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Review of membrane distillation process for water purification

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ABSTRACT

Membrane distillation (MD) is a non-isothermal separation process driven on the vapor pressure difference, induced by the temperature difference across the hydrophobic membrane. This paper offers the review of the potentability of MD process for purification application and water desalination. It covers the basic fundamental of MD process, MD modules, membrane materials, heat and mass transfer phenomena, operating parameters, and performance of MD process. It also covers the review of MD processes driven by renewable energy sources and current innovations in the process. The recent research results in these different areas are presented and discussed. The multi-effect MD process is found to be a new generation MD process and attractive research area in the wastewater treatment and purification application for the commercial approach.

Keywords: Membrane distillation; Membrane configuration; Membrane material; Multi-effect membrane distillation; Water purification

1. Introduction

Membrane technologies such as micro filtration (MF), ultrafiltration (UF), nanofiltration (NF), reverse osmosis (RO), and membrane distillation (MD) have become more attractive for water treatment when compared to conventional purification [1–3]. Among these membrane technologies, MF, UF, NF, and RO is the pressure-driven separation technologies and only MD is a thermal-driven separation process [1,4]. The term MD comes from the similarity of the MD process to conventional distillation. Because both technologies are requiring heat to the feed solution in order to achieve the essential latent heat of vaporization, also both processes are based on the vapor–liquid equilibrium for the separation. In the MD process, only vapor molecules are able to pass through a porous hydrophobic membrane. Due to the hydrophobic nature of the membrane, liquid water cannot penetrate inside dry membrane pores unless a trans-membrane hydrostatic pressure exceeding the liquid entry pressure (LEP) of water, which is characteristic of each membrane, is applied. This separation process is driven by the vapor pressure difference existing between the porous hydrophobic membrane surfaces. It is a non-isothermal membrane separation process, in which saline water is heated to increase its vapor pressure,

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which generates the difference between partial pressure on both sides of the membrane. Hot water evaporates through non-wetted pores of hydrophobic membranes [5–10].

MD technique has been known for about 50 years. The first MD patent was obtained by Bodell in 1963 [11] and the first publication was made by Findley in 1967 [12]. Still the MD process is in the research and development stage due to the economics of the process was not favorable when compared to RO process [13,14]. RO process is the leading membrane technology for water treatment due to the strong separation capabilities and a great potential for water treatment worldwide. But due to high pressure operation, RO has a problem for the formation of polarization film and fouling of membrane [15,16]. Hence, the challenge in front of the researchers is to make the MD process an economical technology, which competes with RO in order to commercialize the process.

MD technology is found to be as a cheaper alternative to conventional RO water treatment process when MD utilizes low-grade waste heat from power stations and other heat generating plants to produce near-distilled water from seawater through vaporization and condensation process. It can be used as alternative energy sources such as solar, wave, or geothermal energy to power it. MD does not require pressure and also it is not limited by high osmotic pressure when compared with other membrane processes. It allows a theoretical 100% separation factor for non-volatile solute. The evaporation and condensation surface of MD unit is tightly packed and therefore result in compact equipment leading to a good relation between output and capital cost. Low use of chemicals, filters, and consumables implies a low running cost of MD. In many situations, the energy is available at minimal cost, so the MD will not be as costly as a typical RO process. Due to the number of such advantages of MD process, it is an interesting and growing technology in water treatment [17–23].

But the MD process is also attended by some drawbacks such as low permeate flux when compared with other separation processes, like RO. The concentration and temperature polarization phenomenon in the MD process reduces the permeate flux to the concentration and temperature of the feed conditions. The trapped air within the membrane introduces a further mass transfer resistance, which also reduces the MD permeate flux. Also, the heat lost by conduction is quite large in the MD process [24]. To overcome these drawbacks of MD process, Memsys (Germany) designed new vacuum multi-effect membrane distillation (V-MEMD) process for the desalination of seawater by using low-grade thermal energy. MEMD is energy efficient through multiple recycling of internal thermal energy. Due to the number of stages in the single module the permeate flux is increasing and hence the process is compete with the existing RO process [25].

Many researchers used the MD process for the desalination of seawater and ground water, and removal of salts like sodium chloride (NaCl), magnesium chloride ($MgCl_2$), sodium carbonate (Na_2CO_3), and sodium sulfate (Na_2SO_4) from water [26–31]. The MD process is used for other purification applications like the removal of dissolved matter [10,32], organic matter [29,33], iron oxide [34], arsenic [35], and Ca, Mg, Na, Fe, Zn [36] from water. It is also used for the concentration of L-lysine HCl [37], removal of ethyl 2,4-decadienoate from water–ethanol–ethyl 2,4-decadienoate mixture [38], and concentration of ethylene glycol [39] and ethanol [40]. Also, it is used in the removal of volatile organic compound [41], removal of water vapor from nitric acid/water mixture [42], and removal of acetone and ethanol from wastewater [43]. MD process was also used in the purification of domestic wastewater [44], potable water [45], and thermal soften water [10], olive mill wastewater [46], and cocking wastewater [33]. It is also used in the food industries for the purpose of concentration of sugar cane juice [47], orange juice [48], apple juice [49], and glucose solution [50].

2. Configuration of MD system and modules

2.1. Configurations of MD system

MD system configurations based on the methods were used to build a vapor pressure difference across a membrane to drive a permeate flux are shown in Fig. 1 [1,5,18,32,40,51,52].

2.1.1. Direct contact membrane distillation

In Fig. 1(a), the membrane is in direct contact with liquid phases. Permeate has condensed inside the module and cannot penetrate in the membrane due to the hydrophobic characteristics. It is a simple configuration and widely used in the desalination and concentrations of aqueous solutions in the food industry. The more research work on the laboratory scale was found in the literature [28,29,53–60]. It reduces the mass transfer resistance at permeate side when compared with other MD forms. The heat loss by conduction is more in Direct contact membrane distillation (DCMD). Hence, this configuration is not used in commercial applications.

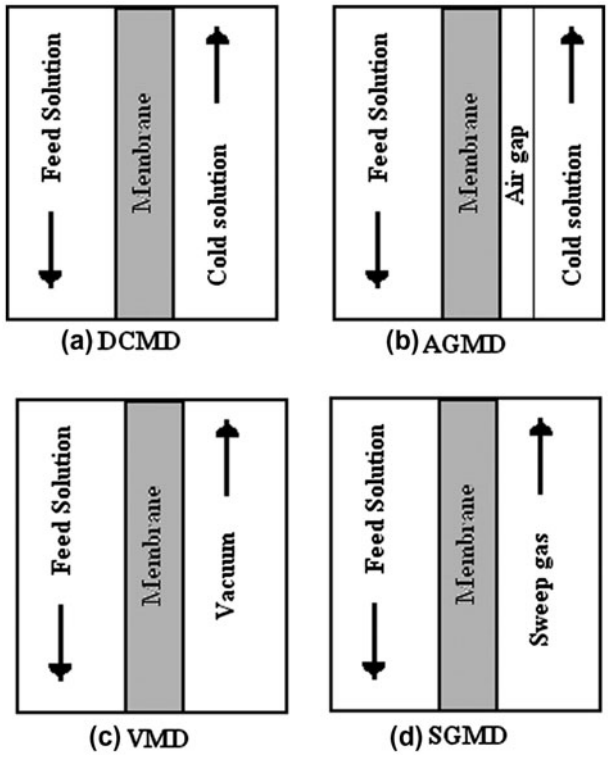

Fig. 1. Membrane distillation configurations.

2.1.2. Air gap membrane distillation

Fig. 1(b) shows the schematic diagram of air gap membrane distillation (AGMD) process, in which an air gap is introduced between the membrane and condensation surface. The vapor of the permeate gas condenses on the cold surface inside module. Due to the additional resistances to mass transfer, the flux obtained is generally low because it operates on low temperature difference, hence requires larger membrane surface area. The heat lost by the conduction is lower; hence, AGMD is using an energy efficient module. The latent heat can be recovered during the condensation of the vapor on cooling plate in the AGMD configuration [61–64]. Hence, the modified MD processes such as memstill technique [65], Scrab AB systems [66,67], and Fraunhofer ISE MD module [68] are based on the AGMD configuration.

