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Electrospun polystyrene nanofibrous membranes for direct contact membrane distillation

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ABSTRACT

Hydrophobic electrospun polystyrene (PS) nanofibrous membranes were developed for desalination using the direct contact membrane distillation (DCMD) technique. These membranes were prepared from electrospinning of PS solutions in N,N-dimethyl formamide (DMF) with the addition of sodium dodecyl sulfate (SDS) as a processing aid. Effects of membrane thickness and fiber diameter on the average pore size and pore size distribution of nanofibrous membranes were systematically studied by capillary flow porometer (CFP), whereas the water contact angle and membrane porosity of these membranes were determined by contact angle meter (CAM) and gravimetric method, respectively. The resulting flux rate and permeate water quality (determined by conductivity) of membranes with different thicknesses and mean pore sizes from DCMD measurements were compared with those of commercially available polytetrafluoroethylene (PTFE) membranes using four different feed solutions, including distilled water, simulated brackish water, 35 g/L NaCl solution and seawater. Effects of flow rates (i.e., 0.2 GPM, 0.3 GPM and 0.4 GPM) and feed solution temperatures (i.e., 70 °C, 80 °C and 90 °C) on the flux rate and permeate conductivity of the optimized PS nanofibrous membrane (with a mean pore size about 0.19 μm) were further investigated during a continuous 10 h DCMD operation. Additionally, the mass and heat transfer coefficients of the optimized nanofibrous membranes in the DCMD operation were calculated. The results indicated that hydrophobic PS nanofibrous membranes can be produced by electrospinning for desalination by the DCMD method, leading to some unique opportunities in off the grid applications.

1. Introduction

Safe drinking water should be considered a basic human right. To ensure the continuation of humanity, robust, sustainable and cost-effective methods to remove contaminants and toxic substances in drinking water resources must be developed, where the recent advances in nanotechnology have offered many new opportunities to meet this goal [1–3]. The present study illustrates one example of using polymeric nanofibers, fabricated by the electrospinning process, for desalination application using the membrane distillation method.

Membrane distillation (MD) is a separation technique that has some unique advantages over more conventional energy-intensive membrane-enabled techniques, such as reverse osmosis (RO) or nanofiltration (NF), for water purification from desalination of seawater and brackish water to removal of heavy metals and contaminants in food processing and wastewater treatments [1–8]. Typically, the permeate flux rate of the MD operation is substantially lower than those of RO or NF. However, the MD process possesses some unique advantages: a 100% rejection capacity of non-volatile solutes (e.g., ions, macromolecules, colloids and cells), lower operating temperatures than traditional distillation methods, lower operating pressures than pressure-driven filtration techniques (e.g. RO and NF), and no concerns with the evaporator corrosion issues. [1,3,4] Typically, there are six types of MD configuration practices: direct contact membrane distillation (DCMD), air-gap membrane distillation (AGMD), sweeping gas membrane distillation (SWGMD), vacuum membrane distillation (VMD), permeate gap membrane distillation (PGMD) and vacuum multi-effect membrane distillation (V-MEMD) [2,3]. Among these, the

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Table 1.
The total membrane thickness (δ) (i.e., the thickness of electrospun PS layer and thickness of PET non-woven substrate (~ 86 μm) together), maximum pore size, mean pore size, porosity and average flux rate of electrospun PS nanofibrous membranes and two commercial PTFE membranes (Four kinds of feed solutions: distilled water, simulated Turkana lake water, seawater and 35 g/L NaCl, testing time: 10 h; feed solution temperature: 70 °C; cold permeate solution temperature: 17 °C; flow rate: 0.2 GMP).

Sample name	δ (μm)	Maximum pore size (μm)	Mean pore size (μm)	Porosity (%)	Feed solution			
					distilled water	Simulated Turkana lake water	Seawater	35 g/L NaCl
					Average flux rate (kg/m^{2}h)			
PS-8–1	109 ± 2	0.53	0.28 ± 0.13	82	32.3 ± 0.5	29.4 ± 0.9	× [a]	×
PS-8–2	125 ± 2	0.53	0.25 ± 0.13	83	28.5 ± 0.6	26.3 ± 0.9	×	×
PS-8–3	147 ± 4	0.44	0.19 ± 0.10	84	26.9 ± 0.5	25.7 ± 0.5	24.9 ± 0.5	19.4 ± 0.9
PS-10–1	114 ± 2	0.71	0.31 ± 0.16	85	31.9 ± 0.6	30.9 ± 0.5	×	×
PS-10–2	131 ± 4	0.68	0.29 ± 0.18	85	27.3 ± 0.5	26.3 ± 0.5	×	×
PS-10–3	154 ± 5	0.60	0.25 ± 0.17	86	23.5 ± 0.4	22.2 ± 0.4	21.7 ± 0.6	×
PTFE-1	241 ± 2	0.41	0.15 ± 0.10	80	25.9 ± 0.9	24.9 ± 1.8	23.7 ± 0.5	18.2 ± 0.8
PTFE-2	84 ± 2	0.29	0.16 ± 0.05	70	23.8 ± 0.9	21.7 ± 0.9	19.9 ± 0.8	14.3 ± 0.8

[a] increased salt leakage through the membrane

DCMD configuration is the simplest one.

