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Energy efficiency of direct contact membrane distillation

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ABSTRACT

Membrane distillation (MD) is a promising technology due to its ability to function using low temperature differences and low-quality heat sources, thus allowing it to operate on solar or waste heat. The flux and energy efficiency of MD are influenced by temperature and concentration polarization, process conditions, and membrane-related parameters like thickness, tortuosity, thermal conductivity, pore size, and porosity. To date, a comprehensive review of membrane and distillation parameters on energy consumption has not yet been conducted. Accordingly, this review introduces the central energy parameters for MD (e.g., energy efficiency, gained output ratio, etc.) and discusses the reported impacts of membrane properties, mass and heat transfer, feed water properties, and system parameters on the energy parameters. The application of solar energy to direct contact MD (DCMD) is also discussed. A critical analysis of the energy efficiency of DCMD processes will help to establish its strengths and limitations and provide a road map for the development of this technology for both large-scale and portable applications.

1. Introduction

The large-scale desalination industry is currently dominated by multi-stage flash distillation, multiple effect distillation, and reverse osmosis (RO) techniques [1,2]. Although reverse osmosis has lower energy requirements relative to the other leading technologies, the method is known to be expensive for small-scale water purification purposes. Membrane distillation (MD) is a promising technology that operates based on the partial vapor pressure difference developed across a membrane. This technique utilizes a porous hydrophobic filter that is capable of preventing feed liquid entry into the pores while allowing the volatile vapors to cross to the distillate side. This characteristic makes MD unique among common water purification technologies as it can completely separate inorganic and non-volatile compounds without the use of traditional distillation techniques. However, the fabrication of a purely hydrophobic membrane that resists internal wetting while maintaining high vapor throughput is a continuing challenge.

In terms of energy efficiency, MD is an attractive technology due to its ability to function using low temperature differences and low-quality heat sources. Thus, it is an economically viable large-scale purification technology because it can utilize either solar thermal energy [3], waste heat, or natural temperature gradients. In fact, the heat requirement for MD is so low that Baghbanzadeh et al. [4] have recently suggested the notion of zero thermal energy input membrane distillation (ZTIMD), where the natural temperature difference between the sea surface water (at 30 °C) and the sea bottom water (at 10 °C) can be used as the process driving force without the need for preheating and zero waste production, which contrasts the seawater reverse osmosis (SWRO) process. Further, a simulation study has suggested that the specific energy consumption of ZTIMD would be in the range of 0.45 kW h/m^3, which is comparable to commercial SWRO processes [4].

The low energy requirement of MD techniques makes it competitive with RO; moreover, it can also be applied to high temperature applications where RO is not suitable. In fact, direct contact MD (DCMD) is a thermally driven process that can operate at temperature above 100 °C, making it a more energetically efficient method for use in onsite wastewater desalination [5]. The US oil and gas industry generates approximately 3.3 billion m^3 of wastewater annually, with salinity concentrations almost 7 times higher than seawater. Onsite desalination using steam assisted gravity drainage (SAGD) systems that produce wastewater have been proven to be more environmentally friendly and economically viable than disposal through deep well injection technology. The energy consumption of wastewater desalination has been

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evaluated using various models to provide a baseline to develop this technology [6]. The minimum energy required for seawater desalination with a recovery ratio of 50% is 1 kWh/m^3; however, this energy consumption rises to 9 kWh/m^3 for the removal of various salt ions from wastewater produced by SAGD. The study suggested that while RO is still more energy efficient, multistage membrane distillation can be utilized for better heat recovery higher recovery rate [6].

Small-scale and portable water distillation units are highly advantageous for use in remote areas and underdeveloped countries that lack appropriate water and electrical infrastructure. Renewable energy assisted MD strategies may serve as an alternative to replace the current expensive water purification approaches to improve the quality of life in such regions without increasing the demand for scarce and expensive electricity. To this end, extensive research has been conducted to utilize solar power in membrane distillation systems [7–16]; however, the cost of this process remains higher than that of photovoltaic-powered RO. Therefore, solar powered membrane distillation (SPMD) requires more research and development to make it an economically viable option in both industrial and small-scale applications. A detailed review on the energy analysis, energy consumption, and water production costs from a system engineering standpoint was conducted in 2012 and noted significant differences in the bench scale and large scale energy consumption of MD technology. Comparisons with commercial water purification processes such as multistage flash (MSF) and RO have concluded that MD is still in the early stages of development and requires parameter standardization for accurate capital cost calculations, particularly for large scale applications [12].

The relationships between the operating conditions such as water recovery, feed temperature, water circulation rate, and membrane scaling and the thermal efficiency of MD have been critically evaluated for seawater distillation using the brine re-cycling technique [17]. Detailed reviews of MD technology for water desalination have evaluated the materials, preparation techniques, and properties of various membrane types and compared the four main types of MD: Air Gap MD (AGMD), DCMD, Gas Sweeping MD (GSMD), and Vacuum MD (VMD) [18,19]. These reviews also discussed the hybridization of MD techniques with RO, forward osmosis (FO), and photocatalysis and concluded that the higher energy consumption of MD is a major challenge that hinders its large-scale application [18,19]. Therefore, the relationship between energy efficiency and process parameters needs to be more deeply explored to help guide improvements towards making MD a more competitive technology.

Compared of other MD technologies such as, GSMD, VMD, and AGMD, DCMD is advantageous due to design and process simplicity, applicability to various types of feed water, and functionality at a wide range of operating energies/temperatures relative [20]. As illustrated in Fig. 1, GSMD, VMD, and AGMD demand extra pressure, inert gas, pumping, and condensers for operation, which make these techniques comparatively more challenging than DCMD [21,22]. Despite the possibilities of membrane scaling, fouling, and wetting in DCMD it has been proposed as the most appropriate technology for wastewater treatment in the oil and gas industry in part because of its addition to 100% salt and organic removal rate [21,23,24].

The overall efficiency of membrane desalination systems is highly dependent on the properties of the membrane itself such as, material selection (e.g., polypropylene (PP), polytetrafluoroethylene (PTFE), and polyvinylidene fluoride (PVDF)) and fiber shape (i.e., flat sheet, hollow, and fibrous). Synthesis routes also have a significant influence on the performance of the membranes and the overall DCMD technology. Recently, much attention has been given to membrane preparation using electrospinning synthesis because of its versatility and simplicity, which allows optimized membrane design through control of the fibers' material, shape, and deposition pattern. A recent review on the application of electrospinning technology for the fabrication of nanofibrous membranes and their property–function relationships has been published. The review critically and technically highlighted the advantages and disadvantages of this technology and suggested further actions that can develop the electrospinning technique for use in large-scale membrane synthesis [19].

Flux and energy efficiency in DCMD are inter-related and strongly influenced by polarization (temperature and concentration), process conditions (such as flow velocities and salinity), and membrane-related parameters like thickness, tortuosity, thermal conductivity, pore size, and porosity [25,26]. A few technical reviews have extensively covered the design and development of membranes and their impacts on the DCMD mechanism, as well as the influence of fabrication techniques on the performance of DMCD desalination technology [11,27–31]. Numerous efforts have been made to reduce the energy consumption of DCMD to make it more energy efficient [6,7,17,32]. As of today, however, a comprehensive review of membranes and distillation parameters on energy consumption has not yet been conducted.

Given all of the above, the need to accumulate and evaluate the updated research is obvious. A critical analysis of the energy efficiency of DCMD processes will help to establish its strengths and limitations and provide a road map for the development of this technology for both large-scale and portable applications. Many technical challenges must still be addressed at the forefront of MD development, including its high energy consumption, low thermal efficiency, membrane wetting, membrane scaling, low water flux, and membrane structure and design [19,25]. The objective of this review is to discuss the recent developments in direct contact membrane distillation, specifically for the improvement of DCMD energy consumption as a function of mechanistic properties.

2. Energy efficiency and desirable energy requirements (< 1 kWh/m^3)

More than 11,000 desalination plants are in operation globally, producing > 26 million m^3/day; approximately 63% of this capacity originates from West Asia and the Middle East, North America accounts for ~11%, while North Africa and Europe account for ~7% each [33]. Desalination plants in Qatar produce over 1 million m^3/day of fresh water alone and by 2030 the country is expected to be nearly 96% urbanized, increasing the demand. Desalinating water on these scales can be restrictively expensive due to the high energy demands of current technologies.

Currently the top three methods of desalination are: multi-stage flash distillation (MSF), multiple effect distillation (MED), and RO [34]. As seen in Table 1, MSF is the primary desalination method currently being used in Qatar and throughout the region. Because it relies on boiling water, however, MSF is one of the most energy intensive techniques, requiring up to 75 kWh/m^3. This energy is generated through combustion of fossil fuels, and two-thirds of the energy is ultimately rejected as waste heat [35]. MED is another thermal technique that uses a sequence of vessels (or "effects") of decreasing pressure and boiling water. Although MED is more efficient than MSF, it still requires up to 55 kWh/m^3 to produce fresh water. RO operates using high pressure applied to a semipermeable membrane, and for this reason it uses less energy than the MSF and MED thermal methods. However, the membrane can become clogged with minerals.

