



Heat transfer in the rectangular cross-flow flat-sheet membrane module for vacuum membrane distillation



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ABSTRACT

This paper presents a study of heat transfer coefficients of boundary layers in a laboratory-scale rectangular cross-flow flat-sheet membrane module by using distilled water vacuum membrane distillation (VMD) experiments. Results show that the traditional heat transfer correlations, which are mostly employed in the membrane distillation literature, are not suitably used to predict the heat transfer process in the VMD system for the Reynolds numbers ranging from 300 to 1090. This study formulates a new semi-empirical heat transfer correlation by suggesting Knudsen-viscous mechanism governs the water vapour across the membrane. Compared to the feed flow rate, the feed temperature is the limit to the heat transfer. The heat transfer coefficients are strongly dependent on the physical properties of the feed solution, but less relied on the design of the membrane module.

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1. Introduction

Recently, the membrane distillation (MD) technology can compete with the conventional separation processes [1]. The advantages of MD over the conventional separation processes include lower cost, more energy saving, fewer mechanical part demands, smaller plant size and safer; because the MD can operate at lower temperatures (<100 °C) and at the atmospheric pressure.

Heat transfer and mass transfer take place simultaneously in MD. The heat and mass transfer coefficients can be evaluated based on energy and mass balances from the feed phase to the permeate phase. Traditional Nusselt and Sherwood correlations, respectively, are extensively employed to estimate the heat and mass transfer coefficients in the most MD literature. However, these correlations are developed especially for the impermeable and rigid heat exchangers instead of for the permeable, porous and polymeric membranes.

For the pure water is continuously heated to a constant temperature (T_b) and flowed over an impermeable and rigid plate surface, a thermal boundary layer formed on the surface (see Fig. 1(a)). Intermolecular attractions at the solid–liquid interface cause the liquid

water to adhere to the solid surface. At the solid–liquid interface, a shear stress exists and the velocity of the liquid is assumed to be zero (no-slip condition). When the temperature on the other side of the plate is kept lower, $T_p < T_b$, heat is transferred across the solid by conduction mechanism. For the non-isothermal process, the temperature of the liquid water at the solid–liquid interface would be lower than the corresponding bulk temperature, $T_1 < T_b$; this phenomenon is known as temperature polarisation. The MD systems employ the porous membranes [1,2]. Both solid–liquid interface and vapour–liquid interface emerge simultaneously on the porous membrane surface (see Fig. 1(b)). To approximate the shear stress at the vapour–liquid interface as zero [3], the temperature polarisation effect reduces because the corresponding total area of the liquid–solid interface becomes smaller on the porous membrane surface. The evaporative mass flux increases with the increasing total area of the vapour–liquid interface as the temperature polarisation effect decreases.

In this work, the VMD process is conducted with a rectangular cross-flow flat-sheet membrane module. Distilled water was used as the feed solution; so that, only the temperature polarisation effect is considered. The heat transfer performances on the membrane module are analysed and discussed in details according to the experimental Nusselt, Reynolds and Prandtl numbers. The developed Nusselt correlation was compared with the traditional heat transfer correlations which are frequently used in the MD publications.

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Nomenclature

<i>a, b, c</i>	empirical constants for Eq. (10)
<i>C</i>	membrane distillation coefficient (kg/m ² s Pa)
<i>d</i> or <i>D</i>	diameter (m)
<i>Gr</i>	Grashof number
<i>h</i>	heat transfer coefficient (W/m ² K)
ΔH_v	heat of vaporisation (J/kg)
<i>J</i>	mass flux (kg/m ² s or kg/m ² h)
<i>k_B</i>	Boltzmann constant (1.38 × 10 ⁻²³ J/K)
<i>k_T</i>	thermal conductivity (W/mK)
<i>K_m</i>	membrane permeability coefficient (s mole ^{1/2} m ⁻¹ kg ^{-1/2})
<i>L</i>	length (m)
<i>M</i>	molecular weight (kg/mol)
<i>Nu</i>	Nusselt number
<i>p</i>	vapour pressure (Pa)
\bar{p}	mean partial pressure (Pa)
<i>P</i>	pressure (Pa)
<i>Pr</i>	Prandtl number
<i>Q</i>	volumetric flow rate (mL/min)
<i>r</i>	radius (m)
<i>R</i>	gas constant (8.31 J/mol K)
<i>Re</i>	Reynolds number
<i>s</i>	standard deviation (kg/m ² s)
<i>s_w</i>	minimum weighed standard deviation
<i>Sc</i>	Schmidt number
<i>Sh</i>	Sherwood number
<i>T</i>	temperature (K)
<i>y</i>	mole fraction in vapour phase