2.1.3. Vacuum membrane distillation

In vacuum membrane distillation (VMD) module, the vacuum is given at the permeate side (Fig. 1(c)) for decreasing the vapor pressure and hence increases the driving force. The condensation takes place outside the membrane module hence the external condensation is required for this configuration. When compared with other MD configurations, VMD configuration can provide the greatest driving force which gives a higher permeation flux and better thermal efficiency if the high efficiency external condenser is used. So, VMD is an attractive module in many applications such as concentration of RO brine, removal of heavy metals, purification of alcohols, etc. [69]. Generally, the VMD was used for the removal of volatile components from aqueous solutions [41,70,71]. The more studies are found on the VMD for various MD applications [1,6,7,18,33,37–40,44,72,73]. The main advantage of this configuration is the negligible conductive heat loss [74].

2.1.4. Sweep gas membrane distillation

Fig. 1(d) shows the sweep gas membrane distillation (SGMD) schematically, in which inert gas is used to sweep the vapor at permeate side. Hence, external condenser is required for this configuration. The disadvantage of this configuration is that a small volume of permeate diffuses in a large sweep gas volume, hence large size condenser is required. Due to this limitation, fewer studies are found in the literature [43,44,75].

2.2. Configurations of MD modules

The different module configurations are used in an experimental work for the MD applications. The selection and agreement of the membrane module in MD application are based on an economic kindness with the right engineering parameters being employed. Plate and frame, spiral wound, tubular, capillary, and hollow fiber membrane modules are commonly used by MD researchers. Table 1 summarizes the advantages and disadvantages of membrane module configurations toward the MD process. In all these modules, the hollow fiber offers high membrane area per unit volume which makes the flux density greater than other configurations. A hollow fiber membrane module is cost effective when compared with other modules. But, hollow fiber module is difficult to control the membrane fouling and hence requires proper pretreatment for the feed solution.

3. Transport phenomena in MD process

3.1. Mass transfer phenomena

The transport mechanism such as mass transport and heat transport are coupled in MD process. The accepted transport mechanisms for mass transfer are usually molecular diffusion, Knudsen diffusion, and

Table 1
Advantages and disadvantages of MD-module configurations

Membrane module	Membrane area/unit volume (m^2/m^3)	Advantages	Disadvantages	Refs.
Plate and frame	400–800	Membrane can be easily exchanged Good fouling control	Exchange of membrane in the module is labor intensive	[172,173]
Spiral wound	800–1,200	It has a good packing density It has an acceptable energy consumption	It is quite sensitive to fouling	[172]
Tubular	20–100	It offers high cross-flow velocities and large pressure-drop It has a low tendency to fouling and easy to clean	It has a high operating cost	[96]
Capillary	600–1,200	Production cost is very low Membrane fouling can effectively be controlled by proper feed flow	It requires low operating pressure (up to 4 bars)	[137]
Hollow fiber	2,000–5,000	It offers high membrane area It is a cost effective module when compared with other modules It can be operated at pressures in excess of 100 bars	It is difficult to control membrane fouling	[174]

viscous flow. These mass transfer mechanisms depend on the Knudsen number (k_n). It is defined as the ratio of mean free path (λ) of transport molecules to the membrane pore diameter (d_p).

$$k_n = \frac{\lambda}{d_p} \tag{1}$$

The mean free path, λ, can be calculated by the following expression as:

$$\lambda = \frac{3.2\mu_v}{p}\sqrt{\frac{RT}{2\pi M}} \tag{2}$$

where μ_v is the viscosity of vapors at atmospheric temperature and ambient pressure, M is the molecular weight, R is the gas constant, T is the temperature, and P is the mean pressure within the pores.

Molecular diffusion (If $k_n < 0.01$) has a partial pressure difference as driving force and forms the mass transfer resistance due to non-identical molecules that are in the way. The driving force for Knudsen diffusion (if $k_n > 10$) is also a partial pressure difference and the mass transfer resistance cause the molecules to bounce into the membrane matrix. The Knudsen diffusion is important for small pores or low pressure operation. The viscous flow (if $0.01 < k_n < 10$) has a total pressure difference as driving force, and the membrane matrix forms the resistance against it [28,31,72,76–79].

Mass transfer in DCMD process includes three steps: (i) hot feed vaporizes from the liquid/gas interface, (ii) the vapor is driven through the membrane pores due to the driving force from hot to cold side, and (iii) the vapor condenses into the cold side [80]. Hence, the major factors controlling the mass transfer are the vapor pressure difference and the permeability of the membrane [81]. In a VMD configuration, the molecular diffusion is not enough due to the vacuum at permeate side and hence low partial pressure of the air develops inside the pores. Thus, the Knudsen and viscous flow diffusion should be preferred. The larger the pore size of the membrane, the molecule–molecule collisions will control and viscous flow also occurs in the membrane [72,77–79]. In AGMD configuration, transport of vapors across the membrane was described by the theory of molecular diffusion and the air inside the pores of the membranes and in the air gap was a stagnant film. The molecular diffusion model has been applied successfully in AGMD [82]. The actual process of the mass and heat transfer in DCMD and AGMD is shown in Figs. 2 and 3, respectively.

The membrane permeate flux is dependent on the membrane characteristics and the established driving force. The flux for MD can be increased by increasing the pore size and porosity and by reducing the tortuosity and thickness of the membrane [83]. The MD flux (j) can be expressed as [5,84]:

$$j_i = B_i \Delta p_i \tag{3}$$

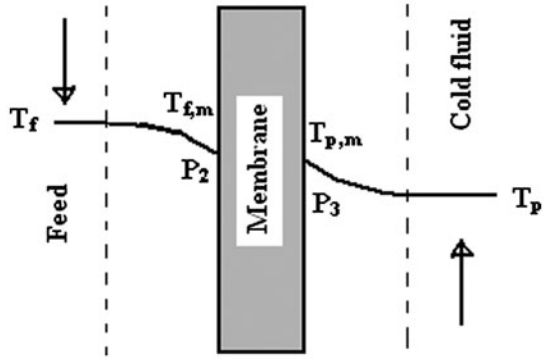

Fig. 2. Transport mechanism in DCMD.

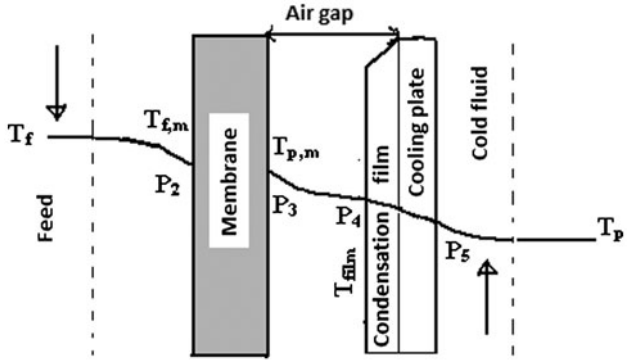

Fig. 3. Transport mechanism in AGMD.

where B is the membrane distillation coefficient of the membrane, Δp_i is the water vapor pressure difference between evaporating and condensing surface. The vapor pressure of the pure water component is determined by using the following Antoine equation.

$$p_i = \exp\left[23.1964 - \frac{3816.44}{T - 46.13}\right] \quad (4)$$

The equations used to determine the mass transfer coefficient in various configurations of MD are summarized in Table 2. The driving force, Δp, used for determining the flux is $p_2 - p_3$ in DCMD (see Fig. 2) and $p_2 - p_4$ in AGMD process (see Fig. 3).

3.2. Heat transfer phenomena

The heat transfer in the MD process occurs by two major steps: (i) the heat transfer from a feed (hot) to permeate (cold) side across the membrane as the latent heat and sensible heat, means the heat transfer by the conduction, and (ii) heat transfer by convection from the bulk flow of the feed to the boundary layer [28,31]. The resistance occurs in heat transfer process are described in Fig. 4. The heat transfer coefficient, thermal conductivity, and heat flow are important parameters in designing the MD module.

