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Application of a porous composite hydrophobic/hydrophilic membrane in desalination by air gap and liquid gap membrane distillation: A comparative study

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ABSTRACT

A first attempt was carried out comparing the two membrane distillation (MD) configurations, liquid gap (LGMD) and air gap (AGMD), using a porous composite hydrophobic/hydrophilic membrane, the same system and the same MD operating parameters. The surface modified membrane was prepared by the phase inversion technique in a single casting step using a fluorinated surface modifying macromolecule (SMM). Different membrane characterization techniques were applied. MD experiments were performed at different feed temperatures and sodium chloride aqueous solutions. The permeate fluxes were found to be slightly higher (2.2–6.5%) for LGMD compared to that of AGMD although the resistance to mass transfer in LGMD is higher due to the presence of the liquid permeate layer between the membrane and the cooling solid surface. This observed enhancement is attributed partly to the small established distance between the liquid/vapor interfaces at both side of the hydrophobic thin top-layer of the membrane in LGMD configuration, and the higher thermal conductivity of water, which is an order of magnitude higher than that of air, resulting in higher heat transfer coefficient of the permeate in LGMD. The salt rejection factors were found to be almost similar for both MD variants and higher than 99.61%. Compared to AGMD, the thermal efficiency is higher for LGMD, whereas the specific internal heat loss is lower. A linear increase of the thermal efficiency with the feed inlet temperature was observed for both MD configurations. The global heat transfer coefficient and the heat transfer of the permeate membrane side were also found to be greater for LGMD. The temperature polarization effect was found to be slightly higher for AGMD, whereas the concentration polarization effect was slightly higher for LGMD due to its higher permeate flux. In general, the LGMD proved to be more attractive than AGMD for desalination when using bi-layered hydrophobic/hydrophilic membranes.

1. Introduction

To establish the necessary driving force in membrane distillation (MD) technology, which is the partial vapor pressure difference across the membrane, four principal configurations were first proposed in the 60s, namely, direct contact membrane distillation (DMCD), sweeping gas membrane distillation (SGMD), vacuum membrane distillation (VMD) and air gap membrane distillation (AGMD) [1]. Then, during last decade some hybrid MD variants termed thermostatic sweeping gas membrane distillation (TSGMD) and liquid gap membrane distillation (LGMD) were considered in order to enhance the water production rate and the thermal efficiency of the MD technology [2–4]. For LGMD mode, which also termed permeate gap MD, the air gap space between the membrane and the condensing surface of the AGMD module is normally filled with the produced water. The permeate water exits from the top part of the membrane module whereas in AGMD the permeate water leaves the module from the bottom. The differences between all these MD configurations are made only in the permeate side.

TSGMD combines both SGMD and AGMD in order to minimize the temperature of the sweeping gas, which increases considerably along the membrane module length because of the heat transferred from the feed side through the membrane to the permeate side [3,4]. LGMD combines both DCMD and AGMD configurations. The gap between the membrane and the condensing surface in the permeate side of the AGMD system is filled by the produced distilled water acting as stagnant cold liquid solution inside the membrane module [2,5–7].

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Nomenclature

Symbols

A_m	membrane area (m^2)
B	membrane permeability in Eq. (11) (kg/(m^2 s Pa))
B_g	gas permeance in Eq. (18) (mol/(m^2 s Pa))
C	salt concentration (g/L)
c_p	specific heat (kJ/(kg °C))
d_p	mean pore size (nm)
D	diffusion coefficient (m/s)
d_e	equivalent diameter of the feed flow channel (m)
EE	thermal efficiency (%)
h	heat transfer coefficient (W/(m^2 K))
H	overall heat transfer coefficient (W/(m^2 K))
HL	specific internal heat loss (kJ/g)
I	intercept in Eq. (18)
J_w	permeate flux (kg/(m^2 h))
k	thermal conductivity (W/(m K))
k_s	mass transfer coefficient (m/s)
L	module length (m)
L_p	effective pore length of the membrane (μm)
LEP	liquid entry pressure of water (Pa)
Nu	Nusselt number
$\dot{m}_f$	feed flow rate (kg/h)
M	molecular weight (g/mol)
p	partial pressure (Pa)
P_m	mean hydrostatic pressure within the membrane in Eq. (18) (Pa)
Pr	Prandtl number
Q	heat flux (W/m^2)
r_p	pore radius (nm)
R	gas constant (J/(mol K))
S	slope in Eq. (18)
T	temperature (°C)
x	mole fraction
Sc	Schmidt number
Sh	Sherwood number
Re	Reynolds number

