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Lab scale assessment of power generation using pressure retarded osmosis from wastewater treatment plants in the state of Kuwait

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HIGHLIGHTS

- PRO is a viable source of generating green energy from TWE and brine in Kuwait.
- Sensitivity analysis were performed on PRO zero model using actual data from Kuwait.
- The results showed that CP is more significant than B′ at low ΔC.
- At high ΔC between the draw and feed solutions CP and B′ effects become negligible.
- PRO is used in reducing environmental impacts by diluting the brine prior discharge.
- It prevents transfer of nutrients in TWE to brine prior discharge into seawater.
- An equation is proposed to calculate the savings that PRO could provide.

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ABSTRACT

Discharge from the desalination plants of Kuwait returns brines of high salinity to the Gulf that contain other contaminants, such as chlorine or chromium, impacting the environment of the coastal region. Conversely, wastewater discharges to the Gulf have low salinity but may drive eutrophication of coastal waters. Pressure retarded osmosis (PRO) is a promising source of renewable energy and an emerging membrane-based technology for recovering energy from concentration differences between water streams. The proposed work examines the feasibility of using PRO to generate energy from wastewater and desalination plants in Kuwait by calculating the power density using a PRO zero-dimensional model. The model accounts for concentration polarization (CP) and salt leakage (B′) effects to produce realistic results. The effects of CP and (B′)on the power density at varying applied pressures and varying concentration differences between the feed and draw solutions are studied. Case studies on the potential re-use of treated wastewater effluent (TWE) and brine reject streams from three wastewater treatment plants (WWTPs) in Kuwait are discussed and compared to determine the maximum power generated from each of the WWTPs. The power densities generated from wastewater treatment (WWT) plants in Al-Jahra city, Um Al-Haiman city and Al-Riqqa were studied. The power density from Al-Haiman WWTP (18.73 W/m^2) is the highest compared to those of the other two WWTPs. The limits of the zero-dimensional model are also presented in this study. The PRO power density (W) was studied as a function of hydraulic pressure (ΔP) at different feed and draw solution concentrations. At higher draw solution concentrations (85 g/L NaCl), the power densities were higher. This increase in power density values was attributed to the higher driving forces acting in the system. Concentration polarization (CP) and salt leakage (B′) reduce the driving forces across the membrane. The power density values (W) were smallest in the presence of both CP and(B′). The effects of CP and (B′) vary depending on the concentrations of the draw and feed solutions.

1. Introduction

Water scarcity, over population and environmental degradation have stressed the water table to an extent that the 21st century has been nicknamed the “century of water” [1]. This crisis has resulted in the depletion of water resources and has limited the availability of fresh water to 0.8% of the earth's total water resources [2]. The global demand for water will increase from 4500 billion m^3 to 6900 billion m^3 by 2030, and this demand will only be solved through the treatment of seawater. Some of the successful treatment models for converting seawater to fresh potable water are reverse osmosis (RO) and electrodialysis (ED)

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[3]. However, managing the effluents from these plants is energy intensive and environmentally unsafe. These concentrated salt effluents have a negative effect on closed water bodies, in particular, the Arabian Gulf and Mediterranean Sea, and are a threat to the marine life of such regions [4].

The advent of renewable energy has taken the world on a path toward sustainable consciousness. Studies demonstrate that renewable energies can power the world with an energy potential of 10,000 TWh every year; out of this total, water sources have an enormous potential. [5]. In the world of hydroelectric generation systems, the use of salinity gradient energy has the highest energy concentration and can produce approximately 1650 TWh every year, making it a viable source of electricity [6,7]. The salinity gradient energy (SGE) is a high potential energy source that utilizes pressure retarded osmosis (PRO), and reverse electrodialysis (RED) techniques to generate power [8].

The concept of extracting energy from water salinity was developed as early as the 1950s. With time and research, the technique was popularized and improved. PRO has gained a strong interest in recent years and shows potential for being an important source of non-intermittent renewable energy. Harvesting energy by mixing freshwater with seawater was first reported in an article in *Nature* by Pattle in 1954 [5]. Pattle was able to demonstrate that when a volume (V) of pure solvent is mixed with a much larger volume of solution of osmotic pressure π, the resulting free energy released during the process is equivalent to πV. He also concluded that the use of this osmotic pressure with selected permeable membranes can be used to generate power [5]. However, no significant research happened in the field of PRO during 1950–1970. The oil crisis of 1973 led to the re-investigation of alternative energy sources, and interest in PRO was renewed. In 1974, a working model of an osmotic salination energy convertor took shape. Norman, the inventor, designed a system wherein freshwater permeates through a semipermeable membrane into a pressurized seawater chamber [9]. The water that spills over the top of the column would run a waterwheel and power the generator. This system effectively shows the conversion of chemical potential of water into hydrostatic potential. A year later, Norman and Loeb coined the term "pressure retarded osmosis" [9].

