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Energy and thermodynamic analysis of power generation using a natural salinity gradient based pressure retarded osmosis process

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HIGHLIGHTS

- Power density and energy generation by PRO processes are mathematically interpreted.
- Discharge behaviour of PRO processes based on natural salinity is obtained and analysed.
- Membrane consumption of a full scale PRO discharge is studied.
- Configurations of two-stage PRO process are proposed and discussed.
- Energy generation is compared for different configurations.

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ABSTRACT

This study presents a thermodynamic and energy analysis of the discharge behaviour of a single-stage pressure retarded osmosis (PRO) process which is then expanded into a proposed two-stage process to enhance total energy extraction in a practical application. A thermodynamic model describing the operational conditions for the optimal power density and the extraction of energy from a single-stage PRO process is introduced. The discharge behaviour of the power generated from the process is analysed and the profiles of water flux, power density, and extracted energy are obtained. The membrane consumption is also studied with respect to different hydraulic pressures on the draw solution, and the flows of both the draw and feed solutions. The inherent inconsistencies in the operational conditions with regard to achieving maximal power density and available energy is discussed and interpreted based on the discharge behaviour. A two-stage PRO process with two alternative feed arrangements (continuous feed and divided feed) is then proposed and its operations are simulated and analysed. The results indicate favourable energetic performance of the two-stage versus the one-stage PRO process in terms of the reduced frictional loss and unused energy involved in the process.

1. Introduction

Rapidly increasing global population and climate change are two of the greatest challenges of our time [1]. Continued dependence on fossil fuels is unsustainable due to the finite fuel supply and climatic effects arising from the emission of carbon dioxide [2]. Renewable energy technology represents an apparent solution in this context [3]. Technologies involving wind, solar, geothermal and biomass have attracted significant attention but have achieved only limited capacity, so far, for local and global electricity generation without or with lower emission of greenhouse gases [4,5]. Research into alternative technologies continues with the goal of providing practical and reliable renewable energy sources (RES) [6–8].

Osmotic energy from natural salinity gradients has been identified as a candidate RES since the 1950s [9], due to its substantial potential energy capacity, estimated to be 2 TW, or about 13% of the current world energy consumption [10]. Research groups worldwide have, investigated the feasibility of capturing energy from the mixture of freshwater and seawater by means of PRO [11]. This technology, is an osmotically driven membrane process that takes the advantage of hydraulic pressure developed in the draw solution to convert osmotic energy into electricity by hydro-turbine [12]. Following rapid developments in the field over the last decade, this technology is now in operational use. In 2009, the world's first PRO plant was launched in Norway with a 4 kW capacity [13].

Prior investigations to improve the performance of a PRO process have focused on developing high performance membranes and setting up appropriate operational conditions to maximize energy yields. Detrimental effects during transportation across the membrane have been identified as a major problem [14], limiting the performance of PRO

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technology [15,16]. Primary performance-limiting phenomena comprise internal concentration polarization (ICP) in the support layer [17], external concentration polarization (ECP) on the draw solution side [18], and reverse solute flux (RSF) [19]. Different membrane types and orientations, as well as varying operational conditions of a PRO process have been investigated with the aim of minimizing these detrimental phenomena [20–22].

The current study also draws on prior investigations of the PRO process not only as an independent power generator but also as a pre- or post-treatment mechanism to recover osmotic energy from high concentration brine discharge, in a hybrid process integrated with reverse osmosis (RO) and forward osmosis (FO) processes [23,24]. Previous studies have mostly focused on improving water flux and power density of the process [19] and only a few also focused on energy generation [25, 26]. Data from these studies indicate that the potential energy from the mixed seawater and freshwater can be calculated using the concept of Gibbs free energy [27]. However, the potential chemical energy represents the maximal energy involved in the mixing process, which cannot be fully used due to intrinsic thermodynamic inefficiency. Taking this unavoidable frictional loss and unutilized energy into account [28], the concept of extractable energy has been incorporated into the energy analysis.

Like power density, the maximum energy generated is also significantly influenced by the applied hydraulic pressure of the draw solution. In the current study, a thermodynamic analysis of the discharge behaviour of a PRO process is carried out to investigate the relationship between the power density and the extracted energy. A thermodynamic model of the PRO process is introduced and used as a basis for further investigations. The study focuses on the influences of different parameters and operational conditions on the discharge behaviour of the process. The inherent inconsistency of optimal conditions for maximal power density and maximal extractable energy generated by a constant pressure PRO process is analysed and discussed.

