Desalination 283 (2011) 237–244

Contents lists available at ScienceDirect

Desalination

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

Energy efficiency evaluation and economic analyses of direct contact membrane distillation system using Aspen Plus

Guangzhi Zuo [a,b], Rong Wang [a,b,*], Robert Field [c], Anthony G. Fane [a,b]

[a] School of Civil and Environmental Engineering, Nanyang Technological University, 639798 Singapore, Singapore
[b] Singapore Membrane Technology Centre, Nanyang Technological University, 639798 Singapore, Singapore
[c] Department of Engineering Science, University of Oxford, UK

ARTICLE INFO

Article history:
Received 13 December 2010
Received in revised form 7 April 2011
Accepted 18 April 2011
Available online 19 May 2011

Keywords:
DCMD
Aspen Plus
Cross-flow configuration
Gain output ratio
Water production cost

ABSTRACT

A direct contact membrane distillation system (DCMD) was simulated by using Aspen Plus for the purpose of energy efficiency and economic analyses. A cross-flow membrane module was firstly modeled and then incorporated into the flowsheet for system simulation. Detailed investigations have been conducted to understand the relationships of the water flux/production, the gain output ratio (GOR) and the water production cost (WPC) with respect to various design and operation parameters of the DCMD system.

Simulation results revealed that in the DCMD studied here, a critical membrane area existed, below which, significant increases of water production and the GOR were observed with increasing membrane area, leading to a significant drop in the WPC. Increasing feed temperature imposes positive impacts on water flux and the GOR. For the higher feed and permeate velocities, there were increases in water flux, water production and the GOR. However for the WPC there were optimum fluid velocities beyond which the penalty of more energy input in the form of electricity consumption for pumping was significant. It was also found that when the temperature difference in the heat exchanger was increased to 6 °C, the WPC can be reduced considerably by cutting down the heat exchanger cost.

1. Introduction

Membrane distillation (MD) is an emerging thermally driven membrane process, where micro-porous hydrophobic membranes serve as a barrier to separate hot feed and cold permeate, and water vapor generated in the hot feed transfers across the membrane and condenses in the cold permeate. Among the four types of MD configurations, direct contact membrane distillation (DCMD) is the most widely used [1–3].

The concept of MD was developed for seawater desalination as early as the 1960s [1], but it has not drawn much attention for decades because of energy demand for heating the feed and the problem of membrane wetting during the operation [2–7]. The resurgence of interest in MD as a potential means for seawater desalination in recent years is being driven by several factors, which include advancement in novel polymer materials, breakthroughs in membrane fabrication technology [8–11] and severe global fresh water scarcity. At present, the main challenge for large-scale MD desalination is energy consumption, which was estimated to be more than 40 kWh/m^3 in comparison with energy consumption of around 7 kWh/m^3 for RO and 40 kWh/m^3 for multiple effect distillation (MED) and multi-stage flash (MSF), leading to a relatively high cost for water production [12–15]. However, MD only requires moderate temperature to generate a thermal driving force across the membrane, which makes it viable to utilize the waste heat to reduce the water production cost. Furthermore, it has been demonstrated that salt concentration has relatively little effect on mass flux for MD process in comparison with RO process, indicating that MD can effectively deal with high concentration brine [16]. It can be economically competitive when low-grade waste heat or renewable energy resources such as solar energy are available for use [2,16,17]. In addition, many efforts have been made to improve the hydrodynamic conditions in MD modules [18–22], as the hydrodynamics are closely associated with the thermal condition for water transfer. It was reported that temperature polarization in a DCMD module can be minimized through proper module design and hydrodynamic improvement [18,23,24]. Moreover, system optimization, by incorporating a heat exchanger in the MD system for heat recovery, can further reduce the energy requirement [7,14,23,25]. The concept of gain output ratio (GOR), which is defined as the ratio of heat associated with mass transfer to the energy input, has been applied to reflect the energy efficiency of the MD process decades ago. Nevertheless, little research has been focused on the influence of the design and operating parameters on the GOR value [7,26]. Currently, no large scale membrane distillation system is reported in use for water production.

---

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

0011-9164/$ – see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.desal.2011.04.048

Economic analyses on pilot MD system have been performed mainly for the situations where all the design and operation variables are fixed [14,17,24,27]. There is a scarcity of economic analysis in terms of the influences of the key design and operating parameters [26].

In order to achieve system optimization, simulation of the MD process has to be carried out. The membrane module, which is the core element of the MD system, has been modeled extensively [21,28–32]. Several researchers have applied Matlab to simulate the heat and mass transfer in the MD module and the results were compared with the experimental data [26,33,34]. In contrast, limited reports are available for system design and optimization [14,26]. The commercial software, Aspen Plus, which is a widely used simulation platform in chemical engineering processes, has been applied recently to study the MD system [35,36]. In these studies, a customized membrane module was programmed by FORTRAN, and then incorporated as a user-defined unit into the system. The mass fluxes based on different operating conditions were predicted for a small membrane unit (membrane area: 0.286 m^2), but no direct linkage of operation and design parameters with economic analysis was provided, though this is very important for practical MD applications.

