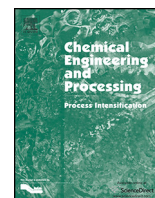




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## Study of the rectangular cross-flow flat-sheet membrane module for desalination by vacuum membrane distillation



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### ABSTRACT

This work presents a study of the heat and mass transfer performance of desalination in a laboratory-scale rectangular cross-flow flat-sheet membrane module by vacuum membrane distillation (VMD) experiments. Results show that the traditional Nusselt and Sherwood correlations, which are frequently employed in the membrane distillation literature, are not suitably used to estimate the heat and mass transfer coefficients in the VMD system for Reynolds numbers ranging from 150 to 1400. In this study, it was observed that approximately 30% of the experimental data fit well with semi-empirical correlations whose empirical constants are  $a = 2.76 \times 10^{-3}$ ,  $b = 0.97$  and  $c = 3.7909$ . The heat transfer process is limited by the resistances in the feed boundary layer and the membrane. The heat transfer resistance in the membrane increases when that in the feed boundary layer decreases and vice versa. More than 50% of the heat transfer resistances occur in the liquid feed phase at feed flow rates below 1200 mL/min, whereas the remaining occur in the membrane itself. At feed flow rates that exceed 1200 mL/min, the heat transfer resistance in the membrane becomes dominant. The Knudsen-viscous resistance controls the mass transfer through the membrane while the mass transfer resistance in the liquid feed phase is absent.

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### 1. Introduction

Desalination is becoming increasingly well-known as a promising alternative source of potable water. Current commercial desalination technologies include those that implement reverse osmosis (RO) and thermal evaporation. These commercial desalination technologies, however, are relatively energy-intensive, e.g. high operating pressure in RO and high operating temperature in thermal evaporation techniques. Compared to RO and thermal evaporation techniques, membrane distillation (MD) consumes less energy, that is, the process can operate with low-grade heating sources under non-pressurised conditions [1–3]. Consequently, MD has been considered a process intensification method because it is less costly and safer [4,5].

Recently, the use of MD for producing fresh water through desalination has been highly recommended [6]. In desalination by the MD process, saline water is brought into direct contact with the upstream side of a porous hydrophobic membrane, and water vapour is thermally driven through the membrane. Water vapour

transport across the membrane occurs when a driving force between the upstream and the downstream sides of the membrane exists. The MD methods designed to maintain the driving force can be categorised into four types of configurations: direct contact MD (DCMD), air-gap MD (AGMD), sweeping-gas MD (SGMD) and vacuum MD (VMD). Desalination using VMD is the most frequently investigated configuration because it exhibits the highest flux amongst the abovementioned types [7,8].

Highly permeable membranes are the most suitable for use in the VMD process for desalination applications [9]. Because such membranes are porous and permeable, heat and mass transfer occur simultaneously during the separation process. Traditional Nusselt and Sherwood correlations, respectively, have been employed in most published studies of VMD as well as other MD configurations to predict the heat and mass transfer coefficients in the feed phase [10–12]. However, these correlations are developed exclusively for heat exchangers, which feature impermeable and non-porous walls. Compared to those in non-porous walls, polarisation effects are reduced in porous membranes because the total solid-liquid contact area is relatively small. As a result, the traditional Nusselt and Sherwood correlations may underestimate the heat and mass transfer coefficients. Although the applicability of the correlations has

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## Nomenclature

$a, b, c$	Empirical constants for Eqs. (23)–(25)
$C$	Membrane distillation coefficient ( $\text{kg}/\text{m}^2 \text{ s Pa}$ ); concentration (wt%)
$d$ or $D$	Diameter (m); diffusivity ( $\text{m}^2/\text{s}$ )
$Gr$	Grashof number
$h$	Heat transfer coefficient ( $\text{W}/\text{m}^2 \text{ K}$ )
$H$	Overall heat transfer coefficient ( $\text{W}/\text{m}^2 \text{ K}$ )
$\Delta H_v$	Heat of vaporization ( $\text{J}/\text{kg}$ )
$J$	Mass flux ( $\text{kg}/\text{m}^2 \text{ s}$ or $\text{kg}/\text{m}^2 \text{ h}$ )
$k_B$	Boltzmann constant ( $1.38 \times 10^{-23} \text{ J/K}$ )
$k_L$	Solute mass transfer coefficient ( $\text{m}/\text{s}$ )
$k_T$	Thermal conductivity ( $\text{W}/\text{m K}$ )
$K_m$	Membrane permeability coefficient ( $\text{s mole}^{1/2} \text{ m}^{-1} \text{ kg}^{-1/2}$ )
$Kn$	Knudsen number
$L$	Length (m)
$M$	Molecular weight ( $\text{kg}/\text{mol}$ )
$n$	Mole fraction
$n_+, n_-$	Valences
$Nu$	Nusselt number
$\bar{P}$	Mean partial pressure (Pa)
$P$	Vapour pressure (Pa); pressure (Pa)
$\Delta P$	Vapour pressure difference (Pa); pressure difference (Pa)
$P^\circ$	Saturated vapour pressure (Pa)
$Pr$	Prandtl number
$Q$	Volumetric flow rate ( $\text{mL}/\text{min}$ ); heat flux ( $\text{J}/\text{m}^2 \text{ s}$ )
$r$	Radius (m)
$R$	Gas constant ( $8.31 \text{ J}/\text{mol K}$ ); resistance ( $\text{Pa m}^2 \text{ h}/\text{kg}$ )
$Re$	Reynolds number
$Sc$	Schmidt number
$Sh$	Sherwood number
$T$	Temperature (K)
Subscript	
b	Bulk
f	Feed
g	Gas
h	Hydraulic
I	Interface
L	Liquid
m	Membrane
p	Permeate; pore
s	Solute
v	Vapour
w	Water
Greek letters	
$\delta$	Thickness (m)
$\varepsilon$	Porosity
$\eta_v$	Viscosity of vapour [ $\text{Pa s}$ ]
$\lambda$	Mean free path (m)
$\lambda_+, \lambda_-$	Limiting ionic conductance
$\mu$	Viscosity of liquid ( $\text{Pa s}$ )
$\rho$	Density ( $\text{kg}/\text{m}^3$ )
$\sigma$	Collisions diameter (m)
$\tau$	Tortuosity
$\gamma$	Activity coefficient