Table 2
The equations used to determine the mass transfer coefficient in different configuration of MD process

Configuration	Mechanism	Equation	Ref.
DCMD/SGMD /AGMD	Molecular diffusion	$B_i^D = \frac{M_w}{RT}\frac{\varepsilon}{\tau\delta}\frac{PD}{p_a}$	[77]
All	Knudsen diffusion	$B_i^k = \frac{2}{3}\frac{\varepsilon r^3}{\tau\delta}\left(\frac{8\pi}{RTM_w}\right)^{0.5}$	[175]
DCMD/SGMD	Knudsen and molecular diffusion (Transition region)	$B_i^c = \left[\frac{3\tau\delta}{2\varepsilon r^3}\left(\frac{RTM_w}{8\pi}\right)^{0.5} + \frac{\tau\delta p_a RT}{\varepsilon PDr^2}\right]^{-1}$	[175]
AGMD	Molecular diffusion	$B_i^T = \frac{DP}{RTbP_{lm}}$ (For membrane & air gap)	[176]
		$B_i^T = \frac{PM_w}{RTP_w}\left[\frac{D}{\frac{\delta}{\varepsilon^{3.6}} + b}\right]$ (For membrane & air gap below 5 mm)	[177]
VMD	Viscous flow	$B_i^v = \frac{\pi r^4}{8\mu_i}\frac{P_{avg}}{RT}\frac{1}{\tau\delta}$	[102]

Notes: ε, τ, r, δ, T, Pa, M_w, b, μ, P, D, P_w, and P_{avg} are the porosity, pore tortuosity, pore radius, membrane thickness, absolute temperature, air pressure within the membrane pore, molecular weight of water vapor, air gap thickness, viscosity, total pressure, diffusion coefficient, water vapor pressure, average pressure in pore, respectively.

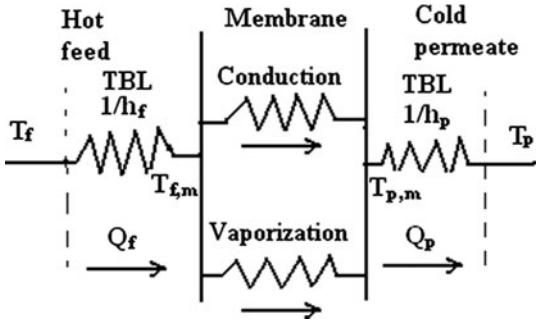

Fig. 4. Heat transfer resistances in MD process (TBL: thermal boundary layer).

Various models have been considered to calculate the thermal conductivity of MD membrane, k_m. The following general equation has been used.

$$k_m = \varepsilon k_g + (1-\varepsilon)k_p \tag{5}$$

where k_p is the thermal conductivity of the membrane matrix and k_g is the thermal conductivity of the gas. Phattaranawik et al. [85] found that the thermal conductivity of membrane distillation is,

$$k_m = \left(\frac{\varepsilon}{k_g} + \frac{1-\varepsilon}{k_p}\right)^{-1} \tag{6}$$

The thermal conductivity of various polymers such as polyvinylidenefluoride (PVDF) material (0.17–0.19 W/mK at 296 K), polypropylene (PP) (0.11–0.16 W/mK at 296 K), and polytetrafluoroethylene (PTFE) (0.25–0.27 W/mK at 296 K) were obtained. The thermal conductivity of water vapor is 0.02 W/mK at 298 K. The PTFE polymer is having more thermal conductivity while the PP polymer is low.

Table 3 summarizes the equations used to determine the heat flux in various configurations of MD process. The similar heat flux equations are used in DCMD and SGMD configuration. In AGMD, the sensible heat loss is less than that in DCMD due to the stagnant air gap introduced between the membrane and the cooling plate. But the additional mass transfer resistance is offered by this stagnant air film in AGMD [86,87]. In SGMD, sweep gas boosts the mass transfer which provides good resistance to heat transfer. But there is more energy consumption from blower and condenser [88,89]. In VMD, heat loss by conduction through the membrane is negligible due to the vacuum at permeate side. But the thermal energy cannot be recovered from the condenser hence it is not competitive with AGMD module.

The surface temperature on both sides of the membranes ($T_{f,m}$ and $T_{p,m}$) cannot be measured experimentally. Hence, the mathematical model has been designed to estimate these temperatures [31].

$$T_{f,m} = \frac{k_m/\delta\left[T_p + \frac{h_f}{h_p}T_f\right] + h_f T_f - j_i \Delta H_{v,i}}{\frac{k_m}{\delta} + h_f\left[1 + \frac{k_m}{\delta h_p}\right]} \tag{7}$$

$$T_{p,m} = \frac{k_m/\delta\left[T_f + \frac{h_p}{h_f}T_p\right] + h_p T_p + j_i \Delta H_{v,i}}{\frac{k_m}{\delta} + h_p\left[1 + \frac{k_m}{\delta h_f}\right]} \tag{8}$$

where δ is the membrane thickness, T_f and T_p are the bulk temperature of the feed and permeate,

Table 3
The equations used to determine the heat flux in different configuration of MD process

Configuration	Heat transfer region	Equation	Ref.
All	Thermal feed boundary layer	$Q_f = h_f(T_f - T_{fm})$	[101,178]
DCMD/AGMD/SGMD	Membrane	$Q_m = \frac{k_m}{\delta}(T_{f,m} - T_{p,m}) + j_i\Delta H_{v,i}$ or $Q_m = h_m(T_{f,m} - T_{p,m}) + j_i\Delta H_{v,i}$	[82]
DCMD/SGMD	Thermal permeate boundary layer	$Q_p = h_p(T_{p,m} - T_p)$	
AGMD	Air gap	$Q_g = \frac{k_g}{b}(T_{p,m} - T_{film}) + j_i\Delta H_{v,i}$	[62,179]
	Condensate film	$Q_d = h_d(T_{film} - T_5)$	

Notes: Q_f, Q_m, Q_p, Q_g, and Q_d are the heat fluxes of feed boundary layers, membrane, permeate boundary layer, air gap, and condensation film, respectively.

h_f, h_m, h_p, and h_d are the heat transfer coefficients of feed boundary layers, membrane material, permeate boundary layer, and condensation film, respectively.

k_m and k_g are the thermal conductivity of the membrane and gas, respectively.

T_f, $T_{f,m}$, $T_{p,m}$, T_p, T_{film}, and T_5 are the temperatures of bulk feed, membrane surface at feed side, membrane surface at permeate side, bulk permeate, condensation film surface, and cooling plate surface, respectively.

respectively, h_f and h_p are the heat transfer coefficient of feed and permeate thermal boundary layer, respectively, ΔH_v is the latent heat of vaporization.

In AGMD, the heat transfer coefficient for the condensate film (h_d) can be calculated by the following equation [63,90].

$$h_d = \frac{2}{3}\sqrt{2}\left(\frac{k_{film}^3 \rho^2 g \Delta H_v}{\mu b (T_{film} - T_5)}\right)^{1/4} \quad (9)$$

where k_{film} is the thermal conductivity of condensation film, ρ is the density, μ is the viscosity of water vapor, b is the thickness of air gap, T_{film} is the temperature at condensate film surface, T_5 is the temperature at cooling plate surface.

The equations used to estimate the boundary layer heat transfer coefficient i.e. h_f and h_p by some researchers in their study of MD process are reviewed in Table 4. The MD flux increases with the feed flow rate because of increased Reynold number (Re) and decreased boundary layer resistances. The boundary layer heat transfer coefficient increases due to the decline in the temperature polarization effect [30,72,78,79]. The temperature at the membrane surface is lesser than the corresponding value of the bulk phase. This creates temperature gradients in the liquid film adjoining the membrane. This phenomenon is called temperature polarization [5,91,92]. The concept of the temperature polarization factor would be used as a tool for evaluating the effect of the input parameters on maximizing the mass flux. For well designed MD modules, the temperature polarization coefficient is reached to unity and it is strongly dependant on membrane characteristics [28,30,72,78].

