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Review

Modelling approaches in membrane distillation: A critical review

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ABSTRACT

Membrane distillation is a technique aimed at separating non-volatile components such as salts from aqueous feed streams. Mathematical modelling of a complex process like membrane distillation allows building further insight needed for effective analysis and optimization of the system, possibly leading to a breakthrough of the technology. Several models have been proposed in the literature for the heat and mass transport in the water channels of the module as well as inside the porous membranes. This article provides a critical review of these models and discusses the pros and cons of the different models to guide the reader into selecting the most suitable simulation approach. Moreover, research gaps in the literature are listed to indicate what is currently missing from a modelling as well as experimental data collection perspective. Areas for further research are suggested.

Contents

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Nomenclature

$\overline{P}$	average pressure (Pa)
δ	membrane thickness (m)
ϵ	porosity (–)
γ	activity coefficient (–)
κ	thermal conductivity (W/m K)
λ_i	mean free path of a the molecule (m)
$\lvert p_a \rvert_{ln}$	logarithmic mean pressure of air across the membrane (Pa)
μ	dynamic viscosity (Pa s)
$\overline{v}$	mean molecular speed $\left(\sqrt{\frac{8RT}{\pi M}}, \mathrm{m/s}\right)$
ρ	density (kg/m^3)
σ_i	water vapour collision diameter (Å)
τ	tortuosity (–)
^{D}	diffusive (superscript)
^{V}	viscous (superscript)
$_a$	air (subscript)
$_b$	bulk (subscript)
$_f$	feed (subscript, superscript)
$_g$	gas (subscript)
$_m$	membrane (subscript)
$_p$	permeate (subscript, superscript)
$_s$	solid (subscript)
$_w$	water (subscript)
ANN	artificial neural network
c	concentration (mol/m^3)
C_p	specific heat capacity (J/kg K)
CFD	Computational Fluid Dynamics
D	diffusion coefficient (m^2/s)
d	characteristic size of channel (m)
$D^m_{ij,e}$	effective molecular diffusion coefficient (m^2/s)
D^K_{ij}	effective Knudsen diffusion coefficient (m/s)
DCMD	Direct Contact Membrane Distillation
DGM	Dusty Gas Model
DoE	design of experiments
EE	Energy Efficiency (%)
h	heat transfer coefficient (W/m^2 K)
H_v	specific heat of evaporation (J/mol K)
HT	Heat Transfer
K	mass transfer coefficient (m/s)
K_B	Boltzmann constant (m^2 kg/s^2)
KTG	Kinetic Theory of Gasses
m	molality (mol/kg)
MT	mass transfer
Mw	molar weight (kg/mol)
N	flux (mol/m^2 s)
P	pressure (Pa)
p	partial pressure (Pa)
P_a	average pressure of air inside the membrane (Pa)
Pr	Prandtl number (–)
Pr_{wall}	Prandtl number at the membrane interface (–)
q	heat flux (W/m^2)
R	universal gas constant (J/mol K)
r	pore radius (m)
Re	Reynolds Number (–)
RSM	response surface methodology
SNM	Structural Network Model
T	temperature (K)
U	overall heat transfer coefficient (W/m^2 K)
v	velocity (m/s)
VMD	Vacuum Membrane Distillation
x	molar fraction (–)

1. Introduction

Membrane distillation (MD) was first developed in 1963 by Bodel when he patented the vapour diffusion through silicone rubber for saline water distillation [1]. The most used and studied MD configuration is the direct contact membrane distillation where the hot feed and the cold permeate solutions are separated by a hydrophobic membrane. The feed solution comes into contact with the membrane and evaporates, the vapour travels through the pores and condenses on the cold permeate membrane interface (Fig. 1).

The temperature difference across the membrane between the feed side (T_{mf}) and the permeate side (T_{mp}) as indicated in Fig. 1 results in different partial pressures of water vapour at the feed (P_{mf}) and the permeate side (P_{mp}). It is noteworthy that the actual driving force for the flux through the membrane is the vapour pressure difference and only the evaporated phase is transported across the membrane. The use of thin membranes creates large vapour pressure gradients, therefore allowing MD to be operated at relatively low feed temperatures, potentially allowing to reuse waste heat from other processes.

The heat and mass transfer in MD are interconnected and lead to a complex relationship. When water is evaporated on the feed side it takes away part of the energy of the feed, which is carried away by the water vapour flux. This energy is transferred to the permeate during the condensation. Moreover, some of the energy is transferred through the membrane matrix itself via conduction in the form of sensible heat. The combined effect of the sensible heat and the heat due to evaporation creates thermal boundary layers near the interface of the membrane, leading to reduction of the intermembrane flux.