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The design of reverse osmosis systems with multiple-feed and multiple-product

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HIGHLIGHTS

► A process synthesis-based optimization technique has been developed.
► Membrane units were approximated by the pressure vessel model.
► The module model takes into account the pressure drop and concentration changes.
► The stream split ratios and logical expressions of stream mixing were employed.
► The design results present optimal structure and the optimal streams distribution.

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ABSTRACT

A reverse osmosis (RO) desalination process with multiple-feed and multiple-product is the main focus of this work. A process synthesis-based optimization technique has been developed for the design of the RO system. The adoption of this approach provides an economically attractive desalination scheme. Membrane separation units employing the spiral wound reverse osmosis elements were approximated by the pressure vessel model presented in this paper, which takes into account the pressure drop and concentration changes in the membrane channel. A simplified superstructure that contains all the feasible design for this desalination problem has also been presented. In this structure representation, the stream split ratios and logical expressions of stream mixing were employed, which can make the mathematical model to be easily handled. The optimum design problem is formulated as a mixed-integer non-linear programming (MINLP) problem, which minimizes the total annualized cost of the RO system. The cost equation relating the capital and operating cost to the design variables, as well as the structural variables has been introduced in the objective function. The solution of the problem includes the optimal system structure and operating conditions, and the optimal streams distribution. The design method could also be used for the optimal selection of the type of membrane elements in each stage and the optimal number of membrane elements in each pressure vessel. The effectiveness of this design methodology has been demonstrated by solving a desalination case. The comparisons of several alternate schemes indicate that the feed position of streams and outlets of the system are the critical variables that should be optimized for the RO system design.

1. Introduction

Desalination of sea and brackish waters is the main source for supplying fresh water in the regions suffering from the scarcity of natural fresh water supply. Since 1960s, due to the development of new reverse osmosis (RO) modules and membranes, RO is experiencing growing applications in the desalination field. Now it has become a major technology for large-scale desalination plants for both seawater and brackish water sources [1–5].

The interest in RO is due to its low energy consumption (as compared to multistage flash distillation process), high product recovery and quality. The other attractive feature of RO process is their modular plant design and ease of operation. Membrane plants are often more compact, can be scaled up easily and installed more quickly than thermal separations plants. Also, it makes the maintenance of RO systems easier. Another advantage of the RO process is that it is able to meet varying feed water concentration and varying production water quantity and quality requirement through the change of system configuration and operation condition. RO membrane manufacturers have developed various membrane types to precisely meeting the varying needs of a wide range of industrial, municipal, commercial and drinking water application. This includes high flux, high rejection, fouling resistant, low pressure, and high rejection membrane, etc [6–10]. These features allow the design of RO processes to be more flexible.

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Considerable efforts have been made for the research of the optimum design of RO system [6,11–14]. El-Halwagi [15] investigated the synthesis of RO networks which involve multiple feed streams for waste reduction. Based on the state-space approach, a structural representation of RO networks was introduced. The RO networks were described using four boxes, i.e. a pressurization/depressurization stream-distribution box, a pressurization/depressurization matching box, a RO stream-distribution box, a RO matching box. The function of the distribution boxes is to represent all possible combinations of stream splitting, mixing, bypass and recycle. The matching boxes locate all possible stream assignments to units. With this formulation, all possible structure arrangements are represented. The mathematical model was formulated as a mixed integer nonlinear programming (MINLP). In their later work, Zhu et al. [16] included a factor for flux decline over time based on their earlier work [15]. Voros et al. [17] simplified El-Halwagi's representation by reducing the distribution boxes to junctions. Consequently, the model was formulated as a nonlinear programming (NLP) model by using a variable split ratio. Maskan and Wiley [19] used a directed graph and connectivity matrix to represent the RO networks superstructure. In the mathematical model of the superstructure, a variable reduction technique is performed to accelerate the computational process. Nemeth [20] studied the behavior of the ultra-low pressure RO membranes in the full-scale system and presented recommendations to improve system design. Van der Meer [21,22] and Wessels [23] developed a simplified mathematical model to optimize the performance of NF and RO membrane filtration plants. The study showed that the productivity of nanofiltration plants can be significantly improved by installing a reduced number of membrane elements serially in pressure vessels (PV) and by changing system configuration. Malek et al. [24] provided a realistic economic model that relates the various operational and capital cost elements to the design variable values.

