Desalination 339 (2014) 1–9

Contents lists available at ScienceDirect

Desalination

journal homepage: www.elsevier.com/locate/desal

Numerical modeling and optimization of vacuum membrane distillation module for low-cost water production

Guangzhi Zuo [a,b], Guoqiang Guan [b,c], Rong Wang [a,b,*]

[a] School of Civil and Environmental Engineering, Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798, Singapore
[b] Singapore Membrane Technology Centre, Nanyang Environment and Water Research Institute, Nanyang Technological University, 1 Ceantech Loop, Singapore 637141, Singapore
[c] School of Chemistry and Chemical Engineering, Southern China University of Technology, Guangzhou 510640, China

HIGHLIGHTS

- A two-dimensional numerical model was developed for VMD process.
- Four design and operation variables were optimized to minimize water production cost (WPC).
- A case study shows that the WPC can be decreased by 38.1% in comparison with the non-optimized VMD process.
- A general guidance for reducing the WPC was also provided.

ARTICLE INFO

Article history:
Received 13 December 2013
Received in revised form 3 February 2014
Accepted 3 February 2014
Available online 3 March 2014

Keywords:
Vacuum membrane distillation
Numerical modeling
Optimization
Low-cost water production

ABSTRACT

A two-dimensional numerical model, involving energy conservation, momentum transport and continuity equations, was developed to provide the profiles of temperature, velocity and pressure of vacuum membrane distillation (VMD) process using hollow fiber module. The theoretical prediction was in good agreement with the experimental results from literature. Four design and operation variables, including feed temperature, hollow fiber length, feed volume flow rate and vacuum pressure, were optimized to minimize water production cost (WPC) using genetic algorithm (GA). A case study shows that the WPC can be decreased by 38.1% in comparison with the non-optimized VMD process. Meanwhile, a general guidance for reducing the WPC was also provided. The feed temperature should be adopted as high as possible, while the hollow fiber length cannot be too long to result in a decrease in water flux and an increase in pressure drop. The flow rate is recommended to take a lower bound value and the moderate degree of vacuum is preferable. This study indicates the importance of VMD system optimization to minimize water production cost.

1. Introduction

Membrane distillation (MD) is a thermally-driven process, which utilizes water vapor pressure gradient to drive the water vapor across a hydrophobic microporous membrane [1]. In general, it is composed of three heat and mass transfer steps: the water vapor evaporates at the membrane surface in the hot feed side, passes through the membrane pores and finally condensates at the other side of the membrane. MD has been considered as a promising technology because of its moderate operating temperature, which means that low-grade heat can be utilized as the heating source. In addition, it is capable of treating high concentration brines without serious performance deterioration [2], enabling it to be incorporated with other processes such as reverse osmosis (RO) and crystallization [3]. Furthermore, it produces high purified permeate water, suggesting its potential for applications in medical and food industries.

Based on different condensation methods, there are mainly four types of membrane distillation configurations: direct contact membrane distillation (DCMD), sweeping gas membrane distillation (SGMD), air gap membrane distillation (AGMD) and vacuum membrane distillation (VMD) [4]. Among the four configurations, VMD has been proved to be the most energy efficient due to its insignificant temperature polarization effect, relatively high mass flux and energy efficiency [5,6]. However, the disadvantage of VMD lies in the fact that it requires an external vacuum pump to facilitate the transfer of the permeate water vapor across the membrane, causing extra energy consumption [7]. Thus, it suggests that more intensive efforts should be made with respect to the optimizations of the design and operating conditions of VMD process.

In order to make VMD process more economic for desalination, many investigations have been carried out in recent years [8–11].

---

* Corresponding author at: School of Civil and Environmental Engineering, Nanyang Technological University, 639798 Singapore, Singapore. Tel.: +65 6790 5327; fax: +65 6791 0676.
E-mail address: rwang@ntu.edu.sg (R. Wang).

http://dx.doi.org/10.1016/j.desal.2014.02.005
0011-9164/© 2014 Elsevier B.V. All rights reserved.

VMD using flat sheet membrane module was preferred because of its relatively easy fabrication [12,13], while some studies also reported hollow fiber VMD modules, given its large specific membrane surface area in comparison with the flat sheet membrane module, as well as its easily scalable potentiality [5,7]. However, to our best knowledge, there is no report on the economic analysis in terms of module design and the optimization of operating conditions for hollow fiber based VMD process, probably due to the fact that VMD requires external vacuum pump consumption in comparison with DCMD, making it unclear to estimate the overall energy cost.

To achieve the goal of VMD system optimization, appropriate modeling of VMD process is required. As a conjugate heat transfer process, VMD essentially features two-dimensional (2-D) heat and mass transfer in both the flow channel and membrane matrix. Therefore, the distributions of temperature, velocity and pressure along the longitudinal (z-axis) and transversal (r-axis) directions are of the concern, as a thorough understanding of the heat and mass transfer inside the VMD module cannot be attained until the profiles of these parameters are determined. Nevertheless, at present, most of the modeling studies still adopt the approach of analytical one-dimensional (1-D) modeling based on energy balance for the control volume by applying empirical heat and mass transfer equations, which were derived from non-porous and rigid heat exchangers [5,6,13], whereas the 2-D modeling employing Navier–Stokes equations as governing equations, which can provide more reliable and comprehensive information, are not commonly applied for investigation. To bridge the gap, some researches utilized commercial program packages such as FLUENT to simulate the flow condition and achieved satisfactory simulation results by comparing with the experimental data [14,15]. However, the computation speed of the commercial program packages is rather slow even with high performance computers. It is widely acknowledged that the numerical methods using scientific programming language (e.g. FORTRAN) or mathematical software systems (e.g. MATLAB) are superior to the commercial program packages (e.g. FLUENT) in terms of computation speed and efficiency [16]. It seems the commercial program packages are more suitable for the cases which have very complex boundary geometries and require extremely high accuracy.

