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Temperature and concentration polarization in membrane distillation: a technical review

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ABSTRACT

Recently, the seawater and brackish water desalination process have gained widespread attention due to the scarcity of drinking water. Among several membrane distillation (MD) methods for desalination, vacuum membrane distillation (VMD), and direct contact membrane distillation (DCMD) are mostly focused techniques. However, there are several technical issues associated with these techniques that have a negative impact on their performance. The most influential of them are temperature polarization (TP) and concentration polarization (CP) that reduces the permeate flux significantly. A state-of-the-art review is presented to gain a clear understanding of, the impact of both the TP and CP on various performance parameters and methods to overcome these obstacles. The main focus is on the causes of TP and CP, theoretical models, experimental key findings for TP and CP, and their impact on the performance of VMD and DCMD. For DCMD, the value of TPC for channels with spacers falls in the range of 0.9–0.97, whereas for flow channels without spacers, the TPC was in the range of 0.57–0.76. Finally, different methods are discussed to overcome the TP and CP.

Keywords: Concentration polarization; Direct contact membrane distillation; Temperature polarization; Vacuum membrane distillation.

1. Introduction

Water is a rich natural resource that occupies 70% of the total earth's surface [1]. Almost 97% of the total earth's water is seawater which is not drinkable [2]. As a result, the scarcity of freshwater is increasing with the passage of time. A satisfactory quantity of freshwater is not available to around 25% of the world's population and the next 10 y of forecasting indicate that around 70% of the total global population can face water scarcity [3–5]. One of the solutions to deal with the scarcity of potable water is to adopt a desalination process for brackish and seawater. Both Isothermal and non-isothermal processes are being adopted for seawater desalination. Isothermal desalination process such as reverse osmosis (RO) [6], in which the osmotic pressure is subdued by using an applied pressure and the chemical potential differences of the solvent is the driving force for RO. MD has emerged as an alternative and attractive technique to previously adopted processes such as multi-effect distillation, multi-stage flash distillation, and RO [7]. MD is a purification technique that employs a porous hydrophobic membrane for permeate flux. The membrane separates the permeate side solution and feeds side solution that are at two different temperatures.

MD is commonly used for clean water production and also for the concentration of solutions [8–10]. The force responsible for vapors transport through the membrane is created by the vapor pressure difference between the permeate side and feed side solutions. Subject to the MD process arrangement, five different modules of MD exists,

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such as air gap membrane distillation (AGMD), water gap membrane distillation (WGMD), direct contact membrane distillation (DCMD), sweeping gas membrane distillation (SGMD), and vacuum membrane distillation (VMD). The fundamental configurations are shown in Figs. 1a–d. In DCMD [11–14], the membrane permeates side and the permeate solution are in direct contact with each other whereas the temperature difference across the membrane induces a vapor pressure difference. Some of the molecules evaporate at the membrane interface on the feed side and cross the membrane where they are condensed. Direct contact membrane distillation is best suited for the desalination of aqueous solutions [15]. In AGMD [16–18], only the feed solution and membrane are in contact whereas the stagnant air is in between the condensation surface and the membrane. In AGMD, the vapors have to cross both the membrane structure and stagnant air in order to condense at the cold side. AGMD is best suited for the separation of volatile compounds from aqueous solutions [19,20]. In SGMD, an inert gas sweeps the volatile molecules at the cold side and condenses them outside the membrane unit [21,22]. Recently, WGMD is introduced, in which a gap is filled with permeate flux to reduce the mass transfer resistance [23,24].

In VMD, vacuum pressure is created at the permeate side and because of this vacuum pressure, a pressure difference is generated across the membrane. In this configuration, condensation of vapors takes place outside of the membrane module. VMD is mostly suitable for removing volatile components from an aqueous solution [25,26]. VMD can provide a higher permeation flux because of the greatest driving force and better thermal efficiency and is widely used for various MD applications [27–34]. VMD can be easily integrated with solar energy to utilize a renewable source of energy [35].

Despite of numerous potential features of MD, however, it also faces some obstacles such as membrane wetting, membrane fouling, loss of heat through the membrane, air trapping in membrane pores, TP, and CP [36]. The TP and CP are the two main complications associated with MD that notably influence the performance of MD. However, the discussion related to TP and CP is limited in the literature. In this paper, temperature and concentration polarization in VMD and DCMD are thoroughly discussed in terms of theoretical models, the effect of operating parameters on TP and CP, impact on the system performance, and the potential methods to overcome the temperature and concentration polarization.

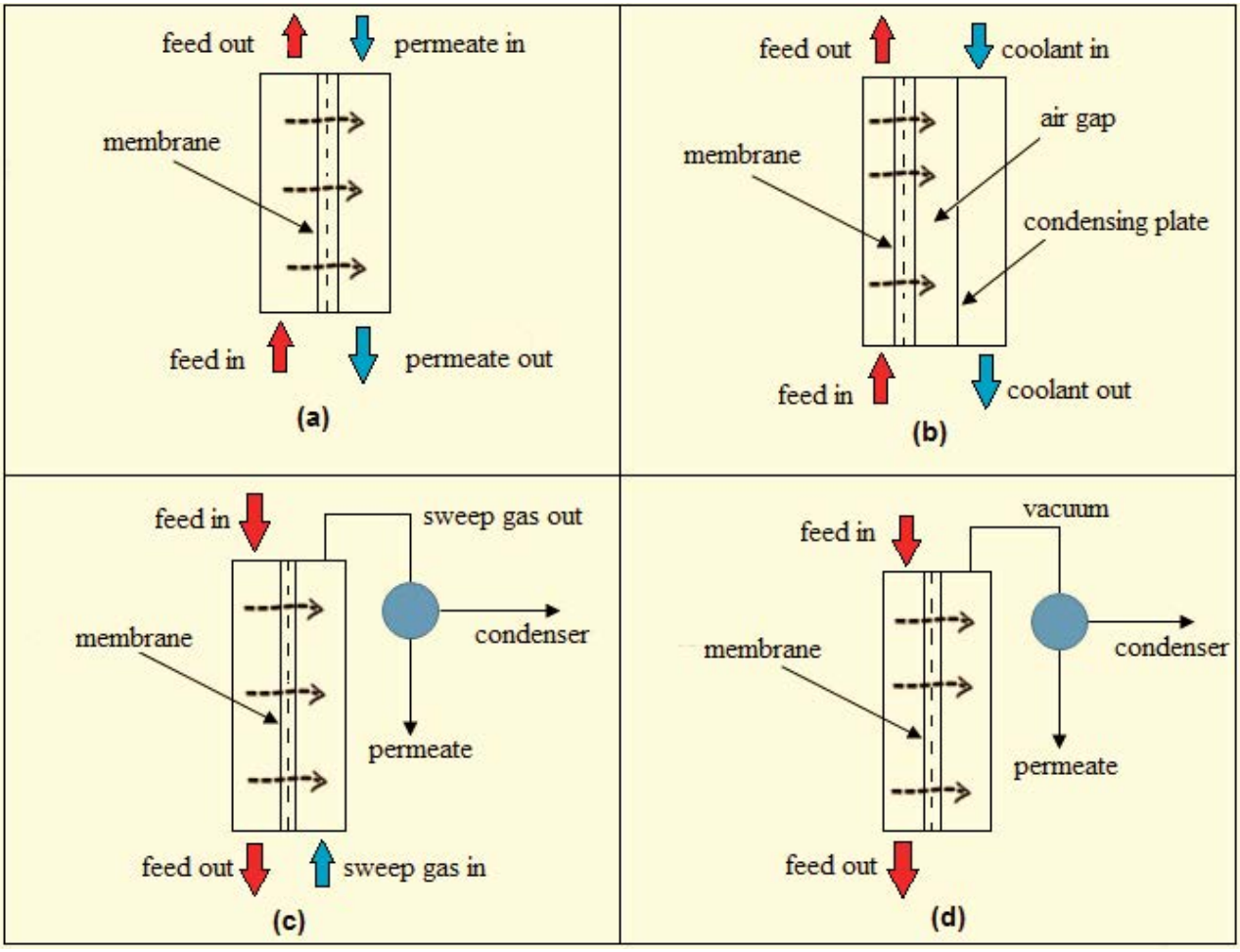

Fig. 1. Vapor transport mechanism in four fundamental modules of MD: (a) DCMD, (b) AGMD, (c) SGMD, and (d) VMD.

