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Detailed modeling and simulation of an out-in configuration vacuum membrane distillation process

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ABSTRACT

In this study, a detailed rigorous theoretical model was developed to predict the transmembrane flux of a shell-and-tube type vacuum membrane distillation (VMD) module for seawater desalination. Two modes of operation are used for performing the VMD, namely lumen-side feed (in-out) configuration and shell-side feed (out-in) configuration. In this study, detailed mathematical formulations are derived for an out-in configuration that is commonly used in seawater desalination applications. Experimental results and model predictions for mean permeate flux are compared and shown to be in good agreement. The results indicate that although the simple VMD model that maintains a constant permeate pressure is easy to use, it is likely to significantly overestimate the mean permeate flux when compared to the detailed model that considers the pressure build-up in the fiber lumen. The pressure build-up of water vapor in the fiber lumen is identified as the crucial factor that significantly affects the VMD performance because it directly reduces the driving force for vapor permeation through the membrane pores. Additionally, its effect is more pronounced at longer fiber lengths and higher permeate fluxes, and this is achieved at higher feed temperatures and velocities and at lower feed salinities. In conclusion, the results of the study are extremely important in module design for the practical applications of VMD processes.
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1. Introduction

Membrane distillation (MD) is a thermally driven and membrane-based separation process that employs a hydrophobic and microporous membrane as a contactor to separate water vapor from a saline water stream at a relatively high temperature. The temperature difference through both interfaces of the membrane generates a water vapor pressure gradient and results in transmembrane vapor flux from the hot feed to the cold permeate. The hot feed comes in contact with the membrane, and only the water vapor passes through its dry pores and condenses on the coolant side (Alkhudhiri et al., 2012; Khayet, 2011). Some of the main advantages of MD processes over conventional separation technologies are as follows: (i) a complete rejection of dissolved and non-volatile species to produce ultrapure water; (ii) a significantly lower operating pressure when compared to pressure-driven membrane processes and a lower operating temperature (60 °C–80 °C) when compared to conventional evaporation integrated with low-grade thermal energy (such as industrial waste heat, solar, and geothermal energies); (iii) lower membrane fouling when compared to that of microfiltration, ultrafiltration, and reverse osmosis; (iv) relatively lower energy costs and reduced vapor space when compared to those of conventional thermal desalination processes such as multi-stage flash (MSF) and multi-effect distillation (MED) (Alkhudhiri et al., 2012; Curcio and Drioli, 2005; Francis et al., 2013; Kim et al., 2013, 2015; Lee et al., 2015a, 2016).

Several common MD configurations were proposed in extant studies, and they include direct contact membrane distillation (DCMD), air gap membrane distillation (AGMD), sweeping gas membrane distillation (SGMD), vacuum membrane distillation (VMD), and more recently, liquid gap MD (LGMD) and material gap MD (MGMD) with an aim to enhance the MD permeate flux and to reduce conductive heat loss (Alkhudhiri et al., 2012; Khayet, 2011). Among them, VMD is deemed to exhibit considerable potential for scale-up as it provides the highest flux and most efficient heat recovery when compared to the other configurations (Khayet, 2011) although the AGMD may provide similar albeit better internal heat recovery when condensation occurs inside the module. However, in the VMD process, the condensation of permeate vapor occurs outside the module via a vacuum pump, and this is considered the

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main disadvantage of this configuration when compared to other configurations such as AGMD. Meanwhile, AGMD has several disadvantages such as complex module design and low permeate flux.

In the VMD process, the hollow-fiber membranes are widely used owing to their high packing densities that lead to high membrane surface area. As a result, its module displays advantages when compared to plate-and-frame and spiral modules for seawater desalination applications. The hollow-fiber MD module has two main operating modes, namely the lumen-side feed (in-out configuration) and shell-side feed (out-in configuration). Previous studies extensively examined both feed configurations for the VMD process, and each model has its own advantages and disadvantages. However, it is observed that the lumen-side feed configuration is restricted by operational constraints, especially due to crystallization in the fiber lumen at high seawater concentrations, and fouling and scaling problems. In this respect, the shell-side feed configuration is commonly used in seawater desalination applications. However, in the case of an out-in configuration module, although the viscosity of water vapor is significantly lower when compared to that of the liquid phase, the vapor pressure build-up in the fiber lumen should not be neglected because the pressure build-up promptly deteriorates the driving force of vapor permeation through the membrane (Sun et al., 2014). Thus, with respect to practical desalination applications in which hollow-fiber modules are employed, the module should be properly designed to ensure that the permeate pressure build-up does not adversely affect the permeate flux, especially for the scale-up design of VMD module. To the best of the authors' knowledge, this aspect is not completely described in detail in previous studies (Kim et al., 2015, 2016; Lee et al., 2015b; Shim et al., 2014; Sun et al., 2014).

