filled channels. The solid line denotes the trend using a linear regression with an R-squared value of 0.8843. The detailed configurations for the twelve experimental cases are described in Table 5.

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