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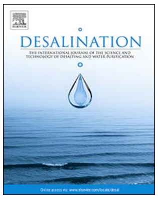

A pilot study on pressure retarded osmosis operation and effective cleaning strategies

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ABSTRACT

A SWRO-PRO pilot was built to systematically investigate the osmotic power generation from state-of-the-art thin-film composite (TFC) hollow fiber membrane modules. For performance benchmarking, three feed pairs were examined. They were (1) synthetic brine and tap water, (2) real seawater reverse osmosis brine (referred to as SWBr) and tap water, and (3) real SWBr and wastewater retentate (referred to as WWBr) feed pairs. All feed pairs had the capabilities to produce power densities ranging from 5 W/m^2 to 5.7 W/m^2, which were obtained based on draw solution pressure and NaCl concentration of 15 bar and 0.8 M, respectively. These results were equal or more than the required power density of 5 W/m^2 proposed by Stafkraft. Various cleaning strategies at pilot level were adopted and proven to be effective and feasible to sustain module performance. Online cleaning approaches; namely, backwash, clean-in-place (CIP) and maintenance cleaning (MC) were performed to evaluate the cleaning efficiencies of the fouled membrane modules. The effectiveness of various cleaning agents was also evaluated using (1) tap water, (2) 200 ppm HCl solutions at pH 2.3 and (3) 200 ppm NaOCl solutions at pH 10.5. The results showed that for the case of SWBr and WWBr feed pair, acid maintenance cleaning was able to fully recover the water flux or power density, whereas caustic cleaning was only able to recover the water flux up to 80%. Chemical-free cleanings by backwash and CIP could only recover water flux from 42% to 51%. The introduction of intermittent CIP cleanings at a fixed interval was found to be effective in slowing down the water flux decline, thereby prolonging the operational duration.

1. Introduction

Pressure retarded osmosis (PRO) is a promising technology to harvest sustainable salinity-gradient energy using semipermeable membranes [1–8]. The energy is harnessed when two solutions of different salt concentrations are combined and flow through semipermeable membranes. The difference in chemical potential of the two solutions causes a driving force that transfers water from the solution with a lower salt concentration to that with a higher salt concentration. This represents a potentially enormous source of renewable energy that can meet the energy challenges of today and tomorrow because there are tremendous feed streams available for osmotic power generation [6,9–14]. In addition, the membrane based PRO technology has advantages over the conventional fossil fuel based energy generation processes as it does not emit any greenhouse gases [15]. The recent demands for clean and renewable energy have brought the PRO technology into global attention.

In previous studies, seawater and river water were used as the feed pair [14–17]. However, the net energy produced from this pair was too small to be economically viable. The application of real seawater reverse osmosis (SWRO) brine (referred to as SWBr thereafter) as the draw solution was therefore proposed because it has a higher salt concentration and is much cleaner than raw seawater [2,5,15,18,19]. The integration of PRO with SWRO plants not only can offset the energy consumption of SWRO but also mitigate the disposal and environmental issues of SWBr [20–22]. Since Singapore is a country with very limited water resources, the use of real wastewater retentate (referred to as WWBr thereafter) from municipal wastewater recycling plants as a feed water for the SWRO-PRO integration is the most economical. However, WWBr contains many inorganic and organic foulants. The composition of WWBr has been investigated in some prior work [20].

Therefore, the first two objectives of this study are to investigate (1) the potential power generation from different feed pairs and (2) long term performance of the SWRO-PRO integration at a pilot level using 1-in. state-of-the-art inner-selective thin-film composite polyethersulfone (TFC-PES) hollow fiber membrane modules. To the best of our

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knowledge, no pilot study to date has been conducted on TFC-PES hollow fiber membrane modules using WWBr as the feed [20–30]. Three different feed pairs; namely, (1) synthetic brine and tap water, (2) real SWBr and tap water, (3) real SWBr and WWBr, would be used for performance benchmarking. In addition to sustaining the osmotic power generation, cleaning strategies would be explored when using real SWBr and WWBr as the feed pair.

As there was very limited knowledge from available pilot studies, a SWRO-PRO pilot was built in 2016 to investigate the osmotic power generation from TFC-PES hollow fiber membrane modules. The pilot-scale studies are crucial because they may expose issues not observed in small laboratory-scale studies. Numerous trials on cleaning methods for PRO membranes have been conducted at the laboratory scale since membrane fouling is one of the major challenges in PRO processes [20,21,31–33]. Fouling not only reduces membrane performance and shortens membrane life, but also imposes extra operating costs in terms of energy and chemical consumptions because of frequent membrane cleaning [34,35]. Since the porous support of PRO membranes is especially prone to fouling [20,24,33,36–38], it is still not known if the recently developed fouling and fouling control methods are practical and feasible if they are carried out at a pilot level [12,13,21,31,37,39]. Therefore, several cleaning strategies, i.e., backwash, clean-in-place (CIP) and maintenance cleaning (MC), with or without chemicals would be conducted in this pioneering pilot study to investigate their feasibility, suitability and effectiveness.

