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Numerical analysis of performance of ideal counter-current flow pressure retarded osmosis

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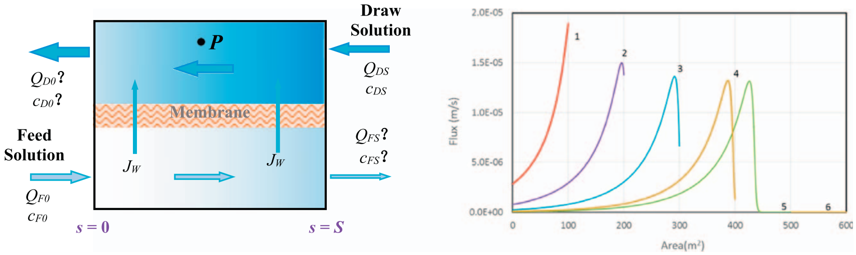
GRAPHICAL ABSTRACT



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ABSTRACT

Pressure retarded osmosis (PRO) operated in counter-current flow mode is more efficient than in co-current flow mode to extract salinity gradient energy. Knowledge of the performance of counter-current flow PRO under various operating conditions (on equilibrium or off equilibrium) is of paramount importance to understand the potential capacity of the technology and to optimize process design. In this study, a systemic and rigorous numerical procedure was developed for performance simulation of counter-current flow PRO. An optimization technique was used to accurately determine the originally unknown flow rate of the draw solution at the feed entrance of membrane channel so that the procedure could also be used for PRO systems not at equilibrium. With this numerical procedure, new interesting findings were made about the ideal counter-current flow PRO. A characteristic parameter of the PRO, the required membrane area to reach equilibrium for any given operating condition, was determined and reported for the first time. Another exciting finding was that the no-flux zone (dead region) occurs adjacent the draw entrance at the critical feed fraction when the membrane area is greater than the required equilibrium area. Power density and specific energy in PRO under various conditions were investigated with this numerical procedure.

1. Introduction

A huge amount of energy is dissipating every day globally when river waters from the inland mix with seawater [1]. This clean and renewable energy is called salination power [2], osmotic power [3], or most often salinity gradient energy [4]. The global fresh water run-off is about 1.1×10^6 m^3/s that contains salinity gradient power of 2.6×10^{12} watts with reference to seawater [5]. In theory, up to 0.8 kW per cubic meter of fresh water is extractable in controlled mixing with seawater — equivalent to the potential energy contained in water of 280 m high hydraulic head [1,6].

Pressure retarded osmosis (PRO) [7,8] is the most studied

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Nomenclature

A	membrane permeability
c_D	salt concentration of draw solution
c_{D0}	salt concentration of draw solution at the feed entrance
c_{DS}	initial salt concentration of draw solution at the draw entrance
c_F	salt concentration of feed solution
c_{F0}	initial salt concentration of feed solution at the feed entrance
c_{FS}	salt concentration of feed solution at the draw entrance
c_D^*	salt concentration of draw solution at equilibrium
c_F^*	salt concentration of feed solution at equilibrium
f_{os}	osmotic pressure coefficient
J_w	water flux
PD	power density
Q_D	flow rate of draw solution
Q_{D0}	flow rate of draw solution at the feed entrance
Q_{DS}	initial flow rate of draw solution at the draw entrance
Q_F	flow rate of feed solution
Q_{F0}	initial flow rate of feed solution at the feed entrance
Q_{FS}	flow rate of feed solution at the draw entrance
Q_{LB}	lower bound of the draw flow rate range at the feed entrance
Q_{UP}	upper bound of the draw flow rate range at the feed entrance
S	total membrane area
s	variable for membrane area
SE	specific energy

Subscripts

i	the ith step from the feed entrance
n	total step number

Greek symbols

θ	feed fraction
θ^*	critical feed fraction
π	osmotic pressure
ΔP	retarded pressure
Δs	step size along membrane channels

technology in harnessing salinity gradient energy and widely considered more promising than the alternative reverse electrodialysis (RED) [9,10]. A semipermeable membrane that allows only water to pass is employed in PRO to extract salinity gradient energy. Two solutions of different salinities are separated by the semipermeable membrane with a hydraulic (retarded) pressure smaller than the osmotic pressure difference added on the higher salinity (draw solution) side of the membrane. Osmotic flow of water from the low salinity (feed solution) side expands the volume of draw solution on the high salinity side. The increased volume under the hydraulic pressure can be converted to electricity with a turbine. Feed solution in PRO can be river, brackish water, or waste water while draw solution can be seawater or brines of high salinities [11–15].

