Journal of Membrane Science 479 (2015) 148–158

Contents lists available at ScienceDirect

Journal of Membrane Science

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

Osmotic power generation by pressure retarded osmosis using seawater brine as the draw solution and wastewater retentate as the feed

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ARTICLE INFO

Article history:
Received 1 October 2014
Received in revised form
2 December 2014
Accepted 23 December 2014
Available online 1 January 2015

Keywords:
Osmotic energy
Pressure retarded osmosis
Thin film composite membrane
Power density
Fouling

ABSTRACT

Pressure retarded osmosis (PRO) is a promising technology to produce clean and sustainable osmotic energy from salinity gradient. Fresh water is of scarcity in Singapore; however, alternative sources of feed solutions and draw solutions are well explored. For the first time, seawater brine from the TuaSpring desalination plant and wastewater retentate from the NEWater plant were used in a state-of-the-art TFC–PES hollow fiber membrane PRO process. The highest power densities obtained with 1 M NaCl solution and seawater brine were 27.0 W/m^2 and 21.1 W/m^2 at 20 bar, respectively, when deionized (DI) water was used as the feed solution. However, the highest power density dropped to 4.6 W/m^2 when wastewater retentate was used as the feed solution. Fouling on the porous substrate induced by the wastewater retentate was identified as the main cause of the reduction in the power densities, while the negative effects of seawater brine on the PRO performances were negligible. Both ultrafiltration (UF) and nanofiltration (NF) pretreatment were employed to mitigate fouling from the wastewater retentate, and the power densities were boosted to 6.6 W/m^2 and 8.9 W/m^2, respectively, beyond the power density of 5 W/m^2 proposed by Statkraft for the PRO process to be economical.

1. Introduction

Osmotic energy from salinity gradient is a promising sustainable energy [1–5]. Pressure retarded osmosis (PRO) is one of the technologies to extract osmotic energy by allowing water to flow through a semi-permeable membrane from a low-salinity feed solution to a high-salinity draw solution against an applied hydraulic pressure [5–7]. The majority of PRO researches are focused on mixing of seawater and river water [7–12], from which up to 2.6 TW osmotic energy is projected to be produced globally [1]. However, the seawater–river water PRO system has a low energy density due to its low osmotic pressure difference [2–10]. It would become less economically feasible when substantial pretreatments are required to mitigate biofouling in both feed streams [2–5].

Freshwater is of scarcity in the context of Singapore, due to the absence of natural aquifer [13]. Four national taps – local catchment water, imported water, reclaimed water from local waste (branded as NEWater) and desalinated water – are essential to secure water from alternative sources in Singapore [13,14]. The five NEWater plants have a combined productivity of 273,000 m^3/day [14]. The NEWater plants receive treated wastewater effluent and further treat it with a three-stage process: microfiltration (MF), reverse osmosis (RO) and ultraviolet (UV) disinfection [15]. The wastewater retentate (referred to as WWRe thereafter) from the RO process has a salinity close to that of river water, and can be potentially used as the feed solution for a PRO process [16,17]. The TuaSpring desalination plant is the largest membrane-based seawater desalination facility in Singapore, with a capacity of 318,500 m^3/day [14]. It utilizes an ultrafiltration (UF) process for pretreatment and a two-stage RO process for desalination [18]. Since the seawater brine (referred to as SWBr thereafter) has a higher salinity than that of seawater, theoretically more osmotic energy can be harvested by mixing the SWBr and the WWRe [2,16–22].

In this study, the SWBr from the first-stage RO in the TuaSpring desalination plant (the second-stage RO brine was not available for collection at the moment of this study) and the WWRe from the NEWater plant were used as the draw and feed solutions, respectively, in a state-of-the-art hollow fiber membrane PRO process (Fig. 1). The SWBr-WWRe PRO process has the following advantages: (1) partially

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http://dx.doi.org/10.1016/j.memsci.2014.12.036
0376-7388/

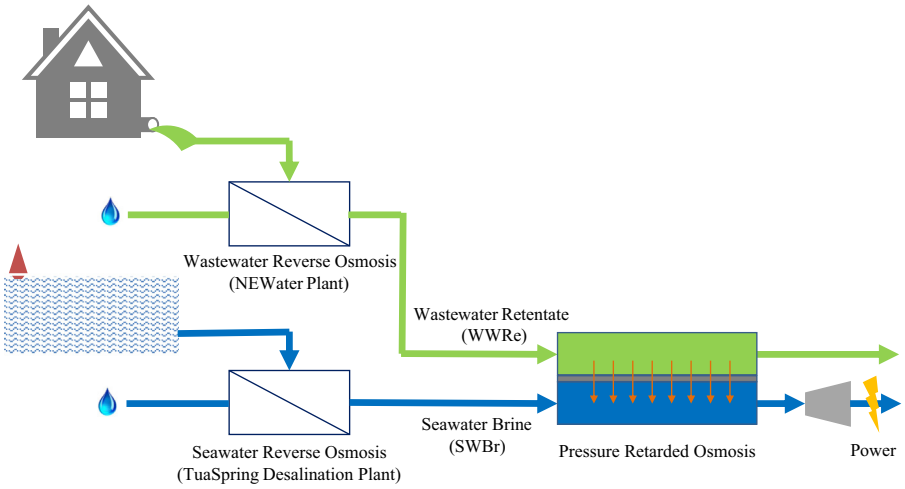

Fig. 1. Illustration of osmotic power generation through pressure retarded osmosis (PRO) utilizing SWBr as the draw solution and WWRe as the feed solution.

recover the energy consumed in the seawater reverse osmosis (SWRO) process [16,17,19]; and (2) dilute the SWBr to mitigate the environmental impact of discharging the concentrate brine [23]. The feasibility of such PRO process is investigated in a lab-scale setup, and potential challenges are discussed.