Given the high-energy costs associated with existing desalination methods, there is a great demand for technologies that can utilize low-temperature sources such as waste heat or solar energy. DCMD is one such technology. Energy efficiency, with respect to DCMD, is commonly defined as "the ratio of the heat transfer due to flux Q_N [convection] to the total heat transported through the membrane Q_m [convection + conduction]" and is given by Eq. (1) [26]:

$$\varepsilon_T = \frac{Q_N}{Q_m} = \frac{Q_N}{Q_N + Q_C} \quad (1)$$

where Q_N is the heat transfer due to convection by the vapor flux, Q_m is the total heat transported through the membrane, and Q_c is the heat

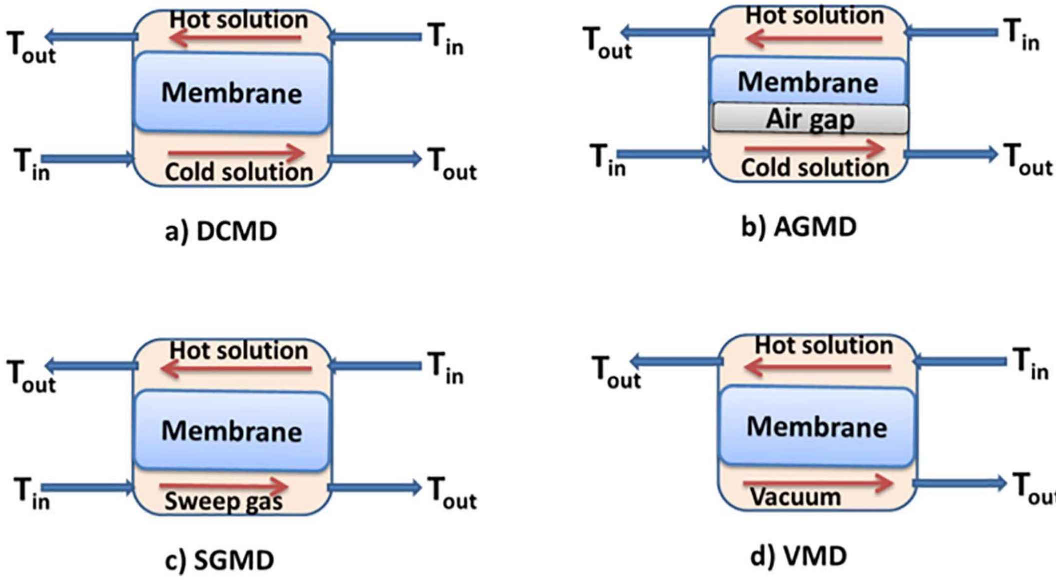

Fig. 1. Illustration of four types of membrane distillation techniques.

loss due to conduction [26]. More appropriately, this efficiency may be called the "membrane thermal efficiency (MTE)" and is a function of the operating conditions. In general, MTE increases as the feed temperature and flux increase [36,37]. For any ideal MD system, the maximum value of this MTE (ε_T) is 1. Notably, DCMD possesses the lowest efficiency when compared to AGMD), permeate gap MD (PGMD), and conductive gap membrane distillation (CGMD) [38].

Eq. (1) only defines the relative rates of heat transfer across the membrane. In reality, however, MD systems consume energy for three main functions: heating hot brine, condensing the permeate stream, and running various pumps based on the design and configuration of the system. Much attention has been given to increasing the MTE by reducing the heat loss due to conduction and convection across the membrane [22,36,39]. In order to improve the overall performance of MD and reduce the energy consumption to < 1 kWh/m^3, the energy usage of the entire system, including the electrical energy consumed by pumps as well as the heat energy given to and lost by the system, must be considered [40]. Thus, Khayet et al. described the energy efficiency (ε_E) in terms of Eq. (2), which includes both the electrical and heat energy consumed during a MD process [12] [12].

$$\varepsilon_E = \frac{J_W A \Delta H_{v,w}}{E_t + E_e} \tag{2}$$

where J_w is the permeate flux, A is the membrane area, $\Delta H_{v,w}$ is the enthalpy of water evaporation, E_t is the thermal energy used and lost, and E_e is the electrical energy. A study conducted to evaluate various models and techniques to desalinate contaminated water from the gas and oil shale industry concluded that seawater desalination requires ~1 kWh/m^3 of energy using forward osmosis techniques, whereas this energy requirement becomes 9 kWh/m^3 for wastewater purification [6]. Returning the hot brine to the feed supply was beneficial for improving the thermal efficiency of the DCMD system, where the thermal energy consumption was reduced to half by brine recycling within the optimal water recovery range of 20–60% for seawater with no membrane fouling or scaling [17]. The specific thermal energy consumption (STEC), which is a measure of thermal energy utilized per unit volume of the distillate and water flux, was found to reduce significantly, whereas the gained output ratio (GOR), which is the ratio of heat associated with the water vapor transfer and the total heat input, was increased by recycling the brine. By introducing to the GOR the heat recovery factor, which is the ratio of the maximum recoverable heat to the heat transferred in the membrane module and depends upon the configuration and number of steps of the MD system, Eq. (2) can be re-arranged as follows [41]:

$$GOR = \varepsilon_E H_R \tag{3}$$

where H_R is the maximum recoverable heat, as defined in the literature as Eq. (3a), and is a function of the temperature drop across both the membrane and the heat exchangers [42]; [41].

$$H_R = \frac{\Delta T_{axMD}}{\Delta T_{MD} + \Delta T_{HX}} \tag{3a}$$

Improvements of the heat recovery have been achieved by making MD a multistage process; however, this approach significantly reduces the flux and increases the system's capital costs [43,44]. As detailed in Table 2 of Ref. [12], GOR is less than unity for most single-stage and AGMD systems, which can be increased either by increasing the number of stages in the system and/or by enlarging the effective membrane area up to > 10 m^2 [20].

In 2012, Summers et al. [9] used GOR as a tool to compare the energy consumption of DCMD with that of VMD and AGMD using theoretical models. It was found that the GOR of VMD is less than one and AGMD has a comparatively better value, but the air gap width has a

Table 1
Energy requirements of desalination methods currently used in Qatar and membrane distillation systems.

Desalination method	Qatari production capacity (m^3/day)	Thermal energy required (kWh/m^3)	Electrical energy required (kWh/m^3)	Recovery rate (%)	Temperature required (°C)
Multi-stage flash (MSF)	974,222	53–70	2.5–5.0	15–50	90–110
Multiple effect distillation (MED)	28,384	40–65	2.0–2.5	15–50	65–70
Reverse osmosis (RO)	5790	0	4.0–6.0	30–50	< 60
Membrane distillation (MD)	n/a	100	1.5–3.65	60–80	60–90

Table 2
Experimental conditions and parameters of DCMD.

No.	Type	Feed			Permeate			Flux = J (L/m^2 h)[a]	Ref.
		Temp. (°C)	Flow Rate (L/min)[a]	Conductivity (mS/cm)[a]	Temp. (°C)	Flow Rate (L/min)[a]	Conductivity (mS/cm)[a]		
1	PP	50	1.25		25	1.25	52.5	9.5	[17]
2	PTFE	130	0.50	1% NaCl	80	0.5		195 kg/m^2·h	[5]
3	PTFE	72	0.14 kg/s	1.2 W/m·K	45	10 kg/h			[9]
4	ePVDF	52.5	0.04–0.28 m/s		20	0.04–0.28 m/s		5 kg/(m^2·h)	[26]
5	ePVDF	50	0.6	3.5 wt% NaCl	20	0.6	19	21 kg/h·m^2	[64]
6	PP	59	200 L/h		14.3	200 L/h		25.4 kg/m^2·h)	[48]
7	PP	85–90	25	1–10% NaCl	40–60	1200–3900 cm/min		60–79 kg/(m^2·h)	[20]
8	PP-167							11.05–3.27 kg/m^2·h	[25]
9	PTFE	38	11–22	Various	20	11–22		2–5	[97]
10	M4–2 (PDMS)	70	1.0	3.5 wt% NaCl, 66.5 mS/cm	26	0.5	1.2–1.8 μS/cm.	42.52	[74]
11	Fluorographite coated PVDF			10 wt% NaCl					[68]
12	PTEF	40–90	4.65	0.14, 2, 43, and 100 g/L	5–25	3.65		55–72 kg/m^2·h	[51]
13	PTFE	43–65	1–1.5	200 g/L NaCl	19.9–29	1–1.5		7.68 × 10^{-7} kg/m^2 s Pa	[81]
14	PP	40–50–60	30, 50, 100 L/h		18	100 L/h		5, 15, 25 kg/m^2 h	[45]
15	PVDF and Halar	25–40	0.4–0.8 m/s	30–60% *w/w*	18	1.2 m/s		5 kg/m^2 h	[40]
16	PTFE	60	4.5	Seawater	20	4.5		28.48 to	[65]
17	PP	70	15–20	0–40 g NaCl/L	20–56	15–20			[100]
18	PVDF	80	6	0.045	30	6		51.4 kg/m^2·h	[52]
19	PTFE	42–68	30 L/min – 180 L/h	45 g/L NaCl	20–30	30 L/min – 120 L/h		7–11 kg/m^2·h	
20	Modified GF	60	0.4	1 M NaCl	20	0.3	1 M NaCl	20	[75]

[a] Unless other indicated.

significant impact on the performance. In DMCD, GOR was found to be a function of both the thickness and flux, which subsequently reduce resistance to heat and mass transfer [9]. Integration of the DCMD unit with three cascaded AGMD units leads to a reduction of the STEC, a two times increase of GOR, and 4-fold increase in the permeate production with respect to the standalone DCMD system [45].

Introducing a conductive medium between the membrane and condenser instead of the insulating material makes the gap a heat sink, which consequently improves the thermal efficiency of conductive gap MD (CGMD) two times higher than permeate gap MD (PGMD). Additionally, it was also demonstrated that GOR increased significantly by increasing the gap conductivity up to a maximum of 10 W/m·K; however, further increasing the gap conductivity was not useful to enhance thermal efficiency [46]. A modeling study of various systems (i.e., CGMD, PGMD, AGMD, and DCMD) has shown that GOR is a function of membrane effectiveness (η), which is a measure of the energy transfer between the hot and cold streams scaled by the total possible energy transfer. It has a maximum value of unity for an infinitely large MD area [47]. According to the modeling study, the GOR of a DCMD system having an infinitely large area external heat exchanger can be evaluated by Eq. (4) and is a function of thermal efficiency and MD effectiveness [47].

$$GOR = \varepsilon\, x\, \frac{\eta}{1-\eta} \tag{4}$$

The investigation showed that ε and η are higher for DCMD compared with CGMD under similar operating conditions due to the reduced overall resistance; as a result, the former has a 5–10% higher GOR than the latter. In practice, many studies have demonstrated that GOR increases with increasing membrane effective area, whereas STEC is significantly reduced when a large surface area membrane was used [45]. A simulation study has been conducted to study the effect of various operation conditions and designs of the DCMD cross flow module on the water flux, gain output ratio, and water production cost [3]. The optimized permeate and feed velocities were 0.48 m/s and 0.04 m/s, respectively, for comparable water production and less energy consumption. For the highest GOR, the maximum membrane area was noted to be 4 m^2 with no further increments. A constant water production cost was maintained for a temperature difference of > 6 °C in the heat exchange of the DCMD system. Notably, given all these optimized conditions and parameters, the water production cost of DCMD was measured to be \$1.5/m^3, which is three times higher than that of a RO desalination system (at \$0.5/m^3). Upon comparing the DCMD and VMD modes under longitudinal flow with the cross flow and transverse flow modules separately using identical experimental conditions and the same type of membrane, it was observed that the cross-flow membrane module consumes ∼1.1 kW/(kg·h) while the former consumes 3.55 kW/(kg·h) for the same flux.

