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Modeling pressure-retarded osmotic power in commercial length membranes

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ABSTRACT

The chemical potential difference of two liquids with dissimilar salinities can produce electrical energy using salinity gradient power (SGP). The pressure-retarded osmosis (PRO) concept can be used to generate SGP across a semi-permeable membrane. This work describes a mathematical model for evaluating PRO processes at both the bench scale and the commercial scale. The effect of concentration polarization is considered, including concentrative external polarization. Bench scale simulation results show agreement with published experimental data. At the commercial scale axial variations in flow rates and concentrations are considered. The model is used to evaluate performance of membranes that have previously only been considered at the bench scale. Commercial-scale simulation results show power densities of up to 5.6 W/m^2.

1. Introduction

Marine sources such as tides, ocean currents and salinity gradients can be used to generate renewable energy. It has been demonstrated that salinity gradient power (SGP) represents a high energy density compared to other marine energy sources [1]. The chemical potential difference available when freshwater (river) meets saltwater (ocean, sea, gulf, saline lake or brine from desalination plant) has the potential to produce 20% of the world's total energy needs [2]. Many technologies have been proposed for exploiting SGP, with pressure-retarded osmosis (PRO) being among the most promising [3].

The working principle of PRO is presented in Fig. 1. After filtration, freshwater is pumped into a chamber. Saltwater with a certain hydraulic pressure (less than the osmotic pressure difference between the freshwater and the saltwater) is pumped into another chamber, again after filtration. By the phenomenon of osmosis, freshwater permeates through the semi-permeable membrane to the saltwater chamber and the hydraulic pressure of the permeate increases to match that of the saltwater. The high pressure water is then divided into two portions: one portion flows through the turbine that drives the generator; the other portion flows to the pressure exchanger, which recycles the hydraulic pressure on the saltwater side of the system. Following convention, the freshwater is here referred to as the feed solution and the saltwater as the draw solution.

This design is based on the first PRO system for electrical energy conversion which was developed by Loeb [4,5]. Since then the development of pressure exchanger technology [6] and of forward osmosis (FO) membranes have improved the system's potential. Starting from power densities of only 0.1 W/m^2 reported in the 1970s [7], the Norwegian power company Statkraft and its partners developed in 2008 a hollow-fiber thin-film composite (TFC) membrane achieving power densities of 3.5 W/m^2 when tested under laboratory conditions [8,9]. This approached their target for projected commercial viability of 5 W/m^2. More recently power densities of 10.0 W/m^2 have been achieved in laboratory tests with freshwater and seawater [10,11].

These results are promising however it is important to recognize that power densities obtained at the bench scale using membrane samples will be significantly higher than those in commercial scale elements. For example, in November 2009 Statkraft launched the first worldwide osmotic power plant prototype in Norway. At the prototype scale gross power densities of only 1 W/m^2 were achieved [12]. Statkraft had plans to develop a 2 MW commercial osmotic power plant but these were canceled in December 2013 [13].

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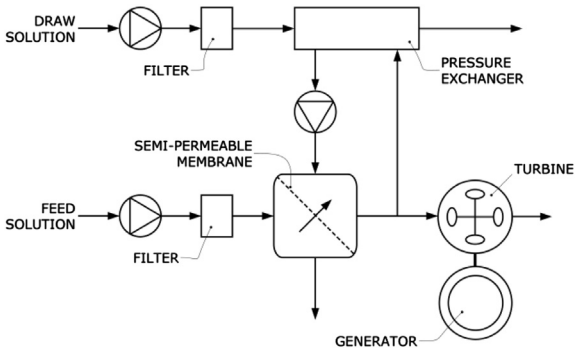

Fig. 1. Pressure-retarded osmosis power system.

The difference between power densities at the laboratory bench scale and at the prototype scale are important to recognize. This is due to additional non-ideal effects which occur at the scale of a commercial membrane element, including the reduction of the concentration gradient and pressure losses along the length of the membrane. Many mathematical models have been developed with the assumption that concentrations and water flow rates on both sides of the membrane are constant [10,14–18]. This is true at the bench-scale where high feed and draw flow rates (relative to the permeate flow rate) are used, however at the prototype scale this assumption leads to inaccurate specific power calculations. More recently some models have been developed to consider the important effect of variations along the membrane length [19]. Using a finite-difference approach, this paper presents an accurate mathematical model for PRO in commercial length hollow-fiber membranes. The model is used to evaluate the full-scale performance of membranes that have previously only been tested at the bench scale.

