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Theoretical modeling and experimental analysis of direct contact membrane distillation

Tsung-Ching Chen, Chii-Dong Ho*, Ho-Ming Yeh

Energy and Opto-Electronic Materials Research Center, Department of Chemical and Materials Engineering, Tamkang University, Tamsui, Taipei 251, Taiwan

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A B S T R A C T

A two-dimensional mathematical model was theoretically developed to predict the temperature polarization profile of direct contact membrane distillation (DCMD) processes. A concurrent flat-plate device was designed to verify the theoretical prediction of pure water productivity on saline water desalination. The numerical results from the temperature polarization profile were obtained using the finite difference technique to reduce the two-dimensional partial differential equations into an ordinary differential equations system. The resultant simultaneous linear equations system was solved with the fourth-order Runge-Kutta method. The results show theoretical prediction agreement with the measured values from the experimental runs. A combination of the Knudsen flow and Poiseuille flow models in the present mathematical formulation for membrane coefficient estimation was used to establish theoretical agreement. The influence of the inlet saline water temperature and volumetric flow rate on the pure water productivity as well as the hydraulic dissipated energy are also delineated.

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1. Introduction

Membrane distillation is a separation process that is categorized into four designs [1] direct contact membrane distillation (DCMD), air gap membrane distillation (AGMD), vacuum membrane distillation (VMD), and sweeping gas membrane distillation (SGMD). DCMD applications to water production systems provide a suitable separation process and purification technique in which water is the major component across the membrane and can be extended to other applications such as temperature sensible separation [2], desalination of saline water [3,4], waste water treatment [5], juice concentration [6] and other innovative applications [7]. The temperature of one of the two flow streams divided by the hydrophobic membrane is higher than that for the other. A temperature difference exists across the membrane, resulting in a vapor pressure difference. The advantages of DCMD lie in its simplicity, the need for only small temperature differences and nearly 100% rejection of dissolved solids [8]. Furthermore, the low energy demand systems in DCMD processes can be equipped with renewable energy equipments such as solar collectors [9] and solar distillers [10]. Seawater is about 97% of the Earth's water resource and may be reclaimed for drinking using desalination systems. According to the Worldwatch Institute [11], more than two-thirds of the world's population may experience water shortage by 2025. The recent status and potential for membrane distillation desalination was reported by Alklaibi and Lior [12]. Since the advance of membrane materials and technology, membrane assisted seawater desalination systems have become economical and technically feasible strategies for drinking water production.

In the mathematical formulations of DCMD processes, the models usually fall into three distinct areas: membrane modeling, macroscopic modeling and microscopic modeling. These three distinct areas focus on the mass transfer resistance of vapor across a membrane attributed to the membrane characteristics (i.e. pore size, porosity and tortuosity) and heat transfer resistances in series were set up to obtain the mean temperature on the membrane surface. However, the two-dimensional heat-transfer equation was developed to simulate the particular application more accurately. Most investigators have selected the macroscopic models to predict the pure water productivity [13–15] on DCMD processes, and used the experimental results to correlate the membrane-based parameter (i.e. membrane coefficient) and system-based parameter (i.e. the vapor pressure difference). The uncertainty of microporous membrane morphology leads to inaccuracy when calculating the mass transfer [16]. Many researchers used the expressions of interfacial temperature in terms of bulk temperature with specified empirical correlations of heat-transfer coefficients [15,17] and these correlations, however, are restricted to specific boundary conditions [18]. Although many semi-empirical models have been developed, a detail model for temperature polarization on flat-plate MD processes is still lacking. In order to obtain the approximate temperature on membrane surfaces, the multi-dimensional model is necessary and helpful to study the transmembrane flux mechanism. Once the temperature distribution is known, the local

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* Corresponding author. Tel.: +886 2 2621 5656; fax: +886 2 2620 9887.
E-mail address: cdho@mail.tku.edu.tw (C.-D. Ho).

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mass flux, the optimize operation and design parameters, and the empirical correlation of heat-transfer coefficient are thus obtained. Therefore, it is important to understand how temperature polarization varies with position in flow ducts. Furthermore, the numerical methods of the present study are easily acceptable and carried out with scientific programming language (e.g. C++, Fortran) or utilize mathematical software systems (e.g. Matlab, Mathematica). The computation speed of the optimized program syntax is superior to the other commercial program packages (e.g. Fluent, Femlab).

The concentration polarization phenomenon of low concentration NaCl solution can be ignored [8] to simplify the calculation procedure and save CPU time. Therefore, this study develops a coupled two-dimensional energy balance model and one-dimensional mass balance model. It is believed that the availability of such a simplified mathematical formulation for simultaneous energy and mass balances for saline water desalination will be an important contribution to the design and analysis the temperature polarization of DCMD processes. In addition, the calculation procedure with the variations in physical properties, which include temperature dependence, in the computer program were carried out to obtain more accurate calculations. The same procedure occurs in dealing with many other possible membrane separation processes. This study developed a two-dimensional flat-plate mathematical model for predicting the pure water productivity of DCMD processes. The temperature polarization profile variations with flow duct position were obtained to study the operating parameter effects on the hydraulic dissipated energy.

