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Heat and mass transfer in membrane distillation used for desalination with slip flow

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HIGHLIGHTS

- Heat and mass transfer in an air gap membrane distillation configuration has been analyzed.
- The boundary conditions are adjusted to include the effect of slip flow on the performance of the distillation device.
- The model was systematically validated with previous experimental and theoretical works.
- The increase of the slip length leads to an increase in the permeate flux and the process thermal efficiency.
- Slip flow model gives a better representation of the process parameters.

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ABSTRACT

A theoretical model for the transport phenomena in an air gap membrane distillation is presented. The model is based on the conservation equations for the mass, momentum, energy and species within the feed water solution as well as on the mass and energy balances on the membrane sides. The slip flow occurs due to the hydrophobic properties of the membrane. The slip boundary condition applied on the feed saline solution–membrane interface is taken into consideration showing its effects on process parameters particularly permeate flow, heat transfer coefficient and thermal efficiency. The theoretical model was validated with available experimental data and was found to be in good agreement especially when the slip condition is introduced. Increasing slip length from zero to 200 μm was found to increase the permeate flux and the thermal efficiency by 33% and 1.7% respectively.

1. Introduction

Membrane distillation (MD) has been widely investigated the last two decades as a novel and promising technique for desalination. The driving force in MD process is the difference in vapor pressure of water caused by an existing temperature difference across the membrane. Thus, vapor molecules are transported from the high vapor pressure (high temperature) side to the low vapor pressure (low temperature) side of the membrane. This trans-membrane vapor pressure difference may be maintained with one of four possibilities applied on the permeate side leading to four different configurations namely Direct Contact Membrane Distillation (DCMD), Air Gap Membrane Distillation (AGMD), Vacuum Membrane Distillation (VMD) and Sweeping Gas Membrane Distillation (SWMD) [1,2]. One of the key parameters affecting the process performance is related to the membrane properties.

For the MD process, the membrane supports the liquid–gas interface on which the evaporation takes place. This can be achieved by using hydrophobic surfaces characterized by alternating patches of either a liquid–solid interface or a gas–liquid interface [2,3]. One can have therefore alternating boundary conditions at the membrane surfaces of either no slip at the solid–liquid interface or no shear at the gas–liquid interface. Modeling the microscopic behavior of the flow over hydrophobic surfaces is not an easy task. However, it is possible as proposed by Ramon et al. [4] to model the macroscopic behavior by introducing an effective slip parameter accounting for the deviations of the flow from the no-slip basic case.

The phenomenon of slip can occur for both gases and liquids. However, there is a fundamental difference between the slip in gas micro-flows and the slip in liquid flows. Slip in liquids is encountered

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Nomenclature

C	Mass fraction of NaCl
C_{in}	Mass fraction of NaCl at the entrance
C_p	Specific heat [kJ/kg K]
c_s	Mole fraction of NaCl
D_s	Diffusion coefficient of NaCl [m^2/s]
$D_{v/a}$	Coefficient of vapor-air mass diffusion [m^2/s]
g	Acceleration of gravity [m/s^2]
h_{fg}	Latent heat of evaporation [kJ/kg]
h_x	Local convective heat transfer coefficient [W/m^2K]
J	Length-averaged permeate flux [kg/m^2h]
J_v	Local permeate flux [kg/m^2s]
K	Permeability of the membrane
k	Thermal conductivity [kW/mK]
L	Membrane length [m]
l	Half-width of the flow channel [m]
M_v	Molar mass of water vapor [kg/kmol]
N_x	Number of nodes along x direction
N_y	Number of nodes along y direction
P	Pressure [Pa]
Pr	Prandtl number
Q_C	Conductive heat flux [kJ/m^2h]
Q_L	Latent heat flux [kJ/m^2h]
Q_T	Total heat flux [kJ/m^2h]
Re	Reynolds number
R_g	Thermal resistance of the air gap
R_f	Thermal resistance of the condensate film
R_m	Thermal resistance of the membrane
R_p	Thermal resistance of the cooling plate
Ru	Universal gas constant [kJ/kmol/K]
Sc	Schmidt number
T	Temperature [°C]
U_{in}	Inlet velocity [m/s]
U	Velocity component in x direction [m/s]
V	Velocity component in y direction[m/s]
x	Coordinate along to the solution flow [m]
y	Coordinate normal to the solution flow [m]
μ	Dynamic viscosity [kg/m/s]
ρ	Density [kg/m^3]
ε	Porosity
δ	Thickness or width [m]
χ	Tortuosity
η	Process thermal efficiency