1.1. Novelty

Various aspects of MD and polarization phenomenon in MD are discussed in the open literature. For example, Lawson and Lloyd [37] provided a brief description of fundamental concepts related to MD as well as developments in MD. They discussed the transport phenomenon and module design in detail. Likewise, Khayet [38] presented a review paper on membrane distillation in which MD performance, Transport mechanism, modeling of different membrane distillation configurations, and recent improvements in MD are discussed. Alkhudhiri et al. [39] briefly explained heat and mass transfer models related to MD, fouling of membrane, and also the effects of operational parameters on the performance of MD.

By exploring the previously reported prominent articles on polarization phenomenon, Martínez-Díez and Gonzalez [40] studied the effects of TP and CP on the reduction of vapor pressure differences across the membrane. Likewise, Alsaadi et al. [41] studied the TP effect in VMD by carrying out both experimental and theoretical analysis. A mathematical model for measuring VMD flux and a graphical method was used to evaluate the extent of the TP effect on permeate flux. Recently, Alsaadi et al. [42] proposed a flashed-feed VMD configuration to eliminate the TP effect. Out of a very large number of publications on MD and polarization phenomenon in MD, no attempt can be found in the literature to present a comprehensive review on temperature and concentration polarization in MD. Consequently, it is considered necessary to provide an updated review on temperature and concentration polarization.

In this updated review, we have presented an overview of TP and CP and theoretical models that deals with TP and CP. Moreover, the impact on the permeate flux and MD performance is also discussed. Furthermore, the impact of influential operating parameters on the TP and CP is also discussed. Lastly, we proposed future prospects of improvement in MD performance with relevance to temperature and concentration polarization.

2. Temperature polarization

2.1. Introduction

A primary reason for flux declination during the MD operation is the temperature polarization near the membrane surface [43]. The simplest configuration of the MD process in DCMD is shown in Fig. 2. As shown, the bulk temperature of the feed side T_{fb} drops to T_{fm} at the membrane surface on the feed side. Some water at the hot (feed) side evaporates and is move through the membrane pores toward the cold (permeate) side. The water vapors also carries heat at the same time which is transferred to the permeate side. The permeate side bulk temperature T_{pb} increases to T_{pm} at the membrane surface as the permeate side obtains heat from the feed side through the membrane. The vapor transport mechanism involves vapor pressure difference between the feed side membrane at surface temperature (T_{fm}) and the permeate side membrane at surface temperature (T_{pm}), which is less than the difference in vapor pressure between the feed side at bulk temperature (T_{fb}) and the permeate side at bulk temperature (T_{pb}). So the driving force for vapors transport should be less in this case. This phenomenon is called TP [44–47].

TP is associated with latent heat release during the water evaporation, result in the decrease of the feed temperature in the vicinity of the membrane surface. The TP effect is only present in non-isothermal processes and it stimulates a reduction in the driving force required for the water vapors to move through the membrane.

2.2. Theoretical models of temperature polarization

The TP effect can be expressed mathematically in terms of a factor known as temperature polarization coefficient (TPC) [48]. In the case of DCMD, the TPC can be defined as the ratio of temperature difference at both sides of the membrane interface to the bulk temperature difference between the feed and permeate side. Lawson et al. [37] presented the following mathematical relation for TPC based on DCMD:

$$\mathrm{TPC} = \frac{T_{fm} - T_{pm}}{T_{fb} - T_{pb}} \tag{1}$$

For efficiently designed DCMD systems, the value of TPC should approach to unity and the system will only be limited by the amount of vapor transported. Whereas, for inefficient designed systems, TPC approaches to zero and the system will be heat transfer limited. Schofield et al. [49] also presented a similar correlation for TPC based on DCMD. Moreover, Schofield [50] and Curcio and Drioli

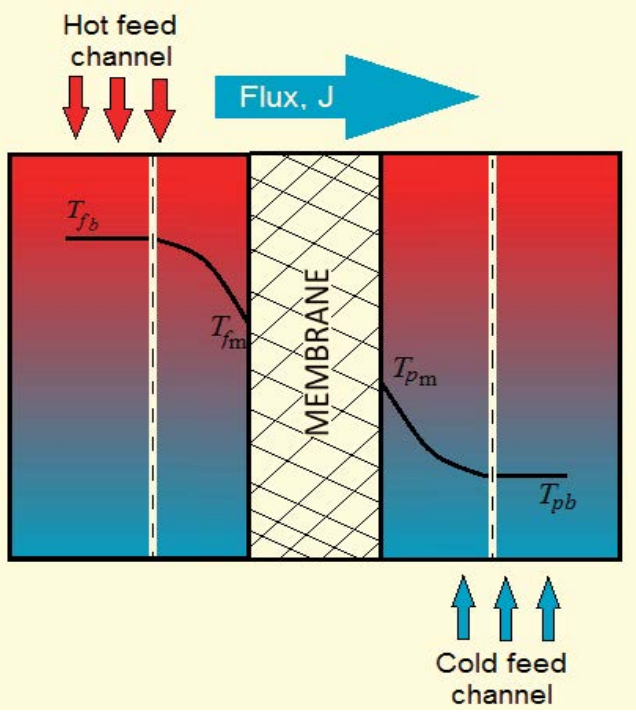

Fig. 2. Temperature polarization in DCMD; where *f* represents feed, *b*: bulk, *m*: membrane, and *p*: permeate.

[51] reported the recommended range of TPC based on DCMD which is between 0.4 and 0.7. No other correlation for TPC has been presented yet for DCMD.

On the contrary, many correlations of TPC based on VMD have been presented in the literature. Bandini et al. [52,53], presented the following correlation for TPC based on VMD:

$$\mathrm{TPC} = \frac{T_b - T_i}{T_b - T_v} \tag{2}$$

where T_b is the bulk temperature of the feed side, T_v is the bulk temperatures of permeate side, and T_i is the membrane interface temperature of the feed side. From this correlation, it is clear that for TPC = 0, the feed side bulk temperature T_b approaches the membrane interface temperature T_i and the process through the membrane is only controlled by mass transfer. Whereas, for TPC = 1, T_i will approach to T_v and the process will be heat transfer limited. Likewise, Mericq et al. [54] proposed the correlation of TPC as the ratio of feed side interface temperature to the feed side bulk temperature, which is given as follows:

$$\mathrm{TPC} = \frac{T_i}{T_b} \tag{3}$$

The TPC correlation mentioned in Eq. (3) is not appropriate due to the fact that the value of TPC can only approach to zero by definition if T_i is zero. The TPC value will approach to zero if T_i approaches the saturation temperature of the permeate side (T_v, irrespective of the value of T_v Thus, this correlation is not a true representation of TPC for all possible cases of VMD. In a similar study, Banat et al. [55] and Al-Asheh et al. [56] also presented the same correlation of TPC for VMD. In another study carried out by Lovineh et al. [57], the following correlation for TPC based on VMD was presented:

$$\mathrm{TPC} = \frac{T_i - T_v}{T_b - T_v} \tag{4}$$

The above correlation agrees with the correlation of TPC for DCMD. Khayet et al. [58] also gives the same correlation of TPC based on VMD as given by Lovineh et al. [57]. A list of correlations given by different authors for TPC based on both VMD and DCMD is given in Table 1.

