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Evaluation of the detrimental effects in osmotic power assisted reverse osmosis (RO) desalination

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ABSTRACT

This study aims to systematically evaluate the detrimental effects, namely concentration polarization (CP) and reverse solute permeation (RSP), and search for the optimum performance of a scale-up osmotic power assisted reverse osmosis (RO) desalination plant. The simulation clearly shows the performance reductions of the hybrid RO-PRO plant due to the CP and RSP effects. However, in both the co-current and counter-current PRO configurations, when the overall dimensionless flow rate decreases, these performance reductions become less significant. In addition, the counter-current PRO has high effectiveness because of the low theoretical net specific energy consumption (SEC) of RO-PRO. It is observed that more severe reduction due to the CP and RSP effects at high overall dimensionless flow rate shrinks the advantageous performance. Furthermore, PRO feed solutions with different concentrations are studied to evaluate the overall performance of the hybrid system. The results indicate that the advantageous performance can be achieved in a range of the concentration of the PRO feed. And with the increase on the PRO feed concentration, the osmotic energy generation reduces but the un-extracted energy due to the detrimental effects is also reduced.

1. Introduction

A remarkable amount of energy is available from the salinity difference between seawater and fresh water [1,2]. Salinity power from the natural salinity gradients has no evident emission of carbon dioxide during its operation. Also it has on demand and/or base load capability as compared with other intermittent renewable energy sources [3]. The extractable potential energy by mixing river water and seawater alone is estimated to be 1650 TWh per year [4]. Among the existing technologies to capture osmotic energy from salinity gradients, pressure retarded osmosis (PRO) has been developing rapidly. In 2009, the world's first PRO plant was launched in Norway with a 4 kW capacity [5]. In addition, several site-specific PRO power plants have been evaluated and showed promising potential power [6–8]. Previous investigations focused on different membrane types [9–12], properties [13–15], orientations [16] and spacers [17], as well as operational conditions of a PRO process [18,19], for the purposes of minimizing the performance limiting phenomena [20], including internal concentration polarization (ICP) inside the porous support layer, external concentration polarization (ECP) on the draw solution side near the membrane surface, and the reverse salt permeation (RSP) across the membrane from the draw solution side to the feed solution side. Several mathematical models have been developed to represent the concentration difference between the two sides of the membrane in terms of bulk concentrations. One of these models developed by McCutcheon et al. [21,22] presented osmotic flux and incorporated a dense, symmetric membrane. Elsewhere, water flux equation considering ICP was derived in terms of the draw solution concentration, draw solution flow rate, feed water flow rate, and membrane orientation [14]. Furthermore, a derivation of the local water flux taking all ICP, ECP and RSP effects into consideration was presented by Yip [23].

However, most studies on PRO membrane have employed a crossflow membrane test cell loaded with a small piece of flat sheet coupon [16,17,24,25]. In those investigations, with such a small scale membrane, the dilution of the draw solution in the crossflow cell was considered negligible, though it could be significant considering the large area of membrane required in a PRO process in practice [26]. As such, the averaged power density of a large scale PRO membrane would be substantially less than the value achieved in the laboratory scale [27]. Therefore, the performance of the

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scale-up PRO plant needs to be investigated [28]. Several studies have been carried out concentrating on the mass transfer and flow of the PRO on module level. In one of our previous works, the modelling framework and the mathematical models of the scale-up PRO considering ICP, ECP and RSP have been developed and validated with the experimental data [29]. Based on the viewpoint of mass exchanger, Sharqawy et al. [30] and Banchik et al. [31] derived systematic effectiveness-mass transfer units (ε-MTU) models. Furthermore, Banchik et al. investigated the overall membrane performance and the optimum operations of a PRO plant based on ε-MTU model and evaluated the effect of CP [32]. Straub et al. also investigated the detrimental effects of ICP, ECP and RSP on the performance of PRO at module level [33]. Recently, Feinberg et al. demonstrated that the power densities achievable from PRO are well below those predicted by extrapolating lab-scale measurement with idealized model and future work should focus on increasing salinity difference and identifying optimum operating conditions [34]. In this context, hybrid RO-PRO becomes a promising solution that the concentrated brine from RO is a foulant-free solution with high chemical potential. In fact, a pilot system with concentrated draw solution flowing into a module-scale PRO was simulated [35] and constructed to evaluate the reduced RO energy consumption by integrating with PRO [36]. Most recently a preliminary study on the solar power assisted hybrid RO-PRO plant was developed [37]. Although a hybrid membrane plant significantly improves the performance of both the RO and PRO subsystems and has been investigated several times previously, from current literature, there is still no specific investigation reported to address the detrimental effects of the scale-up PRO process, i.e. ICP, ECP and RSP, on system level of a hybrid RO-PRO plant. The overall performance of the whole RO-PRO system and interactions between the two sub-systems considering the operations of each plant and the detrimental effects in the scale-up PRO are not clear. It is, therefore, vital to carry out investigations on system level of the hybrid plant to fill the knowledge gap.

