J. Applied Membrane Science & Technology, Vol. 26, No. 2, August 2022, 49–60

Effect of Configurations and Operating Parameters on the Desalination Performance of Membrane Distillation: A Review

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Submitted: 23/5/2022. Revised edition: 1/7/2022. Accepted: 1/7/2022. Available online: 25/7/2022

ABSTRACT

A desalination is a promising approach to addressing the freshwater scarcity caused by limited freshwater resources and salt intrusion (pollution). Membrane distillation (MD) was proposed as a possible technology for desalination. This study review the efficiency of membrane distillation by comparing the permeate flux and thermal energy efficiency of the four configurations, namely, direct contact membrane distillation (DCMD), vacuum membrane distillation (VMD), air gap membrane distillation (AGMD) and sweeping gas membrane distillation (SGMD). It was observed that the sequence of permeate flux and thermal energy efficiency is VMD> DCMD> SGMD>AGMD and VMD> SGMD> AGMD> DCMD, respectively. The results show that the VMD provides the highest permeate flux at 15.2 kg/hm^2 with 99.25% of salt rejection rate. Additionally, VMD possess good energy efficiency at 66% relative to other configuration at the recorded permeate flux. Subsequently, the feasibility of MD in desalination is studied using different case studies. Furthermore, the effect of operating parameters (feed temperature, feed concentration, feed flow rate, and long-term operation) on flux is discussed. The results suggested that the flux increases when feed temperature or feed flow is increased. At the same time, the flux will decrease when feed is in high concentration and long-term operation.

Keywords: Membrane Distillation, Sodium Chloride, Permeate Flux, Configuration, Operating Parameter

1.0 INTRODUCTION

Water pollution is one of the critical threats leading to reducing freshwater supply. Saltwater intrusion is a type of saline water pollution that occurs when saltwater infiltrates groundwater due to a rise in seawater level or lower land elevation; this will eventually lead to excessive saline content in the water and causes water quality to deteriorate [1]. It was reported that high salinity levels in water and soil would trigger machinery corrosion and infrastructures, death of vegetative crops due to dehydration, and impact human health system, such as kidney disease like the formation of kidney stones [2]. Freshwater accounts for only 2.5 % of global water resources, and 97.5 % is saltwater ac. In the freshwater proportion, most of it existed in the glaciers of Antarctica and the Greenland Ice Sheet, which is not accessible to humans. In contrast, the remaining freshwater was present as groundwater and surface water. Indeed, water could be circulated naturally according to global hydrological, allowing natural and

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DOI: https://doi.org/10.11113/amst.v26n2.246

artificial water catchments to be recharged [3]. However, it takes a long time to accumulate and reach the original volume of groundwater reservoirs. This was critical when the rate of withdrawing groundwater in many parts of the world exceeded the rate of water recharging.

Membrane distillation is a hybrid process that combines thermal distillation principles with membrane separation technologies [4]. A hydrophobic microporous membrane maintains a vapour-liquid interface in the membrane distillation process. The operating principle of membrane distillation is based on the temperature gradient, the temperature difference across the membrane [5]. A vapour pressure difference will exist when a temperature gradient is maintained across the membrane. The desalination process operates based on the evaporation of volatiles, the water molecules at the hot interface, followed by the movement of evaporated volatiles across the membrane in the vapour phase and condensation of the water vapours at the cold interface. The movement of volatiles will give rise to a net trans-membrane water flux [6]. In short, volatile vapour molecules tend to pass through the membrane, whereas non-volatile molecules will be retained in the retentate stream. A completely pure product can be collected, which is free from solid content, including the non-volatile contaminants [7]. In the desalination process, the volatile compound refers to the water molecules, whereas the non-volatile compound is the salt molecules. The four common MD configurations adapted in the studies are direct contact membrane distillation (DCMD), air gap membrane distillation (AGMD), sweeping gas membrane distillation (SGMD) and vacuum membrane distillation (VMD) [8, 9]. Each configuration possesses its pros and cons in its performance in the water permeate flux. On the other hand, the effect of the operating parameter such as feed temperature, feed concentration and feed flow rate also play a vital role in the permeate flux obtained. In this study, the effect of MD configuration and operating parameters was studied to evaluate MD's performance in the water permeate flux.

