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Influence of high range of mass transfer coefficient and convection heat transfer on direct contact membrane distillation performance

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ABSTRACT

In order to improve water production of membrane distillation (MD), the development of high performance membrane having better mass transfer and enhancement of convection heat transfer in MD module have been continuously investigated. This paper presents the relationship between the heat and mass transfer resistance across the membrane and the performance improvement. Various ranges of mass transfer coefficient (MTC) from normal (0.3×10^{-6} to 2.1×10^{-6} kg/m^{2}sPa: currently available membranes) to high ($> 2.1 \times 10^{-6}$ kg/m^{2}sPa: membranes under development) were simulated using an experimentally validated model at different ranges of convection heat transfer by varying the inlet flow rates and spacer enhancement factor. The effect of mass transfer and convection heat transfer on the MD performance parameters including temperature polarization coefficient (TPC), mean permeate flux, and specific energy consumption were investigated in a direct contact MD (DCMD) configuration. Results showed that improving the MTC at the low ranges is more important than that at the high ranges where the heat transfer resistance becomes dominant and hence the convection heat transfer coefficient must be increased. Therefore, an effort on designing MD modules using feed and permeate spacers and controlling the membrane surface roughness to increase the convection heat transfer and TPC in the channel aiming to enhance the flux is required because the currently developed mass transfer has almost reached the critical point.

1. Introduction

Membrane distillation (MD) is a thermally driven process that uses a hydrophobic microporous membrane as a contactor between two fluids at different temperatures. MD has been tested for different applications, such as desalination and industrial wastewater treatment [1–3]. It has gained researchers attention as one of the next-generation desalination techniques owing to the benefits it has compared to the avialable conventional systems, which include: (i) operates at low temperature (relative to thermal desalination process); (ii) operates at lower hydraulic pressure (relative to reverse osmosis (RO) process); (iii) has higher boron and other compounds removal efficiency (relative to RO); (iv) needs low footprint; and (v) has lower sensitivity to feed salinity [1,4–10]. However, low water production (flux) with larger modules is one of its limitations which makes its scale-up and commercialization challenging [3,11–13].

Several studies were focused on increasing MD water production. Researchers have also attempted to fabricate novel MD membranes aiming to improve its mass transfer coefficient (MTC), while other groups tried to optimize the process by looking at the optimal operation conditions that yield better flux with lower energy requirement. A proper MD membrane needs to have [14]: (i) high permeability, (ii) lower thermal conductivity, (iii) high hydrophobicity (high water contact angle), (iv) narrow pore size distribution, (v) high mechanical strength, (vi) excellent chemical resistance and (vii) good thermal stability. In theory, the MTC increases with increasing the mean pore size and porosity and decreases with increasing membrane thickness. Furthermore, it increases with an approaching to the lowest tortuosity value (1.0) [1,3]. MTC, which is usually set by the structural parameter of microporous hydrophobic membrane, is the most important factor for the MD performance. It consists of the value of the resistance of water vapor transport through the microporous membrane, which makes it affecting the overall MD performance, such as temperature polarization coefficient (TPC), mean permeate flux (MPF), and specific energy consumption. The latter (see S19)) is one of the standard parameters for the performance similar to the gained output ratio (GOR) in kWh/kg. Therefore, the development of novel membrane having higher MTC is required to overcome the low water production

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Table 1
Reported DCMD membrane MTC [11]. DI water was used as feed solution.

Membrane material	Pore size (μm)	MTC (kg/m^2sPa)
PTFE	0.20	1.45×10^{-6}
	0.45	2.15×10^{-6}
PVDF	0.22	3.8×10^{-7}
Enka (pp)	0.10	4.5×10^{-7}
Enka (pp)	0.20	4.3×10^{-7}
PVDF	0.45	4.8×10^{-7}
GVHP	0.22	4.919×10^{-7}
HVHP	0.45	6.613×10^{-7}

[15–20]. Development of non-polymeric materials embedded membranes (i.e., carbon nanotubes (CNTs)) integrating nanomaterials into polymeric materials have been attempted to improve the membrane's MTC [15,16,21]. Double-layer membranes have also been investigated as a potential MD composite membrane where the enhanced MTC is achieved through making the active layer as thin as possible [1,14,17–20]. With the continual development of novel membranes, various MTCs are being reported and the highest value reported in the MD literature so far is 2.15×10^{-6} kg/m^2sPa [11], as shown in Table 1. Although it was reported in 2011 [11], the 2.15×10^{-6} kg/m^2sPa value is still considred at the highest level, so far [5].