Table 1
Correlations for TPC given by authors in literature

Model used	Correlation of TPC	References
VMD	$\mathrm{TPC} = \frac{T_b - T_i}{T_b - T_v}$	[52,53,59]
Not mentioned	$\mathrm{TPC} = \frac{T_{\mathrm{fm}} - T_{\mathrm{pm}}}{T_{\mathrm{fb}} - T_{\mathrm{pb}}}$	[37]
DCMD	$\mathrm{TPC} = \frac{T_{\mathrm{fm}} - T_{\mathrm{pm}}}{T_{\mathrm{fb}} - T_{\mathrm{pb}}}$	[7,11,51,60–66]
VMD	$\mathrm{TPC} = \frac{T_i}{T_b}$	[54–56]
VMD	$\mathrm{TPC} = \frac{T_i - T_v}{T_b - T_v}$	[57]

2.3. Impact of temperature polarization on MD performance

The declination of permeate flux in MD is greatly caused by the temperature polarization effect [7,40]. Sakai et al. [67] studied the effects of TP and CP on the mass transfer of water vapor in the blood. The experimental setup contains a micro-porous hydrophobic PTFE membrane having a pore diameter of 0.8 μm and having a thickness of 90 μm. Experiments were performed using four different fluids, that is, pure water, NaCl solution with salinity (5, 10, and 20 wt.%), bovine plasma, and bovine blood. PTFE membrane showed a decrease in water vapor mass transfer of 41%, 27%, and 12% upon contact with bovine blood, bovine plasma, and 10 wt.% NaCl solution, respectively, compared to pure water. This decrease in water vapor permeability was due to the formation of TP and CP. In pure water, only temperature polarization was observed, whereas in the other three solutions both temperature and concentration polarization has existed. Hence, permeability was decreased because of an increase in the resistance to flux. The water vapor permeability of bovine plasma constantly declined by enhancing protein concentration owing to concentration polarization. Similarly, Mokhtar et al. [68] studied the possibility of DCMD for the treatment of rubber processing effluent and noticed a decline in permeate flux because of the TP phenomenon. Likewise, EL-Bourawi et al. [69] studied VMD for ammonia removal from its aqueous solution. They adopted a commercial flat plate PTFE membrane having a pore size of 0.23 μm. The influence of temperature polarization was more dominant particularly in the case of the solvent stripping process, whereas the concentration polarization had a trivial impact and was ignored. Higher removal efficiencies occurred at high feed velocities due to high turbulence and eddies occurred at high velocities. This resulted in low temperature and concentration polarization and hence the amount of water vapor transported and efficiency was increased. Shirazi et al. [70] performed a numerical simulation to estimate the TP and CP variation along the membrane surface and to predict their impact on the performance of MD.

There is a significant effect of TP on the driving force in the MD process. Martinez and Maroto [64] used the TPC to approximate changes in the permeate flux and driving force within the MD process. Some other studies [61,71] also adopted TPC to estimate the changes in the vapor pressure within the MD process.

The change in the flux with TPC also depends on the value of TPC. There is trivial variation in the permeate flux at low values of TPC but the permeate flux increases significantly for higher values of TPC. Ali et al. [66] observed

the same results by using a micro-porous hydrophobic PVDF commercial membrane. Water was used as an input feed having a flow rate range of 30–50 L/h, corresponding to Reynolds number (Re) range of 840–4,700, a constant permeate flow rate of 50 L/h, constant inlet feed temperature of 55°C, and a constant permeate temperature of 10°C was used in the experiment. The study revealed that with an increase in Re from 840 to 4,700, the heat transfer coefficient (HTC) was increased from 185 to 1,480 W/m^2 K, while the TPC was changed from 0.69 to 0.89. In the second phase of experiments, water was used with a constant feed flow rate of 70 L/h, and inlet feed temperature was varied from 45°C to 75°C. For a well-designed MD system, the TPC value must be closed to unity. The enhancement in TPC with Re is more substantial at low values of Re (laminar region) but it becomes trivial in a turbulent region where an increase in Re does not significantly affects the TPC.

Recently, Julian et al. [72] carried out a numerical simulation to investigate the effects of TP and CP on the calcium carbonate ($CaCO_3$) scaling rate. By neglecting the TP at bulk feed temperature of 70°C, the $CaCO_3$ deposition rate was 40% higher than the simulation results. Moreover, by neglecting the CP, the results showed a 23% decrease in $CaCO_3$ deposition rate.

2.4. Techniques to overcome temperature polarization

Several techniques have been proposed in the literature to overcome the temperature polarization effect which are described as follows:

2.4.1. Turbulence promoters

One of the methods to decrease TP impact on the permeate flux is to adopt turbulence promoters. The use of spacer-filled channels to create turbulent flow is a suitable technique to decrease the effect of TP. Martinez-Diez et al. [60] studied the membrane distillation using channel spacers. They showed that the TP can be decreased by using mesh-like turbulence promoters, which enhanced the permeate flux by increasing the HTC. Likewise, Phattaranawik et al. [62] also investigated the role of turbulence promoters in heat transfer improvement on two different membranes such as PVDF and PTFE. The bulk feed temperatures were varied from 313 to 343 K, whereas, the permeate side temperature was kept constant at 293 K. They found that the value of TPC for channels with spacers falls in the range of 0.9–0.97, whereas for flow channels without spacers, the TPC was in the range of 0.57–0.76. The same range of TPC for DCMD was found in another reported data [73]. Hence, by using the spacers in MD, the TPC can be increased which results in a decrease in the temperature polarization effect. Likewise, several other studies [74–76] have proposed spacer-filled channels in VMD and DCMD for reducing the temperature polarization effect. The mesh-type turbulence promoters of the type shown in Fig. 3 are usually used in MD modules.

The spacer orientation has also a great influence on TP [77]. Shakaib et al. [78] investigated the effect of various variation in spacer orientation in MD modules using commercial CFD tools such as Fluent V6.3. They used water as a fluid to investigate spacer orientation in the counterflow direction. Their results revealed that when the membrane surface and the spacer filaments were in contact, stagnant zones, and recirculation regions were created near the membrane. The TP effect was decreased in the case of the recirculation region whereas stagnant zones had a negative effect on TP. Moreover, the temperature polarization effect was smaller when spacer filaments were not touching the membrane. In another study carried out by Ramon et al. [79] figured out that the effective velocity slip can reduce the temperature polarization.

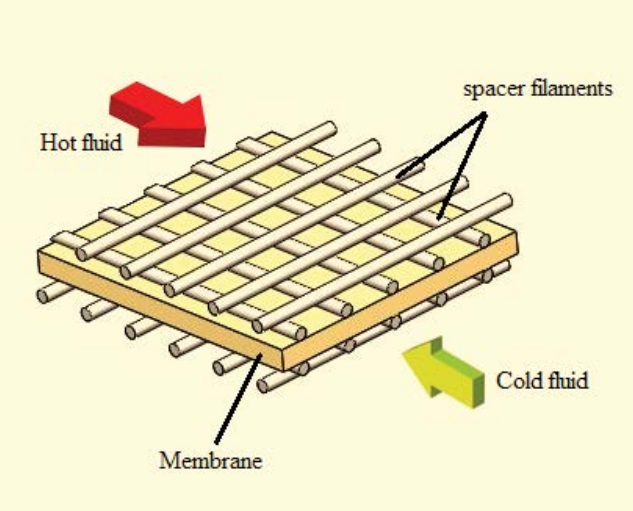

Fig. 3. Schematic of MD filled with spacer filaments.

In another study, Shakaib et al. [80] investigated the impact of spacer filament at higher Re. They observed that those vortices that emerged behind the spacer filaments initially moved in the flow direction and then finally diminishes. Moreover, the TPC was low in the region of high Reynold number that attaches to the bottom surface or hits the top. They concluded that the suitable spacers to use in MD channels are those with comparatively higher spacing and the bottom region of spacer filament was a stagnant zone which was an area of higher TP. Likewise, the impact of spacer-filled channels on TP in DCMD was also analyzed by Tamburini et al. [81]. They used a non-intrusive experimental technique called TLC-IA-TP based on the use of digital image analysis (IA) and thermodynamic liquid crystal (TLCs). Tamburini and his team pointed out that with the help of this technique the local convective HTC can be determined. This HTC provides a useful indication of the weaknesses and strengths of some spacer arrangements. Three different spacer configurations were used in the experiments. The technique is able to find the local temperature, heat transfer, and TPC. The results showed that oblique wires can be used to produce perpendicular components of velocity with respect to the conductive wall. These velocity components improved convective HTC in the channel and hence, resulted in the reduction of the temperature polarization effect. They also found that minimum HTC occurred where spacers are in direct contact with the wall, resulting in an increased temperature polarization effect. Likewise, Teoh et al. [75] studied

the effects of different baffles and estimated the HTC at the feed side. They figured out that the feed side HTC can be increased from 2,600 to 3,150 W/m^2 K for the window baffles, and for the helical baffles it can be increased to 3,750 W/m^2 K, which corresponds to 20% and 28% flux improvement, respectively.

