



Modelling of osmotic energy from natural salt gradients due to pressure retarded osmosis: Effects of detrimental factors and flow schemes



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ABSTRACT

In this investigation, a simplified pressure retarded osmosis (PRO) model incorporating the detrimental effects of internal polarization concentration (ICP), external polarization concentration (ECP) and reverse salt permeation (RSP) is proposed and verified using published data. The results demonstrate the accuracy of the model to address decreased water flux and power density due to the performance limiting effects. Based on the model, the discharge behaviour of a PRO process is reported with respect to different applied pressures on the draw solution and two flow schemes, co-current and counter-current flows. In the co-current flow PRO process, from the flow profiles in the draw and feed channels, it is found that the adverse effects on the process dynamics, such as water flux and power density, and required membrane area, can be regarded as a further retardation by applying 'an extra applied pressure' on the draw solution. In addition, the capacity of extractable energy of the full scale PRO discharge is significantly reduced due to the ICP, ECP and RSP effects. Furthermore, the termination conditions of the PRO discharge and its effects on the dynamics of the PRO process are also investigated in the case of the counter-current flow PRO process.

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1. Introduction

Osmotic energy from natural salinities has been identified as one of the major renewable energy sources (RES) since the 1950s [1]. Compared with other RES, it is, in fact, less periodic and has no significant operational hazards. In addition, the osmotic power production process is eco-friendly with no significant emission of greenhouse gases. It offers a huge potential energy capacity, estimated to be 2 TW, which is about 13% of the current world energy consumption [2]. Research groups worldwide investigated the feasibility of capturing energy from the mixture of freshwater and seawater [3,4]. In this regard, pressure retarded osmosis (PRO) is one of the most explored technologies [5]. It is an osmotic driven membrane process that takes advantage of hydraulic pressure applied to the draw solution and conversion of osmotic energy into electricity by hydro-turbine [6]. Following rapid developments in the field over the last decade, the technology is now in operational use. In 2009, the world's first PRO plant was launched in Norway with a 4 kW capacity.

However, theoretical estimation of potential power generation from natural salinities was based on conditions that are not realistic today, mainly due to the formidable challenges of developing membranes providing sufficient specific power density [7]. There is a need for further optimization of membrane properties such as higher water permeability (A), lower salt permeability (B), and smaller structural parameter (S). Although the current best commercial RO membranes can be used in the PRO process to produce energy, the higher structural parameter results in a serious performance decrease [8]. In addition, the hydraulic pressure applied makes the forward osmosis (FO) membrane, another osmotic-driven membrane, more likely to be deformed [9]. Therefore, a new membrane specifically for PRO needs to be developed.

Prior investigations to improve the performance of PRO membranes have been focused on quantifying, elucidating and then minimizing the performance limiting phenomena, namely the 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 side. In order to minimize these detrimental effects, different membrane types [10], properties [11,12] and orientations [13], as well as operational conditions have been investigated [14]. It was found that the effect of ICP, resulting from an asymmetric membrane structure,

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becomes severe with higher difference of concentration [12]. The ECP effect can be reduced with higher cross-flow velocities [15] and spacers in the flow channels [16]. Moreover, several mathematical models have been developed and verified with experiments to describe the effects on power generation [3,11,13,17–19]. Accordingly, based on these models, many studies have been carried out to investigate the PRO process through numerical simulation [20–24]. However, only a few investigations have addressed the dynamics of the PRO discharge behaviour considering the dilution of the draw solution and the concentration of the feed solution [25,26].

In the current study, by investigating the two fundamental influencing factors, detrimental effects and flow schemes, their impact on the water flux, power density and extractable energy for the PRO process have been numerically evaluated based on discharge behaviour. First, membrane parameters and flow schemes were derived. Then, two PRO models with and without the limiting effects were introduced. For the purpose of simplifying calculations, a simplified PRO model is also proposed to approximate the water flux considering the effects of the ICP, ECP and RSP and verified using both a classic PRO model and experimental data. Besides, on the basis of the PRO models, the framework of modelling the PRO discharge is provided, and the discharge behaviour of PRO is presented with respect to different hydraulic pressures applied on the draw solution and two flow schemes, the co-current and counter-current cross-flows. Finally, water flux, power density and concentration profiles have been derived.