The theoretical minimum energy requirement for desalinating seawater containing 3500 ppm salt with almost a 50% recovery rate by RO is estimated to be 1.06 kWh/m^3. Currently, however, RO plants consume approximately 3–4 times more energy than the theoretical estimation, in addition to 1.8 kg CO_2 emission per cubic meter of clean water [49]. The amount of energy required to produce one cubic meter of distilled water (kWh/m^3) in a distillation plant is termed the specific energy consumption (EC) and is a fundamental parameter for desalination systems. Table 1 of Ref. [12] shows details of technical studies that evaluated various MD technologies. As seen, AGMD using waste energy management has a specific EC of 1.25 kWh/m^3, whereas VMD, which uses both thermal and electrical energies, has an EC of > 9000 kWh/m^3 [50]. The thermal efficiency of a DCMD process using a commercial PTFE membrane increased significantly from 70% to 95% with a feed temperature increase from 40 °C to 90 °C. Additionally, GOR was increased with increasing feed inlet temperature up to a maximum of 60 °C, and further increases in the feed temperature were found to adversely affect the GOR of the system [51]. As mentioned previously, a thermal boundary layer develops due to the temperature polarization effect in the vicinity of the membrane, which in turn reduces the mass transfer. This boundary layer demands more energy to stabilize the product water flux across the membrane. To suppress the effect of the thermal boundary layer and enhance the water flux, corrugated feed channels of various sizes and heights have been introduced in the

DCMD system. Studies of laboratory-scale DCMD systems revealed that the thermal efficiency and water flux were improved by 33% and 44%, respectively, when a PTFE membrane was coupled with corrugated feed channels, irrespective of the operating conditions and channel heights. The corrugated channels create turbulence in the feed flow that prevents the development of a thermal boundary layer; as a result, the thermal efficiency and flux increased across the membrane [52].

It is clear that a barrier to the practical application MD is its large thermal energy requirement relative to MSF and MED (Table 1). However, MD can operate using low quality heat sources such as waste heat or solar thermal energy. In addition, MD requires less electrical energy than MSF, MED, or RO. As previously mentioned, while DCMD has more favorable properties than other MD technologies, it has the lowest internal thermal efficiency. By focusing on improving the internal efficiencies of DCMD, i.e. MTE, GOR, and flux increase at a given temperature, the overall energy efficiency of the method should increase. These topics will be covered in the following sections.

3. Membrane design effects on MTE

3.1. Physical properties: Size, geometry, hydrophobicity, contact angle, and wettability

The physical properties of a membrane such as thickness, fiber morphology, and pore size can significantly influence the permeate flux as well as heat and mass transfer coefficients [53]. Although thinner membranes have higher mass transfer and flux, there is a trade-off between mass and heat transfer across the membrane. That is, heat transfer will increase as the membrane thickness decreases, leading to performance degradation. To address heat transfer and loss it is beneficial to have thicker membranes or multi-layered structures, but this is detrimental to mass transport [53–56]. Clearly, balancing these parameters is an important aspect of membrane design. Simulated and experimental studies have suggested that membranes optimized for energy efficiency should have thicknesses in the range of 20–60 μm [26,57,58]. A detailed review of the optimized membrane parameters for superior performance in the terms of high permeate flux suggests that the membrane should have pore diameters of 0.3 μm to maintain high liquid entry pressure (> 2.5 bar); thickness in the range of 10 to 700 μm, depending upon the mass transport and energy loss; porosity larger than 75%; a tortuosity factor between 1.1 and 1.2; thermal conductivity in the range of 0.06 W/m·K; and a suitable mechanical strength, which depends on the membrane material and thickness [59]. However, theoretical predictions and experimental investigations showed that the MTE of PVDF and ePTFE membranes at a heat transfer coefficient of 600 W/m^2 K decreases as the membrane thickness decreases. Fig. 2 shows the effect of PVDF and ePTFE membrane thickness on the thermal efficiency of the DCMD system. In this case, membranes in the range of 1500–200 μm were assumed to be the most suitable thickness, with efficiency as high as 80% [60].

3.2. Membrane thickness

Jansen et al. defined the energy efficiency of an MD system as the ratio of the energy transferred by the water vapor (latent heat, Q) to the total heat (latent heat + conduction heat), which should be close to 100% for an ideal MD system [50]. To determine the effect of the process parameters on MTE, three different pilot projects using seawater and brackish water were evaluated for a production capacity of 1 m^3/h. The MTE of two pilot projects and similar bench scale units were varied between 50% and 75% based on the process conditions and temperature. The MTE was increased to 90%, where the actual energy requirement decreased from 2400 MJ per m^3 of water production to 520 MJ per m^3 in one pilot; in this case, a membrane almost 150% thicker was used relative to the other pilot studies. Clearly, this result demonstrates the effect of membrane thickness on the heat transfer due to conduction [50].

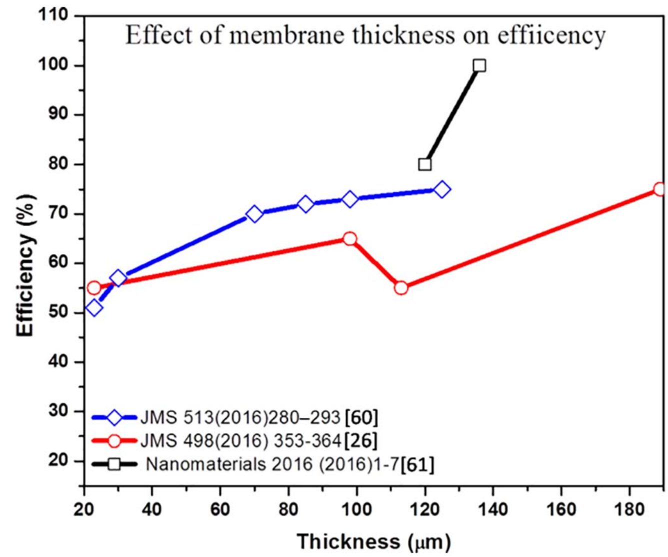

Fig. 2. Effect of membrane thickness on thermal efficiency.

Notably, Eykens et al. have argued that energy efficiency is independent of membrane thickness. For maximum flux at higher salinities, Eykens et al. have instead argued that the optimal membrane thickness is a function of the membrane module and operating conditions [62]. For clean water, it was experimentally confirmed that a thinner membrane was appropriate for higher flux, whereas for NaCl concentrated water in the range of 0 to 24 wt%, a membrane thickness between 2 and 739 μm was suggested to be the best option for different flow velocities and bulk temperatures to achieve higher energy efficiency [26].

Two different types of electrospun nanofibrous membranes (ENMs), termed beaded and bead-free, have been prepared based on the PVDF solution concentration using electrospinning synthesis routes. For each type of membrane (i.e., beaded and bead free), it was found that increasing the PVDF solution concentration reduced the inter-fiber space. However, due to their fibrous structure, bead-free ENMs prepared with concentrations higher than 22.5 wt% possessed high void volume fractions and led to superior DCMD performance, including a high permeate flux and higher salt rejection rate than the beaded ENMs [63]. In addition, the liquid entry pressure (LEP) and permeate flux were augmented after the thickness of the electrospun PVDF nanofibrous membrane was reduced by post synthesis heat treatment up to a maximum of 170 °C, while the hydrophobicity, pore size, and porosity were reduced significantly [64].

Boukhriss et al. [25] have recently observed the effect of membrane thickness and salt concentration on the permeate flow and thermal efficiency of different types of membranes. Due to the concentration polarization effect, the results revealed that the thermal efficiency and permeate flow were considerably reduced for thinner membranes and highly concentrated solutions; this reduction was less pronounced for thicker membranes. By comparing the performance of two commercial PTFE membranes at various feed and permeate conditions and different feed concentrations, Khalifa et al. showed that small thicknesses (154 μm) and large pore sizes (379 nm) offer less resistance to mass transfer, thereby generating a large driving force across the membrane and resulting in a large flux [51]. By comparison, three different pore size PTFE membranes were tested using similar feed conditions for actual seawater distillation with solar thermal energy as the heating source. The results indicated that LEP decreased as the pore size increased and the membrane with the smallest pore size was more hydrophobic relative to two similar membranes composed of the same material [65]. From the above discussion, it can be deduced that the membrane thickness is not the only aspect to influence MD performance in terms of energy efficiency and permeate flux; other physical parameters such as pore size, void volume fraction, pore size distribution, pore wall thickness, and inter-fiber space also have a significant role in membrane performance [64,66]. Optimization of these parameters in conjunction with membrane thickness for energy-efficient and high-capacity water production DCMD systems still requires further investigation for both laboratory and large-scale applications. However, it has been demonstrated that although beaded ENMs are thinner than bead-free ENMs, the latter membrane has a much higher DCMD permeate flux than the former due to its higher void volume fraction [67].

3.3. Hydrophobicity and contact angle

Super-hydrophobicity is a pre-requisite for achieving efficient DCMD processes. Hydrophobicity depends upon pore size, pore size distribution, membrane materials, surface geometry, and surface energy. Ideally, a super-hydrophobic membrane should have a very rough surface with a contact angle > 150° and possess a very low surface energy. Liquid entry pressure is another important parameter for super-hydrophobicity, which can be defined as the minimum pressure at which liquid enters the membrane pores to cause wetting. To avoid membrane wetting, the applied hydrostatic pressure must be lower than the LEP. Membranes made of materials with high hydrophobicity, low surface energy, and small pore sizes are preferred for large LEP. However, relatively small pore sizes are inappropriate for high flux and may lead to fouling and scaling. In other words, high LEP requires small pore sizes while high flux requires large pore sizes. Therefore, a compromise must be established between these two parameters and membranes, and specific features (i.e., high flux with negligible pore wetting) should ideally be fabricated directly into the membrane. Essalhi et al. prepared nanofibrous membranes of PVDF using electrospinning synthesis techniques. It was observed that the membrane thickness increased by increasing the electrospinning time, which resulted in a high LEP; notably, the contact angle and diameter of the electrospun fibers were unaffected [63].

