J. Applied Membrane Science & Technology, Vol. 26, No. 3, December 2022, 45–64

Evolution of Membrane Surface Properties for Membrane Distillation: A Mini Review

Chel-Ken Chiam[a,b]* & Rosalam Sarbatly[b,c]

[a]Oil and Gas Engineering, Faculty of Engineering, Universiti Malaysia Sabah, Jalan UMS, 88400 Kota Kinabalu, Sabah, Malaysia
[b]Nanofiber and Membrane Research Laboratory, Faculty of Engineering, Universiti Malaysia Sabah, Jalan UMS, 88400 Kota Kinabalu, Sabah, Malaysia
[c]Chemical Engineering, Faculty of Engineering, Universiti Malaysia Sabah, Jalan UMS, 88400 Kota Kinabalu, Sabah, Malaysia

Submitted: 29/8/2022. Revised edition: 19/10/2022. Accepted: 19/10/2022. Available online: 20/11/2022

ABSTRACT

To date, the membrane development for membrane distillation (MD) application is growing in line with the increasing volume of various types of wastewaters discharged into environment. MD is a liquid-vapor separation process and a hydrophobic membrane is used to retain the liquid. Theoretically, the hydrophobic membrane can achieve 100% rejection of non-volatile components that dissolved in feed liquids. As a result, MD has received significant attention in water recovery from saline water as well as wastewaters. Nevertheless, in addition to the scaling problem due to salts, the hydrophobicity property of membrane becomes a concern when dealing with challenging wastewaters which contain various types of low surface tension components such as oils, grease, alcohols, organics and surfactants. The membrane pore wetting due to salts deposition fouling and low surface tension components subsequently reduces the flux and even fails the liquid-vapor separation process. This article briefly discusses the transformation of MD membrane from hydrophobic to superhydrophobic and omniphobic which purposely to enhance the flux and eliminate the membrane pore wetting.

Keywords: Water recovery, membrane distillation, membrane modification, flux, wetting

1.0 INTRODUCTION

According to the United Nations Water, 80% of wastewater is discharged into the environment without being treated or reused, and 40% of the world's people are affected by water scarcity [1]. Membrane technology has been examined as one of the promising technologies to treat various types of wastewaters for reuse purpose whereby the water reuse plays a critical role in circular economy and it is a potential strategy to achieve the Sustainable Development Goals [2]. Membrane distillation (MD) has been proven can highly recover the water because MD is not an osmotic limiting process [3, 4].

MD is a liquid-vapor separation process whereby only water vapor is allowed to transport through membrane and theoretically 100% rejection of non-volatile components [5]. The MD is basically categorized into four different configurations, they are direct contact membrane distillation (DCMD), air gap membrane distillation (AGMD), sweeping gas membrane distillation (SGMD) and vacuum membrane distillation (VMD). These MD configurations are differentiated based on the techniques of freshwater recovery of water vapor on permeate sides. Compared to pressurized membrane filtrations such as reverse osmosis and nanofiltration, MD shows

* Corresponding to: Chel-Ken Chiam (email: chiamchelken@ums.edu.my)
DOI: https://doi.org/10.11113/amst.v26n3.252

lower fouling, less scaling, stable permeate flux and higher rejection [6, 7]. Although MD requires thermal energy to elevate the temperature of feed waters, the low grade energy such as solar, geothermal and waste heat are sufficient to operate the MD [8–10]. Recently, MD has been integrated with other membrane separations such as reverse osmosis, membrane bioreactor and forward osmosis to further enhance the water recovery [11–14].

A porous hydrophobic membrane which retains liquid phase and permits water vapor to permeate is used as the liquid-vapor separator. In the early stage of MD development, the materials used for MD membranes include polytetrafluoroethylene [15], polypropylene [16], polyvinylidene fluoride [17] and polyethylene [18]. These polymeric materials are excellent repellents towards liquid water as well as saline waters. However, the real seawater and brackish waters as well as wastewaters discharged from various industries contained the highly concentrated inorganic salts [19, 20], low surface tension contaminants, oils, organics and nutrients can promote membrane pore wetting which eventually deteriorate permeate quality and reduce flux [21–24]. As a result, the basic hydrophobic membranes have been modified to become superhydrophobic [25, 26] and omniphobic [27] to minimize the membrane pore wetting. This short review discusses the evolution of MD membrane in improving the flux and minimizing the membrane pore wetting.

2.0 PHASE INVERSION MEMBRANES

The first patent on MD was filed by Bodell in 1963 and the membrane material was the silicone rubber [28]. Other plastic materials which have a relatively high permeability to water vapor such as cellulose propionate, polyvinyl fluoride and cellulose acetate were also proposed for MD in a few decades ago [29]. During the 1980s, polytetrafluoroethylene (PTFE), polypropylene (PP) and polyvinylidene fluoride (PVDF) were found as the most promising for MD application; and the membrane with high porosity 70 – 80% can be obtained from phase inversion fabrication method [30, 31]. Figure 1 illustrates the phase inversion membrane fabrication technique.

In the early MD development for desalination application, membrane wetting is unavoidable due to salt crystal formed on the membrane surface [32, 33]. A deposit stayed on the hydrophobic membrane surface can cause the pores adjacent to the deposit to be filled with liquid which leads to a wetting of this part of the membrane [34, 35]. Even a low surface porosity can hinder the formation of scale inside the membrane pores, surface wetting is still possible and this also reduces the MD flux significantly [36]. Schneider *et al*. [37] recommended the membranes with wetting angles that greater 90° only are suitable for MD process in which PTFE, PVDF and PP meet this specification. Additionally, a recommended maximum pore diameter of approximately 0.5–0.6 μm can avoid the membrane wetting. While El-Bourawi *et al*. [38] suggested that the pore sizes of the membranes used in MD should range between 10 nm and 1 μm to ensure no pore wetting. Lawson and Lloyd [39] advised that the process equipment and process solutions must be free from the contamination of detergents or other surfacting agents because these materials can greatly reduce the surface tension of process liquid and the wetting angle. Nevertheless, these requirements have limited the applications of MD extended to the real wastewaters.