To generate turbulence flow, another method is stirring the fluid that can decrease temperature polarization. Ortiz-Zárate et al. [82] observed an increase in permeate flux with the increased stirring rate in the DCMD. By increasing the stirring rate, the HTC increases thereby reduces the TP effect. Recently, Kuang et al. [83] and El Kadi et al. [84] investigated that use of baffles in the channel can promote mass transfer but at the cost of the increase in power consumption.

The use of turbulence promoters increases the hydrodynamic conditions and reduces the TP phenomenon without significantly affecting the investment cost and the energy consumption. However, despite its advantages, sustaining membrane stability for longer periods is the big challenge in using turbulence promoters [85].

2.4.2. Thermoplasmonics effect

Recently, Politano et al. [86] used a novel concept of thermoplasmonics and heating of feed spacer techniques to overcome TP in MD. They showed that with the help of UV-irradiated silver nanoparticles (Ag NPs), TP in MD can be reduced. To produce collective thermal effects, these nanoparticles act as nano-heaters resonating at the silver (Ag) plasma frequency. In thermoplasmonics [87], temperature enhancement at a specified point can be obtained by using photoexcitation of plasmons in NPs. Experimental tests were carried out using a VMD system operated with ultraviolet-irradiated membranes containing silver nanoparticles. In this novel system, the existence of Ag NPs in the membrane can produce additional thermoplasmonic heat flux, which increases the membrane feed side interface temperature that resulted into the decrease of the polarization effect.

Politano and his team experimentally computed the thermoplasmonic heat flux. They considered that the sum of heat flux related with the radiation of UV lamp q_{rad} and the thermoplasmonic heat flux equate heat flux associated with liquid feed stream and the heat flux obtained from water evaporation. Hence:

$$q_{\text{plasm}} + q_{\text{rad}} = J_w \cdot \lambda + \dot{m}_f C_p \left(T_{\text{fb,out}} - T_{\text{fb,in}}\right) \tag{5}$$

Best results were achieved by using 25% Ag NPs incorporated in a PVDF membrane, about 11 times higher transmembrane fluxes in the case of pure water and 9 times higher for 0.5 M NaCl solution than the corresponding values for simple membranes. This higher mass flux is because of a reduction in the TP effect. Likewise, Anvari et al. [88] proposed a novel concept of contactless heating of feed spacer through radio frequency that enhanced the overall efficiency by reducing the need for continuous heating to the feed solution and reduced TP in membrane distillation. Similar to turbulence promoters, the stability of NPs-charged membranes is a critical issue in membrane distillation operations [86].

2.4.3. Flashed feed configuration

During the MD process, there is no-slip condition at the membrane surface and due to the transfer of latent heat by condensation and evaporation of the water vapors, it is difficult to meet the hydrodynamic conditions. The effect of large latent heat being an intrinsic property of water vapor, cannot be reduced on the heat transfer limitation. In contrast, the effect of no-slip condition can be reduced by introducing turbulence promoters that can create turbulence near the membrane surface, hence can enhance HTC. However, the turbulence promoters cannot eradicate TP entirely. Thus, the only reliable method to reduce the TP effect is to avoid the contact of the membrane surface with feed side stream.

Recently, Alsaadi et al. [42] used a novel flashed-feed VMD configuration for eliminating the temperature polarization effect. They decoupled the effect of TP with membrane mass transfer coefficient by preventing the contact of the membrane surface with hot feed stream by using a custom-made novel VMD module. In this novel VMD module, the feed was flashed before it comes in contact with the membrane surface in order to reduce the TP effect. For evaluating the effect of TP on VMD performance, both the flashed-feed VMD setup and typical VMD setup were used. Results showed that the proposed novel VMD module eliminated the effect of TP and produced a flux of 3.5 times higher than the typical VMD setup under the same operating conditions.

The difference between the schematics of a flashed-feed VMD and a typical VMD setup is shown in Fig. 4. It can be inferred that in flashed-feed mode, there is no direct contact of feed with the membrane surface as in the case of typical VMD, rather the feed is flashed before coming in contact with the membrane surface.

2.4.4. Minimizing heat loss

As a result of the heat loss that occurs through membrane material, the membrane surface temperature is less compares to the bulk feed temperature. Consequently, the TP effect is produced. By manipulating the membrane heat loss, the TP can be controlled. Increasing membrane porosity, pores size, and also enhancing the thickness of the membrane results in a reduction of membrane heat loss [7]. However, increasing the thickness of the membrane considerably increases the mass transfer resistance and subsequently reduces the permeate flux [89], which could be a drawback of increasing membrane thickness.

Highly porous membranes demonstrate small conductive heat loss due to the low conductive HTC of the entrapped gases in the membrane pores compared to the hydrophobic membrane HTC [7,37,90]. Further research is needed to clarify the effect of minimizing the conductive heat loss on TP.

2.4.5. Membrane coating

Several improvements in the characteristics of membrane surface have been used in the literature by using

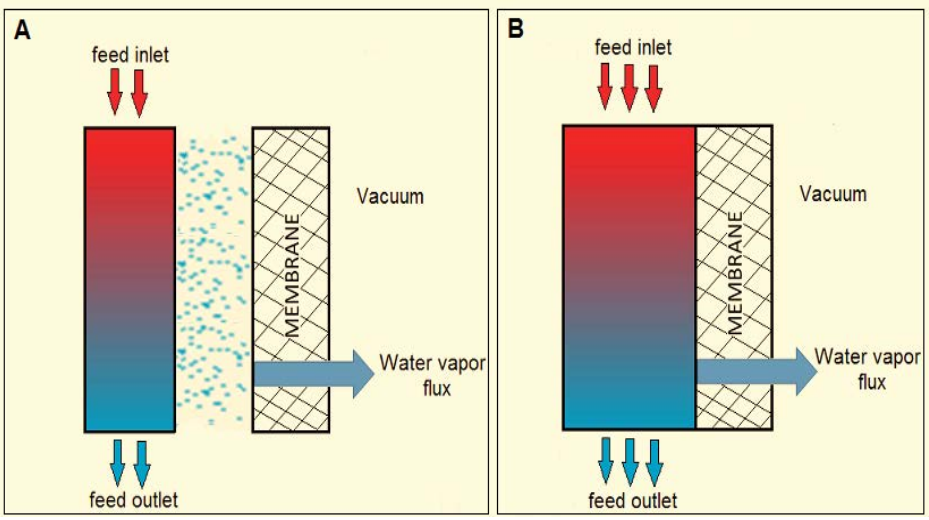

Fig. 4. Representation of VMD configurations: (A) flashed feed mode and (B) feed-membrane contact mode.

different techniques for surface modification including plasma polymerization and coating to reduce the TP effect. Li and Sirkar [91] proposed a novel hollow fiber membrane, that consisted of porous polypropylene (PP) hollow fibers coated with microporous silicone fluoropolymer using plasma polymerization technique. The arrangement of the coated fibers on the PP surface was in cross-flow, having vacuum on the fiber bore side while hot brine flowing outside of the coated fibers. Thus an additional layer of high hydrophobicity than the PP was attained. The reported method reduced the TP effect and increased permeate fluxes. Likewise, Li and Sirkar [92] proposed the same coating phenomenon for DCMD using porous hydrophobic PP hollow fibers to reduce the TP effect and to enhance the performance of the module. Recently, Song et al. [93] introduced coating of nichrome resistance wire (NRW) on PVDF through the thermo-electrical effect that showed a decrease in temperature polarization in MD.

2.4.6. Nanostructured surfaces

Nanostructured membranes have been introduced lately, with an aim to boost MD efficiency. Among other nanomaterials for overcoming the TP phenomenon and enhancing MD efficiency, carbon-based nanoparticles (CNPs) with high thermal conductivity such as graphene and carbon nanotubes (CNTs) are the most prominent ones. The membrane surface thermal conductivity is enhanced via CNP layer coating over polymeric membranes, without affecting bulk membrane thermal conductivity, resulting in an overall reduction in heat loss [94].