One method to increase the hydrophobicity and wetting resistance of fibrous membranes has been the addition of secondary materials to the polymer fibers. For example, fluorographite microcrystalline powder possesses highly hydrophobic properties. This material has been recently deposited on the surface of a PVDF membrane using filtration and dry-jet wet-spinning techniques. The results indicated that the fluorographite-modified hollow fiber membranes can function for up to 200 h without any reduction in performance. In addition, the inclusion of fluorographite yielded a better LEP and improved wetting resistance while negligibly affecting the flux [68].

3.4. Materials: material properties and synthesis

Two major issues concerning the reduction in flux of MD systems are vapor transfer resistance and the temperature polarization effect, which may be partially resolved by membranes with large pore size, large porosity, and low tortuosity. Small pore size may lead to pore wetting due to vapor condensation and membrane fouling/scaling [69]. Therefore, a highly hydrophobic membrane with suitably sized pores and porosity is required that can very selectively allow water vapor to pass with high flux and zero wettability [27]. To overcome the major issue of pore wetting, highly hydrophobic polymers such as (PP, PVDF, and PTFE have been extensively used as building block monomers to fabricate porous membranes [70–72]. In addition to the parent materials, fabrication techniques also strongly influence the physical properties and parameters. Studies have shown that among the various fabrication technologies (i.e., track-etching, interfacial polymerization, and phase inversion), electrospinning is the most appropriate method to prepare flat structure membranes with very high hydrophobicity [18,73].

Very recently, super-hydrophobic membranes with large water contact angles have been fabricated by electrospinning different solutions and ratios of poly-dimethylsiloxane (PDMS) and poly (methyl methacrylate) (PMMA). It has been experimentally demonstrated that the contact angle is directly related to the polymer surface roughness, which in turn increases as the PDMS/PMMA mass ratio increases. The performance of the electrospun membrane was compared with a commercially available PVDF membrane, and it was concluded that a membrane fabricated with a PDMS/PMMA ratio of 1/1 had the largest pore size (8.03 μm), possessed a permeate conductivity of 3.9 μS/cm, and had an average permeate flux of 42.52 $L/m^2 h$ with a 99.99% salt rejection rate [74]. Although the M4–2 membrane showed superior MD performance among all membranes prepared under different experimental conditions, a decrease in the permeate flux and salt rejection was observed when it was continuously used for longer than 24 h due to pore wetting and temperature polarization [74]. It is noteworthy that fabrication of super-hydrophobic membranes requires appropriate materials of a suitable combination and concentration to give a low surface energy, low surface tension, low surface density, and strong water repellent properties [75,76]. Fig. 3 shows a direct relationship exists between the contact angle and permeate flux provided that the other experimental conditions are similar. Specifically, the permeate flux of the membrane increases as long as the membrane contact angle increases parameters such as pore size, pore size distribution, membrane effective area, feed and permeate flow rates, and temperatures are unchanged. As indicated with the circle in Fig. 3, the type and concentration of the feed solution may also affect the flux at some contact angles. Further, the inset of Fig. 3 reveals that a small difference in contact angle (2°) of two membranes prepared from the same material can also significantly influence the permeate flux of the DCMD system. A decrease in the permeate flux, which is mainly associated with pore wetting, causes the temperature and concentration polarization effects, followed by a reduction in the pressure. Super-hydrophobic membranes possess larger contact angles (> 150°) and therefore have less chance of pore wetting and flux reduction [71]. Thus, as shown in Fig. 3, higher permeate fluxes occur for larger membrane water contact angles, irrespective of the type of membrane material.

4. Mass and teat transfer optimization

The formation of two boundary layers: 1) a concentration boundary

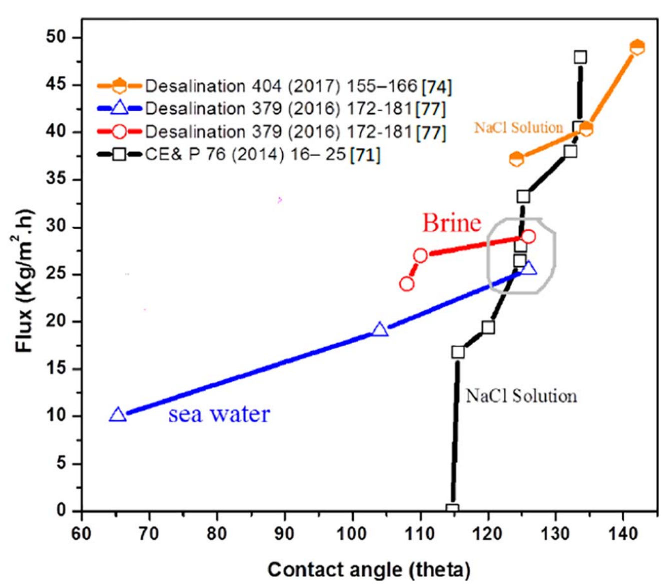

Fig. 3. Effect of contact angle on permeate flux.

layer caused by 100% salt rejection on the feed side, and 2) a temperature boundary layer caused by the temperature polarization effect, are the two main mechanisms associated with hindering mass and heat transfer across DCMD membranes. These key factors are strongly dependent on the membrane materials and its physical parameters. Mass transfer across a membrane is calculated through multiplication of a vapor pressure difference (Δp) originating from the temperature difference and membrane distillation coefficient (MDC). The MDC is obtained through either one of the mass transfer resistance models (i.e., Dusty gas model, Poiseuille flow, Knudsen diffusion, or molecular diffusion) or a combination of two or more of these mass transfer mechanisms [39,78]. These models are very complex, depending on the membrane characteristics such as pore size, pore diameter, and the water vapor mean free path, and require a large number of experiments for verification.

Gustafson et al. have conducted experimental and simulation studies to model constant membrane distillation coefficients to evaluate mass and heat transfer in large-scale DCMD applications. They demonstrated that independent of the membrane materials, MDC can be considered as a common constant value for a feed temperature difference in the range of 40 °C to 70 °C with a distillate temperature of 20 °C [79,80]. The results show that while the model predicted was tested on the laboratory it can be utilized on an industrial scale with a constant MDC scale through a stepwise approach [81].

In contrast, Ding et al. showed that the membrane pore size and feed temperature have a significant impact on MDC, which in turn influences mass transfer across the membrane [78]. By fixing MDC as a constant value, it was demonstrated that the maximum effect of mass transfer on the heat transfer rates in the feed and permeate side are 7.2 and 3.2%, respectively, and can be ignored during the calculations.

In addition, experimental results further revealed that heat transfer due to vapor flow in the membrane is equivalent to or greater than the heat conduction and increased with increasing feed temperature [79]. Simulations predicted that mass transfer also affects the heat transfer (called the Dufour effect) and is approximately 2 times higher on the feed side than the permeate side. Further study confirmed that heat transfer inside the membrane is mostly caused by vapor flow across the membrane, and the Dufour effect can be neglected at all times on the permeate side and only at low feed temperature on the feed side [82]. Increased mass transport across the pores demand thinner membranes, and reduced heat transport across the membrane requires thicker membranes. To balance these two opposing forces certain steps can be taken. To allow for thicker membranes while maintaining mass transfer, vapor transport resistance across the membrane can be reduced by deposition/coating of a hydrophilic layer on a membrane's internal fibers. This has been achieved by the addition of a polydopamine/polyethyleneimine coating on the internal hydrophobic polypropylene hollow fibers membranes without any substantial increase in its thickness. The study showed that the hydrophilic layer-coated membrane has a slightly lower LEP, reduced mass transfer resistance, and augmented water flux, which was further increased with temperature. The contact angle of the outer surface of the modified hollow membrane was found to be 105°, whereas it was just 35.5° for the inner surface coated with a hydrophilic layer. Overall, this contact angle modification at the two surfaces improves the permeate flux and salt rejection of the membrane [83].

4.1. Improving mass transfer through turbulence

Temperature and concentration polarization are two major issues that impede the thermal efficiency and mass transfer coefficients of DCMD technology. Techniques such as increasing the flow rate through additional pumps, changing the flow rate from laminar to turbulent conditions, and introducing empty and filled spacers on both sides of the membranes have been utilized to improve the hydrodynamic conditions and reduce temperature and polarization effects [84–87]. As shown in Fig. 4, spacers are net-like feed channels (turbulence promoters) in any geometrical combination, mesh size, thickness, and voidage [1]. Theoretical and experimental studies have demonstrated the advantages of incorporating spacers into the feed and permeate sides of the membrane, which improve the overall performance of DCMD systems. It has been experimentally demonstrated that spacers (either filled or empty) reduce thermal polarization effects and enhance the permeate flux. Notably, the orientation and design of the spacers has a significance influence on the pressure drop and polarization effects. Specifically, they have been tested experimentally in bench-scale systems to minimize the temperature and concentration polarization effects and improve the water production of MD technology [88,89].

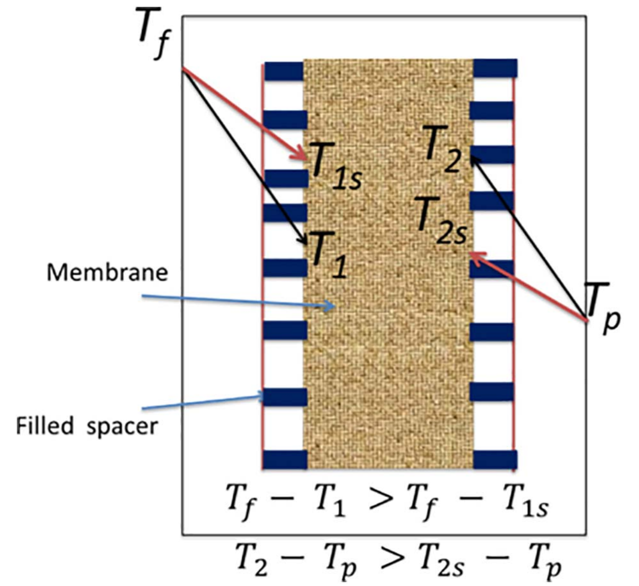

Fig. 4. Filled spacers on the feed and permeate sides of the membrane reduce the temperature boundary layer thickness [90].

