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Modelling of air gap membrane distillation and its application in heavy metals removal

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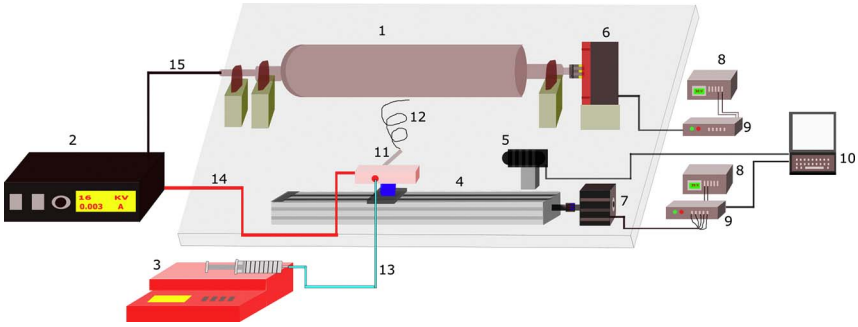
GRAPHICAL ABSTRACT



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ABSTRACT

In the present study, theoretical and experimental investigations were carried out to examine the effect of changing the operating parameters of an air gap membrane distillation (AGMD) system on the performance of electrospun and commercial membranes. These parameters include feed, cooling water temperature and feed flow rate. Analytical models were used, with the aid of MATLAB, to predict the permeate flux of AGMD based on heat and mass transfer. Heat transfer was used to predict the temperature on the membrane surface on the feed side and the thin film layer in the cooling plate on the air gap side, which was used later to calculate the vapour pressure and the permeate flux. The molecular diffusion model corresponded well with the experimental measurements in terms of predicting the permeate flux by varying the feed temperature, while it was poor in term of coolant temperature and feed flow rate. The results also illustrate that high rejection rates of around 99% of heavy metals can be achieved by using superhydrophobic electrospun membranes. The electrospun membrane flux increased with increasing feed tank temperature and flow rate while it was reduced with an increase of cooling line temperature.

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List of symbols

b	Air gap thickness	m
B_m	Thermally driven mass transfer coefficient	kg/m^{2}sPa
C_f	Feed concentration	mg/l
C_{mf}	Feed side membrane concentration	mg/l
de	Isopropanol density	g/m^3
dp	PVDF polymer density	g/m^3
D	Diffusion coefficient	ms^{-2}
h_f	Feed side heat transfer coefficient	W m^{-2}K^{-1}
h_m	Membrane heat transfer coefficient	W m^{-1}K^{-1}
h_p	Permeate heat transfer coefficient	W m^{-2}K^{-1}
H_v	Latent heat of vapourisation	J kg^{-1}
J	Water flux	L m^{-2}h^{-1}
k_{air}	Thermal conductivity of the air	W m^{-1}K^{-1}
k_f	Mass transfer coefficient	ms^{-1}
k_m	Thermal conductivity of the membrane	W m^{-1}K^{-1}
K_n	Knudsen number	–
M	Molecular weight	g mol^{-1}
p	Vapour pressure	Pa
p_{mf}	Vapour pressure at the feed membrane interface	Pa
P	Total pressure	Pa
P_a	Partial pressure of air in membrane pores	Pa
q_f	Feed flow rate	ml min^{-1}
q_p	Permeate flow rate	ml min^{-1}
Q	Heat flux	W m^{-2}
Q_f	Feed side convective heat flux	W m^{-2}
Q_m	Conductive heat flux through the membrane	W m^{-2}
Q_p	Permeate side convective heat flux	W m^{-2}
R	Universal gas constant	J mol^{-1}K^{-1}
T	Average temperature	K
T_f	Feed side inlet temperature	K
T_{mf}	Feed side membrane temperature	K
T_{mp}	Permeate side membrane temperature	K
T_{cd}	Thin film condensate temperature	K
T_{ca}	Cooling plate (permeate side) temperature	K
T_{cp}	Cooling plate (coolant side) temperature	K
T_p	Coolant water temperature	K
W_1	Saturated membrane with isopropanol weight	g
W_2	Dry membrane weight	g
τ	Membrane tortuosity	–
δ	Membrane thickness	m
ε	Membrane porosity	–
ρ	Density	kg l^{-1}

