Desalination 426 (2018) 97–107

Contents lists available at ScienceDirect

Desalination

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

Designing and optimization of continuous direct contact membrane distillation process

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ARTICLE INFO

Keywords:
Desalination
Membrane distillation
Process design
Membrane length
Thickness

ABSTRACT

Membrane distillation (MD) is a relatively less-explored membrane operation with the potential to achieve high recovery factor by using low grade heat. The current study proposes the design of a continuous direct contact MD process to achieve high recovery factors by using a commercial hollow fiber membrane. The design consists of multiple MD stages connected in series to achieve a predefined final solution concentration. Depending upon the outlet temperatures of feed and permeate, the design considers the option of heat recovery from permeate. Under a given set of operating conditions, there exists a module length (named as optimum module length) where the net thermal energy consumption and overall permeate productivity are optimum. The optimum module length has been analyzed as function of feed to permeate flow rate (F/P) ratio, feed temperature and concentration. It has been observed that for given feed temperature and concentration, the optimum module length can be tuned by changing F/P ratio. The minimum value of the optimum length is observed at the highest F/P ratio considered. Mathematical analysis was extended to evaluate the appropriate length and the corresponding thickness for each stage. The results reveal a strong nexus among membrane thickness, solution concentration and optimum length.

1. Introduction

Membrane distillation (MD) is emerging as an interesting solution to treat highly concentrated solutions which otherwise are not treatable with conventional pressure driven membrane processes. The process applies a microporous hydrophobic membrane in direct contact with a hot feed solution to separate the vapors/gas passing through the membrane pores. MD can be operated in different configurations and has the potential to exploit low-grade heat to produce high quality freshwater [1–3].

MD has been investigated extensively for development of appropriate membranes [4–7], understanding of heat and mass transfer phenomena [2,8–11], treatment of various liquid streams and development of novel configurations with the potential to use heat energy more efficiently [12–14]. Potential of MD for treatment of highly concentrated solutions such as brine from seawater desalination plants and produced water has been well acknowledged [15–19]. Similarly, MD has been well-studied for recovery of minerals from various solutions [20–23]. The process has also been investigated for operating with renewable energy such as solar energy [16,24–26] and low grade heat [27,28]. However, most of the investigations have been performed at lab-scale and understanding of designing aspects and membrane features for large-scale applications are scarce. For instance, the process optimization has been performed for the small scale units [29–31] which is not suitable for large-scale applications. The option of heat recovery has not been considered in most of these studies. Similarly, the fundamental membrane features such as thickness have been optimized on the basis of lab-scale membrane dimensions [11,32]. Due to large temperature variations along the long membrane modules, the thickness optimized on the basis of small scale data may not be suitable for large scale applications. Similar to reverse osmosis, where an applied hydraulic pressure greater than the osmotic pressure of the feed has to be applied, a minimum temperature gradient along the membrane is needed to ensure that all parts of the membrane exhibit positive flux. In this context, it is utmost important to determine the suitable length for large scale membrane distillation modules. There are very few studies proposing the process design for continuous membrane distillation process [33,34], process optimization and large scale module designing

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http://dx.doi.org/10.1016/j.desal.2017.10.041
Received 2 August 2017; Received in revised form 24 October 2017; Accepted 24 October 2017

[35,36].

On the other hand, some interesting commercial scale applications of MD are under consideration now. GE Water and Memsys Cleanwater Pvt. Ltd. have developed a pilot scale unit consisting of 50 m^2 membrane area to treat 50 m^3/d of produced water with concentration ranges from 150 to 230 g/L [37]. MD pilot unit with a capacity of 100 m^3/h is being developed under the Global MVP project. On the basis of the experimental data from the set-up, the possibility of up-scaling the process in integration with other innovative operations will be considered. A small scale MD set-up with a capacity of 10,000 L/day is already in operation in Maldives (http://www.aquiva-foundation.com). Bearing into mind these developments, there is a strong requisite to evaluate the suitable process design and membrane characteristics for large-scale applications.

In current study, a continuous DCMD process to achieve high recovery factor has been proposed. The process considers the option of heat recovery from permeate stream and has been optimized in terms of temperature and relative flow rates of feed and permeate streams. The analysis has also been performed to evaluate appropriate membrane thickness as function of module length (also referred as channel or envelope length in literature) and solution concentrations. Specific energy consumption (SEC) as function of membrane thickness, module properties and operating conditions has been evaluated by considering the option of heat recovery.