As shown in Fig. 4, the temperature difference between the bulk and membrane surface (T_f–T_1) decreases (T_f–T_{1s}) on the feed side after the insertion of spacer. Similarly, the temperature difference on the permeate side (T_2–T_p) also decreases to lower values of T_{2s}–T_p because of the spacer. Note that the membrane distillation coefficient (MDC) is a physical property and is material dependent. Therefore, it is not modified by the application of filled- or empty-spacers. Phattaranawik et al. observed flux increases up to a maximum at a spacer voidage of 60% and an optimum hydrodynamic angle of 90° (Fig. 5), though any further increase in the voidaige % was detrimental to mass flux [90]. Another recent experimental and simulation study has shown that the effects of the thermal boundary layer and concentration polarization can be greatly reduced through the use of a spacer (Fig. 4), which in turn increases the mass transfer rate. However, a minute pressure drop occurs due to spacer channels in the DCMD system, which is primarily attributed to the hydrodynamic angle and kinetic losses caused by the change in flow directions [1,91,92].

Clearly, the introduction of voidage into the system either through filled or empty spacers has a significant influence on the permeate flux. The data of Fig. 5 has been adapted from selected articles where only filled spacers were used to reduce the heat transfer and enhance the mass transfer across the membranes. In many cases, the optimal voidage was found to be in the range of 60%, since increasing and/or decreasing voidage above/below this value reduces the flux of the system. Voidage itself is dependent on the composition of the spacers, the inlet flow rate, the spacer orientation and its thickness. Therefore, optimal conditions are required for the installation of spacers in a DCMD system to achieve maximal mass transfer and low heat transfer. However, such conditions depend on the parameters of both the

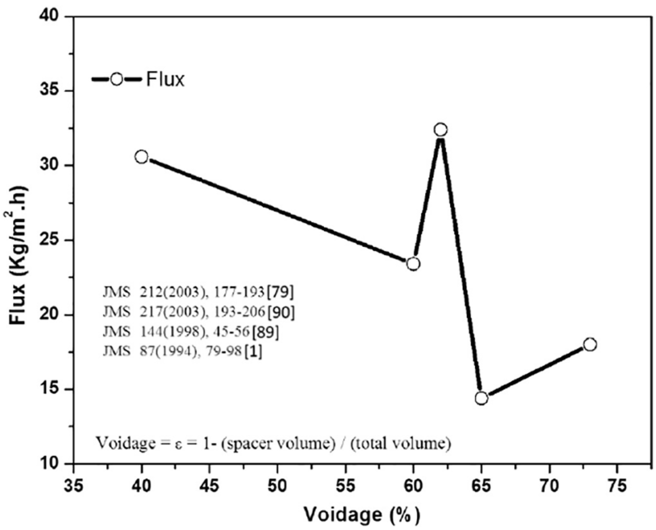

Fig. 5. Effect of voidage on permeate flux.

membrane (physical) and the entire system [1].

5. Feed water properties

Wastewater produced from steam-assisted gravity drainage systems was used as hot brine to determine the performance of a large-scale DMCD process using a PTFE membrane [5]. Singh et al. observed that the water vapor flux and the trans-membrane pressure difference exponentially increased with feed water temperatures above 80 °C; however, increasing the brine flow rate from 50 mL/min to 850 mL/min had no significant effect on the vapor flux. Approximately 2–5 ppm of phenol, cresol, and naphthenic acid were detected in the distillate water after vaporizing the brine water at 128 °C and no traces of NaCl were found in the permeate, indicating the non-wetting performance of the PTFE membrane at high temperature [5]. Song et al. compared the performance of two cross-flow membrane modules as a function of the feed brine temperature, feed salt concentration, linear velocity of the distillate, and distillate temperature [20]. Higher flux was observed as the distillate linear velocity increased, leading to a decline in the distillate outlet temperature. Lower distillate temperatures improved the flux of the system by maintaining the temperature difference between the brine and distillate (i.e., $\Delta T = T_{brine} - T_{dist}$). It was further revealed that the outlet temperature of the distillate rose and almost became equivalent to the brine temperature at lower linear distillate velocity, thus reducing the temperature difference (i.e., ΔT), which in turn reduced the driving force. Alternatively, the water vapor flux exponentially increased as the feed inlet temperature and the distillate inlet temperature at fixed velocity were increased, thereby reducing the driving force and subsequently reduced the vapor flux. Additionally, the feed salt concentration up to a maximum of 10% (NaCl) was found to have a nominal effect on the module performance.

Salinity has a direct impact on the flux and energy efficiency of MD systems. Relative to pure water, both of these aspects are significantly reduced for high concentration saline water. Moreover, the energy efficiency of thinner membranes has been shown to decrease as the salinity increased, whereas that of thicker membranes was less affected, indicating a size-dependent performance of membranes for diluted and concentrated water [26]. For thinner electrostpun-PVDF (ePVDF) membranes (20 µm) in concentrated (20 wt%) water, as found in brine and chemical and pharmaceutical industries [93,94], the flux was negative at low flow velocities and low temperatures; that is, water moved from the permeate side to the feed side owing to osmotic pressure. For thicker membranes like PP (188 µm), PE (95 µm), and PVDF (112 µm), however, a positive flux was observed. At an optimal PP membrane thickness (49 µm) and salt concentration (24 wt%), increasing the temperature difference and flow velocities enhanced the flux of the system, suggesting their direct impact on improving the driving force [26]. The impact of other process parameters such as feed velocity and temperature on the energy efficiency of the DCMD process has been examined in the filtration of fruit juices using five different types of PVDF and ethylene chlorotrifluoroethylene (Halar ECTFE) hollow fiber membranes in the low temperature range of 25 °C to 40 °C. It was observed that Halar fiber membranes (HFMs) performed better than PVDF in terms of water removal and MTE, with 45.65% and 14.9% MTE, respectively. It was further demonstrated that the MTE was slightly increased as the feed velocity increased; however, this effect was reversed at high feed concentration, particularly for HFMs, which may be associated with the concentration polarization effect for high flux [95]. Similarly, at high feed velocity, thinner membranes have better performance, and low feed velocity was more suitable for thicker membranes to achieve a high MTE DCMD process, where the optimal membrane size was 150 µm.

6. System parameter effects on MTE

At water recoveries below 70%, no scaling on the membrane surface was observed, but the water flux was influenced by feed salinity, temperature, and polarization effects [17]. As is common practice with DCMD systems, the distillate flux of the longitudinal flow membrane module increased as the hot feed temperature increased, while further increases in the stream flow rate above 200 L/h was not beneficial for mass transfer [48]. As shown in Table 2, the effects of operating conditions such as feed temperature, feed flow rate, permeate temperature, and permeate flow rate on the DCMD permeate flux have been experimentally investigated for times as long as 48 h. The results indicated that increasing the feed temperature, feed flow rate, and permeate flow rate and decreasing the permeate temperature caused a reasonable increase in flux with 100% salt rejection [96].

6.1. Captured heat recycling

To demonstrate the possibility of using DCMD technology in practical applications for water purification, a commercial PTFE membrane with a pore size of 5 µm and a total membrane area of 0.67 m^2 has been tested through a low-grade waste heat (< 40 °C) obtained from a coal power station to distill the station's effluent, which contains dissolved salt, CO_2, and ammonia as major contaminates. To produce a total of 8000 kL/day using waste heat from a gas power station, the results revealed that the salt rejection of the system was ~99.9%, the total flux was as low as 3 $L/m^2 \cdot h$, and the energy consumption was ~1500 kWh/m^3 [97].

A modeling study has suggested that for low-grade energy consumption, the feed solution must be above 50 °C with a Reynolds number in the range of 3000–5000 (transitioning to turbulent flow) in order to make DCMD a competitive seawater distillation process [37].

6.2. Flow rate

Very recently, Khalifa et al. have investigated both experimentally and theoretically the effect of system parameters, such as feed and permeate temperature, feed-to-permeate temperature difference and ratio, feed and permeate flow rates, feed-to-permeate flow rate ratio, and salt concentration of the feed, on the MTE and GOR of the DCMD process [51]. As shown in Table 2, a maximum flux of 72 $kg/m^2 \cdot h$ obtained at a feed temperature of 90 °C and permeate temperature of 5 °C was mostly attributed to the high temperature difference, which subsequently produced a high driving force (i.e., vapor pressure across the membrane). However, the high temperature difference between the feed and permeate caused a temperature polarization effect, resulting in a reduction of the flux. Relative to the system running with the

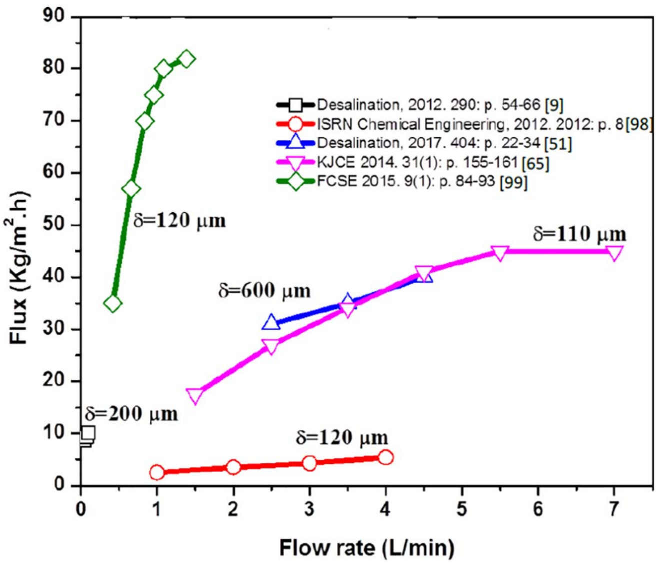

Fig. 6. Effect of the feed flow rate on the permeate flux at 70 °C for commercial PTEF membranes.

permeate temperature around room temperature, an energy penalty was thus imposed on the system. It was also demonstrated that increasing the feed flow rate improves the permeate flux at any temperature, and this effect is multiplicative at high feed temperature. Fig. 6 compares the permeate flux versus feed flow of various systems from the literature. Most of the experimental parameters, including the feed flow temperature, were kept constant except for the membrane thickness. As seen, it is common for the permeate flux of each system to increase as the feed flow rate increases. Increasing the permeate flow rate was also beneficial for the flux, but its effect is less pronounced than the feed flow rate. Although the feed and permeate temperatures and flow rates improve system performance, the higher salt concentration in the feed causes concentration polarization across the membrane and restricts vapor transfer due to fouling and scaling of the membrane surface, which consequently reduces the permeate flux and overall performance of the DCMD process [51]. To achieve the goal of having an energy efficient process, an experimental study supported by steady-state simulations revealed that DCMD could function efficiently at the highest suitable feed temperature and velocity if the permeate temperature and velocity are higher than 10 °C and 0.3 m/s, respectively [40] .