developed correlations were validated by using pure water rather than applied to aqueous solutions [14,15].

In this work, a laboratory-produced rectangular cross-flow flat-sheet membrane module is studied for desalination process. NaCl solutions are examined as the feed solutions in which polarisation effects and transport resistances are considered. The semi-empirical correlation that is formulated especially for the rectangular cross-flow flat-sheet membrane module and pure water as the feed solution in our previous paper [16] is investigated in this study. The fitness of the formulated correlation as well as the traditional correlations are discussed.

## 2. Theory

Generally, mass transfer through a porous membrane in the membrane distillation (MD) process can be governed by different mechanisms: Knudsen diffusion, viscous flow, molecular diffusion or any combination thereof [6,17]. In vacuum membrane distillation (VMD), molecular diffusion is ignored when the partial pressure of air inside the membrane pores is low [4,9]. As a result, Knudsen diffusion, viscous flow or both should be considered in the VMD process [18,19]. These models propose a linear relationship between the water vapour flux ( $J$ ) and the water vapour pressure difference ( $\Delta P$ ) across the membrane [14,20]:

$$J = C \Delta P = C(P_1 - P_p) \quad (1)$$

where  $C$  is the net VMD coefficient which is dependent on the membrane geometric structure and on the temperature.  $P_1$  and  $P_p$  are the partial pressure of water vapour at the membrane surface on the feed side and that on the permeate side, respectively.

The Knudsen number ( $Kn$ ), defined as the ratio between the mean free path and the pore size, is used to determine the mechanism that dominates mass transfer through a membrane.

$$Kn = \frac{\lambda}{d_p} \quad (2)$$

where  $\lambda$  and  $d_p$  are the mean free path and pore size, respectively. In VMD, desalination is a single-component transport process when NaCl aqueous solution is tested as the feed. Thus, only water vapour is transferred through the membrane pores. The mean free path of water vapour molecules is estimated as follows [4,9]:

$$\lambda = \frac{k_B T}{\sqrt{2} \pi P \sigma^2} \quad (3)$$

where  $\sigma$  is the collision diameter of water vapour (i.e.  $2.641 \text{ \AA}$ ),  $k_B$  is the Boltzmann constant,  $\bar{P}$  is the mean pressure within the membrane pores and  $T$  is the absolute temperature. One type of commercial flat-sheet polyvinylidene fluoride membrane (Westran S, Whatman) with a nominal pore size of  $0.2 \text{ \mu m}$ , is employed in this study. Under the experimental conditions applied in this work, feed temperatures ranging between  $65$  and  $90^\circ \text{C}$  under a constant permeate pressure of  $14.5 \text{ kPa}$ , the mean free path of water vapour molecules varies between  $0.38$  and  $0.76 \text{ \mu m}$ . Thus, the value of  $Kn$  varies from  $1.9$  to  $3.8$  for a pore size of  $0.2 \text{ \mu m}$ . Consequently, both Knudsen diffusion and viscous flow should be considered in the VMD process [6,9]. In this case, the Kinetic Theory of Gases, or more precisely the Dusty gas model, suggests that a transition mode of the Knudsen-viscous mechanism governs water vapour transport through membrane pores [16,21]:

$$C = 1.064 \frac{r s}{\tau \delta} \left( \frac{M}{RT_m} \right)^{0.5} + 0.125 \frac{r^2 s}{\tau \delta} \left( \frac{MP_m}{\eta RT_m} \right) \quad (4)$$

where  $r$  is the membrane pore radius,  $\varepsilon$  is the membrane porosity,  $\tau$  is the tortuosity,  $\delta$  is the membrane thickness,  $M_w$  is the molecular weight of water vapour,  $\eta$  is the viscosity of water vapour,  $R$  is the

been questioned over the past decade [13–15], studies on the re-evaluation of the correlations are still limited. Additionally, the

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