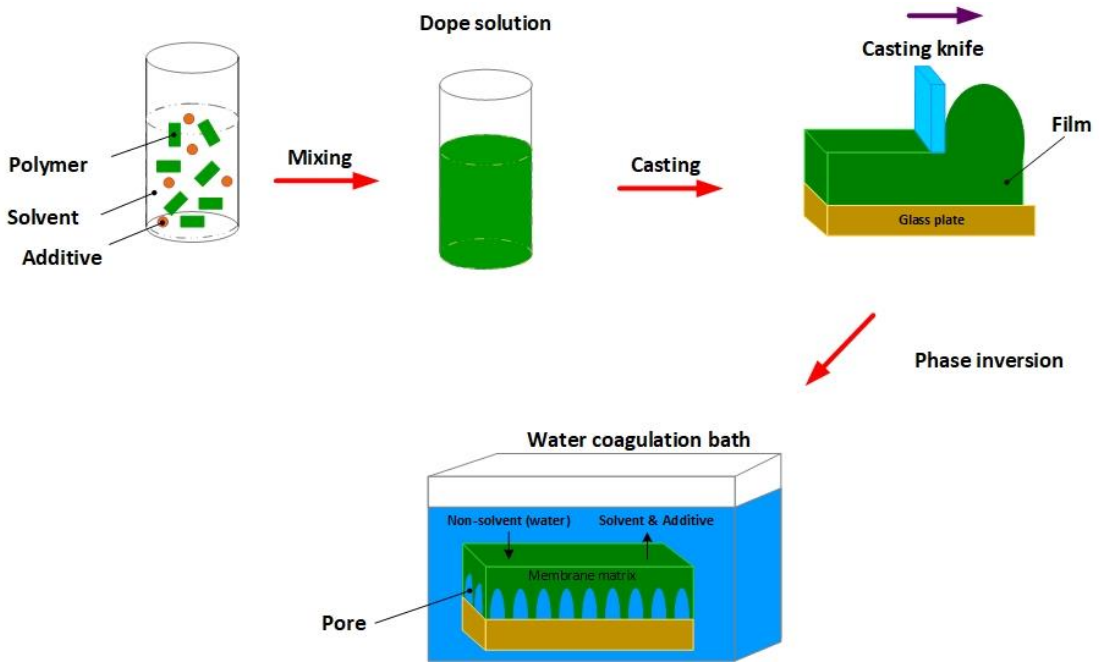

Figure 1 Phase inversion membrane fabrication method

Consequently, various new techniques have been explored to minimize the membrane wetting. Peng *et al*. [40] adopted a hydrophilic layer on the hydrophobic PVDF membrane and revealed that the membrane can prohibit the membrane wetting even 25% ethanol was added to the brine feed solution. Gryta and Barancewicz [41] reported that the incorporation of PTFE particles into the PVDF membrane matrix with sponge-like structure has slow down the membrane wettability. Tian *et al*. [42] used bottom-up strategy to fabricate the PVDF membrane and the resultant membranes possessed high water contact angels (~144°) with rougher surfaces. Alberto *et al*. [43] coated the PVDF membranes with graphene oxide laminate and showed that the membranes were stable for at least 90 h with the feed solutions containing surfactants. Zou *et al*. [44] employed co-casting technique to fabricate the PVDF membranes and found the excellent rejections of brine with sodium dodecyl sulfate (SDS) surfactant and ginseng extracts were 99.9% for 120 h operation. Table 1 presents a few recent membrane fabrication strategies used to improve the performance of phase inversion membranes in MD. In general, the rejection performance of membranes is close to 99% which is satisfactory. However, the water contact angle (WCA) and liquid entry pressure (LEP) affect the MD flux and operating time as well as membrane wetting differently. DCMD fluxes increased and the operation extended when WCA and LEP of the modified membranes increased [42, 45–50]. On a contrary, AGMD flux increased when WCA decreased for the membrane fabricated from PVDF dope solution blended with activated carbon [51].

Table 1 Modification strategy of phase inversion membrane preparation for MD

Membrane fabrication strategy	WCA (°)		LEP (kPa)		Configuration	Flux (kg/m^2 h)		Rejection (%)		Reference
	Pristine	Modified	Pristine	Modified		Pristine	Modified	Pristine	Modified	
Bottom-up: PVDF dope solution was cast on a clean glass plate and the nascent film was covered by a piece of non-woven substrate.	71.7	144	-	-	DCMD	~25 [a]	41.4 [a]	99	99	[42]
Co-casting: PES, which acted as a sacrificial layer was immediately cast on PVDF nascent film.	~75	125–133	-	-	DCMD	5–10 [b]	20–25 [b,c]	> 99.95	> 99.95	[45]
Co-casting: ATBC or PEG400 was used as a sacrificial layer; sacrificial layer was cast on PVDF layer.	-	120–130	-	-	DCMD	-	29–37 [d,e] 25–30 [d,f] 26–32 [d,g]	-	~99.99 [d,e,f] >99.9 [d,g]	[44]
Blending: 10 wt% PVDF dissolved in DMAc solvent with 1 wt% iron nanoparticle	~97.7	99.2 100.1 [h]	~17	~23	DCMD	~11	~15	> 99	> 99	[46]
Blending: 5 – 9 wt.% activated carbon in 12 wt.% PVDF and 79 – 88 wt.% DMAc	~110	80–92	-	-	AGMD	0.02	0.08–3.2	~97	97–99.9	[51]
Texture casting substrate: Tempered glass, stainless steel mesh, Sandpaper and PDMS	-	64.6±3.2 [i] 147.4±1.6 [j] 116±1.8 [k] 150±1.7 [l]	40±10 [m]	120±10 [i] 160±10 [j] 135±10 [k] 210±20 [l]	AGMD	~8.5 [m]	~19 [i,n] ~22 [j,n] ~20.5 [k,n] 21 [l,n]	97 [m,n]	~93 [i,n] ~96 [j,n] ~99.4 [k,n] 99.99 [l,n]	[47]
Dip-coating: PEI hollow fiber membranes were immersed into PDMS solutions.	82.5±0.94	103.8 ± 0.26	250	400	SGMD	~14 [o]	~17 [o]	~99.4 [o,p]	~99.9 [o,p]	[48]
Dilute solution coating: PVDF hollow fiber membranes were immersed into the ZIF-71 /PVDF/PEG/DMF solutions at different compositions.	94.5	115.5–136.5	~170	168–215	VMD	11–14 [q]	19–28 [q]	> 99.9	> 99.9	[50]
Graft copolymerization: Introduced EA monomer onto the backbone of PVC.	79±1	90.5±1 [r] 96±1 [s]	-	-	VMD	2.52	37.5	-	-	[49]

[a] Feed temperature at 70°C; [b] 18–20 wt.% PVDF and 15–21 wt.% PES; [c] same flux when operated for 48 h; [d] 120 h operation; [e] feed contained 35 g/L NaCl; [f] feed contained 35 g/l NaCl and 0.1 M SDS; [g] feed contained 35 g/L ginseng extract; [h] after nanoparticle leaching and stability tests; [i] glass casting substrate; [j] stainless steel mesh casting substrate; [k] sandpaper casting substrate; [l] PDMS casting substrate; [m] commercial PVDF membrane; [n] 40 h operation; [o] 135 h operation; [p] dye rejection; [q] 60 h operation; [r] 14 wt.% PVC; [s] 18 wt.% PVC; ATBC: Acetyl tributyl citrate; DMAc: *N, N*-Dimethylacetamide; LEP: Liquid entry pressure; PDMS: Polydimethylsiloxane; PEG: Polyethylene glycol; PEI: Polyetherimide; PES: Polyethersulfone; PVDF: Polyvinylidene fluoride; SDS: Sodium dodecyl sulfate; WCA: Water contact angle; ZIF: Zeolitic imidazolate framework

3.0 ELECTROSPUN NANOFIBER MEMBRANES

Due to relatively low flux in phase inversion membranes, electrospun nanofiber membranes have been attractive for MD since 2008 [52]. The nanofiber membrane consists of fibers overlap with each other to form a thin film with highly interconnected open pore structure. Figure 2 shows a basic electrospinning method to fabricate the nanofiber membrane. The fluxes obtained from electrospun nanofiber membranes were as high as or even greater than those of commercial membranes, and the rejection of salt was approximately 98.7 – 99.9% which was applicable for a 25-day operation in an AGMD process [52]. Su *et al*. [53] revealed that the composite nanofibrous PVDF and PVDF-co-HFP membranes have exceeded the flux limit of commercial PTFE membrane. Essalhi and Khayet [54] reported that the increase of electrospinning time has decreased the maximum size of inter-fiber space because the thickness of nanofiber membrane increased correspondingly. As a result, the void volume fraction and LEP increased with increasing the electrospinning time. In spite of that, the MD flux decreased with increasing the electrospinning time because higher flux is preferable in thinner membrane. Although the nanofiber membrane made from hydrophobic polymer possesses high WCA, the application of nanofiber membrane alone in MD process is still limited due to its LEP is too low. Prince *et al*. [55] documented that a single PVDF nanofiber layer cannot be used in their AGMD desalination system because the penetration of salt increased dramatically to more than 90% within the first few minutes even WCA of the membrane was 145.7°. The LEP of nanofiber PVDF membrane increased approximately 8.7 times higher when the nanofiber membrane was supported by a casted membrane (i.e. phase inversion membrane) and a support layer. The triple layer membrane made the AGMD desalination process continuously operated at least 40 h without membrane wetting occurred. While the phase inversion membrane was wetted after 10 h of operation. On the other hand, Liao *et al*. [56] applied heat-press post-treatment on the fresh nanofiber membrane and this treatment has increased the LEP of membrane. The MD fluxes obtained from heat-pressed nanofiber membrane were also higher than that untreated nanofiber membrane as well as commercial phase inversion membrane even the pore size, WCA and porosity were slightly reduced due to structural compaction [56, 57]. The properties of PVDF nanofiber membrane shifted from hydrophobic to superhydrophobic when the content of clay nanocomposites blended in the spinning solution increased [58]. No flux declination was observed within 8-h DCMD operation when superhydrophobic membrane was tested. Table 2 compares the recent MD performance between electrospun nanofiber membranes and phase inversion membranes. The MD flux obtained by nanofiber membranes is relatively higher than that attained using phase inversion membranes even either WCA or LEP decreased in the nanofiber membranes [59–62].

4.0 SUPERHYDROPHOBIC MEMBRANES

By definition, the superhydrophobic surface possesses high WCAs that exceed 150° and low water sliding angles which is typically below 10° [63]. In 2009, Ma *et al*. [64] have found that superhydrophobic glass membranes with WCAs exceeded 160° showed better anti-fouling ability and higher flux than conventional hydrophobic membranes in their AGMD desalination system.