A theoretical and experimental study has also been conducted to evaluate the performance of a tubular DCMD process, and the effect of various geometrical and operating parameters on the GOR have been examined using a solar heating system. The results indicated that an increase in salt concentration was unfavorable for permeate water productivity since the viscosity of the water increases, which subsequently reduces the permeate flow rate and the mass transfer driving force. However, the temperature and concentration polarizations became reduced substantially due to shrinkage of the hydrodynamic boundary layer thickness because of the feed water flow rate increase [100]. Through a theoretical investigation, Lee et al. very recently suggested that a high thermal efficiency and partial vapor pressure difference can be obtained in the presence of higher temperature differences between the feed and permeate sides [101].

7. Application of solar energy in DCMD

The possible use of a portable and small-scale MD unit for arid and rural areas has been analyzed through conventional mass and heat transfer theories. A combined experimental and computer simulated study highlighted the sources of three major inefficiencies, including the presence of air in the membrane pores, heat loss due to conduction, and heat loss due to temperature polarization. The study further suggested that a small-scale distillation plant coupled with a solar heater would be economically superior and the most practical process for underdeveloped areas [41].

However, many aspects of large-scale solar ponds (e.g., El Paso, USA and Pyramid Hill Solar Pond Project') have been examined for heat generation, energy production, and water desalination to make use of solar energy stored in saline water in the form of heat. Two basic strategies have been utilized to extract heat from salinity gradient solar ponds: an internal heat exchanger (i.e., circulation of a heat transfer fluid in the heat exchanger through a pipe to the outside) and an external heat exchanger (i.e., pumping the hot brine from the top of the Lower Convection Zone (LCZ) and returning the cold brine to the lower part of the LCZ). Thermal efficiency of salt gradient solar ponds has been defined as the ratio of the total heat removed from the solar pond to the amount of solar radiation irradiated on an exposed surface of the pond for a specific (long) time interval. In addition to the very low thermal efficiency (i.e., up to 20%), technical issues such as the internal instability of the gradient zones, boundary moments between the zones, erosion caused by convection, and salt transport across the zones due to diffusion are among the major challenges that have hindered further development of solar pond technology [102–105].

In a recent study the salinity concentration and temperature differences at three different layers called the upper convection zone (UCZ), non-convection zone [106], and lower convection zone (LCZ) with increasing salinity and temperature from the UCZ to the LCZ have been investigated as a practical demonstration of solar ponds for possible application in DCMD technology. It was assumed that 40% of the solar energy can be absorbed by the LCZ and its temperature can be increased to 80 °C, which can then be utilized as a hot feed supply and the UCZ can be used as the permeate water supply. Experimental and theoretical studies indicated that the heat flux, heat transfer coefficient, mass flux, and evaporation efficiency all increased, though the temperature polarization coefficient decreased with increasing feed temperature [107].

A DCMD system using PTFE membranes of various pore sizes and operated by solar thermal energy showed that the permeate flux increased as the permeate temperature increased, which was mainly attributed to the increased vapor pressure. Conversely, the salt rejection rate remained constant for membranes with smaller pore sizes, and it decreased significantly for larger pore size membranes as the flow rate of the system increased. A flux of 28.27 $L/m^2 \cdot hr$ was recorded by a DCMD system for seawater operated on a sunny day, where the feed temperature at the peak hours (between 11 AM and 3 PM) reached a maximum of 61 °C [65].

The number of modules in solar energy operated multistage direct contact membrane distillation (SMDCMD) can be adjusted dynamically to increase the thermal efficiency and water production. Such a dynamic operating system is a procedure in multistage MD systems where the number of modules used is adjusted based on the inlet feed temperature of each successive module. This theoretical investigation showed that both the water production and thermal efficiency increased with the use of a dynamic operation system in an eight-stage DCMD plant operated with a collector area in the range of 350–550 m^2 and a seawater storage tank volume of 28.8 m^3. Dynamic operation caused the water production to increase from 1.16 m^3/day to 1.17 m^3/day and the thermal efficiency increased from 54% to 58.8% in the month of October [101]. Considering the significant heat loss that occurs in MD and that maintaining a proper temperature difference is paramount to optimal driving force this type of system can be an integral component in when considering intermittent/low quality heat sources for MD.

Upon comparing conventional MD technology with a system assisted by solar photovoltaic cells, it was observed that DCMD operated with solar energy has much better thermal efficiency, higher water production, and lower energy consumption than that operated by electrical energy. In addition, a DCMD system operated by conventional energy has an 83% thermal efficiency whereas a similar system operated by solar energy (i.e., photovoltaic cells) has a thermal efficiency of 95% under similar operating conditions and membrane but a different driving force source. The comparative increase in efficiency of the solar energy operated system was primarily attributed to the large flux compared with the electrical energy operated system [108].

Kim et al. explored the capability of a solar-assisted DCMD process in a large-scale application and used 50 DCMD modules with the parameters and operation conditions given in Tables 1 and 2. A permeate production capacity of 31 m^3/day was reported for a collector area of 3360 m^2, with an overall efficiency of 53%, a seawater tank volume of 160 m^3, and a thermal energy consumption of 436 kWh/m^3 with the heat recovery system. As a result, the experimental and simulation studies suggested that solar assisted direct contact membrane distillation is still an energy intensive technique compared with other desalination technologies (e.g., RO) owing to heat loss caused by conduction and its lower mass transfer [52].

8. Conclusion

On the basis of the current literature, it can be concluded that additional research is necessary for large-scale DCMD to make this technology an energetically efficient and economically viable option for seawater distillation and wastewater treatment. Indeed, many challenges persist such as a relatively low output flux and high energy consumption compared with conventional RO processes, flux decay caused by temperature and concentration polarization effects, and suitable membrane and module design. Among the major issues that require focused research initiatives are the lack of standardized units, process definitions, and identification. The non-availability of standard units and definitions for energy efficiency, differentiations between thermal and total energy consumption, and standard feed and output water properties make it difficult to identify the most appropriate and reliable design and process. Without question, it is crucial to establish standard module designs, standard measuring units, parameters, standard feed seawater, wastewater properties, and standard product water properties to compare membranes in meaningful way. As an example of the unit and parameter non-uniformity, many research articles have reported different energy efficiency definitions and notations (such as gain output ratio, energy efficiency, and thermal energy efficiency), which make it even more challenging to select any particular definition/units as a standard. In addition, it is exceedingly difficult at present to identify the most energetically efficient system. Since membrane properties such as the water contact angle, thickness, design, size, porosity, pore diameter and size, membrane materials, synthesis routes, membrane structure (e.g., hollow, flat, and cylindrical), and membrane active area all have an independent and collective influence on the product water, the standardization of all these membrane-related properties and processes is crucial for DCMD processes to be widely applicable for large-scale water purification.

For DCMD to be maximally energy efficient, the following measures must be considered: i) application of solar or renewable energy, ii) application of low-grade waste heat, iii) improvement of hydrodynamic conditions, vi) module redesign to minimize temperature and concentration polarization effects, and v) incorporation of heat exchanger for recovery. Developing these criteria is highly recommended as an initial step because it will progress the standardization of units, definitions, processes, parameters, module size and design, feed and product water properties, and membranes properties using state-of-the-art research and equipment. Additionally, based on the currently established universal units and definitions, various membrane techniques such as AGMD, SGMD, and VMD must be technically compared with DCMD as such comparisons will be helpful to direct the future of MD technology for large-scale applications.

Technical challenges such as resistance to wettability, liquid entry pressure, membrane scaling and fouling, flux reduction for long-term application, reduction in the salt rejection rate, heat and mass transport across the membrane, and reliable product water quality and quantity can be resolved by selecting suitable membrane materials, membrane synthesis routes, and membrane properties (i.e., porosity, pore size, and thickness). To date, the optimized membrane parameters for high permeate flux are suggested to be a pore diameter of 0.3 μm, which could sustain a high liquid entry pressure of 2.5 bar, membrane thickness in the range of 10 to 700 μm, membrane porosity larger than 75%, tortuosity factor between 1.1 and 1.2, and thermal conductivity in the range of 0.06 W/m·K. Further improvements of these parameters can be obtained through the use of electrospinning synthesis routes, which are capable of fabricating optimized membranes with controllable pore sizes, porosity, and thickness. The most challenging issue in DCMD technology is developing the most effective and standardized membrane thickness that can fulfill the requirement of large mass transport and reduced heat transport caused by conduction via direct contact. Although much progress has been made in DCMD technology, much more work remains to achieve the desired minimum energy target of 1 kWh/m^3 for its practical and widespread application.

Nomenclature

Voidage,	ε $\varepsilon = \frac{V_{tot}-V_{sp}}{V_{tot}}$, V_{tot} = Mesh area × Spacer thickness, V_{sp} = Volume of spacer
PP	Poly-propylene
PTFE	Poly-tetrafluoroethylene
PDMS	Poly-dimethylsiloxane
DCMD	Direct contact membrane distillation
ε_E	Energy efficiency
RO	Reverse osmosis
Re	Reynolds number
MD	Membrane distillation
ZTIMD	Zero thermal input membrane distillation
SWRO	Seawater reverse osmosis
SAGD	Steam assisted gravity drainage
GOR	Gained output ratio
SPMD	Solar power membrane distillation
MSF-RO	Multistage flash reverse osmosis
AGMD	Air gap membrane distillation
FO	Forward osmosis
GSMD	Gas sweeping membrane distillation
ε_T	Thermal energy efficiency
QN	Heat transfer due to convection
Qm	Total heat transport
Qc	Heat transport due to conduction
CGMD	Conductive gap membrane distillation
VMD	Vacuum gap membrane distillation
PGMD	Permeate gap membrane distillation
STEC	Specific thermal energy consumption
EC	Energy consumption
LEP	Liquid entry pressure
LCZ	Lower convection zone
UCZ	Upper convection zone
ENMs	Electrospun nanofibrous membranes
PMMA	Poly-methyl methacrylate
MDC	Membrane distillation coefficient
HFMs	Halar material fiber membranes