PRO is the pressure energy recovered when water is transported from diluted to concentrated solutions through a semi-permeable membrane by osmosis. When two streams of a different salinity are separated by a semi-permeable membrane, osmosis causes water to diffuse from the dilute to the concentrated stream or in the direction of the osmotic pressure gradient. The concentrated stream is pressurized to a hydraulic pressure greater than that of the dilute stream before entering the exchanger. The pressurized diluted draw solution goes into the turbine to generate electricity [7]. In PRO processes, low concentration solutions like freshwater, wastewater effluent, brackish water are usually used as feed solutions; while solutions of high concentration like seawater, RO brine concentrate, etc. is used as draw solutions. To recover energy from desalination plants, brine is used as the draw solution and a TWE stream is used as a feed solution. The process is "pressure retarded" because the osmotic driving potential is deliberately reduced by increasing the hydraulic pressure of the draw stream relative to the feed stream to produce hydraulic power.

Loeb was the first to report on the success of experimental PRO using hollow fibre seawater reverse osmosis (RO) membranes although it was an expensive technique. Research slowed down but the increase in demand for desalination water treatment renewed interest in PRO. Loeb and Mehta investigated various factors such as internal concentration polarization and developed models to predict pressure and flux for the PRO system. Loeb and Mehta theorized that there exist two water permeability constants: one driven by hydrostatic pressure, the other by osmotic pressure [10]. Simultaneously, the research on another type of energy source was ongoing. Loeb developed the closed-loop osmotic heat engine, which converts heat energy into mechanical work through the process of osmosis [5].

In 1981, Lee et al. [11] used the results from RO and forward osmosis (FO) experiments to predict the results for PRO performance, wherein they used the effect of internal concentration polarization to evaluate the water flux (J_w) and power density (W). The concentration polarization, or the accumulation of solutes near an interface decreased the osmotic pressure difference across the membrane. Lee et al. and Mehta also studied the negative effect of concentration polarization on PRO and suggested that membranes used for RO cannot yield good results for PRO [5]. During that time, Reali et al. noted the importance of membrane characteristics and the role they play in PRO through their experiments. Some of the significant membrane characteristics that influence PRO are the water permeability coefficient, the salt permeation coefficient, the thickness of the porous support layer, the effective salt diffusivity on water and the salt permeation though the membrane [12]. The decade ended with positive results showing that energy could be produced at prices comparable to the retail price in the United States.

The oil price rise in 2008 prompted more research in the field, and approximately 20 research papers about PRO were published during the first decade of the new millennium. Loeb proved the use of pressure exchangers in the PRO design, and his model was successfully tested by the Norwegian national power company Statkraft [13].

Progress on the PRO system continued with Achilli et al. [35] improving upon the model developed by Lee et al. [11] by incorporating the factor of external concentration polarization. A lab-scale membrane module was prepared using a flat-sheet triacetate FO membrane, and the results showed power densities exceeding 5 W/m^2. Internal concentration polarization reduces the power density; however, the development of new membranes with high water permeability and low support layer resistivity could improve the power densities. In 2012, Chou et al. successfully tested a new thin film composite (TFC) hollow fibre membrane for the PRO process [14]. The membrane with a water permeability of $A = 0.22 \times 10^{-12}$ m/sPa, salt rejection of $B = 3.68 \times 10^{-8}$ m/s and a structural parameter of $S = 4.6 \times 10^{-4}$ (these parameters describe the inherent properties of an osmotic membrane) could withstand a pressure of 9 bar and produce a density of 10.6 W/m^2 [14]. Research focused on developing membranes with the permeability of nano filtration membranes and a support layer measuring one-tenth of the current membrane thickness while having great structural strength, resulting in a power density of 30 W/m^2.

The late 2000s saw the construction of the first PRO generation plant. Statkraft and SINTEF worked together to develop membranes with the desired characteristics to generate approximately 4–6 W/m^2 of power, making it a profitable energy source in the Norwegian energy market [15,16]. In November 2009, the first prototype of the PRO plant was constructed with a capacity of 10 kW of power generation following the principle of recovering pressure energy from a low salinity feed solution permeated to a high salinity solution and using a hydro turbine [17].

Recent studies have focused on the details of water and salt transportation through PRO membranes [18,19], new membrane materials and structures that can enhance water permeability and energy density [20–22], the effects of fouling on PRO membranes [23–26], and the viability of desalination plants hybridized with PRO systems [27–31]. Researchers have also investigated new membrane module designs such as the modified spiral-wound membrane or optimized hollow-fibre designs [32,33]. With the world's first PRO power plant becoming operational in Norway in 2009, PRO has leapt out of the laboratory and into the marketplace [34].

Achilli et al. [35] provided expressions to calculate the water flux and power density in a PRO membrane considering the effects of both internal and external concentration polarization in a zero-dimensional exchanger. They showed that, ideally, water flux (J_w) decreases with hydraulic pressure (ΔP) until reaching zero at the flux reversal point ($\Delta P = \Delta\pi$). Meanwhile, power density (W) increases until it reaches a maximum (at $\Delta P = \Delta\pi/2$) and then decreases to zero at the flux reversal