Furthermore, similar to the advantages of energy efficiency in two-stage RO configurations [29], two-stage PRO process is also potentially efficient in salinity energy harvest. The configuration is capable to decrease the frictional loss by altering the hydraulic pressure applied on the draw solution, and to increase the energy generation due to the two-stage generation by increasing the water permeation and reducing the unutilized energy loss. However, a review of the literature reveals no investigations to date of two-stage PRO processes, or analysis of their potential for increased total energy extraction. Therefore, a study of two-stage PRO process is also carried out. Relevant targets for study include the analysis and optimization of the possible configurations and operations of two-stage processes. To address this omission, the current investigation defines and analyses the performance of a two-stage PRO with two different feed water operations: continuous feed two-stage PRO and divided feed two-stage PRO. The results show the characteristic of preferable energy generation capacity of the two-stage PRO process and the influences on the performance due to variation in operational conditions and the available volumes of feed and draw water for use in the PRO process.

2. Osmotic energy generated by a PRO

PRO uses the natural phenomenon of osmosis to permeate water across a semi-permeable membrane from a side with low solute concentration and low hydraulic pressure to a side with high concentration and high pressure. The permeated water is then used to generate electricity in a hydro-turbine (Fig. 1). In the PRO process, the draw solution is pressurized by the pump and the energy recovery device (ERD). As water is transported across the membrane, the draw solution becomes progressively diluted and the concentration of the feed solution rises. For simplicity, the efficiency of pumps and turbines is assumed to be 100% in this study.

Two of the key parameters determining the performance of PRO processes are the conditions of available salinity streams and the PRO operations. The two salinity streams determine the total energy capacity that can be harvested. The Gibbs free energy is released when the two streams mix, and is converted into electricity by the PRO process. However, this energy cannot be fully harvested. In addition to the inherent membrane performance, the efficiency of the PRO process also significantly depends on the hydraulic pressure applied on the draw solution, because the applied pressure determines not only the flow rate but also the pressure head of the pressurized permeated water.

Variables in the available water conditions comprise the concentration and volume of the draw and the feed water. Power generation by a PRO process from natural salinity gradients could utilize high concentration saline water such as seawater and brackish water as draw water. The total dissolved solid (TDS) of brackish water is in the range of 1000–5000 mg/L, and the TDS of seawater is larger than 35,000 mg/L. Normally, water with TDS smaller than 1000 mg/L is classified as fresh water. This includes water from rivers, sewage, private effluents and industrial wastewater, but water from such sources would require pre-treatment before use as feed water in a PRO system to prevent membrane fouling.

The available volume of draw and feed water is also very important because it significantly influences the variation of net driving force and, as a consequence, determines the change of osmotic pressure difference, water flux and power density along the membrane. The van't Hoff equation for osmotic pressure (π) applies to dilute, ideal solutions and is given by,

$$\pi = \nu RTc \quad (1)$$

where ν is the number of ionic species each salt molecule dissociates, R is the gas constant, T is the temperature, c is the concentration of the solution. In this study, for simplicity, the seawater is regarded as a hypothetical solution with 35,000 mg/L TDS. Accordingly, the van't Hoff law

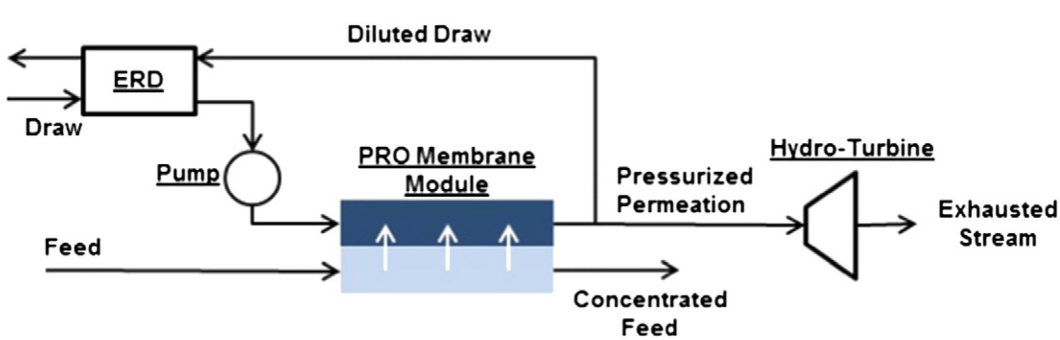

Fig. 1. A schematic illustration of a PRO process. The water permeates through the membrane from the low concentration side (feed solution) to the high concentration side (draw solution), and then is expanded in hydro-turbines.