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References

[1] M. Isaka, Water Desalination Using Renewable Energy Insight for Policy Makers, IEA-ETSAP and IRENA © Technology Policy Brief, (2013).
[2] A.G. Fane, A grand challenge for membrane desalination: more water, less carbon, Desalination 426 (2018) 155–163.
[3] M. Baghbanzadeh, D. Rana, C.Q. Lan, T. Matsuura, Zero thermal input membrane distillation, a zero-waste and sustainable solution for freshwater shortage, Appl. Energy 187 (2017) 910–928.
[4] D. Singh, K.K. Sirkar, Desalination of brine and produced water by direct contact membrane distillation at high temperatures and pressures, J. Membr. Sci. 389 (2012) 380–388.
[5] G.P. Thiel, E.W. Tow, L.D. Banchik, H.W. Chung, J.H. Lienhard V, Energy consumption in desalinating produced water from shale oil and gas extraction, Desalination 366 (2015) 94–112.
[6] G. Zaragoza, A. Ruiz-Aguirre, E. Guillén-Burrieza, Efficiency in the use of solar thermal energy of small membrane desalination systems for decentralized water production, Appl. Energy 130 (2014) 491–499.
[7] F. Xuening, C. Lei, D. Yuman, J. Min, F. Jinping, CFD modeling and analysis of brine spray evaporation system integrated with solar collector, Desalination 366 (2015) 139–145.
[8] E.K. Summers, H.A. Arafat, J.H. Lienhard V, Energy efficiency comparison of single-stage membrane distillation (MD) desalination cycles in different configurations, Desalination 290 (2012) 54–66.
[9] S. Parekh, M.M. Farid, J.R. Selman, S. Al-hallaj, Solar desalination with a humidification-dehumidification technique — a comprehensive technical review, Desalination 160 (2004) 167–186.
[10] E. Mathioulakis, V. Belessiotis, E. Delyannis, Desalination by using alternative energy: review and state-of-the-art, Desalination 203 (2007) 346–365.
[11] M. Khayet, Solar desalination by membrane distillation: dispersion in energy consumption analysis and water production costs (a review), Desalination 308 (2013) 89–101.
[12] A. Chafidz, S. Al-Zahrani, M.N. Al-Otaibi, C.F. Hoong, T.F. Lai, M. Prabu, Portable and integrated solar-driven desalination system using membrane distillation for arid remote areas in Saudi Arabia, Desalination 345 (2014) 36–49.
[13] J. Blanco Gálvez, L. García-Rodríguez, I. Martín-Mateos, Seawater desalination by an innovative solar-powered membrane distillation system: the MEDESOL project, Desalination 246 (2009) 567–576.
[14] M. Asim, N.T. Uday Kumar, A.R. Martin, Feasibility analysis of solar combi-system for simultaneous production of pure drinking water via membrane distillation and domestic hot water for single-family villa: pilot plant setup in Dubai, Desalin. Water Treat. 57 (2016) 21674–21684.
[15] M.R. Qtaishat, F. Banat, Desalination by solar powered membrane distillation systems, Desalination 308 (2013) 186–197.
[16] H.C. Duong, P. Cooper, B. Nelemans, T.Y. Cath, L.D. Nghiem, Optimising thermal efficiency of direct contact membrane distillation by brine recycling for small-scale seawater desalination, Desalination 374 (2015) 1–9.
[17] B.S. Lalia, V. Kochkodan, R. Hashaikeh, N. Hilal, A review on membrane fabrication: structure, properties and performance relationship, Desalination 326 (2013) 77–95.
[18] L.D. Tijing, J.-S. Choi, S. Lee, S.-H. Kim, H.K. Shon, Recent progress of membrane distillation using electrospun nanofibrous membrane, J. Membr. Sci. 453 (2014) 435–462.
[19] L. Song, B. Li, K.K. Sirkar, J.L. Gilron, Direct contact membrane distillation-based desalination: novel membranes, devices, larger-scale studies, and a model, Ind. Eng. Chem. Res. 46 (2007) 2307–2323.
[20] A. Boubakri, A. Hafiane, S.A.T. Bouguecha, Direct contact membrane distillation: capability to desalt raw water, Arab. J. Chem. 10 (2017) S3475–S3481.
[21] A. Alkhudhiri, N. Darwish, N. Hilal, Membrane distillation: a comprehensive review, Desalination 287 (2012) 2–18.
[22] F. Macedonio, A. Ali, T. Poerio, E. El-Sayed, E. Drioli, M. Abdel-Jawad, Direct contact membrane distillation for treatment of oilfield produced water, Sep. Purif. Technol. 126 (2014) 69–81.
[23] D. Singh, P. Prakash, K.K. Sirkar, Deoiled produced water treatment using direct-contact membrane distillation, Ind. Eng. Chem. Res. 52 (2013) 13439–13448.
[24] L. Eykens, I. Hitsov, K. De Sitter, C. Dotremont, L. Pinoy, I. Nopens, B. Van der Bruggen, Influence of membrane thickness and process conditions on direct contact membrane distillation at different salinities, J. Membr. Sci. 498 (2016) 353–364.
[25] P. Wang, T.-S. Chung, Recent advances in membrane distillation processes: Membrane development, configuration design and application exploring, J. Membr. Sci. 474 (2015) 39–56.
[26] A.W. Mohammad, Y.H. Teow, W.L. Ang, Y.T. Chung, D.L. Oatley-Radcliffe, N. Hilal, Nanofiltration membranes review: recent advances and future prospects, Desalination 356 (2015) 226–254.
[27] P.S. Goh, T. Matsuura, A.F. Ismail, N. Hilal, Recent trends in membranes and membrane processes for desalination, Desalination 391 (2016) 43–60.
[28] E. Drioli, A. Ali, F. Macedonio, Membrane distillation: recent developments and perspectives, Desalination 356 (2015) 56–84.
[29] B.B. Ashoor, S. Mansour, A. Giwa, V. Dufour, S.W. Hasan, Principles and applications of direct contact membrane distillation (DCMD): a comprehensive review, Desalination 398 (2016) 222–246.
[30] S. Lin, N.Y. Yip, M. Elimelech, Direct contact membrane distillation with heat recovery: thermodynamic insights from module scale modeling, J. Membr. Sci. 453 (2014) 498–515.
[31] M. Boukhriss, K. Zhani, H. Ben Bacha, Optimization of membrane distillation (MD) technology for specific application desalination, Int. J. Adv. Manuf. Technol. 88 (2017) 55–66.
[32] H.J. Tropp A, Water Scarcity Challenges in the Middle East and North Africa, United Nations Human Development Report, (2006), pp. 1–26.
[33] A. Elhakeem, W. Elshorbagy, Evaluation of the long-term variability of seawater salinity and temperature in response to natural and anthropogenic stressors in the Arabian Gulf, Mar. Pollut. Bull. 76 (2013) 355–359.
[34] S. Lattemann, T. Höpner, Environmental impact and impact assessment of seawater desalination, Desalination 220 (2008) 1–15.
[35] M. Shahzad, M. Burhan, L. Ang, C. Ng, Energy-water-environment nexus underpinning future desalination sustainability, Desalination 413 (2017) 52–64.
[36] A.M. Alklaibi, The potential of membrane distillation as a stand-alone desalination process, Desalination 223 (2008) 375–385.
[37] P.S. Goh, W.J. Lau, M.H.D. Othman, A.F. Ismail, Membrane fouling in desalination and its mitigation strategies, Desalination 425 (2018) 130–155.
[38] M. Qtaishat, T. Matsuura, B. Kruczek, M. Khayet, Heat and mass transfer analysis in direct contact membrane distillation, Desalination 219 (2008) 272–292.
[39] V.A. Bui, L.T.T. Vu, M.H. Nguyen, Simulation and optimisation of direct contact membrane distillation for energy efficiency, Desalination 259 (2010) 29–37.
[40] A.G. Fane, R.W. Schofield, C.J.D. Fell, The efficient use of energy in membrane distillation, Desalination 64 (1987) 231–243.
[41] P.A. Hogan, A.G. Fane Sudjito, G.L. Morrison, Desalination by solar heated membrane distillation, Desalination 81 (1991) 81–90.
[42] J. Gilron, L. Song, K.K. Sirkar, Design for Cascade of crossflow direct contact membrane distillation, Ind. Eng. Chem. Res. 46 (2007) 2324–2334.
[43] H. Lee, F. He, L. Song, J. Gilron, K.K. Sirkar, Desalination with a cascade of cross-flow hollow fiber membrane distillation devices integrated with a heat exchanger, AIChE J. 57 (2011) 1780–1795.
[44] A. Criscuoli, Improvement of the membrane distillation performance through the integration of different configurations, Chem. Eng. Res. Des. 111 (2016) 316–322.
[45] J. Swaminathan, H.W. Chung, D.M. Warsinger, F.A. AlMarzooqi, H.A. Arafat, J.H. Lienhard V, Energy efficiency of permeate gap and novel conductive gap membrane distillation, J. Membr. Sci. 502 (2016) 171–178.
[46] J. Swaminathan, H.W. Chung, D.M. Warsinger, J.H. Lienhard V, Membrane distillation model based on heat exchanger theory and configuration comparison, Appl. Energy 184 (2016) 491–505.
[47] A. Criscuoli, M.C. Carnevale, E. Drioli, Evaluation of energy requirements in membrane distillation, Chem. Eng. Process. Process Intensif. 47 (2008) 1098–1105.
[48] M. Elimelech, W.A. Phillip, The future of seawater desalination: energy, technology, and the environment, Science 333 (2011) 712–717.
[49] Sangkeum Lee, Hong-Yeon Cho, Dongsoo Har, Operation optimization with jointly controlled modules powered by hybrid energy source. A case study of desalination, Renew. Sust. Energ. Rev. 81 (2018) 3070–3080.
[50] A. Khalifa, H. Ahmad, M. Antar, T. Laoui, M. Khayet, Experimental and theoretical investigations on water desalination using direct contact membrane distillation, Desalination 404 (2017) 22–34.
[51] Y.-D. Kim, K. Thu, N. Ghaffour, K. Choon Ng, Performance investigation of a solar-assisted direct contact membrane distillation system, J. Membr. Sci. 427 (2013) 345–364.
[52] S. Meng, J. Mansouri, Y. Ye, V. Chen, Effect of templating agents on the properties and membrane distillation performance of TiO2-coated PVDF membranes, J. Membr. Sci. 450 (2014) 48–59.
[53] S. Bonyadi, T.-S. Chung, Highly porous and macrovoid-free PVDF hollow fiber membranes for membrane distillation by a solvent-dope solution co-extrusion approach, J. Membr. Sci. 331 (2009) 66–74.
[54] M. Khayet, C. Cojocaru, M.C. García-Payo, Experimental design and optimization of asymmetric flat-sheet membranes prepared for direct contact membrane distillation, J. Membr. Sci. 351 (2010) 234–245.
[55] S. Adnan, M. Hoang, H. Wang, Z. Xie, Commercial PTFE membranes for membrane distillation application: effect of microstructure and support material, Desalination 284 (2012) 297–308.
[56] F. Laganà, G. Barbieri, E. Drioli, Direct contact membrane distillation: modelling and concentration experiments, J. Membr. Sci. 166 (2000) 1–11.
[57] L. Martínez, J.M. Rodríguez-Maroto, Membrane thickness reduction effects on direct contact membrane distillation performance, J. Membr. Sci. 312 (2008) 143–156.
[58] L. Eykens, K. De Sitter, C. Dotremont, L. Pinoy, B. Van der Bruggen, How to optimize the membrane properties for membrane distillation: a review, Ind. Eng. Chem. Res. 55 (2016) 9333–9343.
[59] L. Li, K.K. Sirkar, Influence of microporous membrane properties on the desalination performance in direct contact membrane distillation, J. Membr. Sci. 513 (2016) 280–293.
[60] L. Eykens, I. Hitsov, K. De Sitter, C. Dotremont, L. Pinoy, I. Nopens, B. Van der Bruggen, Evaluation of the Optimal Membrane Thickness for Direct Contact Membrane Distillation Via Modeling and Experiments, IV International Scientific Conference on Pervaporation, Vapor Permeation and Membrane Distillation Edition:4 Location:Torun, Poland, (2014).
[62] Y. Liao, R. Wang, M. Tian, C. Qiu, A.G. Fane, Fabrication of polyvinylidene fluoride (PVDF) nanofiber membranes by electro-spinning for direct contact membrane distillation, J. Membr. Sci. 425–426 (2013) 30–39.
[63] N. Palanisami, K. He, I.S. Moon, Utilization of solar energy for direct contact membrane distillation process: an experimental study for desalination of real