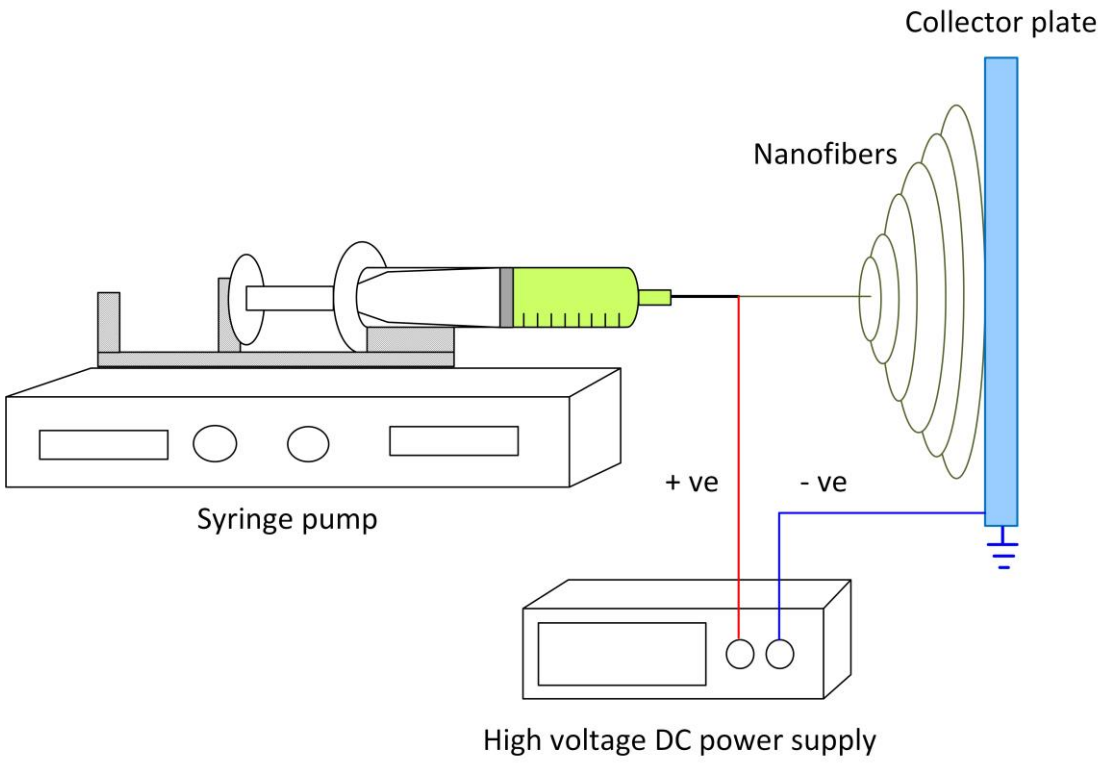

Figure 2 Basic electrospinning of nanofiber membrane fabrication

Starting from 2012, both polymeric phase inversion and electrospun nanofiber membranes [58, 65, 66] have been actively modified to attain the superhydrophobic property to recover freshwater from saline water. The application of superhydrophobic membranes has also been expanded to feed solutions containing organics such as humic acid and surfactants [76, 68]. Table 3 shows a few samples of latest researches of superhydrophobic membranes fabricated from different strategies and their comparisons with pristine hydrophobic membranes. In overall, the WCA and LEP as well as MD flux are improved significantly in superhydrophobic membranes. Although some authors reported that the MD flux gained by superhydrophobic membranes is somewhat lower than that attained by hydrophobic membranes, the superhydrophobic membranes can work for longer operation with good permeate quality [69–71]. Compare to hydrophobic membranes, the superhydrophobic membranes exhibited good anti-scaling, anti-fouling, anti-wetting, high and stable flux, good salt rejection and suitable for long-term MD desalination operation [72–76].

5.0 OMNIPHOBIC MEMBRANES

The performance of MD could be deteriorated if fed with challenging wastewaters that comprise of various types of inorganics and organics including surfactants discharged from oil and gas industries. For instance, membrane wetting occurred when the feed solution contained cationic surfactant *N*,*N*,*N*-trimethyl-1-dodecanaminium bromide even the membrane used was superhydrophobic [68].

Table 2 Comparison of electrospun nanofiber membrane (ENM) and phase inversion membrane (PIM) in MD

Composition of ENM	WCA (°)		LEP (kPa)		Configuration	Flux (kg/m^2 h)		Rejection (%)		Reference
	PIM	ENM	PIM	ENM		PIM	ENM	PIM	ENM	
5 wt% PVDF in DMF/Acetone with 0.004 wt% LiCl	135 [a]	136	-	35	DCMD	10.6 [a,b]	20.3 [b]	-	-	[56]
15 wt% PVDF-HFP in 68 wt% DMF and 17 wt% acetone with 0.005 wt% LiCl and 1.5 AC wt%	140.8±0.8 [c]	142.7±0.6	234±3 [c]	136±4	DCMD	41.8 [b,c]	45.6 [b]	~100	~100	[59]
0.5 wt% CNT and 20 wt% PVDF-HFP in 8 wt% and 2 wt% acetone	-	140.7±2.2	-	50±2.0	DCMD	13.2 [b,d,e]	18.7 [b,e]	> 99.99	> 99.99	[77]
18 wt% SAN in DMF/acetone70/30	124.4±0.87 [f]	148.63±0.65	119.7±3.1	101.6±2.5	DCMD	15–21 [f,g]	21–27 [g]	98.15 [h] 99.91 [i]	97.10 [h] 99.25 [i]	[60]
17.5 wt% PVDF-HEP in 16.5 wt% acetone and 66 wt% DMF with 1–2 wt% AlFu MOF	~100	135±0.3	-	110	DCMD	15.64	22.7 22.1 [j]	> 99.9	> 99.9 > 99.9 [j]	[78,79]
20 wt% PVDF-HEP in DMF/Acetone (8/2, v/v) with 0.5 wt% ZIF-71	142.6±2.4 [d]	134±1.2	90 [d]	90±2	DCMD	~13.8	20 [k]	> 99.99	> 99.99	[61]
17 wt% PVDF in DMAc/Acetone (7/3 to 3/7, w/w)	130.3±0.05 [l]	134–148	-	23.9–107.6	DCMD	~9	10–13	-	-	[80]
15 wt% PVDF in 38.75 wt% DMAc and 38.75 wt% acetone with 7.5 wt% PTFE micro powder	-	122.4±0.3	-	80	AGMD	~14 [m]	27.7	-	> 97%	[81]
15 wt% PVDF in DMF	-	131.8±2.1	230±18	82±17	DCMD	~23 [n,o]	61.8 [o]	> 99.99 [p]	99.94 [p]	[62]
18 wt% PVDF/TBAC in acetone/DMF and 3 wt% FA	107±5 [q]	135±4	180 [q]	210	DCMD	0 [q,r]	53.43 [s]	97.7 [r]	99.6 [s]	[82]

[a] Commercial Millipore Durapore membrane; [b] L/m^2·h is equivalent to kg/m^2·h; [c] commercial PTFE supplied from Porous Membrane Technology (Ningbo, China); [d] commercial PTFE-PVDF/PET microporous membrane purchased from Shanghai Minglie New Material Co. Ltd; [e] 210 min operation; [f] commercial PTFE membrane supplied by Membrane-Solutions Co., China; [g] 10–14 h operation; [h] rejection of COD; [i] rejection of color; [j] 46 h operation; [k] 3 h operation; [l] commercial PVDF membrane purchased from Aquastill (Sittard, Netherlands); [m] commercial PVDF0.22 membrane; [n] commercial PVDF membrane purchased from Millipore; [o] 50 h operation; [p] dye rejection; [q] commercial PVDF membrane supplied by Haining yanguan zhongqi filtration equipment Co., Ltd.; [r] wetted after 3.5 h operation; [s] 5 h operation; AC: Activated carbon; AlFu MOF: Aluminium fumarate metal organic framework; CNT: Carbon nanotube; DMAc: *N*, *N*-Dimethylacetamide; DMF: N,N-dimethylformamide; FA: Fluorinated acrylate copolymer; LEP: Liquid entry pressure; SAN: Styrene-acrylonitrile; TBAC: Tetrabutylammonium chloride; ZIF-71: Zeolite imidazole ester skeleton; PVDF: Polyvinylidene fluoride; PVDF-HFP: Polyvinylidene fluoride-*co*-hexafluoropropylene; PTFE: Polytetrafluoroethylene; WCA: Water contact angle

Table 3 Comparison of superhydrophobic membrane (S-pho M) and pristine hydrophobic membrane in MD

