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Experimental and numerical evaluation of membrane distillation module for oxygen-18 separation

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ABSTRACT

A novel module design for membrane distillation is attempted in this work. For this purpose, three-dimensional numerical simulations were carried out to investigate the effect of baffle configuration on the performance of three modules for liquid gap membrane distillation. Pure water was considered as feed and the simulations were performed based on dusty gas model, which describes the diffusion of vapor through the air entrapped in the membrane pores. The simulation predicted 15–25% improvement for vapor flux by utilizing triangular baffles in the module compared to a module without baffle. In particular, the newly designed triangular baffle provided uniform temperature distribution over the membrane surface, thus contributing to the improvement of vapor flux. The simulated module was constructed in order to conduct ^{18}O isotope water separation from pure water. It is worth noting that the novel module design can be used in any membrane distillation configurations.

1. Introduction

In the last decades, the membrane technology, as a state-of-the-art approach for many separation processes, has gained extensive attentions in various applications including food, chemical and process industries (Baker, 2004; Drioli and Giorno, 2009; Li et al., 2011). In this among, water treatment as a major concern of societies, has become one of the main subjects of membrane process studies. A large number of works have focused on the desalination process and herein some methods e.g., reverse osmosis (RO) and membrane distillation (MD), have been developed extensively. Of particular interest is utilization of an energy efficient membrane process to produce high purity fresh water. It is approved that MD is applicable to integrate to waste energies and in this regard, it has gained much interests among researches. The fundamental mechanism for this process is vapor pressure difference across the membrane that provides the required chemical potential gradient for permeation of water vapor through membrane pores (Khayet and Matsuura, 2011). The membrane used in MD process is either liquid/liquid or liquid/vapor contactor that can separate hot feed stream from liquid or vapor permeate stream by its hydrophobicity feature.

The basic idea of MD was proposed by Findley in U.S. and Van Haute and Henderyckx in Europe at the same time, but it did not attract much attention until 1980s (Kimura et al., 1987). Considering the advantages of MD process, it has the opportunity to have a promising future in several areas, especially in cases where MD has more preference than other separation methods. For instance, low sensitivity to high salt concentration makes MD more applicable for treating high saline water in comparison to RO (Susanto, 2011; Wang and

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Nomenclature

A	membrane area (m^2)
C	concentration of vapor (mol/m^3)
C^{sat}	concentration of saturated vapor (mol/m^3)
d	pore size (m)
D_K	Knudsen diffusion coefficient (m^2/s)
D_{wa}	water–air diffusion coefficient (m^2/s)
Q_f	feed flow rate (ml/min)
H	enthalpy of water (kJ/kg)
Kn	Knudsen number
k_B	Boltzmann constant
k	thermal conductivity (W/m K)
M	molecular weight (kg/mol)
N	mass flux (kg/m^2 s)
P	total pressure of gas in membrane pores (Pa)
p	pressure of feed stream (Pa)
Q	flow rate (ml/min)
q	heat transfer rate (W)
q''	heat flux (kW/m^2)
r	pore radius (m)
R	gas constant (J/mol K)
s	cross section of outlet channel (m^2)
T	temperature (K)
T_1	temperature in feed domain
T_2	temperature in membrane domain
T_3	temperature in permeate domain
$\bar{v}$	Mean velocity of gas molecules (m/s)
u	velocity of fluid in feed region (m/s)

Greek letters

δ	membrane thickness (m)
ε	porosity
θ	temperature polarization coefficient
$\bar{\theta}$	mean temperature polarization coefficient
λ	mean free path of molecules (m)
μ	viscosity (Pa s)
ρ	density of feed stream (kg/m^3)
σ	collision diameter (m)
τ	tortuosity factor
ζ	diffuse reflection coefficient

Subscripts

a	air
c	conductive
eff	effective
f	feed bulk
l	liquid water
m	polymer matrix
mf	membrane-feed interface
mp	membrane-permeate interface
mg	condensed surface in AGMD
p	permeate bulk
t	total
w	water vapor

