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Practical limit of energy production from seawater by full-scale pressure retarded osmosis

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ABSTRACT

Pressure retarded osmosis (PRO) produces energy using the salinity gradient between two solutions (draw solution (DS) and feed solution (FS)). Net energy production (NEP) of PRO was analyzed using a module-scale model developed in this work. The NEP analysis determines net energy from PRO by the difference between energy production by turbine and energy consumption by DS, FS, and booster pumps. Especially, the effects of system capacity and membrane fouling on NEP are investigated using a module-scale modeling approach for the first time. The maximum net specific energy (NSE) per PRO system capacity (sum of DS and FS flow rates) is close to 0.1 kWh/m^3 without pretreatments. The maximum NSE decreases at smaller system capacities, and it becomes around 0.03 kWh/m^3 from a PRO system with 520 m^3/d as capacity. NSE from seawater decreases in the presence of membrane fouling, but it remains positive under the severe fouling condition where water flux decreases by 32% if the system capacity is large enough to have efficient pumps and turbines.

1. Introduction

The salinity gradient is one of emerging renewable energy resources, which are intensively investigated recently [1–3]. The global energy potential by mixing river water and seawater is estimated to be 2 TW [4]. Among the technologies to harvest energy from the salinity gradient, pressure retarded osmosis (PRO) is the most rigorously studied [5] since it was first proposed by Sidney Loeb in 1975 [6]. In a PRO process, a highly concentrated solution (called draw solution (DS)) draws water across a semi-permeable membrane from a less concentrated feed solution (FS) when a hydraulic pressure lower than the osmotic pressure difference between DS and FS is applied on the DS side. The volume-expanded (and diluted) DS with the hydraulic pressure flows through a hydro-turbine to produce energy. PRO can be used not only to produce energy as a power plant, but also to decrease energy consumption in reverse osmosis process [7–11].

Fundamentals of PRO are well studied by previous researches focused on lab-scale PRO experiments and modeling [12–14]. PRO membrane coupons were tested to find out the effects of the active and support layer characteristics, hydrodynamic conditions, and fouling on the performance of lab-scale PRO processes. Power density, which is defined as the produced hydraulic power per unit PRO membrane area, is one of the key characteristics obtained from a lab-scale PRO test.

However, power density obtained from a lab-scale PRO test cannot be used to calculate the actual energy production from a full-scale PRO system, where the actual salinity gradient decreases. This is because DS is diluted by gaining permeate from FS, which is concentrated by losing its volume by the amount of the permeate. In addition, the inefficient hydraulic devices (e.g., pump, motor, energy recovery device (ERD), turbine, and generator), and pressure loss along the channels (e.g., the DS and FS channels, and pipelines) makes the net energy smaller [15,16].

Thus, the net energy produced from full-scale PRO processes should be carefully calculated in consideration of the decreased salinity gradient, inefficient hydraulic devices, and pressure loss along the channel. Straub et al. (2014) analyzed the module-scale performance of PRO based on the modeling approach [17]. In this work, 'performance down' of module-scale PRO processes (compared to lab-scale) is well described by accounting for changes in flow rate, pressure, and concentration inside the module. However, the energy production is rather overestimated due to simplified assumptions in the modeling work (e.g., no pressure loss in the DS and FS channels, and the hydraulic devices with perfect efficiencies). He et al. (2016) evaluated the performance of a scaled-up PRO process considering the various efficiencies of hydraulic devices, but pressure loss along the channel length was not

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considered [18]. Since pressure loss along the channel plays an important role to evaluate the energy consumption in a full-scale PRO process, a net energy production (NEP) analysis should account for this viscous dissipation.

Recently, the modeling approaches for full-scale PRO simultaneously accounted for the changes in parameters (e.g., pressure loss and the inefficient hydraulic devices) along the channel length [19–21]. In these works, the NEP analyses are supported by a fundamental modeling approach to predict the full-scale performance of a PRO process, and account for the energy production by turbine (plus effect), the energy consumption by pumps (minus effect), and the energy saving by ERD (plus effect) with assumed efficiencies of hydraulic devices, respectively. These NEP analyses found that the membrane power density was not coupled with NEP (e.g., the operation condition towards the maximum power density cannot accomplish the maximum NEP.). Instead, the effects of FS and DS flow rates are very important parameters to determine NEP and a wrong selection of FS and DS flow rates may result in a negative NEP.

It is quite interesting that a full-scale PRO cannot always produce a net positive energy from the salinity gradient, and thus it is of paramount importance to select a proper design option (e.g., system capacity, membrane area (or module length), the DS and FS flow rates, and the mechanical pressure on the DS side) to produce a positive energy. The relationships between hydraulic parameters (e.g., flow rates and pressures) and NEP are studied in the previous researches [17–21], and some of these works warn that full-scale PRO may not extract net positive energy from the salinity gradient between seawater and river water because of the pressure loss and the efficiencies of hydraulic devices. According to a recently published review paper [22], net energy cannot be extracted from PRO using the salinity gradient between seawater and river water mostly due to energy consumption for pretreatments.