2.0 EVALUATION OF MEMBRANE CONFIGURATION'S PERFORMANCE

2.1 Water Permeate Flux

The water permeate flux results for different membrane configurations were obtained from the similar operating condition from previous literature studies in sodium chloride (NaCl) rejection, and the performance is VMD>DCMD>SGMD>AGMD (Figure 1). It can be observed that VMD has the highest permeate flux among all the configurations, whereas AGMD has the lowest permeate flux. The amount of permeate flux is related to the mass transfer in the process [10]. This affects the type of configuration used due to the fundamental differences in the transport mechanisms of the configurations. DCMD is the most straightforward configuration that provides a good permeate yield [11]. VMD has a lower resistance to the water vapour when it is transported to the permeate side through the membrane from the feed side because a vacuum state is created on the permeate side by removing all the air in the membrane pores with a vacuum pump. Thus, mass transfer in VMD gets enhanced and is greater compared with DCMD. This also illustrates the air presence on the permeate side of DCMD obstructs the mass transfer and reduces flux [12]. Another aspect to explain the high permeate flux result in VMD is the high-pressure difference across the membrane in VMD. It is hypothesized that the most significant driving force is provided due to the low pressure (vacuum state) on the permeate side. More significant pressure differences between the membrane of the feed side and the membrane of permeate side result in a convective mass flow transport through the membrane that contributes to the total mass transfer [13, 14].

Although sweeping gas is used to enhance the mass transfer coefficient in SGMD, Khayet reported the sweeping gas temperature would increase along the membrane due to heat transfer from the feed side to the permeate [15]. Because of the increasing temperature of the sweeping gas on the permeate side, the pressure differences between the membrane on the feed side and the membrane on permeate side will eventually decrease and cause lesser mass flow. SGMD present a higher permeate flux due to greater evaporation efficiency than DCMD [16]. However, it was found that slow sweeping gas velocity and module length become the limiting factors to the permeate flux [17]. Low sweeping gas velocity and a long membrane module will result in a long retention time of water vapour, which causes a rise in water vapour partial pressure on the permeate side. Subsequently, when more water vapour diffuses through the membrane, more water vapour is produced on the permeate side, and a larger steam partial pressure is induced with the sweeping gas on the permeate side. As a result, SGMD was restricted by its flux due to higher flux having higher steam partial pressure, which eventually reduced the flux [18, 19]. In short, high sweeping gas is required to meet the significant permeate yield.

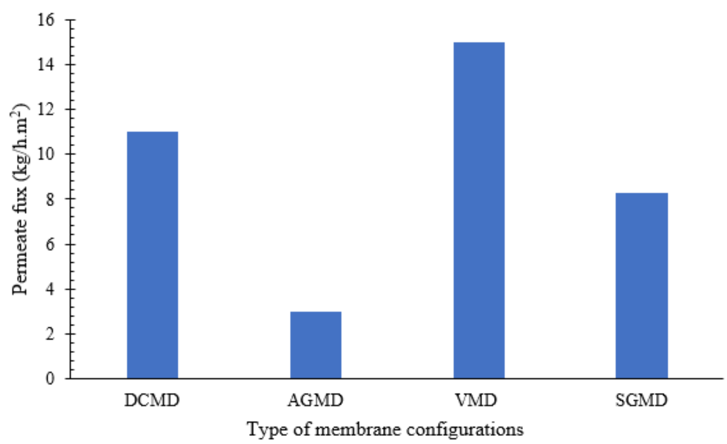

Figure 1 Water permeate flux for different configurations under the feed temperature at 60°C, permeate temperature at 45°C, NaCl concentration of 150g/mL, and vacuum pressure of 20kPa for VMD using flat sheet PTFE polymeric membrane [10]

2.2 Thermal Energy Efficiency

Thermal efficiency is one of the critical considerations when selecting configuration in water desalination. A good configuration will provide a satisfying thermal efficiency to maintain significant permeate fluxes during the desalination process and save enormous costs [20]. The energy efficiency of AGMD is comparable to DCMD due to the introduction of an air gap in the configuration. On the other hand, the energy efficiency is increased by 1.2 when using the VMD configurations. In contrast, the energy efficiency is increased by 1.4 for SGMD when taking DCMD as the benchmark (Table 1). Karanikola and his team reported VMD to produce the highest thermal efficiency. As a result, the order of energy efficiency is VMD>SGMD>AGMD>DCMD [21]. Based on this sequence, it is observed that VMD obtained the highest energy efficiency while DCMD has the lowest energy efficiency. The arrangement in DCMD is the primary cause that results in low energy efficiency in which the distillate is directly in contact with the membrane surface on permeate side [22]. This leads to a high heat transfer coefficient on the permeate side and is responsible for noticeable heat conduction losses through the membrane from the feed side to distillate on the permeate side [23]. As a result, DCMD presents lower thermal energy efficiency when compared with other configurations.

