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Reverse Osmosis–Pressure Retarded Osmosis hybrid system: Modelling, simulation and optimization

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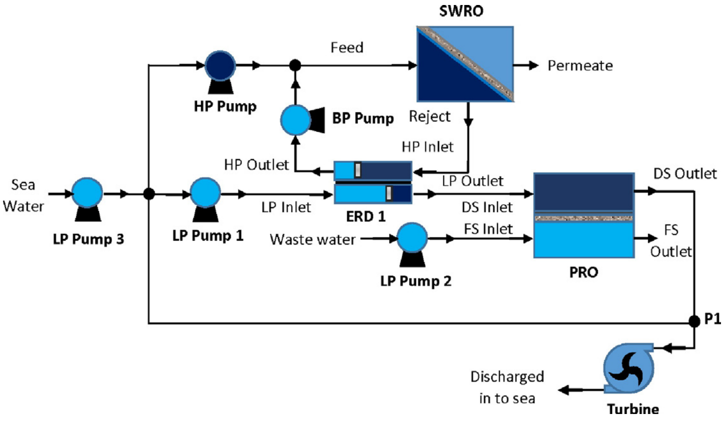
HIGHLIGHTS

- Simulation and sensitivity analysis of integrated SWRO-PRO system configurations for eliminating brine post-treatment step.
- Identification of energy efficient novel SWRO - PRO hybrid desalination process for reducing the SWRO pre-treatment cost.
- Method for optimization of hybrid SWRO-PRO system design and operating parameters to achieve minimum NSEC.

GRAPHICAL ABSTRACT



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ABSTRACT

Theoretical analysis of energy harvesting from concentrated brine of Sea Water Reverse Osmosis (SWRO) system using Pressure Retarded Osmosis (PRO) is presented in this research. The mathematical model of SWRO–PRO hybrid system components such as SWRO unit, Energy Recovery Device (ERD), PRO unit and other auxiliary units were discussed. The mathematical equations were solved adapting an object oriented “Modelica language” framework in Dymola software tool. The complex flowsheet models for six different SWRO–PRO hybrid configurations were created. The performance of the SWRO–PRO hybrid system configurations was studied. The process and design parameters were optimized to reduce the Net Specific Energy Consumption (NSEC) of the system. The optimization studies were performed using SQP technique that is available in optimization library of Dymola. The possibility of using sea water (32,000 g/m^3) and urban waste water (100–10,000 g/m^3) as feed solution to the PRO for all the hybrid configurations were studied. Their performances were compared through simulation and optimization studies. Among the six potentially viable SWRO–PRO configurations, the one which does the direct mixing of diluted PRO draw outlet with feed water of SWRO aided to bring down the NSEC by 49% in comparison with standard SWRO desalination system. This system does not require additional ERD units and turbine at optimized process conditions, which are more expensive.

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1. Introduction

The Sea Water Reverse Osmosis (SWRO) desalination is one of the pioneer technologies for desalination of sea and brackish water. As per latest reported data, desalination industry is able to produce treated water from sea water with an energy consumption of 1.8 kWh/m^3 [1]. The theoretical minimum energy required for desalination of 35,000 g/m^3 concentration of seawater at 50% recovery is 1.06 kWh/m^3 (i.e. multistage operation) and 1.56 kWh/m^3 (i.e. single stage operation). Hence, it can be concluded that the energy demand for seawater desalination was found to be higher by 41% for multistage and 13.3% for single stage desalination than the stated theoretical minimum energy [1], which is not far off the thermodynamic limit for single stage. This was achieved with continuous research and development of fouling resistant SWRO membrane and energy efficient electrical and flow equipment. Therefore, the theoretically zero energy SWRO may be achieved by developing innovative technology which can extract the osmotic energy from SWRO brine.

The Pressure-Retarded Osmosis (PRO) is one of the best technology [2] that can extract osmotic energy by controlled mixing of high and low concentrated water. In 1976, Loeb et al. published the PRO concept with experimental results for the first time [3]. When Loeb et al. proposed the concept of PRO, Dead Sea water (i.e. ≈250,000 g/m^3) was considered as high salinity source. Their results were not very promising because those experiments were performed using SWRO membrane modules (i.e. power density in the range from 1.56 to 3.27 W/m^2). The lower power output for the case was mainly due to severe internal concentration polarization (ICP). The estimated break even membrane power density by Gerstandta et al., [4] varies in between 4 and 6 W/m^2 with respect to TDS of draw and feed solution (DS, FS). As per Statkraft (Norway), it is important to have the power density above 5 W/m^2 for successful commercialization of PRO system. The continuous research on this topic resulted into improved PRO membrane with high power density [23] and stable membrane performance. Saito et al. [5] reported that Toyobo's prototype hollow fibre PRO membrane was able to achieve the maximum output power density of 7.7 W/m^2 at 2.5 MPa hydraulic pressure difference having 38% permeation of pure water into brine.

