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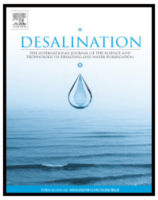

Study of the Reverse Salt Diffusion in pressure retarded osmosis: Influence on concentration polarization and effect of the operating conditions

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HIGHLIGHTS

- Reverse Salt Diffusion (RSD) in Pressure Retarded Osmosis (PRO) is studied.
- The effect of operating conditions on RSD is investigated.
- It is shown how some parameters that enhance the water flux aggravate the RSD.
- Draw solutions with low ion sizes provide high water and salt fluxes.
- It is discussed how ICP and ECP affect the RSD.

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ABSTRACT

Pressure retarded osmosis (PRO) suffers Reverse Salt Diffusion (RSD) and concentration polarization (CP), which reduce its performance. The current work investigates the effect of the operating conditions (concentrations, solutions, pressures, flow rates, and temperatures) on RSD and, as a consequence, on the produced power. The results show that the salt diffusion is severely affected by the operating conditions, which should be carefully controlled to reduce the power losses in osmotic power plants based on PRO. The relationship between CP and RSD is also studied, showing how RSD aggravates the internal concentration polarization (ICP).

1. Introduction

The global primary energy demand has doubled between 1971 and 2012, mainly relying on fossil fuels [1]. This affects the world's environment in aspects such as climate change, due to greenhouse gases emissions [2]. Finding technologies which are competitive to the existing technologies and have low environmental impact is of great interest, so researchers are focusing on alternative energy sources to fulfill this need [3]. This paper concentrates on a promising source of renewable energy currently in development: osmotic power, more precisely on the pressure retarded osmosis (PRO) technology.

PRO is being currently investigated as a controllable source of renewable energy. In this membrane process, water flows from a low salinity feed solution (FS) to a high-salinity draw solution (DS) against a controlled hydraulic pressure [4].The concept of osmotic power was introduced in 1954 by Pattle [5], and further developed by Sidney Loeb, who proposed using salinity gradient for power generation [6].The technical potential for salinity gradient power has been estimated to be around 647 gigawatts (GW): this is equivalent to 23% of electricity consumption in 2011 [7]. In fact, by 2030 osmotic power reportedly could generate up to 1700 TWh of electricity each year, which is around half of Europe's energy demand [8].

A diagram of a typical PRO power plant is shown in Fig. 1: filtered fresh water (called feed solution) is pumped at low pressure into modules containing a specific membrane. There, water migrates through the membrane into the draw solution (typically seawater, although other saline solutions can be used [9,10]) by osmosis. The flow of the diluted but pressurized saline solution is then split in two streams: one is depressurized in a turbine to generate power, whereas the other passes through a pressure exchanger in order to pressurize the incoming draw solution to a desired operating pressure. Thus, the plant has one high pressure loop for the saline and diluted solutions and a separate low pressure circuit for the freshwater. The two key components in a standard PRO plant are the pressure exchanger and the membrane. It is very important that these two components are very efficient: current

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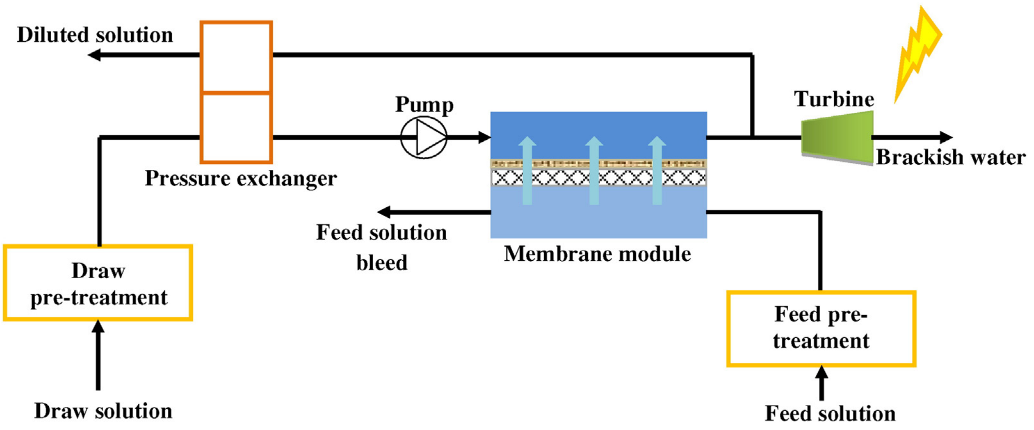

Fig. 1. Scheme of a standard PRO power plant.

pressure exchangers are extremely efficient, but PRO membranes still suffer from several drawbacks, such as the Reverse Salt Diffusion, which is studied here in detail.