In the DCMD operation, hot and cold streams are in direct contact with the membrane surface. Diffusion of liquid water containing dissolved ions across the membranes surface is forbidden due to the hydrophobic nature and small pore size (usually less than 0.2 μm) of the membrane, whereas the passage of water vapor is allowed. The mass transfer of water molecules across the membrane is thus driven by the vapor pressure difference rather than the pressure difference of the flow. The vapor pressure difference can be controlled by the temperature difference between the hot feed solution and cold permeate on each side of the membrane. In other words, the vapor pressure gradient causes the movement of water vapor molecules across the membrane, where pure water is then condensed on the cold side and contaminates are trapped in the feed solution on the hot side [2,3,9]. In general, hydrophobic microfiltration membranes having an average pore size in sub-microns, where the base materials are thermally stable, chemical resistant, and with low thermal conductivity to minimize heat loss, are suitable for the MD operation [1,3]. These base materials include polytetrafluoroethylene (PTFE), polyvinylidene (PVDF) and polypropylene (PP) [4,7]. However, it is also known the superhydrophobic nature of the membranes based on these materials will induce rapid fouling or scaling problems.

Electrospinning has proven to be a technique that can produce of nanofibrous membranes, with microfiltration characteristics, from a wide range of polymers (hydrophobic and hydrophilic). Electrospun nanofibrous membranes with hydrophobic characteristics thus can be used for MD applications due to the controllable pore size in the sub-micron scale, high surface-to-volume ratio, interconnected void structure and high porosity [10–12]. In this study, we chose polystyrene (PS) as the base material for electrospinning because it is hydrophobic, abundant, inexpensive and can be easily modified to improve the fouling and scaling resistance [13]. The aims for the current work are to demonstrate the optimization of electrospinning hydrophobic PS nanofibrous membranes with high flux rate and high rejection capacity for the DCMD operation. The study of modified PS nanofibrous membranes with anti-fouling and anti-scaling properties will be presented later.

In this paper, the relationship among the average fiber diameters, mean pore size, membrane thickness and MD performance of electrospun PS nanofibrous membranes were systematically investigated. In the MD testing, four different feed solutions, including distilled water, simulated brackish water from the Turkana lake in Kenya, 35 g/L NaCl aqueous solution and seawater were used for DCMD measurement. The average flux rate and permeate conductivity were measured for each membrane. In additional, different hot feed temperatures and different flow rates were tested in order to yield the greatest maximize the volume of the pure permeate water that can be produced, respectively. Two commercially available PTFE microfiltration membranes, typically used in the MD operation, were also tested to compare with the performance of the electrospun PS nanofibrous membranes. Finally, the mass and heat transfer coefficients of the optimized PS nanofibrous membranes were also determined from the experiments using the 35 g/L NaCl salt concentration feed solution, to gain further insight into the DCMD operation in this system.

2. Experimental

2.1. Materials

The polystyrene (PS, M_w=260,000) sample, in the particle form, was purchased from Scientific Polymer Products, Inc. The chemicals, including N, N-dimethyl formamide (DMF), sodium dodecyl sulfate (SDS), isopropyl alcohol (IPA), sodium chloride (NaCl), calcium chloride ($CaCl_2$), magnesium chloride ($MgCl_2$), potassium chloride (KCl), sodium fluoride (NaF), sodium nitrate ($NaNO_3$), sodium bicarbonate ($NaHCO_3$), sodium hydroxide (NaOH) and sodium sulfate (Na_2SO_4) were supplied by Sigma Aldrich and used as received without further purification. A polyethylene terephthalate (PET) non-woven cloth (average fiber diameter around 40 μm, membrane thickness around 86 μm), obtained from Junyaku Co., Ltd., (Japan), was selected as the substrate to support electrospun PS nanofibrous scaffold. One polytetrafluoroethylene (PTFE) membrane (GORE® Fine Filtration Products, product-number: L32233) was supplied by the SolarSpring Corporation (Germany). The other PTFE-based microfiltration (MF) membranes (product-number: QL816) were obtained from Sterlitech Corporation (USA). In this study, we labeled these two commercially available PTFE membranes as PTFE-1 (Solar Spring) and PTFE-2 (Sterlitech Corporation), respectively. The characteristics of these two commercial PTFE membranes are shown in Table 1.

2.2. Preparation of PS solutions for electrospinning

The four PS solutions of varying concentrations (i.e., 8 wt%, 10 wt%, 12 wt% and 15 wt%) were prepared by dissolving PS particles into DMF solvent. Following a period of stirring, 0.5 wt% of SDS (with respect to DMF) was added into the solution to facilitate the electrospinning operation. Subsequently, magnetic stirring was applied to form homogeneous PS solutions at different concentrations.