Journal of Membrane Science 470 (2014) 257–265

Contents lists available at ScienceDirect

Journal of Membrane Science

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

Direct contact membrane distillation: An experimental and analytical investigation of the effect of membrane thickness upon transmembrane flux

Ho Yan Wu [a], Rong Wang [b], Robert W. Field [a,*]

[a] University of Oxford, Department of Chemical Engineering, UK
[b] Singapore Membrane Technology Centre, Nanyang Technological University, Singapore

ARTICLE INFO

Article history:
Received 9 January 2014
Received in revised form
30 May 2014
Accepted 2 June 2014
Available online 9 July 2014

Keywords:
Membrane distillation
Electrospun membranes
Structural parameter
Effect of thickness

ABSTRACT

Polyvinylidene fluoride (PVDF) electrospun nanofibrous membranes (ENMs), consolidated with a heatpress process and of various thicknesses were fabricated and tested in a DCMD cell at five different operating conditions. Membranes as thin as 27 μm were sufficiently robust for evaluation and gave a transmembrane flux as high as 60 L/h m^2. An analytical model was created to estimate the optimal membrane thickness for DCMD operations. It is found that the value of optimal thickness increases with reduced heat transfer coefficients; decreased feed inlet temperature; increased membrane permeability; and increased salinity. Even for 10% NaCl the predicted optimum was estimated to be 13 μm which was too thin for experimental confirmation. Based upon this analysis but with due allowance for the variation of heat transfer coefficients with temperature dependent physical properties a single Matlab model was created to fit the five sets of data. With the introduction of a structural derivation factor, which reflected the experimentally determined variation of porosity and pore size with thickness, the model was found to fit the data very well.

1. Introduction

Membrane distillation (MD) has become a popular research area since it has the potential to tackle the shortage of water while using a relatively small amounts of high grade energy. MD is a thermal driven process that can be coupled with solar thermal systems to produce fresh water from brackish or seawater. Direct contact membrane distillation (DCMD) is the most popularly explored configuration due to its simple design that makes it particularly attractive and suitable for application in rural and less developed areas.

One of the major disadvantages of MD is its relatively low transmembrane flux. A number of membrane parameters, including membrane material, porosity, tortuosity, pore size and distribution, are factors that affect the production rate in DCMD operation [1]. Most commercial MD membranes available are made of polytetrafluoroethylene (PTFE) because of its very low surface energy [2]. However PTFE membranes require complicated extrusion, rolling and stretching or sintering procedures. Polypropylene (PP) membranes prepared by phase inversion has also been used for MD membranes [3]. While PTFE and PP membranes exhibit good hydrophobicity and promising MD performance, the structural parameters of the membranes produced are difficult to control. In recent years, the electrospinning technique has been explored extensively to produce nano-fibrous membranes. Previous research studies have shown that electrospun hydrophobic membranes are suitable for DCMD application [4–7]. Being hydrophobic with a good thermal resistivity and readily dissolvable at room temperature in a variety of solvents, poly(vinylidene fluoride) (PVDF) in particular has been adopted for the production of electrospun nano-fibrous membranes for MD applications [13]. Although the production rate from a conventional single needle electrospinning system is very low (which makes it difficult to employ this process in industrial settings) techniques which promote multiple jetting have been developed for large production of electrospun mats from polymer solutions [8].

Membrane thickness plays a significant role in DCMD systems. With a thicker membrane, less heat is conducted away from the feed side to the permeate side, giving a higher difference in transmembrane temperature which results in a higher driving force. However the membrane structure reduces the ease of permeation thus impeding the transmembrane flux. Since the membrane thickness is inversely proportional to both the rate of mass and heat transfer across the membrane, provided other membrane parameters remain the same, many researchers suggested the thickness of the single layer membrane might be

* Corresponding author.
E-mail address: robert.field@eng.ox.ac.uk (R.W. Field).

http://dx.doi.org/10.1016/j.memsci.2014.06.002
0376-7388/

expected to have an optimal value [9,10]. Previously for DCMD configurations, experiments have been carried out using available commercial membranes with pure water as feed and for various membrane thicknesses. For similar pore size and porosity, thicker membranes resulted in flux reduction [11,12]. Gostoli et al. [13] reported that for thin membranes, the transmembrane flux depends on the salt concentration whilst for thicker membranes, salt concentration does not play an important role for the flux; Song et al. [14] found that salt concentrations up to 10% led to only small flux reduction. Schofield showed that with the membranes he used, the permeability of the membrane was virtually independent of membrane thickness [15]. Using a computer simulated counter current hollow fibre DCMD module, Laganà suggested that the optimal thickness of a single hydrophobic layer membrane lies between 30 and 60 μm [10]. Whilst Al-Obaidani et al. identified an optimal thickness value of 700 μm for his model when operating with a low temperature gradient (<5 °C) [16].