Besides various chemical functional groups [95], CNTs have high thermal conductivities [96], which may provide mass transport pathways. The use of membranes modified by CNTs for performance enhancement by lowering TP and raising permeate productivity has been started just recently [97–102]. Graphene oxide (GO) nanoparticles due to their high thermal conductivities have also been used to modify membranes used in MD [103–105]. Graphene has water vapor sorption sites through hexagonal honeycomb lattices containing sp2-bonded carbon atoms in addition to the polar functional groups (i.e., hydroxyl and carboxyl), leading to improved interactions between the membrane and water vapor and consequently enhanced water vapor flux [94].

2.4.7. Metallic membranes

TP mitigation can also be achieved by using metallic membranes. Electrical resistivity makes metallic membranes such as stainless steel hollow fiber, suitable for localized heating by the Joule effect [106–108]. The required porosity and hydrophobicity of hydrophilic nanoparticles-based membranes are obtained using a polydimethylsiloxane (PDMS) binder [106]. Owing to their excellent mechanical, chemical, and thermal stability, metallic membranes can be a good alternative for polymeric membranes. However, lower permeate productivities as compared to polymeric membranes cast a slight shadow on their viability [107]. Hengl et al. [109] used a low voltage/high current (0–10 V and 0–150 A) to heat a stainless steel ASI 316 L metallic membrane to compensate for the loss of membrane surface temperature which is a result of water evaporation. In the absence of applied external potential (i.e., no Joule heating), the temperature of the membrane surface was lower than the bulk feed solution, thus confirming TP. By applying external electrical potential, the membrane's surface temperature increased to values close to the bulk temperature along the membrane length, proving the ability of metallic membrane heating to reduce TP. However, the distillate flux value (0.6 kg/m^2 h) was very low and could be a result of the high thermal conductivity of the bulk membrane, leading to extensive heat loss. Furthermore, the membrane's high thermal conductivity also resulted in similar water temperatures at both sides of the membrane [109].

In order to enhance the energy efficiency of metallic membranes without preheating the feed inlet solution, further research is required for their performance assessment

and optimization. Anvari et al. [94] suggested that a metallic layer on a polymeric membrane could be more beneficial as compared to a whole metallic membrane. Since, the polymeric membrane will act as an insulating layer between the feed and permeate stream due to its lower thermal conductivity, while the conductive metallic layer can be heated accordingly.

2.5. Effect of operating parameters on temperature polarization

The TP is greatly influenced by the operating parameters of the MD process. This section depicts the impact of the most influential operating parameters with respect to temperature polarization.

2.5.1. Feed temperature

The influence of the feed temperature on TP has been widely studied. The TPC decreases in DCMD by increasing the bulk temperature of the feed [62,110,111], which means that the TP effect increases with the feed temperature [11,62,112–114]. This is due to the fact that at the higher temperature the energy consumption from the vaporization is higher. Also, the bulk temperature difference has a great impact on the effective temperature difference across the membrane [115]. Chmielewski et al. [116] investigated theoretical and experimental values of TPC. They figured out that by increasing the feed temperature, the TPC in DCMD was decreased. Although the TP effect enhances with the bulk feed temperature, However, by increasing the feed temperature, there is an increase of MD flux in all MD configurations too [117]. Hwang et al. [118] also pointed out an increase in TP effect for DCMD with the increase in feed temperature. Bahmanyar et al. [65] investigated the effect of feed temperature on TP. The authors also compared the TPC and vapor pressure polarization coefficient:

$$\mathrm{TPC} = \frac{T_{\mathrm{fm}} - T_{\mathrm{pm}}}{T_{\mathrm{fb}} - T_{\mathrm{pb}}} \tag{6}$$

$$f = \frac{P_{\mathrm{fm}} - P_{\mathrm{pm}}}{P_{\mathrm{fb}} - P_{\mathrm{pb}}} \tag{7}$$

where f is the vapor pressure polarization coefficient. The feed temperature effect on TPC is studied using PP and PTFE membranes. They pointed out that when the feed concentration is low (C_b = 1.2 g L^{-1}) the TPC and f values are almost equal and TPC is a better indication of the decrease in driving force, but the difference becomes greater with an increase in feed concentration. The increase in salt concentration in the feed solution has effect on both the TP and also on the vapor pressure polarization coefficient. The increase in salt concentration results in the reduction of the partial vapor pressure according to Raoult's law. Moreover, there is a slight increase of TPC with feed concentration. This is attributed to the fact that increasing the salt concentration results in a decrease in the heat transfer coefficient which subsequently increases the TPC. The effect of an increase in salt concentration on the vapor pressure polarization coefficient is more significant whereas the effect is insignificant on the TPC. Therefore, the coefficient f and TPC coincide when the feed is water. However, they are dissimilar for an increased salt concentration in the feed solution.

The feed temperature has also a strong impact on the permeate flux. The MD flux considerably enhances with the rise in bulk feed temperature [89]. Owing to the fact that the driving force resulted from the vapor pressure difference of the feed side permeate side increases. This increase in vapor pressure with the increase of temperature is according to Antoine equation [119–122]. Banat et al. [59] performed a sensitivity analysis of VMD. They used temperature polarization as a tool to enhance the mass flux by changing the input parameters. They showed that low HTC resulted in high-temperature polarization and a decrease in vapor pressure, hence a decrease in permeate flux. Besides, they also noticed that by increasing the bulk feed temperature, the TP was increased because of the increase in heat of vaporization. To overcome the increase in TP effect that resulted due to an increase in bulk temperature, HTC should be increased [59]. Likewise, Alklaibi et al. [123] also studied the effect of the inlet temperature of hot feed on the mass transfer resistance in the DCMD.

2.5.2. Feed circulation velocity and stirring rate

Increasing the stirring rate and feed side circulation velocity results in enhancing the HTC and also reduces the TP effect [65]. Chen et al. [124] predicted the TP profile of DCMD by theoretically developing a two-dimensional mathematical model. To verify the theoretical prediction, a concurrent flat-plate arrangement was suggested. The feed flow rate influence on the TP was studied and figured out that TP is reduced with increasing the flow rate. Likewise, Srisurichan et al. [125] also investigated the effect of recirculation rate on TP. They showed that working with high recirculation rates maximizes the HTC and minimizes the boundary layer resistance. Consequently, the TP effect can be reduced and a higher flux can be achieved. In another study, Martínez-Díez and Gonzalez [40] observed a sufficient change in TP when the recirculation rate was changed. This is due to the enhancement in the HTC, which leads to an increase in permeate flux. Likewise, Singh et al. [126] showed that TP can be reduced by using high flow rates on either side of the membrane. Cath et al. [127] carried out the parametric analysis of DCMD to analyze the impact of feed velocity. They figured out that the thermal boundary layer was reduced when both sides had turbulent flow regimes. Moreover, they also showed that by increasing feed velocity the flux can be increased. This is because of improved mixing in the flow channel which led to a decrease in thermal boundary layer thickness. Moreover, Walton et al. [128] pointed out that the influence of flow rate on MD flux and TP is more obvious at elevated temperatures, particularly related to high-temperature drop across the membrane.

2.5.3. Properties of membrane

The magnitude of TPC and permeate flux also depends on the type of membrane and surface area in the

MD module. Increasing membrane area will reduce the temperature difference across the membrane and as a result, will reduce the permeate flux [129]. Burgoyne [130] pointed out that by increasing channel length, permeate flux was reduced for a flat-plate module. This was because of the decrease in driving force across the membrane. Moreover, the thermal conductivity of the membrane material also influences the TP. Alklaibi and Lior [117] suggested that membrane material having low thermal conductivity should be used to reduce the TP effect.

TP is inversely proportional to the membrane thickness. To obtain better heat efficiency (less heat loss and low TP effect), the membrane must be as thick as possible because of conductive heat loss through the membrane [11,37,49,112], which is a cause of TP. Besides, for membranes having higher porosity and larger pore size, the TP is higher [58].