It has already been shown that the solute in the draw solution diffuses through the membrane into the feed solution in the reverse direction to the water flux because of the concentration gradient [11]. This phenomenon, known as the Reverse Salt Diffusion, is characterized here in detail, as it reduces the efficiency of PRO power plants: the reduction of the effective osmotic pressure difference across the membrane causes a water flux decrease. Consequently, the performance of PRO is reduced and the energy costs could be much higher than expected if the salt flux diffusion is not controlled.

As other membrane processes, such as Reverse Osmosis (RO) and Forward Osmosis (FO), operating conditions (applied pressure, solution concentration, membrane orientation, cross-flow velocity) play an important role in salt and water transport across PRO membranes with drastic effects on the process [12,13,14]. Recent investigations have studied the RSD as a phenomenon related to the water flux [15,16]. However, a full study investigating the effects of the operating conditions on the RSD is not published yet, which motivates this paper. Thus, here for the first time, a full study of the impact of operating conditions on the RSD in PRO (solution concentrations, temperature, velocity, membrane orientation, solution composition, and applied pressure) is presented. This is investigated by deriving models of the process and then carrying out experiments at lab-scale. As this phenomenon is non-evitable, the best conditions of process to control the salt diffusion are discussed. The models used are developed using those previously presented by some of the authors in [17,37].

2. Theoretical models of the process

2.1. Modeling the reverse salt flux in bench-scale flat sheet membrane

In an osmotically driven membrane process, the water permeation flux J_w across an ideal semi-permeable thin film that allows water passage but rejects solute molecules or ions is related to the water permeability A, the effective osmotic pressure difference $\Delta\pi_m$ and the trans-membrane hydraulic pressure difference ΔP as follows [19,43]:

$$J_w = \mathrm{A}\,(\Delta\pi_m - \Delta P) \tag{1}$$

where

$$\Delta\pi_m = \pi_{D,m} - \pi_{icp} \tag{2}$$

and $\pi_{D,m}$ and π_{icp} are the osmotic pressures at the surface of the active layer and at the interface between the support and active layers, respectively.

In PRO, the power that can be generated per unit of membrane area is equal to the product of the water flux and the hydraulic pressure differential across the membrane:

$$W = J_w\Delta P = \mathrm{A}\,(\Delta\pi_m - \Delta P)\Delta P. \tag{3}$$

The maximum of energy that can be produced is reached when the applied pressure ΔP is the half of the effective osmotic pressure difference between the draw and feed solutions: $\Delta P = \frac{\Delta\pi_m}{2}$; then, the maximum possible power produced is [20]:

$$W_{max} = A\frac{\Delta\pi_m^2}{4}. \tag{4}$$

2.1.1. The internal concentration polarization (ICP)

ICP is an important factor affecting the permeate flux since it cannot be mitigated by enhanced shear stress [21]. ICP occurs when the thin film is supported by a porous substrate. In order to reveal the effects of ICP on the permeate flux, solute mass balance within the porous media can be calculated using the following mass balance [28]:

$$D_{s.l}\frac{dC(x)}{dx} - J_wC(x) = J_s \tag{5}$$

where $C(x)$ is the salt concentration at position x and $D_{s.l}$ is the diffusion coefficient of in the support layer, defined as:

$$D_{s.l} = \frac{\varepsilon}{\tau}D \tag{6}$$

where ε and τ are the porosity and the tortuosity of the support layer, respectively, and D is the bulk diffusion coefficient, which can be estimated as follows [22]:

$$D = 6.725\times10^{-6}\times\exp\left(1.546\times10^{-4}\times\mathrm{C} - \frac{2.513}{T}\right). \tag{7}$$

Eq. (5) can be integrated over the support layer, respecting the following boundary conditions:

$$\begin{cases} \mathrm{C}(x=0) = \mathrm{C}_{\mathrm{F,m}} \\ C(x=\mathrm{t_s}) = \mathrm{C_{icp}} \end{cases}$$

where the distance x is measured from the interface between the support and active layers, C_{icp} is the solute concentration at this

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