In addition, the conventional optimization strategy for a system was mainly single variable dependent, with other variables fixed [17]. This kind of optimization procedures may require a large amount of experiment designs to correlate the object functions and decision variables, which can hardly reflect the interaction of the multi-variable dependent process. Intuitively, the most accurate way of the optimization is to try out all possible conditions and compare the target functions to ultimately identify the optimized match. However, this type of clumsy method is rather time consuming and extremely low efficient, especially for some complicated problems of multi-variables with a large value domain and the requirement of high accuracy.

Genetic algorithm (GA) is one of the advanced numerical methods that mimic the Darwin's natural selection and evolution, so that a better match (offspring) may probably be generated regarding to the requirement (object function). It is able to significantly scale down the choices of the match and facilitate the generation of the desired design and operating conditions from a series of combination of the match rather than from a huge number of the possibilities. Recently, Cheng et al. used the genetic algorithm to perform the optimization of DCMD and AGMD systems with two and three variables based on their 1-D modeling, respectively [18,19], but limited works on multi-variable optimization of VMD process based on 2-D modeling have been reported.

In current study, we intend to optimize the module design and operating conditions of the VMD process. The aim of the study is to develop a VMD system with the lowest water production cost based on the economic analysis of the optimized system. Specifically, a 2-D model was firstly built up for hollow fiber VMD membrane module and solved using finite element method (FEM), which led to the acquirement of the distribution profiles of temperature, velocity and pressure in the membrane module. The objective function was established to minimize water production cost by investigating four variables, including feed temperature, hollow fiber length, volume flow rate and vacuum pressure. The genetic algorithm was applied to seek the best design and operation conditions. A case study was performed to provide guidance for a VMD system with membrane area of 0.1 m^2.

2. Theory and methodology

2.1. VMD model development

2.1.1. Governing equations

The schematic of a VMD hollow fiber module is shown in Fig. 1a, which represents the 2-D model simulating the main configuration of the VMD module. The feed stream flows into the lumen side, while the shell side is under vacuum. N represents water flux across the membrane; q_f is the volumetric flow rate of the feed stream. L is the length of the hollow fiber and membrane module. The r- and z-coordinates are perpendicular and parallel to the hollow fiber membrane surface, respectively.

In principle, the steady state heat transfer in the MD module includes the convective and conductive heat transfer of the feed flow in the lumen side, the latent heat transfer associated with water vapor transport across the membrane pores, and the conductive heat transfer in the polymer membrane matrix. To define and simplify the model, some assumptions were made as follows: (1) the feed stream is a steady-state flow; (2) the flow pattern is within laminar flow region; (3) the feed stream has constant physical properties; (4) only z-axis velocity exists and r-axis velocity is assumed zero; (5) the temperature profile has no influence on the velocity profile; and (6) there is no slip condition at the boundary. By considering these assumptions, the model equations of the feed flow can be expressed according to the Boussinesq approximation [20]:

$$\rho_f C_f u\cdot\nabla T=\nabla\cdot\left(k_f\nabla T\right) \tag{1}$$

$$\rho_f u\cdot\nabla u=-\nabla p+\nabla\cdot\left[\mu\left(\left(\nabla u+(\nabla u)^T\right)-\frac{2}{3}\nabla\cdot uI\right)\right]+\rho_f g \tag{2}$$

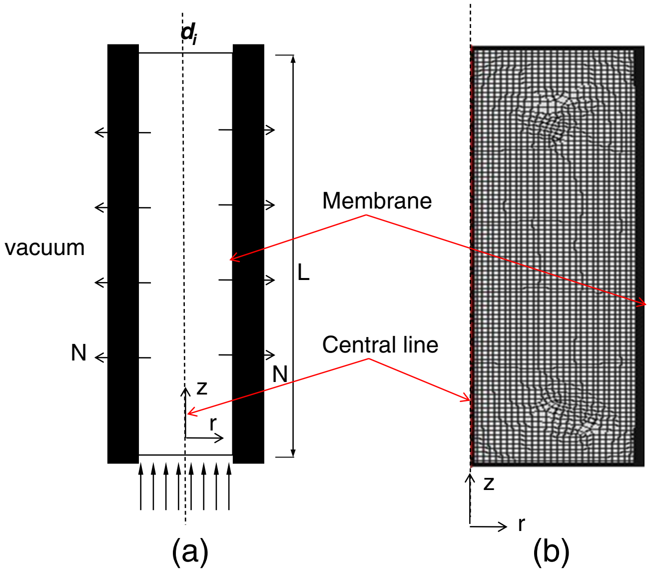

Fig. 1. (a) Schematic of the VMD membrane module. (b) Generated mesh in the flow and membrane domains.