



An experimentally optimized model for heat and mass transfer in direct contact membrane distillation



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ABSTRACT

Membrane distillation (MD), a thermally driven process involving hydrophobic micro-porous membranes has gained widespread interest in academic research and is set to become an alternative solution to other membrane separation processes such as reverse osmosis (RO). Although extensive experimental studies have been carried out since the 1980s [1,2], clear understanding of the heat and mass transport phenomena has yet to be established. This manuscript presents experimental results of direct contact membrane distillation (DCMD) with de-ionized water and aqueous salt solutions of NaCl with concentration levels of up to 15 ppt as feed together with an experimentally optimized and validated model for the prediction of the permeate flux in DCMD for GE Aspire Membrane QL 833 (GE Energy). Different heat transfer prediction methods in combination with the three different forms of the Dusty Gas model for mass transport were used in the comparison of our experimental data in the laminar and turbulent flow regimes under steady-state conditions. The comparison between experimental and predicted results confirmed our expectation that the Knudsen-molecular diffusion transition model yielded the best prediction. We have also identified, based on the comparison of the data, the most accurate heat transfer correlation for the laminar and turbulent flow regimes, taking into account the experimental and permeate prediction uncertainties to optimally address the heat and mass transport equations used in DCMD studies. Hence, it is highly recommended that these heat transfer correlations and the Knudsen-molecular mass transport equation be used in the prediction of heat and mass transfer for flat sheet DCMD experiments.

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1. Introduction

Membrane distillation (MD) has been investigated in academia since the 1980s, triggering a 42-fold increase in scientific journal publications for the period from 1980 to 2005 in comparison with pre-1980 publications [1]. The rapid growth is attributed to the availability of novel membranes, which is a result of rapid advancement in membrane engineering and research [1]. In MD, the feed solution is maintained at temperatures below their atmospheric boiling point, providing the feasibility of using low to medium grade waste heat for the separation process.

In MD, the membranes do not alter the vapor equilibrium of the different components in the process liquids and the driving force is the result of a partial pressure gradient in the vapor phase. The

pressure difference across the hydrophobic membrane provides the driving force for the diffusion of water vapor from the hot feed (saline liquid to be treated) to the cold aqueous stream (salt-free permeate). In general, the distillation principle can be described as follows; (i) evaporation occurs at the liquid/vapor interface at the membrane surface pore entrance, (ii) water vapor diffuses through the porous membrane from the hot feed to the cold aqueous permeate stream and (iii) vapor condenses internally downstream of the membrane or externally outside the membrane module. MD exists in various configurations, namely; (i) direct contact membrane distillation (DCMD), (ii) air-gap membrane distillation (AGMD), (iii) sweeping gas membrane distillation (SGMD) and (iv) vacuum membrane distillation (VMD) [1,49]. The results presented in this manuscript correspond to direct contact membrane distillation (DCMD), where one side of the membrane is in contact with the hot feed while the other side is in contact with the cold permeate stream. Distillation results for de-ionized water and saline feed using Aspire membranes QL833 (GE Energy) are presented in detail in the following sub-sections.