4. Operating parameters and performance of MD

The operating parameters such as temperature, flow rate, and concentration of the feed are affected in the performance of the MD. These effects in various MD configurations are shown in Tables 5–7. A huge difference in permeate flux by using different commercial membranes and operating conditions was found. Moreover, different values of the permeate flux were found in the same membranes working under the same operating conditions. This may depend on the membrane module to be used. Temperature is the main factor affecting on the permeate flux. Due to an increase in temperature, the vapor pressure of the feed solution increases and hence increases the driving force across the membrane surface. An increase in the temperature gradient between the membrane surfaces will affect the diffusion coefficient positively, which leads to increased vapor flux [93]. Similarly, there is a direct relation between diffusivity and temperature; hence, the mass transfer coefficient increases if the MD process is handled at high temperature [59]. In addition, temperature polarization decreases with increasing feed temperature [85]. The effect of the contribution of concentration polarization is very less in association with the temperature polarization effects. The water vapor flux is reduced by increasing the feed concentration because of a decrease in the water activity and the mass transfer coefficient of the boundary layer at the feed side [74]. The temperature polarization resistance, and heat and mass transfer boundary layer thickness decreases by increasing the feed flow rate. Hence, the flux is increasing with the feed flow rate.

Along with all above-cited operating parameters, the vacuum pressure at permeate side is the most

Table 4
The equations used to determine the boundary layer heat transfer coefficient in MD

Flow regime	Equation	Ref.
Turbulent	$Nu = 0.027Re^{\frac{4}{5}}pr^{n}\left(\frac{\mu}{\mu_w}\right)^{0.14}$ n = 0.4 for heating, n = 0.3 for cooling	[175]
	$Nu = 0.036Re^{0.8}pr^{0.33}\left(\frac{d}{L}\right)^{0.055}$	[180]
	$Nu = 0.023Re^{0.8}pr^{1/3}\left(\frac{\mu}{\mu_w}\right)^{0.14}$ ($2{,}500 < Re < 1.25 \times 10^5$)	[74]
Transitional	$Nu = 0.116\left(Re^{2/3} - 125\right)pr^{0.33}\left[1 + \left(\frac{d}{L}\right)^{2/3}\right]$	[72]
Laminar	$Nu = 1.86Re^{\frac{1}{3}}pr^{\frac{1}{3}}\left(\frac{d}{L}\right)^{\frac{1}{3}}\left(\frac{\mu}{\mu_w}\right)^{\frac{4}{7}}$	[181]
	$Nu = 1.62(RePr\frac{d}{L})^{1/3}$	[182]
	$Nu = 0.0298Re^{0.646}pr^{0.316}$ ($150 < Re < 3{,}500$)	[183]

Notes: Re: Reynolds number = $\rho\ v\ d/\mu$; Pr: Prandtl number = $C_p\ \mu/k$; Nu: Nusselt number = $h\ d/k$; ρ, v, d, μ, C_p, k, L, and μ_w are density, velocity, hydraulic diameter of channel, dynamic viscosity, specific heat, thermal conductivity, channel length, and viscosity at the channel wall, respectively.

Table 5
Review of operating conditions and flux obtained of NaCl solution in DCMD and SGMD studies

Configuration	Material	T_{bf} (ºC)	Q_f (L/h)	V_f (m/s)	C (g/L)	w_f	J (kg/m^2 h)	Ref.
DCMD	PTFE	41.6	NA	0.35	NA	0.003	16.2	[184]
		38	NA	0.55	4	NA	7.2	[29]
	PP	85	NA	0.35	1	NA	22.62	[10]
		47.4	2.8	NA	NA	0.01	0.122	[185]
		60	75	NA	35	NA	0.26	[8]
	PVDF	70	NA	3	NA	NA	61	[59]
		80	0.1	NA	NA	NA	27	[60]
		70	NA	3.7	35	NA	56	[31]
		70	NA	0.15	NA	0.246	29.16	[20]
		40	NA	0.7	NA	0.3	0.5	[50]
SGMD	PTFE	50	NA	0.15	45	NA	5.94	[76]
	PP	22	3	NA	NA	NA	0.005	[75]
		70	NA	0.8	NA	NA	18.72	[21]

Table 6
The effect of permeate pressure and other operating conditions on mass flux obtained in VMD for an aqueous NaCl solution

Material	T_{bf} (ºC)	Q_f (L/h)	V_f (m/s)	P_p (kPa)	C (g/L)	w_f	J (kg/m^2 h)	Ref.
PP	65	NA	0.6	4	NA	NA	27.72	[72]
	60	75	NA	8	35	NA	2.6	[8]
	55	75	NA	9.3	35	NA	5.4	[9]
	45	NA	0.02	2	NA	0.01	0.86	[185]
	55	NA	1.8	4	100	NA	13.4	[18]
	55	NA	1.8	4	300	NA	9.1	[18]
	55	NA	1.8	3	50	NA	16.96	[1]
	45	NA	0.9	3	100	NA	5.674	[1]
	35	3.6	NA	3	150	NA	5.57	[1]
PTFE	45	NA	2.65	NA	NA	0.01	52	[40]
	60	NA	0.38	3.2	NA	0.01	10.08	[70]
	60	54	NA	1.5	30	NA	14.62	[186]
	60	54	NA	3	30	NA	11.9	[186]
	77	60	NA	5.3	NA	0.01	78	[77]
PVDF	25	NA	NA	1	60	NA	0.504	[7]
	25	NA	NA	1	300	NA	0.324	[7]

important parameter in the VMD process. The effect of vacuum pressure on the permeate flux by using the commercial membranes in VMD are summarized in Table 6. The driving force also brings by varying the vacuum pressure at permeate side at a constant feed bulk temperature. Increase in vacuum to the downstream side of the membrane at a constant feed bulk temperature increases the vapor pressure of water, consequently, driving force. Hence, the mass transfer resistance decreases because the transport mechanisms for mass transfer across the membrane is usually based on the Knudsen diffusion, has a vapor pressure difference as a driving force. The boundary layer resistance on the permeate side can be neglected in VMD due to the vacuumed permeate. The presence of reasonable high vacuum at the permeate side of the membrane in VMD drastically reduces the extent of conductive heat loss from the hot brine. Potentially, VMD can achieve a very high water vapor flux. The vacuum pressure varies from 1 to 9.3 kPa and the maximum flux achieved to 27.72 kg/m^2 h in VMD configuration as shown in Table 6.

In the AGMD process, the air gap is an additional mass transfer resistance offered, hence an air gap effect is also an important parameter along with other operating parameters in this module. Table 7 summarizes the effect of an air gap on the permeate flux in AGMD configuration. The reduction in the air gap width will increase the temperature gradient within the gap, which leads to increased permeate

Table 7
The effect of an air gap and other operating conditions on mass flux obtained in AGMD for an aqueous NaCl solution

Material	T_{bf} (°C)	Q_f (L/h)	C (g/L)	w_f	b (mm)	J (kg/m^2 h)	Ref.
PTFE	60	NA	NA	0.038	0.3	19	[182]
	60	NA	NA	0.038	9	1.5	[187]
	60	55	30	NA	1.2	12.11	[187]
	60	55	30	NA	3.2	6.1	[187]
	75	0.06	NA	0.003	0.9	28	[62]
PVDF	90	0.08	NA	0.001	1.2	26	[64]
	60	NA	NA	NA	1.9	5	[176]
	60	NA	NA	NA	9.9	2.1	[176]

Notes: b is the thickness of air gap in AGMD process measured in mm.

flux. The most significant effect was found, when the gap is less than 1 mm [13].

5. Membrane material used in MD

5.1. Characteristics of the membrane of MD

The micro-porous hydrophobic types of the membranes are used in the MD process. These membranes should satisfy the following characteristics for good performance of the MD process.

(1) The membrane should be hydrophobic and porous.
(2) The membranes that have high hydrophobicity, small pore size, low surface energy, and high surface tension of the feed solution possesses a high liquid entry pressure (LEP) value.
(3) The membrane should not be wetted by process liquids.
(4) No capillary condensation should take place inside the pores of the membranes.
(5) The tortuosity factor should be small (it is inversely proportional to the permeability of the MD).
(6) The porosity of the membrane should be as high as possible.
(7) The thickness of the membrane should be as thin as possible. (Thickness of the membrane is inversely proportional to the rate of heat and mass transport; hence, it should have an optimized value.)
(8) The thermal conductivity of the membrane should be as low as possible.
(9) The membrane must not alter the vapor equilibrium of the components in the process liquid.
(10) The membrane should have good thermal stability.
(11) The membrane material should have excellent chemical resistance.
(12) The membrane should have long life with stable MD performance.