The use of the SWRO brine as a draw solution can improve the efficiency of PRO system and shall eliminate the necessity of SWRO brine post-treatment. Therefore, the reject water (≈52,000 g/m^3 to 60,000 g/m^3) of SWRO plant had attracted researchers as high salinity source for PRO. A conservative assessment indicates that the SWRO–PRO offers a potential energy reduction of 20–23% and total capital cost reduction of 8.7–20% compared to SWRO process [6]. Thermodynamic analysis on the feasibility of stand-alone SWRO–PRO hybrid system was done by Wang et al. [7] and Sharqawy et al. [8]. The recent theoretical analysis by Prante et al. [9] also inferred that using a well-characterized CTA membrane, the minimum NSEC of the modelled SWRO–PRO system was 1.2 kWh/m^3 for 50% SWRO recovery. Considering a SWRO system of having specific energy consumption of 2.0 kWh/m^3, the SWRO–PRO system can theoretically achieve 40% energy reduction. The SWRO–PRO hybrid system which was considered by Prante et al. was with two ERD units to minimize the NSEC, which is more expensive and may lead to increase in the capital cost of the system. Pressure drop and concentration polarization (CP) along the length of the membrane and pressure drop and frictional loss in ERD were not considered. Therefore, reduction in the NSEC of the system may significantly reduce from 40%. Further, considering the possibility of recirculating the diluted brine water of PRO as feed water for SWRO may even reduce the NSEC.

Considering the above supportive arguments, the objectives of this research work focused upon the identification of energy efficient novel SWRO–PRO hybrid desalination process to achieve reduced NSEC for desalination process. This novel hybrid system aimed at eliminating SWRO brine post-treatment and reducing sea water pre-treatment load. Six different SWRO–PRO process flowsheets were analysed by modelling and optimization of hybrid SWRO–PRO system design and operating parameters to achieve minimum NSEC. Out of six different flowsheets studied in this work, two were synthesized in this work and others were chosen from existing literature. The effect of design and process parameters on SWRO–PRO system performance was simulated by using flowsheet models.

2. Theory

In this study, six different SWRO–PRO hybrid system configurations were considered (i.e. from case II to case VII) along with the currently existing stand-alone SWRO configuration (i.e. case I) used in desalination application. Details of the system configurations are explained with process flowsheet (Fig. 1) and the particulars of those systems are given in Table 1. Throughout this study, the concentration of sea water is taken as 32,000 g/m^3 and waste water concentration may vary from 100 to 10,000 g/m^3.

2.1. SWRO and PRO trains

In industrial practice, a SWRO plant may consist of multiple trains. Each SWRO train will consist of multiple pressure vessels connected in parallel and more than one membrane modules are connected in series to build one pressure vessel. The number of membrane modules per pressure vessels is decided based on required recovery and the number of pressure vessels per train is decided to meet the target production rate. In contrast to SWRO pressure vessel, PRO pressure vessel has two inputs (FS and DS). In this work, model development and optimization framework are limited to SWRO–PRO system consisting of single train.

2.2. SWRO–PRO configurations

Alternate feasible SWRO–PRO hybrid configurations were proposed and studied by many researchers [9–13]. Kim et al. [10] identified four potential hybrid PRO–SWRO configurations and PRO is used for both extracting osmotic energy and dilution of seawater. Diluted sea water is then desalinated in SWRO to produce pure water. In brownfield projects, one of the drawbacks is integration of PRO unit before SWRO unit and it may be challenging and risky in terms of process reliability. Qureshi et al. [14] evaluated performance of case I and II process configuration (Fig. 1) for brackish water desalination using validated mathematical model. They reported that case I is found to be more energy efficient than case II for brackish water desalination. Almansoori et al. [12] studied hybrid configurations consisting of both PRO–SWRO and SWRO–PRO scenarios for sea water application. They concluded that the configuration having SWRO followed by PRO system is better than PRO followed by SWRO system. Therefore, six different possible SWRO–PRO system configurations are considered using various methods of energy recirculation and/or brine recirculation from SWRO to PRO and vice versa (Fig. 1). High pressure (HP) pump is used to pressurize SWRO feed to the desired pressure (i.e. 30–70 bar). Low pressure (LP) pump is used to pressurize the LP inlet of PX ERD such that the LP outlet can be maintained at desired pressure (i.e. LP inlet pressure should be higher than the pressure of LP outlet in order to overcome the pressure drop on LP side of PX ERD). In all hybrid systems (i.e. from case II to VII), the reject of SWRO is depressurized to the required pressure for PRO with the help of ERD. The total feed flow to the hybrid system is measured as a sum of water flow at two points, namely the HP pump and LP pump-1 inlets. Sea water is used as FS for PRO of case II (i.e. waste water is the FS in rest of the hybrid cases).

The HP pump flow rate is taken to be equal to the flow rate of product water according to industrial practice. For case I, the SWRO reject is post treated and sent back to the sea. Whereas in other cases, the reject is fed as DS for PRO. In cases II and III, the entire DS outlet water is depressurized at electric turbine to generate electricity. Whereas in

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