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Optimal operations for large-scale seawater reverse osmosis networks

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ABSTRACT

Optimal operation of large-scale seawater reverse osmosis (SWRO) systems, which include multiple RO plants and storage tanks, are studied to reduce the energy cost; and at the same an effective computing method was introduced for the purpose of real time optimization. With well developed models of the RO process and storage tanks based on the first principle, the optimal operation problem is subsequently formulated in the form of differential-algebraic optimization problems (DAOPs). Simultaneous collocation method was used to transform the problem into a large-scale nonlinear programming problem, and then IPOPT solver, combined with an efficient initial-value and finite-element meshing technique, was used for fast solution. Then the optimal operation problem with different variable parameters that significantly affect the performance and the energy saving of the SWRO system were investigated through case studies. Computational results show that the optimal operation problem under different conditions can be solved with high efficiency and stability, and significant energy-saving potential can be obtained through the optimal operation proposed in this paper.

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1. Introduction

The shortage of freshwater is worsening with the rapid growth of the population and industrialization, which has restricted social and economic development [1,2], and led to a freshwater crisis in the new century [3,4]. The consensus of the scientific community is to obtain new freshwater resources from seawater desalination, particularly for coastal countries [5–7]. With the development of membrane techniques with low cost and high salt rejection and the progress of energy recovery devices with high efficiency, desalination of seawater reverse osmosis (SWRO) is becoming the most popular and attractive seawater desalination technique [8–10]. Its cost per unit of produced freshwater has significantly decreased in recent decades and is comparable with the cost of the traditional freshwater treatment process.

To reduce the unit production cost of the SWRO system, researchers applied systematic methods of optimal design and optimal operation. To obtain the lowest production cost, they decreased the construction and operation cost by configuring the series and the system flow under a certain operation conditions and water quality requirement. Furthermore, the optimizing operation and energy management were adopted in the existing systems to reduce the energy consumption [11].

Kim et al. [12] considered the RO process, particularly on minimizing the production cost using a system engineering approach. Al-Shayji analyzed multi-stage flash (MSF) and SWRO systems, using mechanisms and field data, and subsequently performed modeling, simulation and optimization studies on the system [13]. Both Sassi and Palacin [14,15] studied the optimal operation of the SWRO system with the consideration of minimizing the specific energy consumption (SEC), and their study aimed to reduce the energy cost by reducing the energy consumption per unit production of freshwater. To minimize the energy consumption, Zhu et al. [16] analyzed the pressure of reverse osmosis with so called "thermodynamic restriction", then evaluated the optimal operation with various feed salt concentrations and other operation conditions, and different operating strategies were analyzed to obtain better energy saving potential [17,18]. While Li [19] studied the optimal operation of the brine SWRO system to minimize the energy consumption. With the developed rigid mechanistic model, computational results showed that by optimizing the operation, the specific energy consumption is decreased by 16% compared to the traditional operation. Geraldes considered both the investment cost and operation cost of the SWRO system and provided the differential equations of the RO process with the distributed method. Then, he simplified the simulation process and solved his optimal problem using simple difference equations [20]. Because the operating point of the SWRO system frequently deviates from the default set point, Sassi et al. studied the operation optimization of the SWRO system under the variational load and feed temperature. In this study, the

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storage tank was considered a connection between freshwater production and supply, which obviously increased the flexibility of the optimal operation [21]. Ghobeity investigated time-varying characteristics of the parameters; he considered the time-varying frequency of the high-pressure pump and the time varying of the electricity price and obtained the optimal recovery operation curves under continuous and discontinuous modes by solving the established algebraic equations with Baron under the GAMS platform [22]. However, the computing time was notably long. In terms of design optimization, Voros et al. [23] provided an optimal design method for the SWRO system in the form of a network superstructure. Because each section of the SWRO system is built using the mechanistic model, the optimal operational and structure variables were obtained under minimum cost requirement. Lu et al. studied the optimal design of the one-stage RO process by minimizing the annual total cost including detailed investment and operational cost. The membrane cleaning cost and replacement cost were also included in the objective function [24]. Then, the study was further extended to multi-stage and various steam configuration systems [25]. Zhu et al. considered all operational conditions (for instance, the membrane fouling over time) to optimize an RO system operation and finally obtained the system performances related to the time horizon [26]. See et al. [27,28] studied the further optimization of the RO network structure, such as the optimization of the RO process level and the arrangement of membrane components. Then, they optimized the operation of the fixed network structure and analyzed the optimized network configuration and operation condition. Du et al. [29] studied the operational and the capital costs of SWRO with the pressure exchanger (PX) device. The design optimization of the described spiral-wound SWRO system using MINLP (mixed integer nonlinear programming) with RO flux, feed pressure and RO process was analyzed, and the change of seawater concentration and pressure decrease along the membrane channel were formulated using differential equations. Sassi and Mujtaba [30] analyzed the influence of the seawater feed temperature on the RO network, studied several optimization cases of RO system design with different feed concentrations, and explored the interaction between design and operating temperature and pressure. Because there are several local minima for this strongly nonlinear system, Marcovecchio et al. [31] proposed a new optimization algorithm to handle nonconvex problems. The results of different cases proved that the method had excellent performance and efficiency when it was applied to the design of the global optimum of SWRO network. To realize the energy saving of SWRO process, Christofides et al studied optimization-based control and supervisory predictive control to move the manipulated variables to optimal set point, simulation and experimental results show the effectiveness of the proposed methods [32,33].

