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Effect of non-woven net spacer on a direct contact membrane distillation performance: Experimental and theoretical studies

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ABSTRACT

This study provides a comprehensive and systematic overview of the fundamental characteristics of heat and mass transfer in the direct contact membrane distillation (DCMD) process that employs different types of spacers on one or both surfaces of the membrane. Detailed theoretical investigations were carried out to demonstrate the effects of spacers adjacent to the membrane surface on heat and mass transfer enhancement in the DCMD with a PTFE/PP composite membrane, complemented with experimental data for model validation. Thus, this work aimed to propose and demonstrate the heat transfer correlation for spacer-filled channels to reliably predict the heat and mass transfer improvement by non-woven net spacers in the DCMD process. The results showed that the permeate flux enhancement by the spacers ranged between 7% and 19% only for the spacer-filled permeate channels and between 21% and 33% only for the spacer-filled feed channels even at higher flow rates, thus indicating lower flux enhancements in the spacer-filled permeate channels. This was because the influence of spacers on flux improvement became more evident at higher temperatures owing to higher temperature polarization. In this study, the maximum flux enhancement of approximately 43% over the empty channels was achieved using the thinnest and densest spacer with a hydrodynamic angle of 90°, adjacent to both membrane surfaces.

1. Introduction

Membrane distillation (MD) has attracted significant attention in the last few decades as an emerging technology owing to its numerous advantages [1]. The driving force of MD, which is a thermally driven membrane separation process in which a microporous hydrophobic membrane is used, is the partial pressure difference of water vapor at the liquid-vapor interfaces of the membrane caused by the temperature gradient imposed on both interfaces. There are four types of MD configurations, including the direct contact MD (DCMD), air gap MD (AGMD), material gap MD (MGMD), and vacuum MD (VMD) and those are categorized by the condensation scheme inside the module [2]. In the case of DCMD, the temperature gradient results from evaporation and condensation at the liquid-vapor interface on the feed and permeate sides of the membrane, respectively, as well as heat conduction through the membrane. Therefore, the membrane surface temperature differs from its bulk temperature, a phenomenon known as the temperature polarization, thus resulting in a significant loss of the thermal driving force, and in a lower permeation flux. As a result, the performance of MD is affected mainly by temperature polarization rather than concentration polarization [1], even when treating highly concentrated saline solutions [3]. Reduction in the temperature polarization in MD can be achieved by improving the flow characteristics, such as higher flow rates and turbulence conditions. However, the resulting large pumping energy consumption is not desirable from an economic point-of-view. Moreover, in the case of the composite membrane (double layer), it is necessary to take into account the physical damage, such as the exfoliation of the soft polymer from the membrane owing to the excessively high flow rates. An alternative way to reduce the temperature polarization is the use of a spacer in the flow channel rather than increasing the flow rate [4–7]. Improvement in the flow characteristics may result from the existence of turbulence or eddy currents induced by the spacers. Although a pressure drop can occur in the channel as a result of employing the spacer-filled channels, the total specific energy consumption may be reduced owing to the increase in the water production [8].

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Nomenclature

A	effective membrane area [m^2]
c_p	specific heat capacity [J/kg °C]
d_f	filament diameter [m]
d_h	hydraulic diameter [m]
h	convective heat transfer coefficient [W/m^2 °C]
h_c	channel height [m]
h_s	spacer thickness [m]
$\Delta H\|_{al}$	enthalpy of evaporation at the mean temperature through the active layer membrane [J/kg]
$\Delta H\|_{al\text{-}sl}$	enthalpy of evaporation at the mean temperature through the active/support layers membrane [J/kg]
J	mean permeate flux [kg/m^2 h]
J_z	local permeate flux [kg/m^2 h]
k	thermal conductivity [W/m °C]
k_{dc}	spacer factor [–]
l_m	mesh size [m]
L	membrane length [m]
LEP	liquid entry pressure [kPa]
P	pressure [kPa]
PR	performance ratio [%]
Q_m	heat flux through the membrane [W/m^2]
r	mean pore size [m]
t	time [s]
T	temperature [°C]
TPC	temperature polarization coefficient [%]
v	velocity [m/s]
w	seawater salinity [wt%]
w_c	channel width [m]
W	collected permeate weight [kg]
z	axial coordinate [m]