Membrane fabrication strategy	WCA (°)		LEP (kPa)		Configuration	Flux (kg/m^2 h)		Rejection (%)		Reference
	Pristine	S-pho M	Pristine	S-pho M		Pristine	S-pho M	Pristine	S-pho M	
Three-stage method of superhydrophobic mixed-matrix nanofiber membrane: Synthesize ODA-rGO by a hydrothermal technique; reducing mean pore size by LiCl; and hot-pressed.	130±1 [a] 138±2 [e]	158±1 [b]	134.8±2 [a] 30.4±2 [e]	89.6±1.2 [b]	AGMD	~8 [a] 16.3 [e]	27.6 [b]	99.99 [a,c] 99.98 [e,f]	99.99 [b,d]	[69]
Combination of immersion precipitation with rolling embossing method	~88 [a]	~151 [g]	128 [a]	397 [g]	VMD	~5 [a]	~27 [g]	> 99.6 [a]	> 99.9 [g]	[83]
Dip-coating process: PVDF ENM was dipped in the PDMS-based graft copolymer/TiO_2/ethyl acetate/isopropanol sol	118.2±2.2 [a] 135.5±2.7 [e]	150.4±3.1 [b]	241±17 [a] 88±8 [e]	158±10 [b]	DCMD	~19 [a] ~36 [e]	34.5 [b]	99.9 [a,h] 99.9 [e,i]	99.9 [h]	[70]
Coating and UV-curing: PVDF membrane was coated by 5 wt% PFPE solution and cured by UV lamp	133.4±0.9 [a]	162.6±0.4 [g]	-	-	VMD	19.2 [a,j]	13.9 [g,k]	-	> 99.99 [g,k]	[71]
Sequential electrospinning and electrospraying with low-viscosity CB/F-POSS/PVDF-HFP	132 [e]	162 [b]	102 [e]	176.8 [b]	DCMD	22.72 [a] ~28 [e]	~40 [b]	~100 [a] ~100 [e]	~100 [b]	[84]
Spray-coating of hydrophobic SiO_2	98.5±2.1 [a]	170.8±1.3 [g]	-	-	DCMD	10.3 [a,l]	19.1 [g,l]	~99.6 [a,l]	99.99 [g,l]	[85]
Acid pre-treatment and silanization with FAS	132.2±1.9 [e]	154.6±2.2 [b]	67±3 [e]	143±4 [b]	VMD	7.5 [e,m]	11–12 [b,m]	~83 [e,n]	99.99 [b,n]	[86]
PU electrospinning and PDMS polymeric microsphere electrospraying with pore-size tuning with mechanical strain	> 160 [e]	> 160 [b]	19.6 [e]	12.2 [b]	DCMD	10.13 [e,o]	36.59 [b,o]	99.99 [e,o]	99.96 [b,o]	[87]
One-step electrospinning and immersion in ethanol coagulant to form microsphere/nanofiber membrane	138.5±1.8 [e]	156.6±1.4 [b]	131±20 [e]	149±10 [b]	DCMD	21.2 [e,p]	33.9 [b,p]	> 99.95 [e,p]	> 99.95 [b,p]	[88]

[a] Pristine PIM; [b] modified ENM; [c] durable for 40 h operation; [d] durable for 60 h operation; [e] pristine ENM; [f] durable for 4 h operation; [g] modified PIM; [h] permeate conductivity less than 2.5 μS/cm; [i] permeate conductivity exceeded 5 μS/cm; [j] 10 h operation; [k] 30 h operation; [l] 8 h operation; [m] 15 h operation; [n] 22 h operation; [o] 5 h operation; [p] 40 h operation; CB: Carbon black; ENM: Electrospun nanofiber membrane; FAS: Fluoroalkylsilane; F-POSS: Fluorinated polyhedral oligomeric silsesquioxanes; LEP: Liquid entry pressure; ODA-rGO: Octadecylamine-reduced graphene oxide; PDMS: Poly(dimethyl siloxane); PFPE: Perfluoropolyether; PIM: Phase inversion membrane; PU: Polyurethane; PVDF-HFP: Polyvinylidene-hexafluoropropylene; WCA: Water contact angle

In 2014, Lin *et al*. [89] proposed omniphobic microporous membranes that can resist the wetting due to water and low surface tension substances. A hydrophilic glass fiber membrane was coated with silica nanoparticles, followed by surface fluorination and polymer coating. Afterwards, several fabrication techniques of omniphobic membrane have been developed, such as particle-free approach [90], scalable approach [91], self-roughened approach [92], solvent-thermal induced roughening method [93], etc. A re-entrance structure is created to improve the roughness of membrane surface by employing nanoparticles [94–98] and fluorination [97, 99]. Table 4 shows a comparison between omniphobic membranes and pristine hydrophobic membranes in MD performance. Omniphobic membranes can retain a numerous low surface tension liquids in which contact angles (CAs) exceeding 100°. Basically, the omniphobic membranes can improve the MD flux [100–102]. Some researchers showed that the flux gained by omniphobic membranes is slightly lower than that obtained by pristine hydrophobic membranes, but the omniphobic membranes allowed for longer operation with high rejection of salts as well as low surface tension materials [93, 94, 103]. The omniphobic membranes exhibited good anti-fouling, anti-scaling and anti-wetting in MD processes for salts, surfactants and organic matters [100, 103–106].

6.0 CONCLUSIONS AND FUTURE RESEARCH DIRECTIONS

Membrane distillation (MD) has been receiving rapid attention in water recovery since four decades ago. The MD membrane has been developed from basic hydrophobic, followed by superhydrophobic and omniphobic in either phase inversion or electrospun membrane. The remarks of future research directions include:

- Harvesting freshwater from real wastewaters and produced waters from oilfields using omniphobic membranes could be an interesting research subject in the future.
- Rigorous investigations of modified membranes for long-term MD applications are required, especially the stability of adhesion of nanoparticles and coating layers as well as the modified structures.
- Sustainable and natural materials are recommended to replace the current chemicals used to modify the membrane surface. Thus, to reduce the hazards and cost.

ACKNOWLEDGEMENT

The authors would like to thank UMS for providing the resources to complete this article.

Table 4 Comparison of omniphobic membrane (O-pho M) and pristine membrane in MD

Membrane fabrication strategy	CA (°)		LEP (kPa)		Configuration	Flux (kg/m^2 h)		Rejection (%)		Reference
	Pristine	O-pho M	Pristine	O-pho M		Pristine	O-pho M	Pristine	O-pho M	
Immersion of PVDF membrane in DA, $AgNO_3$/ethanol and PFDT	142.7±2.9 [a] 0 [b] 122±2 [c] 100±1 [d] 134±3 [e] 102±1 [f]	165±1 [a] 157±1 [b] > 150 [c,d,e,f]	80±10	220±20	DCMD	0 [g,i]	21.5±1.2 [h,i]	-	>99.99 [j]	[105]
PDA/PEI co-deposition, silicification by TMOS solution and PDTS coating	121.89 [a] 71.86 [d]	> 150 [a] 157.31 [d]	243.4	326.4	DCMD	49.22 [k]	94.1 [l]	~91	> 99	[100]
Blending of CA and SiNPs, and next immersion in PDTS	125.7 [a] ~90 [m] ~30 [n]	155.6 [a] ~135 [m] ~120 [n] ~100 [o]	-	-	DCMD	8.2 [p]	13.6 [p] 13.8 [q]	> 99	> 99	[107]
Blending of PVDF-HFP and APTES, in-situ growth of SiNP and silanization	~130 [a] ~110 [d]	151.49 [a] 140.64 [b] 119.59 [d] 107.5 [r]	119	223	DCMD	~33 [s]	~20 [s]	~55 [t]	~100 [t]	[94]
Electrospraying of Ti-CNFs on PVDF membrane	~125.0 [a] ~119.0 [u] 80.0±1.0 [d] 100.5±2.5 [f] 86.5±1.5 [v] 108.5±2.0 [w]	172.0±1.8 [a] 170.5±3.5 [u] 160.1±2.6 [d] 165.0±3.0 [f] 162.5±4.5 [v] 151.0±1.5 [r] 153.5±3.5 [w] 118.0±3.0 [x]	240±5	300 – 400	DCMD	~10 [y]	~35 [y]	-	~100	[101]
Immobilization of TiO_2@PDA@Cu composite nanoparticles on PVDF membrane surface via chemical bonding; fluorosilanization treatment with PFDTS	127.0±1.0 [a] 70.8±3.0 [z] 101.1±2.5 [f] 86.6±3.5 [v] 66.3±2.6 [b]	168.0±2.0 [a] 157.1±1.5 [z] 160.0±1.2 [f] 158.3±1.5 [v] 152.5±3.0 [b]	250	420	DCMD	~13 [α]	~35 [α]	-	-	[102]
Blending of PVDF-HFP, FA and ZnO	135.3±1.2 [a] ~0 [β]	161.4±3.4 [a] 131.5±1.8 [β]	101±11	187±15	DCMD	~12 [γ]	~22 [δ]	>90 [γ]	>99.9 [δ]	[108]

