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Numerical modeling of the vacuum membrane distillation process

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HIGHLIGHTS

- A model of a hollow fiber vacuum membrane distillation module is proposed.
- The energy, momentum balance and heat and mass transfer equations are simultaneously solved.
- The mathematical VMD model is validated in comparison with the previous results.
- The effect of the module dimension and operation condition on the VMD performance is demonstrated.

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ABSTRACT

In this study, one-dimensional vacuum membrane distillation (VMD) model is suggested for predicting the performance of seawater desalination to evaluate the performance of hollow fiber type VMD module. The energy and momentum balance equations, as well as the heat and mass transfer equations, are simultaneously solved to determine the concentration of NaCl, temperature and velocity distribution of feed side along the module length, productivity of distilled water and specific energy consumption. The productivity increases with an increase in the inlet feed temperature and velocity, the number of fibers and the total module length. However, it decreases with an increase in the mass fraction of the feed. Specific heat energy consumption decreases with an increase in the inlet feed temperature and velocity and total module length, but it increases with an increase in mass fraction of the feed and number of fibers. The specific electrical energy consumption increases with an increase in mass fraction, velocity and total module length and a decrease in inlet feed temperature and number of fibers, but the specific electrical energy consumption is too small and negligible in comparison with the specific heat energy consumption (less than 2%) on various operating conditions and module dimensions.

1. Introduction

Water shortage is an important global issue due to industrial and population growth [1,2]. The potential advantages of the membrane distillation (MD) process are low operating temperature and hydraulic pressure, nearly 100% rejection (theoretical and practical) of non-volatile species, lower vapor space resulting in low mass transfer resistance between the liquid and condensate phases, low sensitivity to salt concentration, low requirement of plant space and performance not limited by high osmotic pressure or concentration polarization [3–8]. Therefore MD has potential applications in many areas. One of the major disadvantages of MD is its relatively high specific energy consumption compared to other desalination techniques, such as reverse osmosis (RO), multi-effect desalination (MED), and multi-stage flash (MSF) [2,9–11]. However the specific energy consumption can be reduced with the heat recycling method [12,13]. Hollow fiber type membrane devices for the MD process can have a larger effective area compared with other membrane module types [9,14]. Membrane distillation can be classified into four types: direct contact membrane distillation, air gap membrane distillation, sweeping gas membrane distillation and vacuum membrane distillation. These are classified based on the way the pressure difference is created between the feed and the permeate side [15]. The VMD process has two advantages: low mass transfer resistance and low operation temperature [16]. The risk of pore wetting problem is one of the critical issues on the VMD process therefore to avoid it VMD uses smaller pore size (i.e., less than 0.45 μm) than other MD systems [17]. In the design of the VMD process, wetting of membrane pore must be prevented, which happens at the so-called liquid entry pressure [16,18]. The liquid entry pressure is the critical point where the hydrophobic membrane allows the passage of water vapor [19].

Many previous studies highlight that the feed and permeate inlet temperature, the feed and permeate inlet velocity, module dimensions and process design are crucial factors for the cost of distillate water. Mengual et al. [19] presented and verified the heat and mass transfer model in the VMD hollow fiber modules under many well-known heat transfer empirical correlations developed for non-porous and

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rigid heat exchangers, and compared with the experimental results. Li and Sirkar [20] presented the permeate flux of the VMD results under the rectangular cross flow mode for the hot brine flow over the outside of the fibers, as well as the vacuum application in the fiber and vice versa, and they identified a remarkably high water vapor flux up to 71 $\mathrm{kgm^{-2}\ h^{-1}}$ from the 85 °C hot feed in the cross flow with the MXFR #3 module. Wirth and Cabassud [1] showed the experimental results of two VMD hollow fiber module configurations (inside/out and outside/in). Ramon et al. [16] presented a two-dimensional boundary layer model to describe the heat transfer in the feed channel of the VMD module and introduced an 'effective' slip coefficient to account for the possible deviation of the flow and heat transfer characteristics over a liquid–gas interface from those at a solid surface. Banat et al. [21] pointed out that the mass flux of distilled water was highly sensitive to the feed temperature, especially at high vacuum pressure values. The mass flux was more sensitive to the vacuum pressure at low feed temperature levels compared to high ones. Safavi and Mohammadi [2] presented the research focus on vacuum membrane distillation (VMD) using high concentration NaCl aqueous solutions as feed. Soni et al. [15] showed the simulated VMD performance results using an aroma solution compared with laboratory experiments. Khayet and Matsuura [22] showed that two separation processes, pervaporation (PV) and vacuum membrane distillation (VMD), were studied using polyvinylidene fluoride (PVDF) flat-sheet membranes for the separation of chloroform–water mixtures. Bandini et al. [23] presented the evaporation rate and selectivity of all of the relevant resistances on the VMD configuration.

