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Air gap membrane distillation
1. Modelling and mass transport properties for hollow fibre membranes

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Abstract

A predictive model for air gap membrane distillation in a counter current flow configuration using fibre membranes is presented. The water vapour transport across the membrane is described by the dusty-gas model that uses constant membrane mass transport parameters to describe simultaneous Knudsen diffusion, molecular diffusion and viscous flow. This makes the model suitable to describe the membrane distillation process for a wide range of pressures and temperatures. The membrane mass transport properties had to be determined experimentally in separate experiments to obtain a predictive model. The Knudsen diffusion and viscous flow membrane parameters (K_0 and B_0, respectively) were determined with single gas permeation experiments. The molecular diffusion membrane parameter (K_1) was determined with binary gas diffusion experiments. High membrane permeability in combination with small membrane fibre radius, a combination that is advantageous for membrane distillation, made it necessary to pay special attention to effects as pressure drop along the fibre and boundary layer resistances in order to obtain accurate membrane parameters. The gas permeation data show that calculation of K_1 from the K_0 and B_0 values assuming parallel cylindrical pores is accurate within 30% for some membranes but can be wrong by a factor of two for other membranes. This means that (relatively simple) single gas permeation experiments in combination with a cylindrical pore membrane model are, unfortunately, not sufficient to obtain reliable membrane mass transfer properties for model calculations.

Keywords: Air gap membrane distillation; Modelling; Gas permeation; Hollow fibre membrane

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1. Introduction

Membrane distillation has been known as a technique for desalinating water since the late 1960s. The first configuration used was direct contact membrane distillation (DCMD) [1–3], in which a micro-porous hydrophobic membrane is in contact with salt water at one side and with distillate water at the other side. A higher temperature at the salt water side of the membrane is the driving force for water vapour diffusion through the membrane pores to the distillate water side, thus desalinating water. The hydrophobic nature of the membrane prevents liquid water from entering the membrane pores. Thinner membranes which generate much higher fluxes were introduced in the late 1970s [4] and gave rise to a configuration in which a condenser wall is placed at a short distance from the membrane, air gap membrane distillation (AGMD). This introduces a heat insulating air gap between the membrane and the distillate water [5–8] so that conductive heat loss across the membrane is reduced. Drawback of the air gap is that it also reduces the water vapour transport across the membrane. More recently, vacuum membrane distillation (VMD) that is suitable for removing trace components from water [9–11], has been suggested for water desalination [12,13]. In VMD, the space at the permeate side of the membrane is evacuated and the permeate is condensed outside the membrane module. This technique results in relatively high fluxes if compared to DCMD and AGMD, but the driving force has to be created by a higher value energy source.

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Nomenclature

A	membrane surface (m^2)
B_0	viscous flow membrane morphology parameter (m^2)
Δc	concentration difference (mol/m^3)
Cp	heat capacity (J/(kg K))
D	binary diffusion coefficient (m^2/s)
h	heat transfer coefficient ($W/(m^2\,K)$)
H_{vap,T_1}	heat of evaporation for water at temperature T_1 (J/kg)
k	mass transfer coefficient (m/s)
K_0	Knudsen diffusion membrane morphology parameter (m)
K_1	molecular diffusion membrane morphology parameter
m	water mass flow (kg/s)
M	molar mass (kg/mol)
N	molar flux ($mol/(m^2\,s)$)
p	partial pressure (Pa)
P	total pressure (Pa)
Q	energy flux ($J/(m^2\,s)$)
r	radius (m)
R	universal gas constant (8.314 J/(mol K))
T	temperature (K)
v_M	mean molecular velocity (m/s)

Subscripts

1	inner membrane radius, see Fig. 3
2	outer membrane radius, see Fig. 3
3	inner surface product layer, see Fig. 3
4	inner surface cooling plate, see Fig. 3
5	inner cold water flow channel wall, see Fig. 3
a	air
A	component A
B	component B
bulk	bulk of the flow
c	cold water flow, see Fig. 3
cp	cooling plate; cylindrical pore assumption
h	hot water flow, see Fig. 3
in	entering a module slice
m	membrane (average)
mgas	gas phase within membrane pores
mmat	membrane material
out	leaving a module slice
p	product water flow, see Fig. 3; membrane pore
tot	total
w	water
wl	liquid water
wv	water vapour

Superscripts

D	diffusive
V	viscous

Greek letters

δ	membrane wall thickness, $r \ln(r_2/r_1)$ (m)
ε	membrane porosity
λ	thermal conductivity (W/mK)
μ	viscosity (Pa s)
τ	membrane tortuosity
∇	Nabla operator (derivative of argument in all directions)

This study concerns AGMD at reduced pressure with tubular or fibre membranes carried out in an ideal counter current flow configuration for desalination of seawater. A schematic presentation of this technique is given in Fig. 1. Cold seawater feed flows through a condenser tube with non-permeable well-wettable walls via a heater into the membrane evaporator tube in counter current mode. The tubes are separated by a gap from which non-condensable gases have been (partly) removed to reduce its resistance to mass transfer. The wall of the evaporator tube consists of a microporous hydrophobic (non-wettable) membrane through which water vapour can diffuse and by which liquid water (with dissolved salts) is retained. The temperature difference between the flows inside the evaporator and condenser tubes generates a vapour pressure difference. This forces the vapour to diffuse through the membrane pores of the evaporator tube and across the gap to the condenser tube, on which the desalinated vapour condenses, and heat is recovered.

An important tool for development of an optimal desalination module design is a predictive steady state model of the process. Such a model should calculate hot and cold water temperature changes along the fibre length. Furthermore, since modules in series will operate at different temperatures and air gap pressures, see Fig. 1, the model should be able to describe the membrane distillation process for a wide range

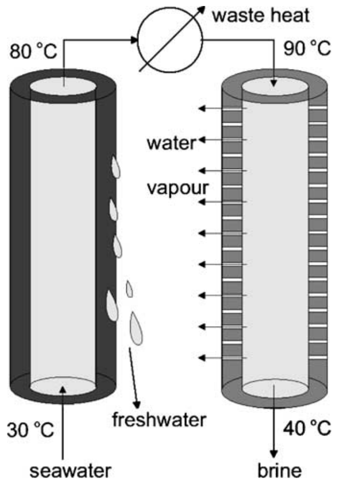

Fig. 1. Schematic presentation of AGMD in counter current flow configuration.