Dimensionless numbers

Nu	Nusselt number, hd_h/k [–]
Pr	Prandtl number, $\mu c_p/k$ [–]
Re	Reynolds number, $\rho v d_h/\mu$ [–]

Greek letters

δ	membrane thickness [m]
ε	membrane porosity [%]
ε_s	surface porosity [%]
ε_{sp}	spacer porosity [%]
η_z	local performance ratio [%]
θ	hydrodynamic angle [°]
μ	dynamic viscosity [kg/ms]
ρ	density [kg/m^3]

Subscripts

exp	experiment
f	feed
m	membrane
p	permeate
sim	simulation

Such MD processes have several potential advantages: low-operating temperature and hydraulic pressure, a rejection of nonvolatile solute that is almost 100%, low sensitivity to salt concentration and concentration polarization, low-footprint requirements, and potentially high-permeation flux [1]. For these reasons, MD has been regarded as an emerging desalination technology for producing freshwater from seawater and a number of studies on MD have been conducted in recent years. The growing interest in MD is reflected in the growth rate of scientific publications over the years. Fig. 1 depicts the number of publications on “membrane distillation” (orange bars) between 1980 and 2017 obtained from ScienceDirect (www.sciencedirect.com) and shows an exponential increase over the years [9]. Conversely, the numbers of publications on “membrane distillation” and “spacers” (purple bars) between 1990 and 2017 obtained from Google Scholar (scholar.google.com) are also shown in Fig. 1 demonstrating a minor increase. In addition, Table 1 presents a detailed comparison of research articles on the MD process employing spacer-filled channels since 2000. It is shown that most of the studies have focused on DCMD processes using flat-sheet membranes. In particular, before 2010, a simple, lumped parameter model (i.e., 0D model) that ignored mass, species, momentum, and energy balances in both bulk feed and permeate flows, was mainly used for simulations. Thanks to recent advances in computational power, computational modeling approaches and methods since 2010, both 2D and 3D modeling/simulation studies has been performed using computational fluid dynamics (CFD) to investigate the heat transfer and pressure drop characteristics in spacer-filled MD.

As it can be deduced from the aforementioned literature, despite evident effects of the spacer on the heat and mass transfer enhancement in different MD processes, investigations on spacer-filled MD are still limited in comparison to other MD research topics. Only a few reports have been found to take a closer look into the effect of spacers on the heat transfer coefficient causing the mass transfer enhancement effect. In addition, despite these efforts, most of the existing theoretical and experimental studies, which have attributed a 0D and a 1D models that only consider heat or heat and mass balance, and a 2D or 3D CFD models that employ a limited computational domain due to high complexity and associated high computational time and cost, based on the lab-scale MD experiments, would be very limited in the performance evaluation of full-scale MD modules. It is important to note that both the pressure loss and the mass transfer enhancement effect of spacers used in full-scale modules can be assessed. Therefore, in regards of the later module design a more reliable and accurate detailed model of spacer-filled MDs is essentially required when evaluating the MD performance.

Therefore, the main objective of this study was to theoretically investigate the influence of spacers adjacent to the membrane on the

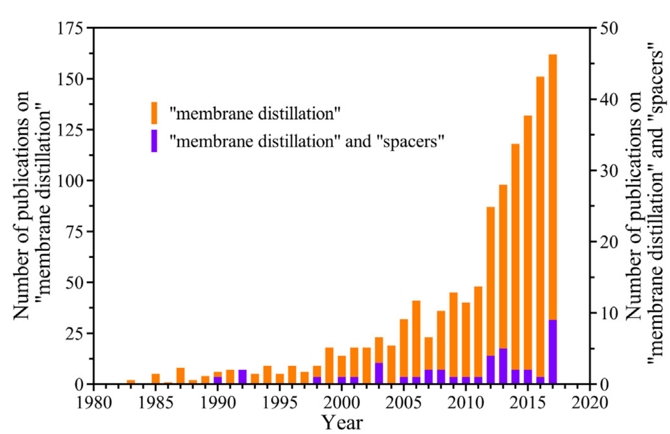

Fig. 1. Trend of the number of publications on MD and spacer-filled MD over the last four decades. The orange bars denote the number of publications on “membrane distillation” [4], and purple bars denote publications on “membrane distillation and spacers” (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).