The above studies show how researchers have analyzed network-based design optimization problems to optimize the flowsheet and reduce the total production cost. In terms of operational optimization, researchers gradually expanded studies from specific production cost to the production operation and energy cost of the entire network system. Furthermore, different factors that affect the operations of the SWRO system were analyzed in detail and are included in the optimal operation of the SWRO system. However, real-time optimization of large scale SWRO system with network structure, where the system's operating point changes dynamically, has been rarely found. Few papers have studied the strategy of the stable and fast solution strategies for the SWRO system.

Because the operating point of the large-scale SWRO system dynamically changes with fluctuation of the operating parameters, such as the feed temperature and freshwater demand, its dynamic optimization leads to a differential-algebraic optimization problem (DAOP) with many nonlinear differential-algebraic equations. The direct solution of this type of problem is difficult, and although the problem can be transformed into a nonlinear programming (NLP) problem using full discretization, the scale of the problem will greatly increase and will introduce a large challenge for its efficient solution with high accuracy [34–36]. Although large-scale NLP solvers such as IPOPT [37,38] and CONOPT perform well with large-scale problems, the efficient and stable solution of the large-scale SWRO requires careful design.

Considering the characteristics and the parameter variation of the large-scale SWRO system with a network superstructure, this study focuses on the dynamic operational optimization of this system with time-dependent parameters. The operational optimization problem is formulated after the models of the RO process, and the dynamics of the storage tanks are established. To satisfy the real-time requirement, a stable and efficient solution strategy is proposed for the solution, and various parameters are discussed in detail during the optimization process. This work aims to contribute to increased energy cost saving and real-time optimization for this large-scale system.

2. Flowsheet analysis and modeling

Fig. 1 shows the basic process of the SWRO system [39]. After the processes of seawater intake, flocculation, chemical treatment and filtering, seawater enters the RO membrane. The reverse osmosis effect separates the seawater into freshwater (permeate water) with low salinity and concentrated brine. Then, after further treatment, the freshwater is pumped to the terminal users from the storage tanks. The high-pressure brine is disposed after pressure recovery, using an energy recovery device.

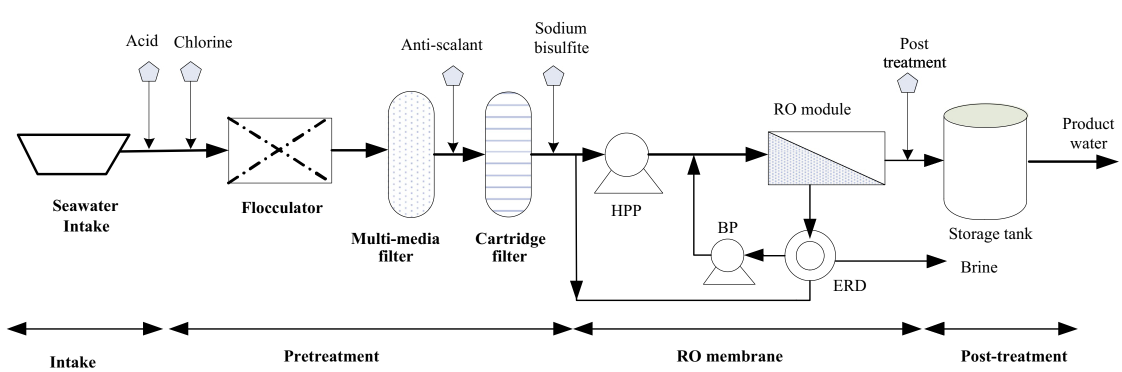

Fig. 1. Basic schematic diagram of the SWRO desalination system.

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