In this paper, the emphasis is upon the effect of membrane thickness and assessing whether there is an optimal value both analytically and experimentally. The membranes were fabricated using electrospinning and the thinnest membrane used in the experiment is about 27 μm. All membranes were fragile and thinner membranes fractured inside the module before water production rates could be determined. The experimental data collected is compared with model simulations based upon an analytical model that indicated an optimal thickness much thinner than that which could be achieved in practice.

2. Theory and analytical approach

To assess optimal thickness, firstly an expression of $dN/d\delta$ is obtained where N is the transmembrane flux (kg m^{-2} s^{-1}) and δ is membrane thickness.

For unit area, the heat and mass transfer process of DCMD are generally expressed as

$$Q = h_f(T_f - T_{fm}) \tag{1}$$

$$Q = h_p(T_{pm} - T_p) \tag{2}$$

$$Q = NH + \frac{k_m}{\delta}(T_{fm} - T_{pm}) \tag{3}$$

$$N = C(P_{fm} - P_{pm}) \tag{4}$$

These are a standard set of equations except that herein the enthalpy change across the membrane, H, is not taken to be independent of temperature. Other terms have their usual meaning and are defined in Nomenclature. Now provided the porosity and pore size do not vary with thickness:

$$C = \frac{K}{\delta} \tag{5}$$

whilst

$$P_{fm} = \alpha_w e^{23.238 - (3841/(T_{fm} - 45))} \tag{6}$$

$$P_{pm} = e^{23.238 - (3841/(T_{pm} - 45))} \tag{7}$$

$$H = mT_{fm} + g \tag{8}$$

where m and g are constants and have the value of -2400 (J/kg K) and 3,200,000 (J/kg). These coefficients were obtained by fitting a line of best fit to the values of specific enthalpy of water phase change given in a standard Oxford Engineering Data book [17], corresponding to water temperature in the range of 293–383 K. The term α_w in (6) is activity of water and is less than unity in the presence of salt.

2.1. Determination of theoretical optimal thickness

We have referred to theoretical optimal thickness in the subheading as the determined thickness may not be practical in most engineering applications. In Appendix A an equation relating the optimal thickness (the thickness at $dN/d\delta$) to two other unknowns T_{fm} and T_{pm} is obtained in terms of known parameters including α_w, k_m and the heat transfer coefficients. A second equation relating T_{fm} and T_{pm} can be obtained straight from Eqs. (1) and (2) by eliminating Q. A third equation relating δ and T_{fm} is obtained from Eqs. (2)–(5).

Thus one has three equations and three unknowns one of which is the optimal thickness. Further mathematical details are in Appendix A and results are given later.

3. Experiments

3.1. Fabrication of the electrospun nanofibre membranes (ENMs)

3.1.1. Materials and chemicals

Commercial polymer PVDF Kynar HSV 900 was purchased from Arkeme Inc., Singapore. Prior to use, the polymer was dried at 323 K under vacuum condition for at least 24 h. Solvents, acetone and N,N-Dimethylformamide (DMF) were obtained from Fisher, Singapore. Lithium chloride (LiCl) was obtained from Merck, Singapore.

3.1.2. Electrospinning dope solution

The PVDF polymer dope solution was prepared by dissolving 5 wt% PVDF into a mixture of DMF and acetone with a weight ratio of 6 to 4. LiCl (0.004 wt% of total spinning dope solution) was added to the solution to enhance the conductivity of the dope. The dope solution was mechanically stirred for 24 h at 333 K and cooled at room temperature for 24 h prior to electrospinning.

3.1.3. Electrospinning of PVDF membranes

The electrospinning conditions were set at: 27 kV electric voltage, 1800 mm^3/h polymer flowrate, 120 mm between the spinning tip and the top of the rotating drum collector, rotational speed of the drum, with a radius of 38 mm is 2 rpm/s and the horizontal movement of the spin tip is 0.1 mm/s across a length of 80 mm. After electrospinning, the membranes were then dried in an incubator, which was set at 323 K, for 24 h, to ensure that all the solvents were evaporated. For the present work, the recorded electrospun membranes were fabricated by spinning for 4–10 h (Fig. 1).

3.1.4. Heat press post-treatment

The dried PVDF membranes were pressed between two flat glass panes, at 423 K, for 1 h. The heat press was operated at just above atmospheric pressure. The melting temperature of PVDF used is around 443 K under ambient pressure.

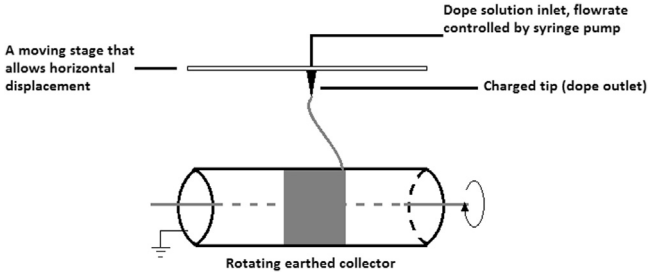

Fig. 1. Schematic of the electrospinning setup used for membrane fabrication.