In this work, an RO-based desalination process is considered for the production of fresh water from three raw feeds (seawater, brackish and regenerated water). A systematic methodology is presented for the optimal design of RO desalination system that processes multiple feed streams simultaneously, and at the same time, supplies various product streams (water) of different quality. The adoption of this approach can provide an economically attractive desalination scheme. This leads to significant energy and raw-materials saving and generates income from the sales of multiple grades of water products. First, a simplified superstructure representation that contains all feasible designs for this desalination problem is presented. Then a pressure vessel model is also developed. The model could be used for the optimum selection of types and number of membrane element, according to its performance characteristics, the prices, and the design requirements of a specific desalination application. Therefore the optimal design of RO systems was formulated as a mixed integer nonlinear programming problem (MINLP). The objective is to determine the optimal system structure, stream distribution and operating conditions; subject to the constraints of the multiple-feed and multiple-product system. The solution to the problem also includes the most appropriate choice of the type of membrane elements in each stage and the optimal number of membrane elements in each PV.

2. RO unit model

2.1. The mass transfer model of RO process

Numerous models to predict membrane performance have been introduced [7,25,26]. They are derived from different theories and all of them may be simplified to the solution diffusion model, as shown in Eqs. (1) and (2). For the RO system design and optimization, it is necessary to adopt the appropriate modeling equations that can satisfactorily predict the membrane performance with reasonable computational complexity. Therefore the solution diffusion model is among the most commonly used model in RO system design. The model is mainly based on two parameters, i.e. water permeability (A) and solute transport parameter (B). Values for these parameters are usually specified by membrane manufacturers. According to the model, the pure water flux, J_w (kg/m^2·s), and the salt flux, J_s (kg/m^2·s), are given as follow:

$$J_w = A\left[\left(P_f - P_p - \frac{\Delta P_f}{2}\right) - \left(\pi_w - \pi_p\right)\right] \times 10^6 \tag{1}$$

$$J_s = B\left(C_w - C_p\right) \tag{2}$$

$$\pi = \frac{0.2641 \times C \times (T + 273)}{1.0 \times 10^6 - C} \tag{3}$$

$$V_w = \frac{J_w + J_s}{\rho_p} \tag{4}$$

$$C_p = \frac{J_s}{V_w} \times 1000 \tag{5}$$

where P_f and P_p (Mpa) denote feed and permeate pressure, respectively; ΔP_f is the pressure drop in the membrane channel; Π_w (Mpa) is the osmotic pressure of the brine at the membrane wall concentration C_w (ppm), and Π_p and C_p are corresponding variables for the permeate; ρ_p denotes the density of the permeate. V_w (m/s) is the permeate velocity.

In mass transfer process, the variation of concentration on membrane surface should be considered. The change can be represented by Eqs. (6) to (8).

$$C_w = C_p + \left(\frac{C_f + C_b}{2} - C_p\right)e^{\frac{V_w}{K}} \tag{6}$$

K (m/s) is the mass transfer coefficient, which can be calculated from empirical relations such as:

$$K = 0.04 \times R_e^{0.75} \times S_c^{0.33} \times \frac{D_s}{d} \tag{7}$$

$$R_e = \frac{V \times \rho \times d}{\mu} \tag{8}$$

where R_e and S_c are the Reynold's and the Schmidt numbers and D_s is the solute diffusivity. d is the feed spacer thickness, ρ is the feed side solution density and μ is the water viscosity. V denotes the flow velocity that was calculated using the averaged values of the inlet and outlet flow rates in the membrane channel.

2.2. The model for RO module

In the practical process, the multiple stages RO configuration would be used, one RO stage consists of multiple parallel RO pressure vessels operating at the same conditions. Each pressure vessel contains several membrane elements that are connected in series. The concentrate of the first element becomes the feed to the second, and so on. The products tubes of all elements are coupled and connected to the module permeate port [21–23]. For different application a suitable hydraulic design can be made (2, 3, 4, 5, 6, 7, 8 serial elements), based on the actual situation. Fig. 1 shows the schematic representation of a RO module. Al-Bastaki and Abbas [25,26] presented the models of the spiral-wound and hollow-fiber membrane elements, which took into account the pressure drop and concentration changes in the membrane channel. The PV performance can be approximately simplified to the performance of the membrane elements connected in series. Therefore, based on the membrane element models, a pressure vessel model is presented as follows which