Subscripts

a	air
c	cooling plate
f	condensate film
g	air gap
in	inlet
m	membrane
mm	membrane material
moy	average
s	saline water
T	total
v	vapor
AGMD	Air gap membrane distillation
DCMD	Direct contact membrane distillation
MD	Membrane distillation
SWMD	Sweeping gas membrane distillation
VMD	Vacuum membrane distillation

as a consequence of the interaction between a coated surface and the adjacent liquid particle. Thus, liquid slip can occur even when the continuum hypothesis is valid [5].

For a hydrophilic surface, Garimella and Sobhan [6] studied the transport in micro-channels and concluded that analyses based on Navier–Stokes and energy equations can adequately predict the flow and heat transfer characteristics in micro-channels having a hydraulic diameter greater than 50 μm. In the case of hydrophilic surface, experimental studies have confirmed the validity of the no-slip boundary condition down to few nano-meters [7]; despite, the occurrence of slip in hydrophilic surface has also been studied and confirmed [8]. When a surface is coated with hydrophobic material, the fluid molecules adjacent to the surface do not stick to the solid boundary resulting in an overall velocity slip. This slip velocity is related to the normal velocity gradient of the fluid adjacent to the wall with a slip length *b* which can be described as the imaginary distance within the solid where the velocity extrapolates to zero. Slip velocity can be presented in the following form [4]:

$$U|_{y=0} = b\frac{\partial U}{\partial y}\bigg|_{y=0}. \tag{1}$$

Tretheway and Meinhart [9,10] experimentally showed an apparent fluid slip in micro-channels with hydrophobic walls. The micron-resolution particle image velocimetry (μ-PIV) was applied to measure velocity profiles of flow through 30 × 300 mm channels. They measured an apparent slip velocity at the wall for water flowing through a microchannel coated with hydrophobic octadecyltrichlorosilane. The slip velocity at the wall was approximately 10% of the free stream velocity which produces a slip length of about 1 μm. Pit et al. [11] provided experimental evidence of liquid slip at the wall for hexadecane flowing between two rotating parallel disks kept at a distance of 190 μm. They measured a slip length of 0.4 μm when the surface was coated with octadecyltrichlorosilane (OTS). Cottin-Bizzone et al. [12] studied experimentally water flow across hydrophilic and hydrophobic surfaces; they found slip lengths of approximately b = 0.02 μm.

On the other hand, a superhydrophobic surface can dramatically reduce the hydrodynamic resistance and a slip length higher than 185 μm has been reported by Choi and Kim [13,14]. They obtained the slip length through torque measurement with a commercial rheometer. A cone and plate arrangement, the most popular geometry because of the uniform shear rate over a sample, was used. For the bottom plate, the prepared test membrane is placed over a rheometer stage with temperature set by a Peltier plate. The test liquids are dispensed between the cone and the test membrane. When a cone of radius r and very small cone angle Θ_0 rotates at angular velocity Ω, the governing equation of the Couette flow with a slip on the substrate using Navier's hypothesis about the wall slip and expanding the wall shear stress into a Taylor series, the torque M on the rotating cone can be calculated. Derived from the torque measurement, slip length can be calculated as [13]:

$$b = \frac{r\theta_0}{4}\left(1-\sqrt{\frac{8\theta_0}{\pi\Omega r^3}\frac{M}{\mu}-\frac{13}{3}}\right) \tag{2}$$

Ou and Rothstein [15] were among the first to demonstrate experimentally that superhydrophobic surfaces could reduce drag in laminar flows. Slip lengths greater than 25 μm were measured.

It's important to notice that many techniques are used to measure slip length. Some techniques are used to have direct measurements of slip length in flows past hydrophobic surfaces. Joseph and Tabeling [16] and Tretheway and Meinhart [10] utilize micro-particle image velocimetry (μ-PIV) measurements to determinate slip length. Pit et al. [17] used total internal reflection fluorescence microscopy (TIRF) to measure the fluorescence recovery after photobleaching and determine the slip velocity of hexadecane flowing past a lyophobically modified, smooth sapphire surface. Jin et al. [18] combined TIRF of