	~0 [r]	131±2.9 [r]								
Solvent-thermal induced roughening method	~130 [a] ~90 [e] ~0 [b]	~172 [a] ~160 [e] ~154 [b]	83±3	216±29	DCMD	~26 [ζ] ~25 [η]	~17 [θ] ~20 [ι]	>99	>99	[93]
Heat-press treatment and dip-coating in a Teflon solution	132.6±0.7 [a] 124.4±3.6 [κ]	148.4±1.5 [a] 143.1±2.4 [κ] 134.2±1.8 [λ] 117.0±2.5 [μ] 112.7±2.5 [σ] 101.8±4.6 [r]	380	700	DCMD	~32 [τ]	~28 [φ]	> 99 [τ]	> 99 [φ]	[103]

[a] water; [b] mineral oil; [c] SLS; [d] SDS; [e] DTAB; [f] CTAB; [g] measured flux after 6 h operation; [h] stable flux for 12 h operation; [i] 3.5 wt% NaCl feed solution contained 150 ppm DTAB; [j] salt rejection; [k] normalized flux (%) during 60-180 min operation with addition of 0.1 mM SDS in 35g/L NaCl feed solution; [l] normalized flux (%) after 420 min operation with addition of 0–0.3 mM SDS in 35g/L NaCl feed solution; [m] methanol; [n] castor oil; [o] decane; [p] fed with 3.5 wt% NaCl for 30 operation; [q] fed with 3.5 wt% NaCl contained 0.2 mM SDS for 120 h operation; [r] ethanol; [s] after 0.1 mM SDS was added at 120 min operation; [t] after 0.4 mM SDS was added with 480 min operation; [u] NaCl solution; [v] Tween-20; [w] soybean oil; [x] dodecane; [y] after 0.4 mM SDS/CTAB/Tween-20 was added at 1200 min operations; [z] SDBS; [α] measured flux after 26 h operation; [β] vegetable oil; [γ] measured flux before 450 min operation; [δ] measured flux after 810 min operation; [ε] surfactant contaminated saline water; [ζ] measured flux after 60 min operation with SDS in feed solution; [η] measured flux after 360 min operation with SDS in feed solution; [θ] measured flux after 150 min with mineral oil in feed solution; [ι] measured flux after 420 min operation with mineral oil in feed solution; [κ] glycerol; [λ] EG; [μ] silicone oil; [μ] toluene; [τ] measured flux after 1 h operation with 0.1 mM SDS in feed solution; [φ] measured flux after 90 h operation with 0.4 mM SDS in feed solution; APTES: 3-Aminopropyl-triethoxysilane; CA: Cellulose acetate; CA(°): Contact angle; CNFs: Carbon nanofibers; CTAB: Cetyl trimethyl ammonium bromide; Cu: Copper; DA: Dopamine; DTAB: Dodecyl trimethyl ammonium bromide; EA: Epoxy acrylic; EG: Ethylene glycol; FAS: 1H,1H,2H,2H-perfluorooctyltriethoxysilane; LEP: Liquid entry pressure; PDA: Polydopamine; PDTS: Perfluorodecyl-triethoxysilane; PEI: Polyethylenimine; PFDT: Perfluorodecanethiol; PFDTS: 1H,1H,2H,2H-perfluorodecyltriethoxysilane; PFTS: Perfluorodecyltrimethoxysilane; SDS: Sodium dodecyl sulfate; SDBS: Sodium dodecyl benzene sulfonate; SiNPs: Silica nanoparticles; SLS: Sodium lauryl sulfonate; Ti or TiO_2: Titanium oxide; TMOS: Tetramethyl orthosilicate; ZnO: Zinc oxide

REFERENCES

[1] United Nations. 2018. Secretary General Assembly – Remarks at Launch of International Decade for Action. *Water for Sustainable Development 2018 – 2028. 22 March 2018.* https://www.un.org/sg/en/content/sg/speeches/2018-03-22/decade-action-water-sustainable-development-remarks.

[2] UNESCO and UNESCO i-WSSM. 2020. Water Reuse within a Circular Economy Context (Series II). Global Water Security Issues (GWSI) Series – No. 2, UNESCO Publishing, Paris.

[3] F. He, J. Gilron, K. K. Sirkar. 2013. High Water Recovery in Direct Contact Membrane Distillation using a Series of Cascade. *Desalination.* 323: 48-54.

[4] W. Shi, T. Li, Y. Tian, H. Li, M. Fan, H. Zhang, X. Qin. 2022. An Innovative Hollow Fiber Vacuum Membrane Distillation-crystallization (VMDC) Coupling Process for Dye House Effluent Separation to Reclaim Fresh Water and Salts. *J. Clean. Prod.* 337: 130586.

[5] L. Francis, F. E. Ahmad, N. Hilal. 2022. Electrospun Membranes for Membrane Distillation: The State of Play and Recent Advances. *Desalination.* 526: 115511.

[6] C. F. Couto, A. V. Santos, M. C. S. Amaral, L. C. Lange, L. H. de Andrade, A. F. S. Foureaux, B. S. Fernandes. 2020. Assessing Potential of Nanofiltration, Reverse Osmosis and Membrane Distillation Drinking Water Treatment for Pharmaceutically Active Compounds (PhAcs) Removal. *J. Water Process Eng.* 33: 101029.

[7] Z. Zhang, S. S. Wadekar, O. R. Lokare, R. D. Vidic. 2021. Comparison of Calcium Scaling in Direct Contact Membrane Distillation (DCMD) and Nanofiltration (NF). *J. Membr. Sci.* 638: 119647.

[8] X. Zhu, Y. Liu, F. Du, J. Han, G. Hao, L. Li, Q. Ma. 2021. Geothermal Direct Contact Membrane Distillation System for Purifying Brackish Water. *Desalination.* 500: 114887.

[9] J. Choi, J. Cho, J. Shin, H. Cha, J. Jung, K.G. Song. 2022. Performance and Economic Analysis of a Solar Membrane Distillation Pilot Plant under Various Operating Conditions. *Energy Convers. Manag.* 268: 115991.

[10] S. Memon, H. S. Lee, W. S. Kim, Y. D. Kim. 2022. Parametric Investigation of Modular Configuration of Multi-stage Direct Contact Membrane Distillation Powered by Waste Heat of Wind Turbine. *Desalination.* 533: 115770.

[11] G. Naidu, S. Jeong, Y. Choi, S. Vigneswaran. 2017. Membrane Distillation for Wastewater Reverse Osmosis Concentrate Treatment with Water Reuse Potential. *J. Membr. Sci.* 524: 565-575.

[12] M. T. T. Ngo, B. Q. Diep, H. Sano, Y. Nishimura, S. Boivin, H. Kodamatani, H. Takeuchi, S. C. W. Sakti, T. Fujioka. 2022. Membrane Distillation for Achieving High Water Recovery for Potable Water Reuse. *Chemosphere.* 288: 132610.

[13] S. Zhang, P. Wang, X. Fu, T. S. Chung. 2014. Sustainable Water Recovery from Oily Wastewater via Forward Osmosis-membrane

Distillation. *Water Res.* 52: 112-121.

[14] J. A. Kharraz, N. K. Khanzada, M. U. Farid, J. Kim, S. Jeong, A. K. An. 2022. Membrane Distillation Bioreactor (MDBR) for Wastewater Treatment, Water Reuse, and Resource Recovery: A Review. *J. Water Process Eng.* 47: 102687.

[15] A. El-Abbassi, H. Kiai, A. Hafidi, M. C. García-Payo, M. Khayet. 2012. Treatment of Olive Mill Wastewater by Membrane Distillation using Polytetrafluoroethylene Membranes. *Sep. Purif. Technol.* 98: 55-61.

[16] M. Gryta, J. Grzechulska-Damszel, A. Markowska, K. Karakulski. 2009. The Influence of Polypropylene Degradation on the Membrane Wettability during Membrane Distillation. *J. Membr. Sci.* 326: 493-502.