2. Experimental section

2.1. Materials

Radel® A polyethersulfone (PES, Solvay Advanced Polymer, L.L.C., GA), N-methyl-2-pyrrolidone (NMP, >99.5%, Merck), polyethylene glycol 400 (PEG, Mw=400 g/mol, Sigma-Aldrich) and deionized (DI) water were used as the polymer, solvent, and non-solvent additive, respectively, for the fabrication of hollow fiber substrates. A 50/50 wt% mixture of glycerol (Industrial grade, Aik Moh Pains & Chemicals Pte. Ltd., Singapore) and DI water was used for the post-treatment of as-spun hollow fiber membranes. Trimesoyl chloride (TMC, >98%, Tokyo Chemical Industry, Co. Ltd., Japan), *m*-phenylenediamine (MPD, >99%, Sigma-Aldrich), sodium dodecyl sulfate (SDS, >97%, Fluka) and hexane (>99.9%, Fisher Chemicals) were used for interfacial polymerization. Sodium chloride (NaCl, 99.5%, Merck) was used for the membrane transport characterizations and PRO performance tests.

The SWBr was collected from the TuaSpring desalination plant, while the WWRe from the NEWater plant. Both samples were stored in a refrigerator at 4 °C until use. NADIR® UH050 UF membranes (Microdyn-Nadir, GmbH, Germany) and CSM® NE2540-70 NF membranes (Woongjin Chemical, Co. Ltd., Korea) were used for the pretreatment studies of the WWRe. The properties of the UF and NF membranes are presented in Table 1.

2.2. Fabrication of the TFC–PES hollow fiber membranes

A dry-jet wet spinning process with the aid of co-extrusion through a dual layer spinneret was employed to spin the PES hollow fiber substrates [24,25]. The spinning solutions and conditions have been described previously with minor modifications to ensure dope stability and improve membrane performance [26,27]. The detailed spinning parameters are shown in Table 2. The as-spun hollow fiber substrates were rinsed with tap water for 2 days to remove the residual solvent. The hollow fiber membranes were then posted by soaking in a 50/50 wt% glycerol/water solution for 2 days before drying in the air at room temperature. Finally, a lab-scale module with three pieces of hollow fiber substrates was made.

Table 1
Characteristics of the UH050 flat-sheet UF and NE2540-70 flat-sheet NF membranes.

Membrane characteristics	Membrane code	
	UH050	NE2540-70
Material	Polyethersulfone	Polyamide
PWP (E-12 $m^3/(m^2 \cdot s \cdot Pa)$)	231.6	12.0
MWCO (Da)	50,000	200
NaCl rejection (%)	N.A.	40–70
$MgSO_4$ rejection (%)	N.A.	99.5

The TFC–PES hollow fiber membranes were prepared via interfacial polymerization [24–26]. Firstly, a 2 wt% MPD aqueous solution containing 0.1 wt% SDS was fed into the lumen side of hollow fibers for 3 min at a flow rate of 4.25 ml/min. After that the excessive MPD residual solution was removed by purging air for 5 min using a compressed air gun. Then a hexane solution with 0.15 wt% TMC was brought into contact with the MPD absorbed on the inner surface of the membrane at a flow rate of 2.50 ml/min for 5 min to form a thin polyamide layer. The resultant TFC–PES membranes were purged with air for 1 min to remove the residual hexane solution.

2.3. Measurements of pure water permeability (PWP or A) and salt permeability (B) of the TFC–PES membranes

The pure water permeability (PWP) and the salt permeability of the TFC–PES hollow fiber membrane were measured under the RO mode using the PRO setup. Before the tests, the TFC–PES membranes were pressurized from inside out at 20 bar using DI water for 30 min. After that, DI water was pumped into the lumen side of the hollow fiber membranes at 5 bar, 10 bar, 15 bar and 20 bar. The permeate from the shell side was collected and the PWP or *A* (LMH/bar) was calculated as

$$A = \frac{\Delta V}{A_m \Delta t \Delta P_h} \quad (1)$$

where ΔV is the volumetric change of permeate collected over a period of Δt (h) during the test, A_m (m^2) is the effective permeation area, and ΔP_h (bar) is the transmembrane pressure difference.

The membrane rejections (*R*) to NaCl at 5 bar, 10 bar, 15 bar and 20 bar were obtained by using a 1000 ppm NaCl solution as the feed at the flow rate of 0.2 ml/min. The conductivities of the permeate