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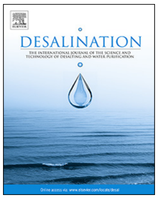

Process economics and operating strategy for the energy-efficient reverse osmosis (EERO) process

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ABSTRACT

The energy-efficient reverse osmosis (EERO) desalination process was recently developed for cost-effective high total water recovery. It feeds the retentate from one or more single-stage reverse osmosis (SSRO) stages in series to a countercurrent membrane cascade with recycle (CMCR) consisting of a terminal reverse osmosis (RO) stage and one or more low salt-rejection stages. The CMCR permits retentate refluxing in the low salt-rejection stages and multi-pass processing of permeate. The novel 2-2 EERO process is advanced that involves two SSRO stages in series with a 2-stage CMCR. To address problems encountered in a pilot-scale test of the EERO process, it develops an operating strategy involving boosting the pressure to the low salt-rejection stage of the CMCR to compensate for using membranes with a higher salt rejection than required. A process embodiment for mitigating concentration polarization is also advanced. The first estimate of the total cost of water production for three EERO process configurations is made. The EERO process can reduce the osmotic pressure differential by 50% relative to conventional SSRO for the same total water recovery and can achieve 75% total water recovery at a lower total cost of water production than conventional SSRO operated at just 50% water recovery.

1. Introduction

The rate of increase in the demand for water during the 20th century was more than twice that of the population [1]. As a result, 40% of the people in the world now live in areas subject to water stress, which is expected to reach 48% by 2025 [2]. In addition, pathogenic contaminants in the limited fresh water supply of the world affect nearly 1 billion people today and are projected to affect as many as 3.5 billion people by 2025 [3]. Although 70% of the earth is covered by water, only an estimated 0.007% of this water is accessible as fresh water to sustain a world population of 7.3 billion people [4]. This limited water supply is being compromised owing to pollution and contamination associated with increased industrial and agricultural use. Hence, increasing our available supply of fresh water is now a global concern.

Seawater desalination via reverse osmosis (RO) has emerged as a technology for increasing the fresh water supply of the world. The International Desalination Association reported that in 2015 there were 18,426 desalination plants in the world supplying fresh water to > 300 million people in 150 countries [5]. However, RO desalination is still an expensive source of fresh water. It costs between $\$0.66/m^3$ to $\$1.32/m^3$ to produce fresh water via RO desalination in comparison to an average cost of $\$0.53/m^3$ for a direct source of fresh water [6]. A major reason for the high cost of RO desalination is the high pressure required to achieve a reasonable water recovery while overcoming the osmotic pressure differential (OPD) between seawater and fresh water. For example, for a typical seawater containing 35,000 ppm of salt producing a fresh product water containing 350 ppm of salt, the minimum applied pressure required to achieve a 50% total water recovery using conventional single-stage RO (SSRO) is 55.5 bar. There is considerable motivation to increase the total water recovery in RO desalination since more than half the total cost for water production is associated with pretreatment of the feed water to the RO (to avoid fouling and scaling) and disposal of the waste brine [7,8]. These costs are projected to increase owing to more demanding environmental regulations. If the total water recovery can be increased, the pretreatment and brine disposal costs normalized with respect to the volume of RO product water produced will be reduced. Increasing the total water recovery not only reduces the brine disposal cost, but also increases the concentration of the brine; this more highly concentrated brine can be used in a hybrid RO-PRO (pressure-retarded osmosis) process for harvesting the osmotic potential energy in the concentrated waste brine [9,10]. However, increasing the total water recovery via conventional SSRO requires a

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much higher operating pressure. For example, achieving a 75% total water recovery via conventional SSRO would require an operating pressure of at least 111 bar; operating RO at this pressure is impractical since conventional commercial RO membranes are typically limited to a maximum pressure of 69 bar, although commercial membrane modules are available that can accommodate a pressure of 80 bar. A promising path to achieving a higher total water recovery at reduced operating pressures is to develop innovative RO desalination technologies, which is the focus of this paper.

This paper is organized as follows. Section 2 reviews conventional SSRO desalination and underscores its limitations. It then provides an overview of the recently advanced energy-efficient reverse osmosis (EERO) process that can achieve a high total water recovery at a considerably reduced OPD and competitive net specific energy consumption (SEC_{net}). A critical assessment of the state-of-the-art then leads to the objectives of this study. Section 3 develops an operating strategy for the EERO process that is supported by a mathematical model. Section 4 gives the performance metrics for three configurations of the EERO process. Section 5 provides an estimate of the total cost of water production for the EERO process that includes both the fixed and operating costs. Section 6 summarizes the conclusions and recommendations emanating from this study.

2. Background

2.1. Conventional RO

Consider first the SSRO process shown in Fig. 1 where Q_i and C_i denote the volumetric flowrate and salt concentration in mass per unit volume of stream i in which the subscripts f and p denote the feed and permeate water product, respectively.