Su et al. [131] investigated both numerically and experimentally the thermal conductivity effect of membranes on TP and MD flux. The model predicted that by increasing the thermal conductivity of the inner hydrophobic layer, a substantial rise in MD flux can be achieved. To enhance the thermal conductivity of the hollow fiber hydrophilic layer, a mixture of graphite particles and multiwall carbon nanotubes were embedded. By incorporating graphite alone, Su et al. [131] figured out a slight improvement in thermal conductivity. However, they reported an increase in thermal conductivity by incorporating both MWNT and graphite, which led to a substantial rise in MD flux. This increase in vapor flux because of thermal conductivity is attributed to the decrease in TP. In order to reduce the TP and to enhance the temperature difference across the membrane, the thermal conductivity of the hydrophilic layer should be increased [132]. Even though the temperature gradient across the whole hollow fiber membrane declined, but the effective temperature gradient across the outer hydrophobic membrane was enhanced. Recently, Donato et al. [133] experimentally tested zeolite-based membrane for VMD and figured out that a very high flux of 20.6 kg/m^2 h was achieved at a feed temperature of 70°C.

2.5.4. Vacuum pressure and feed concentration

The extent of TP in membrane distillation is also a function of various other process parameters, such as vacuum pressure and feed concentration. As compared to feed temperature and feed circulation velocity, the TP phenomenon does not greatly depend on vacuum pressure and feed concentration. Jang et al. [134] numerically studied the impact of these parameters on the TP phenomenon. Overall, the TPC value remained in the range from 0.963 to 0.985. An increase of 0.013 was observed with the decrease of vacuum pressure from 90 to 70 m bar. A rise in feed solution inlet flowrate reduced the TP effect. Similarly, it was found that a higher feed salinity (1–4 M of NaCl) lowers the temperature polarization ratio by 0.008 [134]. Likewise, Alsaadi et al. [41] showed that the TPC value decreases as the absolute vacuum pressure increases.

3. Concentration polarization

3.1. Introduction

In the MD process, the components of the feed solution permeate at different rates through the membrane. A gradual accumulation of non-permeating components occurs as the permeable components permeate through the membrane. Consequently, a layer is formed on the membrane surface, where the amount is higher compared to the concentration in the bulk feed flow. So a concentration gradient is formed nearby the membrane surface. The process is called as CP [39,51,135,136]. The layer near the membrane where the solute concentration varies due to CP is called the polarized layer. Figs. 5 and 6 illustrate the formation of the polarized layer in membrane distillation. The extent of CP can be described by the increase of solute concentration at the membrane surface compare to the solute concentration in the bulk feed. CP reduces mass transfer away from the membrane (in the permeate side) and reduces it towards the membrane (in the feed side) and in addition stimulates fouling and scaling.

The permeate flux can vary with thermal boundary layers when the pure water is adopted in bulk feed. However, with an increase in salt concentration of the feed, the MD flux is affected by both TP and CP.

3.2. Theoretical background and concentration polarization coefficient

Two approaches can be used to describe the effect of CP. In the first approach, both the resistance in the feed flow layers and the resistance across the membrane are considered as series resistances. By assuming that CP takes place

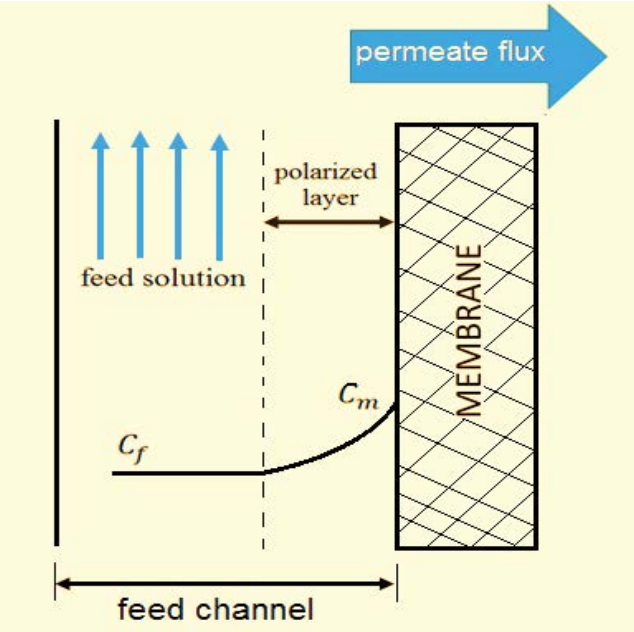

Fig. 5. Illustration of concentration polarization.

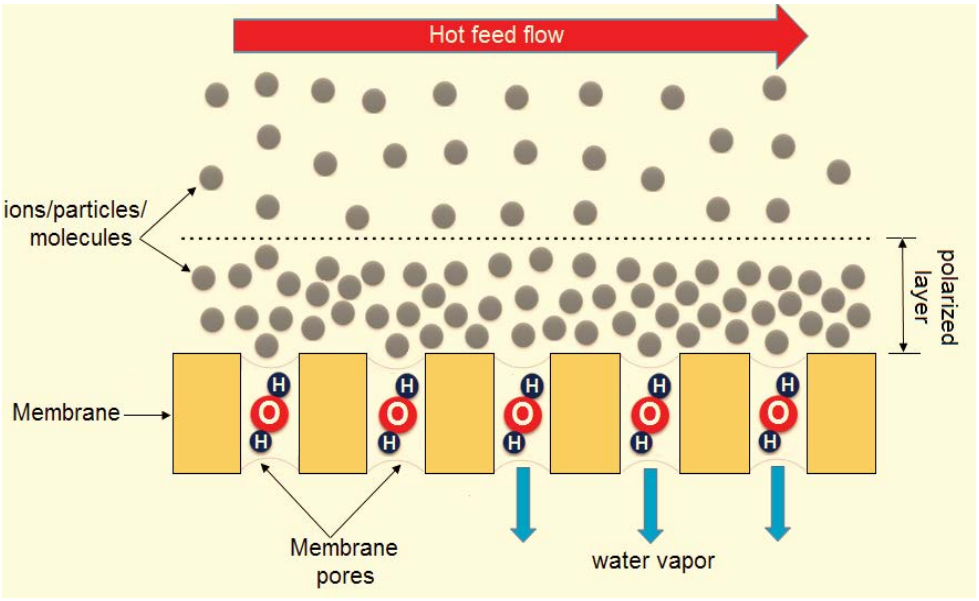

Fig. 6. Mass transfer of species in concentration polarization.j

only on the feed side, the permeate flux across both the resistances can be written as follows:

$$j = k_{ov}\left(C_f - C_p\right) \tag{8}$$

where C_p is the permeate solution concentration, C_f is the feed solution concentration and k_{ov} is the overall mass transfer coefficient (MTC). Similarly, the flux across the fluid layer adjacent to the membrane surface can be written as follows:

$$j = k_f\left(C_f - C_m\right) \tag{9}$$

where C_m is the concentration of the fluid layer at the membrane surface and k_f is the fluid boundary layer MTC.

Also the flux through the membrane can be written as follows:

$$j = k_m\left(C_m - C_p\right) \tag{10}$$

where k_m is the MTC of the membrane.

In the second approach, concentration polarization is modeled by assuming that between the well-mixed bulk fluid and the membrane surface, there exists an unmixed fluid layer having a thickness (δ). This model is very simple and having only one variable parameter known as the fluid boundary layer thickness (δ).

The concentration polarization coefficient (CPC) is defined as the ratio between the feed water concentrations (C_f) to the amount at the membrane surface (C_m) [54]. The empirical relation used for VMD is as follows:

$$\text{CPC} = \frac{C_f}{C_m} \tag{11}$$

A decrease in the value of CPC will indicate that the polarization effect is increasing whereas CPC values close to 1 means that there is no polarization.

The use of pure water in MD is often convenient for experimental purposes because the boundary layer resistances can be ignored. But, in the real MD process, special attention must be given to CP since the concentration boundary layer increases the mass transfer resistance significantly.

For DCMD, Bahmanyar et al. [65] and Peng et al. [137] defined the CPC as the ratio of the concentration at the membrane interface to the concentration in the bulk solution, which is given as follows:

$$\text{CPC} = \frac{C_{mb}}{C_b} \tag{12}$$

Also, Martínez-Díez and Gonzalez [40] and Curcio et al. [51] suggested the same correlation for CPC as given by Peng et al. [137].

