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Energy optimization of a multistage reverse osmosis process for seawater desalination

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ABSTRACT

The water recovery, net specific energy consumption (SEC_{net}) and osmotic pressure differential (OPD) are determined for a multistage reverse osmosis (MSRO) process relative to conventional and the recently advanced energy-efficient RO (EERO) processes. The MSRO process combines RO and nanofiltration (NF) stages in series, and blends permeate from the NF stages with the saltwater feed. This increases the water recovery and lowers the rejections required in the RO stages. The SEC_{net} of the MSRO process to produce water containing ≤ 350 ppm salt is evaluated at the thermodynamic limit for pump and energy-recovery-device efficiencies of 85% and 90%, respectively, which provides a basis of comparison relative to alternative processes. The MSRO process employing one RO and two NF stages in series achieves a 65% water recovery for a 35,000 ppm seawater feed producing a product water with ≤ 350 ppm salt at an OPD of 51.7 bar and SEC_{net} of 2.688 kWh/m^3, reductions of 35% and 8%, respectively, relative to conventional SSRO. For the same conditions, the MSRO process employing two RO and two NF stages in series requires an OPD of 68.0 bar and SEC_{net} of 2.22 kWh/m^3, reductions of 14% and 1.6%, respectively, relative to two-stage SSRO.

1. Introduction

The World Health Organization (WHO) reported in 2015 that 9% of the world population lacks access to improved sources of drinking water and the need for potable water is constantly increasing due to the expanding world population [1]. In the absence or insufficiency of surface and underground potable water sources, the oceans that contain 97% of the water on earth are a major alternative resource. However, ocean water is unsuitable for human consumption without treatment, since it contains typically 35,000 ppm of salt (sodium chloride). Reverse osmosis (RO) is as a major technology for producing potable water from salt water using a salt-rejecting membrane under a pressure higher than the osmotic pressure in order to allow water to permeate through the membrane to obtain potable water while rejecting the salt and other solutes. RO also can be used to produce potable water from inland brackish water whose salt content typically is 10,000 ppm or less.

The production of potable water from seawater by RO is more efficient compared to methods such as evaporation, since it does not involve a phase transition. However, the required pressure in RO is high to overcome the osmotic pressure difference, which contributes significantly to the cost of water desalination. In the case of seawater desalination, a pressure typically above 40 bar or more is required, whereas the recovery of potable water is low, typically around 40 to 50%. As a result, the specific energy consumption (SEC) for producing potable water from seawater is relatively high. In order to produce potable water by reducing the salt content of seawater from 35,000 ppm to 350 ppm, the theoretical SEC required by conventional single-stage RO (SSRO) is 3.086 kWh/m^3 (kilowatt hours of energy per cubic meter of product water) using a membrane with a salt rejection of 0.99 and an ideal pump at an osmotic pressure difference (OPD) of 55.5 bar with a water recovery of only 50% [2].

There are ongoing efforts to reduce the SEC and to increase water recovery simultaneously, by developing new process configurations

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that use multiple membrane stages and recycle streams [3–6], and by optimizing the process parameters [7–9]. This is especially important, since both the feed pretreatment and brine management costs will decrease with increasing water recovery [10], thus improving the process economics. A recent "energy-efficient reverse osmosis (EERO)" process was reported to reduce the salt content of a salt water feed from 35,000 ppm to 350 ppm at an increased water recovery and reduced OPD and SEC relative to the conventional SSRO [2].

This study explores a multistage RO (MSRO) process that combines RO and nanofiltration (NF) stages in series. As such it draws from a recent patent application that uses RO and NF stages in series to produce a concentrated brine [11]. However, it also draws on the recently developed EERO process that employs permeate recycling to an upstream stage (with respect to the direction of the retentate flow) [2]. In particular, this study explores a multistage RO-NF process that employs permeate recycle in terms of optimizing its OPD and SEC requirements via an appropriate choice of the process parameters and compares its performance metrics with those of conventional single-stage and two-stage RO processes as well as the EERO process.

2. Background

Since the performance of the MSRO process is evaluated relative to the EERO process [2], the same nomenclature used in describing the latter is adopted in this study. Accordingly, the fractional overall water recovery Y for an RO stage is expressed as:

$$Y = Q_0/Q_f = 1 - K(C_0 - C_1)/\Delta\pi \tag{1}$$

where, the subscripts f and 0 denote the feed and permeate streams, respectively, and K (0.801 L.bar/g) is the coefficient in the relationship between the concentration (C) and the OPD ($\Delta\pi$) of stage i. For specified feed and permeate concentrations, $\Delta\pi$ and the gross SEC are functions of the fractional overall water recovery:

$$\Delta\pi = K(C_F - C_P)/(1 - Y) \tag{2}$$

$$SEC = \Delta\pi/\eta_P Y = K(C_F - C_P)/[\eta_P Y(1 - Y)] \tag{3}$$

where η_P is the pump efficiency. For a single-stage RO (SSRO) process, the minimum value of the SEC for a typical seawater feed corresponds to a 50% water recovery ($Y_{SSRO} = 0.5$). In practice, the energy requirement of an RO process may be substantially reduced via the use of an energy recovery device (ERD); the net specific energy consumption, SEC_{net}, of the process then is expressed as:

$$\begin{aligned} SEC_{net} &= SEC - \eta_{ERD}\Delta\pi(1 - Y)/Y \\ &= K(C_F - C_P)[1/\eta_P Y(1-Y) - \eta_{ERD}/Y] \end{aligned} \tag{4}$$

where η_{ERD} is the efficiency of the ERD. However, for higher water recoveries, the SEC_{net} increases significantly.

Alternatively, RO stages in series can be used to increase the recovery and decrease the SEC, such as two RO stages in series (TSRO), where the retentate from the first stage is fed to the second stage and the permeate from both stages is collected as the product water. In this case, a booster pump is required between the two RO stages, since the retentate of the first stage has a higher concentration than the feed. However, whereas this configuration increases the recovery and decreases the SEC, it increases the OPD for the second stage.

Recently, the EERO process was proposed as an alternative to obtain increased water recovery with a lower SEC and OPD relative to SSRO. This process combines conventional SSRO with a countercurrent membrane cascade with permeate recycle to an upstream stage (with respect to the direction of the retentate flow) and retentate reflux via the use of one or more nanofiltration (NF) stages. At least three membrane stages are employed in this process that can achieve 75% water recovery with a 33% reduction in OPD and 11% in the SEC_{net} relative to SSRO. The details of the EERO process can be found elsewhere [2]. The higher overall water recovery of the EERO process will translate to a reduction in the pretreatment and brine-disposal costs. However, this comes at the cost of an increased process complexity and control strategy. The reduction in the pumping costs and in the total cost of water production underscores the advantages of employing permeate recycle to an upstream stage and retentate reflux that will be optimized in the novel MSRO process described in this paper.

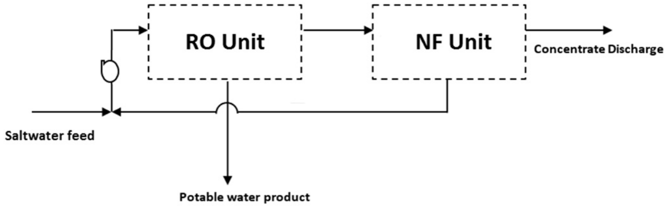

Fig. 1. Generalized representation of the MSRO process where each unit may house one or more membrane modules in series.

The MSRO process can be a viable modification of the EERO process if operated optimally. This process combines RO stages with NF stages, and recycles the permeate from the NF stages to the RO stages as shown in Fig. 1. The main purpose of this study was to identify the optimum design parameters for the RO and NF stages as well as other operating parameters such as the stage recoveries. The analysis is carried out at the thermodynamic limit that sets a reasonable basis for this assessment due to the availability of commercial high flux RO membranes that allow operating at transmembrane pressures only slightly above the thermodynamic limit [5].

3. Model development

Four different configurations of the MSRO process are considered and compared in terms of their energy requirements in this study. These configurations as shown in Fig. 2 differ as to the number of RO and NF stages present in the process and are summarized in Table 1. For each of the configurations, the minimum SEC_{net} and OPD are evaluated by searching through the stage salt rejections as a function of the overall fractional water recovery (Y), which is defined as the ratio of the potable water flow rate (Q_P) to the saltwater feed flow rate (Q_F).

The quantitative analysis of these four configurations is carried out for different feed conditions. For conciseness, only the equations describing the R2N2 configuration are provided here; a detailed mathematical analysis is given in the Appendix A. The equations describing the interrelationship between the volumetric flow rate denoted by Q_i and the salt concentrations expressed as mass per unit volume and denoted by C_i in Fig. 2, where the subscript 'i' denotes the location of the particular stream or concentration, will be solved analytically. The solution to this system of algebraic equations will permit determining the recovery, OPD, SEC_{net}, and the initially unspecified salt rejections in each stage.

The analysis of this 4-stage MSRO process involves solving overall material and solute balances for each of the four stages and at the two mixing points. The balances over stage R1 constitute 2 equations involving 6 unknowns (Q_0, C_0, Q_1, C_1, Q_{10}, C_{10}). The balances over stage R2 constitute 2 equations involving 4 unknowns (Q_{11}, C_{11}, Q_{12}, C_{12}).