While reviewing literature, we have set two questions about NEP of PRO. First, can net energy be extractable if pretreating seawater and river water is not necessary? The module-scale simulation results from the literature have answered this question with yes. However, most of those works did not consider the fact that the efficiencies of hydraulic devices such as turbine and pump are dependent upon their capacities. Selection of hydraulic devices with higher capacities results in the higher efficiencies of these devices [17,23], and thus a smaller PRO system with less efficient hydraulic devices produces less energy from the same salinity gradient compared to a larger one. It may be impossible to extract net energy from clean seawater and river water if the system capacity is too small to have efficient hydraulic devices. To our best knowledge, the effect of system capacity on NEP in a full-scale PRO process has not been reported so far. In our work, the effect of system capacity on NEP of full-scale PRO was systemically investigated by developing and simulating a module-scale PRO model. While most of previous researches [17,19–21,24] simply calculated the energy consumption of the membrane system with pumps and ERD using assumed constant efficiencies of the hydraulic devices, this work considered them as a function of pressure and flow rate.

The second question is whether the net energy from PRO using seawater and river water becomes negative in the presence of fouling. Pretreating DS and FS requires 0.1–0.4 kWh/m^3 of specific energy per treated volume and net specific energy (NSE) per PRO system capacity (sum of DS and FS flow rates) should be less than 0.156 kWh/m^3 with consideration of inefficiencies of hydraulic devices [22]. The pretreatment is believed to be essential to keep the efficiency of energy production from PRO, but the energy requirement to pretreat DS and FS may exceed NSE of PRO. What if we would remove the pretreatment processes in a PRO system? Of course, it is difficult to control fouling and the performance of PRO membranes becomes poorer. However, if NSE of a PRO system remains positive even in the presence of severe fouling, we may take into consideration of removing the pretreatment processes from the system in order to obtain net energy from seawater and river water. Thus, we investigated the effect of fouling on the NSE of a full-scale PRO using the module-scale model developed in this work. We defined levels of fouling by controlling the values for water permeability of membrane (A), solute permeability of membrane (B), structural parameter of membrane support layer (S), and friction factors of DS and FS channels (f_d and f_f). The objective of this work is to answer the two questions discussed above on net energy extractable from PRO using seawater and river water.

2. Methods

2.1. The decreased salinity gradient in a module-scale PRO

The actual salinity gradient in a module-scale PRO decreases because the volume of permeate is enough to change the concentrations of DS and FS. The decreased salinity gradient can be estimated by the mass balance in a module-scale PRO as shown in Fig. 1 using length-averaged parameters (e.g., water flux, J_w, and reverse solute flux, J_s) inside the PRO module. The PRO module in the system is considered as a black-box containing the intrinsic membrane parameters (e.g., water permeability, A, solute permeability, B, and structural parameter of the support layer, S), and module parameters (e.g., width (w), length (l), the heights (H_d and H_f) of the DS and FS channels, and the membrane area ($A_m = wl$); the module is assumed to be an ideal flat sheet module with no dead zone.). This type of approach has been applied to accurately predict the performance of a commercial spiral wound forward osmosis module [25].

DS with a pressure ($P_{d,in}$) flows into the DS side of the PRO module with a flow rate (Q_d) and a concentration (C_d). Inside the PRO module, the DS is diluted by gaining fresh water from the feed side with a water flux, J_w (i.e. the permeate flow rate, Q_p, is J_wA_m.) and loses some pressure by viscous dissipation along the DS channel length. Thus, the DS is changed into the diluted DS with a concentration, C_{dd} ($<C_d$), a flow rate, Q_{dd} ($>Q_d$), and a pressure, $P_{d,out}$ ($<P_{d,in}$) when it comes out of the module. On the other side (i.e, the feed side), FS with a pressure ($P_{f,in}$) enters the module with a flow rate (Q_f) and a concentration (C_f). Inside the module, the FS is concentrated by losing fresh water to the DS side with the same water flux, J_w and the solutes coming from the DS side with a solute flux, J_s, and loses some pressure by viscous dissipation along the FS channel length. Therefore, the FS turns into the concentrate with a concentration, C_c ($>C_f$), a flow rate, Q_c ($<Q_f$), a pressure, $P_{f,out}$ ($<P_{f,in}$).

Water and solute mass balances on the DS and FS sides are described as [16]:

$$Q_d + J_w A_m = Q_{dd} \text{(Water mass balance on the DS side)} \tag{1}$$

$$C_d Q_d - J_s A_m = C_{dd} Q_{dd} \text{(Solute mass balance on the DS side)} \tag{2}$$

$$Q_c + J_w A_m = Q_f \text{(Water mass balance on the FS side)} \tag{3}$$

$$C_f Q_f - J_s A_m = C_c Q_c \text{(Solute mass balance on the FS side)} \tag{4}$$

Before entering the PRO module, the DS flows into the ERD by the DS supply pump with flow rate, Q_d, and pressure, P_d, and it is pressurized by the diluted DS, which partly returns to ERD with flow rate, Q_d, and pressure, $P_{d,out}$ (if the head loss along the pipeline