Desalination 365 (2015) 365–380

Contents lists available at ScienceDirect

Desalination

journal homepage: www.elsevier.com/locate/desal

Optimization of reverse osmosis networks with split partial second pass design

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HIGHLIGHTS

- An optimal study of RO networks with split partial second pass design is proposed.
- Variation of velocity, pressure, and concentration in membrane module is considered.
- Salinity increase caused by volumetric mixing in pressure exchanger is considered.
- SPSP provides lower cost & power consumption, smaller system size than normal design.
- Membrane with large active area and high salt rejection is favored for SPSP design.

ARTICLE INFO

Article history:
Received 8 January 2015
Received in revised form 24 February 2015
Accepted 13 March 2015
Available online 21 March 2015

Keywords:
Reverse osmosis
Seawater desalination
System optimization
Spiral-wound module
Split partial second pass

ABSTRACT

This study proposes an optimal study of reverse osmosis (RO) seawater desalination system based on the split partial second pass (SPSP) design in order to fully utilize better quality and higher flux for the permeate at the front of the pressure vessel (PV). Differential equations in the membrane transport model are solved by finite difference method, which considers the longitudinal variation of the superficial velocity, the pressure and the salinity inside the PV. Superstructure optimization is adopted to determine optimal flow structure, appropriate membrane type, and operation conditions. Firstly, single product RO system has been optimized, cost breakdown and sensitive analysis reveal that membrane with large active area and high salt rejection is favored for SPSP. System recovery, pressure, and split ratio for the permeate of pass 1 should be adjusted with time in order to decrease total annualized cost. Secondly, multiple product RO system has been studied. Three-pass RO configuration with permeate reprocessed and brine recycled is favored for the system with two permeate products. The optimal RO configuration with three permeate products is influenced by flow rates and required permeate concentrations. In general, SPSP could provide lower cost, lower energy consumption, and smaller system size than normal design.

1. Introduction

Nowadays, reverse osmosis (RO) is a commercially attractive seawater desalination technology to obtain fresh water for domestic and industrial facilities. It is a pressure-driven process that requires high pressure gradient across the semi-permeable membrane to overcome the seawater osmotic pressure and allows the passage of water through the membrane, but not ions or other larger molecules [1]. Since most of the pressure energy remains in the brine, energy recovery devices (ERDs) are often introduced to reduce the power consumption for the RO system [2]. RO has improved considerably in the past years, which has many advantages over other desalination technologies, in terms of no phase-change, low energy consumption, modularity, flexibility, as well as less installation space [3,4].

Most RO desalination plants often use the spiral-wound module (SWM) type membranes, which can provide a better balance of pure water permeability, packing density, membrane fouling control, as well as easy operation [5]. Thus, optimal design of the RO system with SWMs has received immense interest in recent years.

Lu et al. [6] developed optimization methodologies for the RO system with SWMs to find optimal membrane types, flow configuration, and operation conditions. However, salinity increase at the outlet of the pressure exchanger (PX) was not considered. Besides, pressure vessel (PV) was treated as an averaged membrane element, as a result, the accuracy of the membrane transport model could not be guaranteed. Geraldes et al. [7] established a numerical model to seek the optimum process flow structure and operation conditions for RO processes. The longitudinal variation of the superficial velocity, the pressure and the

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http://dx.doi.org/10.1016/j.desal.2015.03.019
0011-9164/

salinity inside the feed channel of PV were taken into account. But the superstructure optimization was not introduced, which could embed all possible flow configurations of a RO network (RON). Sassi and Mujtaba [8] optimized RO desalination system with membrane fouling. Studies review that the membrane fouling distribution among RO stages would have significantly influenced the optimization design and operation of RO system. Park et al. [9] developed a stochastic cost framework to evaluate the construction and operating costs of RO seawater desalination plants, so that decision maker could respond to the variation of uncertain future electricity and finance costs for this energy-intensive technology. Some researches focused on the RO network design with boron removal, or combination with other desalination technologies for water and power production [10–13].

In a typical SWRO system with several membrane modules in pressure vessels, the front RO modules produce higher flux permeate with lower salt concentration than modules at the back of the PV. Fig. 1 shows typical combined salt concentration and permeate flux distribution in PV with eight seawater RO membrane modules [14]. Front membrane modules produce the highest permeate flux with the best quality. Based on the concept that making full use of the detailed knowledge of RO membrane performance in PV, Bray proposed split partial second pass (SPSP) design for the first time [15]. Recently, Saif et al. [16] optimized the multiple product RO system with SPSP design for seawater desalination. Permeates branching from each RO membrane module in the PVs were considered. Fig. 2 gives the schematic diagram of RO stage based on SPSP design with auxiliary equipment [16]. Studies show that lower fresh water cost and higher system recovery are obtained by introducing permeate splitting streams in the RON.