Table 1 The effect of configuration on energy efficiency

Configuration	Energy Efficiency (%)	Factors	References
DCMD	67	× 1	[10]
AGMD	68		
DCMD	54	× 1.2	
VMD	66		
DCMD	35	× 1.4	[24]
SGMD	51		

Nevertheless, the heat conduction losses through the membrane have been mitigated in AGMD. Previous studies have claimed that the air gap between the permeate side membrane and condensation surface functions as a heat insulation layer to reduce heat loss caused by conduction [22, 25]. Literature studies show that air gap (trapped air) could be applied as insulating material in other applications to prevent heat loss as air is a well-known poor conductor [26]. Besides, the greater the thermal conductivity, the more heat transferred from a fluid to the surface. Air (0.026 W/m.K) obtained lower thermal conductivity than water (0.58 W/m.K); thus, lesser heat transfer occurs when an air gap is introduced in AGMD [27]. This justifies the thermal energy efficiency of AGMD is slightly higher than DCMD according to the order of the energy efficiency mentioned above. VMD shows an increase of 1.2 factors of energy efficiency compared to DCMD. Since the vacuum is applied on the permeate side, the heat loss due to conduction through the membrane is negligible [28]. As in the vacuum state, significantly fewer molecules act as the medium for heat transfer to occur by conduction and convection. As a result, VMD provides the highest thermal energy efficiency among other configurations.

The thermal conductivity of inert gas is relatively more minor than air except for helium under the same temperature. Therefore, the heat conduction loss in SGMD is lesser than in AGMD, which exhibits high thermal energy efficiency. Although most studies have mentioned that cold, inert gas is used in the principle of SGMD, prior research has recognized that air (humid air or dry air) is also an alternative sweep gas. Shirazi and co-workers reported that cold dry air is the most utilized sweep gas in SGMD compared to inert gas due to its easily accessible and low cost [30]. To further explain from this perspective, the energy efficiency will not be influenced as the thermal conductivity of gas decreases along with the temperature. In short, whether dry air or inert gas is employed, the energy efficiency of SGMD is greater than AGMD, proving the correctness of the energy efficiency sequence indicated before [31].

3.0 INFLUENCE OF OPERATING PARAMETER ON FLUXES

3.1 Effect of Feed Temperature

The feed temperature dramatically influences the permeate flux, exponentially increasing in all configurations when the feed temperature is raised (Figure 2). This could be explained by Antoine Equation, where the vapour pressure increases exponentially with temperature. Because the main driving force of membrane distillation is based on the vapour pressure differences [32]. Indeed, when the feed temperature is high, more liquid molecules will transition to vapour molecules. This will eventually increase the water vapour pressure at the feed membrane surface. Therefore, the mass transfer increases accordingly and results in high permeate flux. Thereby, it is suggested to operate membrane distillation at a high feed temperature.

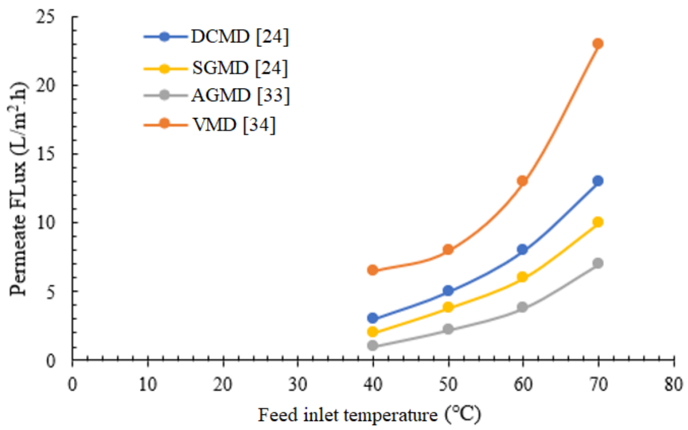

Figure 2 Effect of feed inlet temperature on permeate flux of DMCD, VMD, AGMD and SGMD using PVDF membrane [24, 33, 34]

On the other hand, temperature and concentration polarization are important factors that impact the permeate flux [35]. It defines the temperature and concentration differences between the bulk feed and membrane interfaces. When the polarization effects are high, a decrease in temperature and concentration increases at the feed side membrane interface is observed, resulting in permeate flux reduction (Table 2) [36]. Additionally, Ravisankar (2018) reported that the temperature and concentration polarization effects would slowly become significant as the temperature elevated [36]. Ali and his co-worker suggested the association of increased convective and conductive heat flux through the membrane at higher temperatures, resulting in a more tremendous difference between the bulk and membrane surface temperatures. Furthermore, greater evaporation at the membrane surface at high temperatures causes a cooling effect, resulting in higher boundary layer resistance. As a result, increasing the resistance of the boundary layer aid in enhancing the temperature and concentration polarization [37]. As to literature studies, temperature and concentration polarization will reduce the driving force and lead to low permeate flux [36, 37]. Hence, considering the effects of polarization suggests the feed temperatures in membrane distillation typically range from 60 to 90ºC [38].