Likewise, Martinez et al. [138] presented the correlation of concentration polarization coefficient for DCMD as follows:

$$\text{CPC} = \frac{x_{m1} - x_{b1}}{x_{b1}} \tag{13}$$

where x_{m1} is the feed concentration near the membrane and x_{b1} is the bulk feed concentration. x_{m1} can be found from the following relationship:

$$x_{m1} = x_{b1}\exp\left(\frac{J}{\rho K}\right) \tag{14}$$

where ρ is the density of the feed solution and K is the film MTC.

Several other studies [40,65,139–141] also suggested the same empirical relation as mentioned in Eq. (16) to approximate the solute concentration on the membrane surface.

The film MTC can be estimated by using Sherwood correlation, which can be further used to compute the concentration of the feed adjacent to the membrane:

$$\mathrm{Sh} = \frac{Kdh}{D} = C\,\mathrm{Re}^{a}\,\mathrm{Sc}^{b} \tag{15}$$

where D, Re, Sc, and dh are diffusion coefficient, Reynolds number, Schmidt number, and hydraulic diameter respectively. In Eq. (15), C, a, and b are constants that depends on flow type and flow arrangements. Several Sherwood correlations can be found in the literature as used by the researchers to compute CPC as shown in Table 2.
Where Schmidt number (Sc) is a dimensionless number which can be calculated as:

$$\mathrm{Sc} = \frac{\mu}{\rho D} \tag{16}$$

where μ is the kinematic viscosity, ρ is the density of the feed, and D is the diffusivity of the solute.

3.3. Impact of concentration polarization on MD performance

CP strongly influences the MD performance. As previously discussed, the driving force for vapors transport through the membrane is the difference of vapor pressure between the feed and permeate side of the membrane, so by increasing the vapor pressure at the permeate side and decreasing at the feed side, the mass transfer resistance increases. The feed side vapor pressure reduces significantly by increasing the concentration of the feed. Recently, Wu et al. [147] pointed out that by increasing the salt concentration from 1 to 20 wt.%, there is a 50% decrease in permeate flux. Also, Yan et al. [148] studied the influence of CP on the VMD performance using PVDF hollow fiber membrane. They predicted that with an increase in feed solution concentration, the flux is deceased, whereas retentate remains constant. This decrease in permeate flux is attributed to CP. Likewise, Lokare et al. [149] attributed this decline in mass transfer to CP phenomenon.

For all MD configurations, with an increase in the feed concentration, the most likely impact is a decrease in the MD flux. This decrease in flux is because of the fact that by adding non-volatile solutes in the feed reduces the vapor pressure and subsequently reduces the driving force. This decrease in vapor pressure is in agreement with Raoult's law [150] as given in Eq. (19). Several other studies [151,152] have also stated a decline in the permeate flux because of an increase in the inlet feed concentration:

$$p = p^{0}\left(1 - x\right) \tag{17}$$

In Eq. (17), p^0 is the vapor pressure of pure water, p is the vapor pressure of the feed solution, and x is the solute concentration in the feed solution. Sudoh et al. [143] carried out the parametric analysis to study the effects of both concentration and thermal boundary layers on vapor permeation in MD. They predicted the impact for lithium bromide solution and figured out that when the solution concentration was less than 5%, the concentration boundary layer effect was negligible, whereas the influence of the thermal boundary layer was prominent in the whole concentration range used in the experiments. Martínez-Díez and Gonzalez [40] introduced a coefficient that measured the reduction in the driving force called vapor pressure polarization coefficient f as given in Eq. (7).

The coefficient f and TPC coincide when the feed is water, however, they are dissimilar for an increased salt concentration in the feed solution. Several experiments were carried out with water alone and also with sodium chloride feed solutions having concentrations of 0, 0.55, 1.15, and 1.67 molar. They observed a substantial decline in permeate flux as concentration increases which is attributed to the increase in CP. They also compared the membrane wall concentration with the concentration of feed and found it to be 4% higher than the bulk concentration.

Table 2
Sherwood correlations used in the literature

Type of flow	Sherwood correlation	References
Turbulent flow	$\mathrm{Sh} = 0.023\,\mathrm{Re}^{0.875}\mathrm{Sc}^{0.25}$	[142]
Turbulent flow	$\mathrm{Sh} = 0.023\,\mathrm{Re}^{0.8}\mathrm{Sc}^{1/3}$	[120]
Not mentioned	$\mathrm{Sh} = 2.00\,\mathrm{Re}^{0.483}\mathrm{Sc}^{0.33}$	[143]
Laminar flow through circular pipes	$\mathrm{Sh} = 1.86\,[\mathrm{Re\,Sc\,dh/L}]^{1/3}$	[144]
Turbulent flow through circular pipes	$\mathrm{Sh} = 0.023\,\mathrm{Re}^{0.8}\mathrm{Sc}^{1/3}$	[144]
Laminar flow	$\mathrm{Sh} = 1.62\,[\mathrm{Re\,Sc\,dh/L}]^{0.33}$	[145]
Turbulent flow	$\mathrm{Sh} = 0.023\,\mathrm{Re}^{0.8}\mathrm{Sc}^{1/3}$	[58]
Laminar flow	$\mathrm{Sh} = 1.86\,[\mathrm{Re\,Sc\,dh/L}]^{1/3}$	[146]
Turbulent flow	$\mathrm{Sh} = 0.023\,\mathrm{Re}^{0.8}\mathrm{Sc}^{1/3}$	[146]
Re < 2,100	$\mathrm{Sh} = 0.13\,\mathrm{Re}^{0.64}\mathrm{Sc}^{0.38}$	[65]
Re > 2,100	$\mathrm{Sh} = 0.023\,\mathrm{Re}^{0.8}\mathrm{Sc}^{0.33}$	[65]

3.3.1. Fouling due to concentration polarization

Another negative impact of CP on MD performance is the fouling of the membrane. The phenomena of membrane fouling and CP are interrelated and influence each other. It is the build-up of unwanted deposits on the membrane surface that degrade the performance of the membrane and also reduces the permeate flux by decreasing the overall HTC. Due to CP, the accumulated solute on the membrane surface becomes so high that a scale is formed on the surface of the membrane described as fouling [153]. He et al. [154] and Gryta [155] predicted a significant decrease in permeate flux because of fouling. Fouling of the membrane can be reduced by using carbon nanotechnology-based membranes which eventually results in more permeate flux [156].

There are three types of unwanted deposits on the membrane as shown in Fig. 7. The description of each type of fouling is as follows:

- *Crystallization fouling*: It is also known as scaling. Crystallization fouling results from the crystals growth on the surfaces of membrane, mostly occurs in the treatment of salt concentrated feed solutions [76]. Gryta et al. [157] presented a substantial decline in the permeate flux because of substantial deposition of fouling at the feed side of the membrane when the NaCl solution contained organic matter. Crystallization fouling is greatly influenced by several parameters such as membrane properties, the salinity of feed solution, nature of salt, and process operating conditions.
- *Biological fouling*: The attachment of microorganisms like algae, bacteria to the membrane surface. Biological fouling is commonly associated with aqueous solutions because it is caused by a living matter. A significant flux decline was observed due to biological fouling during the concentration of saline wastewater by DCMD [158]. Biological growth greatly depends on the MD operating conditions.
- **Particulate fouling**: It is the accumulation of solid particles on the membrane surface that are suspended in the feed solution. It is also known as corrosion fouling, which can damage the membrane surface by scratching it, and also can result in pore plugging. The deposition rate strongly depends on the size of the suspended particles.