2. Theory

2.1. The pure water flux membrane distillation system

Direct contact membrane distillation is a process for separating two flow streams at different temperatures using a porous hydrophobic membrane. The mass transfer driving force across the membrane is the difference in saturated pressure components on both membrane surfaces due to the temperature gradient. The general mass flux form can be expressed as follows:

$$N'' = c_m\,\Delta P^{sat} = c_m\left(P_1^{sat} - P_2^{sat}\right) \tag{1}$$

where P_1^{sat}, P_2^{sat} are the saturated pressure of water on the hot and cold feed membrane surfaces, respectively. These pressures are estimated using the Antoine equation [19]

$$P_k^{sat} = 133.322 \times 10^{(8.10765-(1450.286/(T_k+235)))}, \quad k = 1, 2 \tag{2}$$

where T_k is the temperature in °C. The non-volatile solute effect is on the water vapor pressure reduction. For non-ideal binary mixtures, the partial pressure can be determined as

$$P_1^{sat} = y_w P = x_w a_w P_w^{sat} \tag{3}$$

where y_w and x_w are the vapor and liquid mole fractions of water, respectively, and P and P_w^{sat} are the total pressure and saturation pressure of pure water, respectively. The water activity in NaCl solutions, a_w, is a function of the temperature and composition determined using the correlation equation [1]

$$a_w = 1 - 0.5x_{\mathrm{NaCl}} - 10x_{\mathrm{NaCl}}^2 \tag{4}$$

where x_{NaCl} is the mole fraction of NaCl in saline solution.

The membrane coefficient c_m is a significant parameter for mathematical modeling which vastly affects the mass flux across membrane. There are three essential membrane coefficient models that can be used to describe the mass flux across the hydrophobic porous membrane: the Knudsen diffusion model (due to the larger mean free path of vapor molecules than the membrane pore size), Poiseuille flow model (due to the momentum transfer to the supported membrane) and molecular diffusion model (due to the concentration gradient across the membrane). For a single gas system, the distinctions between these three models are determined by the vapor molecule motions which depend on a comparison between the mean free path and pore diameter. If the mean free path is much larger than the pore size, molecule-wall collisions become more important and the gas transport is described using the Knudsen diffusion model. In contrast, if the mean free path is much smaller than the pore size, the molecule motion due to the pressure gradient (i.e. saturated pressure difference across the membrane) becomes the major transport phenomenon and is described using the Poiseuille flow model. The vapor transport mechanism through the membrane was determined by estimating the transmembrane temperature difference. When mass transfer takes place in the membrane, the three models simultaneously affect the diffusion mechanism in the membrane. This microporous membrane morphology (say the effective gas diffusivity) in the molecular diffusion model owing to the collision between diffusing molecules (ordinary diffusion) is difficult to measure and needed to be clarified. The uncertainty of microporous membrane morphology leads to inaccuracy when calculating the mass transfer [16]. Many researchers used the expressions of interfacial temperature in terms of bulk temperature with specified empirical correlations of heat-transfer coefficients [15,17]. The total pressure difference across membrane is established by the transmembrane temperature difference, resulting in Poiseuille flow occurrence (due to the existence of pressure gradient across the membrane). Therefore, the combination of Knudsen diffusion and Poiseuille flow models was proposed in the present study and validated by the theoretical results as compared to experimental runs. Consequently, the membrane coefficient is presumed to be a combination of the Knudsen diffusion model and Poiseuille flow model, which is investigated by Schofield et al. [16,20] and presented by a semi-empirical equation to describe the water vapor flux through a deaerated microporous membrane, this is

$$c_m = c_K + c_P = 1.064\alpha(T)\frac{\varepsilon r}{\tau\delta_m}\left(\frac{M_w}{RT_m}\right)^{1/2} + 0.125\beta(T)\frac{\varepsilon r^2}{\tau\delta_m}\frac{M_w P_m}{\eta_v R T_m} \tag{5}$$

where $\alpha(T)$ and $\beta(T)$ are the Knudsen diffusion model and Poiseuille flow model contributions, respectively. M_w is the molecular weight of water, P_m is the mean saturated pressure in membrane, R is the gas constant, r is the pore radius, T_m is the mean temperature in membrane, δ_m is the thickness of membrane, ε is the porosity of membrane, η_v is the gas viscosity and τ is the tortuosity factor. The tortuosity of such a porous hydrophobic membrane, say PTFE, was estimated by Iversen et al. [21]

$$\tau = \frac{1}{\varepsilon} \tag{6}$$

Therefore, the pure water flux is determined from Eqs. (2)–(6) as

$$N'' = c_m\left((1 - x_{\mathrm{NaCl}})\,(1 - 0.5x_{\mathrm{NaCl}} - 10x_{\mathrm{NaCl}}^2)P_1^{sat} - P_2^{sat}\right) \tag{7}$$

The pure water flux variations due to the temperature distribution along the flow direction, the one-dimensional mass concentration profile can be obtained using the mass balance in a fluid element as follows:

$$\frac{dN}{dz} = N''W \tag{8}$$

where W is the width of channel.

2.2. The temperature distribution in the flow channel

Fig. 1 shows a schematic diagram of the parallel-flow membrane distillation system. The open conduit is divided by inserting

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