Table 2 Relationship of resistance of feed side boundary layer to mass transfer at a different temperature [37]

Temperature (ºC)	Resistance to mass transfer (R_f)
45	401
55	450
65	505
75	534

3.2 Effect of Feed Concentration

Permeate flux can be observed to decline from all types of membrane configuration when feed concentration increases (Figure 3). The increment of non-volatile solutes (salts) in the feed will reduce feed vapour pressure. This is because the presence of salt decreases the free water molecule exits at the solution surface as a bond is formed between the free water molecule and the salt. Hence, lesser free water at the surface evaporates, where water activity is reduced and eventually causes high feed viscosity at the membrane surface [39]. The increase of feed viscosity and density would ultimately result from decreases in heat and mass transfer from the bulk to the membrane surface. Thereby, decline in permeate flux [40]. Notably, the effect of concentration polarization becomes prominent to permeate flux at high feed concentration compared to temperature polarization [37]. The decline of the permeate flux is contributed by the formation of an additional boundary layer due to the concentration polarization effect. This concentration boundary layer, coupled with the temperature boundary layer, acts as extra resistance to the movement of vapour molecules and reduces the evaporation driving force [40].

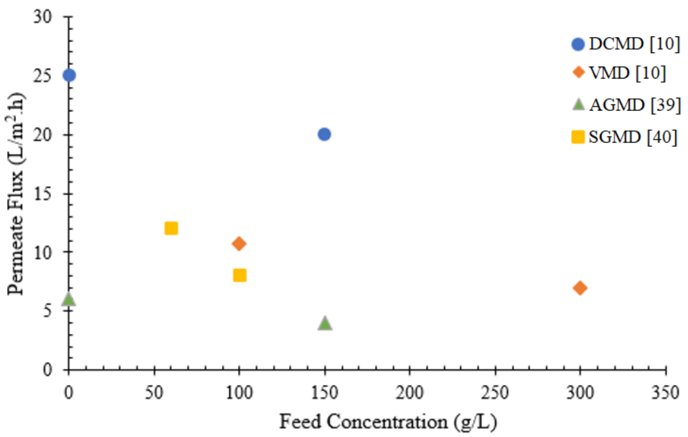

Figure 3 Effect of feed concentration on permeate flux of DMCD (PVDF membrane), VMD (PVDF membrane), AGMD (PVDF membrane) and SGMD (PVDF-co-HFP membrane) [10, 39, 40]

3.3 Effect of Feed Flow Rate

The increase in feed flow rate enhances the flux attributed to the heat transfer coefficient on the feed side attributed to the thinner thickness of the thermal boundary layer and hence, reduces the boundary layer resistance (Figure 4). Thereby, the effect of temperature polarization reduces. Meanwhile, the effects of concentration polarization reduce as well as the high feed flow provides a better mixing which makes lower accumulations of solutes at the active membrane surface [41]. Most studies have identified that the permeate flux reaches asymptotic values as feed flow increases. This is because when the flow turns from laminar to turbulent, the thickness of the boundary layer cannot be further reduced [10]. In addition, Ravisankar reported that DCMD, VMD, and AGMD have apparent effects on permeate flux on the increment of feed flow compared to SGMD [36]. This is mainly because the resistance to the permeate flux of SGMD is more significant on the sweep gas boundary layer. Hence, SGMD is less sensitive to feed flow rate as it is more susceptible to sweep gas flow. An increase in the sweep gas flow could positively affect the permeate flux by reducing the resistance of the sweep gas boundary layer. Notably, excessive-high feed flow will lead to a significant pressure drop in the feed channel. This causes a high risk of membrane wetting phenomenon as different liquid entry pressure occurs at other membrane locations and consequently causes low permeate flux and thermal energy efficiency [42]. In short, the greater the feed flow, the smaller the effects of temperature and concentration polarization and hence the more significant the permeate flux. Generally, it is suggested that the feed flow operates under turbulent conditions [43].