seawater, Korean J. Chem. Eng. 31 (2014) 155–161.
[64] J. Phattaranawik, R. Jiraratananon, A.G. Fane, Effect of pore size distribution and air flux on mass transport in direct contact membrane distillation, J. Membr. Sci. 215 (2003) 75–85.
[65] S.-F. Pan, Y. Dong, Y.-M. Zheng, L.-B. Zhong, Z.-H. Yuan, Self-sustained hydrophilic nanofiber thin film composite forward osmosis membranes: preparation, characterization and application for simulated antibiotic wastewater treatment, J. Membr. Sci. 523 (2017) 205–215.
[66] D. Zhao, J. Zuo, K.J. Lu, T.S. Chung, Fluorographite modified PVDF membranes for seawater desalination via direct contact membrane distillation, Desalination 413 (2017) 119–126.
[67] M. Laqbaqbi, J. Sanmartino, M. Khayet, C. García-Payo, M. Chaouch, Fouling in membrane distillation, osmotic distillation and osmotic membrane distillation, Appl. Sci. 7 (2017) 334.
[68] S. Nejati, C. Boo, C.O. Osuji, M. Elimelech, Engineering flat sheet microporous PVDF films for membrane distillation, J. Membr. Sci. 492 (2015) 355–363.
[69] M.M.A. Shirazi, A. Kargari, M. Tabatabaei, Evaluation of commercial PTFE membranes in desalination by direct contact membrane distillation, Chem. Eng. Process. Process Intensif. 76 (2014) 16–25.
[70] M. Gryta, Long-term performance of membrane distillation process, J. Membr. Sci. 265 (2005) 153–159.
[71] M. Essalhi, M. Khayet, Self-sustained webs of polyvinylidene fluoride electrospun nano-fibers: effects of polymer concentration and desalination by direct contact membrane distillation, J. Membr. Sci. 454 (2014) 133–143.
[72] L.-F. Ren, F. Xia, J. Shao, X. Zhang, J. Li, Experimental investigation of the effect of electrospinning parameters on properties of superhydrophobic PDMS/PMMA membrane and its application in membrane distillation, Desalination 404 (2017) 155–166.
[73] C. Boo, J. Lee, M. Elimelech, Engineering surface energy and nanostructure of microporous films for expanded membrane distillation applications, Environ. Sci. Technol. 50 (2016) 8112–8119.
[74] J. Elbert, M. Gallei, C. Rüttiger, A. Brunsen, H. Didzoleit, B. Stühn, M. Rehahn, Ferrocene polymers for switchable surface wettability, Organometallics 32 (2013) 5873–5878.
[75] Z. Ding, R. Ma, A.G. Fane, A new model for mass transfer in direct contact membrane distillation, Desalination 151 (2003) 217–227.
[76] J. Phattaranawik, R. Jiraratananon, A.G. Fane, Heat transport and membrane distillation coefficients in direct contact membrane distillation, J. Membr. Sci. 212 (2003) 177–193.
[78] R.D. Gustafson, J.R. Murphy, A. Achilli, A stepwise model of direct contact membrane distillation for application to large-scale systems: experimental results and model predictions, Desalination 378 (2016) 14–27.
[79] J. Phattaranawik, R. Jiraratananon, Direct contact membrane distillation: effect of mass transfer on heat transfer, J. Membr. Sci. 188 (2001) 137–143.
[80] H.-C. Yang, W. Zhong, J. Hou, V. Chen, Z.-K. Xu, Janus hollow fiber membrane with a mussel-inspired coating on the lumen surface for direct contact membrane distillation, J. Membr. Sci. 523 (2017) 1–7.
[81] F. Li, W. Meindersma, A.B. de Haan, T. Reith, Novel spacers for mass transfer enhancement in membrane separations, J. Membr. Sci. 253 (2005) 1–12.
[82] J. Balster, D.F. Stamatialis, M. Wessling, Membrane with integrated spacer, J. Membr. Sci. 360 (2010) 185–189.
[83] J. Schwinge, P.R. Neal, D.E. Wiley, D.F. Fletcher, A.G. Fane, Spiral wound modules and spacers: review and analysis, J. Membr. Sci. 242 (2004) 129–153.
[84] G. Chen, X. Yang, Y. Lu, R. Wang, A.G. Fane, Heat transfer intensification and scaling mitigation in bubbling-enhanced membrane distillation for brine concentration, J. Membr. Sci. 470 (2014) 60–69.
[85] 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.
[86] J. Phattaranawik, R. Jiraratananon, A.G. Fane, C. Halim, Mass flux enhancement using spacer filled channels in direct contact membrane distillation, J. Membr. Sci. 187 (2001) 193–201.
[87] 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.
[88] J. Phattaranawik, R. Jiraratananon, A.G. 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.
[89] Y. Taamneh, K. Bataineh, Improving the performance of direct contact membrane distillation utilizing spacer-filled channel, Desalination 408 (2017) 25–35.
[90] J. Schwinge, D.E. Wiley, A.G. Fane, R. Guenther, Characterization of a zigzag spacer for ultrafiltration, J. Membr. Sci. 172 (2000) 19–31.
[91] M.S. El-Bourawi, Z. Ding, R. Ma, M. Khayet, A framework for better understanding membrane distillation separation process, J. Membr. Sci. 285 (2006) 4–29.
[92] Y. Guan, J. Li, F. Cheng, J. Zhao, X. Wang, Influence of salt concentration on DCMD performance for treatment of highly concentrated NaCl, KCl, MgCl2 and MgSO4 solutions, Desalination 355 (2015) 110–117.
[93] V.A. Bui, M.H. Nguyen, J. Muller, The energy challenge of direct contact membrane distillation in low temperature concentration, Asia Pac. J. Chem. Eng. 2 (2007) 400–406.
[94] H.M. Ahmad, A.E. Khalifa, M.A. Antar, Water desalination using direct contact membrane distillation system, ASME International Mechanical Engineering Congress and Exposition, Proceedings (IMECE), 2015.
[95] N. Dow, S. Gray, J.-d. Li, J. Zhang, E. Ostarcevic, A. Liubinas, P. Atherton, G. Roeszler, A. Gibbs, M. Duke, Pilot trial of membrane distillation driven by low grade waste heat: membrane fouling and energy assessment, Desalination 391 (2016) 30–42.
[96] A.M. Elzahaby, A.E. Kabeel, M.M. Bassuoni, A.R.A. Elbar, Direct contact membrane water distillation assisted with solar energy, Energy Convers. Manag. 110 (2016) 397–406.
[97] J.-G. Lee, W.-S. Kim, J.-S. Choi, N. Ghaffour, Y.-D. Kim, Dynamic solar-powered multi-stage direct contact membrane distillation system: concept design, modeling and simulation, Desalination (2017).
[100] J. Leblanc, A. Akbarzadeh, J. Andrews, H. Lu, P. Golding, Heat extraction methods from salinity-gradient solar ponds and introduction of a novel system of heat extraction for improved efficiency, Sol. Energy 85 (2011) 3103–3142.
[101] A.E. Kabeel, M. Abdelgaied, E.M.S. El-Said, Study of a solar-driven membrane distillation system: evaporative cooling effect on performance enhancement, Renew. Energy 106 (2017) 192–200.
[102] M. Tomaszewska, L. Białończyk, Ethanol production from whey in a bioreactor coupled with direct contact membrane distillation, Catal. Today 268 (2016) 156–163.
[103] K. Rahaoui, L.C. Ding, L.P. Tan, W. Mediouri, F. Mahmoudi, K. Nakoa, A. Akbarzadeh, Sustainable membrane distillation coupled with solar pond, Energy Procedia 110 (2017) 414–419.
[104] S. Selvi, R. Baskaran, Solar photovoltaic-powered membrane distillation as sustainable clean energy technology in desalination, Curr. Sci. 109 (2015) 1247.
[105] 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.
[106] Ó. Andrjesdóttir, C.L. Ong, M. Nabavi, S. Paredes, A.S.G. Khalil, B. Michel, D. Poulikakos, An experimentally optimized model for heat and mass transfer in direct contact membrane distillation, Int. J. Heat Mass Transf. 66 (2013) 855–867.
[107] G. Mancini, P. Roccaro, F.G.A. Vagliasindi, Water intended for human consumption — part II: treatment alternatives, monitoring issues and resulting costs, Desalination 176 (2005) 143–153.
[108] A. Boubakri, A. Hafiane, S.A.T. Bouguecha, Direct contact membrane distillation: capability to desalt raw water, Arab. J. Chem. (2011).