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Nomenclature

A	area of membrane (m^2)	Pr	Prandtl number (–)
a_w	water activity in NaCl solution (–)	Q	heat flux (W/m^2)
B_m	membrane distillation coefficient ($kg/m^2 s Pa$)	r	nominal pore radius (m)
D	diffusivity of vapor-air mixture (m^2/s)	R	universal gas constant ($8.314 Pa m^3/mol K$)
D_w^k	Knudsen diffusion coefficient for water (m^2/s)	Re	Reynolds number (–)
D_{w-a}^0	pressure independent molecular diffusion coefficient for water and air (m^2/s)	Sc	Schmidt number (–)
D_{AB}	binary diffusion coefficient (m^2/s)	Sh	Sherwood number (–)
c	molar concentration (mol/L)	$T_{m,avg}$	average temperature in the membrane (K)
c_m	concentration at membrane surface (mol/L)	$T_{m,1}$	feed side temperature at the membrane surface (K)
c_b	bulk concentration (mol/L)	$T_{m,2}$	permeate side temperature at the membrane surface (K)
d	diameter (m)	T_f	bulk temperature on the feed side (K)
d_h	hydraulic diameter (m)	T_p	bulk temperature on the permeate side (K)
d_p	pore diameter (m)	V	fluid flow rate (l/min)
G_{Zm}	Graetz number (–)		
ΔH_{Lv}	latent heat of vaporization (J/kg)		
h_f	heat transfer coefficient in the boundary layer on the feed side of the membrane ($W/m^2 K$)	Greek symbols	
h_p	heat transfer coefficient in the boundary layer on the permeate side of the membrane ($W/m^2 K$)	δ	membrane thickness (m)
k	mass transfer coefficient (m/s)	ε	membrane porosity (–)
k_B	Boltzmann constant ($1.381 \times 10^{-23} J/K$)	λ	mean free path (m)
k_m	membrane thermal conductivity (W/mK)	μ	dynamic viscosity (Pa s)
k_s	solid thermal conductivity (W/mK)	ρ	density (kg/m^3)
k_v	vapor thermal conductivity (W/mK)	σ	collision diameter (m)
L	length of the membrane module (m)	τ	membrane tortuosity (–)
Kn	Knudsen number (–)	ϕ_μ	Sieder-Tate heating/cooling correction
M	molar mass (kg/mol)	χ	mole fraction (–)
\dot{m}	mass flow rate (kg/s)		
N	mass flux ($kg/m^2 s$)	Subscripts	
Nu	Nusselt number (–)	1	feed side membrane surface
p	total pressure inside pores (Pa)	2	permeate side membrane surface
p_1	vapor pressure at the feed side of the membrane surface (Pa)	b	bulk
p_2	vapor pressure at the permeate side of the membrane surface (Pa)	f	feed
P_t	total pressure (Pa)	h	hydraulic
p_w	vapor pressure of pure water (Pa)	m	membrane
		p	permeate
		s	solid
		t	total
		v	vapor
		w	water

The aim is to provide a comprehensive comparison of different heat and mass transfer relations to substantiate the development of an experimentally validated model for accurate prediction of the DCMD flux through the porous membrane. Both laminar and turbulent flow conditions together with two different salinity levels for the feed were considered, where the acquired experimental fluxes were compared with model flux predictions. In the scope of this work, we have also highlighted the importance of uncertainty analysis to account for the measurement errors and permeate flux prediction uncertainties, usually encountered during an experimental membrane distillation campaign.

2. State-of-the-art review: heat and mass transport in DCMD

Numerous laboratory scale experiments involving AGMD, VMD, SGMD and DCMD have been performed to date, as reported in selected references [3–15], with [8–15] dedicated to direct contact membrane distillation (DCMD). Numerous reviews on the types of membrane distillation techniques and configurations have been reported in literatures [1,2,4,49,53] and thus, is not described again in this manuscript. In the MD process, better understanding of the dominant heat and mass transport mechanisms is necessary to

yield accurate and reliable predictions. This is the primary focus of our current work.

Trans-membrane flux predictions for MD require the use of an empirical heat transfer correlation developed for rigid systems, such as a single-phase heat transfer correlation developed for internal flow in conduits or rigid heat exchangers. The heat and mass transport resistance in MD systems is significantly dependent on the module configuration and operating conditions of the distillation process. In all MD systems, the heat transfer at the feed and permeate side of the membrane is governed by the temperature polarization (thermal boundary layer resistance) that is adjacent to the feed side of the membrane surface and the cold aqueous stream (permeate for DCMD) surface. A high driving force can be achieved only when the temperature difference between the bulk feed/permeate and the temperature between the liquid–vapor interfaces (at the membrane pore opening) is minimized. For a given hydraulic cavity, the heat transfer is dependent on the flow regime, i.e. laminar or turbulent flow, Reynolds number, concentration polarization and the fluid property, namely the fluid viscosity, thermal conductivity and diffusivity. As for mass diffusion, the presence of air molecules in the membrane pores (for DCMD) and membrane/non-permeable air gap (AGMD) significantly increases the diffusion resistance when the water molecules

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