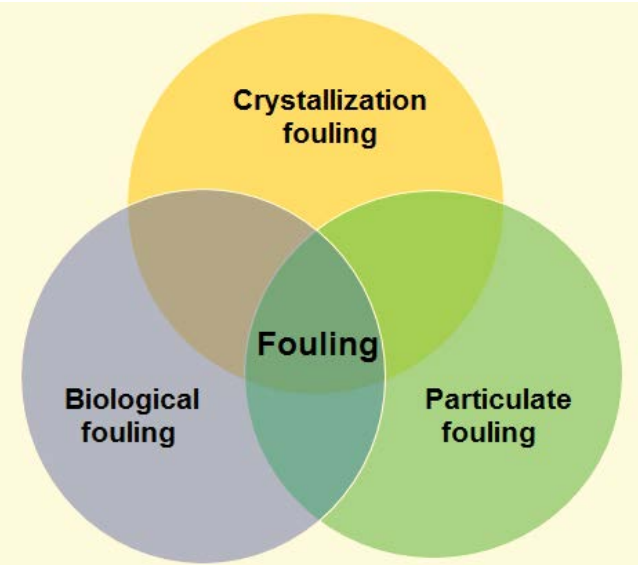

Fig. 7. Types of fouling in MD.

In the real world MD processes, the amalgamation of various fouling types happening simultaneously.

Fouling in MD is a time-dependent process and it must be emphasized that its effect on the performance of MD cannot be ignored. A substantial study on fouling has declared that after 50–100 h of MD process, the performance of MD could be reduced by more than 50% because of the existence of fouling effects [159]. The formation of the fouling layer can be better understood by analyzing the forces of interaction between the membrane surface and the particles. If the particle and surface have different charges, they will attract each other and if they have the same charges then they will repel each other. In order to reduce fouling, the interaction between particle and surface should be reduced, that is, CP should be minimized.

Fouling can also be reduced by frequent flushing of the membrane which can be done with the help of deionized water and also by using concentrated HCl solution. Nghiem and Cath [160] used regular flushing of deionized water for mitigating $CaSO_4$ scaling in DCMD. Srisurichan et al. [161] uses PVDF membrane in a DCMD unit. They used both clean water and a 0.1 M NaOH solution for regular flushing of the membrane. The permeate flux was recovered to 100% of initial flux by using NaOH solution whereas the permeate flux was recovered to 87% of initial flux by using deionized water. Likewise, Gryta et al. [162] used 2–5 wt.% HCl solutions for the removal of $CaCO_3$ deposits from the fouled MD module.

Concentration polarization reduces the efficiency of an MD process by decreasing the permeate flux and the solute rejection. Furthermore, CP is detrimental to a membrane as it increases the possibility of membrane fouling and deteriorates the selectivity of separation and membrane lifetime.

3.4. Minimization of concentration polarization

Several techniques have been proposed in the literature to minimize the effect of CP that is described as follows:

CP can be significantly reduced by employing cross-flow in the MD module. In a cross-flow module, the direction of feed flow is made parallel to the membrane. A flow tangential to the membrane will sweep the solute molecules downstream along the feed channel. This will lead to a lower buildup of solute particles on the membrane surface and hence it can effectively reduce the CP.

CP can be reduced by decreasing the boundary layer thickness, which can be done by introducing turbulent mixing at the membrane surface. By using turbulence promoters, the flux of the required quantity can be achieved at optimum entrance velocity while significantly reducing the length of the tubing. Thus the turbulence promoters permit the process at lower velocities by lessening CP effects [163]. Another way to enhance mixing is to increase the velocity of the fluid flowing in the MD module.

Consequently, most of the membrane modules operate at relatively high feed velocity in order to reduce both the boundary layer thickness and CP.

Any method that disturbs the formation of a continuous boundary layer and stimulates the mixing of the fluid is likely to reduce the polarization phenomenon. Membrane spacers are commonly used to promote the mixing of the fluid and to decrease CP in the MD module channels. Ahmad et al. [164] showed that introducing spacer filaments in the membrane channel can control the formation of CP. Various spacer filaments geometries were examined using FLUENT CFD code. Based on Ahmad et al. [164] results, triangular filament showed the highest degree of concentration minimization ability followed by square and circular filaments.

Another, most important factor that affects the CP is the polarized boundary layer thickness (δ). As the polarized boundary layer decreases, the CP becomes exponentially smaller. The most simple way to reduce the polarized boundary layer thickness and to decrease the effect of CP is by increasing turbulence near the membrane surface [165].

It is worth mentioning that CP strongly influences the performance in the case of pressure-driven membrane separation processes like ultrafiltration and RO, where CP is considered a prime cause for flux decline [166–170]. However, in VMD and DCMD, Souhaimi et al. [171] pointed out that compared to TP, the concentration boundary layers near the surface of the membrane results in a smaller involvement of CP to the mass transfer resistance. Likewise, various other authors have reported the insignificant impact of CP on permeate flux as compared to that of TP in MD [11,40,64,71,145].

4. Conclusion and future prospects

MD can be used as a promising segregation process in numerous applications such as brackish and seawater desalination, water purification, removal of ammonia, resource concentration, and process water treatment. The ability of VMD to efficiently work at low-temperature provides an alternate routine to utilize renewable energy resources like geothermal and solar energy. However, for such a process that has been attractive for long, has been known for more than 40 y and also claimed to be a promising technique, most of the literature reveals that the MD process still lack of information related to TP and CP. On the basis of attained knowledge and gathered information on polarization phenomenon in MD, a state-of-the-art review associated with TP and CP in VMD and DCMD is presented in this study.

The TP and CP are the major barriers that may weaken the MD operation and retard it from being a viable option. TP and CP are strongly influenced by the operational parameters of the MD setup. Additionally, different approaches are used in the literature in order to overcome the TP and CP. On the basis of the review presented here, most of the conducted polarization research is based on lab-scale experimentation. Therefore, more attention should be paid to the polarization studies covering industrial applications in order to enhance the system efficiency and to make the MD system useful for industrial applications.

Furthermore, it is worth mentioning that majority of the polarization studies carried out by researchers focused on the DCMD module, thus the reported polarization problems may not be representative of the other MD setups like VMD, AGMD, and SGMD. Thus more detailed information regarding the polarization phenomenon is needed to provide on different types of MD modules. Unlike ultrafiltration, RO, where CP is considered a major cause for flux decline, in MD modules TP has a more significant effect on performance compared to CP. Thus focus should be given in the future to TP and additional investigation of TP in MD modules should be carried out.

Understanding the polarization phenomenon in MD is the initial step to solve the polarization problem. This review gives an overall view of temperature and concentration polarization for VMD and DCMD. Aside from optimizing the operational parameters, using common techniques for turbulence along with improving the membrane structure for minimizing the TP and CP, addressing the polarization phenomenon with novel methods such as flashed-feed VMD configuration can be one of the directions for future research.

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Abbreviations

MD — Membrane distillation
DCMD — Direct contact membrane distillation
VMD — Vacuum membrane distillation
TP — Temperature polarization
CP — Concentration polarization
TPC — Temperature polarization coefficient
CPC — Concentration polarization coefficient
RO — Reverse osmosis
AGMD — Air gap membrane distillation
SGMD — Sweeping gas membrane distillation
HTC — Heat transfer coefficient
PTFE — Polytetrafluoroethylene
PP — Polypropylene
PVDF — Polyvinylidene difluoride
Re — Reynolds number
MWNT — Multiwall carbon nanotubes
Ag NPs — Silver nanoparticles
MTC — Mass transfer coefficient

Symbols

T_{fb} — Feed side bulk temperature, K
T_{fm} — Feed side membrane surface temperature, K
T_{pb} — Permeate side bulk temperature, K
T_{pm} — Permeate side membrane surface temperature, K
T_b — Bulk temperature of the feed side, K
T_v — Permeate side bulk temperature, K

T_i — Membrane interface temperature, K
PC — Protein concentration, wt.%
HT — Hematocrit percentage, Vol.%
J_w — Transmembrane flux, kg/m^2 h
$\dot{m}$ — Feed flow rate, L/h
f — Vapor pressure polarization coefficient, dimensionless
C_f — Concentration of the feed solution, moles/volume
C_m — Concentration at the membrane surface, moles/volume
k_{ov} — Overall mass transfer coefficient, m/s
k_m — Membrane mass transfer coefficient, m/s
k_f — Polarized layer mass transfer coefficient, m/s
x_{b1} — Concentration of the bulk feed, g/kg
x_{m1} — Concentration at the feed side membrane surface, g/kg
Sc — Schmidt number, dimensionless
Sh — Sherwood number, dimensionless

Greek

δ — Polarized layer thickness, mm
λ — Latent heat of vaporization, J/kg
σ — Surface tension, N/m

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