5.2. Commercial membranes used for MD

MD was known from the year 1960s. It was not commercialized at that time for desalination and water treatment purposes due to unavailability of the specific membrane and unfavorable economics when compared to RO process [94]. MD process goes up again from the year 1980s with the availability of the new membranes [23,94,95]. The commercial membranes for MD are made up of different polymers such as PP, PTFE, polyethylene (PE), and PVDF. All these micro-porous commercial membranes are available in tubular, capillary, or flat-sheet forms. All these are used in MD experiments on a lab scale [23,32,95]. The membranes used in various configurations of MD and their properties with literature references are listed in Table 8. The pore size of the membrane is used, in the range of 0.03–0.5 μm, membrane thickness is in the range 30–450 μm, and the porosity is 40–80%.

The PTFE is an ideal material for MD since it exhibits one of the highest hydrophobic characters. The PTFE polymer is having a good thermal stability and chemical resistance when compared with other polymers. The commercial PTFE membranes are usually produced through complicated extrusion, rolling, and stretching or sintering procedures. PP shows excellent solvent resistant properties and high crystallinity. PP membranes are generally manufactured by stretching and thermal phase inversion. PVDF membrane also exhibits good thermal and chemical resistance. PVDF membranes are usually prepared by the phase inversion method. In recent years, more

Table 8
Review on the commercial membranes used by some researchers for MD application

Configuration	Material	Trade name	Manufacturer	r (μm)	ε (%)	δ (μm)	Ref.
DCMD	PTFE	TF200	Gelman	0.2	80	178	[188]
		NA	Osmonic	0.45	70	175	[135]
		FGLP14250	Millipore	0.22	70	61	[100]
		FGLP1425	Millipore	0.25	70	NA	[28]
		TF200	Gelman	0.156	60	NA	[29]
	PP	Accurel PP	Membrane	0.22	73	NA	[56]
		Accurel PP	Membrane	0.2	NA	91	[57]
		NA	Osmonic	0.22	70	150	[135]
		Accurel PP	Membrane	0.2	75	450	[58]
	PVDF	GVHP	Millipore	0.11	75	125	[59]
		GVHP	Millipore	0.22	75	110	[58]
		GVHP22	Millipore	0.16	70	55	[29]
		NA	NA	0.2	75	60	[60]
AGMD	PTFE	Fluropore	Millipore	0.5	85	175	[61]
		NA	Millipore	1	85	150	[62]
	PP	NA	NA	0.45	50	96	[63]
	PVDF	NA	Millipore	0.45	75	110	[64]
VMD	PTFE	TF200	Gelman	0.2	60	60	[41]
		M05E0020	GVS	0.2	NA	218	[6]
		Fluropore	Millipore	0.22	NA	55	[6]
		Desal K150	Millipore	0.1	NA	34	[6]
	PP	MD020TP2N	Membrana	0.2	70	NA	[72]
		Accurel PP	Membrana	0.2	75	163	[39]
		Accurel PP	Membrana	0.2	75	163	[18]
		NA	NA	0.1	50	52.5	[100]
	PVDF	M09G0020	GVS	0.2	NA	199	[6]
		Durapore	Millipore	0.2	NA	125	[6]
		NA	NA	0.16	85	NA	[33]
		Pall-Microza	NA	0.2	NA	NA	[73]
SGMD	PTFE	TF200	Gelman Sci.	0.198	69±5	55±6	[135]
	PP	Liqui-cel	Celgard	0.04	40	40	[75]
		Liqui-cel	Celgard	0.03	40	30	[189]

Notes: r: Membrane pore radius in μm, ε: Membrane porosity in %, δ: Membrane thickness in μm.

attention has gone into preparing hydrophobic PVDF membranes mainly for MD process [24].

5.3. Surface modified and fabricated membranes for MD

The commercially available membranes does not meet all the characteristics of the MD membrane listed above, hence the design of the novel membranes fabricated mainly for MD purposes have been recommended by the various MD investigators [17]. Many studies have been performed on new applications of MD but from the commercial standpoint, MD has a little acceptance and yet to be fully implemented in industry. Hence, since 2004 too much work is found in the fabrication and modification of the membrane material specifically for MD applications. Some significant results have been achieved on the fabrication and modification of polymeric membranes for MD purposes [52,82]. The flux obtained in the various MD configurations by using flat-sheet and hollow fiber fabricated and modified membranes in the MD applications is reviewed in Tables 9 and 10, respectively, which shows more MD flux when compared with the commercial available membranes. The novel hydrophobic membranes for MD applications can be used by surface modification of hydrophilic membranes. The limited studies on the MD applications by using surface modifications of the membranes are found in the literature [96–99]. Different membrane preparation methods have been used by the researchers such as surface segregation [62,100], cross linking [64,101], co-extrusion [102], plasma polymerization [91], coating [4], grafting [63], phase inversion [103–105], and spinning technology [106,107].

Table 9
Review on the flat-sheet membrane surface modification and fabrication methods used and flux obtained for MD applications

Membrane material	Modifying material/fabricated method used	MD Configuration	Feed solution	J (kg/m^2 h)	Ref.
CN	Modified by plasma polymerization using VTMS/CF_4	DCMD	Aq. NaCl	29.98	[97]
CA	Modified by grafting using styrine–pyridine–CCl_4	DCMD	Aq. NaCl	1.37	[97]
Alumina anodisc	Modified by surface treatment using PFS	DCMD	Aq. NaCl	17.2	[98]
PVDF	PVA blended with PEG and crosslinked by aldehydes and sodium acetate	DCMD	Distilled water	24.2	[128]
			Aq. NaCl	23.51	
Nanospiked glass	Modified by different chemical etching	AGMD	Aq. NaCl	11.3	[99]
PEI	Fabricated using surface modifying macromolecules (SMMs)	DCMD	Aq. NaCl	12.6	[123]
PEI				20.88	[190]
PEI				14.04	[112]
PS				8.28	[113]
PES				9.36	[114]
CNT BP	Chemical vapor deposition by using vacuum filtration	DCMD	Aq. NaCl	11.98	[117]
PVDF–TFE	Copolymer fabricated by phase inversion and casting with LiCl solution	DCMD	Aq. NaCl	3.5	[108]
PVDF–TFE	Copolymer fabricated by phase inversion and additive using trimethyl phosphate	DCMD	Aq. NaCl	7.31	[191]
PVDF–Nanofiber	Fabricated by electro-spinning method	AGMD	Aq. NaCl	11.59	[116]
PVDF unsupported	PVDF membrane casting with solvent DMF or DMAC and the additive LiCl	DCMD	Aq. NaCl	9.72	[192]
		VMD	Chloroform/water	16.06	[193]
PVDF-Supported	PVDF membrane casting with solvent DMAC and supported by non-woven polyester backing material	VMD	Chloroform/water	14.08	[193]

Notes: CN: cellulose nitrate; CA: cellulose acetate; VTMS: vinyltrimethylsilicon; CF4: carbon tetrafluoride; CCl4: carbon tetrachloride; PFS: perfluorodecyltriethoxysilane; PVA: polyvinyl alcohol; PEG: polyethelene glycol; PEI: polyetherimidie; PS: polysulfone; PES: polyethersulfone; CNT BP: carbon nanotube Bucky-paper; LiCl: lithium chloride; TFE: tetrafluoroethylene; DMF: dimethyl formamide; DMAC: dimethyl acetamide.