However, despite the benefits of the design provided by Saif et al. [16], there are still some disadvantages. On the one hand, the structure of the PV should be redesigned, and on the other hand, the operation of the optimized RO system is more complicated than normal design, since several permeate flows are extracted from one PV.

In this study, the RO system with simple SPSP design is based on the concept provided by Rybar et al. [14]. As shown in Fig. 3, flow control valves (FCVs) on permeate lines allow continuous adjustment of split ratio (the ratio of front permeate to back permeate inside PV) according to actual membrane performance, feed seawater temperature, and salinity, which make the operation of the RO system easier. Moreover, the structure of the PV does not need to be changed, thus the new design could be utilized in the existing RO desalination plant to decrease the costs and energy consumption.

The current work proposes an optimization study of RO networks with SPSP design for seawater desalination. Differential and algebraic equations are used to describe the membrane transport phenomena inside PV. Besides, SPSP model is represented through binary variables, which are utilized to control the sub-element permeate flow direction. A multiple product RO superstructure that contains all possible process flow alternatives is put forward, and salt concentration increase caused by volumetric mixing between the seawater and brine inside the PX is calculated. System flow constraints are added to ensure that the obtained optimal RO system could operate in a safe state. The obtained mixed-integer non-linear programming (MINLP) is solved to determine the optimal flow structure, stream distribution (including optimal split ratio with SPSP design) and operating conditions, and the optimum design without SPSP is also presented for comparison. The advantages of the proposed RO system with SPSP design will be illustrated through several case studies.

2. Process modeling

2.1. Spiral-wound module model

The performance of spiral-wound module RO system is predicted by the solution diffusion membrane transport model, which is based on the one proposed by Geraldes et al. [7], Avlonitis et al. [17], and Du et al. [18, 19]. The sketch of a flat feed channel with a thickness h and dimensions of L_{PV} (length of pressure vessel) × W (width of membrane leaf) is illustrated in Fig. 4. L_{PV} is the product of the number of modules (n_m) and the module length (L_m).

The material and momentum balances to the infinitesimal control volume are as follows:

$$\frac{dV}{dz} = -2\frac{V_w}{h} \tag{1}$$

$$\frac{dVC_{ch,b}}{dz} = -2\frac{V_w C_{ch,p}}{h} \tag{2}$$

$$\frac{dP}{dz} = -K_\lambda 6.23\mathrm{Re}^{-0.3}\frac{\rho}{d_e}\frac{V^2}{2} \tag{3}$$

where V is the feed superficial velocity; z is the axial distance along membrane module (increasing with the main flow direction); V_w is the permeate local volumetric velocity; C is the salt concentration; h is the thickness of feed channel; P is the feed hydraulic pressure; ρ is the mass density of seawater, and d_e is the equivalent diameter of feed channel. The introduced K_λ is to calculate the pressure drop caused by friction in the feed channels and membrane element fittings [7]. Subscript ch denotes the channel inside the membrane module, b denotes brine, and p denotes permeate.

Finite difference method is adopted to solve the previous differential equations and detailed in Table 1. The concept of SPSP design is based on the fact that the front part membrane modules in PVs are always providing better permeate quality than modules at the back part of the PVs. For the PV with SPSP design (Fig. 3), permeates are collected

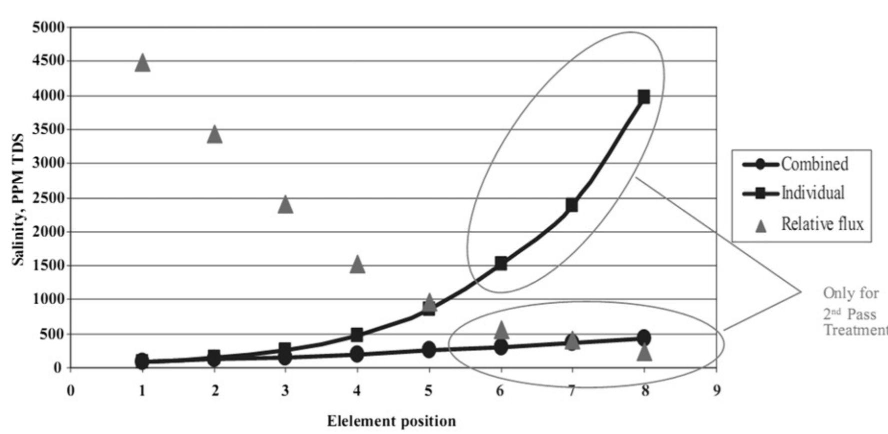

Fig. 1. SWC3 permeate flux and salt concentration distribution in pressure vessel with 8 membrane modules [14].