Chung, 2015). RO should be driven by high hydraulic pressure to overcome osmotic pressure of high salt concentrations (>3.5%) (Guo et al., 2015). It can be estimated from van't Hoff equation (Levine, 2009) that each 10% (w/w) increase in NaCl concentration leads to 80 bar increase of osmotic pressure approximately, while the vapor pressure decreases by only 0.2 kPa in MD. Complete rejection of heavy metal ions is also another advantage of MD, which makes it suitable for treating heavy metal contaminants (Moradi et al., 2016a,b,c) and radioactive wastewater (Ambashta and Sillanpää, 2012). Separation of oxygen-18 water (Karbasi et al., 2017; Moradi et al., 2016a,b,c), removal of VOCs from water (Wijekoon et al., 2014), concentration of chemicals (Shao et al., 2014), treatment of metabolic wastewater in spacecraft (Cath et al., 2005) and various applications in the metallurgical industry (Zeng and Gao, 2010) are other examples of MD usages.

MD process has the benefit of low operating pressure and capability to use low-grade energy sources (Manzoor et al., 2017). The required energy for this process could be provided from various sources such as solar energy, heat ponds, geothermal energy, and industrial waste energies (Francis et al., 2014). In this regard, a number of interesting studies were made on energy consumption of MD process (Khayet, 2013; Zuo et al., 2011). Moreover, using an optimal design of multistage MD could reduce the final cost of product water (Lu and Chen, 2011).

Different configurations of MD have been defined according to the method of collecting permeated vapor. In the direct contact membrane distillation (DCMD), both hot and cold streams are in contact with membrane surfaces and the permeated vapor condenses at the membrane–cold stream interface. In the air gap membrane distillation (AGMD), a coolant plate is placed near the membrane where the vapor condenses on it before exiting the module. In both sweep gas membrane distillation (SGMD) and vacuum membrane distillation (VMD), the permeated vapor is condensed out of the membrane module. Further demonstration of other MD configurations, relating mechanisms and applications can be found elsewhere (Camacho et al., 2013; Khayet and Matsuura, 2011). Another configuration that can be considered as a hybrid scheme of DCMD and AGMD is liquid gap membrane distillation (LGMD) (Ugrozov et al., 2003). In some literatures LGMD is regarded as one of members of a higher class named permeate-gap membrane distillation (Swaminathan et al., 2016) in which the gap between membrane and coolant plate is filled with various materials. In LGMD, a coolant plate is placed near the membrane, to provide the required heat sink, similar to AGMD, but the liquid water fills the gap and comes into contact with membrane as in DCMD. Fig. 1 demonstrates these configurations schematically. The water accumulates in the gap and leaves the module gradually without any external force. It was proven that LGMD had higher energy efficiency than AGMD (Essalhi and Khayet, 2014; Swaminathan et al., 2016). Although the air gap in AGMD minimizes the conductive heat, it declines the permeate flux due to weak heat extraction from permeate side which induces low temperature difference across membrane thickness. Hence a slightly better thermal efficiency is found for LGMD (Guillen-Burrieza et al., 2015). On the other hand, LGMD has some advantages of both DCMD and AGMD, i.e. less heat resistance than AGMD due to high conductivity of water, and ease of applying in a cascade design with usage of different types of coolant fluids. Therefore, LGMD configuration is chosen for further investigation in this work.

The ultimate goal of our works is utilizing MD for producing a high value material, i.e. oxygen-18 water. $H_2{}^{18}O$ is a stable isotope to be used as a precursor in positron emission tomography (PET scan) and as a tracer in various chemical or environmental researches (Jouzel and Merlivat, 1984; Yang et al., 1995). The abundance of oxygen-18 among other isotopes of oxygen is about 0.2%. In this among, water could be