Subscript

<i>b</i>	bulk
<i>cal</i>	calculated
<i>exp</i>	experimental
<i>f</i>	feed
<i>G</i>	gas
<i>h</i>	hydraulic
<i>I</i>	interface
<i>Kn</i>	Knudsen diffusion
<i>L</i>	liquid
<i>m</i>	membrane
<i>p</i>	permeate
<i>percen.</i>	percentage (%)
<i>U–D</i>	upstream to downstream
<i>v</i>	vaporisation; vapour
<i>vis</i>	viscous flow
<i>w</i>	water

Greek letters

δ	thickness (m)
ε	porosity
η	viscosity of vapour (Pa s)
λ	mean free path (m)
σ	collisions diameter (m)
τ	tortuosity

2. Theory

In the membrane distillation (MD), water vapour is transferred through the porous membrane. Mass transfer through the porous membrane can be explained by different mechanisms: the Knudsen diffusion model, the viscous flow model, the molecular diffusion model, or any combination among them. In a VMD configuration,

the molecular diffusion model is ignored when the partial pressure of air inside the pores is low [1]. As a result, the Knudsen diffusion and the viscous flow are chosen as the most suitable mechanisms. These models describe a linear relationship between the water vapour flux (*J*) and the water vapour pressure difference (ΔP) across the membrane:

$$J = C\Delta P = C(P_1 - P_p) \tag{1}$$

where *C* is the net VMD coefficient. *P*₁ and *P*_p are the pressures at the membrane surface on the feed side and on the permeate side, respectively. The pressure at the membrane surface on the feed side is estimated by the Antoine equation:

$$P_1 = \exp \left[23.1964 - \frac{3816.44}{T_1 - 46.13} \right] \tag{2}$$

where the *T*₁ is the temperature at the membrane surface. The pressure at the membrane surface on the permeate side is calculated with:

$$P_p = y_w P_v \tag{3}$$

where *y_w* is the molar fraction of the transporting component, i.e., the water vapour, and *P_v* is the absolute pressure applied on the permeate side. Because of the water vapour at the liquid–vapour (L–V) interface is saturated and dissolved gas content is too low for a single component transport process of VMD in which a relative humidity is almost equal 100%, the partial pressure of water vapour at the membrane surface on the permeate side is equal to *P_v*.

In the present VMD system, the pore size of the membrane is comparable with the mean free path of water molecules (λ). The mean free path of water molecules is calculated as follows [1]:

$$\lambda = \frac{k_B T}{\sqrt{2} \pi \bar{P} \sigma^2} \tag{4}$$

where σ is the collision diameter of water vapour (that is, 2.641 Å), *k_B* is the Boltzmann constant, \bar{P} is the mean pressure within the membrane pores and *T* is the absolute temperature. By considering the experimental conditions of this work, the feed temperatures ranging between 75 and 95 °C under a constant permeate pressure of 14.5 kPa, the mean free path of water molecules varies between 0.25 and 0.45 μm. This means that the Knudsen number, defined as the ratio between the mean free path and the pore size, varies from 1.3 to 2.2. Consequently, both molecular–wall collisions and molecular–molecular collisions should be considered for a VMD process [1]. In this case, the Kinetic Theory of Gases, or more precisely the Dusty gas model, suggests that a transition mode of Knudsen-viscous mechanism governs the water vapour molecules through the pores [4,5]:

$$C = 1.064 \frac{r\varepsilon}{\tau\delta} \left(\frac{M}{RT_m} \right)^{0.5} + 0.125 \frac{r^2\varepsilon}{\tau\delta} \left(\frac{MP_m}{\eta RT_m} \right) \tag{5}$$

where *r* is the membrane pore radius, ε is the membrane porosity, τ is the tortuosity, δ is the membrane thickness, *M_w* is the molecular weight of water vapour, η is the viscosity of water vapour, *R* is the gas constant, *T_m* is the average temperature of the membrane, and *P_m* is the average partial pressure in the membrane pore.

The VMD coefficient *C* is dependent on the membrane geometric structure and on the temperature. Gas permeation test using N₂ gas is employed to quantify the physical characteristics of the membrane [1]. The mass transfer of the gas through the porous membrane is expressed as follows:

$$J_G = C_G \Delta P_{U-D} \tag{6}$$

where *J_G* is the flux of the gas, *C_G* is the mass transfer coefficient, and ΔP_{U-D} is the absolute pressure difference between the upstream and downstream side of the membrane.

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