Table 10
Review on the hollow fiber membrane surface modification and fabrication methods used and flux obtained for MD applications

Membrane material	Modifying material/fabricated method used	MD Configuration	Feed solution	J (kg/m^2 h)	Ref.
PVDF	Fabricated by dry/jet wet phase inversion	DCMD	Aq. NaCl	41.5	[103]
PVDF MM		DCMD	Aq. NaCl	79.2	[122]
PVDF (M2)		VMD	TCA	0.51	[104]
PVDF (M3)		VMD	TCA	0.5	[104]
PVDF	Fabricated by wet phase inversion	VMD	TCA	0.273	[105]
PVDF (M4)	Fabricated by phase inversion	DCMD	Aq. NaCl	40.5	[194]
PVDF dual layer	Fabricated by co-extrusion dry/jet wet spinning	DCMD	Aq. NaCl	55.08	[195]
PVDF/PTFE	Fabricated by dry/jet wet phase inversion	DCMD	Aq. NaCl	40.39	[196]
PP	Fabricated by melt extruded/cold-stretched	DCMD	Aq. NaCl	0.324	[8]
		VMD		2.99	
PE	Fabricated by melt extruded/cold-stretched	DCMD	Aq. NaCl	0.86	[8]
		VMD		3.99	
Ceramic Al_2O_3	Modified by grafting using PFS	DCMD	Aq. NaCl	5.853	[197]
Ceramic ZrO_2		DCMD		8.427	[197]
TiO_2		VMD		6.084	[96]
TiO_2		VMD		0.832	[96]
ZrO_2		VMD		7.488	[96]
ZrO_2		AGMD		4.708	[96]
PP	Coating by plasma polymerization using silicone fluoropolymer	DCMD	Aq. NaCl	78.984	[100]
		VMD		68.98	[100]
PVDF	Fabricated by dry/jet wet spinning	DCMD	Ethanol/water	3.153	[106]
PVDF–HFP	Fabricated by dry/wet spinning	DCMD	Distilled water	1.296	[109]

Notes: MM: mixed matrix; Al_2O_3: alumina; ZrO_2: zirconia; TiO_2: titania; HFP: hexafluoropropylene.

The most of the publications on the fabrication of membranes for MD applications are found from the year 2009 to 2013. Some of the researchers designed new techniques for the generation of MD membranes using different types of SMMs, other polymers, solvents, additives for growth in the MD performance. Some of these are co-polymers like polyvinylidenefluoride–hexafluoropropylene (PVDF–HFP) and polyvinylidenefluoride–tetrafluoroethylene (PVDF–TFE) [107–111], the fabricated Polyethersulfone (PES) and Polysulfone (PS) [112–115], new hydrophobic poly (phthalazinone ether sulfone ketone) hollow fiber composite membranes coated with silicon rubber and with sol–gel polytrifluoropropylsiloxane [4], nanofiber membranes [116], carbon nanotube bucky-paper membranes [117–119], carbon nanotube (CNT)-based composite materials [120], oxidized (using HNO_3 and H_2SO_4) carbon nanotube [121], and mixed matrix PVDF [122].

The hydrophobic/hydrophilic composite type of the membrane concept was invented for the MD application by Khayet et al. [123–125] where hydrophobic surface modifying macromolecules (SMM41) was synthesized and blended with the hydrophilic polymer (PEI). A new porous composite hydrophobic/hydrophilic flat-sheet membrane was prepared and projected by Khayet et al. [126,127]. The advantages of these composite membranes are high mass transport facilitated by thin hydrophobic layer, while low heat transfer by a thick overall membrane thickness. The hydrophobic layer prevents water penetration into its pores. The heat conductance of the composite membrane can be reduced and the temperature polarization effect will be decreased with the use of a relatively thick hydrophilic sub layer [114]. Some composite membrane fabrication studies are found in the literature which shows the good performance in the MD applications [96,128–130].

Despite all the cited research in the field of MD membrane engineering, comprehensive studies regarding the design of membranes and proper exploration of the effects of membrane parameters are still deficient. More efforts must be done on the fabrication of the membranes appropriate for MD configurations and application with wonderful performances in order to achieve a fully commercial status. More studies are originated on the membrane surface modification from the cited literature, but currently, it is not likely to obtain membranes that are fitting for long-term industrial application of surface modification. The composite membrane shows better results in MD application on the laboratory scale from cited studies. However, only few studies were found on the industrial feasibility and long-term performance of MD by using fabricated membranes in order to look for MD industrialization. More efforts must be done to explore the cost-effective dual layer membrane in order to develop the membrane suitable for long-term industrial MD application.

5.4. Fouling of membranes

Membrane fouling is a major issue in water treatment and desalination with the MD process particularly when high concentrations of natural organic and inorganic constituents occur in the water. Disadvantages of the fouling of the membrane are as follows: (i) fouling reduces the membrane area for water vaporization due to the membrane pore clogging, (ii) it reduces the flow channel area which causes a pressure drop and lower flow rates of feed, (iii) higher temperature polarization and lower flux, (iv) it may cause membrane partially wetting or severe membrane damage and shortens membrane life, (v) it increases the costs by increasing an energy consumption, system down time, membrane area and construction, labor, time, and material costs for backwashing and cleaning processes [20,34,45,95,131,132]. Hence, the overall efficiency of the MD process decreases due to the fouling of the membrane. Hence, it is needed to understand the fouling phenomena in the MD process. Very few studies are found on the membrane fouling in MD [6,32,34,95,133]. Most of the fouling studies so far examined in seawater desalination or waste water treatment application [20,34,59,95].

Theoretically, MD performance is not so sensitive to high concentration of feed. But, the presence of these sparingly soluble salts may direct to membrane fouling at a reasonable concentration [6,95]. Fouling is a little problem in the MD process when compared with RO or UF processes, because MD is operating at vapor pressure of water and also the MD membrane have larger pore size when compared with other RO/UF [13].

Some researchers tried to control the membrane fouling by the pre-treatment of feed and membrane cleaning along with the use of the suitable MD process conditions [32,34]. But any advanced pre-treatment system appreciably increases the installation costs of the process. So, the development of a simple and inexpensive method for controlling the membrane fouling is necessary in order to realize the MD on a commercial scale.

6. Economic in MD

Economics in the MD process for desalination and water purification is based on technical factors such as energy source, plant capacity, salinity, and design features [134]. Among these factors, energy requirement for the process has an important effect on the overall process economics. Thermal and electrical energy is required for the MD process and on the other hand the RO requires only electrical energy. Hence, the consumption of high thermal energy in the MD process is a barrier for the commercialization in the industry. Most of the researchers [101,134–136] reported that RO is the least expensive process and hence it is favored in the industry economically.

The MD effectively operates at low temperature and this is the thermal-driven process which can utilize a waste heat or solar energy more conveniently. So, the MD process can compete with the RO plant. The MD is an economical technology in terms of energy; since the heat source for the process is solar energy and also the energy is recovered continuously [137,138]. Kesieme et al. [139] found that MD opportunities arise when heat is available at low cost. If waste heat is used for the process, then the cost of MD plant for desalination (30,000 m^3/d capacity plant) is reduced from 2.2 to 0.66 $\$/m^3$ water produced. It is an economical technology when compared to the cost of RO plant is 0.8 $\$/m^3$ water produced. Al-Obaidani et al. [136] found that the estimated water cost of MD plant by using a heat recovery system is 1.17 $\$/m^3$ and it is reduced to 0.64 $\$/m^3$ if MD plant is operated with lower grade waste heat. So, the cost of MD plant can be minimized by using lower grade waste heat and installation of proper heat recovery system. Hence, the economic modernization of the traditional MD process is needed for the commercialization of the MD process in industry.

7. MD systems driven by renewable energy sources

MD is a thermal membrane technology, which requires both heat and electricity. Higher consumption of the thermal energy is a major issue for an implementation of the MD process in the industry. In comparison, the energy required in the RO process was found to be more than the MD process like DCMD and VMD [57,73,140]. The cost of performance of the MD process can be evaluated on the basis of heat recovery [136]. Only few studies are found in the literature on energy calculations of the lab scale MD processes until now [5,66,73,100,141,142]. MD process is operating effectively at low temperature and vapor pressure difference across the membrane. So, it is possible to utilize a lower grade waste heat which is generally available in the industry [54,57,141,143]. The MD process has an advantage that permits coupling with waste heat or renewable energy systems like geothermal or solar energy [144,145].

The major components such as solar collector, heat exchanger, heat storage tank, and MD module are required for solar-driven MD system [146]. Some of the studies on solar MD are found based on lab- and pilot-scale [146–156]. But few of them are compared with known and well-liked solar-driven RO process. The limitation of the solar MD system is the high initial installation cost, but once installed and in operation, the cost of operation, and the energy is lower [149]. The MD configuration will be an impact on the water cost of the solar panel MD system [151]. The difficulty found in the solar MD process is reaching the steady-state operation due to the irregular nature of the solar radiation [148,157]. Some researchers proposed the MD process by using geothermal energy for desalination processes [158,159]. In this, only energy is required for the pumping process.