1. Introduction

Membrane distillation (MD) is an emerging technology for water and wastewater treatment. It is based on phase change of the feed stream due to the application of thermal energy to the feed side and cooling to the product side of the membrane. This leads to a difference in the vapour pressure, which is the main driving force of the process. A hydrophobic membrane can be used to allow only the vapour to transfer, preventing passage of solutes. Air gap membrane distillation, which is one of four membrane distillation configurations (which also includes direct contact membrane distillation, vacuum membrane distillation, sweep gap membrane distillation), is based on using an air gap on the permeate side to reduce the heat lost by conduction and temperature polarization, increasing the effectiveness of the separation method [1]. In terms of AGMD, desalination is considered to be one of the major applications for producing high quality water, particularly from sea water [2,3]. However, AGMD can be used for other applications, such as treatment of oil-produced water [4], removal of dyes from textile wastewater [5] and other environmental waste water issues such as tackling of heavy metal contamination [6–8].

It is well documented in the literature that many parameters play a crucial role in hindering commercialization of membrane distillation, such as high energy consumption, shortage of high effectiveness membrane cells, low productivity and shortage of membranes with high hydrophobicity [9]. In terms of membrane hydrophobicity, many attempts have been made to overcome this problem, such as fluorosilanization of PVDF-SiO_2 blended membranes [10] and TiO_2 nanocomposite membranes [11], incorporation of carbon nanotubes (CNT) [12], use of PVDF-clay nanocomposites [13] and surface modification using a CF_4 plasma to increase membrane hydrophobicity [14]. However, the majority of these methods involve using silane and fluorinated groups which have potential environmental consequences [15]. Recently, a research group lead by Alexander [16] has suggested using alumina NP functionalized with environmentally friendly hydrocarbon branches instead of using silane and fluorinated groups to produce superhydrophobic surfaces. Based on this fact, Attia et al. [8] reported fabrication of a superhydrophobic electrospun membrane using PVDF mixed with alumina NPs functionalized with isostearyl acids (hydrocarbon branch) with a WCA 150°.

Apart from membrane hydrophobicity, flux prediction in MD has gained great attention in recent years. In terms of AGMD modelling, the majority of work has been done by using one dimensional models to predict the permeate flux through hollow fibre or flat sheet membranes. The heat transfer model is similar for the two cases, but different models have been used to describe the mass balance. Ibarra-Bahena et al. [17] used the dusty-gas model (DGM) to calculate the mass transfer resistance for the membrane with a polytetrafluoroethylene (PTFE) flat sheet membrane with a pore size of 0.45 μm and air gap thickness of 3 mm. Alsaadi and colleagues [18] applied molecular diffusion and Knudsen diffusion in their model to calculate mass transfer resistance by using PTFE membrane. While Rochd et al. [19] carried out a full simulation of AGMD by applying several mass resistance models (Knudsen, Molecular diffusion, Viscous diffusion, DGM, Schofield, KMPT, and KMT) to predict the pure water flux.

In this work, high lead concentrations were removed from feed water via AGMD by using a novel superhydrophobic electrospun membrane prepared from PVDF polymer and environmentally friendly superhydrophobic alumina. Furthermore, a modelling program was used to enhance membrane performance in terms of increasing the permeate flux. The model was used to predict membrane flux based on mass and heat transfer balance for AGMD and validated by experimental results. AGMD parameters, such as the effect of feed solution temperature, cooling water temperature and feed flow rate, were studied and applied to different models for father validation.

2. Model description and theory

Modelling of the MD process has been accomplished most commonly for the DCMD configuration, which is considered the simplest and is the most often used. These models rely on measuring the mass and heat resistance which simultaneously occur in the MD process. In the case of AGMD, the heat balance is used to predict the membrane surface temperature on the feed side as well as the temperature of the thin film of condensed water on the cooling plate in the air gap side.

In AGMD, mass transfer occurs by the movement of water molecules in the vapour phase through the membrane pores and this movement can be attributed to one of the following mass transfer mechanisms: Knudsen diffusion, Poiseuille flow (viscous flow), molecular diffusion, transition flow (which is a combined effect of Knudsen diffusion and molecular diffusion) and surface diffusion [20–22]. Knudsen flow dominates a MD system when there are frequent collisions between the water vapour molecules and the pore wall of the membrane [23,24]. When the water vapour molecules collide with each other and, less frequently, with the membrane, Poisseuille flow occurs [23]. While the collisions happen between water molecule and the pore wall, as well as