Most recent studies have investigated a VMD module with an out-in configuration where vacuum is applied to both ends of the hollow fiber, to alleviate the adverse effects of vapor pressure build-up on the permeate flux (Kim et al., 2015, 2016; Lee et al., 2015b; Shim et al., 2014). It is assumed that the permeate-side pressure (vacuum) is kept constant and not affected by the number of hollow fibers. Based on this assumption, they have established a transport model by formulating mass, momentum, and energy balances for the feed side without considering the permeate pressure build-up. Conversely, in order to demonstrate the local mass transfer in VMD process that considers the vapor pressure build-up in the fiber lumen under isothermal operation, a mathematical model was developed based on the basis of the Hagen-Poiseuille equation to describe the pressure build-up and the permeation equation based on Knudsen diffusion of water vapor through the membrane pores (Sun et al., 2014). However, the Hagen-Poiseuille equation is commonly used to describe the pressure drop in an incompressible Newtonian fluid in a laminar flow flowing through a long cylindrical impermeable tube with a constant cross-section while the equation may fail in the limit of low viscosity, wide and/or short tube. It should be noted that low viscosity or a wide tube may result in turbulent flow, and this makes it necessary to use complicated models such as the Darcy-Weisbach equation. In the case of excessively short tubes, the Hagen-Poiseuille equation may result in unphysically high flow rates, and the flow is bounded by Bernoulli's principle under less restrictive conditions (Cengel and Ghajar, 2011). Thus, the limitations of the Hagen-Poiseuille equation significantly detract from its practical applications because it does not consider the effect of transmembrane flow resistance on the local permeate flux and pressure drop.

The aims of the present study are as follows: (i) to develop a detailed mathematical model for the shell-and-tube type VMD with a shell-side feed configuration for seawater desalination by simplifying the mass, momentum, and energy balance on both the feed and permeate sides, (ii) to illustrate the effects of major factors involving module configurations (cocurrent- and countercurrent-flow configurations and hollow-fiber length) and operating parameters (feed temperature, flow rate, and salinity) on the permeate flux, and (iii) to demonstrate the pressure build-up characteristics of water vapor in the fiber lumen.

2. Hollow-fiber VMD process

Fig. 1 illustrates a schematic of a hollow-fiber VMD module with two different flow configurations that are considered in the study: countercurrent flow configuration (Fig. 1a) and cocurrent flow configuration (Fig. 1b, baseline configuration). The VMD module comprises an array of microporous hydrophobic hollow-fiber membranes that are collectively assembled in a shell-and-tube module. As shown in Fig. 1, a hot feed is circulated in direct contact with the shell side of the hollow fibers that is maintained at atmospheric pressure at the module outlet ($z = L_f$) while a permeate is removed in the vapor state from the opposite side of the membrane that is maintained under vacuum pressure. An end of the fiber lumen is open to provide an outlet for the discharge of water vapor from the module, and vacuum is applied to the interior at the open end of the hollow fibers. Therefore, the permeate flux increases along the fiber from the dead end ($z = L_f$ for the countercurrent flow and $z = 0$ for the cocurrent flow). Thus, the vapor pressure in the fiber lumen increases from the open end to the dead end, and this results in a vapor pressure build-up along the fiber lumen, leading to a decrease in the driving force ($P_{f,m}$–P_p). This phenomenon is examined in detail in the following sections to elucidate the effects of pressure build-up in the fiber lumen on the VMD permeate flux.

3. Theoretical model

3.1. Transmembrane flux

As depicted in Fig. 1, the VMD process involves heat transfer across the feed-side boundary layer adjacent to the membrane surface and through the membrane that is coupled with the mass transfer of water vapor through the membrane pores. The heat transfer process mainly consists of convective heat transfer across the feed-side boundary layer and subsequently of conductive and convective heat transfer through the membrane. The heat transfer by conduction through the membrane and by convection across the permeate-side boundary layer can be ignored (El-Bourawi et al., 2006; Kim et al., 2015, 2016; Lee et al., 2015b).

The convective heat transfer (Q_f) across the feed-side boundary layer is given as follows:

$$Q_f = h_t\left(2\pi r_o N_f\right)\left(T_f - T_{f,m}\right), \quad (1)$$

where h_t, r_o, N_f, T_f and $T_{f,m}$ denote the convective heat transfer coefficient, the outer radius of fiber, number of hollow fibers, bulk feed temperature, and liquid-vapor interface temperature on the feed side, respectively. Here, the convective heat transfer coefficient (h_{tf}) at the shell side is calculated as follows (Groehn, 1982):

$$Nu = \frac{h_t d_h}{k_f} = 0.206(\mathrm{Re}\cos\alpha)^{0.63}\mathrm{Pr}^{0.36}, \quad (2)$$

where k_f denotes the thermal conductivity of the bulk feed, and α denotes the yaw angle that varies between 0° for the cross flow and 90° for the parallel flow. Additionally, d_h denotes the hydraulic diameter of the shell, $d_h = d_o(1-\phi)/\phi$, and this is a function of the module packing density ϕ, $\phi = N_f(d_o/d_s)^2$ in which d_s denotes shell inner diameter.

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