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Structural optimization of osmosis processes for water and power production in desalination applications

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HIGHLIGHTS

- Superstructure optimization analyzes RO/PRO system for water and power production.
- The objective function maximizes the total annual profit for the RO/PRO system.
- RO stages generate salinity gradient for the PRO operation.
- Process layouts show RO/PRO stages with several recycled streams.
- High performance PRO membrane may eliminate recycled streams in process layouts.

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ABSTRACT

Osmotic pressure is a separation barrier during the reverse osmosis (RO) desalination operation. Hydraulic pressure must be inserted on the membrane surface to overcome the osmotic pressure and to facilitate the desalination process. Pressure retarded osmosis (PRO) is a renewable source for power production. Power generation through PRO is achieved through salinity gradient generated across an asymmetric membrane. In this study, we seek an optimal integrated system of RO and PRO for seawater desalination and power generation. A mixed integer nonlinear programming (MINLP) model is developed to find optimal osmosis processes arrangement with auxiliary equipment, and their optimal operation conditions for seawater desalination and power generation. Several case studies were analyzed to show the applicability of the proposed model. In general, the results show that the operation of RO can be a feasible source of salinity gradient for power generation by PRO technology while producing desalinated water streams. The process layouts show arrangement of RO and PRO stages with recycled streams in order to increase the salinity gradient in the PRO stages. This is an undesirable condition for the RO operation and it is suggested from our results that high performance PRO membrane with high water permeation and salt rejection may eliminate this condition.

1. Introduction

Population growth, water scarcity, industrial activities, and stringent environmental regulations are main drivers for sustainable and renewable processes penetration in water and energy markets. In fact, water and energy are strongly linked to each other. Cogeneration of water and power is a common practice especially in Middle East and North African (MENA) countries [1]. Reverse osmosis (RO) is a very well proven technology in desalination applications. The process requires high pressure gradient across the RO membrane to counteract the osmotic pressure build up during the RO operation. Traditionally, high pressure pumps deliver this form of energy during the separation process, while pressure exchanger units minimize the energy consumption. Therefore, finding a sustainable and renewable source of energy for the RO system is a topic of great interest. Another issue of RO system is the generation of brine solution which has a negative environmental impact if it is discharged directly into the sea [2,3]. A recent study suggested the use of pressure retarded osmosis (PRO) for power generation and as a mitigation option for RO brine minimization [4].

PRO process exploits osmotic pressure as a driving force for power production. This is achieved by an asymmetric membrane separating two streams with different salinity [5]. Due to water chemical potential difference, water permeates through the membrane from the low to the high salinity sides. In order to drive the process toward power production, a differential pressure has to be inserted on the high salinity side. In general, the osmotic pressure difference has to be higher than the hydraulic pressure difference. It is worth pointing out that the PRO has an opposite operation compared with RO system. However, membrane orientation is similar in both processes (i.e., the active layer faces the high salinity solution side and the porous support layer faces the low salinity solution side). This process is not new and it was proposed in 1954

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for harvesting electric power by mixing fresh and salt water [6]. It is estimated that the potential global energy production from PRO technology is an order of 1650 TWh per year [7].

The power generation by the PRO process can be promoted when relatively salt and fresh water are in contact with semipermeable membrane. Water will permeate from the feed side (low salinity stream) into the draw solution side (high salinity stream) that is pressurized. Besides, the draw solution stream will be diluted at the end of the process as water diffuses through the membrane. The draw solution stream is split into two streams after the PRO stage which run the hydroturbine and the pressure exchanger units. Ultimately the hydroturbine is linked with a power generator for electricity production. The pressure exchanger unit pressurizes the draw solution stream going through the PRO module [8]. It is clear that the salinity difference may exist between any streams with different osmotic pressure. Such condition already exists within the RO seawater desalination plants.

A significant research effort for PRO advancement is attributed to Loeb and his coworkers [9–16]. In Europe, continuous research collaboration between different organization (e.g., Statkraft SF of Norway, ICTPOL of Portugal, SINTEF of Norway, GKSS-Forschungszentrum of Germany, and Helsinki University of Finland) has resulted with an PRO prototype in Norway in 2009 by mixing river water with seawater [17,18]. In the near future, PRO systems could be considered an effective form of power production from renewable energy sources, alongside other established renewable technologies (e.g., solar and wind). However, several challenges were identified especially with membrane development to reduce internal polarization in the support membrane layer.