The optimization of MD operating conditions can reduce the effects of concentration polarization and temperature polarization. It was reported that CP effect can be negligible in the MD process [8,22], while temperature polarization was considered as one of the main issues that can lower MD performance since it is significantly affecting the driving force (i.e. water vapor pressure) [1,23,24]. This phenomenon is caused by the temperature difference with bulk and liquid/vapor interface on the membrane surface. In addition, due to the lack of measuring technique for the transmembrane temperature, the theoretical simulation study of MD process is necessary. And through the simulation study, the temperature polarization coefficient as a key factor of MD process can be estimated (see Eq. (S20)). Therefore, recent studies have been focused on reducing temperature polarization effect by improving convective heat transfer in the flow channel without increasing the inlet flow rate (even at laminar flow). The use of polymeric spacers [25–31] and the enhancement of membrane surface roughness [32–34] act as turbulence promoter techniques to improve the convection heat transfer coefficient.

Generally, higher MTC and convection heat transfer coefficient can lead to high MD performance. However, the latter cannot be expected to have a proportional increase with an increase of MTC and convection heat transfer coefficient due to the balance of heat and mass transfer. Thus, research is required to achieve a better understanding of the effect of these two parameters on the MD performance and to subsequently improve it. In this study, the theoretical simulations at various ranges of these coefficients were conducted to investigate their effects on TPC, mean permeate flux, and specific energy consumption. Results of this study show the predictable results however, to our knowledge it is not reported in the literature. The effect of heat and mass transfer on the direct contact MD (DCMD) process is necessary to be explained and reported using a variety of thermal and MTCs. This study also tried to provide research and development guidelines aiming to set ranges at which these parameters are more or less effective in enhancing the MD process performance. The investigation was assessed using a small-scale DCMD unit. An extensively and experimentally validated theoretical based simulation model under different conditions [1,4,35] consisting of mass, momentum and energy balances in the bulk feed and permeate channel flows was employed (see more details in the supplementary information).

Table 2
Properties of the pseudo hydrophobic microporous membrane (assumed for this study).

Property	Unit	Hydrophobic pseudo microporous membrane
MTC (C)	kg/m^2sPa	0.3×10^{-6}-6.3×10^{-6} Developed based on reported values: 0.3×10^{-6} to 2.1×10^{-6}, Normal To be developed: 2.1×10^{-6} to 6.3×10^{-6}, High
Thermal conductivity of	W/mK	0.25 (Assumed PTFE)
Membrane (k_m)	W/mK	0.026
Thermal conductivity of Air (k_a)	%	80
Porosity (ε)		
Thickness (δ)	μm	100

2. Scenarios for DCMD simulation

In all simulated scenarios, a lab-scale DCMD process setup was considered and its operational parameters are as follows:

(i) Feed and permeate flows are circulated in a counter-current manner at the same flow rate.
(ii) The dimensions of membrane module channel are 5 cm × 10 cm × 0.3 cm (width × length × depth) with an effective membrane surface area of 50 cm^2.
(iii) The *pseudo* properties of the microporous hydrophobic MD membrane and operating conditions used for this study are given in Tables 2 and 3, respectively. A small lab-scale module was used in this study to avoid the prediction error for scaling up.

The thermal conductivity coefficient (0.25 W/mK) and thickness of the membrane (100 μm) were employed as normal values (Table 2). The thermal conductivity coefficients of hydrophobic polymers at 23 °C are 0.17–0.21 W/mK (polypropylene, PP), 0.19 W/mK (Polyvinylidene fluoride, PVDF), and 0.25 W/mK (Polytetrafluoroethylene, PTFE). MTC values were categorized as (i) developed, based on Table 1 (0.3×10^{-6} kg/m^2sPa to 2.1×10^{-6} kg/m^2sPa, referred as normal), and (ii) to be developed (2.1×10^{-6} kg/m^2sPa to 6.3×10^{-6} kg/m^2sPa, referred as high). It is reported that the MTC is not only determined by the structural parameter of hydrophobic membrane but also the characteristic of hydrophobic membrane [21]. Therefore, it is believed that the MTC can be increased over the limitation of structural theory. The normal ranges of operating conditions were also employed. The membrane thicknesses were not provided in a privious study [11]. However, most hydrophobic membranes used in the MD process possess thicknesses ranging from 10 μm to 200 μm [5]. Thus, in this study, the membrane thickness was assumed to 100 μm. As shown in Eq. (S1), the MTC of membrane is associated with the structural parameters which means that the hydrophobic membrane having the proper pore radius, the high porosity, the proper tortuosity ($\tau \approx 1$), and low thickness can

Table 3
Detailed operating conditions for DCMD process (F and P represent the feed and permeate, respectively).

Parameters	Unit	Value
Temperature	°C	60 (F) and 30 (P)
Flow velocity	m/s	0.044 to 0.222 (F and P)
Feed salinity	g of NaCl/L	40
Modified convection heat transfer coefficient of feed inlet ($CHT_{f\ and,p,m}$[a])	Times (×)	1.0 to 1.5 (F and P)

[a] Flow rates of both feed and permeate sides = 2.0 L/min.