[17] M. Tomaszewska. 1996. Preparation and Properties of Flat-sheet Membranes from Poly(vinylidene fluoride) for Membrane Distillation. *Desalination.* 104: 1-11.

[18] J. Zuo, S. Bonyadi, T. S. Chung. 2016. Exploring the Potential of Commercial Polyethylene Membranes for Desalination by Membrane Distillation. *J. Membr. Sci.* 497: 239-247.

[19] M. Liu, Q. Li, H. Sun, S. Jia, X. He, M. Li, X. X. Zhang, L. Ye. 2018. Impact of Salinity on Antibiotic Resistance Genes in Wastewater Treatment Bioreactors. *Chem. Eng. J.* 338: 557-563.

[20] A. Panagopoulos, K. J. Haralambous, M. Loizidou. 2019. Desalination Brine Disposal Methods and Treatment Technologies – A Review. *Sci. Total Environ.* 693: 133545.

[21] L. Fortunato, Y. Jang, J. G. Lee, S. Jeong, S. Lee, T. Leiknes, N. Ghaffour. 2018. Fouling Development in Direct Contact Membrane Distillation: Non-Invasive Monitoring and Destructive Analysis. *Water Res.* 132: 34-41.

[22] J. Ren, J. Li, Z. Chen, F. Cheng. 2018. Fate and Wetting Potential of Bio-refractory Organics in Membrane Distillation for Coke Wastewater Treatment. *Chemosphere.* 208: 450-459.

[23] H. Elcik, L. Fortunato, A. Alpatova, S. Soukane, J. Orfi, E. Ali, H. AlAnsary, T. Leiknes, N. Ghaffour. 2020. Multi-effect Distillation Brine Treatment by Membrane Distillation: Effect of Antiscalant and Antifoaming Agents on Membrane Performance and Scaling Control. *Desalination.* 493: 114653.

[24] S. Pillai, A. Santana, R. Das, B. R. Shrestha, E. Manalastas, H. Mishra. 2020. A Molecular to Macro Level Assessment of Direct Contact Membrane Distillation for Separating Organics Form Water. *J. Membr. Sci.* 608: 118140.

[25] Y. Shao, M. Han, Y. Wang, G. Li, W. Xiao, X. Li, X. Wu, X. Ruan, X. Yan, G. He, X. Jiang. 2019. Superhydrophobic Polypropylene Membrane with Fabricated Antifouling Interface for Vacuum Membrane Distillation Treating High Concentration Sodium/magnesium Saline Water. *J. Membr. Sci.* 579: 240-252.

[26] G. H. Teoh, J. Y. Chin, B. S. Ooi, Z. A. Jawad, H. T. L. Leow, S. C. Low. 2020. Superhydrophobic Membrane with Hierarchically 3D-microtexture to Treat Saline Water by Deploying Membrane

Distillation. *J. Water Process. Eng.* 37: 101528.
[27] K. J. Lu, Y. Chen, T. S. Chung. 2019. Design of Omniphobic Interfaces for Membrane Distillation – A Review. *Water Res.* 162: 64-77.
[28] B. R. Bodell. 1963. Silicone Rubber Vapor Diffusion in Saline Water Distillation. United States Patent Serial No. 285,032.
[29] B. R. Bodell. 1968. Distillation of Saline Water Using Silicone Rubber Membrane. U.S. Patent 3,361,645.
[30] E. Drioli, V. Calabrò, Y. Wu. 1986. Microporous Membranes in Membrane Distillation. *Pure & Appl. Chem.* 58: 1657-1662.
[31] E. Drioli, Y. Wu, V. Calabrò. 1987. Membrane Distillation in the Treatment of Aqueous Solutions. *J. Membr. Sci.* 33: 277-284.
[32] F. A. Banat, J. Simandl. 1994. Theoretical and Experimental Study in Membrane Distillation. *Desalination.* 95: 39-52.
[33] M. Gryta. 2005. Long-term Performance of Membrane Distillation Process. *J. Membr. Sci.* 265: 153-159.
[34] S. T. Hsu, K. T. Cheng, J. S. Chiou. 2002. Seawater Desalination by Direct Contact Membrane Distillation. *Desalination.* 143: 279-287.
[35] K. Karakulski, M. Gryta. 2005. Water Demineralization by NF/MD Integrated Processes. *Desalination.* 177: 109-119.
[36] M. Gryta. 2007. Influence of Polypropylene Membrane Surface Porosity on the Performance of Membrane Distillation Process. *J. Membr. Sci.* 287: 67-78.
[37] K. Schneider, W. Hölz, R. Wollbeck. 1988. Membranes and Modules for Transmembrane Distillation. *J. Membr. Sci.* 39: 25-42.
[38] M. S. El-Bourawi, Z. Ding, R. Ma, M. Khayet. 2006. A Framework for Better Understanding Membrane Distillation Separation Process. *J. Membr. Sci.* 285: 4-29.
[39] K. W. Lawson, D. R. Lloyd. 1997. Membrane Distillation. *J. Membr. Sci.* 124: 1-25.
[40] P. Peng, A.G. Fane, X. Li. 2005. Desalination by Membrane Distillation Adopting a Hydrophilic Membrane. *Desalination.* 173: 45-54.
[41] M. Gryta, M. Barancewicz. 2010. Influence of Morphology of PVDF Capillary Membranes on the Performance of Direct Contact Membrane Distillation. *J. Membr. Sci.* 358: 158-167.
[42] M. Tian, S. Yuan, F. Decaesstecker, J. Zhu, A. Volodine, B. V. der Bruggen. 2020. One-step Fabrication of Isotropic Poly(vinylidene fluoride) Membranes for Direct Contact Membrane Distillation (DCMD). *Desalination.* 477: 114265.
[43] M. Alberto, C. Skuse, M. Tamaddondar, P. Gorgojo. 2022. Immobilized Graphene Oxide-based Membranes for Improved Pore Wetting Resistance in Membrane Distillation. *Desalination.* 537: 115898.
[44] D. Zou, C. Hu, E. Drioli, Z. Zhong. 2022. Engineering Green and High-flux Poly(vinylidene fluoride) Membranes for Membrane Distillation via a Facile Co-casting Process. *J. Membr. Sci.* 655: 120577.
[45] M. Tian, J. Zhu, S. Yuan, Y. Zhang, B.V. der Bruggen. 2021. A Co-casting Route Enables the Formation of Skinless, Hydrophobic Poly(vinylidene

Fluoride) Membranes for DCMD. *J. Membr. Sci.* 630: 119299.

[46] T. A. Agbaje, S. Al-Gharabli, M. O. Mavukkandy, J. Kujawa, H. A. Arafat. 2018. PVDF/magnetite Blend Membranes for Enhanced Flux and Salt Rejection in Membrane Distillation. *Desalination.* 436: 69-80.

[47] M. A. Azeem, D. U. Lawal, H. A. Abdulgader, T. N. Baroud. 2022. Enhanced Performance of Superhydrophobic Polyvinylidene Fluoride Membrane with Sandpaper Texture For Highly Saline Water Desalination in Air-gap Membrane Distillation. *Desalination.* 528: 115603.

[48] S. A. Mousavi, Z. A. Aboosadi, A. Mansourizadeh, B. Honarvar. 2021. Surface Modified Porous Polyetherimide Hollow Fiber Membrane for Sweeping Gas Membrane Distillation of Dyeing Wastewater. *Colloids Surf. A* 610: 125439.

[49] M. A. Tooma, T. S. Najim, Q. F. Alsalhy, T. Marino, A. Criscuoli, L. Giorno, A. Figoli. 2015. Modification of Polyvinyl Chloride (PVC) Membrane for Vacuum Membrane Distillation (VMD) Application. *Desalination.* 373: 58-70.

[50] H. Li, H. Liu, W. Shi, H. Zhang, R. Zhou, X. Qin. 2020. Preparation of Hydrophobic Zeolite Imidazolate Framework-71 (ZIF-71)/PVDF Hollow Fiber Composite Membrane for Membrane Distillation through Dilute Solution Coating. *Spe. Purif. Technol.* 251: 117348.

[51] M. Alqaydi, M. O. Mavukkandy, I. Mustafa, A. Alnuaimi, H. A. Arafat, F. Almarzooqi. 2022. Activated Carbon as a Photothermal Absorber in PVDF Membranes for Solar Driven Air-Gap Membrane Distillation. *Desalination.* 541: 116031.