Several research attempts were conducted to find suitable integration of renewable energy technologies with desalination systems. This coupling between desalination and renewable energy sources requires compatibility in order to attain reduced production cost and less environmental impact. There has been success in the past to desalinate seawater with single basin solar stills in many locations in Tunisia [19]. However, the integration of renewable energy sources with desalination plants are limited which represents about 0.02% of the total desalination technology. In general, photovoltaic and wind are efficient renewable source of energy in RO desalination plants [20]. Many research papers have proposed the PRO technology as a renewable source of energy in the RO desalination plants [21–23]. The existence of salinity gradient between the RO brine and seawater can generate power by the PRO system. Common intake and pretreatment system for both PRO and RO is another advantage. Besides, dilution of the RO feed stream by the PRO system may reduce the brine disposal problem in RO plants. Other sources of saline water can also be integrated in the RO/PRO system such as brackish water and municipality water to generate salinity gradients.

Process synthesis through superstructure optimization with emphasis on hybrid membrane systems has attracted immense research interest [24–26]. The approach evaluates large process layouts simultaneously. It has been applied for the design of RO network to seek optimal RO stages, auxiliary equipment, and their optimal operation for seawater desalination, and wastewater treatment [27–31]. Other research efforts were focused on the RO network design with membrane cleaning and replacement [32–34]. The previously mentioned RO network optimization models minimize the total annual cost subject to the technical and the operational constraints. These studies presented mixed integer nonlinear programming (MINLP) models to seek an optimal RO network.

Hybrid desalination systems were also addressed in the literature to find an optimal mixed of desalination technologies through superstructure optimization and cogeneration option (e.g., water and power) [35–38]. Other research efforts were primarily focused on the evaluation and integration of renewable energy technologies (e.g., solar) with desalination technologies [39–43]. The integration of PRO with RO system was proposed in the literature with the objective of minimization of RO plant energy consumption [22,23]. Therefore, there are several advantages of the proposed integration of PRO with RO system. A common intake and pretreatment system can be shared by both technologies and high capital investment may not be needed. The PRO technology is a renewable source of energy and can deliver baseline power demand without intermittent interruption as compared with other renewable technologies (e.g., solar and wind technologies). Labor training for the new technology is minor since both technologies are membrane processes and have common operational and maintenance practices. Besides, PRO can be considered as a mitigation option for RO brine management in the RO desalination plants.

A recent study presented different structures of the integrated RO/PRO system for water and power production [44]. The study simulated these structures sequentially in order to evaluate these structures based on the operational cost under various conditions (e.g., different TDS concentration of seawater). However, the study ignores the capital cost of the integrated system. To the best of our knowledge, the integration of PRO/RO systems has not been addressed as a research study for the cogeneration of water and power production through superstructure optimization. Superstructure optimization evaluates large number of process layouts simultaneously [27–31,45]. An economical objective function (i.e., a function which combines capital and operation cost) can be optimized to extract the best process layout subject to the model constraints. Optimal capacities of the process units can be obtained by the solution of the mathematical programming model. In addition, detailed connectivity of the process streams in the separation network can be identified upon the solution of the mathematical programming model.

The current study presents an MINLP model for the process synthesis of integrated PRO/RO system in the desalination applications. The mathematical programming model describes the PRO/RO network through superstructure representation of the integrated system. Upon the solution of the mathematical programming model, optimal selection and operation of PRO/RO system can be identified for the production of water and power to maximize the total annual profit of the integrated system. The following section gives the superstructure representation for the integrated PRO/RO system followed by the model development in Section 3. Section 4 covers two case studies with different power demand scenarios and shows the application of the proposed MINLP model. Finally, Section 5 concludes the main findings of the proposed research work.

2. Superstructure of PRO/RO system

Process synthesis problems look for optimal selection of process operation units, their operation conditions, and stream assignments in the treatment network. The input streams to every unit operation is linked with the network fresh streams and the network unit operation exit streams. Similarly, every unit operation exit stream is linked to the input nodes for every unit operation and the final network product streams. This representation defines a graphical superstructure of a process synthesis problem which provides large number of process layouts [24,25,45]. In our analysis, we give compact representation of the major process unit such as PRO and RO, which includes auxiliary equipment (e.g., pump, pressure exchanger and hydroturbine).

It is appropriate at this point to define the operation requirements for the RO and PRO units, and the auxiliary equipment. Fig. 1a depicts an RO stage that may exist in the final integrated treatment network. A feed stream is split into two parts: one going through a high pressure pump; and another one going through a pressure exchanger unit followed by a booster pump. The RO reject stream may supply its energy to the RO feed through the pressure exchanger unit. The exit streams from the high pressure and the booster pumps are combined as a high pressure feed for the RO stage. This high pressure stream is fed to the RO stage which is composed of several parallel RO modules operating under the same conditions. Permeate and reject streams are the results from the RO separation task which may go for further processing in other stages or may go out of the treatment network.

In Fig. 1b, PRO is considered to receive two streams with different salinity (e.g., different osmotic pressure) in order to transport water