Greek letters

β	concentration polarization coefficient
δ	total membrane thickness (μm)
δ_h	hydrophobic layer thickness (μm)
ε/L_p	effective porosity (m^{-1})
ε	void volume fraction (%)
λ	mean free path (nm)
μ	dynamic viscosity (kg/(m s))
θ	temperature polarization coefficient (%)
θ_a	water contact angle (°)
ρ_w	water density (kg/m^3)
ΔH_v	latent heat of vaporization (kJ/kg)
ΔT_{ln}	logarithmic mean temperature difference (K)
ΔT_1	temperature difference between feed and permeate at the inlet of the membrane module
ΔT_2	temperature difference between feed and permeate at the outlet of the membrane module
Δp	vapor pressure difference (Pa)
Δp_{ln}	logarithmic mean vapor pressure of water difference (Pa)
γ	activity coefficient
ψ	vapor pressure polarization coefficient (%).

Subscripts

b	bulk
c	conduction
f	feed
g	gas
in	inlet of the membrane module
l	heat loss
m	membrane
$NaCl$	sodium chloride
out	outlet of the membrane module
p	permeate or pore
v	vapor
w	water

Superscripts

0	pure water

It is worth quoting that the most used MD variant is DCMD with 58.6% (calculated taking into consideration the MD published studies in International Journals up to 31st December 2013) because its simplicity in operation as condensation phenomenon is carried out inside the membrane module. On the contrary, SGMD is the least studied MD variant with a contribution of only 4.5% because it requires external condensers to collect the permeate and a gas source to generate the sweeping gas. On the other hand, a negligible number of studies were performed using the two MD hybrid variants TSGMD and LGMD (i.e. contribution of only 0.5% and 0.3% for LGMD and TSGMD, respectively).

It must be pointed out that very few comparative studies have been performed between the four principal MD configurations [6–11]. For an adequate comparison, the same membrane, module if possible, feed side hydraulic installation and MD operating conditions must be maintained. Moreover, not only the MD performance (i.e. permeate flux and rejection factors) have to be compared but also the thermal efficiency of the membrane module, the heat loss and the specific energy consumption defined as the ratio between the total applied energy and the water production rate.

Khayet et al. [8] compared the permeate flux, the thermal efficiency, the heat loss and the salt rejection factor of the DCMD, SGMD and VMD configurations using the same shell and tube capillary membrane module and the same feed MD operating conditions. It was found that the VMD permeate flux was 2.8–3.1 times higher than that of DCMD and the SGMD permeate flux was about 1.4 times greater than that of DCMD. These results were attributed to the internal heat loss by conduction through the membrane, which was very low in SGMD and VMD modes. Cerneaux et al. [9] used chemically modified zirconia and titania ceramic membranes in desalination by DCMD, AGMD and VMD variants, and observed higher permeate flux for AGMD configuration than for DCMD one; whereas the greatest permeate flux was obtained for VMD configuration with salt rejection factors varying from 99% to 100%.

In general, it is known that the air entrapped within the pores of a membrane used in DCMD results in a high mass transfer inefficiency, while the heat transferred by conduction through the membrane, which is considered heat loss in MD is high in DCMD configuration [1,12]. On the other hand, compared to AGMD configuration, SGMD combines a relatively low conductive heat loss through the membrane with a reduced mass transfer resistance. In other words, in both AGMD and SGMD variants, there is a gas barrier that reduces the heat loss by conduction through the