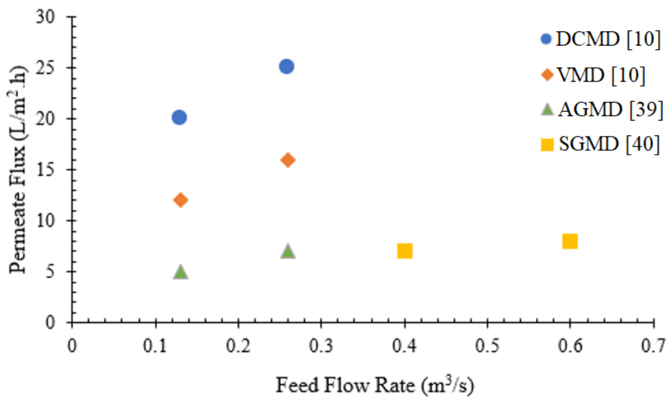

Figure 4 Effect of feed flow rate on permeate flux of DMCD, VMD, AGMD and SGMD using PVDF membrane

3.4 Effect of Long-Term Operation

The permeate flux decreased linearly over time with the continuous operation for 100 days. The researchers have suggested membrane wetting and membrane fouling would be the factors that cause reducing in permeate flux. There is a 30% flux decline in one month observed by Franken and co-workers where during the progress, it is found that many pores became wetted, which causes a backflow of permeate to the feed side [45]. This issue was further validated by adjusting the hydrostatic pressure on the permeate side, where the flux decreases as the hydrostatic pressure increases. On the other hand, the influence of flux decrement due to membrane fouling can be caused by bacteria growth on the membrane surface and scaling of the membrane. McGaughey, Gustafson and Childress discovered a small degree of fouling phenomenon is likely to occur over a long period even using tap water as the feed for membrane distillation [45, 46]. This was due to the trace amount of organic matter in the NaCl feed solution, although no foulants were added. This is also applicable when seawater is used in desalination as abundance of various organic matter could exist in seawater such as dissolved organic matter, particulate organic matter, phytoplankton, and zooplankton fishes [47]. Besides, there is a possibility of dust entering the feed solutions from the environment and resulting in membrane fouling. Moreover, the nature of the hydrophobicity membrane and increment of feed temperature could eventually result in resistance to mass transfer due to the attraction of organics to the membrane surface. Furthermore, high salinity solutions (seawater) would build upscaling on the membrane surface, leading to pore clogging and pore wetting problems.

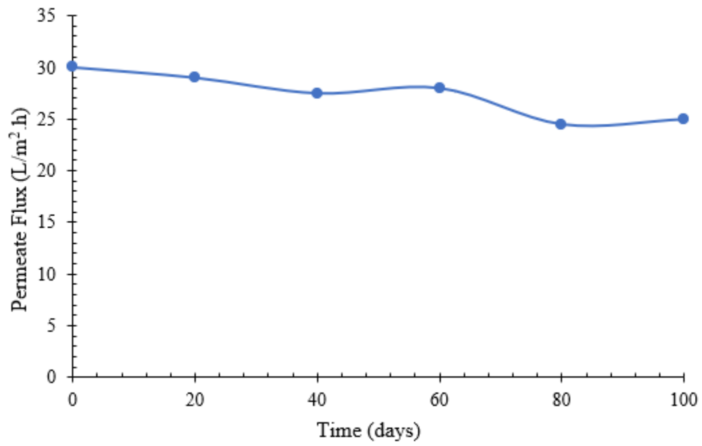

Figure 5 Effect of long-term operation on permeate flux performance by DCMD using PTFE membrane with the operation condition of feed temperature at 65°C, permeate temperature at 35°C, NaCl concentration at 35 g/L. [44]

4.0 CONCLUSIONS

Adoption of membrane distillation in seawater desalination can be a potential and promising solution for the water scarcity issues that are caused by the high demand for fresh water due to the world's population increase and industrial development. Each configuration in membrane distillation obtains its superiority and inferiority due to differences in features. In this work, the effectiveness of each configuration in terms of permeate flux and thermal energy efficiency is investigated, and the order is VMD>DCMD>SGMD>AGMD and VMD>SGMD>AGMD>DCMD, respectively. The results show VMD provides the highest permeate flux and thermal energy efficiency among all the configurations. The increases in feed temperature and feed flow rate could provide higher permeate flux. This is because the water vapour pressure increases along with temperature, increasing mass flux. In comparison, an increase in feed flow causes the reduction of the polarization effect and, thus, less boundary resistance to mass flux. At the same time, high feed concentration and long-term operation negatively affect the permeate flux. Raise in feed concentration results in a reduction of water activity and high polarization effects, causing a decline in permeate flux. For the long-term operation of membrane distillation, the permeate deteriorates due to membrane fouling and membrane wetting. Nevertheless, based on the findings obtained from this study, it is suggested that the MD possess the feasibility to be applied in the commercial desalination application subjected to further advancement in tackling the fouling issue.

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