2. Preliminary concepts and theories

2.1. Membrane parameters

Thin-film composite (TFC) polyamide membranes are widely utilized in separating and salt-rejecting membrane processes [27]. In general, with a given structural parameter, increasing the membrane water permeability and decreasing the salt permeability will increase the specific power density [23]. However, achieving high performance is limited by the permeability-selectivity

trade-off relationship of the TFC polyamide membrane [28,29], such that an increase in the membrane water permeability, A , is commonly accompanied by a corresponding increase in salt permeability, B . The trade-off relationship between the permeability and selectivity can be approximated by a non-linear empirical relation proposed by Yip and Elimelech [29]. In addition, the range of the values of the structural parameter, S , is also restricted by the types and functions of the membrane. The structural parameter usually ranges from 10 to 10,000 μm , including conventional TFC reverse osmosis membranes ($S = 10000 \mu\text{m}$) [11], hollow fibre membranes ($S = 600 - 1400 \mu\text{m}$) [30], hand-cast flat sheet membranes ($S = 300 - 3000 \mu\text{m}$) [31] and nano-fibre composite membranes ($S = 80 - 110 \mu\text{m}$) [32]. Some current membrane properties from selected publications are listed in Table 1.

2.2. Flow parameters

The geometry of the simple cross-flow chamber model used in this study is shown in Fig. 1. A feed solution with low salt concentration flows through a channel with a PRO membrane side wall. On the other side of the semi-permeable membrane, a draw solution with higher salinity flows in the same direction (co-current scheme in Fig. 1(a)) or in the opposite direction (counter-current scheme in Fig. 1(b)).

The flow parameters are determined by local water conditions that comprise concentration and mass flow rates of both the high and low concentration solutions. In the context of natural salinities, seawater and brackish water could be used as the draw solution. The low concentration water from river, sewage, industrial wastewater and private effluent can be used as feed water. Furthermore, if high concentration brine water is available, brackish water and seawater can also be regarded as potential feed water. However, the water needs to be pre-treated for the purposes of preventing membrane fouling. In this study, the draw solution was selected with a concentration of 35 g/kg and the feed solution, fresh water, with a concentration of 0.1 g/kg. Both solutions are hypothetically considered as ideal based on the fact

Table 1
Membrane properties selected from the literature.

No	Reference	Water permeability, A ($\text{L m}^{-2} \text{h}^{-1} \text{bar}^{-1}$)	Salt permeability, B ($\text{L m}^{-2} \text{h}^{-1}$)	Structural parameter, S , (μm)
1	[33]	0.44	0.27	481
2	[13]	0.74	0.63	480
3	[11]	1.74	0.16	307
4	[34]	1.90	0.48	776
5	[35]	3.32	0.14	460
6	[36]	4.02	1.65	350
7	[11]	5.81	0.88	370
8	[11]	7.55	5.45	327

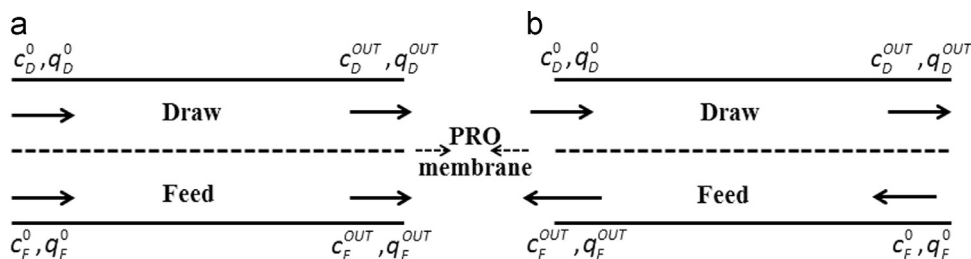


Fig. 1. Illustrative flow schemes of a PRO chamber in co-current cross-flow (a) and counter-current cross-flow (b). In the figure, c_D^0 and c_F^0 represent the initial concentrations of the feed and draw solutions, respectively, q_D^0 and q_F^0 represent the initial mass flow rates of the feed and draw solutions, respectively. And c_D^{OUT} and c_F^{OUT} are the final concentrations of the draw and feed solutions at the outlets, respectively, and q_D^{OUT} and q_F^{OUT} are the final mass flow rates of the draw and feed solutions at the outlets, respectively.

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