Moreover, the potential of the practical hybrid RO-PRO application is significantly affected by the availability of the low concentration stream, namely PRO feed solution. In a coastal region, with enormous volumes of seawater, dilute water bodies are always limited. Therefore, the influence of the concentration of the PRO feed solution is further investigated in this study. Six PRO feed solutions with different concentrations representing freshwater, river water, brackish water, seawater and other possible salinities or mixtures are investigated to evaluate the overall performance of the hybrid RO-PRO plant. In addition, the detrimental effects on the overall performance due to the different concentrations of the PRO feed are also addressed.

Therefore, in this study, an investigation of the CP and RSP effects on the overall performance of hybrid RO-PRO plant are carried out on system level. Firstly, mathematical models describing power density and energy generation of the PRO process are introduced. Then, on the basis of models and theories assembled, a case study on the PRO membrane performance is carried out in the case of a hybrid RO-PRO plant, including both co-current and counter-current flow schemes of the PRO. The overall performance of the hybrid plant is considered and discussed with respect to the performance limiting effects in salinity energy recovery from the system level. Finally, the overall performance of the hybrid RO-PRO plant and the detrimental effects are evaluated by using different concentration of the PRO feed solution.

2. Mathematical models of reverse osmosis and pressure retarded osmosis

A hybrid process of RO and PRO with hydraulic energy recovery by an energy recovery device (ERD) is presented. The schematic process is illustrated in Fig. 1 in which seawater is pressurized by the high-pressure (HP) pump and ERD before flowing into the RO plant. After the freshwater separation, the brine is depressurized via ERD to pressurize the RO feed solution, and then pressurized by ERD and HP before flowing into the PRO process as the draw solution. In the PRO process, the brine becomes diluted and the wastewater becomes concentrated according to the permeation across the membrane. The diluted draw solution is expanded in the hydro-turbine (HT) to generate electricity. This work aims to analyse the energy performance of the scale-up RO and PRO plant and the energy conversion between these two plants. Generally, as shown in Fig. 1, in RO, partial work done by the HP is used to separate the freshwater and another part is converted into the chemical potential of brine. And the enhanced chemical potential is recovered by PRO. Because this study focuses on the CP and RSP effect on the scale-up hybrid system, for simplicity, the efficiencies of the HP, ERD and HT are first assumed to be 100% [30,38]. Without considering the energy loss, the performance of the hybrid RO-PRO plant is mainly determined by the states of the flowing saline streams, namely flow rate, concentration, pressure and other related physical quantities. Therefore, a thermodynamic and energy analysis of the hybrid system can be developed based on the changing solution states. Furthermore, the influences of these components' inefficiencies are discussed later.

This study aims to concentrate on the overall detrimental effects on the performance of the hybrid system subject to different flow schemes and operations. Therefore, at the early stage, simple configuration as shown in Fig. 1 is selected to be investigated. It should be noted that other configurations of the hybrid RO-PRO plant can be investigated based on the modelling framework [39]. For example, a second smaller HT can be added to the concentrated wastewater stream if the stream still has a small pressure about 2–4 bar. Low head turbines may be used to further increase the overall efficiency of the osmotic energy harvest and reduce the energy consumption of the desalination. In addition, the osmotic energy of the concentrated wastewater stream can be potentially recovered. After the permeation in the PRO, the osmotic pressure of the concentrated wastewater stream would be significantly increased, mainly depending on design of the RO-PRO system and permeability-selectivity of the fabricated membrane. However, at the early stage, these scenarios are not considered in the current work, which could be investigated in future.

In a PRO plant, the membrane power density is determined by the trans-membrane hydraulic pressure and the water permeation flux across the membrane [40] and the overall performance is evaluated by integrating the water flux and power density over the entire membrane used. Details of the modelling framework of a scale-up PRO can be found in Ref. [29]. For a clear understanding, key equations describing a PRO process are listed in Table 1.

Generally, for a scale-up PRO process, the peak water flux occurs at the inlet of the membrane module. Due to the two directions of the mass transfer, the concentrations of both the draw and feed solution are rapidly varied along the flow channel. At a particular position along the membrane channel, the water flux and reverse solute flux are determined by the local concentration difference between the membrane surfaces and the membrane permeability-selectivity, which are represented by equations (T1) and (T2) in Table 1. The water and salt fluxes incorporate the detrimental effects of ICP, ECP and RSP and hydrodynamics of the flow channel. Accumulated permeation of water flux and salt flux can be obtained by equations (T4) and (T5). Therefore, the concentration and flow rate of the draw and feed at each position in the flow channel can be updated by equations (T6), (T7), (T8) and (T9).

Additionally, in a RO desalination plant, with the present