In the present study, a DCMD system was simulated using the process simulation platform, Aspen Plus, for the purpose of energy efficiency and economic analyses. A cross-flow membrane module, which is not available in Aspen Plus, was firstly defined and modeled, and then incorporated into the flow sheet for system simulation. Detailed investigations have been conducted to understand the relationships between the water flux/production and design and operation parameters, including membrane area, feed temperature, feed and permeate velocities, etc. Moreover, this study examined the variation of the GOR with the design and operation parameters. With the assumption of using an alternative energy such as waste heat in the MD system, economic analysis was also performed. It is expected that based on this study, a guideline for optimal design and operation of DCMD system in terms of energy efficiency and water production cost can be attained, which will benefit practical applications of DCMD for desalination.

2. Theory and methodology

2.1. Heat/mass transfer in DCMD

2.1.1. Heat transfer in DCMD

The heat transfer from the feed side to the permeate side consists of two components: (a) latent heat associating with the water vapor across the membrane (Q_v), and (b) conduction heat by membrane matrix (Q_c). Fig. 1 illustrates the heat transfer processes, which can be expressed for unit area as follows:

$$Q_f = h_f\left(T_f - T_{fm}\right) \tag{1}$$

$$Q_p = h_p\left(T_p - T_{pm}\right) \tag{2}$$

$$Q_m = Q_v + Q_c = N\Delta H + \frac{k_m}{\delta}\left(T_{fm} - T_{pm}\right). \tag{3}$$

At steady state, the heat balance guarantees that the three consecutive heat transfers satisfy the following equation:

$$Q_f = Q_m = Q_p. \tag{4}$$

The heat transfer coefficients in the feed and permeate boundary layers, h_f and h_p can be calculated using a number of methods [34].

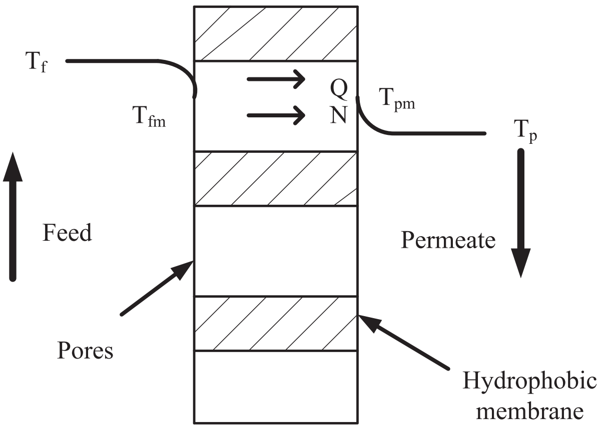

Fig. 1. Schematic of DCMD module.

Here, one simple and effective form, which has been proved to be valid in the cross-flow configuration of MD module, was taken from the literature [37,38]:

$$Nu_p = \frac{h_p d_i}{k_p} = 1.86\left(\frac{d_i}{L}\right)^{0.33}\left(Re_p Pr_p\right)^{0.33}\left(\frac{\mu_p}{\mu_{pm}}\right)^{0.14}$$
$$Re_p = \frac{d_i u_p \rho_p}{\mu_p}; \qquad Pr_p = \frac{C_p \mu_p}{k_p} \tag{5}$$

$$Nu_f = \frac{h_f d_o}{k_f} = 0.71 Re_f^{0.5} Pr_f^{0.36}\left(\frac{Pr_f}{Pr_{fm}}\right)^{0.25} F_c$$
$$Re_f = \frac{d_o u_f \rho_f}{\mu_f}; \; Pr_f = \frac{C_f \mu_f}{k_f}; Pr_{fm} = \frac{C_{fm}\mu_{fm}}{k_{fm}}. \tag{6}$$

where Nusselt number (Nu) is correlated with Reynolds number (Re) and Prandtl number (Pr), the former is related to hydrodynamic conditions, while the latter is only temperature dependent. The definitions of the symbols can be found in the nomenclature.

2.1.2. Mass transfer in DCMD

In the DCMD process, the vapor pressure difference arising from the temperature difference between the two surfaces of the membrane is the driving force for water vapor transfer across the membrane. From Eqs.(1) to (4), the membrane surface temperatures can be derived as follows [39]:

$$T_{fm} = T_f - \left(T_f - T_p\right)\frac{1/h_f * d_i/d_o}{1/h_f * d_i/d_o + 1/\left(N\Delta H/\left(T_{fm} - T_{pm}\right) + \frac{k_m}{\delta}\right) + 1/h_p} \tag{7}$$

$$T_{pm} = T_p + \left(T_f - T_p\right)\frac{1/h_p}{1/h_f * d_i/d_o + 1/\left(N\Delta H/\left(T_{fm} - T_{pm}\right) + \frac{k_m}{\delta}\right) + 1/h_p} \tag{8}$$

$$p = exp\left(23.20 - \frac{3816.44}{T - 46.13}\right). \tag{9}$$

Although various mathematic models such as Knudsen, Poiseuille and molecular diffusion models have been developed for the predication of mass flux, it is generally accepted that the water flux across the membrane can be expressed empirically as [7]

$$N = C\left(p_{fm} - p_{pm}\right). \tag{10}$$