Efficiency of PRO is an important consideration for economically harvest and utilization of salinity gradient energy [16,17]. There are basically two operation modes of the module scale PRO process: counter-current flow and co-current flow. It can be shown that counter-current flow mode is more efficient in extracting salinity gradient energy than co-current flow mode [18–20]. Knowledge of the thermodynamic limit on the performance of counter-current flow PRO system and the affecting factors is of critical importance to assess the viability of the technology and to optimize the process [18].

A numerical procedure that is capable to model and simulate the performance of the counter-current flow PRO system under any operating conditions would be a powerful tool for viability assessment of PRO. One particular difficulty for such numerical solution is that adequate boundary conditions cannot be specified at either side of the counter-current flow PRO. To start the numerical calculation, there are four parameters including concentrations and flow rates of both the feed solution and the draw solution are needed in one side. However, on one side of counter-current flow PRO, only the stream into the membrane module is of known flow rate and salt concentration while the flow rate and salt concentration of the stream out of the module are determined as a result of PRO performance. To overcome this difficulty, an assumption of sufficiently large membrane area was employed in the previous studies so that either the draw limiting regime or the feed limiting regime was reached. In that case, the flow rate and salt concentration of outgoing stream of PRO module can be determined by simple mass balance calculation. However, the method cannot be used for the general cases without knowledge of attainment of the limiting regimes.

In this study, a systemic and rigorous numerical procedure was developed for modeling and simulation of counter-current flow PRO. Bisection method of optimization technology was used to accurately determine the unknown boundary conditions on one end of the channels that match the given values on the other end. The numerical procedure can be used to simulate the performance of counter-current PRO under any conditions regardless equilibrium state. The new numerical procedure enables the investigations on many interesting aspects of the counter-current flow PRO that could not be done previously.

2. Mathematical model and numerical procedure

2.1. Mathematical model of counter-current flow PRO

A counter-current flow PRO module is schematically shown in Fig. 1. A semi-permeable membrane separates the module into two channels. Draw solution enters at the right end of a channel flowing to the left while feed solution enters at the left end of the other channel flowing oppositely. Water transports through the membrane from the feed solution to draw solution under the net driving pressure, which is the osmotic pressure difference minus the hydraulic pressure added on the draw solution side. The increase in draw solution flow rate (or decrease in feed solution flow rate) along the module is a primary

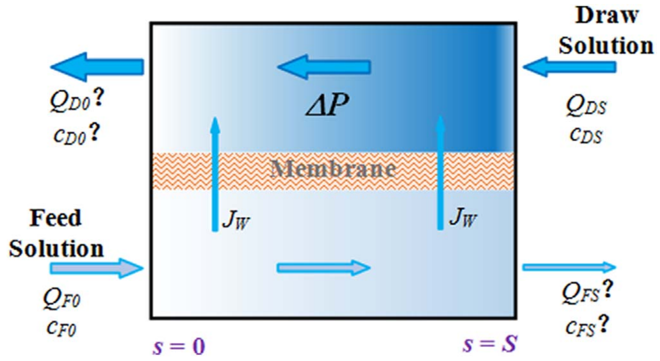

Fig. 1. A schematic of counter-current flow PRO. Feed and draw solutions of known flow rates (Q_{F0} and Q_{DS}) and salt concentrations (c_{F0} and c_{DS}) are provided to feed entrance $s = 0$ and draw entrance $s = S$, represented. The flow rate (Q_{FS} and Q_{D0}) and salt concentrations (c_{FS} and c_{D0}) at the opposite ends of the membrane channels are unknowns. ΔP and J_w are the retarded pressure and the water flux, respectively.