Some of the pilot plant studies of MD process for water treatment purpose are found in the literature. Gryta [34] presented the practical approach in the MD pilot plant for the treatment of saline effluents generated during the regeneration of ion exchangers. The pilot plant was constructed using a typical heat exchanger made of stainless steel; though, the employed construction material was found to undergo the corrosion in studying solutions. Kullab and Martin [45] obtained the performance of MD-based water treatment regarding removal of heavy metals. He encompasses field trials which contains the details of a test rig installed at an Idbacken cogeneration facility with a five module MD unit and obtained 1–2 m^3/d production capacity of purified water. Full scale simulation was performed, based on the experimental results, assuming 10 m^3/h production capacities. MD facility was connected to the district heating line for heating and municipal water for cooling. Banat and Jwaied [155] presented the results obtained from the solar-driven MD pilot plant unit over one year of continuous operation. This plant was installed by Fraunhofer Institute for Solar Energy Systems in the Aqaba city by Jorden. The membranes are made of PTFE material and flow channels were made in the membrane spiral wound geometry with 10 m^2 effective membrane area in each module. Maximum 800 L/d of high quality permeate were reached in good weather summer days by using untreated seawater. Scaling was a problem that deteriorated the membrane performance. Solar-driven pilot plants are found in five different countries such as Egypt, Jorden, Germany, Italy, and Grand Canaria [152,155,160–162]. Keith et al. [163] operated a solar thermal MD pilot plant for over 70 d. They were using a single spiral wound permeate gap MD style of the module. This pilot plant was capable to produce 75 L/d of pure water in a full sunny day in April 2013. This system is likely to find application in remote and arid regions to produce drinking water without using electrical energy.

8. Modernization in MD processes

MD is a heat sensitive process and hence the proper design of the heat recovery facilities is the great practical values in the energy saving [164]. But heat recovery systems are very expensive and it increases the cost of the process. For low energy consumption and better performance of the MD process it need to optimize the membrane properties along with the module configuration design in order to reduce the temperature polarization phenomena. Hence, the challenge is there in front of the researchers about the design of energy efficient MD modules for the realization of the industry. Limited studies were found in the literature on design of new energy efficient MD modules, particularly in the MD applications. These studies are explained in this section.

8.1. Fraunhofer ISE AGMD process

Presently, the solar spring uses AGMD technology in a spiral wound module with counter current heat exchanger. Solar spring produces all MD modules in collaboration with the Fraunhofer Institute for Solar Energy Systems, ISE, Freiburg (Germany). The dimensions of equipped solar spiral wound AGMD modules are, channel length: 5–10 m; module height: 0.9 m; module diameter: 300–450 mm; membrane area: 5–14 m^2; and the detailed design is shown in Fig. 5.

The variation of the parameters is for adapting the modules for specific needs. This module is reducing the thermal energy requirement by the recycling of internal energy and hence minimizes the loss of latent heat. The thermal energy requirement can be as low as 130 kWh/m^3. The suitable applications of these modules in MD system is in the remote and rural communities for a sufficient water supply [68].

8.2. Memstill process

The disadvantages of MD processes such as high heat consumption, heat loss, low flux, expensive membranes, susceptibility to pore wetting, and fouling are solved by the Memstill technology [165]. The process is driven by minor temperature differences, thus a small energy is essential and which is easily available in the industrial countries [165–167]. The principle and concept of the Memstill technology based on AGMD configuration is described in Fig. 6 [website: http://www.pub.gov.sg/research/Key_Projects/Pages/Membrane3.aspx]. The important advantages of the Memstill process are low energy consumption, simple construction, lesser total cost, high salt separation factors, lesser corrosion, easy maintenance, and minimal site work based on prefabricated module [166].

The first pilot plant of the Memstill technology was tested in Singapore on bench scale on Senoko Refuse Incineration Plant from February 2006 to June 2007. In which M26 type of Memstill module was used for seawater purification. A second trial was done in Netherland for brackish water and found the best results when compared to first pilot plant due to the improved material and configurations. A more recent third pilot with further improvements is being tested out in AVR, Netherland. This trail was conducted on brackish water from the harbor Rotterdam and weakens due to lack of monitoring and incorrect pre-treatment [168]. Currently, the conventional desalination technology in Europe RO has been compared to the newly developed membrane-based technology, i.e. Memstill by means of life cycle assessment. The thermal energy required is as low as 56–100 kWh/m^3 waters produced [65]. Hence, the Memstill technology can produce (drinking) water at a lower cost compared with existing technologies like RO and distillation process.

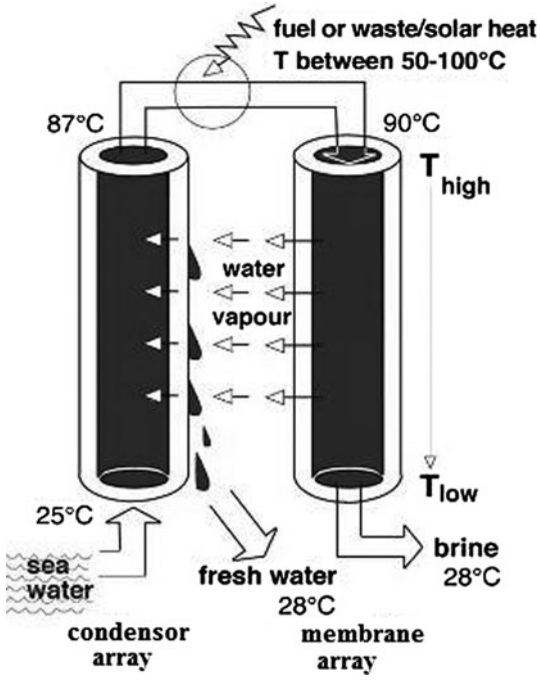

Fig. 6. Memstill process based on AGMD [Adopted from Memstill Project website].

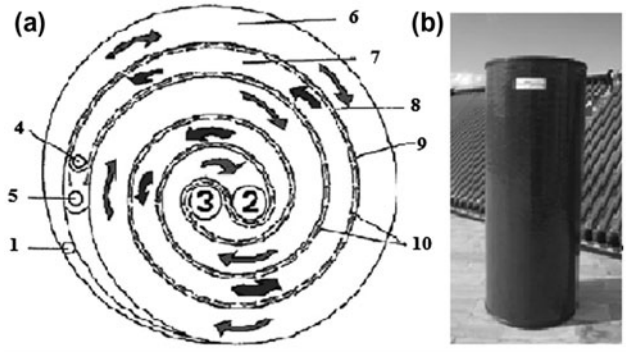

Fig. 5. (**a**) Section of Fraunhofer ISE's spiral wound AGMD module: (1) condenser inlet, (2) condenser outlet, (3) evaporator inlet, (4) evaporator outlet, (5) distillate outlet, (6) condenser channel, (7) evaporator channel, (8) condenser foil, (9) distillate channel, and (10) hydrophobic membrane; (**b**) picture of the modules [68].

8.3. Aquastill process

The Aquastill process uses in essence waste heat and a water source. This technology uses hydrophobic membranes to separate pure distillate from warm water. The Aquastill modules houses a continuum of evaporation stages in an almost ideal countercurrent flow process, a very high recovery of evaporation heat is possible. This process works at low pressures (up to 1, 0 bar). Aquastill developed the MD modules based on DCMD and AGMD as shown in Fig. 7. These are in spiral wound configuration. The Memstill technology has been licensed to Aquastill [Aquastill website: http://www.aquastill.nl/Process.html].