[52] C. Feng, K. C. Khulbe, T. Matsuura, R. Gopal, S. Kaur, S. Ramakrishna, M. Khayet. 2008. Production of Drinking Water from Saline Water by Air-gap Membrane Distillation using Polyvinylidene Fluoride Nanofiber Membrane. *J. Membr. Sci.* 311: 1-6.

[53] C. I. Su, J. H. Shih, M. S. Huang, C. M. Wang, W. C. Shih, Y. S. Liu. 2012. A Study of Hydrophobic Electrospun Membrane Applied in Seawater Desalination by Membrane Distillation. *Fiber. Poylm.* 13: 698-702.

[54] M. Essalhi, M. Khayet. 2013. Self-sustained Webs of Polyvinylidene Fluoride Electrospun Nanofibers at Different Electrospinning Times: 1. Desalination by Direct Contact Membrane Distillation. *J. Membr. Sci.* 433: 167-179.

[55] J. A. Prince, V. Anbharasi, T. S. Shanmugasundaram, G. Singh. 2013. Preparation and Characterization of Novel Triple Layer Hydrophilic-hydrophobic Composite Membrane for Desalination using Air Gap Membrane Distillation. *Sep. Purif. Technol.* 118: 598-603.

[56] Y. Liao, R. Wang, M. Tian, C. Qiu, A. G. Fane. 2013. Fabrication of Polyvinylidene Fluoride (PVDF) Nanofiber Membranes by Electro-spinning for Direct Contact Membrane Distillation. *J. Membr. Sci.* 425-426: 30-39.

[57] B. S. Lalia, E. Guillen-Burrieza, H. A. Arafat, R. Hashaikeh. 2013. Fabrication and Characterization of Polyvinylidenefluoride-co-hexafluoropropylene (PVDF-HFP) Electrospun Membranes for

Direct Contact Membrane Distillation. *J. Membr. Sci.* 428: 104-115.

[58] J. A. Prince, G. Singh, D. Rana, T. Matsuura, V. Anbharasi, T. S. Shanmugasundaram. 2012. Preparation and Characterization of Highly Hydrophobic Poly(vinylidene fluoride) – Clay Nanocomposite Nanofiber Membranes (PVDF-clay NNMs) for Desalination using Direct Contact Membrane Distillation. *J. Membr. Sci.* 397-398: 80-86.

[59] L. Zhao, C. Wu, X. Lu, D. Ng, Y. B. Truong, Z. Xie. 2018. Activated Carbon Enhanced Hydrophobic/hydrophilic Dual-layer Nanofiber Composite Membranes for High-performance Direct Contact Membrane Distillation. *Desalination.* 446: 59-69.

[60] M. M. Shirazi, S. Bazgir, F. Meshkani. 2020. A Dual-layer, Nanofibrous Styrene-acrylonitrile Membrane with Hydrophobic/hydrophilic Composite Structure for Treating the Hot Dyeing Effluent by Direct Contact Membrane Distillation. *Chem. Eng. Res. Des.* 164: 125-146.

[61] M. Huang, J. Song, Q. Deng, T. Mu, J. Li. 2022. Novel Electrospun ZIF/PcH Nanofibrous Membranes for Enhanced Performance of Membrane Distillation for Salty and Dyeing Wastewater Treatment. *Desalination.* 527: 115563.

[62] L. Deng, K. Liu, P. Li, D. Sun, S. Ding, X. Wang, B. S. Hsiao. 2020. Engineering Construction of Robust Superhydrophobic Two-tier Composite Membrane with Interlocked Structure for Membrane Distillation. *J. Membr. Sci.* 598: 117813.

[63] B. Bhushan, Y. C. Jung. 2011. Natural and Biomimetic Artificial Surfaces for Superhydrophobicity, Self-cleaning, Low Adhesion, and Drag Reduction. *Prog. Mater. Sci.* 56: 1-108.

[64] Z. Ma., Y. Hong, L. Ma, M. Su. 2009. Superhydrophobic Membranes with Ordered Arrays of Nanospiked Microchannels for Water Desalination. *Langmuir Lett.* 25: 5446-5450.

[65] H. Maab, L. Francis, A. Al-saadi, C. Aubry, N. Ghaffour. G. Amy, S. P. Nunes. 2012. Synthesis and Fabrication of Nanostructured Hydrophobic Polyazole Membranes for Low-energy Water Recovery. *J. Membr. Sci.* 423-424: 11-19.

[66] J. Zhang, Z. Song, B. Li, Q. Wang, S. Wang. 2013. Fabrication and Characterization of Superhydrophobic Poly(vinylidene fluoride) Membrane for Direct Contact Membrane Distillation. *Desalination.* 324: 1-9.

[67] A. Razmjou, E. Arifin, G. Dong, J. Mansouri, V. Chen. 2012. Superhydrophobic Modification of TiO_2 Nanocomposite PVDF Membranes for Applications in Membrane Distillation. *J. Membr. Sci.* 415-416: 850-863.

[68] Y. Liao, G. Zheng, J. J. Huang, M. Tan, R. Wang. 2020. Development of Robust and Superhydrophobic Membranes to Mitigate Membrane Scaling and Fouling in Membrane Distillation. *J. Membr. Sci.* 601: 117962.

[69] M. Fouladivanda, J. Karimi-Sabet, F. Abbasi, M. A. Moosavian. 2021. Step-by-step Improvement of Mixed-matrix Nanofiber Membrane with Functionalized Graphene Oxide

for Desalination via Air-gap Membrane Distillation. *Sep. Purif. Technol.* 256: 117809.

[70] D. Liu, J. Cao, M. Qiu, G. Zhang, Y. Hong. 2022. Enhanced Properties of PVDF Nanofibrous Membrane with Liquid-like Coating for Membrane Distillation. *Sep. Purif. Technol.* 295: 121282.

[71] J. Pan, F. Zhang, Z. Wang, S.P. Sun, Z. Cui, W. Jin, O. Bamaga, H. Abulkhair, M. Albeirutty, E. Drioli. 2022. Enhanced Anti-Wetting and Anti-fouling Properties of Composite PFPE/PVDF Membrane in Vacuum Membrane Distillation. *Sep. Purif. Technol.* 282: 120084.

[72] Y. Liao, R. Wang, A. G. Fane. 2013. Engineering Superhydrophobic Surface on Poly(vinylidene fluoride) Nanofiber Membranes for Direct Contact Membrane Distillation. *J. Membr. Sci.* 440: 77-87.

[73] K. K. Yan, L. Jiao, S. Lin, X. Ji, Y. Lu, L. Zhang. 2018. Superhydrophobic Electrospun Nanofiber Membrane Coated by Carbon Nanotubes Network for Membrane Distillation. *Desalination.* 437: 26-33.

[74] Z. Xiao, Z. Li, H. Guo, Y. Liu, Y. Wang, H. Yin, X. Li, J. Song, L.D. Nghiem, T. He. 2019. Scaling Mitigation in Membrane Distillation: From Superhydrophobic to Slippery. *Desalination.* 466: 36-43.

[75] Z. Ding, Z. Liu, C. Xiao. 2021. Excellent Performance of Novel Superhydrophobic Composite Hollow Membrane in the Vacuum Membrane Distillation. *Sep. Purif. Technol.* 268: 118603.

[76] Y. C. Woo., M. Yao, W. G. Shim, Y. Kim, L. D. Tijing, B. Jung, S. H. Kim, H. K. Shon. 2021. Co-axially Electrospun Superhydrophobic Nanofiber Membranes with 3D-Hierarchically Structured Surface for Desalination by Long-term Membrane Distillation. *J. Membr. Sci.* 623: 119028.

[77] J. Song, Q. Deng, M. Huang, Z. Kong. 2022. Carbon Nanotube Enhanced Membrane Distillation for Salty and Dyeing Wastewater Treatment by Electrospinning Technology. *Environ. Res.* 204: 111892.

[78] X. Q. Wu, N. R. Mirza, Z. Huang, J. Zhang, Y.M. Zheng, J. Xiang, Z. Xie. 2021. Enhanced Desalination Performance of Aluminium Fumarate MOF-incorporated Electrospun Nanofiber Membrane with Bead-on-string Structure for Membrane Distillation. *Desalination.* 520: 115338.

[79] D. Cheng, L. Zhao, N. Li, S. J. D. Smith, D. Wu, J. Zhang, D. Ng, C. Wu, M. R. Martinez, M. P. Batten, Z. Xie. 2019. *J. Membr. Sci.* 588: 117204.