2. Materials and methods

2.1. Model development

Heat transfer in MD takes place through convection and conduction.

$$J_H = H(T_{W,F} - T_{W,P}) = J_M \Delta h_V + \frac{\kappa_m}{\delta}(T_{W,F} - T_{W,P})$$

Here H is the overall heat transfer coefficient, $T_{W,F}$ and $T_{W,P}$ are the membrane surface temperatures in the feed and permeate sides, Δh_V is the latent heat, k_m is the membrane thermal conductivity and δ is the membrane thickness. *k_m can be calculated by using the following correlation* [3].

$$k_m = k_p(1 - \varepsilon) + K_g\varepsilon$$

where k_p and k_g are thermal conductivities of polymer and air, respectively.

Mass transfer flux

$$J_M = C(P_{W,F} - P_{W,P})$$

where C is the membrane distillation coefficient, $P_{W,F}$ and $P_{W,P}$ are the vapor pressures at the membrane surfaces in the feed and permeate sides, which can be obtained by the Antoine equation.

The average pore size of the membrane considered in current study is close to the mean free path of water molecules, therefore, combined Knudsen-molecular diffusion model has been considered in current study to calculate membrane distillation coefficient.

$$C = \left[\frac{3\tau\delta}{2\varepsilon r}\left(\frac{\pi RT}{8M}\right)^{1/2} + \frac{\tau\delta P_a RT}{\varepsilon PDM}\right]^{-1}$$

where τ is the membrane tortuosity factor, R is the gas constant, T is the temperature inside the membrane, ε is the membrane porosity, r is the average pore size of the membrane, M is the molecular weight of water, P_a is the air pressure in the membrane, P is the total pressure inside the pore, and D is the diffusion coefficient of vapor.

In DCMD, two liquid streams with different temperatures are in contact with two opposite sides of membrane thus therefore, due to heat transfer through conduction and convection, the temperature of feed at membrane surface is less than its bulk value while permeate at membrane surface has more temperature than its value in bulk. This phenomenon is termed as temperature polarization defined as following:

$$\begin{cases} J_H = h_F(T_F - T_{W,F}) \\ J_H = h_P(T_{W,P} - T_P) \end{cases}$$

here h_F and h_P are the film heat transfer coefficients of the feed and permeate sides, respectively, whereas T_F and T_P are the bulk temperatures of the feed and permeate streams. h_F and h_P are essential to determine the temperatures at the membrane surfaces.

For the type of membrane and module consider in the current study, the following correlations were found to be the most suitable to calculate the Nusselts number and, thereupon, the corresponding heat transfer coefficients [21,33], therefore, these were used also in current study.

Feed side:

$$Nu = 3.66 + \frac{0.19Gz^{0.8}}{1 + 0.117Gz^{0.467}}\left(\frac{\mu}{\mu_W}\right)^{0.14}$$

Permeate side:

$$Nu = 0.16\mathrm{Re}^{0.6}\mathrm{Pr}^{0.33}\left(\frac{\mu}{\mu_W}\right)^{0.14}$$

where *Nu*, *Gz*, *Re* and *Pr* are Nusselt number, Graetz number, Reynolds number and Prandtl number, respectively.

The following equation was used to determine the pressure drop along the module.

$$\Delta P_L = f\frac{L}{D_{in}}\frac{\rho v_{ave}^2}{2}$$

where f is the Darcy friction factor that is $f = 64/Re$, L is the length of the membrane module, ρ is the density of the feed solution, v_{ave} is the average feed velocity (V_f) and D_{in} is the inner diameter of the hollow fiber.

Energy balance can be experessed with the following equation.

$$(n\pi D_{in}\Delta L)J_H = \begin{cases} W_F C_{P,F}[T_F^{(i-1)} - T_F^{(i)}] \\ W_P C_{P,P}[T_P^{(i)} - T_P^{(i+1)}] \end{cases}$$

where W_F and W_P are the mass flow rates of the feed and permeate streams, whereas $C_{P,F}$ and $C_{P,P}$ are the heat capacities of the solutions on feed and permeate sides, respectively.

The flowsheet simulation was developed using commercial software Aspen Plus V8.8. The physicochemical properties for NaCl solution were correlated by the "ELEC-NRTL" model. The schematic of module and an element from the module taken for the analysis has been shown in Fig. 1. The simulation of the MD module was developed using the Aspen user customized unit model based on the model demonstrated above. In all cases, Fast Newton was chosen to calculate models due to its short calculation time. For estimation and optimization, the Hypsqp optimizer was adopted, which is a feasible path successive quadratic programming optimizer. It ensures that all upper and lower bounds on the decision, and variables are never violated.

2.2. Membrane and feed solutions characteristics

PP hollow fiber membrane from Membrana GmbH, Germany were used in experimentation and initial analysis. The membrane had overall porosity of 73%, thickness of 450 μm and average pore size of 0.2 μm. The fibers were assembled into 17 and 45 cm long modules having surface areas of 0.006 and 0.1 m^2, respectively. In later section, the