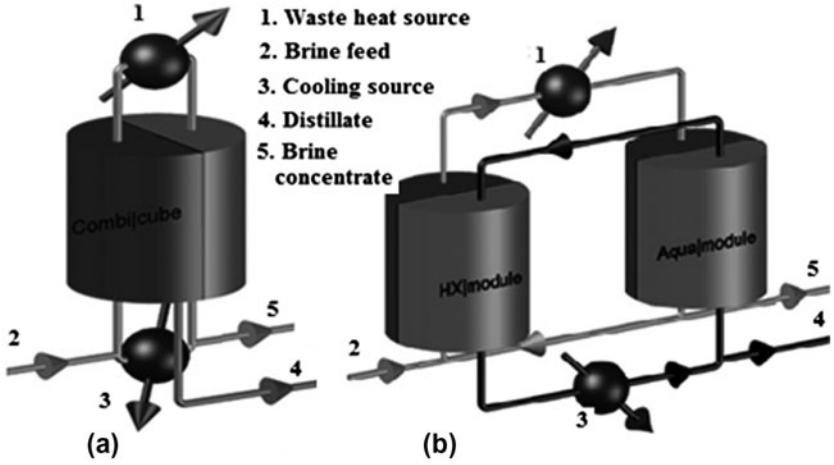

Fig. 7. Aquastill process configuration based on (a) AGMD and (b) DCMD [Aquastill website].

8.4. Memsys (multi-effect membrane distillation) MEMD process

Since last two years i.e. 2011, the MEMD process has been raising and very few studies are found in the MEMD process. MEMD process uses the multi-effect operations like used in conventional processes such as multi-stage flash and multi-effect distillation (MED). The heat recovery from the MD process is the characteristic of multi-effect operation. The key to the MEMD process is the use of superior multi-effect process which reduces the feed volume for energy supply significantly. By which the mechanical stress is reduced to the membrane and increases the membrane life. Hence, the MEMD is a growing and interesting technology in the purification application. In a working memsys module, each stage recovers the heat from the previous stage. The distillate is produced in each stage and in the condenser. The basic principle of the memsys MEMD process is described in Fig. 8 and the structure of single stage with alternating membrane frames and foil frames for evaporation and condensation is shown in Fig. 9 [169].

The memsys has successfully commercialized the V-MEMD module. This V-MEMD technology combines the advantages of multi-effects and vacuum to achieve highly efficient heat recovery when compared with conventional MD processes. The solar and diesel heater was used as heating sources to drive the memsys V-MEMD module [169]. The V-MEMD process set up a special multi-effect evaporation zone for the first time where heat exchange and MD happened at the same time. The flux of the system can reach the maximum value (34.8 kg/m^2 h) and the additional cooling water consumption is only 30.8% of traditional VMD

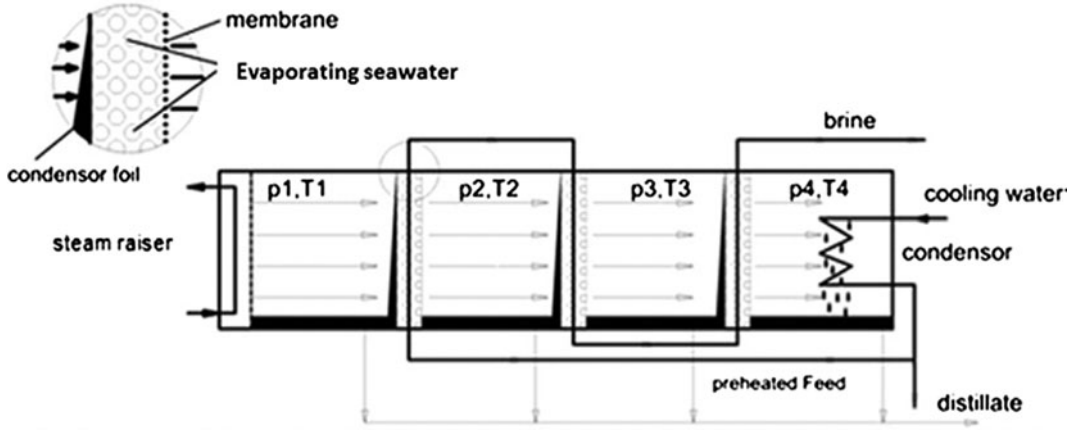

Fig. 8. Basic principle of memsys process [169].

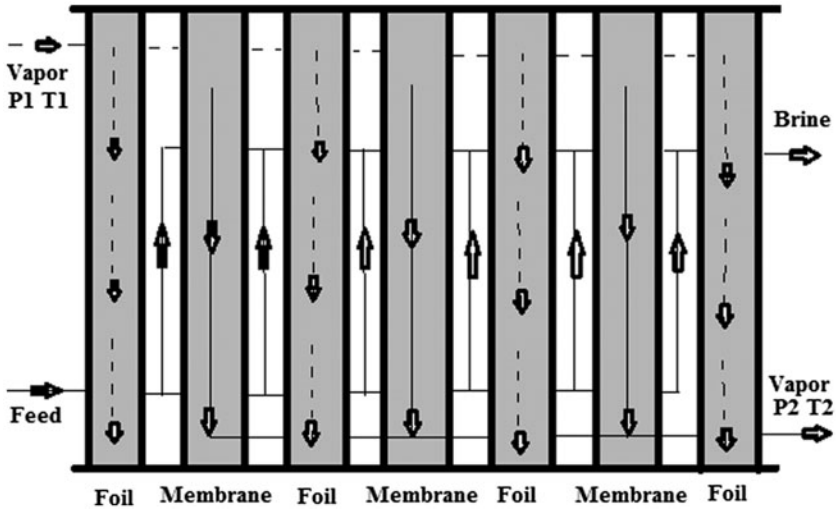

Fig. 9. Feed, brine, and vapor flows in the single stage of MEMD module [169].

process [25]. Liu et al. [170] used a hollow fiber-based AGMD module in an MEMD process for concentrating aqueous hydrochloric acid. The performances of the MEMD module were found stable during the operational stability test that lasted for 30 d. Heinzl et al. [171] designed a new plate and frame type of module for V-MEMD. Memsys in Germany made-up a new MD device based on multi-effect desalination process under vacuum. V-MEMD combines the advantages of the MD and MED. A memsys module has the dimensions: $330 \times 700 \times 480$ mm. The setup contains surfaces of membranes of 3.5 m^2 each for condensation and distillation. Due to the industrial scale production of the memsys modules a very high and applicable quality can be assured. The field demonstration unit is under construction. The sample setup supports the theoretical prospect.

9. Conclusions

The fields of MD have been rapidly growing over the past 50 years and it has a promising alternative to replace other membrane separation processes. This review deals with the status and potential of MD process in desalination, wastewater treatment, and food industry. This is summarized for the MD process where fundamental aspects of MD, configuration of MD and module, heat and mass transfer phenomena, effects of operating parameters on the performance of MD process, characteristics of membranes, commercial membranes, surface modified and fabricated membranes used in MD along with the fouling of the membrane were discussed. The economics in MD along with the process driven by the renewable energy sources were presented. MD process is competing with RO when the MD operates on the low-grade energy sources with proper heat recovery system. Hence, the modernizations of the MD are required and were discussing various recent MD processes. The step up of the research in the MD process for various purification applications were found as follows:

(1) MD was known from the year 1960s. It was not commercialized at that time for desalination and water treatment purposes due to unavailability of the specific membrane and unfavorable economics when compared to RO process.
(2) MD process rose again from the year 1980s with the availability of the new membranes and novel MD modules. The modules designed by many researchers were based on the improved understanding of the mass and heat transfer phenomena of the MD process. But it did not find any commercial MD module at that time due to the limitation of the MD flux and energy efficiency.
(3) Since 2004, many studies are found in the fabrication and modification of the membrane material specifically for MD process and found more MD flux when compared with the commercial available membranes. Also, the MD process has emerged with numerous commercially oriented devices and novel process integrations. Some pilot plants like Memstill and Aquastill energy efficient modules based on MD process was found by using the

waste heat/solar energy. But still found the consumption of high thermal energy and excessive cooling water consumption are the major issues and which are the biggest barriers for MD industrialization.

(4) From last two years i.e. 2011, the research again improved in the MD process with inventive MD module such as MEMD system in the application of MD process. Memsys successfully implemented the first commercial V-MEMD module for the industrial purposes.

Hence, the researchers are again engaged in the development of MEMD process for various applications and suitable implementations with reducing thermal as well as electrical energy. Also, the long-term performance of MEMD process needs to study along with the newly and improved characteristics of the membrane on the large-scale industrial implementation.

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