2. Membrane technology

Efficiency in the PRO process depends on achieving high water permeation while minimizing reverse salt permeation and the tendency of permeate to accumulate on the membrane surfaces (external concentration polarization) and within the membrane's support layer (internal concentration polarization).

Semi-permeable membranes have asymmetric geometries. They are composed of a thin active membrane skin attached to a porous support structure. This support layer hinders osmosis as it provides an area for the accumulation of salt. During PRO, the effect can be reduced when the support layer is oriented towards the feed side [20].

Previously, when reverse osmosis (RO) membranes have been used in PRO experiments low power densities have been reported. This is because commercial RO membranes have thick and dense support layers that are needed in order to withstand the large hydraulic pressures used during RO. Consider for example membrane 2 shown in Table 1, which is a commercial RO cellulose-acetate (CA) membrane. The high structure parameter S leads to low maximum power densities of only 1.6 W/m^2 as reported in experimental tests with freshwater and seawater [21].

In the cases of PRO and FO where membranes are subjected to much lower hydraulic pressures, the thickness of this support layer can be significantly reduced and its negative effect on osmosis can be minimized. This has been done in the case of membrane 1 (Table 1) which is a cellulose-triacetate (CTA) membrane designed for commercial FO applications. Experimental results reported power densities of 2.7 W/m^2 using freshwater and seawater [16].

Table 1
Membrane parameters.

	Description	A ($\times 10^{-12}$ m^3/m^2 s Pa)	B ($\times 10^{-7}$ m^3/m^2 s)	S (μm)	Source
1	Commercial FO-CTA	1.87	1.11	678	[16]
2	Commercial RO-CA	2.00	0.60	1000[a]	[21]
3	Lab FO-TFC	7.10	1.10	670	[21]
4	Lab PRO-TFC	16.14	2.44	349	[10]

[a] Without fabric support.

In addition to a minimal support structure, the ideal membrane for PRO applications should have high water permeability A and low salt permeability B. In reality, a tradeoff between A and B must be optimized. This is necessary because as A increases, so does B. In other words, as the membrane becomes more permeable to water a corresponding increase in power is not always observed due to the associated increase in salt permeability. It is with this approach that membranes 3 and 4 (Table 1) were developed. Both are TFC experimental membranes and both show high water permeability. Lab tests using membrane 3 have reported power densities of 2.7 W/m^2 [21], while tests using membrane 4 have reported 10.0 W/m^2 [10]. These are encouraging results and represent a significant advance in the potential for PRO power development. In comparing these reported power densities it is important to note that different draw concentrations and cross-flow velocities were used from one experiment to the next [22].

3. Methodology

3.1. Mathematical model for pressure-retarded osmosis in a bench-scale membrane sample

A model for bench-scale PRO processes is presented here and is used to evaluate the membranes listed in Table 1. This model considers the effects of internal concentration polarization (ICP), external concentration polarization (ECP) (both dilutive and concentrative) and reverse salt permeation. At the bench scale, feed and draw flow rates are usually significantly greater than permeate flow rates and therefore bulk concentrations and flow rates are assumed to be constant along the membrane length. A comparison between the proposed model and the published experimental results shows the accuracy of the model. The concepts behind this model are then extended to consider a full length hollow fiber membrane in Section 3.2.

In a basic system that contains two solutions, solvent (water) and dissolved solute (ions, macromolecules, etc.), brought in to contact across a semi-permeable membrane, the osmotic pressure difference $\Delta\Gamma$ can be approximated by the van't Hoff equation.

$$\Delta\Gamma \approx i_v \times \Delta c_m \times R_g \times T/M_s \quad (1)$$

where i_v, Δc_m, R_g, T and M_s are the van't Hoff coefficient, the concentration difference across the membrane, the gas constant, the temperature and the molar mass of the solute respectively. In this study the solute is assumed to be sodium chloride and the ideal van't Hoff coefficient of 2 is used.

The water permeate flux J_w (water flow rate across the membrane per unit membrane area) is given by,

$$J_w = A \times (\Delta\Gamma - \Delta P) \quad (2)$$

where ΔP is the hydraulic pressure difference across the membrane. The power density W is given by,

$$W = J_w \times \Delta P \quad (3)$$