The 1-D model by Soni et al., [15] considered only the temperature gradient, and velocity gradient as a function of module length and the 2-D model by Ramon et al., [16] also considered only the temperature gradient, velocity gradient, and pressure gradient as a function of module length and radial direction. Furthermore, the 1-D model did not consider bulk mass fraction, and bulk pressure as a function of module length and the 2-D model did not consider the bulk mass fraction as a function of module length. Generally these parameters affect the VMD performance. The suggested modeling of VMD considered simultaneously the energy and momentum balance equations with the heat and mass transfer equations. And the variations of liquid properties are considered with temperature in the modeling of VMD [24].

In this study, the aim is to develop new systematic model that is able to identify the phenomena in the vacuum membrane distillation and to compare the results from the model with the experimental results [19]. A modeling approach to predict the performance of a hollow fiber type VMD configuration under an experimental operating condition [19] was presented for specific inlet feed temperatures (40–65 °C) and inlet feed velocities (0.2–1.0 m/s). The performance of the VMD configuration when the mass fraction of the salt was between 0.025 and 0.04 was also analyzed. The effects of the feed temperature, feed velocity, feed mass fraction of NaCl, module length and number of fibers on the permeate flux, productivity and specific energy consumption are presented. The physical properties of water and NaCl [24] are required in order to solve the model to predict the physical behavior. The specific energy consumption and productivity were analyzed to find the dominant operation parameter of the performance of VMD on various operation conditions such as temperature, velocity and mass fraction and module dimensions such as module length and number of fibers.

2. Model of the hollow fiber VMD module

The hollow fiber type VMD module consists of three layers, the shell feed side, the membrane layer and the lumen vacuum permeate side. Vacuum membrane distillation (VMD) is a selective membrane separation process driven by a vapor pressure gradient across the membrane. The numerical analysis is performed on a commercial shell and tube type membrane module MD020CP2N. The feed water flows in the shell side and the lumen side is kept under vacuum. The heat and mass transfer across the membrane is typically obtained by counter current flowing from the hot feed through the shell side and the vacuum permeate side through the lumen side of the module. The vacuum membrane distillation processes are as follows: (i) preheated brine water flows over the membrane surface, (ii) evaporation of the volatile solute from the liquid–vapor interface on the feed side of the membrane and (iii) diffusion of vapor through the membrane pore [9,10,17]. The physical processes in the VMD membrane are depicted in Fig. 1.

2.1. Membrane properties

The commercial membrane used was polypropylene (PP) hollow fiber type membrane module from Mycrodyn-Nadir GmbH (MD020CP2N) and the schematic of hollow fiber type membrane module is shown in Fig. 2. Its basic properties, provided by the manufacturer, are listed in Table 1.

2.2. Heat transfer in the vacuum membrane distillation

The heat transfer coefficient on the feed brine side is a dominant factor in defining the permeate flux and the heat energy consumption. For tubular flows in the shell side of the hollow fiber modules, cross and parallel flows may occur simultaneously. In these cases, Grohn proposed the following correlation for cylindrical heat exchangers that are not normal to the flow [19,25]:

$$Nu = 0.206 \cdot (\mathrm{Re} \cdot \cos\theta)^{0.63}\mathrm{Pr}^{0.36} \tag{1}$$

where $\mathrm{Re}^F = d_h v^F \rho^F / \mu^F$, $\mathrm{Pr}^F = C_P{}^F \mu^F / k^F$ and the yaw angle θ is the angle between the direction of flow and the hollow fiber axis (e.g., $\theta = 0°$ for the cross flow). In this case, yaw angle is $\theta = 87°$ at the MD020CP2N module [7]. The heat transfer process for the shell feed side VMD includes the heat transferred through the boundaries of the feed side (Q^F) and the energy transferred through the membrane (Q^m).

2.2.1. Within the boundary of the shell feed side

$$Q^F = h^F A_r^F \alpha \left(T_b^F - T_m^F\right) \tag{2}$$

where $A_r^F = 1$ and $\alpha = \pi N d_o$. N is the number of fibers and d_o is the

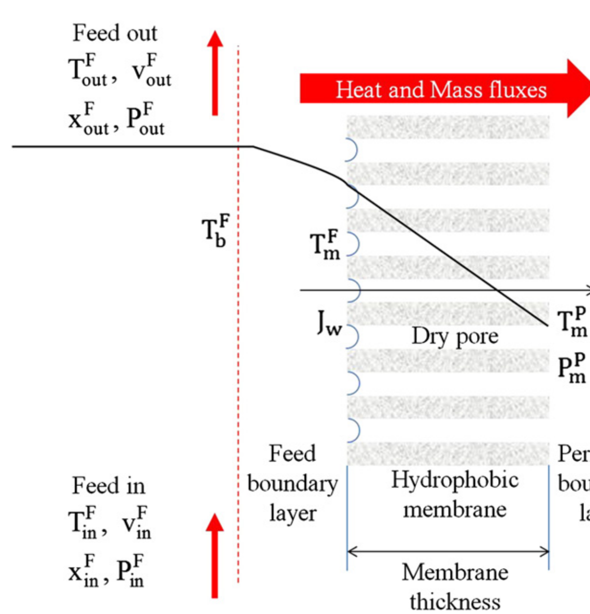

Fig. 1. Schematic of mass and heat transfer during vacuum membrane distillation.