Because effective cleaning not only prolongs the SWRO-PRO operations to produce sustainable osmotic energy and lower the overall energy consumption for desalination but also reduces the frequency of membrane cleaning and decreases the overall chemical costs. The third objective of this work is to develop suitable fouling control strategies for the laboratory-scale SWRO-PRO pilot. We aim to sustain the pilot operations by means of membrane modifications, efficient cleaning, influent pre-treatment and process optimizations [12,21,34,40–44]. This study may provide useful insights and facilitate the commercialization of the SWRO-PRO technology in the foreseeing future.

2. Materials and methods

2.1. The SWRO-PRO pilot plant and operation

2.1.1. Design of the SWRO-PRO pilot plant

As shown in Fig. 1, the SWRO-PRO pilot comprised of an SWRO system, a PRO system and two units of clean-in-place (CIP) systems. A pressure exchanger (PX) was installed to pressurize the seawater feed or NaCl solution to the SWRO system. The SWRO system was designed to run at a recovery of 45% in order to generate 0.8 M (46,750 mg/L) of concentrated brine, which was used as the draw solution in the pilot tests. The PRO system, on the other hand recovered the osmotic energy from the concentrated brine to compensate for the energy consumption of the SWRO system [45]. The PRO system consisted of 6 trains, with 10 modules in each train. 1-in. thin-film composite polyethersulfone (TFC-PES) hollow fiber membrane modules were prepared and installed on the first train of the PRO system. The PRO modules were developed in-house from the state-of-the-art inner-selective (TFC-PES) hollow fiber membranes [26,38].

For performance comparison, both tap water and WWBr were utilized as the feed solutions in the pilot tests, while two types of brines were employed as the draw solutions. They were real SWBr from SWRO and synthetic brine (0.8 M NaCl); which both have the same osmolality. The flowrates at the lumen side (i.e., draw solution side) and the shell side (i.e., feed solution side) were set and maintained at 1 l/min (LPM). A constant hydraulic pressure of 15 ± 0.5 bar was applied at the draw side.

The SWRO-PRO pilot was operated by either manual or automatic mode. The automatic mode allowed four different options (SWRO, SWRO + PX, SWRO + PRO, SWRO + PX + PRO) for selection with the aid of a Human Machine Interface (HMI) screen as illustrated in Fig. 2. The choice of the operating mode depended on the process requirements. The electronic data was stored in a memory card and extracted for further analyses via MS Excel.

The power density W was determined by:

$$W = \frac{J_w \Delta P}{36} \tag{1}$$

where J_w is the water flux in liter/m^2/h (LMH), ΔP is the operating pressure in bar, and W is the power density in W/m^2. The pressure exchanger (PX) efficiency η was determined by:

$$\eta = \frac{\Delta LP}{\Delta HP} \times 100\% \tag{2}$$

where ΔLP and ΔHP were the low pressure differential and high pressure differential around the pressure exchanger in bar, respectively; and η is the PX efficiency in the unit of %.

2.1.2. Testing and commissioning of the SWRO-PRO pilot

Testing and commissioning of the pilot were carried out prior to the actual operation in order to assure that all components were designed, installed, and operated in accordance to the operational requirements. The commissioning data was obtained by using a 0.8 M (46,750 mg/L) synthetic brine as the draw solution and tap water as the feed solution at a constant applied pressure of 15 ± 0.5 bar. The operating parameters remained unchanged for a certain period of time to assess the stability of the pilot plant. Successful commissioning of the pilot was achieved because of its operability in terms of performance, reliability, safety and information traceability.

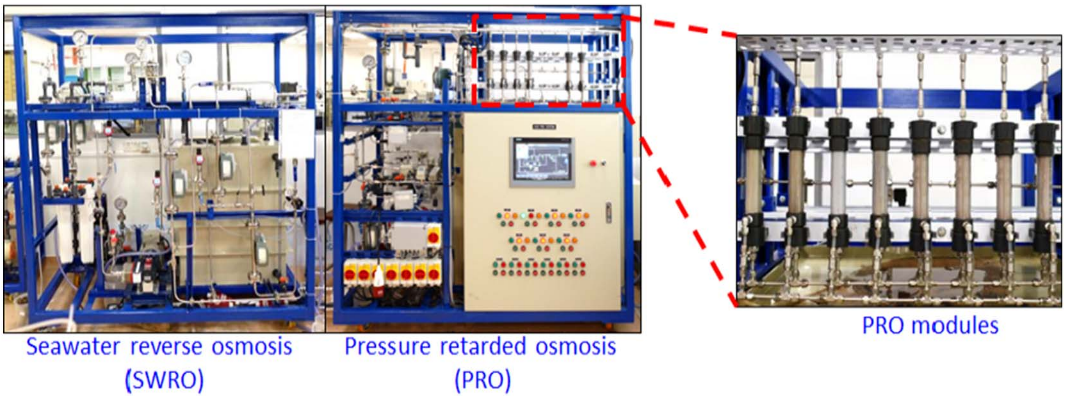

Fig. 1. The SWRO-PRO pilot with dimensions of 4.8 m × 1 m × 2 m (L × W × H) consisting of PRO membrane modules.