For operation at the thermodynamic limit (i.e., at a transmembrane pressure corresponding to thermodynamic equilibrium between the feed and permeate in the stage), the total water recovery Y and SEC_{net} are unique functions of the OPD, Δπ, and the specified salt concentrations in the feed and product water given by the following:

$$Y = \frac{\Delta\pi - K(C_f - C_p)}{\Delta\pi} \tag{1}$$

$$SEC_{net} = \frac{K(C_f - C_p)}{\eta_P Y(1 - Y)} - \frac{\eta_{ERD} K(C_f - C_p)}{Y} \tag{2}$$

where η_P and η_{ERD} are the pump and energy-recovery-device (ERD) efficiencies, respectively, and K is the proportionality constant in the assumed linear relationship between osmotic pressure and the salt concentration. The derivation of Eqs. (1) and (2) is included in Appendix A. The first term on the right-hand-side of Eq. (2) is the gross specific energy consumption (SEC_{gross}), whereas the second term is the specific energy recovered by the ERD. For a typical seawater feed having a salt concentration of 35,000 ppm producing a product water with a salt concentration of 350 ppm, assuming pump and ERD efficiencies of 85% and 90%, respectively, the OPD and SEC_{net} required to achieve 75% water recovery are 111 bar and 3.915 kWh/m^3, respectively. The assumed ERD efficiency corresponds to using an isobaric pressure-exchanger device that is appropriate when the retentate pressure is only slightly less than the required feed pressure [11].

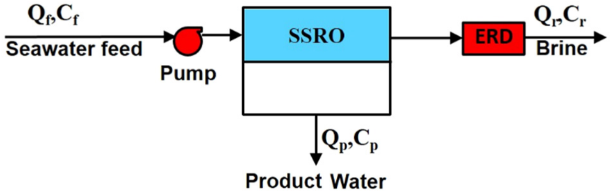

Fig. 1. Schematic of single-stage reverse osmosis (SSRO).

Hence, a high water recovery with an SSRO requires an unreasonably high OPD and incurs a very high SEC_{net}.

The SEC_{net} can be reduced by employing two SSRO stages in series to increase the pressure in two steps, which reduces the amount of water that must be pumped up to the maximum pressure. A schematic of two SSRO stages in series is shown in Fig. 2 in which the retentate from the first RO stage is the feed to the second RO stage.

The product water is the blended permeate stream from the two SSRO stages, both of which are specified to have the same concentration to avoid entropy-of-mixing effects. Note for the specified feed and product water concentrations that this would require using membranes with salt rejections of 0.990 and 0.995 in SSRO-1 and SSRO-2, respectively, owing to the increase in salt concentration. For operation at the thermodynamic limit the total water recovery Y and SEC_{net} are given by the following:

$$Y = Y_{SSRO\text{-}1} + Y_{SSRO\text{-}2}(1 - Y_{SSRO\text{-}1}) \tag{3}$$

$$SEC_{net} = \frac{Y_{SSRO\text{-}1}\Delta\pi_{SSRO\text{-}1} + (1 - Y_{SSRO\text{-}1})\Delta\pi_{SSRO\text{-}2}}{\eta_P Y} - \frac{\eta_{ERD}(1 - Y_{SSRO\text{-}1})(1 - Y_{SSRO\text{-}2})\Delta\pi_{SSRO\text{-}2}}{Y} \tag{4}$$

where $\Delta\pi_{SSRO\text{-}1}$ and $\Delta\pi_{SSRO\text{-}2}$ are the specified OPDs in SSRO-1 and SSRO-2, respectively, and, $Y_{SSRO\text{-}1}$ and $Y_{SSRO\text{-}2}$ are the water recoveries in SSRO-1 and SSRO-2, respectively, that are given by the following:

$$Y_{SSRO\text{-}1} = 1 - \frac{K(C_f - C_p)}{\Delta\pi_{SSRO\text{-}1}} \tag{5}$$

$$Y_{SSRO\text{-}2} = 1 - \frac{\Delta\pi_{SSRO\text{-}1}}{\Delta\pi_{SSRO\text{-}2}} \tag{6}$$

For a specified OPD in SSRO-2, the OPD in SSRO-1 was chosen to minimize the SEC_{net} for the two SSRO stages in series and is given by the following:

$$\Delta\pi_{SSRO\text{-}1} = [K(C_f - C_p)\Delta\pi_{SSRO\text{-}2}]^{0.5} \tag{7}$$

The derivation of Eqs. (3) through (7) is included in Appendix B. For a seawater feed having a salt concentration of 35,000 ppm producing a product water having a salt concentration of 350 ppm, assuming pump and ERD efficiencies of 85% and 80%, respectively, for 75% total water recovery, the OPD in SSRO-2 is 111 bar and the SEC_{net} is 2.808 kWh/m^3. The lower ERD efficiency corresponds to using an energy-recovery turbine device, since a more efficient isobaric pressure exchanger device cannot be used when the retentate pressure is significantly higher than the required feed pressure [11]. Using two SSROs in series significantly reduces the SEC_{net} because only that portion of the feed that is not recovered as product water in SSRO-1 is pumped up to $\Delta\pi_{SSRO\text{-}2}$ in SSRO-2 as can be seen from the first term on the right-hand-side of Eq. (4). However, using two SSROs in series does not reduce the maximum OPD required. Hence, a total water recovery of 75% still requires an OPD of 111 bar in SSRO-2 that is not possible with currently available RO membranes.

Adding three or more SSRO stages in series will reduce the SEC_{net} further. However, the terminal stage in the series of SSROs will still be required to operate at an OPD of 111 bar to achieve a 75% total water recovery for a typical seawater feed having a salt concentration of 35,000 ppm. Hence, high total water recoveries cannot be achieved at reasonable operating pressures using SSRO stages in series.

2.2. Energy-efficient reverse osmosis (EERO) process

Section 2.1 established that conventional SSRO or two or more SSRO stages in series cannot achieve a high total water recovery at a reasonable operating pressure. This challenge was addressed by the recently advanced EERO process that capitalizes on the advantages of SSRO and of a countercurrent membrane cascade with recycle (CMCR).