[80] X. Hu, X. Chen, M. Giagnorio, C. Wu, Y. Luo, C. Hélix-Nielsen, P. Yu, W. Zhang. 2022. Beaded Electrospun Polyvinylidene Fluoride (PVDF) Membranes for Membrane Distillation (MD). *J. Membr. Sci.* 661: 120850.

[81] B. Ozbey-Unal, E. Gezmis-Yavuz, B. Eryildiz, D. Y. Koseoglu-Imer, B. Keskinler, I. Koyuncu. 2020. Boron Removal from Geothermal Water by Nanofiber-based Membrane Distillation Membranes with Significantly Improved Surface Hydrophobicity. *J. Environ. Chem. Eng.* 8: 104113.

[82] Z. Li, Y. Liu, J. Yan, K. Wang, B. Xie, Y. Hu, W. Kang, B. Cheng. 2019. Electrospun Polyvinylidene Fluoride/fluorinated Acrylate

Copolymer Tree-like Nanofiber Membrane with High Flux and Salt Rejection Ratio for Direct Contact Membrane Distillation. *Desalination.* 466: 68-76.

[83] Q. Sun, Z. Yang, C. Hu, C. Li, G. Yan, Z. Wang. 2020. Facile Preparation of Superhydrophobic PVDF Microporous Membranes with Excellent Anti-fouling Ability for Vacuum Membrane Distillation. *J. Membr. Sci.* 605: 118106.

[84] G. Tan, D. Xu, Z. Zhu, X. Zhang, J. Li. 2022. Tailoring Pore Size and Interface of Superhydrophobic Nanofibrous Membrane for Robust Scaling Resistance and Flux Enhancement in Membrane Distillation. *J. Membr. Sci.* 658: 120751.

[85] J. Lin, J. Du, S. Xie, F. Yu, S. Fang, Z. Yan, X. Lin, D. Zou, M. Xie, W. Ye. 2022. Durable Superhydrophobic Polyvinylidene Fluoride Membranes via Facile Spray-Coating for Effective Membrane Distillation. *Desalination* 538: 115925.

[86] P. Yadav, R. Farnood, V. Kumar. 2022. Superhydrophobic Modification of Electrospun Nanofibrous Si@PVDF Membranes for Desalination Application in Vacuum Membrane Distillation. *Chemosphere.* 287: 132092.

[87] S. K. Hong, H. Kim, H. Lee, G. Lim, S. J. Cho. 2022. A Pore-size Tunable Superhydrophobic Membrane for High-flux Membrane Distillation. *J. Membr. Sci.* 641: 119862.

[88] L. Zhou, C. L. Li, P. T. Chang, S. H. Tan, A. L. Ahmad, S. C. Low. 2022. Intrinsic Microspheres Structure of Electrospun Nanofibrous Membrane with Rational Superhydrophobicity for Desalination via Membrane Distillation. *Desalination.* 527: 115594.

[89] S. Lin, S. Nejati, C. Boo, Y. Hu, C. O. Osuji, M. Elimelech. 2014. Omniphobic Membrane for Robust Membrane Distillation. *Environ. Sci. Technol. Lett.* 1: 443-447.

[90] W. Wang, X. Du, H. Vahabi, S. Zhao, Y. Yin, A. K. Kota, T. Tong. 2019. Trade-off in Membrane Distillation with Monolithic Omniphobic Membranes. *Nat. Commun.* 10: 1-9.

[91] C. Boo, J. Lee, M. Elimelech. 2016. Omniphobic Polyvinylidene Fluoride (PVDF) Membrane for Desalination of Shale Gas Produced Water by Membrane Distillation. *Environ. Sci. Technol.* 50: 12275-12282.

[92] L. Deng, H. Ye, X. Li, P. Li, J. Zhang, X. Wang, M. Zhu, B. S. Hsiao. 2018. Self-roughened Omniphobic Coatings on Nanofibrous Membrane for Membrane Distillation. *Sep. Purif. Technol.* 206: 14-25.

[93] W. Qing, Y. Wu, X. Li, X. Shi, S. Shao, Y. Mei, W. Zhang, C. Y. Tang. 2020. Omniphobic PVDF Nanofibrous Membrane for Superior Anti-wetting Performance in Direct Contact Membrane Distillation. *J. Membr. Sci.* 608: 118226.

[94] Y. Xu, Y. Yang, X. Fan, Z. Liu, Y. Song, Y. Wang, P. Tao, C. Song, M. Shao. 2021. In-situ Silica Nanoparticle Assembly Techniques to Develop an Omniphobic Membrane for Durable Membrane Distillation. *Desalination.* 499: 114832.

[95] H. Li, H. Feng, M. Li, X. Zhang. 2022. Engineering a Covalently Constructed Superomniphobic

Membrane for Robust Membrane Distillation. *J. Membr. Sci.* 644: 120124.

[96] J. Li, L.F. Ren, M. Huang, J. Yang, J. Shao, Y. He. 2022. Facile Preparation of Omniphobic-ZnO-PVDF Membrane with Excellent Anti-wetting Property in Direct Contact Membrane Distillation (DCMD). *J. Membr. Sci.* 650: 120404.

[97] S. A. Alftessi, M. H. D. Othman, M. R. Adam, T. M. Farag, A. Mustafa, T. Matsuura, J. Jaafar, M. A. Rahman, A. F. Ismail. 2022. Omniphobic Surface Modification of Silica sand Ceramic Hollow Fiber Membrane for Desalination via Direct Contact Membrane Distillation. *Desalination.* 532: 115705.

[98] H. Feng, H. Li, M. Li, X. Zhang. 2022. Construction of Omniphobic PVDF Membranes for Membrane Distillation: Investigating the Role of Dimension, Morphology, and Coating Technology of Silica Nanoparticles. *Desalination.* 525: 115498.

[99] Y. H. Chiao, Y. Cao, M. B. M. Y. Ang, A. Sengupta, S. R. Wickramasinghe. 2022. Application of Superomniphobic Electrospun Membrane for Treatment of Real Produced Water Through Membrane Distillation. *Desalination.* 528: 115602.

[100] L. Meng, J. Mansouri, X. Li, J. Liang, M. Huang, Y. Lv, Z. Wang, V. Chen. 2022. Omniphobic Membrane via Bioinspired Silicification for the Treatment of RO Concentrate by Membrane Distillation. *J. Membr. Sci.* 647: 120267.

[101] W. Zhang, Z. Wang, B. Li. 2021. Omniphobic Membrane with Nest-like Re-entrant Structure via Electrospraying for Robust Membrane Distillation. *J. Membr. Sci.* 640: 119824.

[102] W. Zhang, B. Hu, Z. Wang, B. Li. 2021. Fabrication of Omniphobic PVDF Composite Membrane with Dual-scale Hierarchical Structure via Chemical Bonding for Robust Membrane Distillation. *J. Membr. Sci.* 622: 119038.

[103] Y. Chen, K. J. Lu, T. S. Chung. 2020. An Omniphobic Slippery Membrane with Simultaneous Anti-wetting and Anti-scaling Properties for Robust Membrane Distillation. *J. Membr. Sci.* 595: 117572.

[104] Z. Zhu, L. Zhong, T. Horseman, Z. Liu, G. Zeng, Z. Li, S. Lin, W. Wang. 2021. Superhydrophobic-Omniphobic Membrane with Anti-deformable Pores for Membrane Distillation with Excellent Wetting. *J. Membr. Sci.* 620: 118768.

[105] X. Liao, Y. Wang, Y. Liao, X. You, L. Yao, A. G. Razaqpur. 2021. Effects of Different Surfactant Properties on Anti-wetting Behaviours of an Omniphobic Membrane in Membrane Distillation. *J. Membr. Sci.* 634: 119433.

[106] S. Xie, Z. Pang, C. Hou, N. H. Wong, J. Sunarso, Y. Peng. 2022. One-step Preparation of Omniphobic Membrane with Concurrent Anti-scaling and Anti-wetting Properties for Membrane Distillation. *J. Membr. Sci.* 660: 120846.

[107] D. Hou, C. Ding, C. Fu, D. Wang, C. Zhao, J. Wang. 2019. Electrospun Nanofibrous Omniphobic Membrane for Anti-surfactant-wetting Membrane Distillation Desalination. *Desalination.* 468: 114068.

[108] B. J. Deka, J. Guo, A. K. An. 2021. Robust Dual-layered Omniphobic Electrospun Membrane with Anti-wetting and Anti-scaling Functionalized for Membrane Distillation Application. *J. Membr. Sci.* 624: 119089.